

**EXPERIMENTS CONCERNING THE COMMERCIAL EXTRACTION OF
METHANE FROM COALBED RESERVOIRS**

by

Ian Morton Loomis

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Approved:

Dr. Malcolm McPherson
Dr. Michael Karmis
Dr. Gerald Luttrell
Dr. Ertugrul Topuz
Dr. Mark Widdowson

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Ian Morton Loomis
Malcolm J. McPherson, Chairman
Department of Mining and Minerals Engineering

(ABSTRACT)

In late 1992 coalbed methane became the most significant source of natural gas produced in Virginia. This gas is held within the coal formations adsorbed to the coal matrix. The current well stimulation technology applies a high pressure fluid to the coal formation surrounding the wellbore to induce a series of fractures. The research documented in this thesis investigates several new technologies that could replace or augment the current well stimulation approach of hydraulic fracturing.

The application of liquid carbon dioxide, as the stimulation agent was investigated in a series of permeability tests. These measurements were made using a radial flow technique developed specifically for this research project. The results of the tests using liquid carbon dioxide to enhance the permeability of coal samples, to methane gas, indicated a significant increase in permeability of the samples. Comparison to a reference material showed, however, that the increase was of a general nature, not by specific interaction with the coal matrix. Rather, the permeability increase was due to reduced resistance of the borehole skin. Studies of the new, radial flow, permeability measurement approach showed good agreement to a conventional, axial flow, approach for similar sample bedding orientation to the gas flow.

The documented experiments also include investigations into the potential for using custom designed nitrocellulose/nitroglycerin/RDX based propellant charges to produce extensive fracturing away from the wellbore. The first series of these experiments concerned the characterization of the burn properties for these propellants and their mixtures. Utilizing an interior ballistics approach, these laboratory small-scale shots were numerically modeled with a program written as a part of this project. Using the small-scale results and the modeled data, a series of large-scale test shots were developed and fired to gain understanding of the scale effects. The small-scale constant volume bomb, and the large-scale vented bomb were both custom designed and fabricated for this project. Comparisons of the laboratory data and modeled predictions show good agreement for both the small and large-scale test series.

This work concludes by presenting considerations for utilizing the propellant based well stimulation approach in the water filled wells in southwest Virginia.

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Table of Contents

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
	Cover	i
	Abstract	ii
	Acknowledgments	iii
	Table of Contents	v
	List of Tables	xii
	List of Figures	xiii
	List of Plates	xix
	Lexicon	xxii
1	Introduction	1
1.1	<i>State of Affairs</i>	1
1.2	<i>Existing Technology</i>	5
1.3	<i>Current Investigations</i>	7
2	Literature Review	9
2.1	<i>Nature of the Problem</i>	10
2.1.1	Unconventional Methane Sources	10
2.1.2	Distribution of Coalbed Methane	12
2.1.2.1	Throughout the United States	12
2.1.2.2	Within Virginia	13
2.1.3	Economic Assessment	14
2.2	<i>State of the Art</i>	15
2.2.1	Open Hole-Stable Cavity Completions	15
2.2.2	Cased Hole Completions	19
2.2.2.1	Cross-Linked Gels	20
2.2.2.2	Water Fracturing	20
2.2.2.3	Foam Fracturing	21
2.2.3	Effect of Permeability	21
2.2.3.1	Methane Desorption Characteristics	22
2.2.3.2	Diffusion of Methane in Coal Matrix	25
2.2.3.3	Movement of Methane in Cleats and Fractures	25

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
2.2.3.4	Effect of Relative Permeability and Two-Phase Flow	26
2.2.3.5	Permeability Assessment	27
2.2.3.5.1	Field Methods	27
2.2.3.5.2	Laboratory Methods	32
2.2.3.6	Coal Swelling	33
2.3	<i>Advanced Techniques in Well Stimulation</i>	34
2.3.1	Multiple Fracturing (Tailored Pulse)	34
2.2.3	Liquid Carbon Dioxide	38
2.4	<i>Performance Assessment</i>	39
2.5	<i>Methane Production Simulation</i>	40
3	Tests Involving Liquid Carbon Dioxide	42
3.1	<i>Basic Theory</i>	42
3.1.1	Permeability Measurement	47
3.1.1.1	Axial Samples	47
3.1.1.2	Radial Samples	48
3.1.1.3	Conditions of Flow and Pressure Effects	49
3.1.1.3.1	Reynold's Number Criteria	49
3.1.1.3.2	Pressure Effects on Viscosity	50
3.1.1.3.3	Porous Media Parameters	51
3.1.2	Approach to Laboratory Measurement of Radial Permeability	52
3.1.3	Baseline Procedure for Comparison Between Axial and Radial Measurements	53
3.1.4	Comparison of Mean Pressure and Pressure Gradient in Baseline Samples	53
3.1.5	Effects of Carbon Dioxide on Coal	58
3.1.6	Effects of Pressure State of the Sample	61
3.2	<i>Test Procedure and Parameters</i>	62
3.2.1	Sample Preparation	65
3.2.2	Test Cell Configuration	77
3.2.3	Data Collection	80
3.2.3.1	Manual Data Collection	80
3.2.3.2	Automatic Data Collection	80
3.2.4	Evaluation	81
3.2.4.1	Sandstone Samples	81
3.2.4.2	Coal Samples	82
3.2.5	Possible Patent Information	83

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
3.3	<i>Results</i>	85
3.3.1	Baseline Samples	85
3.3.1.1	Axial Samples	88
3.3.1.1.1	Sample SSAXI1	88
3.3.1.1.2	Sample SSAXI2	91
3.3.1.1.3	Sample SSAXI3	94
3.3.1.2	Radial Samples	97
3.3.1.2.1	Sample SSRAD1	97
3.3.1.2.2	Sample SSRAD2	99
3.3.1.2.3	Sample SSRAD3	102
3.3.1.2.4	Sample SSRAD4	105
3.3.2	Coal Samples for Evaluation	109
3.3.2.1	Sample PMOGS	110
3.3.2.2	Sample PMOG01	113
3.3.2.3	Sample PMOG05	115
3.3.2.4	Sample PMOG09	119
3.3.2.5	Sample PMOG10	121
3.3.2.6	Sample PMOG11	123
3.3.2.7	Sample PMOG12	125
3.3.2.8	Sample PMOG13	127
3.3.2.9	Sample PMOG16	129
3.3.2.10	Sample PMOG17	129
3.3.3	Other Samples of Interest	132
3.3.3.1	Liquid Carbon Dioxide	132
3.3.3.2	Gaseous Carbon Dioxide	133
3.4	<i>Discussion</i>	135
3.4.1	Disking Phenomenon	135
3.4.2	Effect of Sample Make Up	135
3.4.3	Comparison of Permeability Measured in Axial and Radial Samples	136
3.4.4	Parametric Effects	137
3.4.4.1	Effect of Variation of Temperature	141
3.4.4.2	Effect of Variation of Mean Gas Pressure	141
3.4.4.3	Effect of Variation of Mass Flow Rate	142
3.4.5	Effect of Liquid Carbon Dioxide Treatment	143
3.4.6	Effect of the Radial Flow Sample Design	146
3.4.7	Potential for Carbon Dioxide in Coalbed Methane Stimulation	147
3.5	<i>Nomenclature</i>	151

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
4	Tests of Propellant Characterization	153
4.1	<i>Basic Theory</i>	153
4.1.1	Confined Fracturing Fundamentals	154
4.1.2	Hydraulic Fracturing	159
4.1.3	Fracturing with High Explosives	159
4.1.4	Propellant Fracturing	161
4.2	<i>Apparatus and Test Parameters</i>	165
4.2.1	Propellant Properties	166
4.2.2	Confined Tests	168
4.2.2.1	Pressure Vessel	168
4.2.2.2	Charge Design	170
4.2.2.3	Data Logging System	171
4.2.3	Test Assembly	173
4.2.4	Data Evaluation	182
4.3	<i>Results</i>	182
4.3.1	Commercial Propellant Particle Size Distribution	182
4.3.2	Confined Burning Tests	190
4.3.2.1	100 Percent No. 5	197
4.3.2.2	75 Percent No. 5, 25 Percent No. 8700	204
4.3.2.3	66 Percent No. 5, 34 Percent No. 8700	209
4.3.2.4	50 Percent No. 5, 50 Percent No. 8700	213
4.3.2.5	100 Percent No. 8700	216
4.3.2.6	75 Percent No. 5, 25 Percent Model Rocket Fuel	216
4.3.2.7	66 Percent No. 5, 34 Percent Model Rocket Fuel	216
4.3.2.8	50 Percent No. 5, 50 Percent Model Rocket Fuel	216
4.3.2.9	100 Percent Model Rocket Fuel	222
4.3.2.10	100 Percent No. 2 - Improved	225
4.3.2.11	100 Percent Commercial Black Powder	230
4.4	<i>Determination of Linear Burn Rates</i>	237
4.4.1	100 Percent No. 5	242
4.4.2	75 Percent No. 5, 25 Percent No. 8700	251
4.4.3	66 Percent No. 5, 34 Percent No. 8700	257
4.4.4	50 Percent No. 5, 50 Percent No. 8700	263

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
4.5	<i>Discussion</i>	265
4.5.1	Effect of Temperature Sensitivity of the Pressure Transducer	265
4.5.2	Internal Reflection and End Effects	266
4.5.3	Effect of Pressure Rise-Time and Rise-Rate	267
4.5.4	Effect of Propellant Mixture	268
4.5.5	Comparison of Linear Burn Rate Measurements	270
4.6	<i>Nomenclature</i>	272
5	Numerical Modeling	273
5.1	<i>Thermodynamic Principles</i>	273
5.1.1	Conservation of Mass	274
5.1.2	Conservation of Energy	274
5.1.3	Noble-Abel Equation of State	274
5.1.4	Velocity of Vented Gases	275
5.2	<i>Model Development</i>	276
5.2.1	Burning Rate	276
5.2.2	Propellant Properties	277
5.2.3	Numerical Modeling	279
5.2.4	Deterrent of Propellant Burning	280
5.2.4.1	Instantaneous Ignition of Propellant	283
5.2.4.2	Axial Burn Profile	289
5.2.4.3	Radial Outward Burning	294
5.2.4.4	Altered Models	297
5.2.4.5	Effect of Venting of the Products of Combustion	297
5.3	<i>Results of Modeling Bench Scale Experiments</i>	298
5.3.1	100% No. 5 Propellant	307
5.3.2	75% No. 5, 25% No. 8700 Propellants	311
5.3.3	66% No. 5, 34% No. 8700 Propellants	314
5.3.4	50% No. 5, 50% No. 8700 Propellants	317
5.4	<i>Discussion</i>	319
5.5	<i>Nomenclature</i>	320

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
6	Laboratory Large-scale Propellant Shots	322
6.1	<i>Apparatus and Test Parameters</i>	322
6.1.1	Test Vessel	322
6.1.2	Data Collection	325
6.1.3	Shot Configuration	325
6.1.4	Data Evaluation	333
6.2	<i>Results</i>	335
6.2.1	100 gram Shots	335
6.2.2	250 gram Shots	340
6.2.3	500 gram (Nominal) Shots	344
6.2.4	750 gram (Nominal) Shots	348
6.3	<i>Discussion</i>	350
6.3.1	Linear Burn Rates	351
6.3.2	Numerical Model Comparison	357
6.3.2.1	Predicted Behavior	362
6.3.2.2	Laboratory Behavior	364
7	General Discussion	367
7.1	<i>Results of Tests with Liquid Carbon Dioxide</i>	367
7.2	<i>Results of Propellant Characterization Testing</i>	368
7.3	<i>Results of Numerical Modeling Exercises</i>	369
7.3.1	Burn Rate Equation and Parameters	369
7.3.2	Comparison of Predictions of Laboratory Behavior (Small-Scale)	369
7.4	<i>Observations from Large-scale Tests</i>	370
7.4.1	Linear Burn Rates	370
7.4.2	Numerical Modeling Results	370
8	Conclusions and Future Work.	372
8.1	<i>Radial Permeability Methods</i>	373
8.2	<i>Liquid Carbon Dioxide Stimulation</i>	374
8.3	<i>Propellant Characterization</i>	376
8.3.1	Pressure-Time	376
8.3.2	Linear Burn Rate	376
8.3.3	Numerical Model Development and Output	376

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
8.4	<i>Laboratory Large-scale Tests</i>	377
8.4.1	Predicted Behavior	378
8.4.2	Laboratory Behavior	378
8.5	<i>Consideration and Design of Field Charge</i>	379
8.5.1	Field Test Conditions	379
8.5.2	Pre-existing Well	380
8.5.3	New Well	380
8.5.4	Evaluation of Enhancement	381
8.5.5	Basic Design of Propellant Charge	382
8.5.5.1	Necessary Rise-Time	382
8.5.5.2	Estimated Charge Weight	383
8.5.5.3	Charge Layout	383
8.6	<i>Future Testing</i>	386
8.6.1	Radial Permeability	386
8.6.2	Propellant Based Stimulation	386
9	Summary	388
9.1	<i>Introduction</i>	388
9.2	<i>Carbon Dioxide Tests</i>	389
9.3	<i>Propellant Characterization</i>	393
9.4	<i>Numerical Modeling</i>	396
9.5	<i>Large-scale Tests</i>	398
9.6	<i>Conclusions</i>	401
9.6.1	Permeability Testing	401
9.6.2	Effect of Liquid Carbon Dioxide Treatment	401
9.6.3	Small-scale Propellant Characterizations	401
9.6.4	Numerical Modeling of Propellant Burns	402
9.6.5	Large-scale Propellant Tests	402
9.7	<i>Recommendations</i>	402
9.7.1	Radial Permeability Test Procedure	402
9.7.2	Future Work Involving Propellant Testing	402
9.7.3	Application of Propellant Stimulation Methods	403

<u>Chapter</u>	<u>Description</u>	<u>Page</u>
10	References Cited	404
	Appendix A - Carbon Dioxide Properties	416
	Appendix B - Patent Abstracts	421
	Appendix C - Small-scale Vessel Design	435
	Appendix D - Propellant Shot Pressure-Time Traces	455
	Appendix E - Code Listing for BURNIT.FOR Program	495
	Appendix F - Large-scale Vessel Design	535
	Vitae	548

List of Tables

<u>Table</u>	<u>Description</u>	<u>Page</u>
3-1	Viscosity Parameters for Methane and Carbon Dioxide.	51
3-2	Estimations of Mean Pressure Gradient for Radial Samples.	82
3-3	Patents with Possible Relation to Radial Permeability Technique.	84
3-4	Coal Samples Tested in Tri-Axial Test Cell.	110
3-6	Change in Permeability of Coal Samples.	136
3-7	Results of Permeability Testing.	138
3-8	Estimation of Sample Annulus Permeability by Shepherd's Method.	146
3-9	Parameters for Analysis of the Effect of Vent Holes in Radial Sample.	147
3-10	Patents Applicable to Carbon Dioxide Stimulation of Coalbed Methane Wells.	148
4-1	Primary Composition of Accurate Arms Propellants Employed.	167
4-2	Manufacturer's Specification for PCB108A02 Transducer.	172
4-3	Particle Size Distribution for Accurate Arms No. 5 Spherical Propellant.	184
4-4	Particle Size Distribution for Accurate Arms No. 8700 Spherical Propellant.	184
4-5	Particle Size Distribution for Accurate Arms No. 2-I Spherical Propellant.	184
4-6	Basic Propellant Burn Results for Shots Performed.	191
4-7	Linear Burn Rate Coefficients for Samples Indicated.	242
4-8	Comparison of Linear Burn Rate Coefficients.	270
5-1	Properties of Propellant M18.	278
5-2	Experimental and Estimated Peak Pressures.	284
5-3	Comparison Between Laboratory and Model Shots, Small-scale.	301
6-1	Basic Propellant Burn Results for Large-scale Shots and Numerical Models.	350
6-2	Comparison of Linear Burn Rate Coefficients for Samples Indicated.	352
6-3	Relationship Between Three Models of 465 gram Shot.	352
8-1	Affective Properties of Coalbed Methane Wells.	382
8-2	Propellant Charge Rise-Time, Basic Parameters.	383

List of Figures

<u>Figure</u>	<u>Description</u>	<u>Page</u>
1-1	Graph Illustrating Relationship Between Conventional and Coalbed Methane Production in Virginia.	3
2-1	Illustration of Cased Hole and Openhole Cavity Completion Methods.	18
2-2	Typical Adsorption/Desorption Isotherm	24
2-3	Typical Curves Illustrating the Relationship of Permeability to a Liquid and a Gas of a Two-Phase Flow System in a Porous Medium.	30
2-4	Gas and Water Relative Permeability Curves for a Coal Sample.	31
3-1a	Falling Head Permeameter.	44
3-1b	Constant Head Permeameter.	44
3-2	Permeability Experiment in Hoek Cell.	45
3-3	Three Dimensional Flow Field.	46
3-4	Relative Pressure as a Function of Position in a Hypothetical Well.	56
3-5a	Relative Pressure as a Function of Relative Radial Position.	57
3-5b	Relative Pressure Gradient as a Function of Relative Radial Position.	57
3-6	Quantity of Adsorbed Gas as a Function of Methane Partial Pressure.	60
3-7	Radial Permeability Sample Configuration.	64
3-8	Schematic Drawing of Hoek Cell and Ancillary Systems.	79
3-9a	SSAXI1 Methane Permeability, Combined Data.	89
3-9b	SSAXI1 Methane Permeability, Combined Data Averages.	89
3-9c	Klinkenberg Graph, SSAXI1 Methane Permeability, Combined Data.	90
3-9d	Klinkenberg Graph, SSAXI1 Methane Permeability, Data Averages.	90
3-10a	SSAXI2 Methane Permeability, Combined Data.	92
3-10b	SSAXI2 Methane Permeability, Combined Data Averages.	92
3-10c	Klinkenberg Graph, SSAXI2 Methane Permeability, Combined Data.	93
3-10d	Klinkenberg Graph, SSAXI2 Methane Permeability, Data Averages.	93

<u>Figure</u>	<u>Description</u>	<u>Page</u>
3-11a	SSAXI3 Methane Permeability, Combined Data.	95
3-11b	SSAXI3 Methane Permeability, Combined Data Averages.	95
3-11c	Klinkenberg Graph, SSAXI3 Methane Permeability, Combined Data.	96
3-11d	Klinkenberg Graph, SSAXI3 Methane Permeability, Data Averages.	96
3-12	Methane Permeability SSRAD1.	98
3-13a	SSRAD2 Methane Permeability.	100
3-13b	SSRAD2 Methane Permeability, with Full Range.	100
3-13c	Klinkenberg Graph, SSRAD2 Methane Permeability.	101
3-14a	SSRAD3 Methane Permeability, Combined Data.	103
3-14b	Klinkenberg Graph, SSRAD3 Methane Permeability, Combined Data.	104
3-14c	Klinkenberg Graph, SSRAD3 Methane Permeability, Data Averages.	104
3-15a	SSRAD4 Methane Permeability, Combined Data.	107
3-15b	Klinkenberg Graph, SSRAD4 Methane Permeability, Combined Data.	108
3-15c	Klinkenberg Graph, SSRAD4 Methane Permeability, Data Averages.	108
3-16	PMOGS Methane Permeability.	112
3-17	PMOG01 Methane Permeability.	114
3-18	PMOG05 Methane Permeability.	117
3-19	PMOG09 Methane Permeability.	120
3-20	PMOG10 Methane Permeability.	122
3-21	PMOG11 Methane Permeability.	124
3-22	PMOG12 Methane Permeability.	126
3-23	PMOG13 Methane Permeability.	128
3-24	PMOG17 Methane Permeability.	131
3-25	Response of Parameters to Liquid Carbon Dioxide.	134
3-26	Response of Parameters to Gaseous Carbon Dioxide.	134
3-27	General Comparison Between Pre-Treatment and Post-Treatment Permeabilities for Sandstone and Coal Samples.	145

<u>Figure</u>	<u>Description</u>	<u>Page</u>
4-1	Illustration of Tri-Axial Cube and Fracture Plane.	156
4-2	Typical Relationship of Fracture Regime as a Function of Hole Diameter and Pressure Rise-Time for Sandstone.	157
4-3	Illustration of Three Fracture Regimes.	158
4-4	General Configuration of Small Bomb Tests.	169
4-5	Size Distribution of Three General Propellants Tested.	185
4-6	Illustration of Pressure Rise Parameters, Based on 5-29-96-A2.	193
4-7a	Example of Typical Pressure-Time Profile Curve, Ignition Inclusive.	194
4-7b	Example of Typical dP/dt Profile Curve, Ignition Inclusive.	194
4-8	Illustration of Peak Pressure as a Function of Charge Weight.	195
4-9a	Bomb Pressure as a Function of Time, Shot 5-29-96-A1.	199
4-9b	Bomb Pressure as a Function of Time, Shot 5-29-96-A1.	199
4-10a	Bomb Pressure as a Function of Time, Shot 5-29-96-A2.	200
4-10b	Bomb Pressure as a Function of Time, Shot 5-29-96-A2.	200
4-11a	Bomb Pressure as a Function of Time, Shot 5-29-96-A3.	201
4-11b	Bomb Pressure as a Function of Time, Shot 5-29-96-A3.	201
4-12a	Bomb Pressure as a Function of Time, Shot 6-13-96-D1.	202
4-12b	Bomb Pressure as a Function of Time, Shot 6-13-96-D1.	202
4-13a	Bomb Pressure as a Function of Time, Shot 6-13-96-D2.	203
4-13b	Bomb Pressure as a Function of Time, Shot 6-13-96-D2.	203
4-14a	Bomb Pressure as a Function of Time, Shot 5-31-96-A1.	205
4-14b	Bomb Pressure as a Function of Time, Shot 5-13-96-A1.	205
4-15a	Bomb Pressure as a Function of Time, Shot 5-31-96-A2.	206
4-15b	Bomb Pressure as a Function of Time, Shot 5-31-96-A2.	206
4-16a	Bomb Pressure as a Function of Time, Shot 6-13-96-C1.	207
4-16b	Bomb Pressure as a Function of Time, Shot 6-13-96-C1.	207
4-17a	Bomb Pressure as a Function of Time, Shot 6-13-96-C2.	208
4-17b	Bomb Pressure as a Function of Time, Shot 6-13-96-C2.	208
4-18a	Bomb Pressure as a Function of Time, Shot 5-29-96-B1.	210
4-18b	Bomb Pressure as a Function of Time, Shot 5-29-96-B2.	210
4-19a	Bomb Pressure as a Function of Time, Shot 5-29-96-B2.	211
4-19b	Bomb Pressure as a Function of Time, Shot 5-29-96-B2.	211
4-20a	Bomb Pressure as a Function of Time, Shot 5-29-96-B3.	212
4-20b	Bomb Pressure as a Function of Time, Shot 5-29-96-B3.	212
4-21a	Bomb Pressure as a Function of Time, Shot 6-13-96-B1.	214
4-21b	Bomb Pressure as a Function of Time, Shot 6-13-96-B1.	214

<u>Figure</u>	<u>Description</u>	<u>Page</u>
4-22a	Bomb Pressure as a Function of Time, Shot 6-13-96-B2.	215
4-22b	Bomb Pressure as a Function of Time, Shot 6-13-96-B2.	215
4-23a	Bomb Pressure as a Function of Time, Shot 6-13-96-A1.	216
4-23b	Bomb Pressure as a Function of Time, Shot 6-13-96-A1.	216
4-24a	Bomb Pressure as a Function of Time, Shot 6-13-96-A2.	219
4-24b	Bomb Pressure as a Function of Time, Shot 6-13-96-A2.	219
4-25a	Bomb Pressure as a Function of Time, Shot 6-5-96-B1.	220
4-25b	Bomb Pressure as a Function of Time, Shot 6-5-96-B1.	220
4-26a	Bomb Pressure as a Function of Time, Shot 6-5-96-B2.	221
4-26b	Bomb Pressure as a Function of Time, Shot 6-5-96-B2.	221
4-27a	Bomb Pressure as a Function of Time, Shot 6-5-96-A1.	223
4-27b	Bomb Pressure as a Function of Time, Shot 6-5-96-A1.	223
4-28a	Bomb Pressure as a Function of Time, Shot 6-5-96-A2.	224
4-28b	Bomb Pressure as a Function of Time, Shot 6-5-96-A2.	224
4-29a	Bomb Pressure as a Function of Time, Shot 6-19-96-A2.	226
4-29b	Bomb Pressure as a Function of Time, Shot 6-19-96-A2.	226
4-30a	Bomb Pressure as a Function of Time, Shot 6-19-96-A3.	227
4-30b	Bomb Pressure as a Function of Time, Shot 6-19-96-A3.	227
4-31a	Bomb Pressure as a Function of Time, Shot 7-2-96-A1.	228
4-31b	Bomb Pressure as a Function of Time, Shot 7-2-96-A1.	228
4-32a	Bomb Pressure as a Function of Time, Shot 7-2-96-A2.	229
4-32b	Bomb Pressure as a Function of Time, Shot 7-2-96-A2.	229
4-33a	Bomb Pressure as a Function of Time, Shot 7-2-96-B1.	232
4-33b	Bomb Pressure as a Function of Time, Shot 7-2-96-B1.	232
4-34a	Bomb Pressure as a Function of Time, Shot 7-2-96-B2.	233
4-34b	Bomb Pressure as a Function of Time, Shot 7-2-96-B2.	233
4-35a	Bomb Pressure as a Function of Time, Shot 7-2-96-B3.	234
4-35b	Bomb Pressure as a Function of Time, Shot 7-2-96-B3.	234
4-36a	Bomb Pressure as a Function of Time, Shot 7-2-96-C1.	235
4-36b	Bomb Pressure as a Function of Time, Shot 7-2-96-C1.	235
4-37a	Bomb Pressure as a Function of Time, Shot 7-2-96-C2.	236
4-37b	Bomb Pressure as a Function of Time, Shot 7-2-96-C2.	236
4-38a	Linear Burn Rate Model Example, Linear Axes.	239
4-38b	Linear Burn Rate Model Example, Logarithmic Axes.	239
4-39	Linear Burn Rate as a Function of Pressure, for Shots of 100 Percent No. 5 Propellant.	244
4-40a	Linear Burn Rate, Entire Model, Shot 5-29-96-A-Average.	245
4-40b	Linear Burn Rate Model, Shot 5-29-96-A-Average.	245

<u>Figure</u>	<u>Description</u>	<u>Page</u>
4-41a	Linear Burn Rate, Entire Model, Shot 5-29-96-A1.	246
4-41b	Linear Burn Rate Model, Shot 5-29-96-A1.	246
4-42a	Linear Burn Rate, Entire Model, Shot 5-29-96-A2.	247
4-42b	Linear Burn Rate Model, Shot 5-29-96-A2.	247
4-43a	Linear Burn Rate, Entire Model, Shot 5-29-96-A3.	248
4-43b	Linear Burn Rate Model, Shot 5-29-96-A3.	248
4-44a	Linear Burn Rate, Entire Model, Shot 6-13-96-D1.	249
4-44b	Linear Burn Rate Model, Shot 6-13-96-D1.	249
4-45a	Linear Burn Rate, Entire Model, Shot 6-13-96-D2.	250
4-45b	Linear Burn Rate Model, Shot 6-13-96-D2.	250
4-46	Linear Burn Rate as a Function of Pressure, for Propellant Mixture 75% No. 5, 25% No. 8700.	252
4-47a	Linear Burn Rate, Entire Model, Shot 5-31-96-A1.	253
4-47b	Linear Burn Rate Model, Shot 5-31-96-A1.	253
4-48a	Linear Burn Rate, Entire Model, Shot 5-31-96-A2.	254
4-48b	Linear Burn Rate Model, Shot 5-31-96-A2.	254
4-49a	Linear Burn Rate, Entire Model, Shot 6-13-96-C1.	255
4-49b	Linear Burn Rate Model, Shot 6-13-96-C1.	255
4-50a	Linear Burn Rate, Entire Model, Shot 6-13-96-C2.	256
4-50b	Linear Burn Rate Model, Shot 6-13-96-C2.	256
4-51	Linear Burn Rate as a Function of Pressure, for Propellant Mixture 66% No. 5, 34% No. 8700.	258
4-52a	Linear Burn Rate, Entire Model, Shot 5-29-96-B-Average.	259
4-52b	Linear Burn Rate Model, Shot 5-29-96-B-Average.	259
4-53a	Linear Burn Rate, Entire Model, Shot 5-29-96-B1.	260
4-53b	Linear Burn Rate Model, Shot 5-29-96-B1.	260
4-54a	Linear Burn Rate, Entire Model, Shot 5-29-96-B2.	261
4-54b	Linear Burn Rate Model, Shot 5-29-96-B2.	261
4-55a	Linear Burn Rate, Entire Model, Shot 5-29-96-B3.	262
4-55b	Linear Burn Rate Model, Shot 5-29-96-B3.	262
4-56a	Linear Burn Rate, Entire Model, Shot 6-13-96-B1.	264
4-56b	Linear Burn Rate Model, Shot k6-13-96-B1.	264
4-57	Comparison of Pressure Rise Time as a Function of Propellant Mixture.	269

<u>Figure</u>	<u>Description</u>	<u>Page</u>
5-1	Relative Burn Rate, Logarithmic Form.	277
5-2	Relative Burn Rate, Polynomial Form.	281
5-3	Effect of Deterrent on Time to Reach Peak Pressure.	282
5-4	Instantaneous Ignition Profile, General Algorithm.	285
5-5a	Relationship of Pressure with Time During Modeled Propellant Burn.	286
5-5b	Relationship of Temperature with Time During Modeled Propellant Burn.	286
5-5c	Relationship of Specific Volume with Time During Modeled Propellant Burn.	287
5-5d	Relationship of Grain Size with Time During Modeled Propellant Burn.	287
5-6	Experimental and Estimate Peak Pressures of Various Charge Weight in Closed Bomb Tests.	288
5-7	Diagrammatic Basis for Axial Burn Profile Problem.	290
5-8	Computational Algorithm for Axial Burn Profile Problem.	291
5-9	Typical Pressure-Time Output from Axial Burn Model.	292
5-10a	Illustration of Pressure Step, Entire Shot.	293
5-10b	Illustration of Initial Pressure Step, Step Only.	293
5-11	Problem Basis for Radial Outward Burning Configuration.	295
5-12	Typical Pressure as a Function of Time for Radial Outward Burn Profile.	296
5-13	Rise Time Error Versus Linear Burn Rate Coefficient of Determination.	302
5-14	Rise Rate Error Versus Linear Burn Rate Coefficient of Determination.	303
5-15	Comparison Between Rise Time Error and Rise Rate Error.	304
5-16	Time to Peak Error Versus Linear Burn Rate Coefficient of Determination.	305
5-17	Peak Pressure Error as a Function of Charge Mass.	306
5-18	Pressure as a Function of Time, Model 5-29-96-A-Average.	308
5-19	Pressure as a Function of Time, Model 5-29-96-A1.	308
5-20	Pressure as a Function of Time, Model 5-29-96-A2.	309
5-21	Pressure as a Function of Time, Model 5-29-96-A3.	309
5-22	Pressure as a Function of Time, Model 6-13-96-D1.	310
5-23	Pressure as a Function of Time, Model 6-13-96-D2.	310
5-24	Pressure as a Function of Time, Model 5-31-96-A1.	312
5-25	Pressure as a Function of Time, Model 5-31-96-A2.	312

<u>Figure</u>	<u>Description</u>	<u>Page</u>
5-26	Pressure as a Function of Time, Model 6-13-96-C1.	313
5-27	Pressure as a Function of Time, Model 6-13-96-C2.	313
5-28	Pressure as a Function of Time, Model 5-29-96-B-Average.	314
5-29	Pressure as a Function of Time, Model 5-29-96-B1.	314
5-30	Pressure as a Function of Time, Model 5-29-96-B2.	316
5-31	Pressure as a Function of Time, Model 5-29-96-B3.	316
5-32	Pressure as a Function of Time, Model 5-31-96-B1.	318
6-1	General Configuration of Large-scale Test Vessel.	324
6-2	General Shot Configuration for Large-scale Shots.	326
6-3a	Raw Pressure-Time Data, Example from 12-18-96-A2.	334
6-3b	Filtered Pressure-Time Data, Example 12-18-96-A2.	334
6-4a	Pressure as a Function of Time, Shot 12-18-96-A1.	337
6-4b	dP/dt as a Function of Time, Shot 12-18-96-A1.	337
6-5a	Pressure as a Function of Time, Shot 12-18-96-A2.	338
6-5b	dP/dt as a Function of Time, Shot 12-18-96-A2.	338
6-6a	Pressure as a Function of Time, Shot 12-18-96-A3.	339
6-6b	dP/dt as a Function of Time, Shot 12-18-96-A3.	339
6-7a	Pressure as a Function of Time, Shot 12-18-96-B1.	341
6-7b	dP/dt as a Function of Time, Shot 12-18-96-B1.	341
6-8a	Pressure as a Function of Time, Shot 12-18-96-B2.	342
6-8b	dP/dt as a Function of Time, Shot 12-18-96-B2.	342
6-9a	Pressure as a Function of Time, Shot 12-18-96-B3.	343
6-9b	dP/dt as a Function of Time, Shot 12-18-96-B3.	343
6-10a	Pressure as a Function of Time, Shot 12-18-96-C1.	345
6-10b	dP/dt as a Function of Time, Shot 12-18-96-C1.	345
6-11a	Pressure as a Function of Time, Shot 12-18-96-C2.	346
6-11b	dP/dt as a Function of Time, Shot 12-18-96-C2.	346
6-12a	Pressure as a Function of Time, Shot 12-18-96-C3.	347
6-12b	dP/dt as a Function of Time, Shot 12-18-96-C3.	347
6-13a	Pressure as a Function of Time, Shot 12-18-96-D3.	349
6-13b	dP/dt as a Function of Time, Shot 12-18-96-D3.	349
6-14	Linear Burn Rate, Entire Model, Shot 12-18-96-A1.	353
6-15a	Linear Burn Rate, Entire Model, Shot 12-18-96-B2.	354
6-15b	Linear Burn Rate Model, Shot 12-18-96-B2.	354
6-16a	Linear Burn Rate, Entire Model, Shot 12-18-96-C1.	355
6-16b	Linear Burn Rate Model, Shot 12-18-96-C1.	355

<u>Figure</u>	<u>Description</u>	<u>Page</u>
6-17	Comparison of Modeled Shots, 465 grams No. 5 Propellant.	356
6-18	General Comparison in Pressure-Time Profiles for 12-18-96 Shot Series.	359
6-19	Pressure as a Function of Time Comparison, Shot 12-18-96-A.	360
6-20	Pressure as a Function of Time Comparison, Shot 12-18-96-B.	360
6-21	Pressure as a Function of Time Comparison, Shot 12-18-96-C.	361
6-22	Pressure as a Function of Time Comparison, Shot 12-18-96-D.	361
6-23	Comparison of Differences in Ignition Front Advance Ratio.	363
6-24	Comparison of Rise-Rate and Peak Pressure Based on Loading Density.	364
8-1	Schematic Diagram of Recommended Propellant Based Stimulation Package.	385
9-1	Schematic Drawing of Hoek Cell and Ancillary Systems.	391
9-2	Comparison of Pre-treatment and Post-treatment Permeability of Samples Tested.	392
9-3	General Configuration of Small Bomb Tests.	394
9-4a	Typical Pressure versus Time Profile for Small-scale Shot.	395
9-4b	Typical Linear Burn Rate versus Pressure for a Small-scale Shot.	395
9-5	Comparison of Physical and Modeled Small-scale Shot.	397
9-6	Relationship between Predicted and Physical Large-scale Propellant Burn, 250 grams No. 5 Propellant, loading density 35.9 kg Propellant per Cubic Meter of Chamber.	399
9-7	Linear Burn Rate as a Function of Pressure, Large-scale Shot Example.	400

List of Plates

<u>Plate</u>	<u>Description</u>	<u>Page</u>
1-1	Scanning Electron Micrograph of Coal Structure.	4
3-1	Sample Ready to be Placed in Lathe, with Faceplate Attached.	66
3-2	Sample Configured for Cutting in Lathe.	67
3-3	Sample after Diameter Reduction, Faceplate Removed.	68
3-4	Sample with Casting Mold.	69
3-5	Mold with Resin Top Cap Poured.	69
3-6	High-Speed Cutter Facing Top of Sample.	70
3-7	Drilling Center Hole Into Sample.	71
3-8	Drilling Lower Vent Holes, Through Guide Holes in Mold Base Cap.	72
3-9	Steel Wool in Lower Vent Holes, Mold Base Cap Removed.	73
3-10	Automatic Data Logging System.	73
3-11	View of Hoek Cell Configured for Tests (1).	74
3-12	View of Hoek Cell Configured for Tests (2).	74
3-13	Photomicrograph from Sample SSRAD1, 32.4x.	87
3-14	Photomicrograph from Sample PMOG05, 80.5x.	118
4-1	Photograph of Data Logging System Configured for Test Shot.	174
4-2	Inserting Test Charge into Test Vessel.	175
4-3	Test Vessel Closed, Valve Open, Transducer not In-place.	176
4-4	Inserting Pressure Transducer into Access Port.	177
4-5	Pressure Transducer Connected to Power Supply Lead.	178
4-6	Ignition Lead Wires Connected to Vessel Leads.	179
4-7	Debris Removed from Test Shot.	180
4-8	Close-up of Test Results Logged on Data Logging System.	181
4-9	Photomicrograph of No. 8700 Propellant, 24.7x.	186
4-10	Photomicrograph of No. 5 Propellant, 24.7x.	187
4-11	Photomicrograph of No. 5 Propellant, 183x.	188
4-12	Photomicrograph of No. 5 Propellant, 1080x.	189
6-1	Data Logger Table, with Logger, Disk Drive, Plotter and Pressure Transducer Power Supply.	327
6-2	Preparing to Arm Propellant Charge with Igniter Charge.	328
6-3	Loading Ignition Charge into Igniter Tube.	329
6-4	Installing Pressure Transducer into Large-scale Bomb.	330
6-5	View of Bomb Prior to Shot Firing.	331
6-6	View of Bomb After Firing, with Smoke Plume.	332

Lexicon

Bulk Density - for the propellant charges this refers to the density of the packed propellant including the porous space surrounding grains.

Explosive Fracture - (*n.*) refers to fractures induced by extremely rapid energy release methods (typically high-explosives) that extend radially outward in all directions from the source wellbore. These may be accompanied by a region of pulverized material near the energy release source.

Hydraulic Fracture - (*n.*) refers to fractures induced by high-pressure fluid injected into the target seam, these tend to develop normal to the least principal stress.

Linear Burn Rate - ballistics term for the rate of flame front advancement normal to the burning surface.

Loading Density - refers to the mass of propellant with respect to the total volume of the firing chamber.

Multiple Fracture - (*n.*) refers to fractures induced by rapid energy release methods wherein the energy release rate is slower than that obtained from high-explosives, yet much more rapid than a hydraulic fracture. These fractures can extend in all directions from the source, but do not exhibit the pulverized zone observed in explosive fractures.

Propellant Density or **Grain Density** - for the propellant charges this refers to the density of the solid portion of the propellant charge.

Proppant - material, typically sand, injected into a well during stimulation to hold the induced fractures open when the treatment fluid is removed.

Chapter 1. Introduction

The potential of producing methane gas from coalbeds economically has become clearer in recent years. There are several reasons that this may be so: the identification of coalbed gas fields suitable for methane production, the ability to control the quality and quantity of produced gas, and economic incentives such as tax credits. The quantity of methane gas in the coalbeds of the United States is estimated to be around 400 trillion cubic feet. Despite the immense potential of this resource, current technologies limit the economic recovery to less than 25 percent, or about 95 trillion cubic feet (Puri and Yee 1990). Annual natural gas consumption in the United States is on the order of 21.6 trillion cubic feet (anon. 1997).

Methane gas contained in the coalbeds and surrounding strata is considered to be an unconventional source. This differentiates it from the natural gas (methane) that is produced from wells that are, typically, associated with conventional petroleum formation types and strata. The production and consumption of petroleum based fuels continues to be a matter of course in today's society. The availability of energy for consumption in our homes, for transportation, and for industrial and commercial applications is often taken for granted. As the demand for access to energy increases the sources must also be broadened. The current trend towards the production of methane from coalbed sources appears to indicate that there is an interest in making the best possible use of America's coal and coal related resources. While available technology proves to be viable for profitable production, investigations into means of expanding the technology base must be addressed.

1.1 State of Affairs

The first deliberate production, or drainage, of methane from coal was an effort to reduce the methane that would be liberated by high production mining methods (Boxho *et al.* 1980). The gas produced in this manner was initially vented to the atmosphere as a waste product. Later, the relative quality of the gas became an apparent source of additional income to the producing mines. Further interest was aroused, much later, at the United States Environmental Protection Agency

(EPA) where the vented methane was recognized as a so-called “greenhouse gas.” Since methane is understood to be more damaging to the atmosphere than carbon dioxide, the EPA set forth to promote the capture and combustion of the liberated methane (anon. 1995a).

The economic viability of gas produced from this unconventional source has led to the development of several coalbed methane fields in the United States, most notably the Fruitland Basin of northern New Mexico and southern Colorado, and the Black Warrior Basin in Alabama. The coal fields in southwestern Virginia have also received significant interest and are currently under production in Buchanan and Dickenson counties. During the five year period of 1988 to 1993 the cumulative production, in Virginia, exceeded 28 billion cubic feet, with an estimated worth of over 62 million dollars (Nolde 1995). Figure 1-1 illustrates the growth of coalbed methane production in Virginia from 1989 through 1994. Notice that coalbed methane has been a larger source of natural gas, in Virginia, than conventional sources since late 1992.

Production of methane from coalbed wells is governed by several physical factors, one of the most important of these is the dual-porosity nature of the coal itself. At the microscopic level coal appears much like a sponge, with numerous interconnected and isolated pores, see plate 1-1. Most of the methane held in the coal is adsorbed onto the surface of these pores. Flow between the pores is in general a diffusive process. At the macroscopic level the coal is layered and fractured. The general fractures, referred to as cleats, typically are oriented normal to the layers and consist of two types, face and butt, oriented perpendicular to each other. The face cleats tend to be long reaching, with the butt cleats cross cutting the face cleats, and hence often abruptly terminated. The flow of methane in these fractures is governed by Darcy’s law. In addition to the contained methane, the coal may also be saturated with water. Prior to production of the gas, the coal needs to be de-watered. The dewatering accomplishes two necessary conditions, first it increases the relative permeability to the gas phase, second the associated depressurization of the well permits the adsorbed methane to desorb and begin to flow within the coal structure.

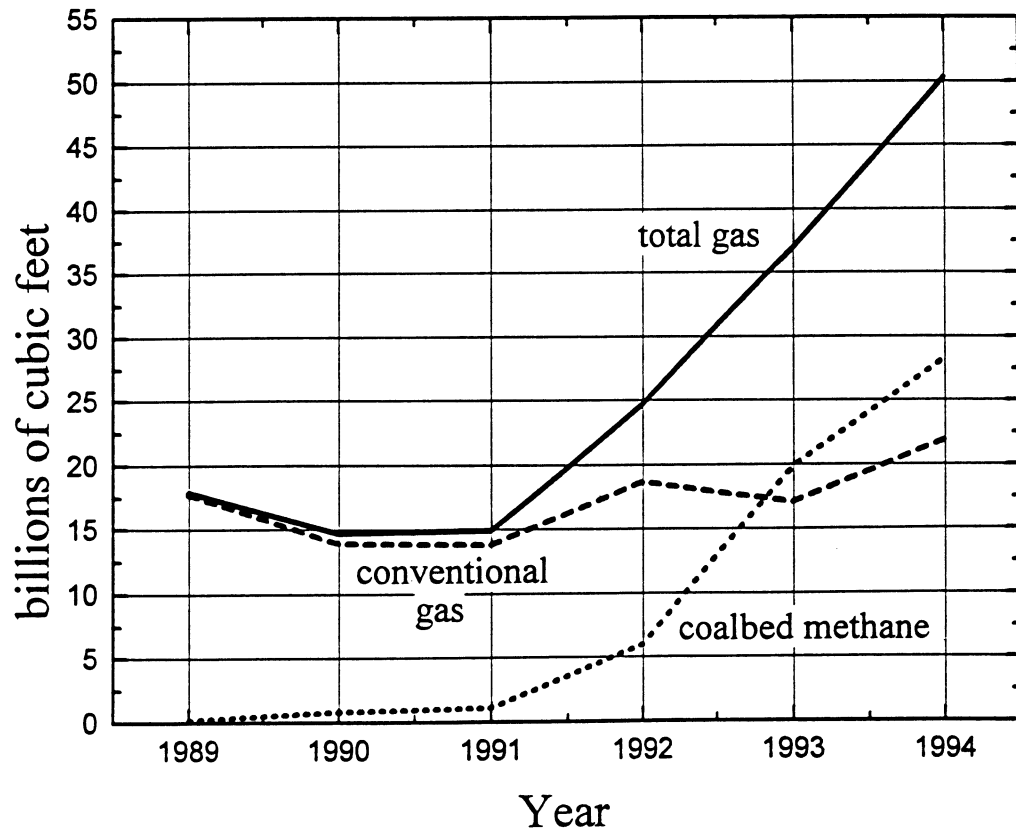


Figure 1-1: Graph illustrating Relationship Between Conventional and Coalbed Methane Production in Virginia (after: McPherson 1996).

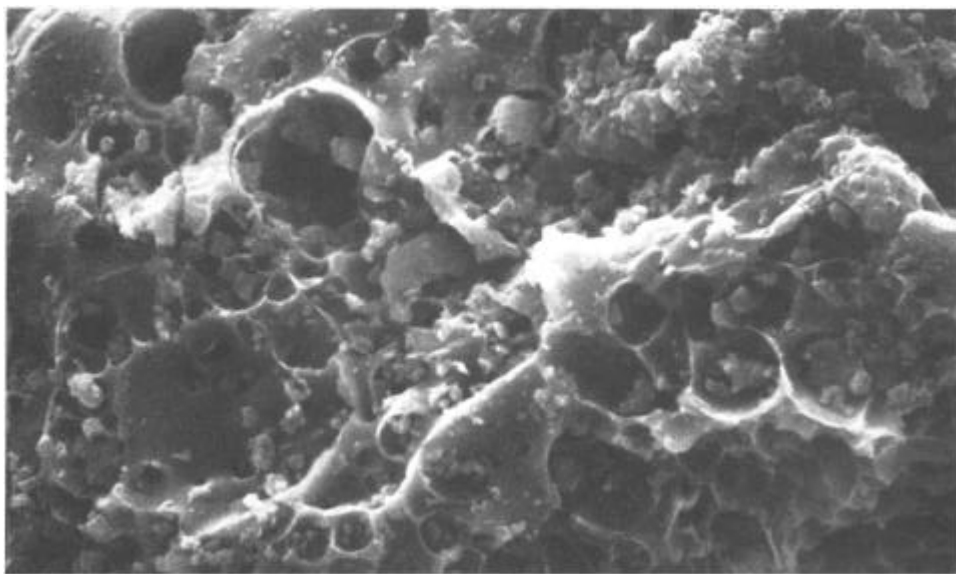


Plate 1-1: Scanning Electron Micrograph of Coal Structure (after: McPherson 1996).

1.2 Existing Technology

Current production techniques are based upon one of two main completion procedures. The first, and most prevalent, is a foam based hydraulic fracture through a perforated casing. The second technique is the open hole cavity completion. Both of these techniques have proven to increase the producibility of the stimulated well, although limitations of application exist. The general techniques and areas of application will be discussed briefly below.

The basic hydraulic fracture entails driving a foam under very high pressure outwards into the formation surrounding the wellbore. Access to the formation is through a series of perforations burned, or punched, through the well casing and cement. Under usual conditions the fractures generated by the hydraulic stress extend in the plane normal to the least principal stress.

In an open hole cavity completion the well casing is terminated above the coal formation of interest. Drilling of the well is completed through the coal and the well is then allowed to “jet out,” that is to flow uninhibited for several days. During this period the damaged coal around the wellbore is removed, along with free particles of coal, by the rapidly escaping gas and water. This debris is blown or pumped out of the borehole as the well is dewatered. In a variation of this basic technique air or methane gas is cyclically compressed into the formation and vented. In this manner the diameter of the bore at the producing strata is increased, ideally increasing the productivity of the well. This technique has shown to be most effective in the high permeability, over pressured wells in the center “fairway” of the Fruitland basin of New Mexico and Colorado. Attempts at using this technique in under-pressured reservoirs have met with mixed results, generally indicating that it is not viable in low permeability or under pressurized reservoirs.

The question at hand concerns the potential for increasing the producibility of coalbed methane wells in southwest Virginia. In general, wells drilled into the high points of the prevalent geological structure are the best producers (Holman 1996). This fact is easily explained as being based on the de-stressing of the coal, increases in permeability, and the tendency for gas to migrate to the higher points of the formation. The gas fields in Virginia are under-pressurized, that is the pore pressure is less than the hydrostatic equivalent of the depth. This very point tends to indicate that an open hole cavity completion is impractical, as have previous technical reviews of the field¹.

The current approach to stimulation in southwest Virginia is based on the hydraulic fracture technique utilizing foam as the fracturing and proppant transport agent. In general, the perforations through the well casing are not specifically aligned to take advantage of the structure of the coal. That is, the initial fracture direction is not aligned to either the face or butt cleat

¹ Based on personal discussion with Mr. Gerald Clark, Pittston Corporation, 22 October 1995.

structure of the coalbed. This fact alone may be significant since one might expect that the fractures would extend along the face cleats preferentially, compared to crossing through and along the more tortuous butt cleats.

Reflecting momentarily, it is possible to identify three areas that may be worthy of investigation regarding increasing the productivity of the coalbed methane wells. The first is to increase the communication between the microscopic pore structure and the macroscopic cleats. The second means is to increase the radial permeability cross-cutting the butt and face cleats. Third, is to move away from reservoir pressure depletion techniques of production.

The first suggestion may be one of significant importance, since if the pores cannot communicate with the permeable structure of the coal, the gas contained in the pore will not be recovered. Part of the problem with this approach lies in the fact that many of the pores and internal passages are on the same order of magnitude as the mean free paths of the gas molecules. Thus techniques employed to disrupt the microscopic structure of the coal should not have a tendency to remain adsorbed to the coal matrix.

The second technique, increasing the radial permeability around the well, seems to hold significant promise. It is well documented that hydraulic fracturing tends to produce a single pair of fractures extending on the plane normal to the least principal stress. In coal, an alternate path may be an existing structural weakness, the face cleats. In effect, the hydraulic fractures may simply be increasing the permeability in what is already the most permeable direction. The use of explosives to cause a great number of dynamic radial fractures has failed dismally, due to the extensive pulverization surrounding the wellbore. Previous research (see section 2.3.1) has indicated that a region exists in which the a multitude of fractures may be generated, without extensive damage to the wellbore. Such fractures may be generated by a specially designed "Tailored-Pulse," which lies between the slow pressure rise rates of hydraulic fracturing and the highly dynamic rates associated with explosive fracturing. The basis of the research conducted for, and reported in, the second and following phases of this thesis was to investigate the feasibility of utilizing a tailored-pulse to produce a multiple fracture regime for enhancing the producibility of the coal seam.

The third of the above mentioned techniques is noted primarily in novelty. Some research (Puri and Yee 1990) has indicated that overly reducing the formation pressure will inhibit the total producibility of the well by eliminating the main driving force. The authors of this research suggests the application of nitrogen flooding to maintain the initial driving force, as well as reducing the partial pressure of the methane in the formation to enhance its desorption. In addition to the suggestion, of Puri and Yee, utilizing nitrogen, the use of carbon dioxide may be feasible. One possible advantage to carbon dioxide is that it has a higher adsorptive affinity to the coal than does methane, hence it should tend to displace the methane from the coal matrix. An obvious limitation is that the driving gas, nitrogen or carbon dioxide, will tend to contaminate the produced gas, possibly requiring extensive separation equipment. The carbon dioxide could, fairly easily, be separated by compression and condensation. Carbon dioxide has proven to be

highly effective at stripping methane from coal (Fulton, et al. 1980; Reznik, Singh and Foley 1984).

1.3 Current Investigations

This thesis covers a range of research projects concerned with enhancing the production of methane gas from the coal seams of southwestern Virginia. In order to accommodate the variety of the tasks, each of the major chapters is essentially independent. That is they each have self-contained the relevant sections concerned with background theory, materials and methods, results, and discussion. A general review of literature precedes the project chapters, and general discussion and conclusion sections follow the project chapters. Several appendices are attached that contain information that is not readily available to the general reader, as well as program listings and information germane to the main body but without a clear place there.

Four separate sub-projects are reported in relevant chapters. The first, chapter 3, deals with testing of coal core in a tri-axial, Hoek, cell to determine the sample permeability in an orientation perpendicular to the core cylinder axis. These tests compared the permeability, to methane gas, of the sample prior to and following treatment by the introduction to and venting of liquid carbon dioxide from the sample. These tests indicate that although there is a noticeable increase in the sample permeability following treatment the change cannot be significantly attributed to modification of the coal structure. It is more evident that the treatment process merely removed debris from the central drill hole, used as a gas inlet point, in the core samples.

The second section, chapter 4, is concerned with the characterization of common propellants that were proposed for use in the generation of tailored-pulse phenomena. The scope varies from the determination of propellant grain size distribution and unconfined burn gas production to the indirect determination of closed bomb burn rate coefficients. Preparation for this section required the design and fabrication of a constant volume closed bomb, in which small-scale propellant charges were burned while the bomb pressure was monitored as a function of time. Five different propellant types were considered, as well as combinations of the individual types.

The third sub-project, reported in chapter 5, entailed the development of a numerical simulator to model the propellant burn process within the closed and vented bomb, configurations. The computer program used for this analysis was written in the FORTRAN-77 language, a copy of the code is provide in appendix E of this thesis. This analysis considered the various configurations that are reasonably assumable based on the charge geometry. Numerical investigations were considered for instantaneous ignition and for staged ignition processes. The arrangements considered for the staged processes included ignition axially and ignition radially outward on a cylindrical charge. Furthermore, the phenomenon of determent was also considered, wherein the burn rate equation can be varied as a function of the depth into the propellant grain, in addition to the standard approach of merely considering the ambient pressure. The outcome from this phase

showed that utilization of the burn-rate parameters determined in the chapter 4, can adequately reproduce the majority of the burn-rate profiles observed in the laboratory. Due to several physical factors, there were observed some timing errors; however, the basic shape and slopes of the computed case to the measured case were substantially similar.

The final phase of the projects reported in this thesis, chapter 6, was concerned with laboratory tests on larger scale propellant charges. These charges were scaled up to be consistent with loading densities that were expected for cases physically located in a new or active coalbed methane well. These tests were conducted in a vented bomb with an internal diameter very close to that of the actual well casing used by Pine Mountain Oil and Gas. The end effects of this fore-shortened model were evident by observing the pressure pulse reflections in the data recorded in the laboratory.

Through the experimentation documented in this thesis, the conclusions are directed toward the possible application of these novel technologies in the coalbed methane fields currently under production in southwest Virginia. The use of carbon dioxide injection and release is observed to present a low degree of confidence in the ability to enhance production. The potential for application of tailored-pulse fracturing appears to be more viable, its use may, however, require modification to the well completion strategies currently employed.

Chapter 2. Literature Review

In the concluding article of the *Oil and Gas Journal* series on coalbed methane, Schraufnagel, McBane and Kuuskraa (1990) presented six challenges ahead of this industry, these were:

1. Measuring and understanding permeability in coal seams.
2. Finding the highly permeable, productive spots in a new coal area or basin.
3. Predicting gas production and reserves and optimizing field development.
4. Conducting well completions and stimulations in new and more complex coal settings.
5. Reducing the costs of coalbed methane production.
6. Overcoming or mitigating the environmental impacts of coalbed methane development.

A fairly significant quantity of literature has been published concerning methane in coal, and the removal thereof. The breadth of available material covers aspects of all six areas mentioned above, to varying degrees of detail. The focus of this research project is directed at items 1, 4 and 5 in the preceding list.

This literature review is intended to provide a general background of the problems associated with the commercial production of methane from coalbeds. Section 2.1 covers the nature of the problem, basically the where and the why questions. Section 2.2 covers the current state of the art used in commercial coalbed methane gas wells. Section 2.3 covers advanced and novel techniques that indicate promise in the production of methane from coalbed reservoirs. Section 2.4 addresses performance assessment of production wells. Finally, section 2.5 briefly covers methods available for coalbed methane well system simulations.

2.1 Nature of the Problem

In late 1989 and early 1990 the *Oil and Gas Journal* produced a series of articles addressing the potential and problems associated with the production of methane gas from coal beds. The first of these articles was prepared by Kuuskraa and Bradenburg (1989) in which the authors provide an overview into nature of methane production from coalbeds and its potential as an energy source to the United States.

The second of the *Oil and Gas Journal* articles was prepared by Ayers and Kelso (1989). These authors address the growth in basic understanding of the coalbed methane problem, but express concern that there is still much to learn. They address that factors affecting one basin may or may not be fully applicable as other basins are explored. These authors present as topics for future study the following three areas: studies of the fractures and interaction of fractures and other linear patterns, heterogeneity of the permeability patterns in the coalbeds, and application of geophysical exploration techniques.

Convention wisdom in the coalbed methane industry accepts that there is some maximum depth to which the gas can be economically recovered. In a brief by Wyman and Kuuskraa (1995) they address the concern that in areas of relaxed stress there is a potential that coalbed methane could be produced from well much deeper than currently targeted. They identify that good producing wells have been completed to depths between 5000 and 10000 feet, despite industry reservations regarding wells deeper than 5000 feet.

Concerns regarding the potential of methane as a “greenhouse” gas have lead the United States Environmental Protection Agency (EPA) to consider environmental as well as economic issues associated with methane production. Since methane is reported to have a global warming potential of eleven times that of carbon dioxide (Kruger 1994) a promising solution for controlled emission is capture and combustion. A study of the environmental and economic impacts of coalbed methane production in the Appalachian region was prepared by Kruger (1994) on behalf of the EPA. This study endeavors to assess the benefits associated with deliberate methane production. The author concludes that significant gains can be taken by regions able to exploit this resource, including employment and the resulting inflow of money. Furthermore, methane gas emissions can be diverted to energy production and conversion to carbon dioxide, a less potent “greenhouse” gas.

2.1.1 Unconventional Methane Sources

Conventionally, methane gas is produced from what one would consider as petroleum type reservoirs. That is, the gas is held in a “gas-cap” above a liquid petroleum or water reservoir, or

is dissolved into the liquid petroleum. This source of methane represents the most important source of currently produced gas. Evaluation of several unconventional formation types has indicated that a significant amount of additional natural gas may become a viable resource in the present to near future. Estimates show that the amount of methane held in the unconventional reservoirs may exceed the conventional reserves.

The general definition of unconventional methane sources includes Devonian shale, tight sands, geopressurized aquifers, and coalbed reservoirs. Each of these sources will be given brief treatment in this section.

Considering Devonian shale and the tight sand reservoirs together, their over-riding characteristic is very low permeability. Both of these formation types require special treatment and stimulation in order to induce production at economic levels. In general, there is little difference between these reservoir types and those of conventional petroleum producers. The methane is held in the formation as a compressed gas and production can generally begin with stimulation.

Geopressurized aquifers are a potential source of methane in which the gas is dissolved into ground water. Like most gases, methane exhibits retrograde solubility at low to medium pressures. However, under very high pressures (greater than 2000 psi) methane exhibits significant prograde behavior at temperatures above 95° C (200° F) (Satriana 1980). It is also worth noting that although the total amount of methane dissolved remains fairly small on a unit basis, the total amount of gas available from this resource is considered extensive due to the large quantities of water affected. This resource is generally considered to be aquifers in the Gulf of Mexico, off the Texas and Louisiana coasts, at depths exceeding 3000 meters (10,000 ft) (Satriana 1980).

Later work by Doherty *et al.* (1982) determined that, at that time, the production of methane gas from geopressured aquifers was fraught with uncertainty. In particular, they identified a lack of information concerning “drive mechanisms, pressure and temperature dependency of permeability, (and) relative permeability to gas and to water.” Based upon their assessment, the risks of geopressured aquifer methane production were too high due to the marginal profitability that could have been expected.

Methane from coalbed sources can be obtained ahead of mining, during or following mining, and in stead of mining. Production of methane ahead of mining can be performed to degas the seam to reduce the methane liberated into the workings during mining. Collection of methane following mining generally occurs in the gob areas behind longwall sections. Again, this practice was developed to reduce the methane concentration in the underground workings. In the early days of these practices the methane was simply vented to the outside atmosphere, the quality of the gas and lack of infrastructure did not make this gas a reliable economic asset. In recent years, the United States Environmental Protection Agency has taken a position that coalbed methane gas

should be captured as a viable fuel source, the hypothesis being that methane represents a more significant “greenhouse” gas than does carbon dioxide, a product of methane combustion.

2.1.2 Distribution of Coalbed Methane

The creation of coal associated methane is a product of the coalification process. As the decaying flora progresses from peat through lignite towards coal, methane is created. Due to decreasing permeability and isolation from the atmosphere this methane becomes trapped within the organic pile. As the coalification progresses the methane adsorbs onto the developing carbon substrate. This methane is released when the coal is disturbed or removed from the confines of the earth.

The generation of methane continues as the rank of the coal increases, hence higher ranked coals have a greater potential for methane than lower ranks. The depth of burial also has an effect on the amount of the methane that is trapped within the coal. It is for these reasons that exploration for coalbed methane reservoirs is generally limited to bituminous coals for fairly significant depth.

Many promising coal fields have been investigated in the United States, the most significant of these will be discussed in section 2.1.2.1, below. Another area that is receiving serious consideration is the Tangshan fields in the Hebei province of the People’s Republic of China (Stevens, et al. 1992).

2.1.2.1 Throughout the United States

Current production of methane gas from coalbed reservoir sources is underway in three principal regions of the United States. These regions include the Fruitland Basin in northern New Mexico and southern Colorado, the Black Warrior Basin in Alabama, and the Central Appalachian region in southwestern Virginia, eastern Kentucky, and southern West Virginia. Although the main interest, at hand, is that area in Virginia, the other regions will be covered briefly, for completeness.

The San Juan (Fruitland) basin is characterized by low volatile bituminous coal buried under less than 4000 feet of cover. There are 14 seams of interests with a maximum of 100 feet of total coal. The state of the gas in place varies fully between underpressured to overpressured. There is generally less than 600 cubic feet of gas per ton of coal. The basin is estimated to contain nearly 90 trillion cubic feet of gas. Compiled in Ayers and Kelso (1989).

The Black Warrior Basin is characterized by low volatile bituminous coal buried under less than 4000 feet of cover. There are 4 seams of interest with a maximum of 20 feet of total coal. The gas ranges between an underpressured to normally pressured state. The coal contains less than

600 cubic feet per ton of coal. The basin is estimated to contain about 20 trillion cubic feet of gas. Compiled in Ayers and Kelso (1989).

The Central Appalachian region is characterized by low volatile bituminous coal buried under less than 2500 feet of cover. There are six seams of interest with a maximum of 15 feet of total coal. The pressure regime in this region is under pressured with less than 680 cubic feet of gas per ton of coal. The region is estimated to contain about 5 trillion cubic feet of gas. Compiled by Ayers and Kelso (1989).

2.1.2.2 Within Virginia

Distribution of coal resources in Virginia covers four fields of significant interest. The Taylorsville and Richmond basins are located in the eastern part of the state. The Valley Coal Field follows the Blue Ridge Mountains from the Roanoke area southwest towards Abingdon. By far the most productive of the coal fields is the Southwest Virginia Coal Field. This field, primarily, covers the counties of Buchanan, Dickenson, and Wise.

Concerning the occurrence of coalbed methane Nolde (1995) reports that in 1982 three wells were cored out, by the Virginia Division of Mineral Resources, in the Valley coal field. Later, in 1987, four additional wells were drilled, in 1987-88, by the New River Gas Company. All of these wells proved to be incapable of producing methane gas. Wells were also drilled in the Taylorsville and Richmond basins, that also proved incapable of producing methane in commercially viable quantities.

Methane is currently being produced from wells drilled in Dickenson and Buchanan counties. Nolde (1995) reports the cumulative production of methane from Virginia wells, between 1988 to 1993, was 28.7×10^9 cubic feet, worth \$62.3 million. In 1995 coalbed methane, from Buchanan, Dickenson, Russell and Wise counties, was 30.4×10^9 cubic feet and accounted for 61 percent of natural gas produced within Virginia (Anon. 1996).

Reservoir and production engineering practices of wells in southwest Virginia are based on the “best-available” technology for the formation type. The gas bearing formation in this region is under-pressurized (meaning that the pore pressure in the formation is less than the expected hydrostatic pressure associated with the well depth). The wells are usually completed and cased through the coal bearing zone of the stratigraphy. The casing is perforated to provide flow paths between the wellbore and the formation. Enhancement to the pre-existing permeability is accomplished utilizing a foam based hydraulic fracture technique, see section 2.2.2.3, of this thesis.

2.1.3 Economic Assessment

Kuuskraa, Boyer, and McBane (1989) investigated the general economics of coalbed well methane production. They noted that the ability for coalbed wells to be economically viable was being enhanced by three factors; the discovery of high productivity wells, the development of long-lived wells at a low-cost, and the qualification for unconventional gas tax credit. Although the assessment methods put forth by these authors do not appear to differ greatly from what might be considered normal net present value (NPV) treatment, it is clear that a thorough understanding of the process is a necessity. When considering investment, these authors suggest three indices of comparison, rate of return, discounted net present value, and minimum required selling price, as appropriate methods. They also point out that the pay back time is not an appropriate index for coalbed methane. This is due in part to the more stable, longer duration, production of methane from a coalbed well compared to a conventional well. They cite an example of a coalbed well with a pay back time nearly forty percent longer than conventional well, but having a rate of return nearly five percentage points higher and an NPV nearly 4 times greater.

In this paper, (Kuuskraa, Boyer and McBane 1989) the authors also make note of several environmental issues that affect the economic assessment of coalbeds as a methane source. Most notable of the possible environmental benefits is the recovery of methane that would otherwise be released to the atmosphere. The concern being that methane is a more severe “greenhouse gas” than the carbon dioxide that is released as a product of combustion. This concern is shared by the United States Environmental Protection Agency (EPA) (Kruger 1994; anon. 1995a; anon. 1995b). Other environmental issues that must be addressed during the assessment of the well economics concern the produced water. Depending on the quality of the water drained from the coal seam, necessary to stimulate gas flow, it may be used directly for agricultural purposes or may need to be reinjected or disposed of by other means.

The issue of ownership presents some special considerations regarding the development of coalbed methane reserves. Counts (1990) provides a review of these issues, both in general and regarding the local laws of several states, including Virginia. The general ownership of the in-place gas has been asserted by multiple parties, the surface owner, the coal lessee or owner, and the oil and gas lessee or owner. Legitimate arguments have been made by each of these groups for a resource that has, until recently, been of little economic interest. Virginia Law has assigned the ownership of these gases to the surface owner. Promulgation of this statute was affective 1 January 1978. At the time that this article was written several questions regarding the constitutionality of this law remained, with relation to both the United States Constitution and the Virginia Constitution. It appears evident that as coalbed methane becomes a more significant resource the claims to ownership will increase.

Considering the ownership of minerals, Mutchler and Sachse (1981) state that under the practices of common law it is well established that the “landowner begins owning every resource of value, even of no current value, on or underneath his land.” They continue by reviewing several key

issues regarding the ownership of coalbed methane gas, and suggest methods to avert the possibility of damaging litigation. None of the approaches that they suggested appear to have been settled decisively by the time the Counts article, above, (Counts 1990) was prepared.

2.2 State of the Art

Many of the techniques employed to stimulate the coalbed methane wells are a direct application of methods developed in the petroleum industry. Currently, the most common approaches to methane well stimulation fall into two categories, open hole and cased hole completions. Due to several factors, which will be discussed in the following section, the open hole technique does not appear to be directly applicable in southwest Virginia. For this reason the review of open hole completions will be limited in extent compared to that concerning cased hole completions.

The basic differences between the physical properties of conventional natural gas and coalbed methane sources leads to several factors governing well engineering. The dominant characteristics, unique to coal are given by Holditch (1990) as:

- High injection pressure during stimulation;
- The production of coal fines;
- The coal cleat system must be effectively connected to the wellbore;
- The coal seam must be dewatered before gas production can occur;
- The well should be produced at minimum bottomhole pressure to maximize gas desorption;
- Coal seams are usually thin and spread over a large vertical interval;
- In coal seams, a low Young's modulus is normally encountered; and
- Complex hydraulic fractures are often encountered.

The physical state of the gas in the target formation is also a defining factor. That is, the approach to producing gas from the well may be governed in part by the state of pore pressure at the time of stimulation. In general, however, the most economical method currently available is to fully case the well bore and follow with a conventional hydraulic fracture program (Holditch 1990). To be thorough, both of the principal techniques of completion will be given coverage in the following sections.

2.2.1 Open Hole-Stable Cavity Completions

As the name tends to suggest, this method does not involve installing a well casing in the production section of the wellbore. Instead, the well is drilled and cased to the top of the target formation. The well is then completed by drilling through the reservoir bed, see figure 2-1. The stable cavity is developed by naturally or artificially "blowing down" the well.

During the blow-down process debris is removed from the open hole by the massive flow of gas from the well. This action tends to produce a cavity of enlarged diameter at the base of the well. The process of developing the cavity often requires repeatedly shutting-in and blowing-off the well. A natural blow-down utilizes the gas naturally in the formation to provide the energy to clear the open well. In an artificial blow-down compressed air is pumped into the formation and then released into the atmosphere.

One of the principal limiting factors governing the economic utilization of the open hole - stable cavity technique appears to be that the formation must be in an over-pressurized state. Furthermore, there is a permeability range that seems to lend itself to the application of this method. In the United States only one region of significance appears conducive to this completion and stimulation strategy, that is the Fairway of the Fruitland Formation in the San Juan Basin of northwestern New Mexico and southwestern Colorado.

Many of the considerations relevant to completing coalbed methane wells are addressed by Holditch (1990). He mentions that in general open hole wells tend to be plagued by soughing in the well requiring frequent cleanout. Many of the original wells completed in the manner were of fairly low permeability and required the use of hydraulic fracturing to achieve stimulation. The use of the stable cavity, surrounding the open hole, seems to be viable in formations that exhibit high permeability and high pressure. Holditch concludes that "In areas containing thick, geopressurized, high permeability coals, an openhole stable cavity completion may be an acceptable completion technique."

A significant review of the openhole cavity completion technique is given in Palmer, et al. (1992). This paper analyses several wells completed in the San Juan Basin. The authors point out that in the fairway zone of that basin, wells stimulated using the cavity technique out-produce hydraulically fractured wells by as much as ten times. They attribute this to damage that may be caused by the hydraulic fracturing process. An important parameter to the application of the openhole technique in the San Juan Basin is that this region tends to have a fairly high initial permeability and is overpressured.

Palmer, et al. (1993) continue on from the previous publication (Palmer, et al. 1992) by pointing out that "the permeability surrounding a cavity appears to be enhanced by a tensile fracture induced during air/water injection and shear failure zones induced during blowdown." They also address that there is no correlation between the success of open cavity completions and compressive strength or geological structure. Correlation is evident between the total coal thickness, reservoir pressure, and pressure state (that is whether the well is over or under pressured).

Palmer, Lambert, and Spitler (1993) cover a range of stimulation techniques available for application in coalbed methane wells. These authors identify 4 elements behind the geomechanics

of the open cavity. The increase in production from an open cavity seems to be associated with: (1) collapse and fragmentation near the wellbore, (2) failure of the coal due to shear stresses, (3) “extrusion of coal” and (4) “subsidence.” In the wells examined by these authors the average radius developed was on the order of four to five feet.

A more recent paper by Holditch (1993), follows directly from a previous paper by the same author (Holditch 1990). In the more recent paper, the author indicates the difficulty of stimulation in an openhole environment. He does not, however, provide a detailed explanation of this phenomenon. Concerning the economics of stable cavity completions the author cites (Logan, Clark, and McBane 1989) that the total cost of the cavity can be more expensive than the cost of a hydraulically fractured perforated casing well.

Mavor and Logan (1994) present an openhole stimulation technique that they call “dynamic openhole completions.” The technique that they describe produces the cavity as a by product of the process rather than the main goal. This method allows the well to freely blowdown rather than repeatedly injecting and releasing compressed gas from the well to attain the stimulation. Application of this technique is dependent on the reservoir properties. In general, the well must exhibit fairly high initial permeability, and a normal to over pressured state.

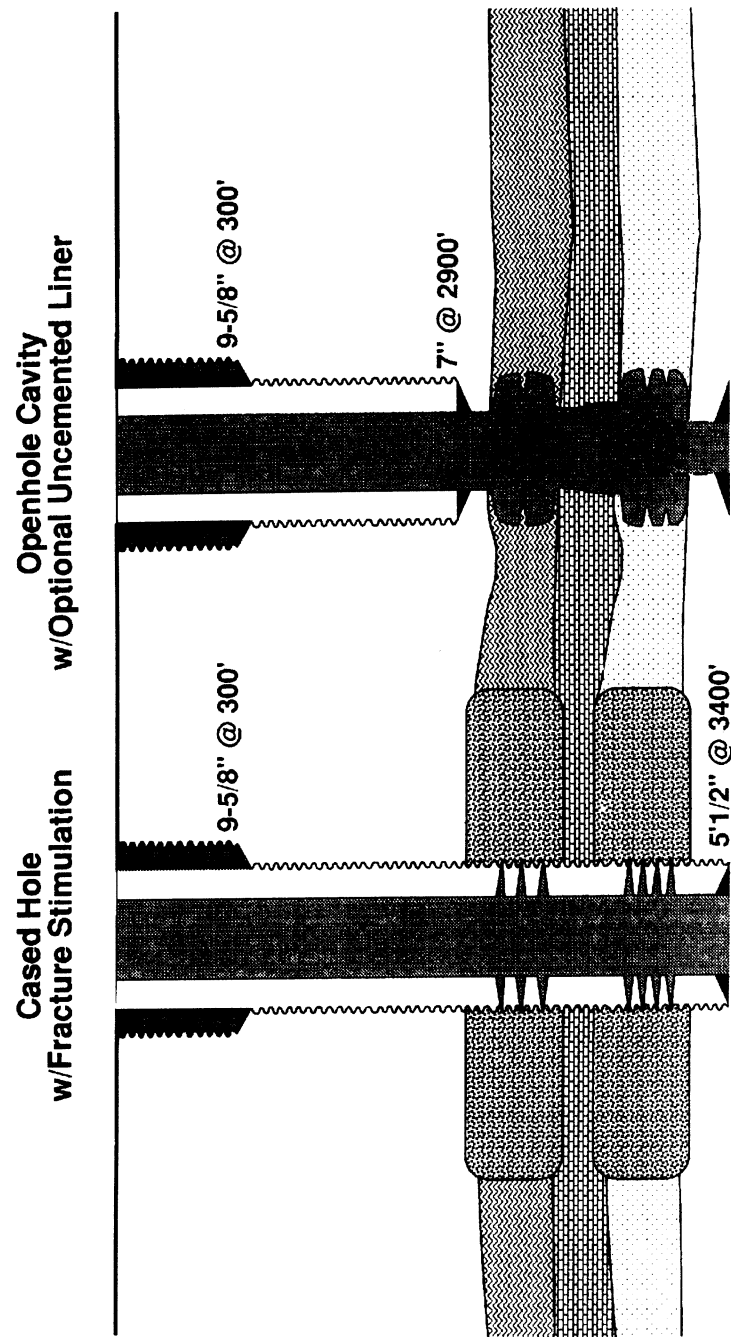


Figure 2-1: Illustration of Cased Hole and Openhole Cavity Completion Methods (after: Palmer, Lambert and Spitler 1993)

2.2.2 Cased Hole Completions

The cased hole completion strategy seeks to maintain the wellbore integrity by installing a well casing fully through the target formation. In this approach the well is drilled and cased to the full intended depth. The casing is then perforated in the production horizon to connect the well to the formation. After clearing the cement from the vicinity of the perforation, usually with a hydrochloric acid solution, well stimulation can begin. The stimulation most prevalent today is hydraulic fracturing with a nitrogen gas based foam.

Compared to other methods, which have been used in the past, the foam appears to be highly effective without inducing damage to the formation. As will be addressed in following sections the use of cross-linked gels, and water have been attempted to varying degrees of success and failure. In general, the use of hydraulic fracturing seeks to increase the natural permeability of coal in the neighborhood of the well, without inducing chemical damage to the coal formation.

In discussing completion techniques, Holditch (1990 and 1993) identifies that experience gained in the field had shown that by correctly choosing the drilling fluids, casing cement, and the treatment fluid, a perforated casing completion can be the most economical approach. Such an approach does, however, require the use of a strong well casing to sustain the high pressures associated, specifically, with hydraulic fracturing in coalbeds.

Palmer, Lambert, and Spitler (1993) cite that the use of cased well completion techniques ensures that the desired seams can be stimulated in a selective manner. In a reference to Jeu et al. (1988), the authors list four purposes behind hydraulic stimulation:

- (1) to bypass near-wellbore formation damage; (2) to more effectively connect to the natural fracture system of the coal reservoir; (3) to stimulate production and thereby accelerate dewatering (to increase the rate of gas desorption); (4) to widely distribute the near wellbore pressure drop (and reduce fines production).

In a paper directed towards openhole cavity completions, Mavor and Logan (1994) point out that the performance of hydraulically fractured wells may be controlled by the butt cleats. Fractures generated by hydraulic processes do not tend to cross the more permeable face cleats. Hence, production from the well will be limited by the restricted flow of gas and water through the less permeable butt cleat system. The further point out that the hydraulic fracturing and proppant placement process may alter the horizontal stress system in such a manner as to decrease the effective size of the gas flow paths.

2.2.2.1 Cross-Linked Gels

A fairly extensive review of the use of cross-linked gels as treatment agents is given by Palmer, Lambert and Spitler (1993) in their treatise on coalbed methane stimulation. A cross-linked gel stimulation generally involves the application of HPG (hydroxypropyl guar) cross-linked to a borate. One of the first elements of gel treatments pointed out by the authors is that significant formation damage can be caused by the treating agent. The damage arises from swelling induced by sorption of the treating agent onto the coal matrix, and sealing of cleat structure.

Due to the possibility of damage that can arise from cross-linked gels such treatments have fallen out of favor and have been replaced by the more common foam fracturing methods.

2.2.2.2 Water Fracturing

The impact of high viscosity fluids with a sand proppant was investigated by Lambert and Trevits (1978) in the Mary Lee (in the Black Warrior Basin, Alabama) coalbed. Their experiments were conducted in a jet slotted casing, in which the slots were cut ninety degrees apart. The average gas production from their wells was 15,000 cubic feet per day. A peak production of 80,000 cubic feet per day was noted, following repairs to a water pump and removal as standing water from the well.

Palmer et al. (1991) compared the performance of water fractured and gel fractured wells in the Black Warrior Basin of Alabama. The work conducted by these authors found that the wells stimulated by water techniques outperformed those stimulated by gel treatments. In their study the gel fractures utilized nearly twice as much sand, on a fluid volume basis, than did the water induced fractures. In this research a total of 20 wells were treated, ten by either method, furthermore, the wells were randomly assigned treatment. The inhibited production of the gel fractured wells appeared to be due to swelling of the coal matrix caused by sorption of the gel. This paper also points out that a gel fracture job can cost nearly twice as much as a straight water stimulation, with little or no significant benefit.

Consideration of plain water and treated water fracturing in the San Juan Basin, and other fields, is presented by Palmer, Lambert, and Spitler (1993). Based on their investigations the use of water treatment produces better initial production results than gel or foam techniques where the initial permeability is fairly high. The use of a straight water fracturing system produces the worst proppant transport into the formation; straight water, however, produces the least amount of formation damage due to the various fracturing techniques.

2.2.2.3 Foam Fracturing

A brief assessment of the effectiveness of foam fracturing is presented by Steidl (1978). Although no distinctive comparison was evident in the paper, the author commented that the stimulation of wells, in Greene County, Pennsylvania, was conducted with a 75% nitrogen foam. The advantages noted, regarding foam, include; a “high sand carrying capacity, low fluid loss, little formation damage, and quick fluid recovery.” In this field the wells were spaced on 12.9 acres, compared to 60 acres per well in southwest Virginia.

The technique of foam fracturing is similar to a conventional hydraulic fracture, except that a foam, generated on the surface and pumped into the well, is used rather than water or gel. Treatments of this type are effective in coal seams that are underpressured, “sensitive to liquid damage,” or that may have a fairly high initial permeability (Palmer, Lambert, and Spitler 1993).

The application of foam fracturing techniques, without the conventional use of proppants was discussed by Mahoney *et al.* (1981). In the experimental borehole described, the gas well was produced for degassing a coal seam ahead of mining. Subsequent mine-through of the treated region indicated production of both vertical and horizontal fractures, without evidence of damage to the overlying strata. The authors concluded that, in conjunction with local geology, “effective horizontal abrasive jetting, and low foam treatment without proppant, a degasification borehole was produced that yielded an acceptable degasification rate.” There was not coverage of the cost benefit of foregoing the proppant in this paper.

2.2.3 Effect of Permeability

The economic production of methane from a coalbed well is dependent on several factors, which include: gas pressure, gas content, seam thickness and permeability. Of these factors only the permeability can be affected by manual techniques. The general trend that is observed is that the permeability in the coal seam decreases with depth. Data suggest that this parameter can decrease by 1 to 2 orders of magnitude as the pressure is increased by 13.8 MPa (2000 psi) (McKee, Bumb, and Koenig 1988).

Flow of methane in coal is related to a number of factors. Much of the methane, perhaps more than 95 percent, is held as an adsorbed gas rather than as a compressed gas. This gas is dispersed on the surface of the coal pore structure. A mathematical model used to describe the adsorption/desorption process is the Langmuir Isotherm. This model describes the amount of a gas that is adsorbed onto an adsorbant at a given pressure. The physics of the problem indicate that the process is non-linear with much more gas being adsorbed at lower pressures, than when the pressure increases.

The release and transport of methane from coal is a process that spans from desorption to diffusion through the coal matrix and eventually Darcy flow through the fracture system. Each of these elements will be addressed separately, along with special considerations that play a role in the transport of methane from its stored condition to extraction at a wellbore.

2.2.3.1 Methane Desorption Characteristics

Most of the methane stored in a coalbed reservoir is in a state of being adsorbed to the coal matrix, rather than in the compressed gas state. The adsorbed gas can account for as much as 98% of the total gas in the coal (Harpalani and Schraufnagel 1990a and b). The relationship between the quantity of gas adsorbed to the partial pressure of the gas phase in non-linear, a typical curve, for coal, is shown in figure 2-2. From the figure it is evident that for a significant amount of the gas to desorb, the partial pressure of methane must also be decreased significantly. There are several methods used to describe the pressure/adsorption relationship (Yang 1984), the most commonly employed in coal/methane systems is the Langmuir Isotherm.

A fairly early investigation into the adsorption of methane onto coal was performed by Jolly, Morris, and Hinsley (1968). In this work the authors investigated the adsorption of methane to coal at pressures up to 140 MPa (1400 atmospheres). It is evident from their work that the amount of methane that can be adsorbed is a function of several factors, including the nature of the coal itself.

McElhiney, Koenig, and Schraufnagel (1989) suggest that due to the adsorptive nature of methane to coal, a coal formation can store 3-7 times more methane than could be stored in a conventional formation of similar depth and pressure.

In terms of the capacity of coal to store gas in a adsorbed phase the Langmuir equation can be expressed in the form (Mavor, Owen, and Pratt 1990):

$$g = g_L (1 - a_d) \frac{p}{p + p_L},$$

where g is the gas storage capacity in Standard Cubic Feet per Ton (SCF/Ton), g_L is the Langmuir volume (gas storage capacity) in SCF/Ton, a_d is dry basis ash fraction of the coal in question, p is the reservoir pressure in psia, and p_L is the Langmuir pressure in psia. It should be noted that the standard practice in the natural gas industry is to use English Engineering units of measurement; the arrangement of this equation would allow for the direct substitution of SI units as long as consistency was maintained. The Langmuir volume, g_L , and the Langmuir pressure, p_L , are constants specific to the coal sample and are derived from the experimental Langmuir Isotherm, as illustrated in figure 2-2.

Mavor, Owen and Pratt (1990) considered the “Measurement and Evaluation of Coal Sorption Isotherm Data.” This paper begins with a discussion of the Langmuir Isotherm and the methods used to determine the necessary coefficients for coal specimens. For the analytical methods described a crushed sample was used. Utilizing samples of between 80 and 150 grams the adsorption isotherms were evaluated for a number of coal types from around the United States. Data presented on coal from the Appalachian basin indicate a total Langmuir volume of about 24.75 m³/tonne (795 ft³/ton) and a Langmuir pressure of about 1.03 MPa (150 psia). The storage capacity of this coal, at 6.9 MPa (1000 psia) was determined to be about 21.5 m³/tonne (690 ft³/ton). The coal used for this analysis was obtained from Wyoming County West Virginia, located about 30 miles north of Richlands Virginia, and was of low volatile bituminous rank.

The use of pressure transient analysis as a tool for determining methane desorption properties in coal is presented by Anbarci and Ertekin (1991). The time and pressure dependent sorption present in coalbed methane wells presents special considerations.

Determination of gas content and an appropriate sorption isotherm generally requires extensive laboratory testing. Hawkins, Schraufnagel, and Olszewski (1992) present an approach for determining these parameters using well log data.

A concise view of the liberation of methane from coal is provided by McPherson (1993). In this text the author presents the current understanding of the means in which gases, nitrogen, carbon dioxide, and methane, are adsorbed to and desorbed from the coal matrix and pore surfaces. A section of this text is also devoted to the development of the steady state and transient flow equations for radial conditions. The conditions behind the stress dependent nature of coal permeability is given both for the effective stress load on the coal formation as well as the effect on permeability measurements due to the in-situ pressure of the gas. The interaction of total stress and pore pressure on the measured permeability suggest the conclusion that permeability varies inversely to the total (hydrostatic) pressure and that it initially decreases as the pore pressure increases but that the main trend is an increasing permeability for increased pore pressure.

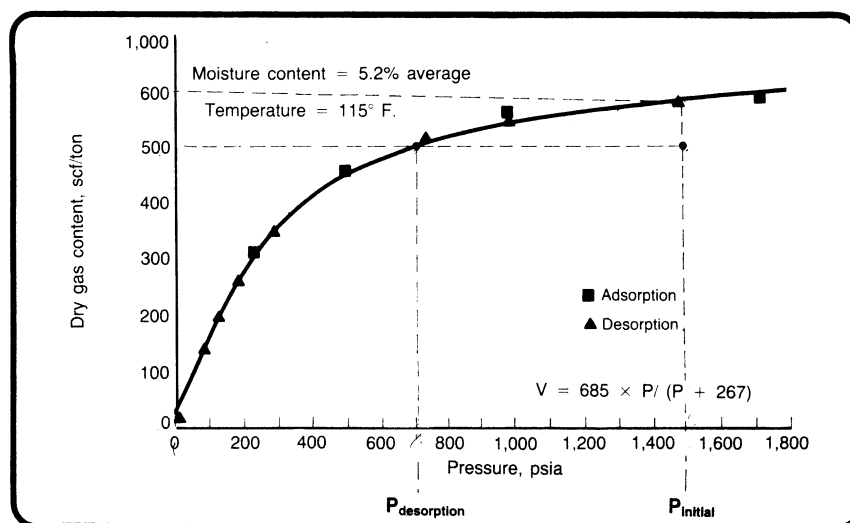


Figure 2-2: Typical Adsorption/Desorption Isotherm (after: McElhiney, Koenig, and Schraufnagel 1989).

2.2.3.2 Diffusion of Methane in Coal Matrix

A paper by Nandi and Walker (1970) investigated the activation energy of diffusion to the size of the pore structure within the coal.

In a fairly early paper Thimons and Kissell (1973) investigate the process by which methane diffuses through coal. This paper covers experiments conducted by the authors on samples of Pittsburgh, Pocahontas No. 3, and Oklahoma Hartshorne coals.

The effects of methane diffusion in respect to gas production from coalbeds is covered by Smith and Williams (1984). In this paper the authors relate the physical nature of the coal to the mathematical models usually used to describe diffusional processes. Most significant is that the use of a unipore model is inadequate, and that a bidisperse model is required. In the unipore model a series of non-connected uniform cylindrical pores are assumed. In reality movement of methane occurs as a product of both diffusional transport and Darcy Flow. A bidisperse model accounts for both the micro and macro structure of the coal, and was shown by the authors to more accurately predict the flow with respect to time, over the entire time range than the unipore model. These authors also present an experimental technique to determine the parameters required for the bidisperse model.

2.2.3.3 Movement of Methane in Cleats and Fractures

Once the methane has made its way into the natural cleat and fracture system the flow process is governed by Darcy's law. That is the flow exhibits laminar characteristics, and the rate is directly proportional to the pressure gradient. The exception to this case may be near a wellbore, where turbulent conditions may exist and for which Darcy's law is invalid.

In cases of fairly high pressure, the tendency is that the permeability of the porous medium decreases as the fluid pressure increases. This is particularly true when the sample is saturated with a gas phase fluid. This trend is referred to as the Klinkenberg effect, after its initial investigator. The nature behind the observation has been explained as the slippage of gas molecules on the surfaces within the porous medium matrix. The original investigation showed that this effect was inversely proportional to the gas pressure, and that a straight line relationship would exist between the measured permeability and the reciprocal of the gas pressure. McPherson (1993) reports that this linear relationship does not, specifically, hold in the case of coal. The effect of molecular movement on the surfaces of the porous media can, generally, be considered when modeling flow processes in rock samples.

Ertekin, King, and Schwerer (1986) considered a model of flow within tight gas formations wherein the general Darcy's law flow requires adjustment for the Klinkenberg effect. The research reported here had been undertaken to provide some theoretical and experimental investigation of gas slippage behavior. The results of the initial work were applied to several reservoir production schedules. The general differences between their new dynamic gas slippage model, and conventional Darcy models were less than 10%, considering both single-phase and two-phase models. Greater variations were shown for wells on which an economic limit had been set for production. The gas slippage model indicated a longer viable well life.

2.2.3.4 Effect of Relative Permeability and Two-Phase Flow

In order for methane gas to begin to desorb from the coal it is necessary to reduce the well pressure to a point that the sorption isotherm is intersected. Since most coalbed reservoirs contain a significant amount of water, to the point of saturation, dewatering of the well is generally required as a part of the simulation process. During this phase of the well production period the well transitions from producing mostly water, through a two-phase flow period resulting in the production of principally gas, with some water.

This transitory phase accounts for the commonly observed response in which the well appears to have an increasing gas production rate that is coupled with declining water production. Following this delayed peak, the gas production rate begins the common declining production as the well system pressure begins to decrease.

The problem of two-phase flow, and the accompanying relative permeability changes, to liquid and gas phases, were addressed fairly early in the development of coalbed methane reservoir system. Key aspects of research in this phenomenon were conducted by the University of Pittsburgh and the United States Bureau of Mines.

Dabbous et al. (1974) investigated the permeability of coal to air and water, individually, in coals from the Pittsburgh and Pocahontas seams. Their research showed that variations exceeding 4 orders of magnitude would not be uncommon for a single phase-phase permeability. The fact that the water permeability was, generally, less than the gas permeability was attributed to the adsorption of water to the coal matrix surface, resulting in substantial swelling of the matrix. Although these researchers identified coalbed methane as a potential source of natural gas, their gas phase permeability studies were conducted with air, rather than methane. The major constituent of air, nitrogen, has a much lower adsorptive affinity, on the order of $\frac{1}{2}$, to coal than does methane (McPherson 1993).

The work reported in the previous paragraph (Dabbous et al. 1974) was expanded by Reznick et al. (1974) to include two-phase flow investigations. One of the key results of their research was the observation that permeability to gas increases rapidly with drainage of water. They report that

the permeability to gas can reach 80% of its maximum value by the time that the water saturation falls to 50%. A similar characteristic was reported for conditions of water imbibition.

An investigation of two-phase flow in coalbeds was conducted by Kissell and Edwards (1975). This work investigated the results obtained in an underground coal mine that indicated the two-phase flow characteristics. In the study that they reviewed, methane gas emission and water flow from working areas were monitored. The trend in the obtained data indicated that changes in the relative permeability were occurring as a result of water run off from the coal. Monitoring over a period of several days, an increase in the methane emission was observed in conjunction with a decreasing make of water. A study by Zabetakis et al. (1972), cited by these authors had concluded that methane permeability was higher in older workings due to the decreased water content of the coal.

2.2.3.5 Permeability Assessment

Regarding a coalbed methane field, the assessment of the permeability characteristics of a production field is an important part of determining its economic potential. The evaluation of the flow of fluids through porous media is fairly well understood and is the subject of numerous texts. The range of material available in this field is associated with ground water systems, petroleum and gas production, and geotechnical engineering. Due to the generally heterogeneous nature of natural formations the results obtained from field measurements often vary greatly from those obtained in the laboratory. A general description of testing methods for these two conditions will be discussed below.

A study by Harpalani and Schraufnagel (1990a) investigated the phenomenon of increases in coal permeability as the pore pressure is decreased, a characteristic that appears to be unique to the coal/methane system. In general as the pore pressure is decreased in a formation the increase in effective stress is coupled with a decreasing permeability, as the pore space within the matrix shrinks. In coal, however, there is evidence that the coal matrix, itself, shrinks as a result of the methane desorption process. The evidence suggests that the shrinkage of the matrix more than offsets the loss of volume due to increasing the effective stress, resulting in an increase in permeability.

2.2.3.5.1 Field Methods

Testing methods and guidelines are also provided by the American Society for Testing and Materials (ASTM D4043-91, ASTM D4044-91, ASTM D4050-91, ASTM D5473-93). ASTM D4043 is a guide to determining the appropriate techniques in measuring of well hydraulic properties. ASTM D4044 addresses the standard field procedures applicable to the use of slug test methods for determination of aquifer hydraulic properties. ASTM D4050 presents the

standard field procedures for the performance of withdrawal and injection tests of well hydraulic parameters. ASTM D5473 covers the analytical approach to analyze the hydraulic parameters of an aquifer system using a partial penetration well.

Assessment of gas producing petroleum wells are tested in the following manner. Deliverability testing is covered by Ikoku (1984), general flow behavior in porous media is covered by Smith (1983).

In coalbed methane wells three distinct flow phases are observed to occur: “(1) saturated water with no gas phase; (2) Unsaturated water flow with an immobile gas phase; and (3) two-phase flow of gas and water” (McKee and Bumb 1987). The first of these flow phases need not be present, depending on the initial pressure state of the well. As a transition occurs between these flow phases the amount of the liquid or gas phase that will be transported varies as the effective permeability to that fluid changes. A typical graph illustrating the relationship between the relative permeability to water ($k_{r,w}$) to that of a gas ($k_{r,g}$) is shown in figures 2-3 and 2-4.

Figure 2-3 illustrates the most basic relative permeability pattern for two phase flow in which the permeability of each phase is affected by the degree of saturation of that phase, as well as the relative wettability of the phase to the matrix. Figure 2-4 shows a more complicated relative permeability graph. This figure indicates that there is a step in the relative permeability to gas, even while the permeability to water is practically zero. Since this step occurs as the water saturation is less than 0.50 and the permeability to water approaches zero it is reasonable to assume that it may be associated with the liberation of adsorbed gas from the coal as the formation water is removed. As the water is completely removed the relative permeability of gas approaches its nominal value.

McElhiney, Koenig, and Schraufnagel (1989) cite that single-well, single-phase testing can be used reliably to obtain reservoir properties. The use of an injection test is preferred to drawdown tests, since a pumping on the well can induce two-phase flow. A reliable test method for obtaining reservoir pressure and permeability is the STEP (Short Term Permeability) test. This test procedure amounts to a modification of the slug test, in which a perturbation is made to the well fluid level. The permeability can be determined from the time and rate taken for the well to return to the undisturbed state. Automated systems for performing this tests are available (Stubbs 1989). It is noted by Stubbs that tests of this nature measure the coupled effect of the formation permeability and the wellbore damage.

In the introduction to their paper, Semmelbeck and Lee (1990), observe that:

Well performance in coalbed methane reservoirs is strongly dependent on the amount of pressure interference between wells. Interference allows the reservoir pressure to be lowered rapidly. This allows gas to be released from the coal matrix and flow to the producing wells through the coal's natural fracture network or cleats.

The method suggested by these authors for evaluating the production potential from a coalbed methane field is the five-spot approach. Wherein the general field production is estimated based on the center well of the five well pattern. Other factors and tests that are important, based on the assessment of these authors, are pre- and post-fracture injection/falloff tests as well as multirate production tests. Conducting tests of these types on several wells in the field allow for better understanding of the field potential and optimum production rates. Thus enhancing the ability of the reservoir engineers to forecast production and necessary development schedules.

Seidle, Kutas, and Krase (1991) investigate the application of pressure falloff tests (PFOT) in new coalbed methane wells. Based upon their research, on wells in the San Juan Basin, these authors concluded that there are some modifications needed to adapt conventional PFOT methods to use in coal deposits that are water saturated. When applied, a PFOT can determine the reservoir parameters of “permeability, wellbore skin, and initial reservoir pressure.” The authors further note that in the presence of free gas in a well, the PFOT will indicate “a permeability too low, a skin too negative, and an erroneous reservoir pressure.” While the authors present an approach to correcting the first two of these weaknesses, they note that they had no means to correct the third.

The inverse problem concerning the determination of the wellbore radial permeability, in the vicinity of petroleum production wells, is covered by Oliver (1992). The so called forward problem is based on estimating the pressure history from formation properties. In this paper the author attempts to characterize the formation properties based on the pressure history recorded during well tests. Using the technique presented in this paper, the author notes, can only produce a radial permeability around the well. The use of various interference tests could be used to better grasp the permeability distribution in the target formation.

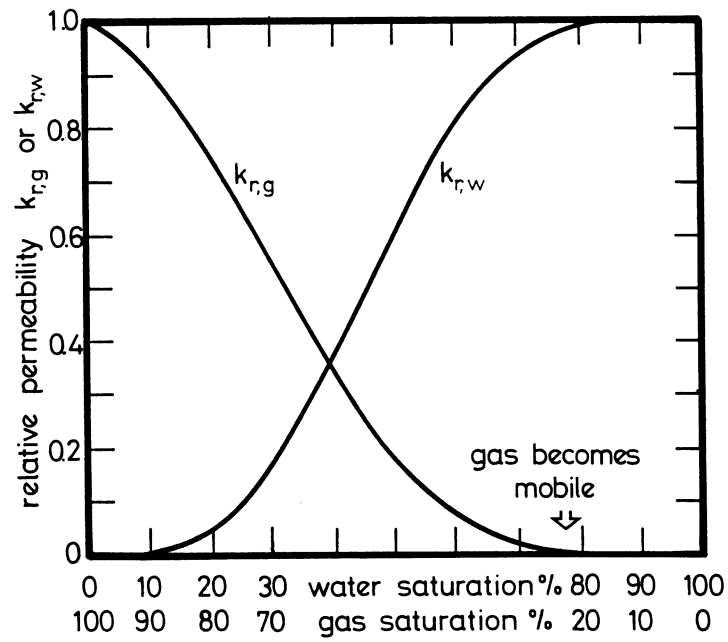


Figure 2-3: Typical Curves Illustrating the Relationship of Permeability to a Liquid and a Gas of a Two-Phase Flow System in a Porous Medium (after: McPherson 1993).

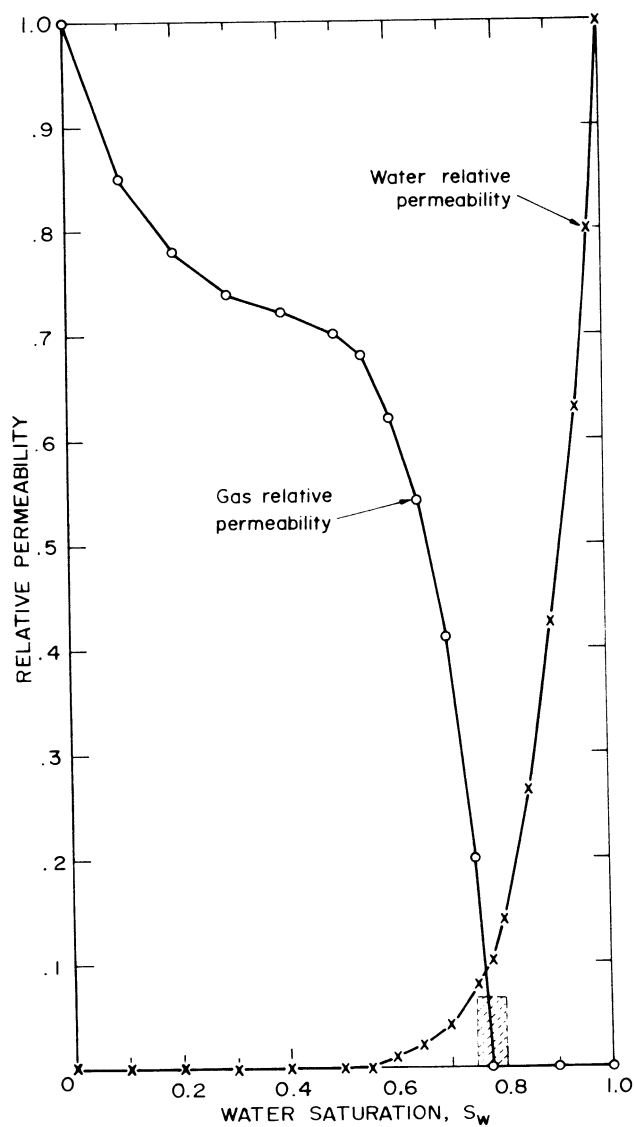


Figure 2-4: Gas and Water Relative Permeability Curves for a Coal Sample (after: Kissell and Edwards 1975)

2.2.3.5.2 Laboratory Methods

An early approach to the measurement of material properties of triaxially confined samples is presented by Donath (1965). The technique presented here allows the researcher to vary the pore pressure within the sample. This system allowed for the study of both consolidated and unconsolidated samples. Theoretical pore pressures up to 36,000 psi were available to the researcher, axial loads of up to 50 tons could be applied to the confined sample. The configuration that Donath presents appears clumsy relative to methods available today, the origins of modern equipment, such as the Hoek cell, are visible, however.

The preparation of coal samples for property testing is addressed by Harpalani (1988). In this paper the author addresses the development of a method of obtaining coal samples for permeability testing. These samples were obtained and prepared with the horizontal laminations of the coal parallel to the cylindrical axis of the sample. In the method described, block samples of coal were obtained directly from underground coal mines. These blocks were then placed into a lathe, with the face cleat structure parallel to the axis of rotation. The samples were reduced to cylindrical by the repeatedly grinding away a fraction of a milli-meter with a high-speed grinding wheel. The ends of the sample were squared using a surface grinder.

The basic permeability experiments, such as those carried out by Darcy, are described in numerous texts on the subject of ground water and of porous media. In general, these tests utilize a subject medium of known dimensions to which a fluid, with known properties, is applied at a constant or falling pressure. Then by determining the flow rate of the fluid, or the time for the pressure to fall a given amount, the media's permeability can be determined.

For samples that are relatively homogeneous and isotropic, the basic radial flow model developed in McPherson (1993) can be applied to obtain a permeability value for the sample being tested.

Roy and Pyrak-Nolte (1995) investigated "the effect of drying and re-saturation on the gas permeability of coal." These researchers found that drying of the coal samples can increase the measured permeability by 2 orders of magnitude. The action of drying the samples is shown to permanently damage the structure of the coal, following re-saturation of the sample the original permeability could not be restored. The authors employed CAT-scan technology to evaluate the changes in the samples as a result of handling. They report that no "significant change in the micro-structure of the samples" was observed. Also noted in this paper is the stress dependent behavior of the coal samples relative to the measured permeability, and the potential for changes in coal sample due to de-saturating the samples with respect to both water and gas.

The effect of stress on the measurement of permeability within a triaxial cell is addressed by Azeemuddin et al. (1995). The material used by the investigators was limestone and Berea

sandstone. They observed that under conditions of hydrostatic stress the “permeability decreases continuously with increasing confining pressure.” These authors considered several conditions of stress configurations on the sample and found that the results in measured permeability were consistent with the predicted results based on volume changes of the sample, i.e. compressive or dilatant changes in effective stress. The method used for the measurement of permeability in this research was based on a pressure pulse technique, rather than a conventional steady-state flow approach.

2.2.3.6 Coal Swelling

One of the interesting phenomena associated with gas adsorption processes is the swelling that can occur in the adsorbate matrix. This action occurs in coal and has been shown to affect the permeability of the coal during degassification (Harpalani and Schraufnagel 1990). This authors indicate a measured volume loss of approximately “0.4% when the gas pressure falls from 6.9 MPa to atmospheric pressure.” This response leads them to conclude that it is possible to expect production to increase as the well system is depressurized.

Reucroft and Patel (1983) investigated the effects on the measurement of surface area within the coal structure and the swelling of the coal matrix as the various gases adsorbed onto the pore surfaces. These researchers showed that there is a dependence on the measured surface area and the solubility of the vapor used to make the determination. That is, the coal matrix surface area measurement is affected by swelling of the coal sample as the analytical gas is adsorbed onto the coal pore surface.

In a follow-up to their earlier paper (1983) Reucroft and Patel (1986) sought to quantify the degree of swelling experience by coal samples when exposed to various gas atmospheres. Their results show that use of carbon dioxide gas can cause swelling of as much as 1.31% in the sample volume as the gas becomes adsorbed to the coal surfaces. The effect of nitrogen, and other inert gases, was shown to be one of contraction of the coal matrix as the gas reached equilibrium adsorption to coal structure.

2.3 Advanced Techniques of Well Stimulation

A number of novel techniques for well stimulation and production control have been proposed and evaluated. This section will cover the literature generally available on these techniques.

2.3.1 Multiple Fracturing (Tailored Pulse)

The so-called tailored pulse concept of rock fracturing in well bores seems to have received a fair degree of investigation. The nature of this concept is to produce a dynamic loading of the well bore to produce a more diverse fracture pattern than would be achieved through conventional hydraulic fracturing; but, without the extensive damage associated with explosive fracturing. A basic chronological review of previous experiments and investigations is provided in this section.

Warpinski, et al., (1979) address the problem of a “Controlled Propellant Deflagration” in their discussion of experiments conducted in the G-tunnel at the Nevada Test Site. The test reported occurred in the ash fall tuffs of the NTS. The fracturing device was a propellant canister which was instrumented and grouted in the hole. These tests included the benefit of mining back through the fractured region. This early paper develops what appear to be the general conclusions regarding tailored-pulse loading. In particular, the authors note that: (1) the initial loading rate must be sufficient to initiate multiple fractures from the borehole, (2) the propellant must continue to burn throughout the development of fractures, and (3) too high a pressure in the bore hole will adversely affect the hole skin. These authors claim that applications for this technique are in Devonian shale.

Schmidt, Warpinski and Cooper (1980) performed a series of experiments to evaluate the tailored-pulse concept. They identified 5 cases for investigation in the ash-fall tuffs of the Nevada Test Site. These cases included: “a decoupled explosive” (i.e., one in which ullage remains between the charge and the borehole wall), “a decoupled explosive with propellant booster,” “a small diameter propellant charge with a pressurized water booster,” “three successive shots” of the previous case, and “a full-diameter charge of a progressively-burning propellant.” The authors present results which indicate that a significant stress cage was produced as a result of the decoupled explosive, resulting in a decrease in the local permeability. The second, third, and fourth cases produced “modest stimulation.” While the fifth case “produced a highly stimulated zone around the wellbore. The authors further indicate that borehole pressure loading rate is a more important criterion for multiple fracture initiation than is the peak pressure.

The effect and behavior of deeply confined explosions and deflagrations were investigated by Schmidt, Boade, and Bass (1981). In the introduction to this paper the authors note that:

Multiple fractures are desirable for eliminating skin damage, which may occur during drilling, and for connecting the wellbore to an existing fracture system, as might be present in a gas-bearing Devonian shale. Connecting a well to a fracture network often is not possible by hydraulic fracturing, since there is little or no control over fracture orientation and the hydrofracture often will run parallel to existing fractures.

The conclusions reached by the authors indicate that: (1) the magnitude of the stress cage caused by high-explosives can be reduced by decoupling the charge from the bore wall. (2) The use of propellants can keep the available energy high enough to produce extensive fractures while also reducing the peak stress load to the surrounding formation. The authors also indicate that the generation of a stress cage around the wellbore impedes the development of fractures by cutting off flow paths for the gases generated by the explosives used for stimulation.

Swift and Kusobov (1981 and 1982) conducted a series of tests in which the tailored-pulse was generated by a cam driven piston. These authors arrived at several conclusions, including: (1) breakdown pressure is proportional to loading rate, (2) breakdown pressure is proportional to confinement, (3) loading rate to initiate multiple fractures is inversely proportional to water content, and (4) the number of fractures increases with loading rate. They also suggest that tailored pulse techniques may be more applicable to high permeability formations rather than those of low permeability. They do not, however, indicate what magnitude of permeability is most amenable to tailored pulse methods.

Fourney, Barker and Holloway (1981) conducted a series of experiments investigating explosive techniques of well stimulation. The experiments reported in this paper were conducted using Plexiglas as the media being fractured. Tests were conducted with straight holes drilled into the media and with grooved holes, which created an initial point of stress concentration. Experiments using PETN (Pentaerythritol Tetranitrate) as the fracturing energy source were conducted for both air and fluid filled holes. In all cases the charge was de-coupled from the borehole.

Further experiments by Fourney, Barker, and Holloway (1983) were conducted to evaluate the use of propellant charges for well stimulation. This paper describes a series of tests conducted that are similar to those above, however, a Kinetech Propellant (KTP) was used for fracturing rather than the explosive PETN. The propellant charge in the fluid filled holes was approximately 25% of that used in the air filled holes. Of the seven grooved bore tests described, all of them fully cleaved the sample of Plexiglas. The authors note that the deflagrating device is much more efficient than the use of an explosive type device. The exact benefit could not be determined since the test samples were fully split during testing. While the use of a water filled hole for these experiments was found to increase the efficiency of the charge this result may not translate to the field where clay in formations may be detrimentally affected by the presence of water. That is that water contained in, or added to, the clay may inhibit the growth of fracture system by responding in a plastic manner to the passing pressure pulse.

Numerical modeling investigations have been conducted by Nilson, Proffer, and Duff (1985) into the gas-driven fractures associated with propellant combustion. In this work the authors compared theoretical conditions of propellant burns and formation fracturing to conditions observed in the field.

The transfer of tailored-pulse technology to enhanced gas production appears to be creditable to Cuderman and Northrop (1986). These authors cover the scaling of technology from the laboratory to the field, culminating in tests conducted in Devonian shale formations in Kentucky and Ohio. These authors present criteria of pressure rise time to obtain fracture behavior falling between the limited range of hydraulic fractures and the highly damaging explosive fractures. The required pressure rise time was shown to be inversely proportional to the wellbore diameter. The down-the-hole propellant charges utilized in the reported experiments were constructed using a surplus military artillery propellant. The conclusion reached by the authors indicate that the technology performed as expected in the field, based on the earlier results at the Nevada Test Site (i.e. Schmidt, Warpinski, and Cooper, 1980), furthermore the fractures obtained were predictable based on the pressure pulses obtained.

Further studies, using liquid propellants in the Appalachian Basin have been conducted by Watson, Benson, and Fillo (1986). These authors report a series of experiments using a liquid propellant rather than the solid/dry propellants by previous investigators. The propellant (RE-FLO[®] 403) used was developed by IRECO Inc. This propellant has the properties of being heavier than water and immiscible with water. Thus, it can be poured into water filled holes, knowing that it will sink to the bottom of the hole without dilution. The propellant was ignited at the top of the charge column, causing the pressure pulse to be directed downwards. Typical results included "several vertical fractures in random directions." Field tests of this method indicated that production from the treated wells continued to show an enhanced trend 30 days following treatment.

Investigations into the mode of the multiple fracturing model have been conducted by Schatz and Hanson (1986). These experiments included laboratory studies utilizing a stress block of a uniform simulated rock material. The authors discuss the behavior of the multiple fracturing process, from the point of view of parameters necessary for modeling. They identify three key phases of the process: (1) "wellbore pressurization," (2) "flaw rupture," indicated by a momentary peak pressure, and (3) "fracture extension," driven by the continued production of hot gases. These authors discuss the application of this fracturing technique for situations where it is desired to cut across the primary in-situ fracture pattern, with particular emphasis on Devonian shale. Experimental tests were conducted on 12*12*12 inch samples. The sample was confined tri-axially in a specially constructed apparatus. Fracture stimulation was accomplished using a propellant/explosive charge. This paper does not present any quantitative results of the experiments described by the authors.

Detailed investigation into the role played by wellbore liquids during fracturing by propellant deflagration was conducted by Cuderman (1986). This paper indicates that the generation of fractures in liquid filled holes is far more complex than that associated with dry holes. This is compounded by the observed reactions of lower peak pressures and shorter pressure risetimes. The liquid filled holes showed evidence of hydraulic, multiple, and explosive fracturing. The investigator believes that this is due to very high pressure gradients. This may be evidenced by pressure rise rates that were 5 to 10 times those in the dry holes, despite the fact that the peak pressures were significantly lower. The author further indicates that the lower peak pressures may be associated with enhanced hydraulic fracturing at the extreme limits of the test zone.

Further work into the mode of radial fracturing from wellbores is reported by Schatz, et al. (1987). These researchers employed a variety of charges including black powder, regular gun propellant, and high explosive. The material was standardized as a gypsum-base cement. Experiments were conducted in a tri-axial test cell on blocks measuring approximately 12*12*15 inches. A series of tests was conducted for both isotropic and anisotropic stress states. Confinement pressures varied between 400 and 1500 psi. The authors conclude that initiation of multiple fractures is governed by the “gas pressure risetime, material parameters, and stress on the fracture planes.” Growth of the fractures is controlled by optimizing the rate at which additional gas is made available to the fractures. Concerning the presence of liquids in the holes the authors indicate a positive response during fracturing, “unless significant steam generation occurs.” It is interesting to note that the authors indicate that a perforated casing does not adversely effect the development of fractures, in comparison to holes without a casing. They do not indicate that any failure of the casing occurred in holes so equipped.

Coursen (1987) present research indicating the ability to estimate the fracturing radii as a function of the wellbore radius. The model considers factors such as gas production and pressures during and after the detonation of the charge, the resulting cavity volume ratios and the effects of isentropic cooling of the product gases. Also included are the in-situ stresses and the shear and compressive strength of the rock mass.

Recent investigations into role of perforations in the initiations of fractures in wellbores is documented by Behrmann and Elbel (1990). These experiments were conducted in tri-axially stressed samples, approximately 28*29*33 inches, of quarried sandstone. The general conclusions reached by the researchers included observations that the fractures initiated from “the base of the perforations” and “the intersection of the plane normal to the minimum far field stress...” Furthermore, they indicate that the initiation of the fractures will depend on the orientation of the perforations to the far field stresses, and the build up in pore pressure. These fractures were based on conventional hydraulic fracturing technology, rather than tailored-pulse (multiple) fractures.

2.3.2 Liquid Carbon Dioxide

While there appears to be very little literature available on concept of utilizing liquid carbon dioxide as a stimulating fluid, the general effect of carbon dioxide gas on the coalbed methane is covered in limited detail. The most pronounced effect of displacing the adsorbed methane from the coal matrix arises from the greater affinity of carbon dioxide to carbon, relative to methane. This tends to release the methane from the coal matrix.

There is a secondary effect based on the relative size differences between the carbon dioxide and methane molecules. The mean diameter carbon dioxide molecule is of the same order of magnitude as the smallest of the passages in the coal matrix. The net result of the adsorption of carbon dioxide could be the closing of some of the pores within the coal, inhibiting the release of methane. It is not clear if the slip-flow mechanism could influence this case.

Regarding the use of carbon dioxide to liberate methane from coal a laboratory investigation was conducted by Fulton, et al. (1980). This investigation included both dry and wet samples. The researchers showed that use of carbon dioxide was very effective at liberating methane from the coal. Repeated treatment was shown to remove virtually all of the adsorbed methane. This paper indicates an optimistic outlook on the use of this carbon dioxide as a means of enhanced methane recovery.

Further investigations regarding the application of carbon dioxide to enhance methane recovery were conducted by Reznik, Singh, and Foley (1984). These authors noted that the natural desorption of methane will only produce about 30% of the gas in place. Cyclic treatment with carbon dioxide at pressures between 3.5 and 5.5 MPa was shown to desorb all of the methane in place. (It should be noted that at the vapor pressure of carbon dioxide at room temperature is about 850 psi.) The researchers found that the methane concentration of the “produced” gas, injected carbon dioxide and methane, never exceeded 20%. With this in mind the authors indicated that the use of carbon dioxide may have more application in degassing coal ahead of mining, rather than as a technique for commercial gas production.

An enhanced method of methane recovery has been proposed, and patented, by Puri and Yee (1990). The technique utilizes nitrogen injection wells to maintain the formation pressure, while driving the methane towards a production well. This is opposed to the conventional reservoir depletion technique commonly employed. Furthermore, the authors note that desorption of methane is enhanced by the reduced partial pressure of methane due to the presence of nitrogen. The authors do not indicate what additional cost might be associated with the technique, particularly in the area of separating the methane and nitrogen production gas.

As an extrapolation of the Puri and Yee (1990) technique, it is conceivable that carbon dioxide, rather than nitrogen could be used as the injected gas. An enhanced release of methane from the coal could be expected due to the coals higher affinity to the carbon dioxide relative to methane.

Obvious limitations, however, include the separation problem as well as the cost of transporting carbon dioxide to the injection sites.

In 1992 a patent² was issued to the Atlantic Richfield Company for the use of liquid carbon dioxide as a coalbed methane well stimulating agent. As described in the patent abstract the well would be of an open-cavity completion type. The carbon dioxide would then be pumped, at critical temperature, into the coal seam. Once the liquid carbon dioxide had been allowed to disperse into the coal seam the pressure would be quickly relieved, causing some of the coal seam to fail, dispersing the coal particles into the well.

A review of the state of carbon dioxide injection relevant to petroleum recovery is given by Hadlow (1992). In this paper the author arrives at several conclusions relevant to the application of carbon dioxide. One of the most enlightening of these is the observation that significant improvements in production can be obtained by better reservoir management, prior to the application of CO₂. He also notes that the breakthrough of carbon dioxide follows with the predicted behavior.

2.4 Performance Assessment

The consideration of a coalbed methane prospect and its performance is discussed by Ely, et al. (1990). The region of interest to these authors was the Warrior Basin in Alabama. The project described was intended to:

- (1) gather baseline reservoir data, (2) determine the viability of further development by field experience, (3) provide insights into potential operational problems involved with drilling and completing wells in this area, and (4) learn how to complete and stimulate the coal seams in this area.

The authors indicate that in the early phase of their project they investigated a deeper coal seam as a potential additional target. Based on the assessment of the potential for production they removed this seam as a target, the seam simply would not prove to be profitable. This pilot program was used to assess the potential for gas production from the target seams.

Deimbacher et al. (1992) compare the potential production enhancement of a horizontal well compared to a vertical well. The research indicates that wells completed horizontally will outperform those completed vertically. There is further evidence that the orientation of the horizontal wells plays a role in the production of methane from those wells. Horizontal wells

² United States Patent Number 5,147,111, *Official Gazette*, United States Department of Commerce, Volume 1142, September 15, 1992.

drilled normal to the expected fractures tend to out produce those drilled in the same direction as the expected fractures.

2.5 Methane Production Simulation

The mathematical and numeric theory behind coalbed methane flow is presented by King, Ertekin, and Schwerer (1986). The research presented in this paper utilizes finite-difference models to investigate the flow of gas and water within the coalbed formation. The models apply the dual porosity approach, a technique that accounts for diffusion of methane through the coal matrix micro-pore structure, and the Darcy flow of gas and water in the macro-pore (fracture system) of the coal. The specific advance made by the authors in this research was the inclusion of the transient phenomenon of dewatering the coal. In most coalbed methane fields the formation must be, at least partially, dewatered prior significant production of methane begins to occur.

A paper prepared by Paul, Sawyer, and Dean (1990) compares the results obtained from models developed by ICF Resources Inc. (COMETPC 3-D) and by Atlantic Richfield Corporation (IMPES). These simulators were applied to three different coal seam gas problems. The outputs were in close agreement. The authors state that the problems and output should serve as valuable baseline data for other coalbed simulators. The required input data included: thickness, horizontal permeability, vertical permeability, porosity, initial water saturation, initial pressure, desorption pressure, sorption time, Langmuir volume, and Langmuir pressure. As the name suggests, the COMETPC model is designed to operate on a personal computer, the IMPES model, however, was design to operate on a Cray supercomputer system.

Zuber and Semmelbeck (1990) compare the basic parameters of methane flow through coal to the assumptions used in typical coalbed methane production simulation programs. The basis for the simulation techniques reviewed is the dual-porosity model, in which diffusion and desorption are considered in the coal matrix elements, whereas Darcy flow is assumed within the cleat and fracture structure of the coal formation. The authors note that although there were (in 1990) several modeling packages available for both personal computer and super computer systems, most typical problems could be handled by the more user-friendly personal computing systems. The authors suggest that some refinement is needed in the diffusion/desorption sections of the models, but concede that such refinements would require a better understanding of the physical process. Another area that the authors suggest for enhancing the capabilities of the simulation capacity is to account for dynamic changes within the reservoir. In particular, changes in the permeability and porosity as water and gas are produced.

A thesis prepared by Fan (1991), details the development of a software package for estimating the production of methane gas associated with mining activities. This package considers both gob wells and wells drilled into areas otherwise affected by mining activities.

Stevens, et al. (1992) used the COMET - PC and COMET3D - PC models to aid in the assessment of the Tangshan coalbed in the Hebei Province of the People's Republic of China. The results of this modeling appears to have given reasonably good results leading to the desire to develop the investigated field.

Utilizing laboratory methods for determining coalbed parameters necessary for gas production modeling is covered by Harpalani, Ouyang, and Chen (1995). The key elements that these researchers observed are the diffusion coefficient, permeability, and cleat characteristics. In their work the diffusion coefficient describes the transport of methane through the "solid" coal (Fickian Diffusion); and the permeability is the proportionality value to satisfy Darcy's law. The approach taken by the authors in establishing the cleat parameters was the application of Computer Aided Tomography (CAT) techniques. Through the application of software intended for medical analysis the shape, size and interaction of the cleats could be assessed.

In addition to testing methods, discussed above in section 2.2.3.5.1, the ASTM also has recommendations for application of ground water models (ASTM D5447-93, ASTM D5490-93). ASTM D5447 presents a standard approach to "Application of a Ground-Water Flow Model to a Site-Specific Problem." ASTM D5490 is a standard for the comparison of ground-water flow model data to that gained from site specific investigations.

Returning to the challenges identified by Schraufnagel, McBane, and Kuuskraa (1990), which lie ahead of the coalbed methane industry (see introductory section of this chapter), the work reported in this thesis seeks to address the first, fourth, and fifth of these hurdles.

Chapter 3. Tests Involving Liquid Carbon Dioxide

This section will address the series of tests that were conducted to evaluate the effect that liquid carbon dioxide might have as a stimulating agent in coalbed methane wells. The work described here formed the first section of the ongoing research. The principal question that was posed concerned the possibility of injecting carbon dioxide, as a liquid, into a coalbed then rapidly releasing it to the atmosphere as a means of stimulating methane production from the well.

The basis for the assessment was a number of coal core samples. These samples were obtained from coal seams used for methane gas production in southwest Virginia. The key interest in altering the permeability of the basic structure of the coal necessitated that measurements of flow through the samples be made in the direction that that gas would be expected to flow in the field. The coal samples, however, were such that the desired flow direction was not in line with the cylindrical axis. Therefore, flow along the coalbed laminations could not be measured, by conventional means, in a tri-axial cell.

To accomplish the task of measuring gas flow perpendicular to the sample axis a unique method of sample preparation was developed and utilized. This method and the results of testing and evaluation are presented in following pages.

3.1 Basic Theory

The theory that underlies the measurement of permeability in laboratory scale samples is fairly well understood. The general darcy experiment is shown in figure 3-1. Figure 3-2 illustrates a modern method for measuring the permeability of a rock sample, wherein the axial and radial stresses on the sample can be controlled independently. The details of permeability measurement will be discussed below.

A compounding factor in the measurement of permeability is the possibility of variation in the material properties, including permeability, with respect to orientation of measurement. Figure 3-

3 shows an example, similar to coal, where the permeability varies with respect to orientation. The bedded nature of coal, and other sedimentary rocks, lends to directional differences in the permeability. An additional factor is the joints, or cleats, in coal. Considering these two controlling parameters, it is expected that there can exist an anisotropic environment where significant variations in a flow field through the media can exist.

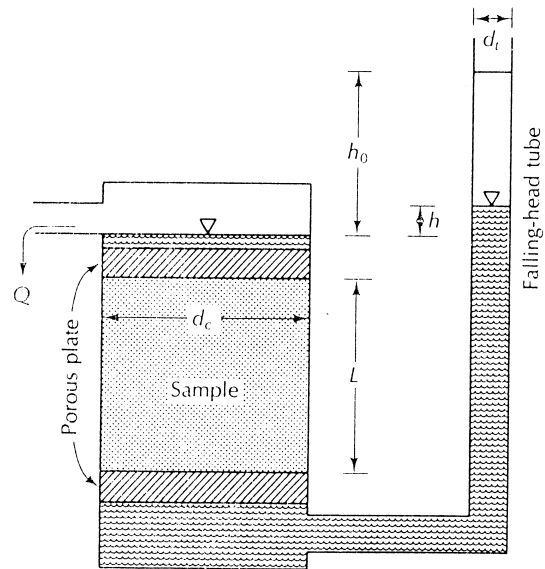


Figure 3-1a: Falling Head Permeameter (after: Fetter 1994)

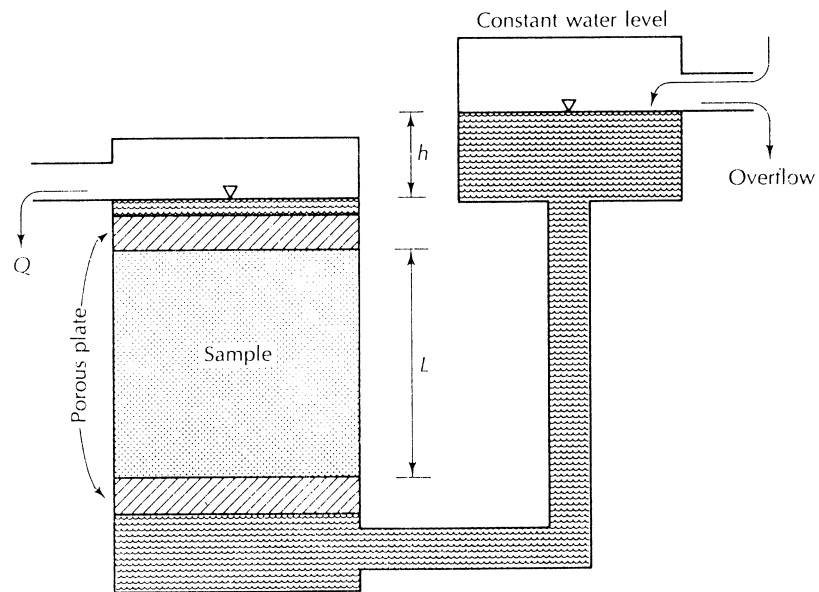


Figure 3-1b: Constant Head Permeameter (after: Fetter 1994)

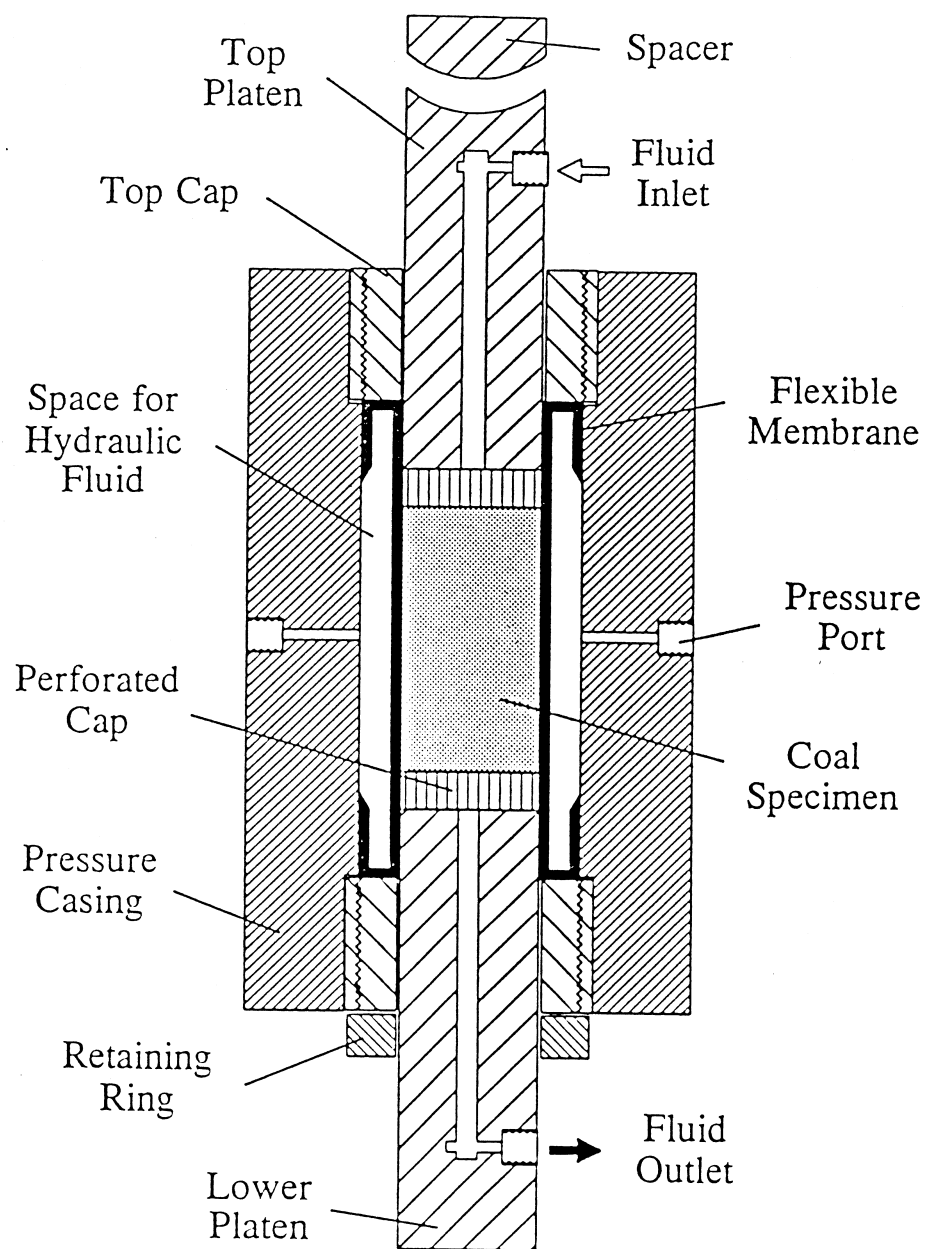


Figure 3-2: Permeability Experiment in Hoek Cell (after: Harpalani 1984).

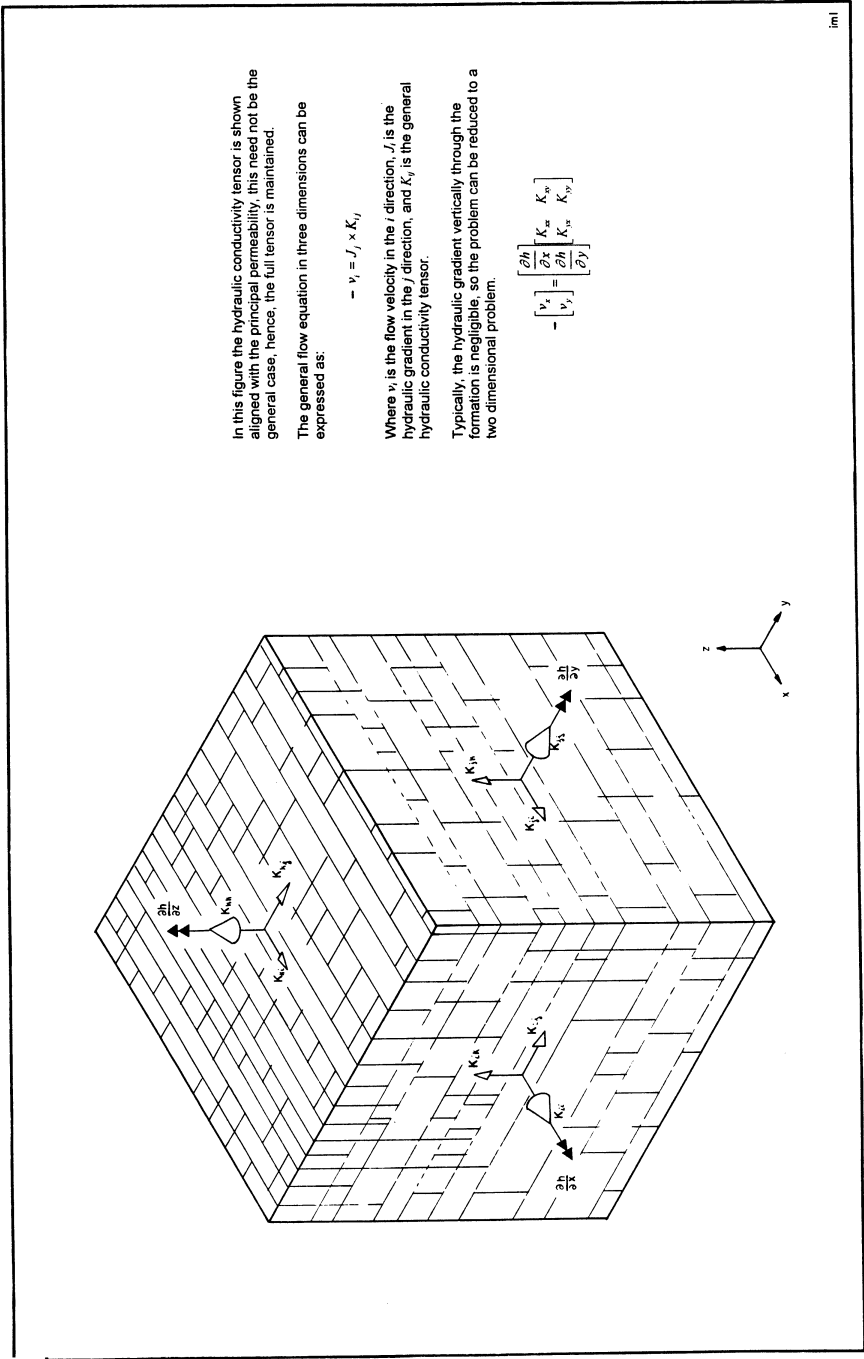


Figure 3-3: Three Dimensional Flow Field

Another consideration is that in a horizontally bedded aquifer, little of the fluid motion is considered to occur in the vertical direction (Fetter 1994). Referring back to figure 3-2 and 3-3, it can be seen that measurement of the permeability along the axial direction of a sample cored vertically gives little indication of the horizontal permeability of the sample in question. The first task undertaken in this project was to develop a technique by which the horizontal permeability could be assessed from coal samples taken as vertical cores from a deeply buried seam. Once this method had been developed it was then possible to inject the coal sample with liquid carbon dioxide and appraise the impact that this treatment had on the permeability of the sample.

This section is divided into several sub-chapters dealing with relevant topics, section 3.1.1 covers permeability measurement. Section 3.1.2 covers the baselining procedures for comparison between axial flow and radial flow samples. Section 3.1.3 addresses the comparison between mean pressure and pressure gradient in the baseline samples. Section 3.1.4 presents the theoretical considerations of the impact of carbon dioxide to affect the production of methane gas from coal. Section 3.1.5 covers the role of formation pressures on the permeability of the samples.

3.1.1 Permeability Measurement

Measurements of the permeability of the various samples were made on a mass flow basis. This was due to the consideration that gas is highly compressible and as such the volumetric flow rate and the fluid velocity are dependent of the gas pressure at the point of measurement. Some gas flow theories are based on volumetric flow; however, these must account for the physical properties of the gas, i.e., molecular weight, compressibility, etc. (Smith 1983, Ikoku 1984).

3.1.1.1 Axial Samples

The general approach to determining the permeability of the axial flow samples is based on Darcy's law. This empirical law is generally given as:

$$Q = KA \frac{dh}{dl},$$

where Q is the volumetric flow rate of the fluid, K is the hydraulic conductivity, A is the total cross-sectional area of flow, and dh/dl is the hydraulic (pressure) gradient driving the flow. The hydraulic conductivity represents the volume of flow across a unit area when the hydraulic gradient is 1 unit of fluid height per unit of linear distance. The hydraulic gradient expresses the pressure loss of the fluid in terms of pressure lost per distance moved. In this case the pressure is

expressed in terms of the height of the column of fluid. Based on the analysis given by Fetter (1994) the intrinsic permeability (in units of area), and substituting k for K_i , is given as:

$$k = \frac{K m}{r g}.$$

Where K is the hydraulic conductivity, m is the dynamic viscosity, r is the fluid density, and g is the acceleration of gravity. Substituting back into Darcy's law the intrinsic permeability can be determined for volumetric flow, Q , as:

$$k = -\frac{Q dl}{A dh} \frac{m}{r g}.$$

Where A is the cross-section normal to the flow, dl is the sample length, and dh is the head drop across the sample. In this equation the head loss is expressed in dimensions of length (height of fluid column). It can easily be shown that the $(dh r g)$ term can be replaced with a pressure drop in units of Pascals. Furthermore, by replacing the volume flow term (Q) with a mass flow term (M/r) the permeability expression becomes:

$$k = -\frac{M l m}{A r (P_o - P_i)}.$$

Where P_o and P_i are the outlet and inlet pressures, respectively. By further substituting for the density in terms of the gas constant R , temperature T , and the average pressure, this equation becomes:

$$k = -\frac{2 M l m R T}{A (P_o^2 - P_i^2)}.$$

Which has the same form as that expressed for radial flow conditions in the following section.

3.1.1.2 Radial Samples

The basic approach taken to determining the permeability of a sample in the radial configuration is based on the approach given by McPherson (1993). The permeability equation for a radial bore hole, based on mass flow is given as:

$$M = \frac{k}{m} \frac{2 p a}{R T} \frac{P_s^2 - P_b^2}{2} \frac{1}{\ln(r_s/r_b)}$$

This can be manipulated to give the intrinsic permeability, k , as:

$$k = -M \frac{\mu RT \ln(r_s/r_b)}{\rho a (P_s^2 - P_b^2)}$$

Where M is the mass flow rate of gas, μ is the dynamic viscosity, r_b is the radius of the borehole, r_s is the radius of the sample, a is the thickness (axial dimension) of the sample, P_b is the gas pressure in the bore hole, P_s is the pressure outside of the sample, T is the absolute temperature and R is the gas constant. The interjection of the negative sign is necessitated to account for flow down the pressure gradient.

3.1.1.3 Conditions of Flow and Pressure Effects

Several factors can affect the measurements of flow in the samples. These include the Reynolds flow criteria, the fluid viscosity, and the porous medium itself. Each of these three will be reviewed in the following brief sections.

3.1.1.3.1 Reynold's Number Criteria

The analysis given above is based on the assumption that the flow is such that Darcy's law is valid, that is that the flow is not turbulent. A Reynold's number criterion for this condition can be expressed as:

$$N_{RE} = \frac{r n d}{\mu}$$

Where N_{RE} is the Reynold's number, r is the fluid density, n is the fluid bulk velocity, d is the matrix particle size, and μ is the dynamic viscosity. In this formulation, Darcy's law is valid if N_{RE} is less than or equal to 1. The general Darcy conditions, of laminar flow, are assumed as valid for N_{RE} less than 10 (Bear 1972). By rearranging, and solving for n , the maximum velocity for which Darcy's law holds can be determined based on the Reynold's Number criteria:

$$n = \frac{N_{RE} \mu}{r d} = \frac{N_{RE} \mu RT}{P d}$$

The volumetric and mass flow rates can be determined in an appropriate manner:

$$Q = n A = \frac{N_{RE} \, m A}{r \, d},$$

and

$$M = Q \, r = \frac{N_{RE} \, m R T A}{P d} \frac{P}{R T} = \frac{N_{RE} \, m A}{d}.$$

Where Q is the volumetric flow rate, M is the mass flow rate, and A is the total cross-sectional area. From the expression for mass flow rate, above, it can be seen that the maximum flow rate for which Darcy conditions exist is a function of the viscosity and the particle size, as well as the obvious Reynold's number and sample cross-sectional area.

Considering that the Reynold's number is to be fixed at 1, and the cross-sectional area will be determined by the sample, estimates for the values of the fluid viscosity and the particle diameter must be made in order to ascertain the maximum mass flow.

3.1.1.3.2 Pressure Effects on Viscosity

The dynamic viscosity of a gas varies directly with temperature, as opposed to a liquid in which the viscosity varies inversely with temperature. In addition to the temperature effect, there is also a pressure effect on the gas viscosity. Generally, the viscosity of a gas at a temperature, with constant pressure, can be expressed as:

$$\eta(T) = \eta^\circ + T \frac{d\eta}{dT}.$$

Where η° is the viscosity at the reference temperature. The effect of pressure, at a constant temperature, is expressed in the form (Kestin 1988):

$$\eta(r) = \eta^\circ + \sum_{i=1}^n b_i r^i,$$

where b are density coefficients. The viscous parameters for methane and carbon dioxide are given in table 3-1, below.

Table 3-1: Viscosity Parameters for Methane and Carbon Dioxide (after: Kestin 1988).

	Zero-Density Viscosity 25°C	Viscosity 0.1 MPa, 25°C	Temperature Correction	First Density Coefficient
	η^0	η	$d\eta/dT$	b_1
Gas	$\text{Pa s} * 10^{-6}$	$\text{Pa s} * 10^{-6}$	$\text{Pa s K}^{-1} * 10^{-6}$	$\text{Pa s m}^3 \text{ kg}^{-1} * 10^{-6}$
Methane (CH ₄)	11.07	11.09	0.0326	0.01827
Carbon Dioxide (CO ₂)	14.91	14.92	0.0462	0.001232

For computational purposes, only the first density coefficient need be considered. It can be shown that the effect of the density is about the same magnitude as that of temperature over the range of pressures investigated below. The gas viscosity can then be computed, as a function of both pressure and temperature as:

$$\eta(r, t) = [\eta_{t=25}^0 + br] + \left[(t - 25) \frac{d\eta}{dT} \right],$$

where the reference condition is at 25°C, and η^0 is the zero density viscosity. Further information on the pressure and temperature effects on viscosity can be found in Reid, Prausnitz, and Poling (1987). This was one of the sources used in the development of the properties listed in appendix A.

3.1.1.3.3 Porous Media Parameters

The other factor in the maximum mass flow is the particle diameter. Given that the permeability and porosity of the sample are characterized, there are several means to estimate the effective particle size. The size distribution can be estimated from relationships between the particle makeup of the material and its permeability. Those relationships that are reported by Fetter (1994) are the Hazen, and Shepherd methods. Both of these methods are empirical in nature and include coefficients that account for the material type and size distribution.

The Hazen method is expressed, in terms of particle size as:

$$d_{10} = \sqrt{\frac{K}{C_H}} = \sqrt{\frac{k r g}{\eta C_H}}.$$

Where K is the hydraulic conductivity, k is the permeability, r is the fluid density, g is the acceleration of gravity, η is the fluid viscosity, and C_H is an empirical constant based on material

type and degree of sorting. The effective grain size, d_{10} , is that particle size which has a diameter greater than 10%, by weight, of the sample.

The Shepherd Method for estimating hydraulic conductivity can be rewritten for mean grain size as:

$$d_{50} = j \sqrt{\frac{K}{C_s}} = j \sqrt{\frac{k \ r \ g}{m C_s}},$$

where j is an index and C_s is an empirical constant, both based on sediment types and degree of textural maturity (the degree to which the standard deviation of the particle size distribution has been minimized). The mean particle size, d_{50} , represents the diameter of the particle for which half of the total mass is larger than that diameter.

The particle size distribution can also be estimated from a photomicrograph of the sample media. In this method, the distribution can be obtained by counting and classifying the individual grains on the photograph taken at sufficient magnification to allow good resolution and an adequate population.

3.1.2 Approach to Laboratory Measurement of Radial Permeability

The measurement of permeability in cylindrical core samples is usually undertaken with gas or liquid flow along the cylindrical axis of the sample. The configuration of this method, in a tri-axial Hoek cell, is shown in figure 3-2. The concept of this approach is analogous to the Darcy experiments illustrated in figure 3-1. This approach works well for porous media that are reasonable homogeneous and isotropic, or where the cores have been obtained that are aligned to the direction of flow that is of interest.

In the present case, the coal cores were obtained from holes drilled vertically through the seam. The assumed direction of gas flow in coalbed reservoirs is parallel to the laminations of the formation. Thus, in the samples that were tested, the relevant permeability was that in the planes normal to the cylinder axis. Attaining the permeability of the sample in the conventional means would not provide a value relevant to the problem. To this end, a specialized sample preparation technique was developed, as a part of this research project, that allowed for measuring the permeability, of the sample, perpendicular to the cylinder axis. This sample configuration is illustrated in figure 3-7. The sample preparation method is given in section 3.2.1 of this thesis.

When this sample is placed in the Hoek cell, see figure 3-2, the center bore aligns with the fluid inlet in the upper platen. As the fluid is applied to the sample it flows into the sample through the center bore. This establishes a pressure gradient radially outward through the sample. Fluid flows outward to the sand filled annulus. The fluid then moves downwards to the lower vent

holes, which are aligned to the lower perforated plate, to be collected at the fluid outlet port. This system is equipped to measure fluid inlet pressure, differential pressure across the sample, and fluid flow rate. Using these parameters, along with others, previously discussed, the permeability of the samples can be determined. The permeability measured in this manner is that which is parallel to the bedding of the coal strata.

3.1.3 Baseline Procedure for Comparison Between Axial and Radial Measurements

In order to assess the reliability of the method chosen to evaluate the radial permeability of the coal samples a comparison to a known technique was employed. This baselining procedure utilized a “known” entity, Berea Sandstone of a specified permeability. By measuring the permeability of each of these samples by either the axial flow technique or the radial flow technique it was possible to establish the reliability of the radial flow technique. Additionally, if the data did in fact differ between the two techniques, but by a generally fixed amount, an offsetting factor could be arrived at for the new, radial, method relative to the older, axial, method.

The general procedure used to baseline the radial flow technique involved obtaining sandstone cores, which had been drilled such that the laminated structure of the rock was aligned to the intended flow direction. Thus samples intended for axial flow were cored parallel to the laminations, whereas, samples intended for radial flow were cored perpendicular to the laminations.

The radial flow samples were prepared in a manner similar to the preparation of the coal core samples, described below. The axial flow samples were prepared by under coring the appropriate core size (BX, 42.0 mm) from the delivered core sample (77 mm diameter). The initial core had been cut into three pieces, each about the intended final length for the axial flow tests. Thus, the BX cores needed only to be surface ground on the faces perpendicular to the core axis.

The axial cores were configured in the Hoek cell (see figures 3-2 and 3-8, as well as plate 3-11 and 3-12) using the frill plates provided to distribute and collect the gas across the face of the samples. The pressure distribution of the gas in the samples was chosen to closely match both the mean gas pressure and the pressure gradient in the radial flow tests.

3.1.4 Comparison of Mean Pressure and Pressure Gradient in Baseline Samples

In order to fully assess the differences in the permeability measured by the techniques described here a means to compare the two basic parameters is necessary. Comparison based on either the mean pressure or the pressure gradient may be considered as independent approaches.

The mean pressure is assumed to be the pressure at the midpoint of the axial flow samples and at the log-mean (geometric mean) radius of the radial samples. This pressure value is taken as the arithmetic mean of the inlet and outlet side pressures. In either case, the simplest means to attain this similarity is to use a constant inlet and differential pressure (the two measurements available on the laboratory apparatus). The result, however, is that the axial flow sample is subjected to a much lower pressure gradient than the radial flow sample for similar differential pressures.

The other alternative is to use mean pressure gradient as the scaling factor. This approach would set the pressure gradient along the axial flow samples at the same level as that estimated at the log mean radius in the radial flow samples. This condition, however, forces a much larger pressure drop through the axial flow sample in comparison to the radial flow sample. Since the area through which the fluid must pass is proportional to the radial position, in the radial flow configuration, the pressure gradient is not uniform through those samples. Due to the smaller area presented to flow at the well bore the pressure gradient must be higher for the same fluid flow relative to a point at a further radius.

Figure 3-4 illustrates the variation in pressure gradient for radial flow, towards the well, near a well bore. This figure shows the results of incrementally solving for the formation pressure around the well. That is the equation used to determine permeability in section 3.1.1.2, above, has been rearranged to:

$$P_s = \left[\frac{M \ln(r_s/r_b) m RT}{\rho a k} + P_b^2 \right]^{\frac{1}{2}}.$$

Utilizing the equation in this form, and knowing the parameters M , r_b , m , T , h , k and P_b , it is possible to determine P_s for each of a number of values for r_s . The location of the mean gas pressure at the geometric mean radius is illustrated in figure 3-5a, for flow away from the bore.

By taking the differential form of the radial flow equation, presented by McPherson (1993) in the form of dP/dr :

$$\frac{dP}{dr} = \frac{M m R T}{2 k \rho a} \frac{1}{r P},$$

it is possible to obtain the pressure gradient through-out the sample. In this case the solution of the gradient is based on the radial position and pressure solved for earlier. The variation of relative pressure gradient as a function of the relative radial position is shown in figure 3-5b. Notice in this figure that the mean gradient occurs at a position somewhat less than the geometric mean radius. This indicates that the mean pressure gradient occurs, in general, closer to the wellbore than the mean gas pressure.

The equations above, and the pressure versus position diagrams, do not contain a variable of time, hence the condition illustrated is valid only for the steady state case. Since the experiments described in this thesis are based on a constant value for the inlet pressure and the differential pressure, the steady state assumption is reasonably valid.

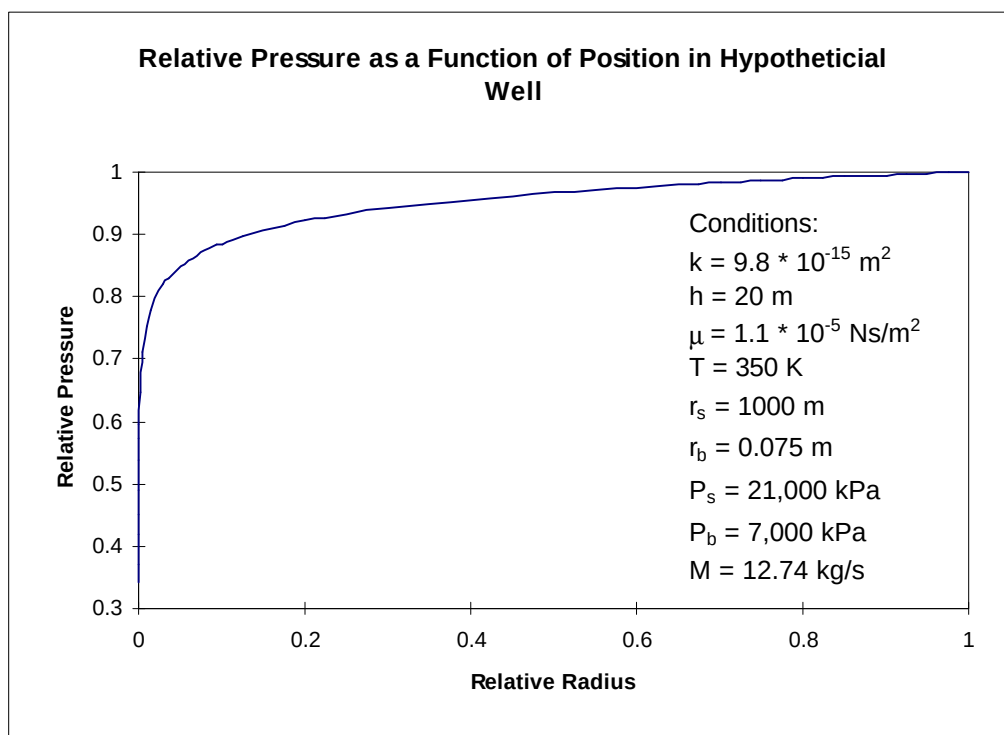


Figure 3-4: Relative Pressure as a Function of Position in a Hypothetical Well.

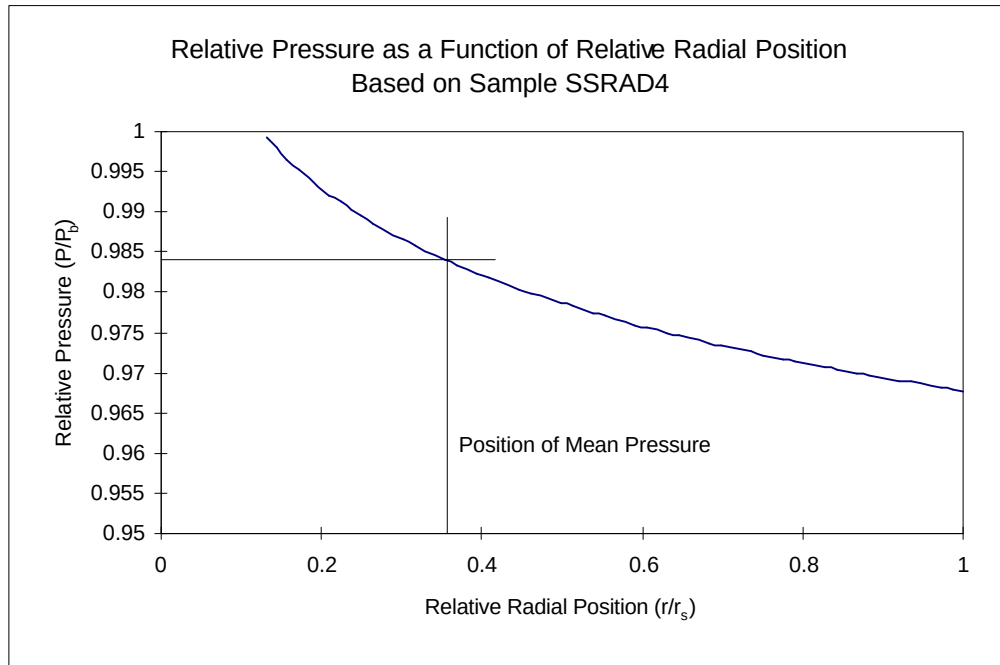


Figure 3-5a: Relative Pressure as a Function of Relative Radial Position.

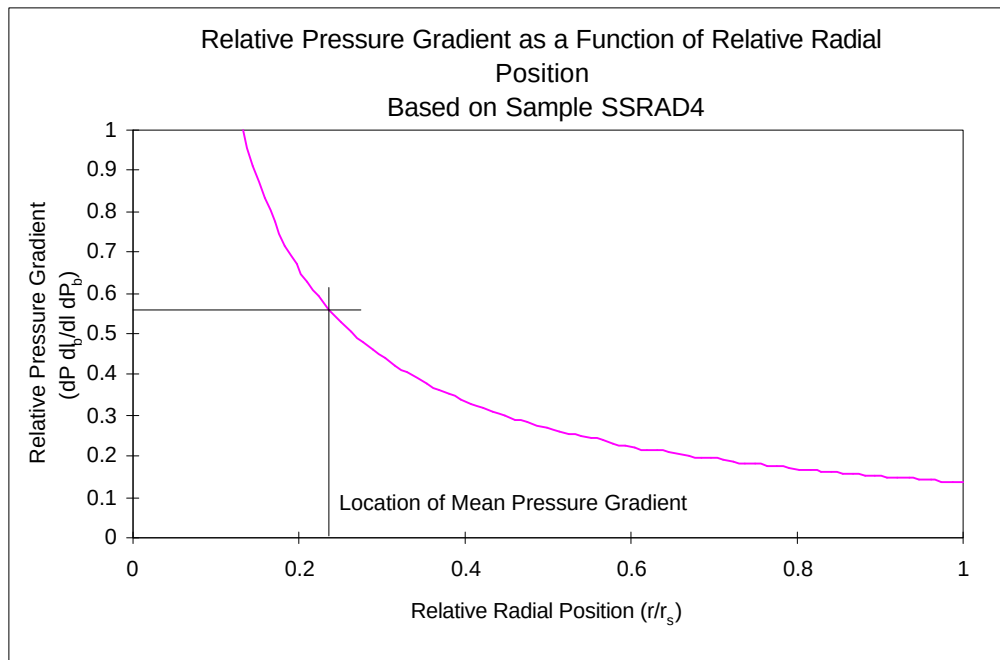


Figure 3-5b: Relative Pressure Gradient as a Function of Relative Radial Position.

3.1.5 Effects of Carbon Dioxide on Coal

The application of carbon dioxide in the field of hydrocarbon production has proven to enhance the ability of wells to continue production beyond the stage of primary drive. In conventional petroleum production, carbon dioxide flooding of wells falls into the category of secondary or tertiary recovery practice.

Generally, the application of carbon dioxide in the petroleum industry falls into two categories. The first role is to serve as a solvent for heavy hydrocarbons. By dissolving them, their viscosity is decreased which increases the amount of the fluids and tars that can be produced. The second function is to aid in the maintenance of formation pressure, thus keeping the pressure gradients from the outreaches of the well zone towards the borehole high enough to ensure continued economic production.

In coalbed methane wells the effect of carbon dioxide may be significantly different. Carbon dioxide has an affinity to coal that results in about 66% more retention than methane (McPherson 1993). A result of this higher affinity is the ability to displace adsorbed methane in favor of the adsorption of carbon dioxide. Experiments by several different researchers (Fulton, et al. 1980; Reznik, Singh, and Foley 1984) have shown the ability of carbon dioxide to strip nearly all of the adsorbed methane from laboratory samples. The limitation of the processes employed in these tests is that a fairly high to very high concentration of carbon dioxide is produced with the liberated methane; So much so that the researchers suggested that the method was more amenable to the strict degassing of coal, rather than the production of methane as a commodity.

The research concerning the use of carbon dioxide to aid the liberation of methane from coal is not explicit regarding the mechanisms that cause the competing adsorption reactions to occur. It is clear, however, that the physical process of adsorption is controlled by the partial pressure of the non-adsorbed, or free, gas that is in the pore space near the adsorbate. Puri and Yee (1990) suggest using nitrogen gas to decrease the partial pressure of methane in the coalbed to cause methane to desorb for the pore surfaces. Assuming a multi-component system, the adsorbed equilibrium conditions can be modeled as (Yang, 1984):

$$u_i = \frac{u_{mi}(B_i/h_i)P_i}{1 + \sum_{j=1}^n (B_j/h_j)P_j}.$$

Where u_i is the amount adsorbed of species i , u_{mi} is the monolayer amount for species i , B is a Langmuir constant for the respective species, P is the gas phase species partial pressure, and h is a coefficient of interaction between the adsorbed phases. This approach is one of several

presented by Yang (1984), but it allows for a brief investigation into the effect of the presence of both methane and carbon dioxide in the coal pore structure.

Assume that there is no interaction of the adsorbed phases ($h = 1$). Then, utilizing data presented by McPherson (1993) a gas content diagram for a mixture of both methane and carbon dioxide, based on the partial pressure of methane can be illustrated, as shown in figure 3-6.

One might also consider the effect of carbon dioxide, in a liquid form, flowing through the coal matrix. Carbon dioxide is much more wettable to the coal than is water, thus it would tend to displace the water as it flowed through the formation. The use of injected liquid carbon dioxide has been proposed and patented by Montgomery (U. S. Patent 5,147,111). The technique described (see section 3.4.5) uses the rapid release of the injected liquid to fragment and displace coal in the near vicinity of the wellbore, thus increasing the effective radius.

A factor that is not evident in the literature is the impact of the carbon dioxide fluid on the structure and physical state of the coalbed. This situation is relevant, due primarily to the unique characteristics of carbon dioxide, relative to other common gases at similar pressures and temperatures. A partial listing of physical properties of carbon dioxide is provided in Appendix A, of this document. One of the more interesting factors concerning carbon dioxide is the possibility of reaching its critical point (i.e. where the liquid and gas phases both have the same specific volume) at conditions that might be expected in the well. A possible condition is the presence of a supercritical gas. That is the temperature of the formation may be high enough that the carbon dioxide must exist in a supercritical state, neither liquid nor gas, regardless of the pressure applied. During the continued injection of carbon dioxide into a well, a zone of this supercritical gas would likely develop ahead of the injected liquid, the presence of a liquid phase being made possible by the cooling effect of the requisite phase change.

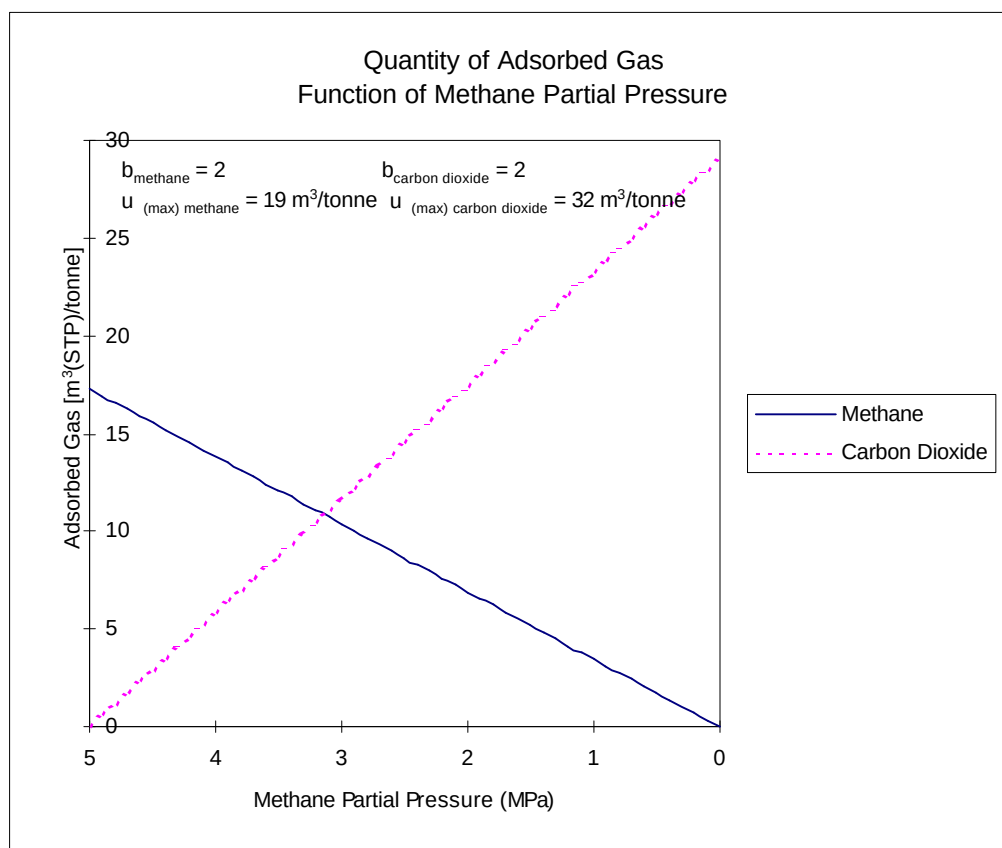


Figure 3-6: Quantity of Adsorbed Gas as a Function of Methane Partial Pressure.

The potential impact of carbon dioxide on the production of methane from the coalbed may involve several factors:

- (1) The direct use of injected carbon dioxide as an agent to maintain formation pressure and to release methane by competitive adsorption. In this situation a significant amount of carbon dioxide is likely to be produced along with the methane, as reported in germane research (Fulton, et al. 1980; Reznik, Singh, and Foley 1984). Such a case would require the separation of the gases, either at the well or at a common collection point, prior to introduction of the methane to a pipeline system. The advantage of injecting carbon dioxide, at a late stage of the methane well life, is that it would maintain the formation pressure, and consequently the driving force towards the production well, as suggested by Puri and Yee (1990). This method requires the use of injection wells and production wells. Ordinarily, an injection well may be placed so as to serve several production wells.
- (2) Use of liquid carbon dioxide injected and released to affect very high velocity gradients near the wellbore. As identified by Montgomery (U.S. Patent 5,147,111), this technique is intended to fragment and remove coal immediately adjacent to the wellbore. Such a technique amounts to an artificial means of attaining an openwell cavity completion, see section 2.2.1. This technique is likely to strip off much of the methane in the area of the formation contacted by the carbon dioxide, the liberated methane would then be released to the atmosphere, unless capture of all of the vented gas was affected. Even so, the relatively low concentration of methane that would be expected might limit the ability to recovery it economically.
- (3) Utilization of the physical properties and phase changes of the carbon dioxide to physically alter the micro-structure of the coal pores. The basic concept of this hypothesis, is that liquid and/or gas phase carbon dioxide is permeated into the pore structure of the coal. Upon rapid release of the pressure at the wellbore, the carbon dioxide undergoes a phase change causing a rapid drop in temperature. Such a drop in temperature may cause micro-fracturing to occur in the coal matrix, increasing the communication between the individual pores. It is worth noting here, again, that although coal is very porous, those pores are not necessarily all in communication with one another.

3.1.6 Effects of the Pressure State of the Sample

In common porous media three general stresses are discussed. These are the total stress, the pore stress, and the effective stress. The total stress is generally taken as the stress due to the mass above the point of interest. The pore stress is taken as the pressure being exerted against the total stress due to fluids in the pore structure. The effective stress is then the difference between the total and pore stresses. The effective stress represents the average stress distributed through the

porous media; it does not, however, represent the contact stress between the individual grains within the matrix.

Considering a tested sample as a Hookean solid the expected response as the compressive stress is increased is a decrease in the permeability. As the sample is stressed it reduces in volume, the loss of volume is taken in the two elements of the sample, the matrix and the pores. However, in general the pore space is much more compressible than the matrix, hence a general reduction in permeability results from an increase in the effective stress. In a methane well situation, an increase in the effective stress will occur due to the decrease in pore pressure, as gas and water are produced.

The obvious results of reducing the pressure in the formation is the production of gas, either from a compressed or adsorbed state, and a shrinkage in the host media. The loss of volume in the formation results in a decrease in the permeability, hence a decrease in the rate at which the formation can be depressurized.

Harpalani and Schraufnagel (1989) report that in coal there is a tendency for production of methane to remain constant or even increase, when conventional predictions would indicate that production should be decreasing. These authors account for this phenomenon in the desorption process. Due to the nature of the chemical interactions between coal and adsorbed gases the coal matrix shrinks as the methane desorbs. This matrix shrinkage increases the permeability at a greater rate than can be offset by the increase in effective stress caused by the reduction in pore pressure. Dimensional changes in coal samples, due to the presence of adsorbed gases, have been measured and reported by Roy and Pyrak-Nolte (1995).

During a conventional attempt to stimulate production from a well, the formation is repeatedly pressurized and depressurized. One possible effect of a process of pressurizing and depressurizing the formation is the impact of changes in the stress state of the target zone. That is, rapid changes in the pore pressure could affect the structure of the media at an interstitial level, that is to change the nature of the cementation of the material rather than the material itself. Such a situation, however, would require that the changes in stress levels occur at a dynamic rate, rather than quasi-steady-state conditions that would be expected in a case where the reduction in pore pressure was being controlled by flow rates at a relatively small wellbore.

3.2 Test Procedure and Parameters

One of the key factors in the experiments described in this report was the development of a technique that allowed horizontal permeability measurements to be made from samples collected from vertical boreholes. Figure 3-7 shows the ideal configuration of a sample of coal prepared for the method that was developed. Other than a mold for sample preparation and a lathe to

dimension the coal sample no equipment that would be considered as “special” is required. The evaluation of permeability described here can be performed in a standard tri-axial, Hoek, cell.

The samples for testing utilized here were cores obtained from exploratory holes. Since the orientation of the cores was perpendicular to the coal seam, and the principal permeability directions, a technique was developed to measure the permeability through the radius of the samples. This is opposed to the situation enjoyed by Harpalani (1988), in which his lump samples were obtained from a coal mine, and the permeability paths could be aligned to the axis of the cylindrical samples during preparation.

This section describes the preparation and testing of the samples utilized in the Hoek cell for the evaluation of permeability radial to the axis of a cylindrical sample. Section 3.2.1 covers the preparation of the basic sample. Section 3.2.2 covers the configuration of tri-axial (Hoek) cell used for testing. Section 3.2.3 addresses the instruments and methods used for data collection. Section 3.2.4 discusses the approach taken in the evaluation of the data that was collected. Section 3.2.5 briefly covers literature related to the possible patent of the novel technique used in these experiments.

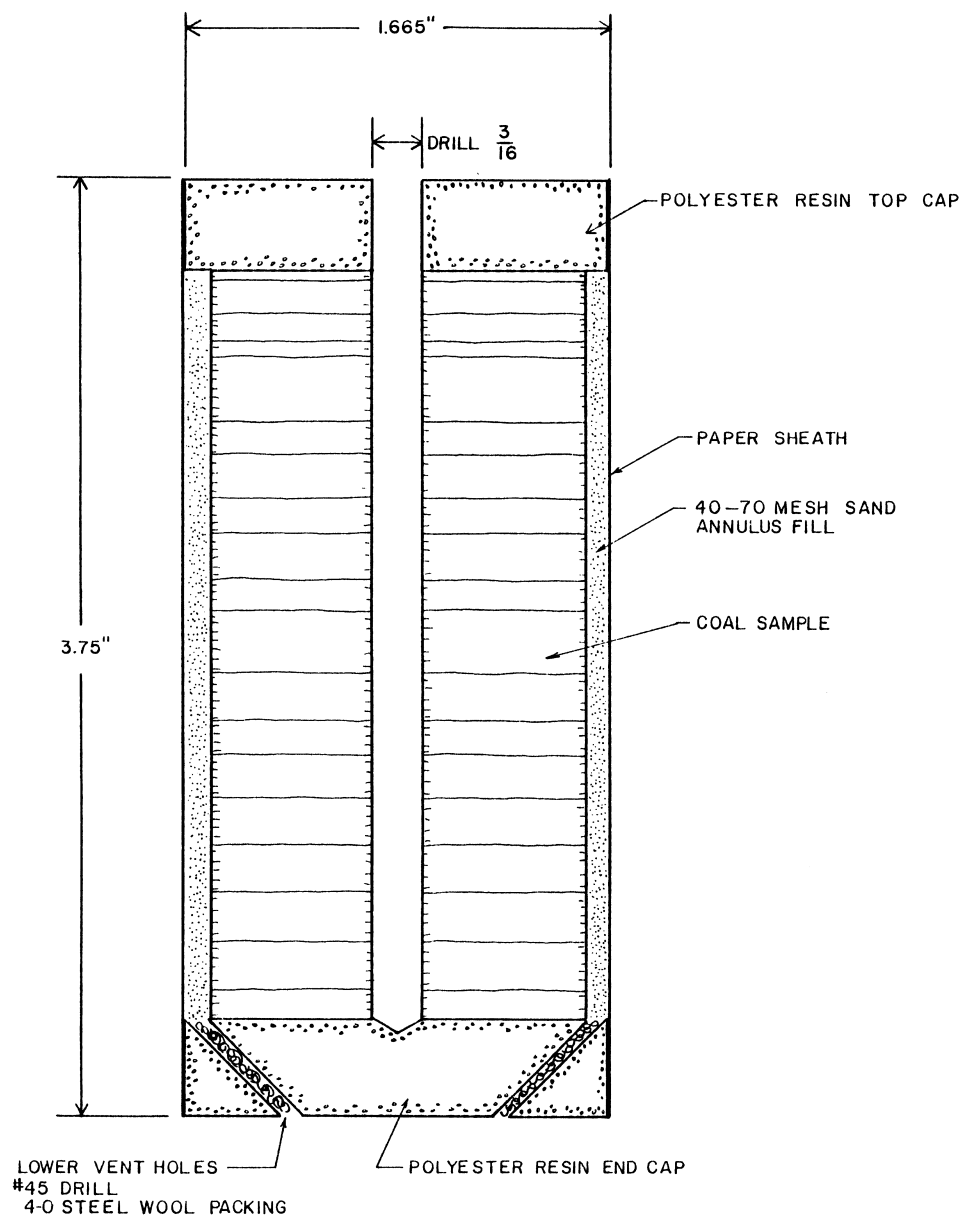


Figure 3-7: Radial Permeability Sample Configuration.

3.2.1 Sample Preparation

The samples of coal utilized for these experiments were derived from about 200 pounds of core provided by Pittston. Much of the core was not structurally capable of being used in this test program. Of the coal samples that, initially, appeared to be suitable for testing problems were encountered in producing adequate specimens. Overall, the most successfully prepared specimens exhibited a fairly uniform structure with virtually no apparent, pre-existing planes of weakness.

The coal samples used for radial testing began as core collected perpendicular to the coal seam. This condition necessitated the development of a special procedure and configuration to obtain the permeability in the horizontal plane. This section will describe the method in which the core was prepared for experimental evaluation. The final configuration of the test specimens is shown in figure 3-7. A series of photographs detailing the preparation procedure is shown in plates 3-1 through 3-12.



Plate 3-1: Sample Ready to be Placed into Lathe, with Faceplate Attached.

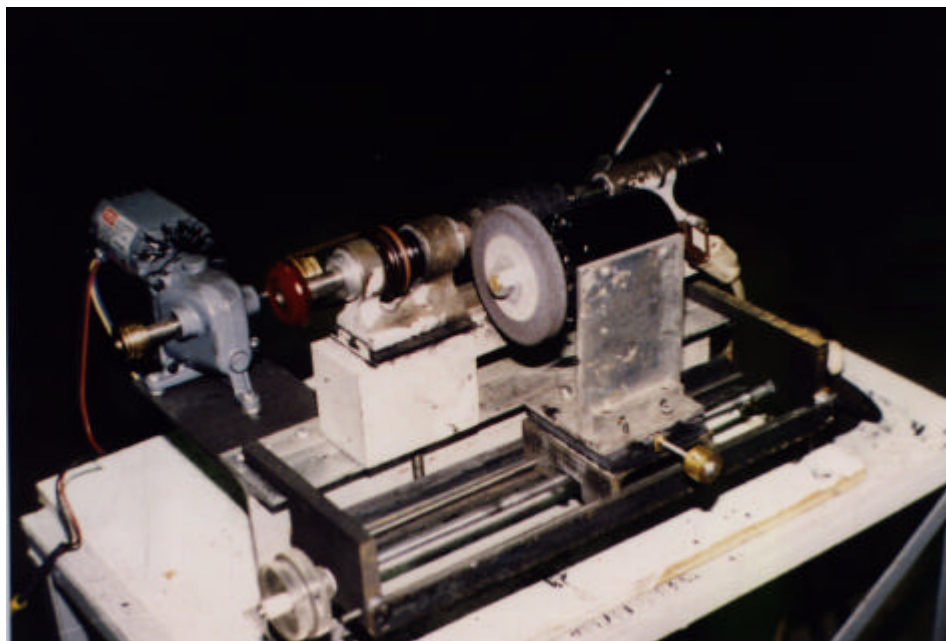


Plate 3-2: Sample Configured for Cutting in Lathe.



Plate 3-3: Sample after Diameter Reduction, Faceplate Removed.



Plate 3-4: Sample with Casting Mold.



Plate 3-5: Mold with Resin Top Cap Poured.



Plate 3-6: High-Speed Cutter Facing Top of Sample.



Plate 3-7: Drilling Center Hole Into Sample.



Plate 3-8: Drilling Lower Vent Holes, Through Guide Holes in Mold Base Cap.



Plate 3-9: Steel Wool in Lower Vent Holes, Mold Base Cap Removed.



Plate 3-10: Automatic Data Logging System.

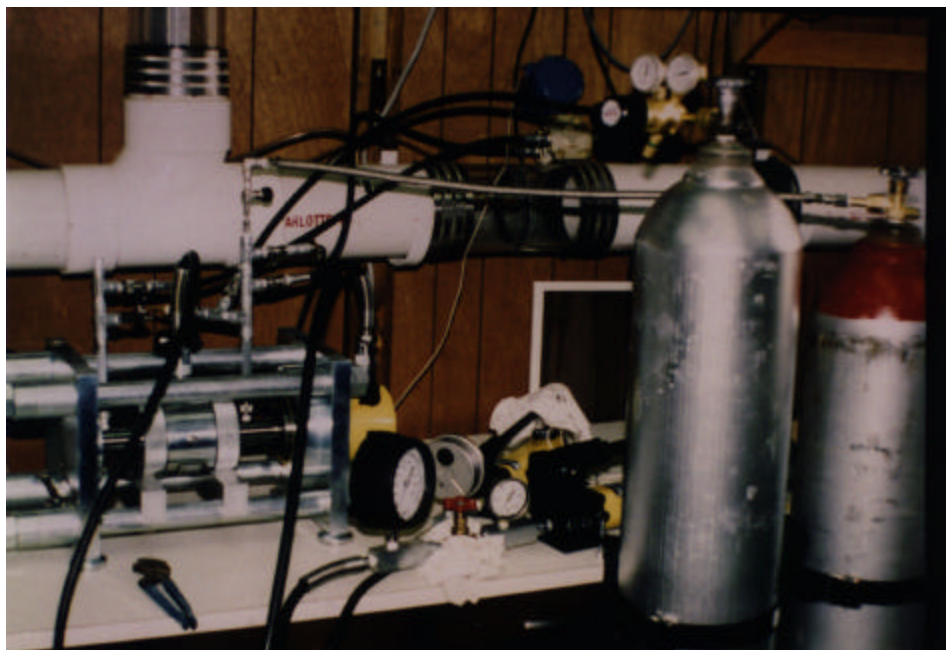


Plate 3-11: View of Hoek Cell Configured for Tests (1).

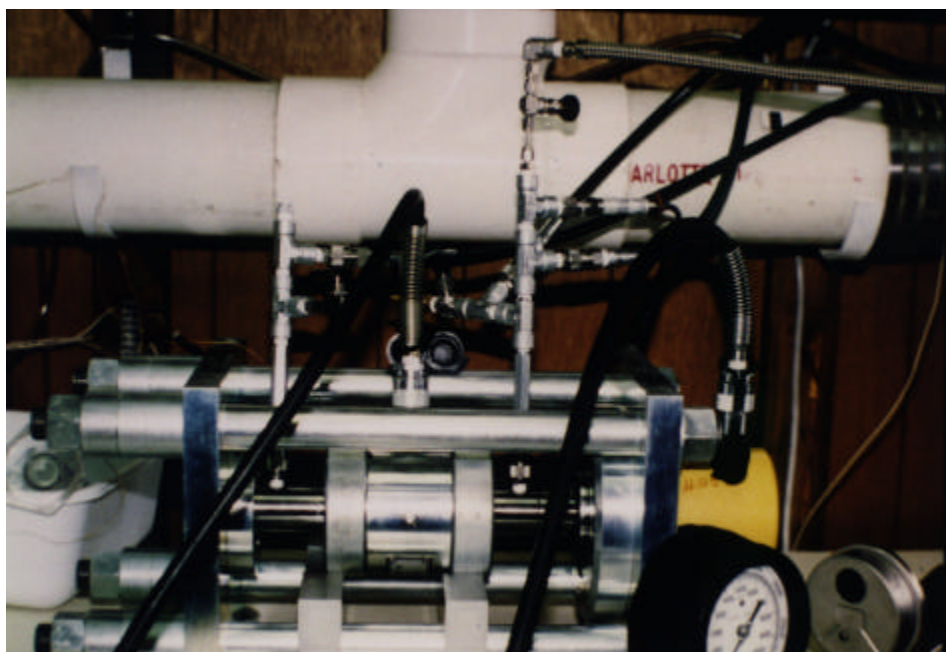


Plate 3-12: View of Hoek Cell Configured for Tests (2).

The core samples arrived from Pittston in plastic bags, much of the coal appeared to have been used for other testing purposes. Some care had been taken in packing to minimize damage during transit. From the bags of core provided, candidate samples were selected and cataloged. These specimens met the basic criteria of having the appearance of being capable of surviving the rigorous treatment to which they would be subjected. Lengths of about 3.0 inches were obtained using a band saw set to a very low feed rate. This allowed the sample to be cut rather than split.

The core that was provided was about 2.0 inches (5.1 cm) in diameter. This diameter needed to be reduced to 1.5 inches (3.8 cm) for the test program. To accomplish this task a jewelers lathe was used to turn the sample. A high speed grinding wheel was configured as the cutting tool. The end faces of the sample were sanded such that they were parallel. A face-plate was then glued to one end of the sample, plate 3-1. Once the glue had fully dried the sample was aligned into the lathe collet and tightened. An end-plate was fitted at the opposite end of the sample, this was held in place with a center fitted in the tail-stock of the lathe. The sample was placed into compression between the face and end plates. Practice with several samples revealed that the most effective and quickest way to reduce the diameter of the sample was to use a high speed, tool post, grinding wheel, plate 3-2. Using this type of cutting tool a full depth cut could be taken, i.e. the sample was reduced to final diameter in a single pass.

Other cutting tools were tried, some requiring a series of passes across the sample, removing small fractions of an inch from the diameter with each pass. Techniques of this type were significantly affected by the changing hardness of the layers in the sample. Two key problems encountered with the multiple pass techniques was “bouncing” of the cutter as the hardness of the sample changed, and, as a result, out of round and wavy samples. A previous researcher (Harpalani 1988) described removing very small increments off of the sample diameter with each pass of a high speed grinding wheel. This approach was not affected by the “bouncing” experienced in this research due to the much stiffer lathe employed by Harpalani.

Once the sample had been reduced to the appropriate diameter, 1.5 inches, it was removed from the lathe, plate 3-3. Some of the samples experienced failure through the axis of the sample, methods used to repair the samples is discussed below. The ends of the coal sample were sanded to be visually parallel, using a carpenter’s square. An end facing machine was not used, so that the sample would not be subjected to a wetting/drying cycle. The sample was then ready to be cast to the correct dimensions for the tri-axial cell.

Assembly of the sample “package” began by lining the mold with a vellum base and the vellum sheath, plate 3-4. A small amount of spray oil (WD-40) was used as a mold release. Once the sheath was in the mold a polyester resin base was poured. This resin was prepared according to the manufacturer’s instructions for mixing, once the hardener had been added, however, about 1 part of -240 mesh quartz flour was added for each two parts of resin. The addition of the quartz appeared to minimize plastic deformation of the resin in the tri-axial cell.

Once the resin base had gelled, and would support the sample, the coal sample was placed in the mold and centered. The resulting annulus was filled with 40-70 mesh quartz sand. This sand was tamped by repeatedly rapping the mold with an oak dowel. The excess sand was removed from the mold to expose the top of the coal sample. A polyester resin top cap was poured in on top of the coal sample, plate 3-5. The top cap resin mixture was prepared in the same manner as the bottom cap. This top cap was poured to extend about 1/8 inch above the top of the mold.

Once the resin top cap had fully hardened, usually over-night, final preparation of the sample could begin. The threaded cap at the bottom of the mold was removed, and the mold with sample was placed in the vise of a vertical milling machine. The excess resin was cut off using a high-speed cutting tool, plate 3-6. This produced a face that was parallel to the bottom face. Next, the 3/16 inch diameter bore hole was drilled through the center of the coal sample, plate 3-7. To ensure consistent cutting, the power feed on the mill was used at the lowest speed setting (1/2" per minute). The depth was set on the drill bit to ensure that the sample would be fully bored, without breaking through the resin bottom cap. This hole was repeatedly cleaned using the rotating drill bit following completion of drilling.

Following the drilling of the borehole, the sample and mold were removed from the milling machine vise and the threaded mold cap replaced. In this cap four alignment holes were drilled (as a part of the mold fabrication) such that the drain holes for the sample could be correctly aligned and quickly drilled, plate 3-8. These drain holes needed to intercept the sand filled annulus above the sample base cap and be aligned to the collection ring of the frill plate in the tri-axial cell. Once the drain holes were drilled and cleaned they were filled with loose, extra fine steel wool to prevent the sand from running out, plate 3-9.

This action completed the sample preparation for the coal samples. Preparation of the sandstone samples was similar, except that the samples arrived 1.5 inches in diameter and did not need to be reduced in diameter. The samples were cut to length in a cut-off saw which produced ends sufficiently parallel to obviate the need for further treatment.

For those samples that developed fractures during the machining process some means of repair were attempted. The most successful, for those with failures perpendicular to the core axis, was simply to glue the sample back together with epoxy resin. Further use of these samples can be justified since the affected region is small compared to the total sample, and that the repair was made parallel to the direction of flow of interest. Furthermore, the existence of the fracture would have provided a path of fairly low resistance minimizing the ability to obtain a permeability measurement for the entire sample.

The use of repaired samples is discouraged by Harpalani (1988). However, considering the difference in orientation it is readily apparent that repairs made in the direction of flow for the radial samples are far less affected than those made in the direction of flow in an axial sample.

Consider a radial flow sample that has been repaired in the plane normal to the cylindrical axis. Let the sample be 85 mm (3.375 inches) long and the patch be 0.5 mm (0.02 inches) thick. Then the effective length of the sample is 84.5 mm, or 99.4 percent of its original length. Since, as has been shown in section 3.1.1.2, the permeability is inversely proportional to the length (height) of the sample the patch will introduce an error of $(1-1/994)$ or about 0.6% to the calculated permeability.

Clearly, the analysis above applies only to those repairs limited to the plane in which the gas will flow. Any repair that extends parallel to the cylinder axis of the sample will inhibit flow of gas along the radius, thus introducing what could amount to significant error by isolating whole pieces of the sample. Therefore, samples that would have required repair by gluing parallel to the cylindrical axis of the sample were not used for permeability evaluation.

3.2.2 Test Cell Configuration

The basic test cell utilized for these experiments was a BX tri-axial (Hoek) cell manufactured by RokTest, Inc. This system was designed for static measurements and the platens were configured for the performance of permeability tests. This system is illustrated in figure 3-8, and plates 3-10 through 3-12. See also Figure 3-2 for Hoek Cell details.

The Hoek Cell is designed for tri-axial testing of cylindrical material samples. To accomplish this two independent sets of stresses can be applied, first in the direction of the cylinder's z axis (in a cylindrical coordinate system), the second in the radial direction towards the cylinder center. The net result is that this system allows the loading of samples in a stress field of two independent principal stresses. It can be easily shown that such a state, on a cylindrical specimen, is theoretically identical to stressing a sample with three independent principal stresses where two of those stresses are equal in magnitude (Popov 1976).

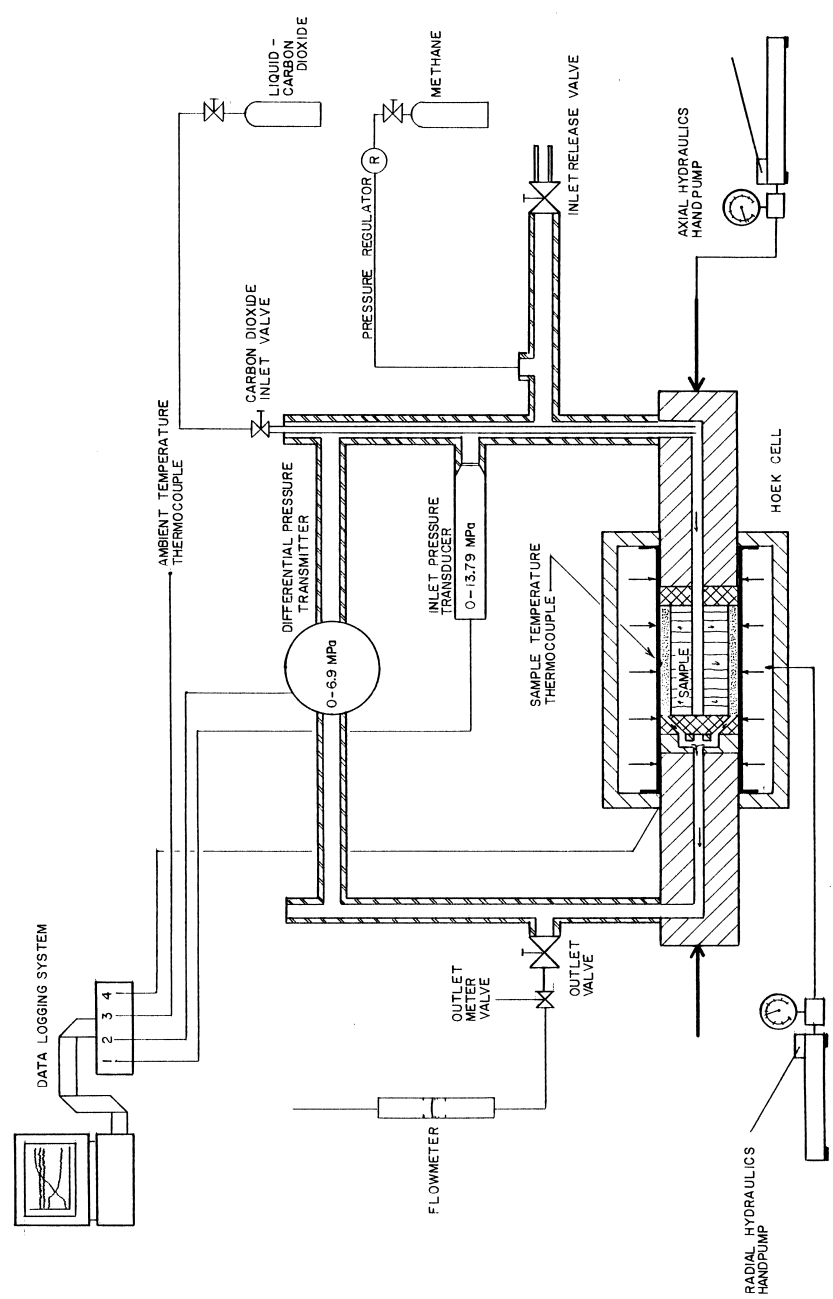
For these experiments, effort was made to obtain, as nearly as possible, a hydrostatic loading condition on the sample. That is, the axial stress, supplied by the main ram, was loaded equal to the radial stress, supplied by the cell body.

Sample loading was accomplished through the use of two separate hydraulic hand pump systems. One pumped provided the axial load, the second provided the radial load in the Hoek cell. A back-flow preventor valve was placed in line with the axial pump to hold the pressure on that axis, maintenance of the radial pressure could be attained by simply securing the pump handle.

To ease set-up and tear-down, connections of the manifolds to the platens and the connections for the differential pressure transmitter to the manifolds were fitted with quick-connectors. As shown in the illustration (Figure 3-8) the inlet side manifold was equipped with the following features: methane inlet point, inlet pressure transducer, high-pressure tap to the differential pressure

transmitter, an inlet side gas release valve, and a liquid carbon dioxide inlet system. The outlet side manifold was equipped with the following features: outlet gas shut-off valve, outlet gas metering valve (on some tests), and the low pressure tap to the differential pressure transmitter.

Measurement of the sample temperature was obtained by placing a very small thermocouple between the sample sheath and the gland of the Hoek cell. The ambient room temperature was measured with a similar thermocouple suspended in the direct vicinity of the Hoek cell test frame.



iml

Figure 3-8: Schematic Drawing of Hoek Cell and Ancillary Systems.

3.2.3 Data Collection

Two different sets of data were collected during the permeability tests of each of the samples. Data regarding the flow of gas through the sample, as well as basic event data, were manually collected and recorded to be entered into the evaluation spreadsheet later. Data concerning the inlet and differential pressures, the sample temperature, and the ambient temperature were recorded by an automatic data logging computer.

3.2.3.1 Manual Data Collection

Data that was manually collected included that necessary to obtain a permeability measurement. This included the inlet gas pressure, the differential pressure, the axial and radial hydraulic pressures, the sample temperature, and the gas flow rate. This data, combined with the physical measurements of the samples are sufficient to determine the permeability of the sample.

Depending on the gas flow resulting from the sample permeability two different methods of measurement were used. The most basic of these was to measure the time needed to displace a fixed volume of water from an inverted graduated cylinder. The second technique, for lower flow rates, used an automated bubble meter. This meter would automatically measure the flow rate, from the time required for a soap bubble to move past two optical sensors. The bubble, however, had to be manually initiated.

3.2.3.2 Automatic Data Collection

The automated data collection system was used to record the following parameters, inlet gas pressure, differential pressure, sample temperature, and ambient temperature. The original intent had been to have all of the data collected, however, the gas flow measurements proved to be difficult to be automated, so the manual practice remained.

The data collection system used was manufactured by OMEGA Engineering. This system is capable of monitoring up to 16 analog and 16 digital channels per installed card. Analog data can be evaluated by the system as a voltage signal or a current signal, in addition special functions are available for the evaluation of thermocouples and Platinum Resistance Thermometers (RTD). This data logger was installed in a personal computer. A graphically based software package was supplied with the data logger hardware. This package allowed the user to specify the input parameters for each of the channels being monitored. Computations necessary to properly scale and offset the data could also specified in the software package. The graphic capability of the user interface allowed for graphs of the collected data to be displayed while recording

simultaneously on disk. Additionally, numeric display meters were used to display the data that was also to be manually recorded.

Measurement of the differential pressure was made with an OMEGA PX750-HDI heavy duty differential pressure transmitter. This transmitter was rated for service from 0 to 6.895 MPa (0 to 1000 psi) differential. The output was linearly scaled from 4 to 20 milli-amperes³.

Measurement of the inlet pressure was made with an OMEGA PX603 pressure transducer. This transducer was rated for service from 0 to 13.79 MPa (0 to 2000 psi) gauge. The output was linearly scaled from 1 to 5 volts DC⁴.

Initially a pressure transducer was fitted to the outlet side manifold. However, it was not rated to the pressure that could be expected from the liquid carbon dioxide system, so it was removed.

Pressures on the hydraulics were observed manually and adjusted as needed.

3.2.4 Evaluation

The approach taken regarding the evaluation of the data collected will be covered in two sections. The first will cover the sandstone samples and the second will cover the coal samples.

3.2.4.1 Sandstone Samples

For all of the axial flow and two of the radial flow sandstone samples an approach was taken in which a limited number of measurements were taken at each of a series of pore pressure states. In this way it was possible to determine the effect that pore pressure and hydraulic gradient had on the sample permeability. Analysis of the change in permeability due to treatment with liquid carbon dioxide was performed in the same manner as used for the coal samples. That is, the percent change between the pre-treatment and post-treatment conditions was determined from available data. The comparisons were made for similar pore pressure states, that is an effort was made to match the mean gas pressure and the hydraulic gradient.

The basis for comparison of the pressure gradients between the radial and axial flow samples was first to maintain a similar pressure gradient at a similar mean gas pressure. In the evaluation of the collected data the permeability is plotted, primarily as a function of the pressure, then secondarily as a function of the differential pressure (pressure gradient).

³ "Heavy Duty Differential Pressure Transmitters - Operator's Manual," Omega Engineering Publication M0609/0793.

⁴ Specification sheet for PX6xx series Pressure Transducers, Omega Engineering Publication M947/0892.

Based upon the equations for mean gradient listed, developed in section 3.1.1, above, the expected mean gradients can be determined for the radial samples. Table 3-2, below lists the general properties for the gradient determination based on the various equations.

Table 3-2: Estimations of Mean Pressure Gradient for Radial Samples

Parameter	Value
Sample Radius	$r_s = 19.1 * 10^{-3} \text{ m}$
Bore Radius	$r_b = 2.38 * 10^{-3} \text{ m}$
Bore Pressure	$P_b = 500 \text{ kPa}$
Outlet Pressure	$P_s = 475 \text{ kPa}$
Permeability	$k = 1.70 * 10^{-14} \text{ m}^2$
Temperature	$T = 300 \text{ K}$
Gas Constant	$R = 518 \text{ J/kg K}$
Viscosity	$\mu = 1.1 * 10^{-5} \text{ Ns/m}^2$
Mass Flow Rate	$M = 3.40 * 10^{-5} \text{ kg/s}$
Mean Gradient:	
Linear on Radius	1.5 MPa/m
Average In and Out	2.76 MPa/m
At Log Mean Dia.	1.3 MPa/m
Average dP/dr	1.54 MPa/m

Based on the mean gradient analysis it can be seen that a 25 kPa pressure drop across a 19 mm (0.75 inch) radius radial sample is roughly consistent with a 100 kPa pressure drop along a 85 mm (3.375 inch) long axial flow sample. The gradient associated with the axial sample is 1.2 MPa/m.

3.2.4.2 Coal Samples

For the coal samples, the evaluation of the effect of liquid carbon dioxide was based on comparing the permeability before and after treatment. It was not practical to attempt direct comparison between the samples. The main reason for this is that the samples were physically small and there was no means to ensure that the same seam was being tested from borehole to borehole. A compounding effect was the general dearth of quality samples for evaluation.

Furthermore, it is not possible to compare the data obtained in the laboratory to conditions in the field. This is based on the way in which the testing was conducted. Considering the manner in which the core itself was obtained and the treatment received during sample preparation the data is based on the strongest portions of the seams, which may also prove to be the least permeable.

In an effort to obtain as much information as possible from each of the samples a large number of permeability measurements were taken. For most of the samples this means that sufficient measurements were obtained to apply statistical techniques to arrive at a permeability value as well as an error range. With these data the computed values before and after treatment were compared to arrive at a level of enhancement. The fractional change in permeability was computed as the difference between the post-treatment and pre-treatment values divided by the pre-treatment permeability. In this manner a positive value indicates that the permeability increased as a result of the treatment, conversely a negative value indicates that the permeability decreased due to the treatment.

3.2.5 Possible Patent Information

Based upon the review of literature on the measurement of permeability in laboratory samples no technique similar to that taken in this research could be found. To this end a brief patent search was undertaken to determine if this technique is indeed new and novel. Table 3-3 lists those patents that appeared to have some relevance to the technique used in these experiments.

Table 3-3: Patents with Possible Relation to Radial Permeability Technique

Patent Number (USA)	Description	Applicable
5337596	Apparatus for measuring the permeability of a rock sample.	No
5326969	System for characterizing flow pattern and pressure of a fluid.	No
5324956	System for characterizing movement and temperature of fluids	No
5311766	Method and apparatus for determining two-phase flow in rock fracture.	No
5297420	Apparatus and method for measuring relative permeability and capillary pressure of porous rock	Yes
5272333	System for characterizing pressure, movement, and temperature of fluids.	No
5271675	System for characterizing pressure, movement, temperature and flow patterns of fluids.	No
5261267	Method and apparatus for rock property determination using pressure transient techniques and variable volume vessels.	Yes
5249864	System for characterizing temperature of fluids.	No
4599891	TCH - Tri-axial core holder.	Yes
4555934	Method and apparatus for nonsteady state testing of permeability.	Yes

The third column in this table, *applicable*, addresses the possible application of the respective patent to the test cell used for these experiments. For those patents which appear to be in any way applicable a copy of the patent abstract is included in appendix B of this document.

3.3 Results

The experimental results presented here are separated into two sections, the first being the base line samples and the second being the coal samples for evaluation. In actuality, the base line measurements were obtained after the coal samples had been tested.

3.3.1 Base Line Samples

In order to validate the procedure chosen for the measurement of radial permeability in the coal samples a series of sandstone samples were evaluated. This assessment was based on measuring the permeability of the sandstone using the axial procedure and comparing the results to those obtained using the radial procedure developed as a part of this project. To ensure that the results would be consistent, the axial sample core was taken perpendicular to the radial sample core. In this manner the structural laminae would be uniform for either of the sample orientations.

The baseline samples were obtained as 50 milli-darcy ($4.935 \times 10^{-14} \text{ m}^2$) Berea Sandstone from Cleveland Quarries in Amherst, Ohio. The permeability measurement made by the quarry is an air test. In their test configuration the time required for the pressure to drop from 50 to 30 psi (0.344 to 0.207 MPa) is proportional to the permeability⁵. Based on tests of this type the quarry classifies the sandstone into the permeability ranges that they offer. These samples were ordered with the core for radial measurements cut perpendicular to the laminations and the core for axial measurements cut parallel to the laminations.

The character of the sandstone samples is visible in plate 3-13. This photograph appears to be representative of the sandstone in general. The sand grains appear as medium gray, the light gray surrounding the sand is clay. Pore spaces show up as black, the remaining light colored material is various other mineral matter. A cursory scan of the mineral material, utilizing the elemental scan feature of the SEM, indicated the makeup was likely a mixture of oxides and carbonates.

For this sample the mean particle size is $0.12 \text{ mm} \pm 0.04 \text{ mm}$, based on a population of 146. This is certainly much larger than the size estimates that would be computed based on either the Hazen or Shepherd methods ($d_{10} = 2.8 \times 10^{-4} \text{ mm}$ and $d_{50} = 1.5 \times 10^{-4} \text{ mm}$ respectively). The explanation of these two methods is given in section 3.1.1.3.3. For these two methods the hydraulic conductivity (K) was based on an intrinsic permeability (k) of 50 mD ($4.935 \times 10^{-12} \text{ cm}^2$), a gas density (ρ) of $1.773 \times 10^{-6} \text{ kg/cm}^3$, and a viscosity (μ) of $1.11 \times 10^{-7} \text{ kg/cm-s}$. The Hazen method coefficient (C_H) used in this technique was 80, at the high end of “Fine sand with appreciable

⁵Discussion with Cleveland Quarries technical personnel, 22 July 1996.

finer.” In the Shepherd method, the coefficient (C_s) used was 450 and the index (j) was 1.65, these factors are listed as appropriate to “Channel deposits.”

Fetter (1994) notes that the Hazen method is most appropriate for samples with an grain size range of “0.1 to 3.0 mm.” The lower end of this range is approximately equal to the mean grain size in the current sample. Based on the fairly uniform size distribution of the sandstone sample, pictured in plate 3-13, the effective grain size (d_{10}) would also be very near, or below, the lower point of the effective range of the Hazen method. The Hazen method appears to assume a larger standard deviation than is observed in the present sandstone sample.

No practical size range is given for the application of the Shepherd method in Fetter (1994). This method predicts the mean grain size (d_{50}). Considering the significant difference between that predicted and that measured it is reasonable to assume that this method is not applicable to the sandstone samples at hand.

A probable effective cause of the difference, between the measured and estimated grain sizes, would appear to be the significant quantity of clay that is evident in the photograph. The presence of the clay appears to reduce both the porosity and the permeability of the sample by filling free space in the matrix that would otherwise enhance the measured permeability of the samples. This consideration can be supported by evaluation of the sample porosity.

The porosity estimate from the photograph is 8.3%, compared to the value 12.3% obtained by differential mass measurements between dry and wet samples. The differential mass technique used was as follows. Obtain the sample volume, three height measurements, as well as three diameter measurements at each end were used. Dry the sample in a drying oven. Obtain the sample mass when dry. Saturate the sample with water in a vacuum chamber, by submerging the sample and drawing a vacuum above the water. Wipe the sample of free water and obtain its mass. Considering the mass of water is filling the all of the void space the difference in mass divided by the density of water must be the pore volume. Then the pore volume divided by the total volume is the porosity.

The porosity based on the photomicrograph was computed as the proportion of the area that appears as black, indicating void space. A possible area for error between the two methods is the likelihood that water was drawn into the clay. The volume of water in the clay would not be accounted for in the void spaces observed in the photomicrograph.

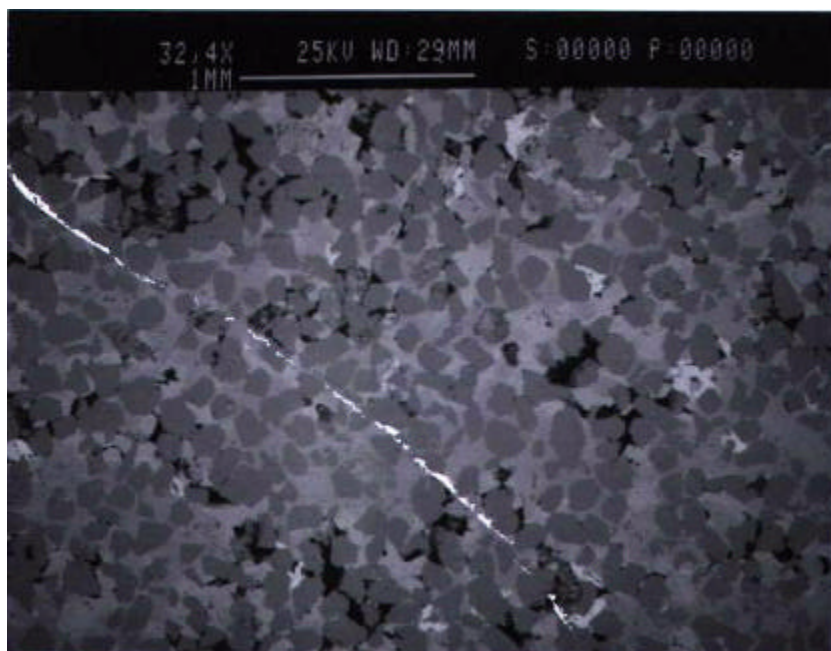


Plate 3-13: Photomicrograph from Sandstone Sample SSRAD1 (32.4x magnification).

3.3.1.1 Axial Samples

Three samples for axial flow permeability measurements were taken from a single 30 cm long core initially 77 mm in diameter. The samples were individually cored using a BX core barrel. The ends were finished using an end mill. The results of the individual axial flow tests are expounded below.

3.3.1.1.1 Sample SSAXI1

This sample was taken, at random, from the three axial flow samples cut from a single core of Berea Sandstone, reported to have a permeability of 50 milli-darcys. Initial attempts to bring this sample to conditions comparable to the radial flow samples, i.e. mean gas pressure and pressure gradient, indicated that the flow rate of gas would be too high to measure reliably. Therefore a modified test sequence was developed and implemented to ascertain the relationship between permeability and mean gas pressure in the sample.

This test consisted of step wise raising the input pressure to the sample while using the outlet meter valve to maintain a constant pressure gradient across the sample. The flow rate of methane gas was then measured several times at each of the pressure steps. The resulting permeability measurements are illustrated in figure 3-9a and b. This figure clearly shows the relationship of intrinsic permeability to the mean gas pressure.

A further expression of this data is presented in figure 3-9c and d, where the measured permeability is plotted to the reciprocal of the mean gas pressure, in the manner of Klinkenberg (McPherson 1993, Klinkenberg 1941). Figure 3-9c illustrates all of the measured data points, with associated linear fits to those points. A noticeable characteristic of these data is the increasing slope of k versus $1/P_{\text{mean}}$ as the pressure gradient across the sample increases. The relationship between the best fit lines and the mean of the respective data sets is shown in figure 3-9d, where each set average and ± 1 standard deviation error bars are illustrated. For the most part the data is reasonably well suited to the linear fit (the expected result), as is seen by the lines passing through the error window for permeability of most of the individual measurement sets.

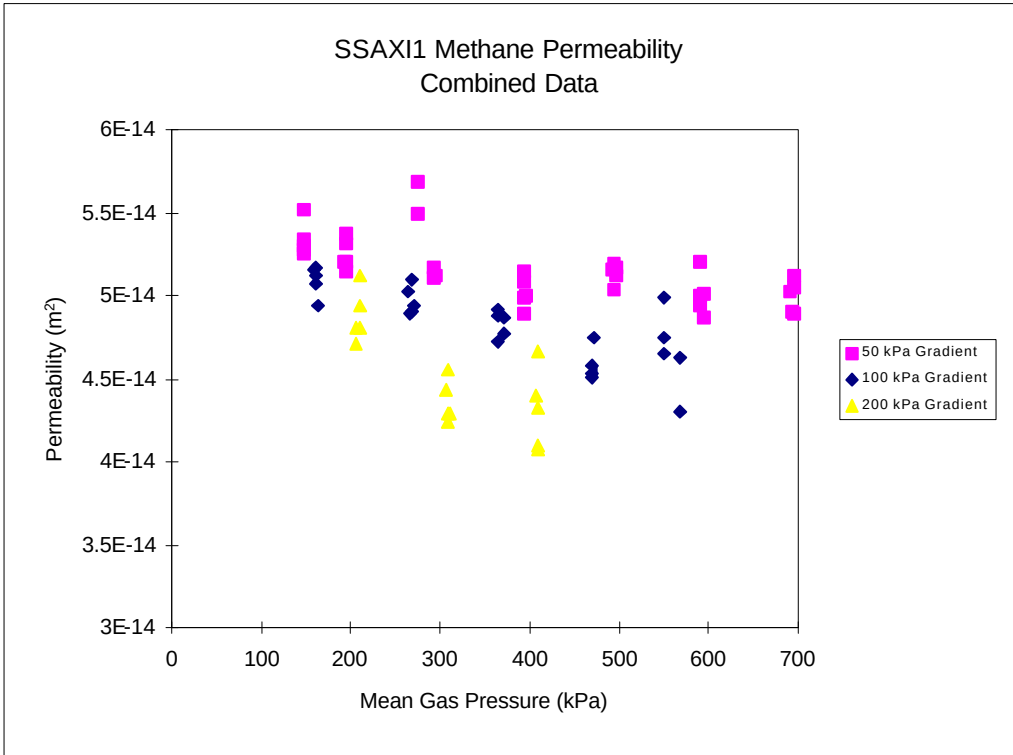


Figure 3-9a: SSAXI1 Methane Permeability, Combined Data.

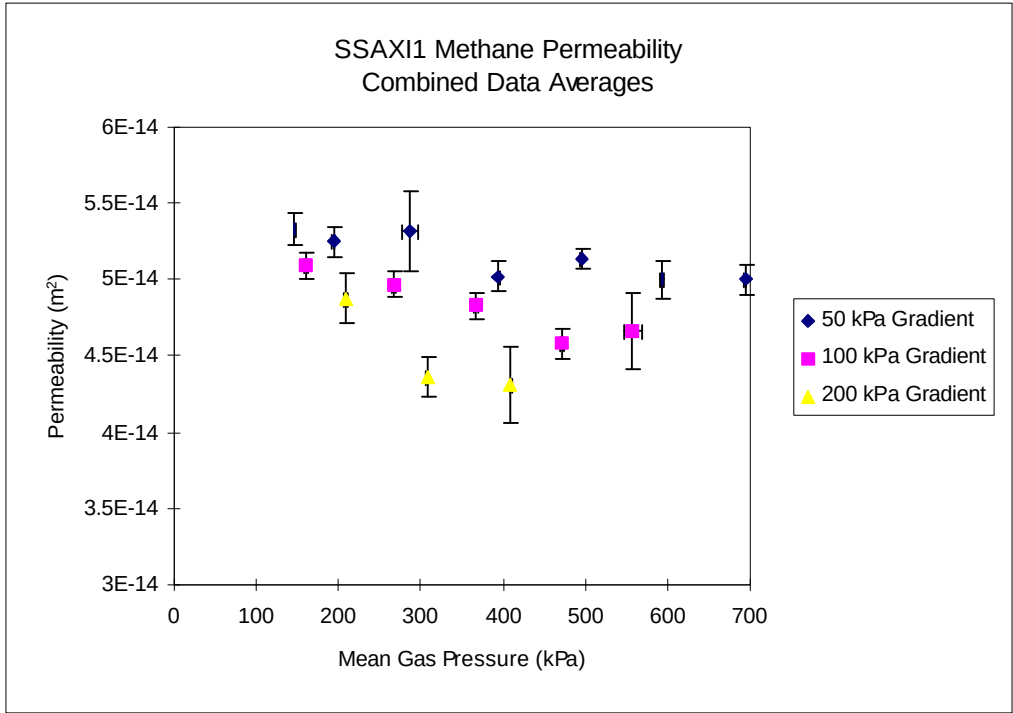


Figure3-9b: SSAXI1 Methane Permeability, Combined Data Averages.

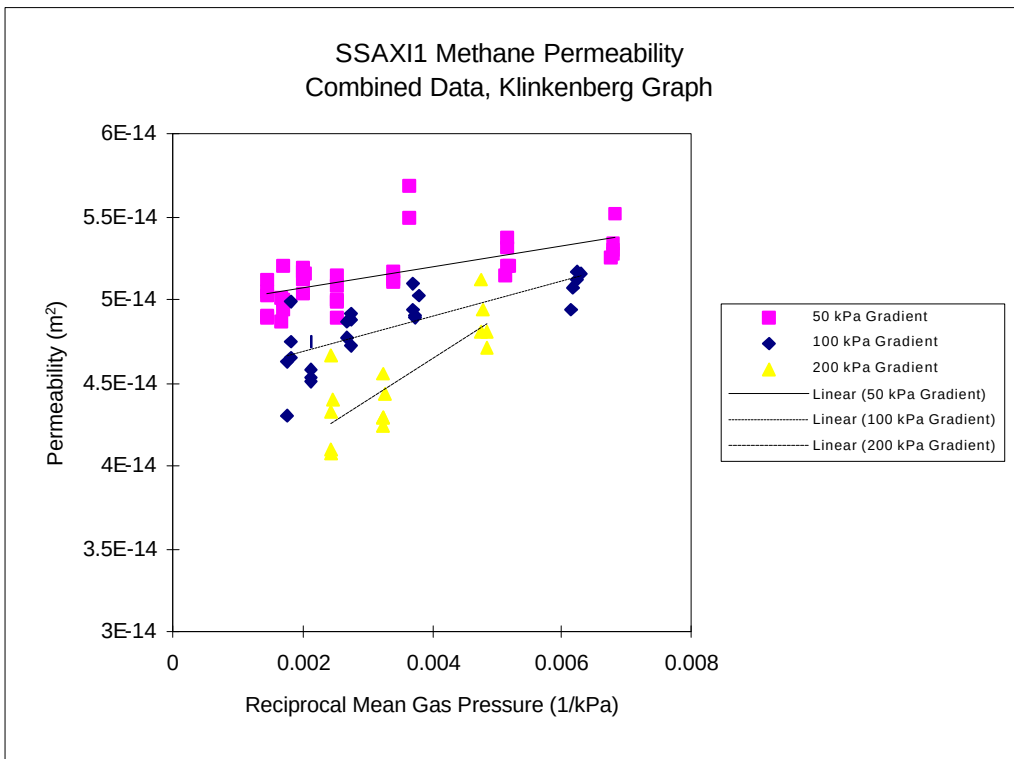


Figure 3-9c: Klinkenberg Graph, SSAXI1 Methane Permeability, Combined Data.

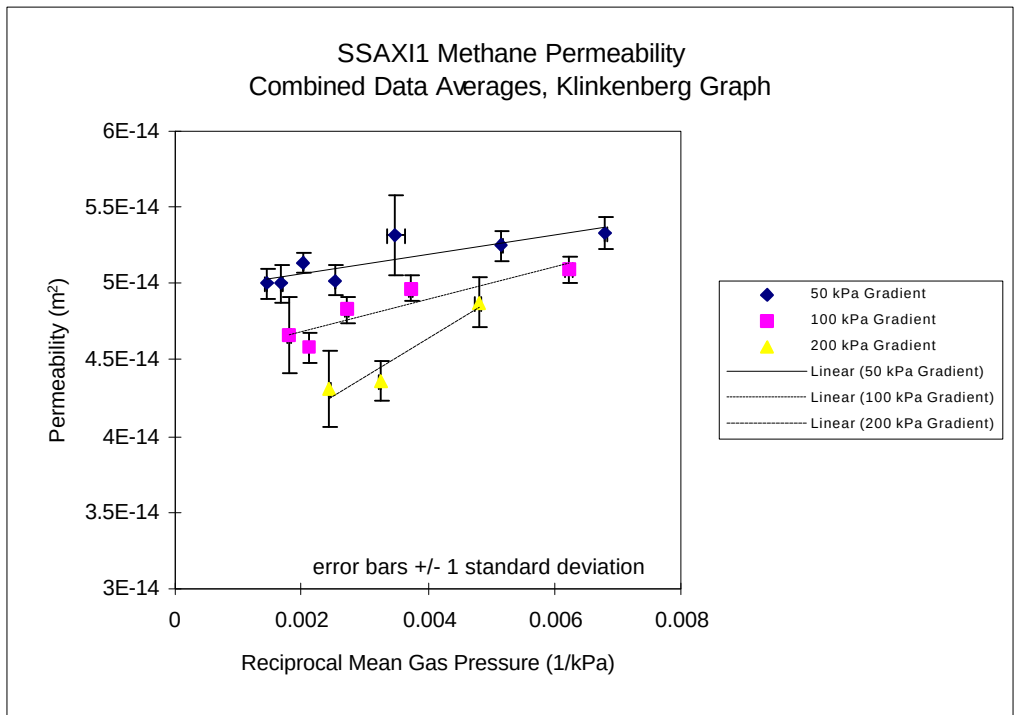


Figure 3-9d: Klinkenberg Graph, SSAXI1 Methane Permeability, Data Averages.

3.3.1.1.2 Sample SSAXI2

A second section of axial flow core was selected, at random, and identified as SSAXI2. This sample was subjected to a series of permeability measurements at differing mean gas pressures and at two different gradients. As with sample SSAXI1 measured permeability increased, in a power law curve, as the mean gas pressure was increased. This pattern, and the permeability measured, is shown in figure 3-10a. Note that the 200 kPa gradient series was not conducted in this sample.

This sample was also subjected to a treatment with the liquid carbon dioxide. A permeability measurement was taken prior to the treatment to verify the point on the curves established by the previous series of measurements. Following the treatment two separate permeability measurements were obtained to determine if there was a significant variation from the pretreatment curves. The three data series are shown, as identified, in figure 3-10b.

The Klinkenberg effect in this sample is illustrated in figures 3-10c and d. The individual data points measured for this sample, along with appropriate best linear fit lines, are shown in figure 3-10c. The 50 kPa gradient data appears to fit fairly well to the linear form, however, there does appear be a non-linear form to the 100 kPa data that does not fit to the linear form. This assessment is also visible in figure 3-10d, where the data set averages and ± 1 standard deviation error bars are illustrated.

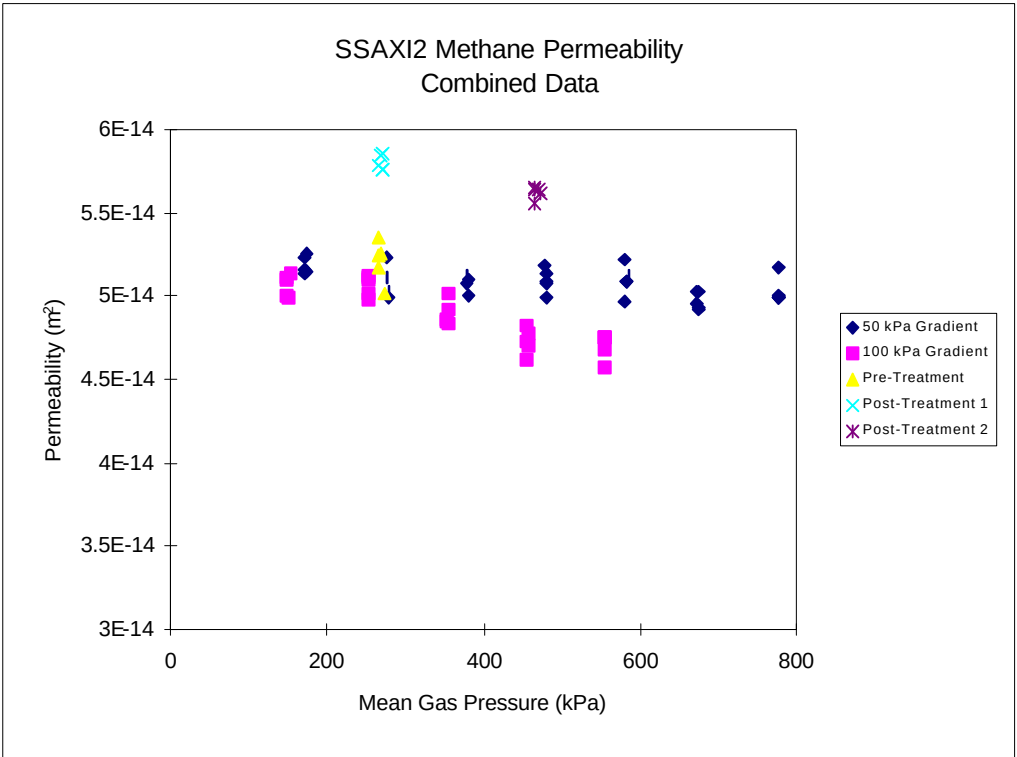


Figure 3-10a: SSAXI2 Methane Permeability, Combined Data.

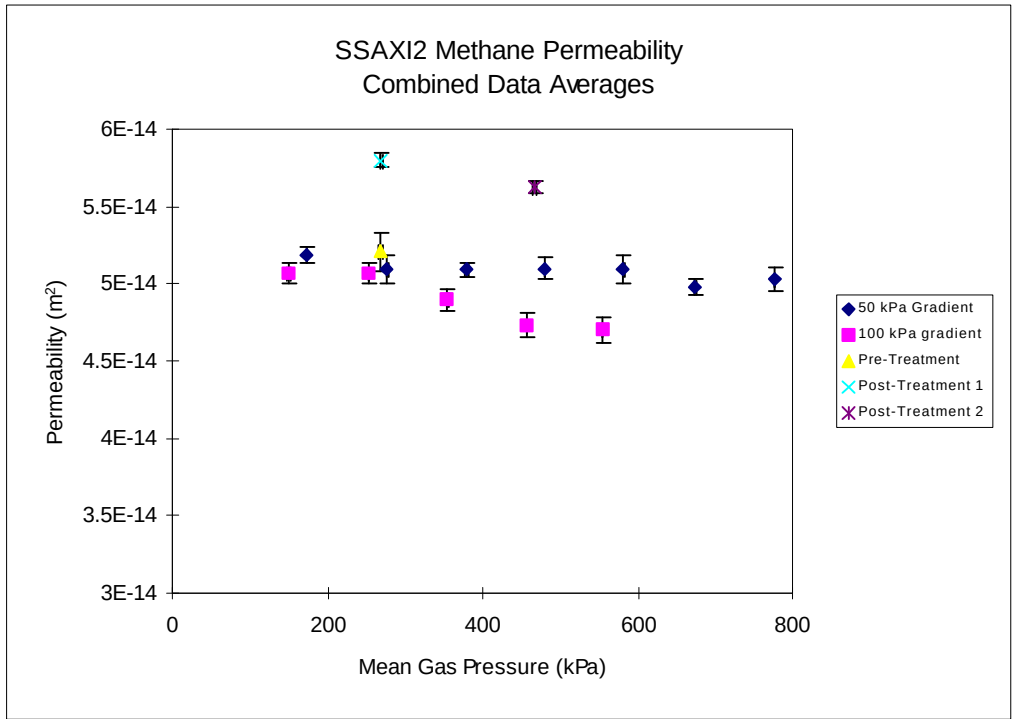


Figure 3-10b: SSAXI2 Methane Permeability, Combined Data Averages.

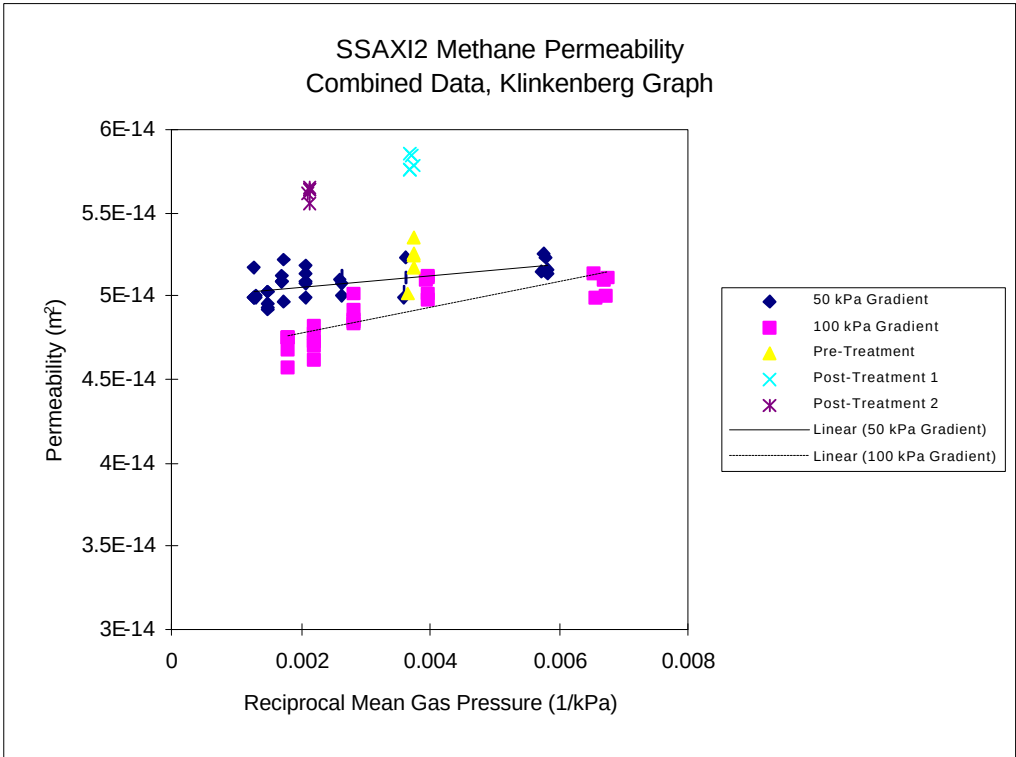


Figure 3-10c: Klinkenberg Graph, Methane Permeability, Combined Data.

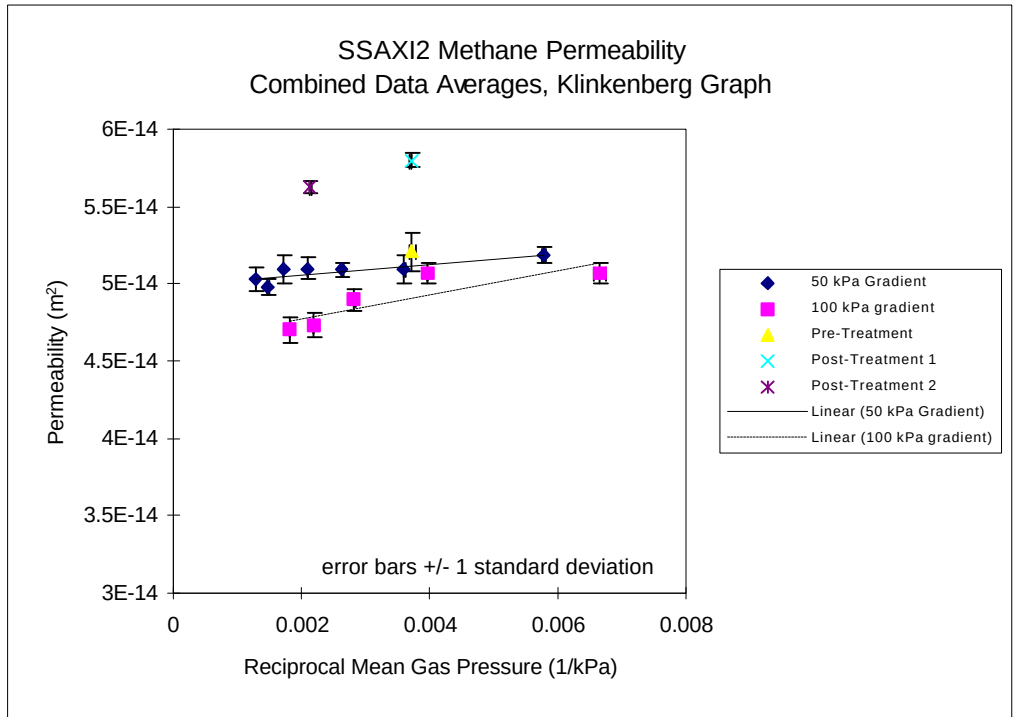


Figure 3-10d: Klinkenberg Graph, SSAXI2 Methane Permeability, Data Averages.

3.3.1.1.3 Sample SSAXI3

The remaining section of axial flow core was identified as SSAXI3, this sample was subjected to the same series of measurements taken on sample SSAXI2. The permeability curves for 50 and 100 kPa gradients are shown in figure 3-11a and b. In a manner similar to that of SSAXI2 the three data series associated with the carbon dioxide treatment are shown as indicated.

This data is represented in the form of Klinkenberg in figures 3-11c and d. These figures show a reasonably linear trend of the measured permeability (k) to the reciprocal mean gas pressure ($1/P_{\text{mean}}$). The line for the 100 kPa gradient data exhibits the expected positive slope. On the other hand, the line of the 50 kPa gradient data shows a negative slope, a condition that appears to run counter to the expected outcome.

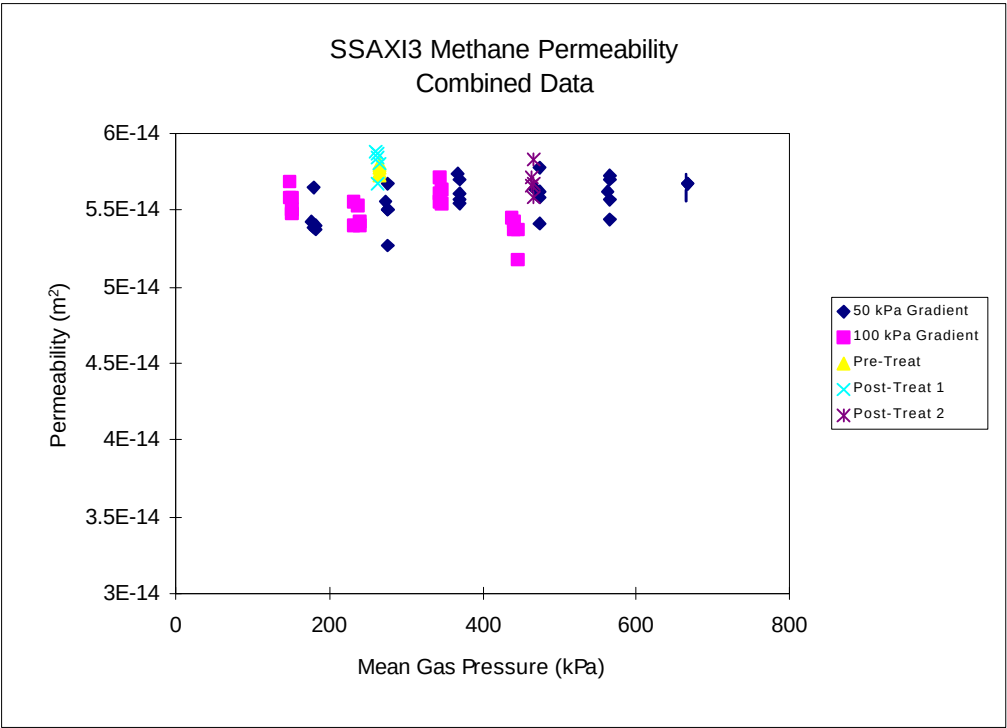


Figure 3-11a: SSAXI3 Methane Permeability, Combined Data.

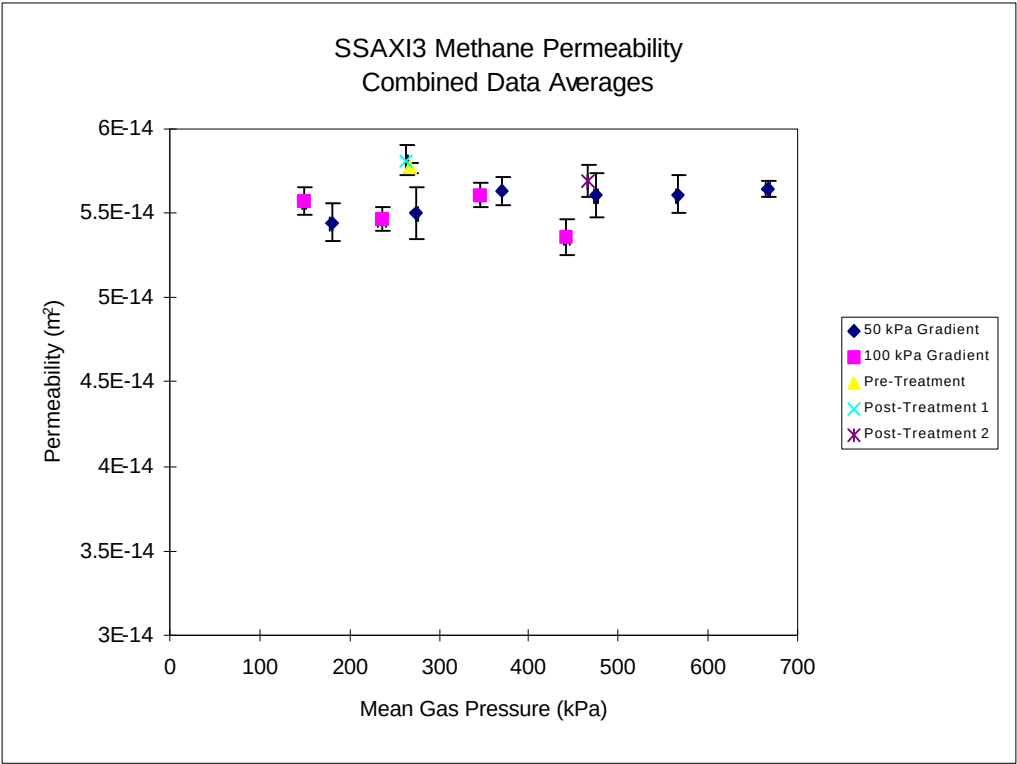


Figure 3-11b: SSAXI3 Methane Permeability, Combined Data Averages.

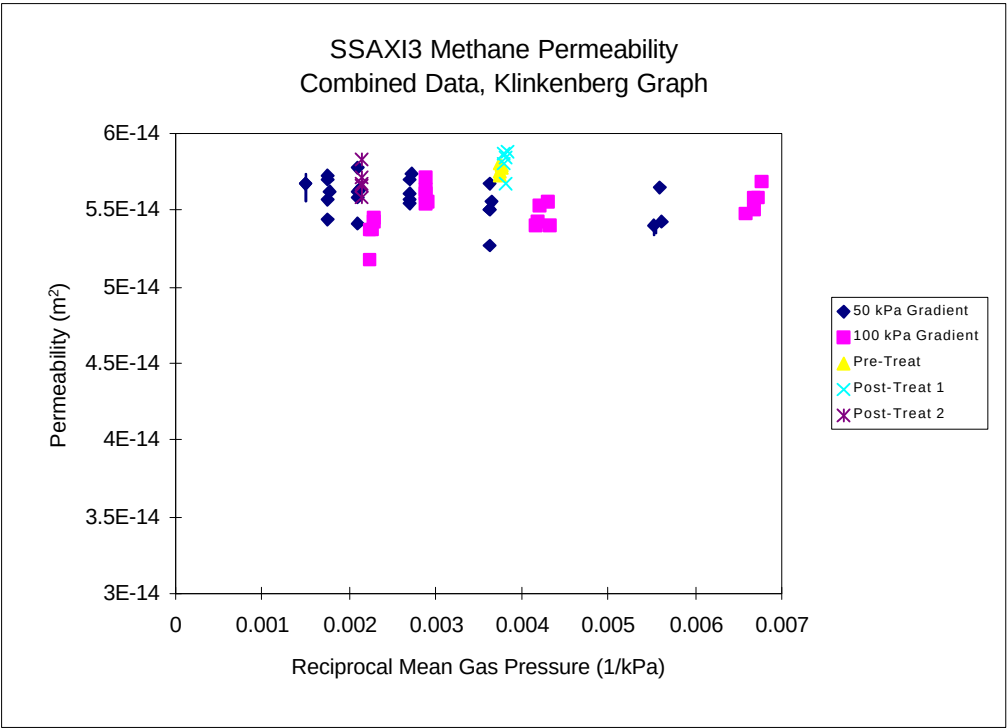


Figure 3-11c: Klinkenberg Graph, SSAXI3 Methane Permeability, Combined Data.

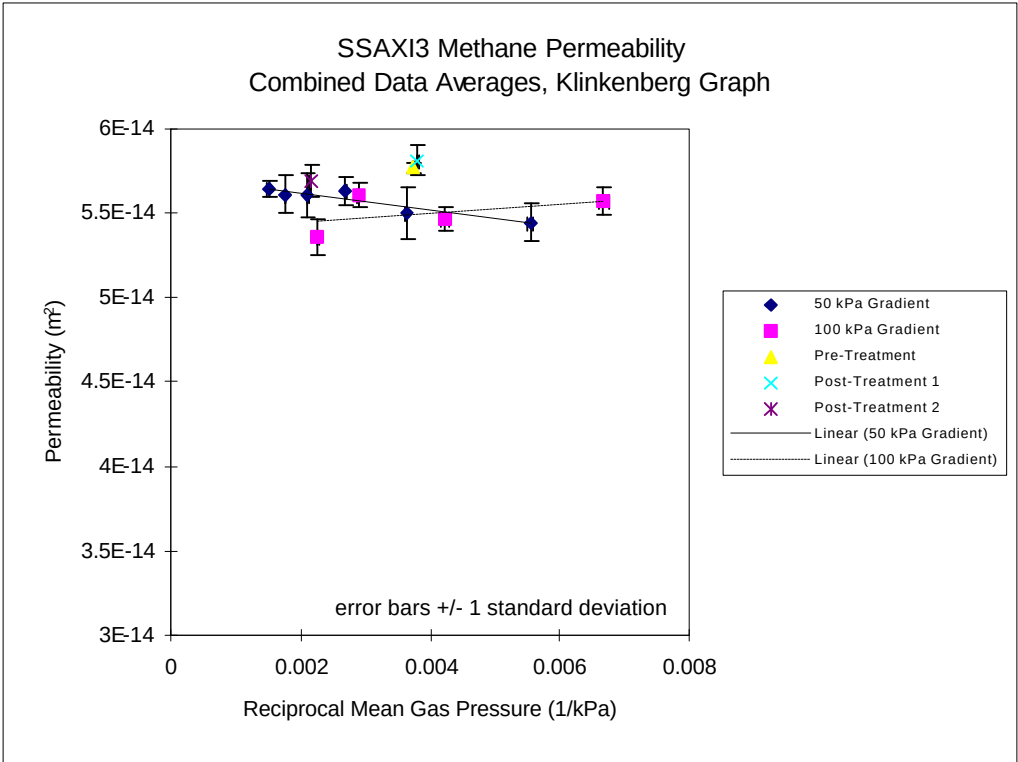


Figure 3-11d: Klinkenberg Graph, SSAXI3 Methane Permeability, Data Averages.

3.3.1.2 *Radial Samples*

Four samples for radial permeability measurement were obtained from a single 30 cm long piece of core. The samples were cut utilizing a cut-off saw, with diamond blade. Preparation of the samples for testing was accomplished using the procedure described above, section 3.2.1

3.3.1.2.1 Sample SSRAD1

This sample was the first of four used for radial permeability measurements. It was taken at random from the set obtained from a single piece of 1.5" diameter core. The photomicrograph shown in plate 3-13 is of this sample.

Sample SSRAD1 showed an initial radial permeability of $7.29 \times 10^{-15} \pm 4.77 \times 10^{-16} \text{ m}^2$ (7.38 ± 0.48 mD). These numbers indicate an error of about -85% compared to the permeability reported by the quarry. No liquid carbon dioxide stimulation was performed on this sample. The initial permeability measurements for this sample are illustrated in figure 3-12.

It may be noteworthy that during the initial gas loading of the sample, it was heard to emit a cracking and popping as the gas pressure was raised. Based on the measurements obtained compared with the other samples this does not appear to have been a significant factor. No physical damage was evident when the sample was removed from the test cell.

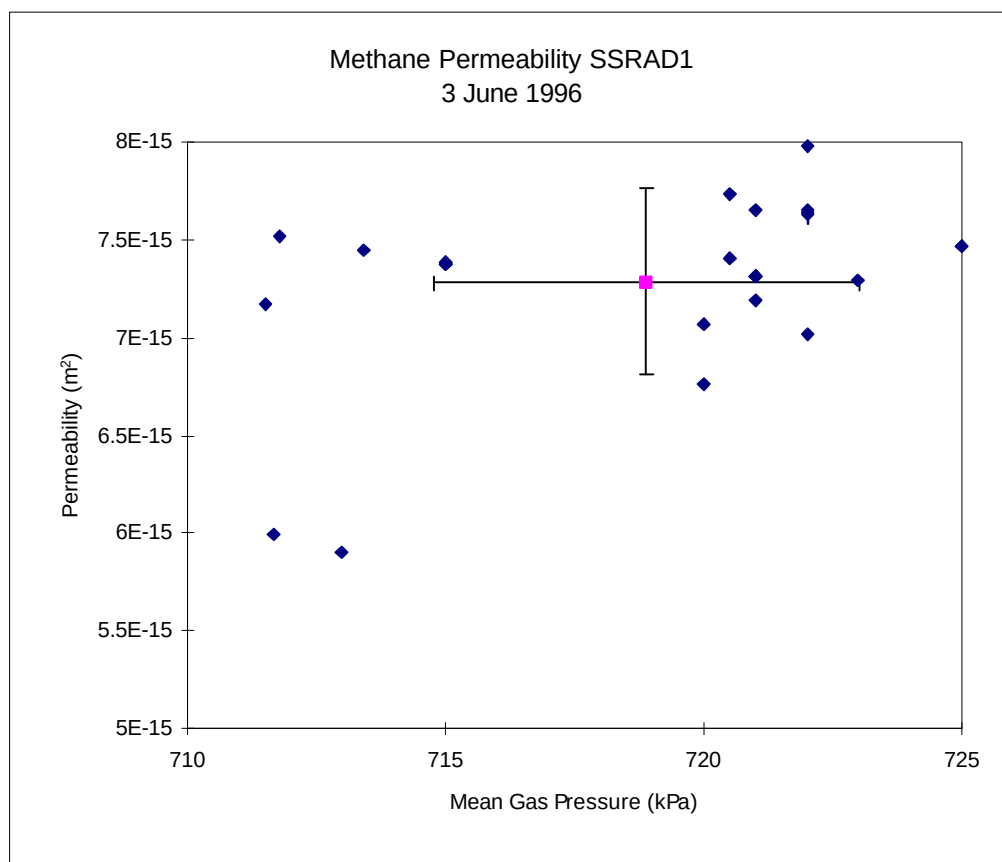


Figure 3-12:Methane Permeability SSRAD1

3.3.1.2.2 Sample SSRAD2

The second of the sandstone radial samples, SSRAD2, showed an initial permeability of $3.66 \cdot 10^{-15} \pm 1.24 \cdot 10^{-16} \text{ m}^2$ ($3.71 \pm 0.126 \text{ mD}$). Following treatment with liquid carbon dioxide the permeability was increased to $6.26 \cdot 10^{-15} \pm 3.71 \cdot 10^{-16} \text{ m}^2$ ($6.34 \pm 0.376 \text{ mD}$). These permeability measurements are about -93% and -87% off of the expected value of 50 mD. This data is illustrated in figure 3-13a.

This figure indicates that the mean gas pressure measurements for both series, pre and post treatment (individual measurement points are not shown), can be considered in the same population. It is, however, obvious that the permeabilities are of different populations before and after treatment with the liquid carbon dioxide. The increase in permeability due to the carbon dioxide treatment is approximately 71%.

Figure 3-13b illustrates the pre and post treatment permeability data, along with a permeability curve that was obtained as the mean gas pressure was slowly raised during the initial pressurization of the sample. The permeability curve is based on a single measurement at each of the mean gas pressures indicated. The curve shown is a “best fit” power curve. The fit of the curve appears to be skewed a little bit high in the mid-range of mean gas pressures. Although a “better” fit could be obtained, this curve is used since it is of the same form as curves used in the previous axial flow tests and in the following radial flow tests, which were based on far more data. The observation of the initial permeability measurement group aligned on this curve should not be considered coincidental, but rather an indication of repeatability.

A portion of this sample was prepared and observed under the scanning electron microscope. Despite the increase in permeability, there were no obvious differences in the structure compared to SSRAD1.

The Klinkenberg representation of the gas pressure step data is illustrated in figure 3-13c. This graph is based on a single measurement of permeability taken at each pressure step. The curvature of this series, with respect to the mean gas pressure, is seen in figure 3-13b; the same presentation, based on the reciprocal of the mean gas pressure is presented in figure 3-13c. In this figure a good linear fit, with a positive slope, is observable, as the expected results suggest.

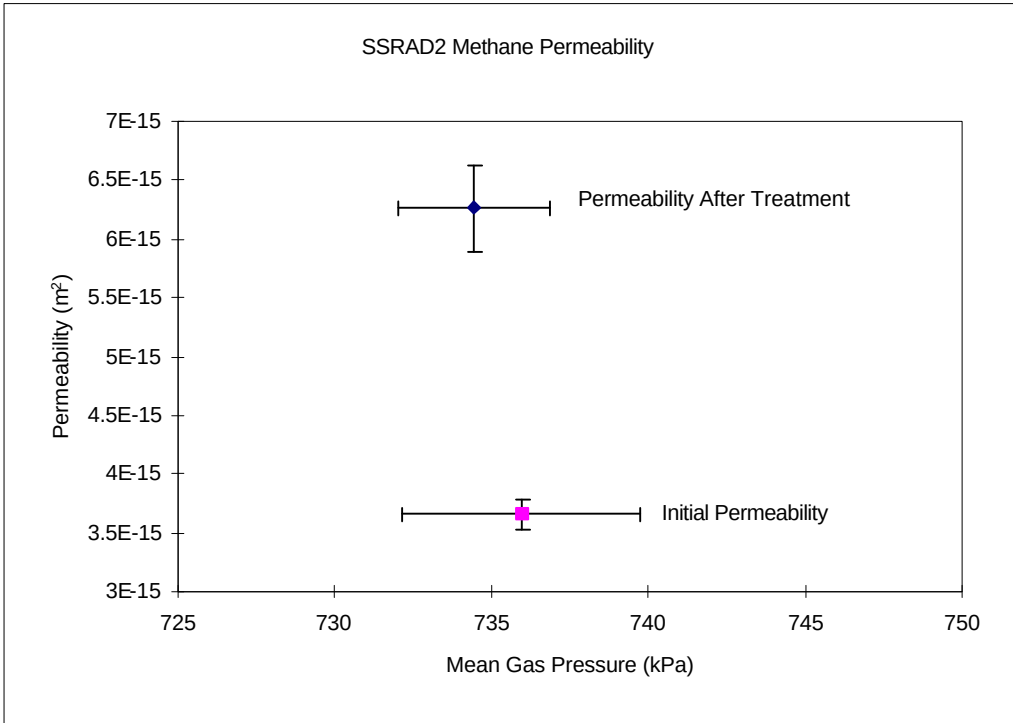


Figure 3-13a: SSRAD2 Methane Permeability.

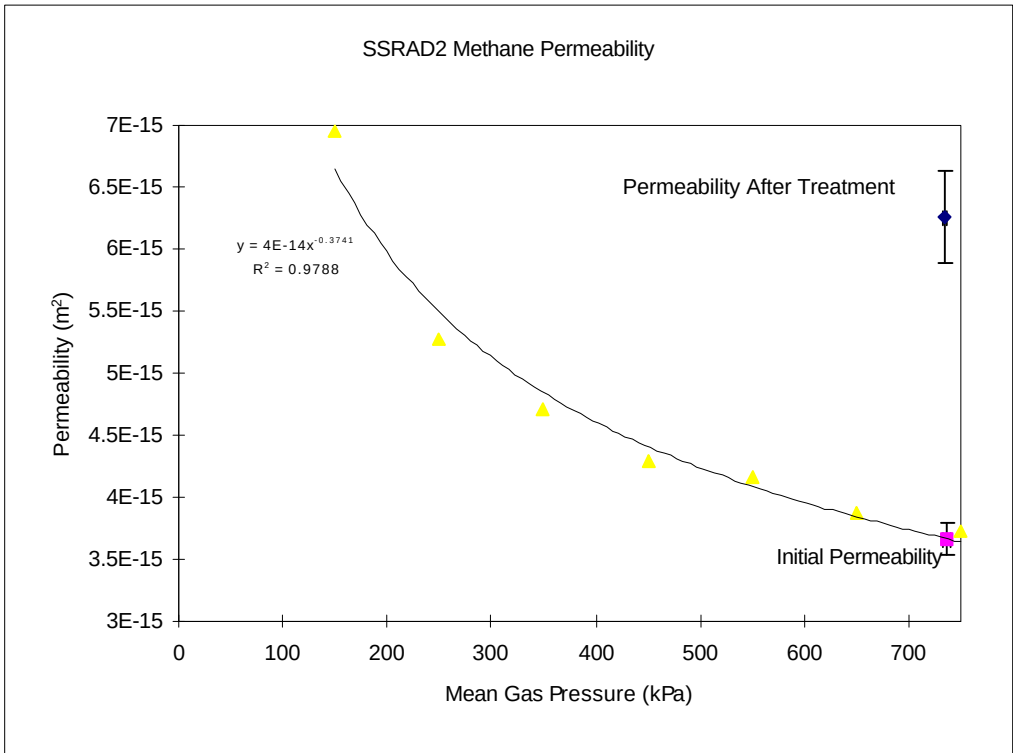


Figure 3-13b: SSRAD2 Methane Permeability, with full range.

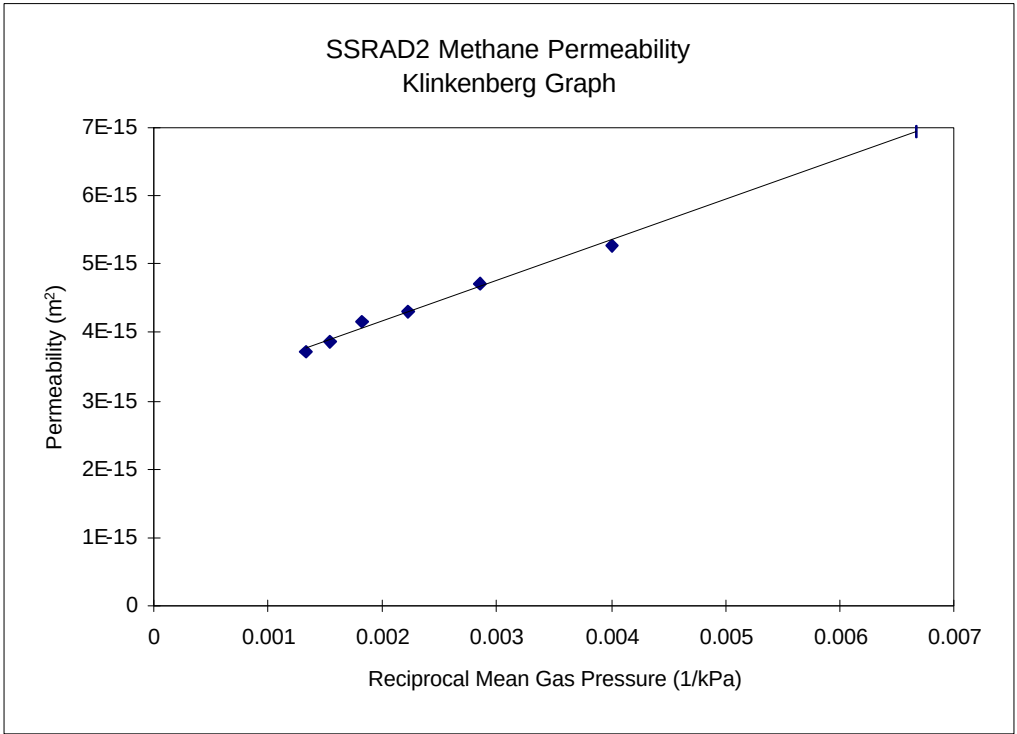


Figure 3-13c: Klinkenberg Graph, SSRAD2 Methane Permeability.

3.3.1.2.3 Sample SSRAD3

The third radial flow sample was designated as SSRAD3. Preparation of this sample was in accordance with the method described previously. This sample exhibited a decreasing permeability as the mean gas pressure was increased, a similar pattern is seen in sample SSRAD4. Due to the high initial permeability of this sample, a measurement series was only obtained at the 25 kPa gradient, and at a maximum mean gas pressure of about 500 kPa. The initial permeability, at 275 kPa was measured as $5.36 \times 10^{-14} \text{ m}^2$ (54.3 mD). Following treatment with liquid carbon dioxide the permeability was measured as $1.19 \times 10^{-13} \text{ m}^2$ (121 mD). This represents a 122% increase in permeability associated with the treatment cycle. The measured results for this sample are illustrated in figure 3-14. The permeability measured for this sample is of the same order of magnitude as that determined for the axial flow series (SSAXI).

It should be noted here that the post-treatment permeability may be reported slightly high. This is due to the fact that following the treatment the maximum gradient that could be obtained with the meter valve was about 20 kPa, in comparison to the 25 kPa for the pre-treatment measurement. Based upon the conditions observed in other samples, SSRAD4, and the SSAXI series, the permeability is seen to increase as the pressure gradient is decreased. Based on the rate of difference in the measurements of SSRAD4, the lower post-treatment gradient of this sample may provide a reported permeability about 20% higher than if the 25 kPa gradient had been obtained.

Figures 3-14b and c illustrate the Klinkenberg representation of the measured permeability with respect to the mean gas pressure. The pre-treatment data sets show a close “clumping” of the points, in each set. A good linear fit of the data is evident, with the expected positive slope. The nature of this fit is evident in figure 3-14c as the line passes through the bounds of the vertical ± 1 standard deviation error bars.

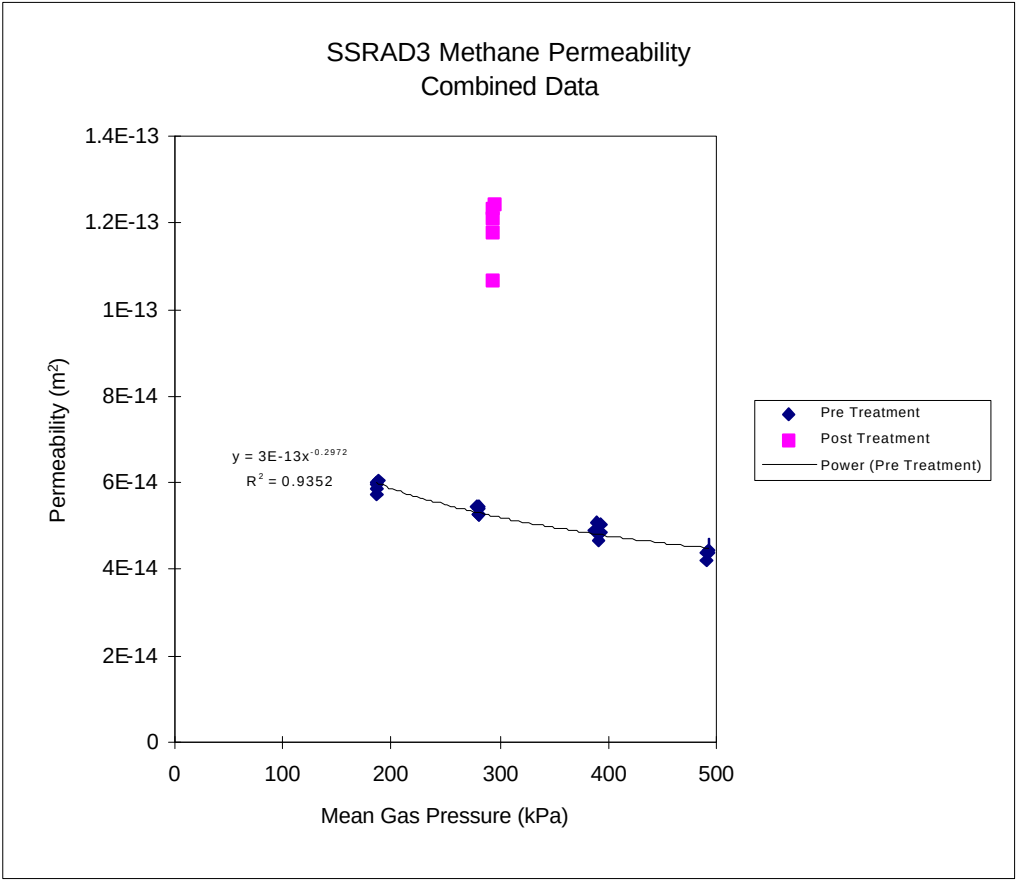


Figure 3-14a: SSRAD3 Methane Permeability, Combined Data.

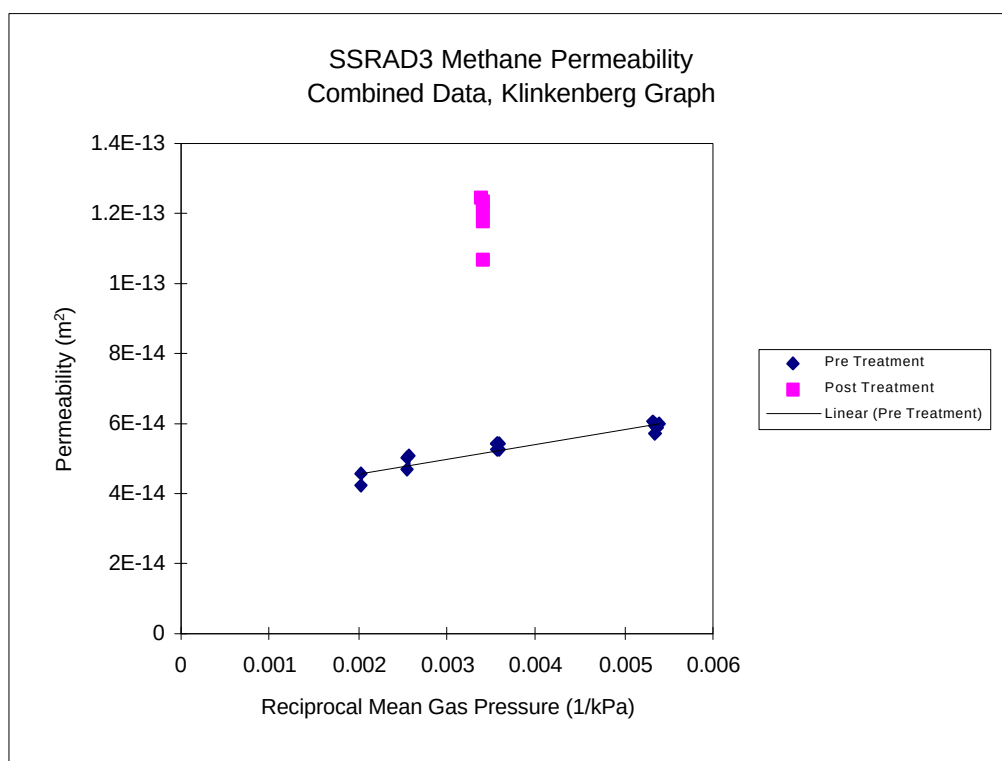


Figure 3-14b: Klinkenberg Graph, SSRAD3 Methane Permeability, Combined Data.

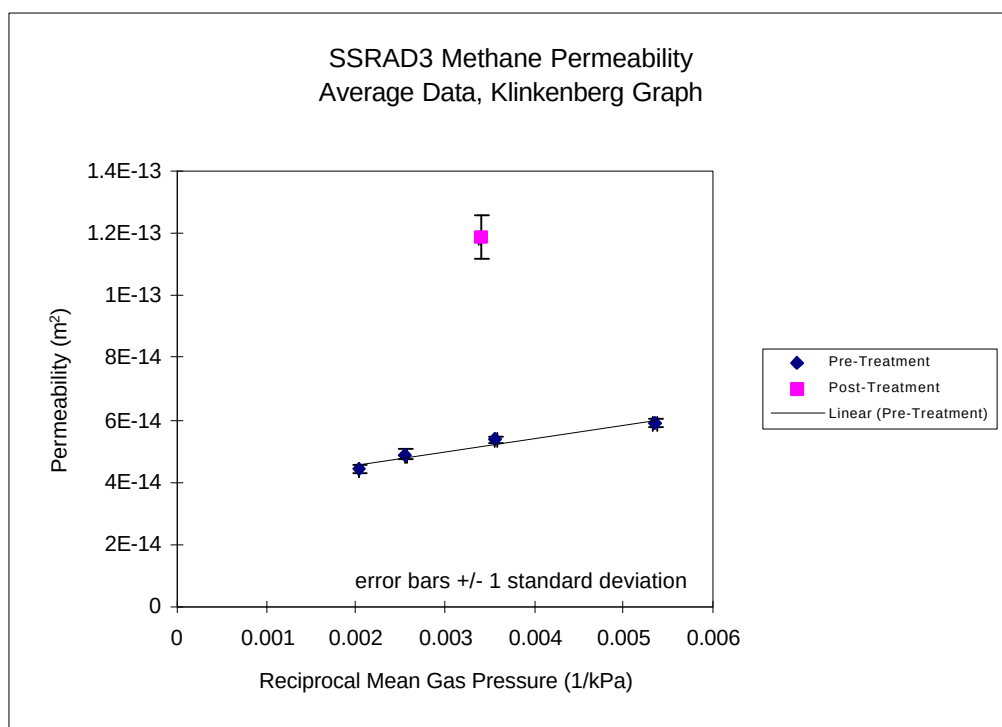


Figure 3-14c: Klinkenberg Graph, SSRAD3 Methane Permeability, Data Averages.

3.3.1.2.4 Sample SSRAD4

The fourth of the radial flow sandstone samples was designated as SSRAD4. This sample was prepared as describe under sample preparation, above. The specimen was selected at random from the 12 inch long by 1.5 inch diameter core obtained from Cleveland Quarries.

The testing performed on this sample consisted of a stepped test in which the mean gas pressure was incrementally raised while maintaining a constant pressure gradient. This pattern was conducted for both a 25 kPa and 50 kPa gradient, roughly analogous to the 100 and 200 kPa gradients on the axial samples. Following collection of the pre-treatment permeability data the sample was treated with the liquid carbon dioxide in the manner described previously. The permeability, at a 25 kPa gradient, was measured following treatment. This data is illustrated in figure 3-15a.

The pre-treatment permeability of this sample, at the 25 kPa gradient, appears to approach about $1.6 * 10^{-14} \text{ m}^2$ (16.2 mD) as the mean gas pressure is increased. This is nearly 2.5 times the permeability measured for the sample SSRAD1 and 5 times that of SSRAD2.

A noteworthy observation is that the permeability appears to decrease as the mean gas pressure is increased. This is similar to the pattern observed for the axial flow samples. The permeability appears to decrease as a function of the gradient, as was seen in the axial flow samples. In this sample the first set of 25 kPa gradient permeability measurements was conducted, the sample was then allowed to sit for about a day and a half in a stressed state. Following this period two “check point” measurements of the permeability, at a 25 kPa gradient were made. These points are approximately 15 percent lower than the initial data at the same mean gas pressure. For the coal samples such a result can be explained by plastic creep of the coal sample while under stress (Harpalani and McPherson 1986), such an explanation does not appear to be valid for sandstone, however. The sandstone samples are not expected to exhibit plastic characteristics, thus there should not be a time dependent parameter in the permeability assessment.

Considering the pre-treatment permeability to be on the 5 Aug 96 data line, the post treatment data suggest an increase in the permeability of about 60 percent. This level of enhancement is consistent with that observed in the coal samples subjected to the same treatment.

Expression of the data collected on this sample in the Klinkenberg form is illustrated in figures 3-15b and c. In both of these figures a linear fit of the data of the 25 and 50 kPa gradients prior to treatment and the data of 25 kPa gradient show good linear fits with a positive slope, as the expected results suggest. Comparing the first two of these data sets, a relationship where the slope decreases as the gradient increases is also evident. This situation is the opposite as that

observed for the axial flow samples covered previously (sections 3.3.1.1.1, 3.3.1.1.2, and 3.3.1.1.3).

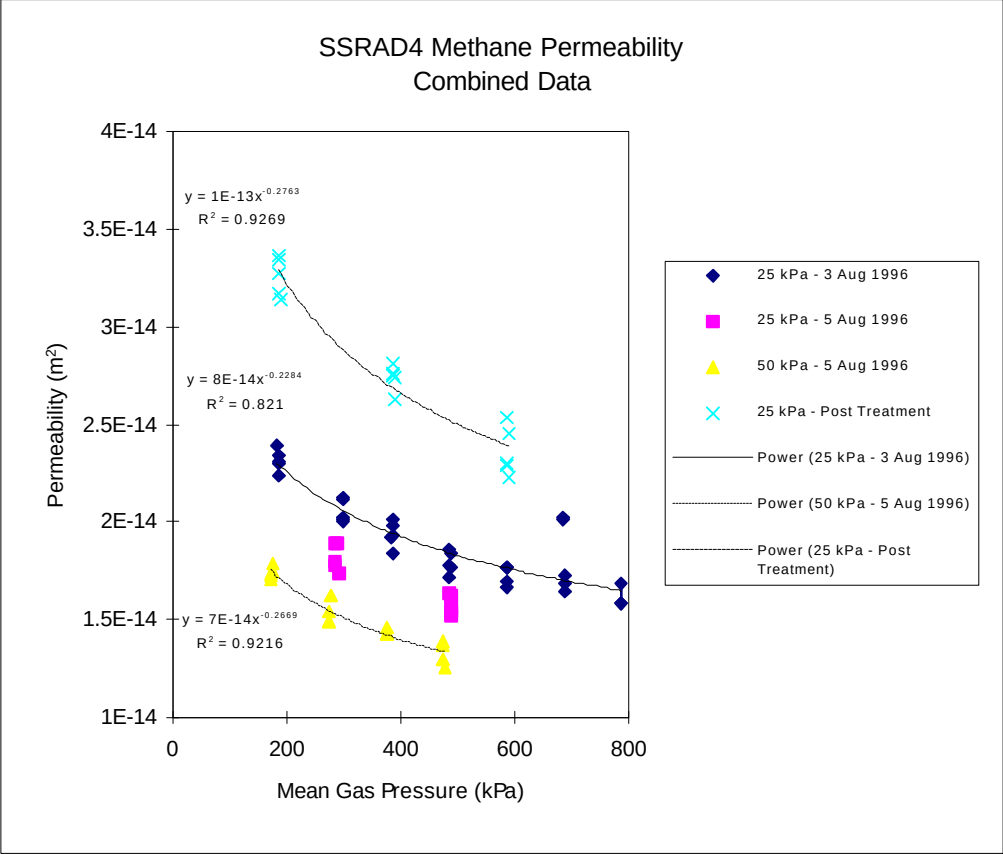


Figure 3-15a:SSRAD4 Methane Permeability, Combined Data.

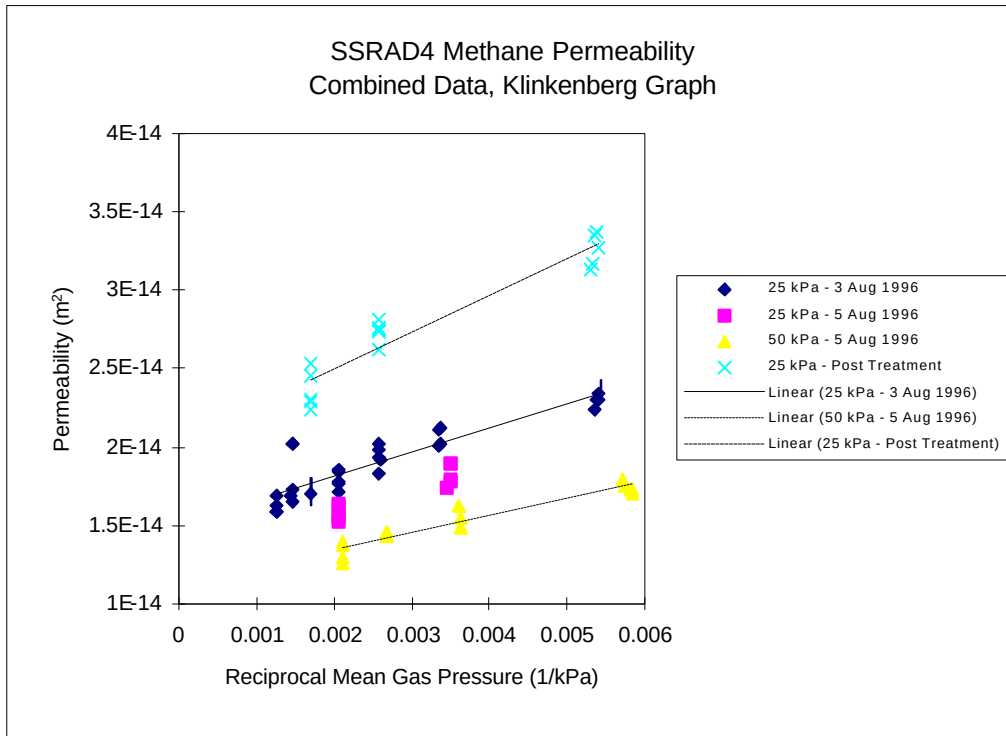


Figure 3-15b: Klinkenberg Graph, SSRAD4 Methane Permeability, Combined Data.

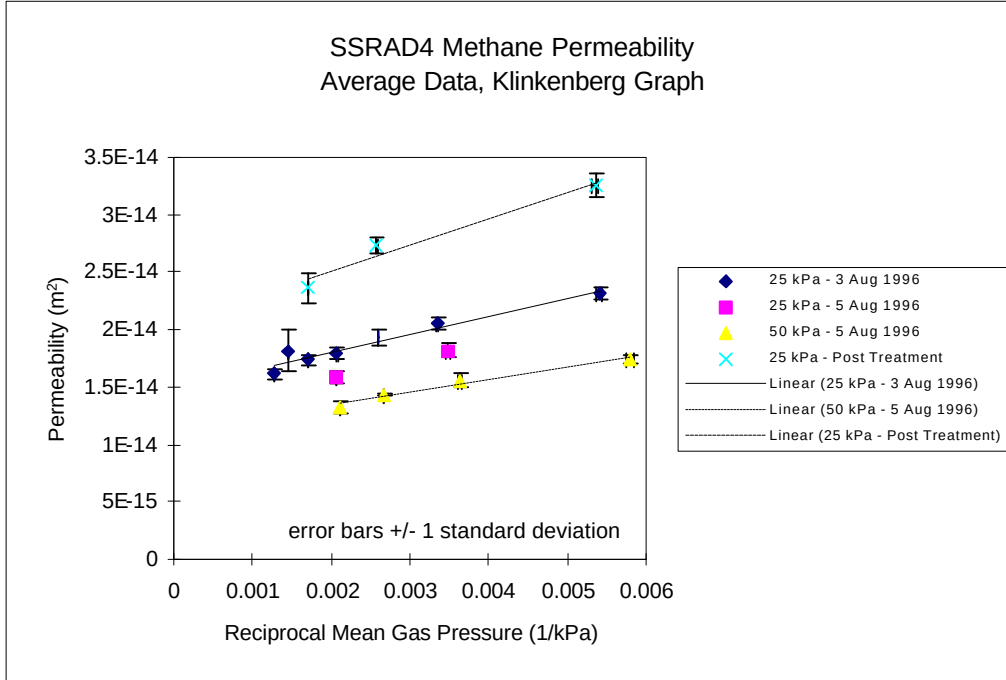


Figure 3-15c: Klinkenberg Graph, SSRAD4 Methane Permeability, Data Averages.

3.3.2 Coal Samples for Evaluation

The samples of coal used for evaluation are covered below. Those samples discussed here are those which fully survived the process of preparation through to the generation of useful data. Table 3-4 lists the basic parameters of all samples placed in the in the tri-axial cell. Under the column *test* an entry of “none” indicates that the sample did not have an initial permeability conducive to further evaluation. This initial permeability could have been too low to measure, or it could have been so high that measurement was not practical.

The Klinkenberg effect has been illustrated in the previous study section pertaining to the sandstone samples. Due to the adsorptive nature of methane to coal, the Klinkenberg effect, and equation, is not fully valid for these samples, for this reason figures of this nature are not used in reference to the coal specimens. When applied to coal, and presumably other adsorptive porous media, the permeability becomes a function that includes the general Klinkenberg effect and an exponential factor which accounts for dilation of the flow paths. This case is illustrated, along with a brief explanation, in McPherson (1993).

Table 3-4: Coal Samples Tested in Tri-axial Test Cell

Sample	Date	Description	Test
PMOGS			liq CO ₂
PMOG01	4 May 95	Pine Mtn., Bag C, Peerless A, Spangler Pros.	liq CO ₂
PMOG02	27 Apr 95	PMOG #2 Gas	None
PMOG03	2 May 95	Bag K, Powellton, PMOG	None
PMOG04	4 May 95	Pine Mtn., Bag B, Peerless A, Spangler Pros.	None
PMOG05	12 May 95	Pine Mtn., Bag B, Peerless A, Spangler Pros.	liq CO ₂
PMOG06	22 May 95	PMOG, Spangler, Bag A, Cedar Grove, Top	None
PMOG07	30 May 95	Pine Mtn. Oil and Gas, #6713, Sample BB	None
PMOG08	31 May 95	Pine Mtn. Oil and Gas, Sample E, 6713	None
PMOG09	12 Jun 95	Pine Mtn. Oil and Gas, Sample K	liq CO ₂
PMOG10	1 Jun 95	Pine Mtn. Oil and Gas, Sample CC, 6713	liq CO ₂
PMOG11	14 Jun 95	Pine Mtn. Oil and Gas, 6713, Sample RR	liq CO ₂
PMOG12	14 Jun 95	Pine Mtn. Oil and Gas, Sample E, 6713	liq CO ₂
PMOG13	29 Jun 95	Pine Mtn. CM-16-90 Sample T	liq CO ₂
PMOG14	N/A ⁶	N/A	None
PMOG15	N/A	N/A	None
PMOG16	14 Jul 95	Pine Mtn. Oil and Gas, 6713, Sample CC	liq CO ₂
PMOG17	26 Oct 95	8B VSP3204u230 2611083	liq CO ₂

3.3.2.1 Sample PMOGS

The initial Pine Mountain Oil and Gas sample for which data was collected and evaluated was identified as PMOGS. This sample was subjected to the basic experimental technique over several cycles. This was done to verify the procedures and expected effects. This sample is mentioned for this role only, due to the variety of handling that this sample received it is not included in the analysis of data. The measurements of permeability obtained from this sample are illustrated in figure 3-16. Prior to treatment the permeability of this sample was $6.86 * 10^{-17} \pm 8.32 * 10^{-18} \text{ m}^2$. Following treatment the permeability was measured to be $1.49 * 10^{-16} \pm 3.57 * 10^{-18} \text{ m}^2$, an increase of about 117 percent. The level of permeability measured for this sample, as well as most of the other coal samples was 2 to 3 orders of magnitude lower than that of the sandstone, evaluated above. An overall comparison is shown in figure 3-27 in section 3.4.4.

Figure 3-16 illustrates two sets of data collected on the sample PMOGS. The main set of data, shown as triangles, illustrates a generally downward trend in the permeability as the mean gas pressure increases. The trendline shown with this data is an ordinary power law fit. While it does

⁶N/A - Not Applicable, these samples were not successfully prepared, the numbers are retained for continuity.

not appear to be the best-possible fit (being generally lower than is illustrated), it is affected by the higher permeability data point at a pressure of about 470 kPa, as well as the clump of data around a pressure of 550 kPa. Removal of the data point located at 470 kPa would tend to lower the fit curve, this would not, however, bring the power law curve into close coincidence with the data points. A close approximation of the trendline to the data points is possible if the assumption were to be made that permeability tends to increase at pressures higher than 550 kPa. This behavior is supported by a modification to the Klinkenberg equation (McPherson 1993) in which dilation of the gas flow paths is taken into consideration. Therefore it is not without basis to assume that actual physical condition closely fits to the measured data, with an increasing permeability as the pressure increases beyond the recorded levels. However, in the absence of permeability measurements for pressures greater than 600 kPa, it may not be prudent to force a very close fit based only on expected behavior.

The average of this data and the ± 1 standard deviation error bars is shown near the middle of the graph. Following a treatment cycle another permeability measurement series was performed, these data, along with the average and error bars, are located in the upper right of the graph.

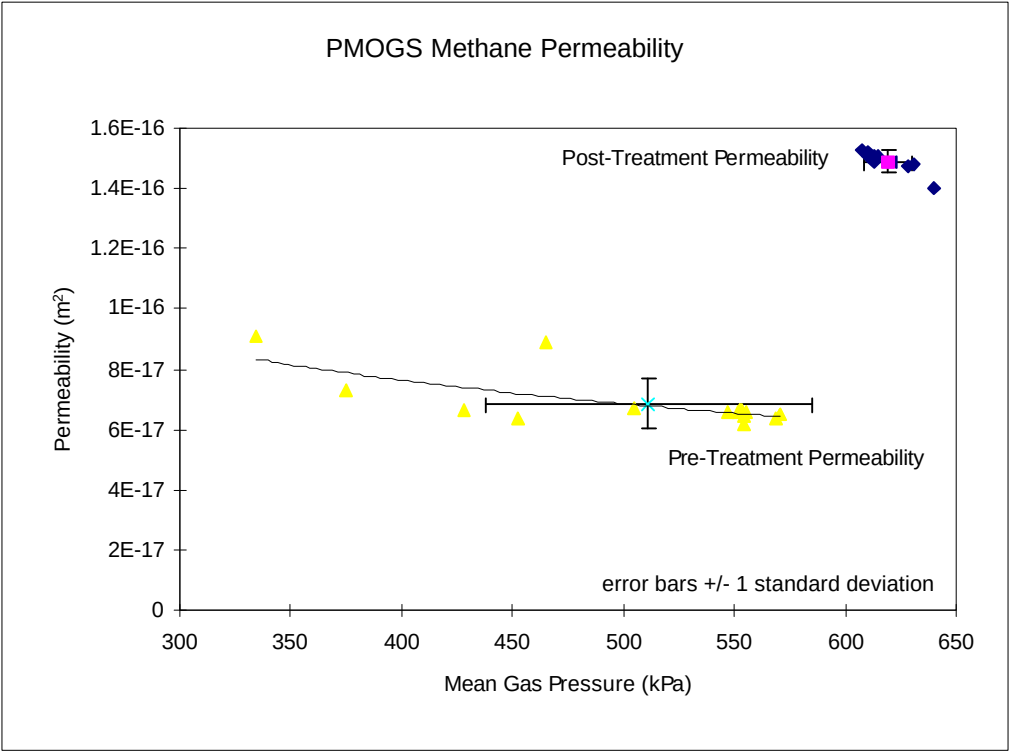


Figure 3-16: PMOGS Methane Permeability.

3.3.2.2 Sample PMOG01

This Pine Mountain Oil and Gas sample was prepared utilizing the procedure described above, except that the sample diameter was reduced incrementally, rather than all at once. This sample also experience a fracture perpendicular to the sample axis, this fracture was repaired with epoxy, as described above.

This initial permeability of this sample was measured as $9.31 \cdot 10^{-18} \pm 5.98 \cdot 10^{-19} \text{ m}^2$ ($9.4 \cdot 10^{-3} \pm 6.1 \cdot 10^{-4} \text{ mD}$). Following the treatment with liquid carbon dioxide the permeability was measure as $2.38 \cdot 10^{-18} \pm 1.76 \cdot 10^{-19} \text{ m}^2$ ($2.4 \cdot 10^{-3} \pm 1.8 \cdot 10^{-4} \text{ mD}$). This represents a decrease in the permeability of about 75 percent. The data collected for this sample are illustrated in figure 3-17. These results suggest that the expected process of physical alteration to the coal matrix has not occurred, or that some other phenomenon is producing an overwhelming effect. One possible explanation, at this phase, is that carbon dioxide molecules are adsorbing onto the coal matrix surfaces with the net effect of closing off some of the micro pores to the flow of methane gas molecules. This effect, and its surrounding consequences, has been addressed in a previous section of this thesis, see section 3.1.4. The true nature of this phenomenon would be difficult to ascertain in the present experimental configuration. These current tests measure, primarily, the flow of methane through the primary permeability paths in the samples, the effect at the microscopic level would require experimental procedures directed to flow measurements of the diffusive properties.

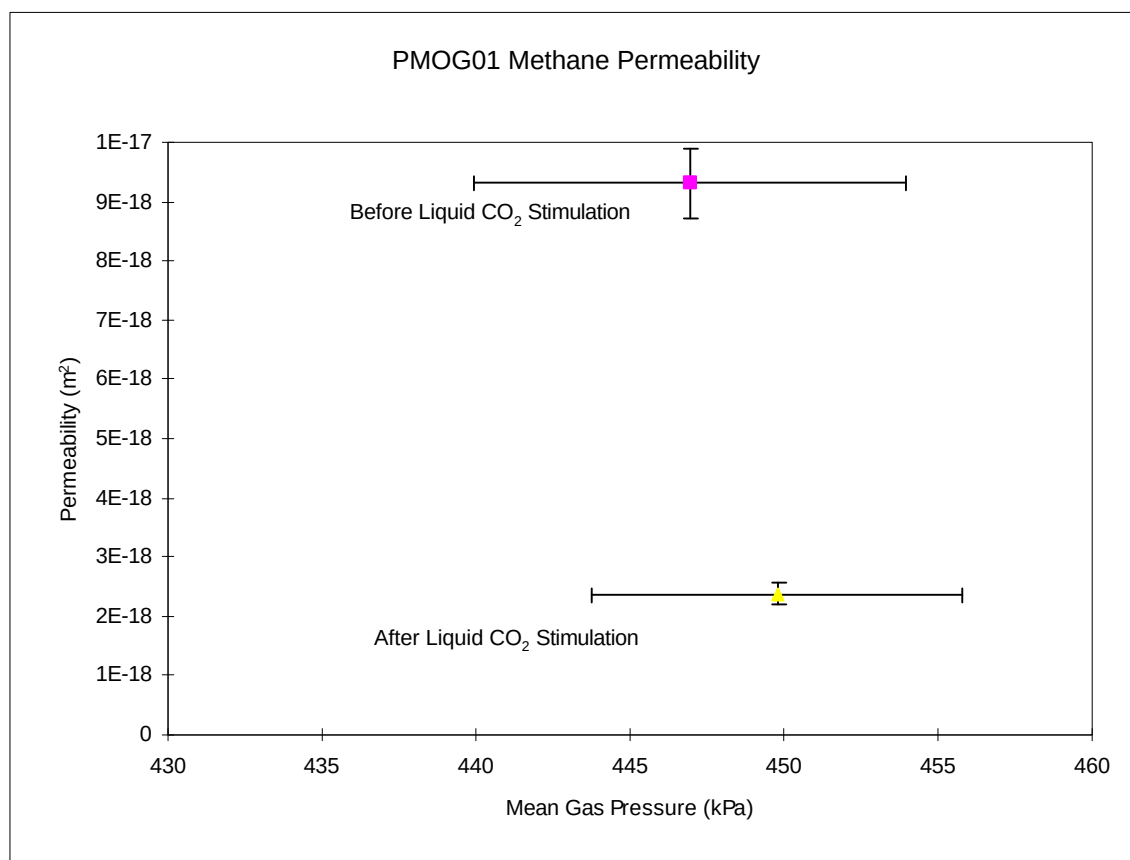


Figure 3-17: PMOG01 Methane Permeability.

3.3.2.3 Sample PMOG05

This sample was prepared from the initial batch delivered by Pine Mountain Oil and Gas utilizing the procedure described above. No repair work on this sample was conducted. The initial permeability of this sample was measured as $5.79 \times 10^{-16} \pm 3.93 \times 10^{-17} \text{ m}^2$ ($0.59 \pm 0.040 \text{ mD}$). Following the first treatment with liquid carbon dioxide the permeability was measured as $7.71 \times 10^{-16} \pm 5.19 \times 10^{-17} \text{ m}^2$ ($0.78 \pm 0.053 \text{ mD}$). The sample was treated a second time, with a resulting, final, permeability measured at $7.40 \times 10^{-16} \pm 2.83 \times 10^{-17} \text{ m}^2$ ($0.75 \pm 0.029 \text{ mD}$). These results are illustrated in figure 3-18. The resulting increase in permeability was approximately 30%.

Based upon these results the permeability of this sample was enhanced by the first treatment cycle, followed by a degrading of the enhanced permeability following the second treatment cycle. The initial enhancement of the permeability is consistent with the expected results, the results of the second treatment are contradictory to the expected results. The observed loss of permeability, associated with the second treatment cycle, is an unexpected result. It may, however, offer some insight to real nature of the treatment process. The initial assumption was that the carbon dioxide would physically alter the coal structure resulting in a higher permeability due to increase communication amongst the pre-existing micro-fracture network. The measured results of a loss in permeability following the second treatment cycle tends to imply that the physical process of the first cycle may be occurring at a much larger scale than is the basis of the process assumption. Based upon the observations made in the sandstone samples, see section 3.3.1.1 and 3.3.1.2, the first treatment cycle may remove debris from around the drill hole in the center of the sample. The removal of the debris from this bore and the resulting increase in permeability near the bore may allow for higher velocity flow of carbon dioxide within the body of the sample during the second treatment cycle. Higher velocity liquid and/or gas flow could cause material within the sample to become dislodged into the primary permeability paths, thus decreasing the overall permeability of the sample.

As can be seen in the figure the Mean Gas Pressures for the pre-treatment and post-treatment permeability do not align with in the horizontal error bars, thus it cannot be assumed that the populations are at equal pressure. Furthermore, there appears to be a positive linear relationship between the measured permeability and the mean gas pressure. Such a result might be expected in an untreated sample, based upon results presented by McPherson (1993). The general explanation of this trend is that the increasing gas pressure compresses the coal matrix resulting in an increase in pore volume that overcomes the presence of adsorbed gas on the matrix surfaces. Two factors to consider in evaluating the observed trend, in relation to that illustrated by McPherson (1993), are: (a) that for the effective range where permeability increases with increasing mean gas pressure, the rate at which the permeability increases with gas pressure decreases as the hydrostatic pressure increases, and (b) that the hydrostatic pressure of the present

sample was much higher than those shown by McPherson. Unless observations in the other coal samples, of the current research, indicate otherwise it will be considered that the increase in measured permeability of this sample is due, in a much higher degree, to the treatment process rather than to differences in mean gas pressure.

Plate 3-14 is a photomicrograph of this sample. After this sample was removed from the test cell it was cut down for visual observation. Two of the pieces were prepared for observation in the scanning electron microscope. This photograph was taken on a plane of lamination that was polished to 6 microns. Visible in the picture is the edge of a low angle fracture at the intersection of a fracture normal to the observed surface. The lower section of the picture illustrates the fracture surface on the sample. The fracture appears to continue under the lip visible in the upper portion of the picture. Running diagonally across the upper middle of the photograph there is a fracture normal to the observed surface. This is evident by the string of voids. Unfortunately, observation of this sample, on planes parallel and normal to the laminations, revealed no visible signs that alteration had taken place that could account for the increase in permeability that was measured.

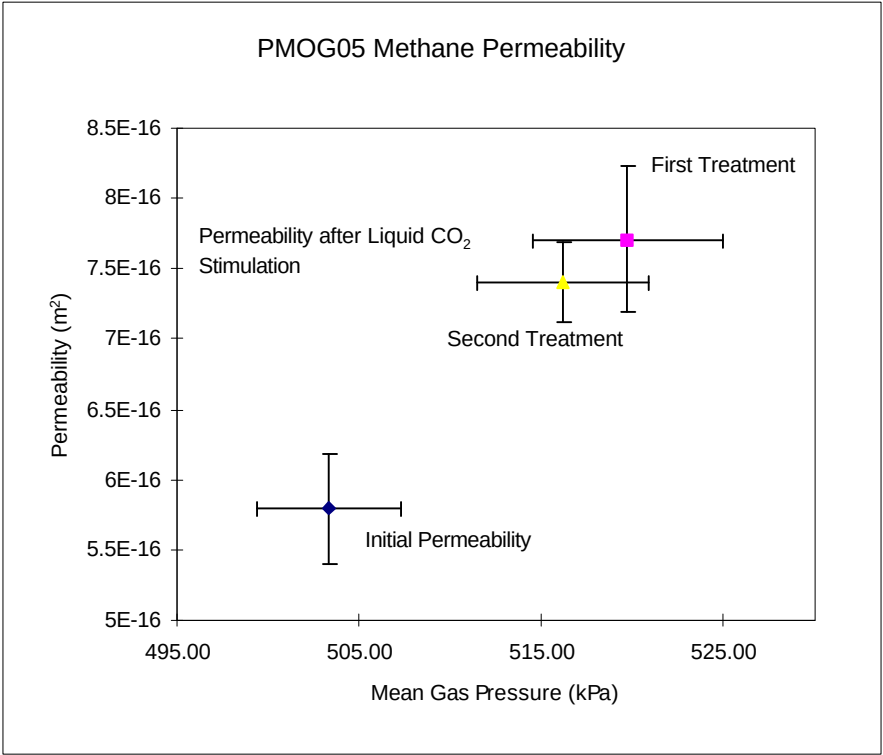


Figure 3-18: PMOG05 Methane Permeability.

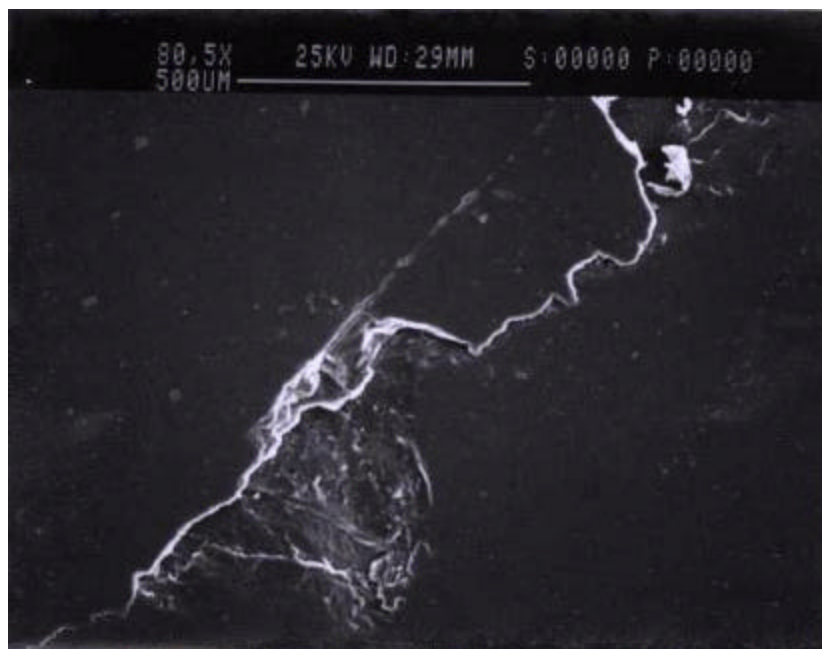


Plate 3-14: Photomicrograph from Sample PMOG05, 80.5x

3.3.2.4 Sample PMOG09

The sample identified as PMOG09 was obtained from the first batch of core delivered by Pine Mountain Oil and Gas. This sample was prepared following the procedure described above. Observations of the prepared sample indicated distinctive possible flow paths in the vitrain layers.

Experimental measurements indicated an initial permeability of $1.49 \times 10^{-15} \pm 3.08 \times 10^{-17} \text{ m}^2$ ($1.51 \pm 0.031 \text{ mD}$). Following the liquid carbon dioxide treatment the permeability was measured as $3.81 \times 10^{-15} \pm 2.73 \times 10^{-16} \text{ m}^2$ ($3.86 \pm 0.28 \text{ mD}$). This data is illustrated in figure 3-19. The measured change in permeability is on the order of 156 percent.

As can be seen in this figure both of the data sets, prior to and following treatment, are at the same mean gas pressure. From this it is possible to presume that the increase in the permeability is due to the treatment and not due to differences in the gas pressure.

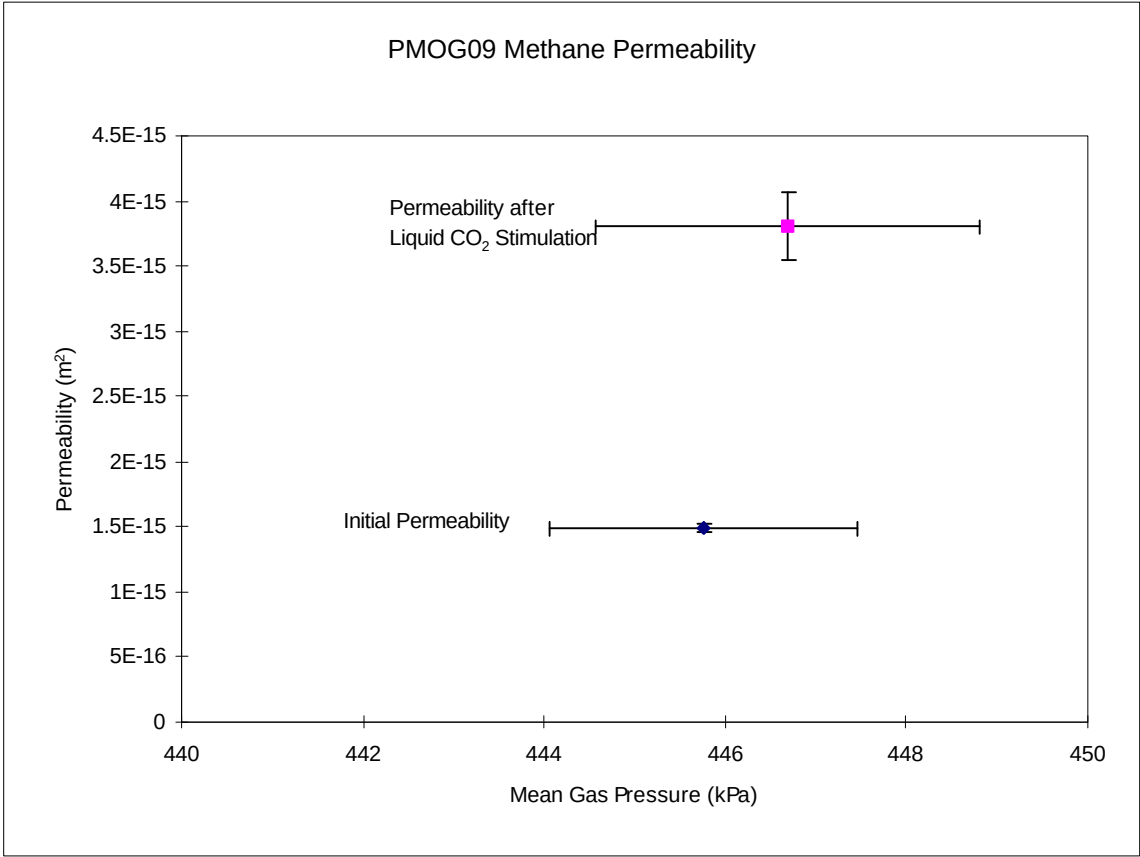


Figure 3-19: PMOG09 Methane Permeability.

3.3.2.5 Sample PMOG10

The sample identified as PMOG10 was taken from the batch delivered by Pine Mountain Oil and Gas. This sample was prepared following the procedure described above. Observations following preparation indicate that the sample had no distinct vertical fractures, although there was a degree of horizontal laminations that could lead to “disking,” a phenomenon that has been seen in post-test observations in other samples. The general observations regarding wafering of the samples is addressed in section 3.4.1

Permeability testing of this sample indicated a first pre-test permeability of $4.65 \times 10^{-16} \pm 5.66 \times 10^{-18} \text{ m}^2$ ($0.47 \pm 0.0057 \text{ mD}$) and a second of $4.38 \times 10^{-16} \pm 5.45 \times 10^{-18} \text{ m}^2$ ($0.44 \pm 0.0055 \text{ mD}$). Following the liquid carbon dioxide treatment the permeability was measured as $1.20 \times 10^{-15} \pm 2.55 \times 10^{-17} \text{ m}^2$ ($1.21 \pm 0.026 \text{ mD}$). This data is shown in figure 3-20.

This figure shows that the two pre-stimulation series can be considered at the same mean gas pressure, although based the mean permeability ± 1 standard deviation there appears to be a difference between the two series. During the intervening period of time, 13 hours, the sample was maintained under confinement and with methane gas pressurization of about 690 kPa gauge, the inlet pressure used for these tests. In this case it is the later of the two series that shows the lower permeability, however, in comparison to the permeability following treatment this minor difference is of little consequence.

There is evident a variation in the mean gas pressure between the pre and post treatment permeability measurement series. The relationship, however, indicates a negative slope relative to the pressure, not the positive slope that would be expected if the variation were due to mean pressure alone, compare to sample PMOG05 above. This sample indicates an increase in permeability of about 164% due to the liquid carbon dioxide treatment.

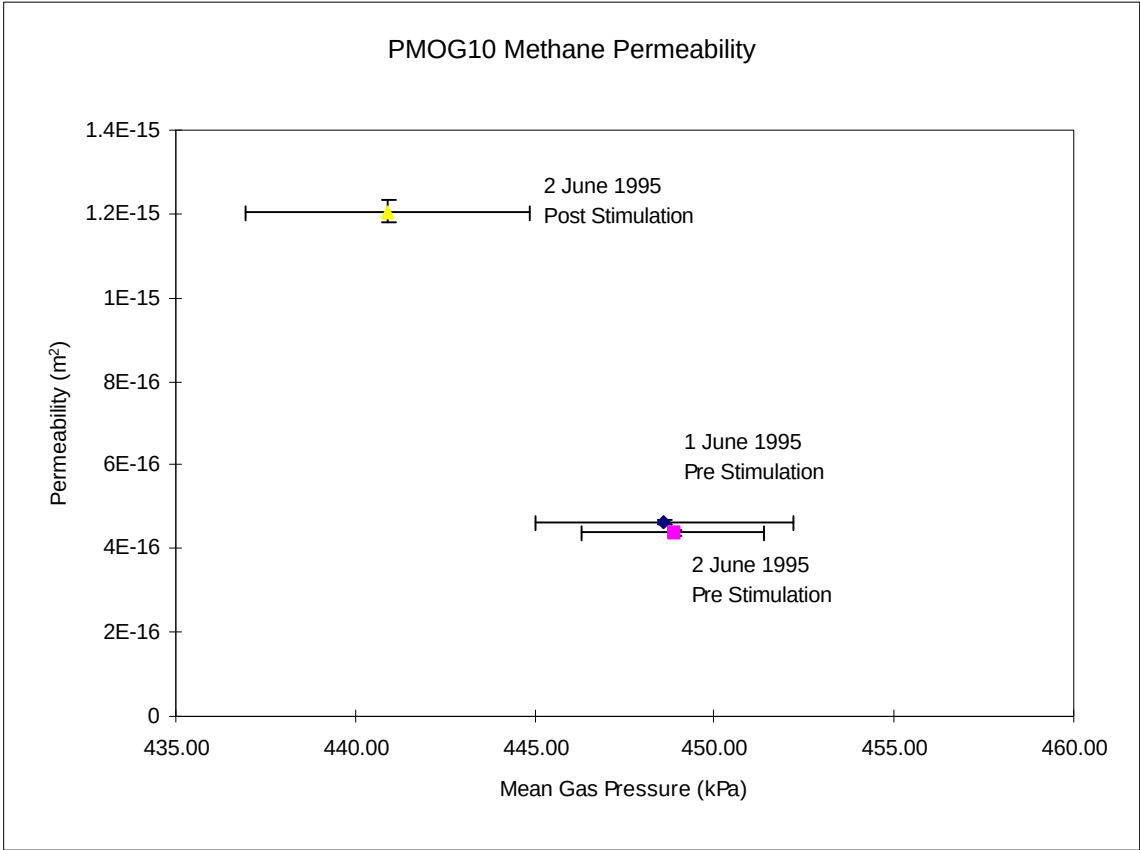


Figure 3-20: PMOG10 Methane Permeability.

3.3.2.6 Sample PMOG11

The sample identified as PMOG11 was taken from the shipment delivered by Pine Mountain Oil and Gas. This sample appeared to be highly fractured with an indistinct structure affecting the entire sample. The pieces of this structure were on the order of 5-7 mm cubic.

This sample was subjected to the treatment procedure twice, with an intervening permeability measurement. The initial permeability was measured as $2.47 \times 10^{-16} \pm 2.50 \times 10^{-18} \text{ m}^2$ ($0.25 \pm 0.0025 \text{ mD}$). Following the first treatment procedure the permeability was measured as $3.38 \times 10^{-16} \pm 3.76 \times 10^{-18} \text{ m}^2$ ($0.34 \pm 0.0038 \text{ mD}$) and as $3.35 \times 10^{-16} \pm 3.33 \times 10^{-18} \text{ m}^2$ ($0.34 \pm 0.0034 \text{ mD}$) on subsequent days. During the intervening time the sample was left under confinement and with methane pressurization. There is a slight variation in the mean gas pressure between the two permeability measurements following the first treatment, this is based on the observation that the mean gas pressure error bars do not overlap. Concerning the measured permeability, there is a slight difference in the means of the two samples, but within the expected range of error, ± 1 standard deviation, the two sets of measurements appear to be consistent. When the range between these two data sets is considered relative to the other sets (prior to treatment and following the second treatment) the difference appears to be inconsequential.

Following the second treatment the permeability was measured as $2.53 \times 10^{-16} \pm 6.51 \times 10^{-18} \text{ m}^2$ ($0.26 \pm 0.0066 \text{ mD}$) and as $2.57 \times 10^{-16} \pm 2.32 \times 10^{-18} \text{ m}^2$ ($0.26 \pm 0.0023 \text{ mD}$), on subsequent days. Again, the sample was left under confinement and with methane gas pressure at the level that the permeability measurements were made. With the range of error expressed for both mean gas pressure and permeability these two suites of measurements appear to be consistent.

This data is illustrated in figure 3-21. The initial permeability gain, due to treatment, was about 36 percent. The second treatment resulted in about a 24 percent loss in permeability, from that of the first treatment. The overall permeability gain was on the order of 3 percent, an amount for which no claim of enhancement can be made. As has just been stated, within the limits of error there is not significant difference between the initial and final permeability of this sample.

The results of this sample are, in form, consistent with those observed in sample PMOG05, see section 3.3.2.3. The reasoning behind the observed effects has been discussed in that section. To recap, there is the likelihood that the initial treatment cycle clears debris away from the borehole allowing for easier penetration of the fluid (gas or liquid) into the main sample body. The second treatment cycle could, uninhibited by skin effects in the bore, cause movement of debris within the primary permeability paths resulting in a loss of permeability relative to the first treatment results.

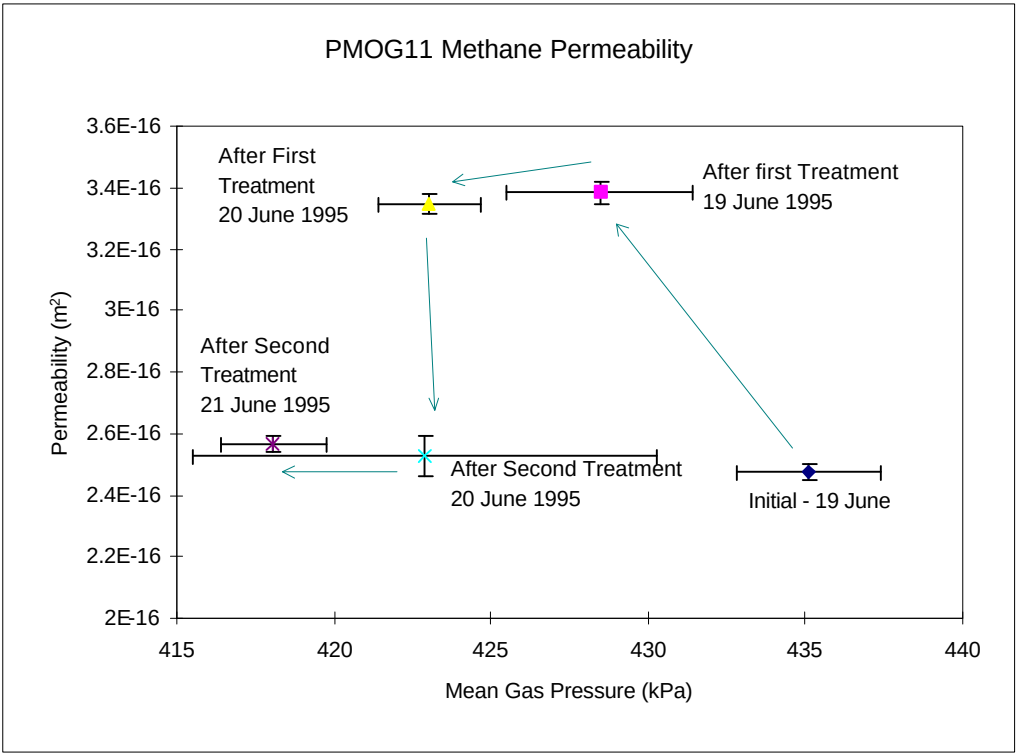


Figure 3-21: PMOG11 Methane Permeability.

3.3.2.7 Sample PMOG12

The sample identified as PMOG12 was taken from the initial shipment of core delivered by Pine Mountain Oil and Gas. This sample exhibited areas of vitrain, which appeared to provide possible paths of high permeability. The sample also indicated a large axial fracture which appeared to affect about 1/3 of the diameter of the sample, extending the full length on one side and about 1/2 of the length about 1 diameter around the sample.

The initial permeability of this sample was measured as $3.75 \times 10^{-16} \pm 4.90 \times 10^{-18} \text{ m}^2$ ($0.38 \pm 0.0050 \text{ mD}$). Following the liquid carbon dioxide treatment, the permeability was measured as $5.49 \times 10^{-16} \pm 7.48 \times 10^{-18} \text{ m}^2$ ($0.56 \pm 0.0076 \text{ mD}$). This data is illustrated in figure 3-22.

Because of the proximity of the mean gas pressures, and their 1 standard deviation error bars, it is possible to assume that the measurements were made at similar mean gas pressures. Thus it can be assumed that differences in the permeability are based on physical changes to the sample and not by differences in gas pressure. This sample indicates an increase in permeability of about 46%, that can be attributed to the treatment.

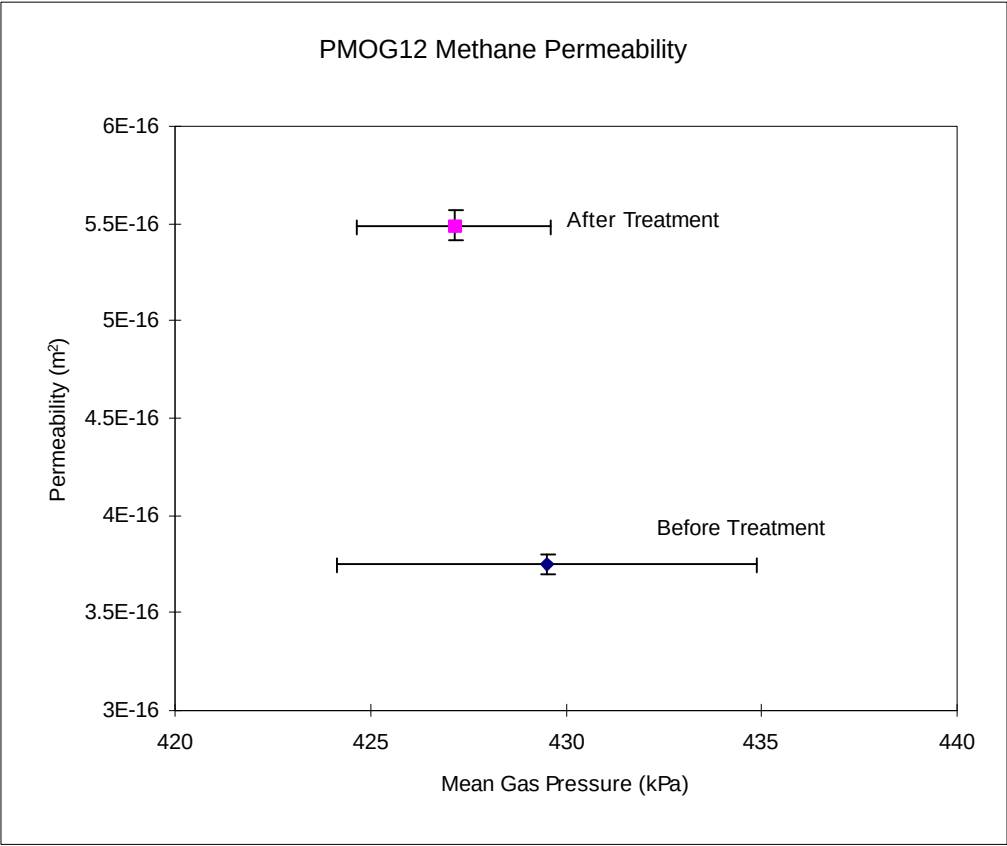


Figure 3-22: PMOG12 Methane Permeability.

3.3.2.8 Sample *PMOG13*

The sample identified as PMOG13 was taken from the second shipment of core delivered by Pine Mountain Oil and Gas. This sample had two, apparent, holes deep into the sample sides that were filled with epoxy resin to prevent an unusually high permeability region from affecting the overall measurement taken on the sample. This sample also exhibited a axial crack running the entire length.

This sample indicated a pre-treatment permeability of $1.82 \cdot 10^{-16} \pm 3.62 \cdot 10^{-18} \text{ m}^2$ (0.18 ± 0.0037 mD). The post-treatment permeability was measured as $5.59 \cdot 10^{-16} \pm 1.22 \cdot 10^{-17} \text{ m}^2$ (0.57 ± 0.012 mD). These results are illustrated in figure 3-23. Based upon the error analysis of the mean gas pressure it is possible to assume that the pre and post-treatment measurements were made under similar pressure conditions. For this stimulation test the increase in permeability due to treatment was about 207%.

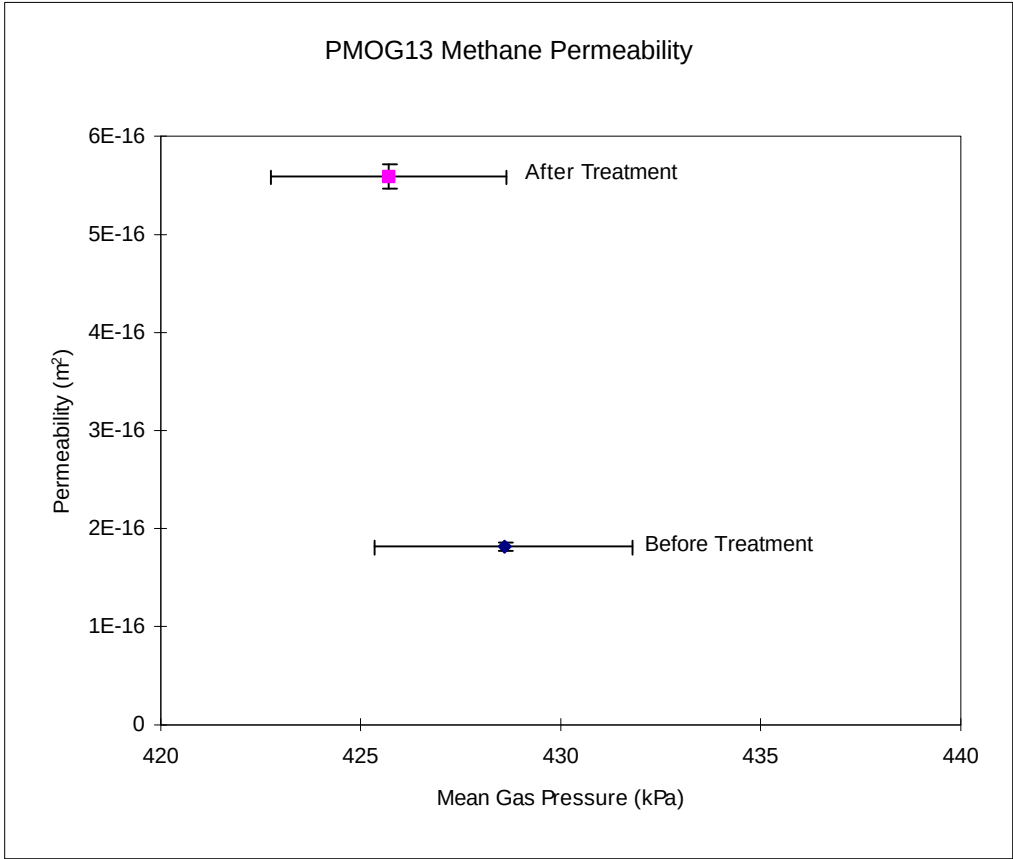


Figure 3-23: PMOG13 Methane Permeability.

3.3.2.9 Sample PMOG16

The sample identified as PMOG16 was obtained from the second shipment of core delivered by Pine Mountain Oil and Gas. A fracture had occurred in a vitrain layer at one end of the sample, which was repaired with epoxy resin as described above. This repair allowed keeping a larger portion of the sample than if the ends had been reworked following disposal of the fractured piece.

This sample exhibited an initial permeability of $2.05 \times 10^{-17} \pm 5.57 \times 10^{-19} \text{ m}^2$ ($2.08 \times 10^{-2} \pm 5.6 \times 10^{-4} \text{ mD}$). Following treatment with liquid carbon dioxide the sample became completely impermeable, within the bounds of the measurement techniques available. The affect behind this result is not known, the sample did not appear to show any visible signs of sealing within the sample itself or in the ancillaries of the sample package. Rather than disposing of this sample a series of pressure decay traces were taken of the carbon dioxide venting process. These results will be discussed in section 3.3.3 below.

3.3.2.10 Sample PMOG17

The sample identified as PMOG17 was taken from the second lot of core delivered by Pine Mountain Oil and Gas. No repair work was necessary to this sample, and no distinguishing characteristics of mention were observed.

Two separate measurement series were made of the initial permeability, these indicated permeabilities of $2.71 \times 10^{-17} \pm 2.49 \times 10^{-19} \text{ m}^2$ ($2.7 \times 10^{-2} \pm 2.5 \times 10^{-4} \text{ mD}$) and $2.85 \times 10^{-17} \pm 5.61 \times 10^{-19} \text{ m}^2$ ($2.9 \times 10^{-2} \pm 5.7 \times 10^{-4} \text{ mD}$). These two measurements were separated by about 19 hours, in this intervening time the sample remained under confinement and with methane gas pressure at the inlet pressure. A comparison of the two pre-treatment permeabilities shows that there is a slight increase in permeability at the higher mean gas pressure. This effect would be expected in accordance with the modified Klinkenberg equation (McPherson 1993) which accounts for compression of the coal matrix due to the pore pressure of the gas. However, to be consistent with the expected plastic, time dependent, deformation of the sample (Harpalani and McPherson 1986) the expectation should be that the later permeability measurement should be lower than the earlier. Based on the two expected responses and that observed in the laboratory, on this sample as well as others in this series, it appears that time dependent behavior is minimal in these samples and that in the experimental pressure range the permeability measured is relatively insensitive to the mean gas pressure.

Two series of measurements taken following treatment indicated a permeability of $5.01 \times 10^{-17} \pm 1.40 \times 10^{-18} \text{ m}^2$ ($5.1 \times 10^{-2} \pm 1.4 \times 10^{-3} \text{ mD}$) and $5.17 \times 10^{-17} \pm 1.06 \times 10^{-18} \text{ m}^2$ ($5.2 \times 10^{-2} \pm 1.1 \times 10^{-3} \text{ mD}$).

The time interval between these two sets of measurements was 3 hours between the end of the first and the beginning of the second. During this period of the sample remained under confinement with gas flowing through at the differential pressure used for permeability measurements. There is about a 2 percent difference between mean gas pressures of these two data sets, however, there is not overlap in the ± 1 standard deviation error bars. This indicates that the two data sets should be considered independent in the mean gas pressure. The measured permeability of the second data set, at the lower mean gas pressure, is slightly higher than the first. The mean permeability of these two sets are at the extreme of the other's ± 1 standard deviation error bars, this would tend to indicate that there is similarity in the measured permeability that may be independent of the mean gas pressure. Another explanation for the higher, though only slightly, permeability in the later measurement series is that in the passage of time any carbon dioxide that may have adsorbed to the coal could have become dislodged allowing for larger permeability paths for the methane. There appears to be little evidence available to support the preceding conclusion, therefore the basic assumption that there is no significant difference in these permeability measurements is valid.

These results are shown in figure 3-24. Overall an increase in permeability of 83% appears to be attributable to the treatment with carbon dioxide.

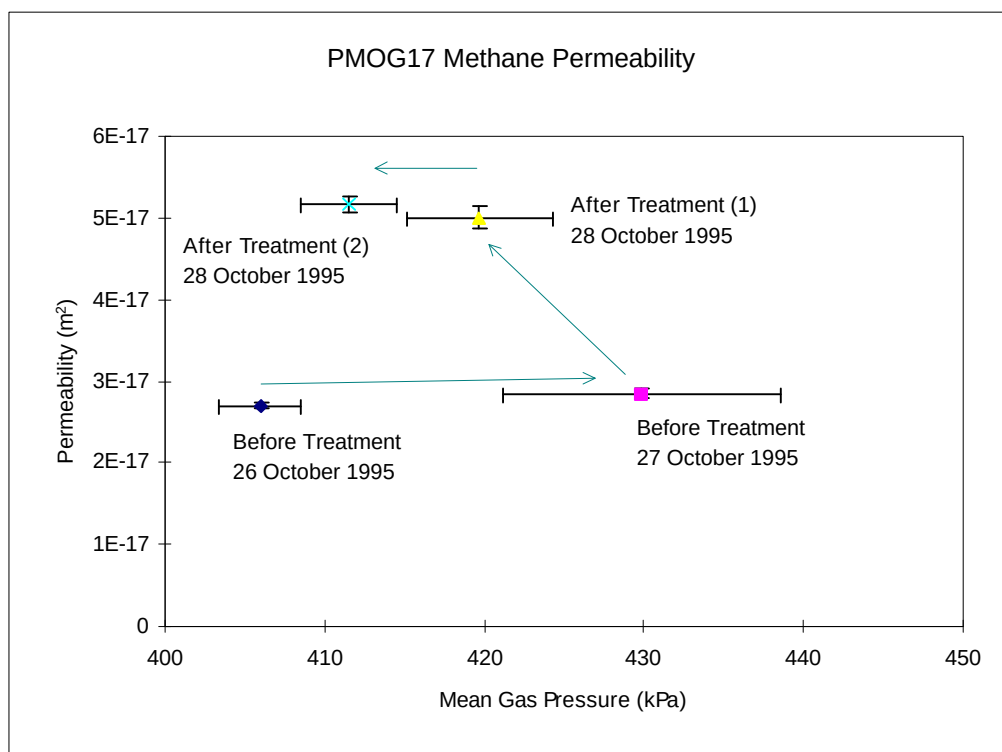


Figure 3-24: PMOG17 Methane Permeability.

3.3.3 Other Samples of Interest

The sample PMOG16 is an interesting case, which does not fit into the treatment categories discussed above. The attempt to treat this sample with liquid carbon dioxide left the sample unable to flow gas. As mentioned in section 3.3.2.9, this sample was initially permeable to methane and did not appear to have any distinguishing characteristic that would lead to a conclusion that the sample was flawed. As measured, the initial permeability was the second lowest measured, relative to the other coal samples. Only sample PMOG01 exhibited an initial permeability lower than PMOG16.

Following the first treatment, from which the zero flow through condition resulted, this sample was utilized to observe the pressure and temperature response as the carbon dioxide was released from the sample. A typical release of carbon dioxide, from the liquid state, is shown in figure 3-25, and from the gaseous state in figure 3-26. For these series of tests both of the source bottles, liquid and gas phase carbon dioxide, were liquid phase in the bottle. The liquid was delivered through a “dip-tube” that extended towards the bottom of the bottle, the gas was delivered through a conventional valve that opened to the bottle head space. Since the carbon dioxide was actually stored as a liquid the delivery pressure of both the gas and liquid was equal to the vapor pressure of the gas at the ambient temperature.

3.3.3.1 Liquid Carbon Dioxide

Figure 3-25 shows a depressurization and pressurization cycle in which liquid carbon dioxide is released from the sample and then readmitted to the sample. Beginning at time zero seconds the pressure is released from this sample, the pressure decays at a fairly constant rate for about 90 seconds. During this period of time the sample temperature (measured at the sample/Hoek cell gland interface) stays constant for the first ten seconds, then falls, about 4°C over 15 seconds, then begins to rise eventually leveling off about 3°C cooler than the starting temperature. When the sample is pressurized, with liquid carbon dioxide, about 110 seconds in figure 3-25, pressure rises quickly back to ambient vapor pressure of the source bottle. Concomitant with the sample pressurization a response is observed in the measured sample temperature. This temperature rises briefly, followed by a noticeable downward spike which returns upward to slightly higher than the starting temperature (at time zero).

One of the most striking differences between these two figures is the downward spike that occurs in sample temperature as the liquid carbon dioxide is let into the sample. This is visible in figure 3-25, at a time of about 110 seconds. This condition was observed in all of the cases where the liquid state was let into the sample. The most likely explanation for this phenomenon is the

following: (1) As the sample is pressurized, carbon dioxide as a gas and at ambient temperature flows through the sample to the thermocouple causing the temperature to rise. (2) The flow of additional carbon dioxide is the result of boiling of the liquid being transported through the injection lines, this cools the mass (solid and gas) as the additional gas reaches the thermocouple. (3) The arrival of the liquid state, at nearly ambient temperature causes the temperature to rise. The reduced condition of the sample temperature, relative to ambient is due to the repeated action of releasing the carbon dioxide from the sample, causing cooling of the Hoek cell surrounding the sample.

3.3.3.2 Gaseous Carbon Dioxide

Figure 3-26 illustrates the pressure and temperature responses measured in this sample that are associated with the release of gas phase carbon dioxide from the sample. This case begins with a very rapid decrease of the pore pressure of gas phase carbon dioxide in the sample, occurring in a period of time of less than twenty seconds. The temperature of the sample begins to drop simultaneously with the pressure. The sample temperature reaches a minimum, about 6°C cooler than the starting point, about 10 seconds after the pressure begins to drop. Even while the pressure is still falling the temperature begins to rise, eventually coming to rest about 3°C cooler than the initial temperature. Upon readmission of gaseous carbon dioxide to the sample pressure quickly rises back to the ambient vapor pressure of the source bottle. The temperature increases uniformly after the gas pressure is increased. Again, the temperature after pressurization is slightly higher than the initial temperature.

The continuous upward trend in the sample temperature during the injection of gaseous carbon dioxide, figure 3-26, is explainable in the following manner: (1) The carbon dioxide is being drawn from a vent tube from the compressed gas state and is initially at ambient temperature. (2) The gas expands momentarily while the gas pressure in the sample is still below that of the gas in the cylinder, due to the rate at which pressurization occurs this condition is not observed in the temperature log. (3) The gas initially released into the sample is adiabatically compressed by the subsequent flow, thus arriving back at its original temperature.

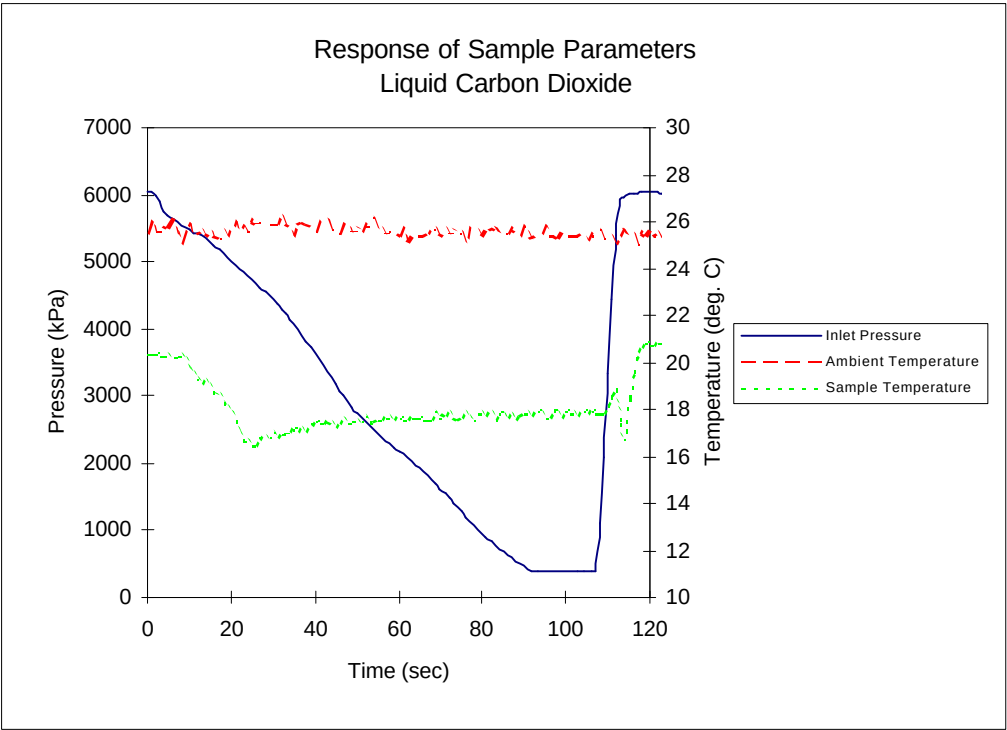


Figure 3-25: Response of Parameters to Liquid Carbon Dioxide.

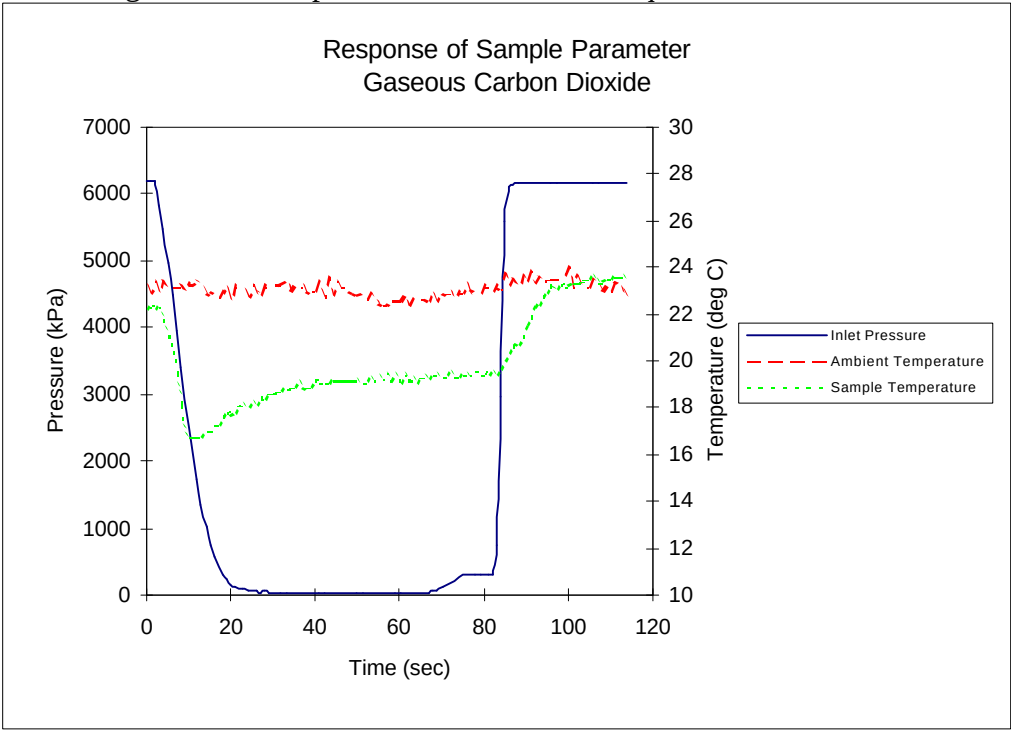


Figure 3-26: Response of Parameters to Gaseous Carbon Dioxide.

3.4 Discussion

As was addressed in the Basic Theory section, above, there are several factors that play into the measurements of permeability that have been assessed in this chapter. This section seeks to place these effects into perspective, relative to the data that has been collected as a part of these experiments.

3.4.1 Disking Phenomenon

To some degree, all of the coal samples exhibited a “disking” of the sample as a result of the testing process. In most of the cases it was restricted to the interface where the coal is bonded to the resin caps, although in some instances it did occur some distance from the sample ends. It appears to be that the coal split near the coal/resin interface as a result of stress concentration in this region. None of the Sandstone samples exhibited the disking response. This tends to imply that it was a factor of the coal and not of the sample itself. Further, this also indicates that the disking did not result from bending of the sample, either during the loading process or as an effect of non-parallel end faces.

In testing conditions, disking occurs due to differences in the modulus of elasticity between the sample and the loading platen. Under this influence the sample experiences excess compressive or tensile loads at the sample ends⁷. Excess differential movement within the sample, under a load, could cause separation on planes of weakness. This would be a predominant effect in the coal, which naturally exhibits planes of weakness between the various laminated layers.

3.4.2 Effect of Sample Make Up

One concern that can be raised is based on the effect that the make-up of the sample may have on the change in permeability due to the initial liquid carbon dioxide treatment. Table 3-6 lists the samples in ascending order of change in permeability, following the first treatment where multiple treatments were applied.

⁷ Personal Conversation; Dr. Mario Karfakis, Virginia Tech, 7 February 1997.

Table 3-6: Ordered Permeability Change

Sample	Permeability Change (%)
PMOG01	-75
PMOG05	30
PMOG11	36
PMOG12	46
PMOG17	83
PMOGS	117
PMOG09	156
PMOG10	164
PMOG13	207

Notice that there is a significant variation in the degree of enhancement obtained. A visual comparison of the samples does not tend to suggest any consistent difference in the samples that might lead to better or worse enhancements due to treatment. In the tests conducted it is difficult to weigh any significance to observations regarding the individual samples and possible sample classes to measured changes in permeability. This fact is based on the same principle discussed earlier regarding the limited number of samples that have been addressed. See section 3.2.4.2.

3.4.3 Comparison of Permeability Measured in Axial and Radial Samples

The measured permeability for the axial flow sandstone samples show a consistent value of between 4.0 and $6.0 * 10^{-14} \text{ m}^2$. Samples SSAXI1 and SSAXI2 appear to exhibit a downward trend in permeability as the mean gas pressure is increased. Sample SSAXI3 does not appear to show this trend. The permeabilities measured in these samples was consistent with the expected results accounting for the Klinkenberg effect. This is shown in figures 3-9c and d; 3-10c and d; and 3-11c and d.

The measured permeability for the radial flow sandstone samples show a wide range of values ($3.66 * 10^{-15} \text{ m}^2$ to $5.36 * 10^{-14} \text{ m}^2$). These data, however, show a fairly consistent downward trend in permeability as the mean gas pressure increases. As with the axial flow samples, the radial flow samples tested over a range of mean gas pressures also exhibited behavior consistent with the Klinkenberg effect, see figures 3-13c, 3-14b and c; and 3-15b and c.

The depressed permeability that was generally observed in the radial flow configuration samples may be due to clogging of the pore structure near the drilled borehole. Such a condition would create a region of low permeability, relative to the remainder of the sample, through which all of the gas would have to flow. In well hole terminology this effect is referred to as the “skin.”

Another condition that may have introduced differences between the similar axial and radial samples is the arrangement under which the core samples were obtained. That is, the three axial samples were all taken from the same bedding planes, whereas the radial flow samples were taken from a single core cross cutting different bedding planes. This case could explain differences between the measured permeability of the radially configured samples. Furthermore, since the samples were taken from a fairly uniform horizon of sandstone the spread of measured permeability within an order of magnitude may not be unexpected. Such a case leads to good confidence that the radial permeability measurement technique developed for this research produces reasonable results compared to the conventional approach.

3.4.4 Parametric Effects

The standard approach taken to determine the permeability of each of the samples, prior to and following treatment was to take series measurements of the sample temperature, inlet gas pressure, differential pressure, and flow rate at intervals of about 5 minutes. For each of the measurement sets the permeability was computed as described in section 3.1.1. These individual measurements were then averaged to determine the reported permeability for the sample state. In this way the reported permeability is the mean of numerous measurements, rather than a single point evaluation. This approach was taken so that variations induced by fluctuations in the parameters would be minimized. A brief discussion of the measured parameters and errors that may be induced is given in the following paragraphs.

Table 3-7: Results of Permeability Testing

Sample	Condition	Permeability			
		k (m ²)	k_T (m ²)	k_P (m ²)	k_M (m ²)
PMOG01		9.31×10^{-18}	9.31×10^{-18}	9.32×10^{-18}	9.32×10^{-18}
		5.98×10^{-19}	5.92×10^{-19}	6.56×10^{-19}	1.25×10^{-19}
		2.38×10^{-18}	2.36×10^{-18}	2.38×10^{-18}	2.38×10^{-18}
		1.76×10^{-19}	1.75×10^{-19}	1.63×10^{-19}	4.45×10^{-20}
PMOG05		5.79×10^{-16}	5.79×10^{-16}	5.79×10^{-16}	5.79×10^{-16}
		3.93×10^{-17}	3.91×10^{-17}	3.81×10^{-17}	6.88×10^{-17}
		7.71×10^{-16}	7.71×10^{-16}	7.71×10^{-16}	7.71×10^{-16}
		5.19×10^{-17}	5.3×10^{-17}	4.78×10^{-17}	9.99×10^{-18}
		7.40×10^{-16}	7.40×10^{-16}	7.40×10^{-16}	7.40×10^{-16}
		2.83×10^{-17}	2.8×10^{-17}	2.00×10^{-17}	1.57×10^{-17}
PMOG09		1.49×10^{-15}	1.49×10^{-15}	1.49×10^{-15}	1.49×10^{-15}
		3.08×10^{-17}	3.08×10^{-17}	3.26×10^{-17}	7.34×10^{-18}
		3.81×10^{-15}	3.81×10^{-15}	3.81×10^{-15}	3.81×10^{-15}
		2.65×10^{-16}	2.67×10^{-16}	2.63×10^{-16}	2.53×10^{-17}
PMOG10		4.65×10^{-16}	4.65×10^{-16}	4.65×10^{-16}	4.65×10^{-16}
		5.66×10^{-18}	5.66×10^{-18}	5.11×10^{-18}	3.84×10^{-18}
		4.38×10^{-16}	4.38×10^{-16}	4.38×10^{-16}	4.38×10^{-16}
		5.45×10^{-18}	4.99×10^{-18}	4.57×10^{-18}	3.33×10^{-18}
		1.20×10^{-15}	1.20×10^{-15}	1.20×10^{-15}	1.20×10^{-15}
		2.55×10^{-17}	2.54×10^{-17}	2.43×10^{-17}	1.23×10^{-17}

k = Permeability based on all parameters varying.

k_T = Permeability based on holding temperature fixed at series average.

k_P = Permeability based on holding pressures fixed at series average.

k_M = Permeability based on holding mass flow fixed at series average.

Table 3-7: Results of Permeability Tests (Con't)

Sample	Condition	Permeability			
		$k \text{ (m}^2\text{)}$	$k_T \text{ (m}^2\text{)}$	$k_P \text{ (m}^2\text{)}$	$k_M \text{ (m}^2\text{)}$
PMOG11		$2.47*10^{-16}$	$2.47*10^{-16}$	$2.47*10^{-16}$	$2.47*10^{-16}$
		$2.50*10^{-18}$	$2.56*10^{-18}$	$3.28*10^{-18}$	$1.89*10^{-18}$
		$3.38*10^{-16}$	$3.38*10^{-16}$	$3.38*10^{-16}$	$3.38*10^{-16}$
		$3.76*10^{-18}$	$3.77*10^{-18}$	$3.68*10^{-18}$	$2.66*10^{-18}$
		$3.35*10^{-16}$	$3.35*10^{-16}$	$3.35*10^{-16}$	$3.35*10^{-16}$
		$3.24*10^{-18}$	$3.21*10^{-18}$	$3.48*10^{-18}$	$1.54*10^{-18}$
		$2.53*10^{-16}$	$2.53*10^{-16}$	$2.53*10^{-16}$	$2.53*10^{-16}$
		$6.51*10^{-18}$	$6.58*10^{-18}$	$8.26*10^{-18}$	$4.26*10^{-18}$
		$2.57*10^{-16}$	$2.57*10^{-16}$	$2.57*10^{-16}$	$2.57*10^{-16}$
		$2.32*10^{-18}$	$2.35*10^{-18}$	$2.40*10^{-18}$	$9.70*10^{-18}$
PMOG12		$3.75*10^{-16}$	$3.75*10^{-16}$	$3.75*10^{-16}$	$3.75*10^{-16}$
		$4.90*10^{-18}$	$4.71*10^{-18}$	$5.01*10^{-18}$	$6.98*10^{-18}$
		$5.49*10^{-16}$	$5.49*10^{-16}$	$5.49*10^{-16}$	$5.49*10^{-16}$
		$7.48*10^{-18}$	$7.47*10^{-18}$	$7.78*10^{-18}$	$2.89*10^{-18}$
PMOG13		$1.82*10^{-16}$	$1.82*10^{-16}$	$1.82*10^{-16}$	$1.82*10^{-16}$
		$3.62*10^{-18}$	$3.61*10^{-18}$	$3.80*10^{-18}$	$1.42*10^{-18}$
		$5.59*10^{-16}$	$5.59*10^{-16}$	$5.59*10^{-16}$	$5.59*10^{-16}$
		$1.22*10^{-17}$	$1.23*10^{-17}$	$1.05*10^{-17}$	$3.84*10^{-18}$

k = Permeability based on all parameters varying.

k_T = Permeability based on holding temperature fixed at series average.

k_P = Permeability based on holding pressures fixed at series average.

k_M = Permeability based on holding mass flow fixed at series average.

Table 3-7: Results of Permeability Tests (Con't)

Sample	Condition	Permeability			
		k (m ²)	k_T	k_p (m ²)	k_M (m ²)
PMOG17		2.71×10^{-17}	2.71×10^{-17}	2.71×10^{-17}	2.71×10^{-17}
		2.49×10^{-19}	2.51×10^{-19}	1.94×10^{-19}	2.65×10^{-19}
		2.85×10^{-17}	2.85×10^{-17}	2.85×10^{-17}	2.85×10^{-17}
		5.61×10^{-19}	5.59×10^{-19}	2.91×10^{-19}	6.50×10^{-19}
		5.01×10^{-17}	5.01×10^{-17}	5.01×10^{-17}	5.01×10^{-17}
		1.40×10^{-18}	1.37×10^{-18}	1.48×10^{-18}	5.51×10^{-19}
		5.17×10^{-17}	5.17×10^{-17}	5.17×10^{-17}	5.17×10^{-17}
		1.06×10^{-18}	1.06×10^{-18}	1.07×10^{-18}	3.56×10^{-19}
SSRAD1		7.29×10^{-15}	7.29×10^{-15}	7.29×10^{-15}	7.29×10^{-15}
		4.77×10^{-16}	4.73×10^{-16}	5.02×10^{-16}	6.85×10^{-17}
SSRAD2		3.66×10^{-15}	3.66×10^{-15}	3.66×10^{-15}	3.66×10^{-15}
		1.24×10^{-16}	1.24×10^{-16}	1.23×10^{-16}	2.11×10^{-17}
		6.26×10^{-15}	6.26×10^{-15}	6.26×10^{-15}	6.26×10^{-15}
		3.71×10^{-16}	3.70×10^{-16}	3.94×10^{-16}	4.25×10^{-17}
SSRAD3		5.36×10^{-14}	5.36×10^{-14}	5.36×10^{-14}	5.36×10^{-14}
		1.19×10^{-13}	1.19×10^{-13}	1.19×10^{-13}	1.19×10^{-13}
SSRAD4	580 kPa, 25 kPa	1.40×10^{-14}	1.40×10^{-14}	1.40×10^{-14}	1.40×10^{-14}
		1.83×10^{-15}	1.84×10^{-15}	2.1×10^{-16}	1.91×10^{-15}
		2.40×10^{-14}	2.40×10^{-14}	2.40×10^{-14}	2.40×10^{-14}
		1.26×10^{-15}	1.26×10^{-15}	7.84×10^{-16}	5.07×10^{-16}

k = Permeability based on all parameters varying.

k_T = Permeability based on holding temperature fixed at series average.

k_p = Permeability based on holding pressures fixed at series average.

k_M = Permeability based on holding mass flow fixed at series average.

3.4.4.1 Effect of Variation of Temperature

Perhaps one of the most obvious areas for the introduction of error into these experiments was in the variation of sample temperature. The Hoek cell was situated in an open laboratory directly exposed to the room air. This condition permitted the temperature of the sample to fluctuate as the room temperature changed, due to the air conditioning system, opening and closing of doors and windows, etc. Permeability is proportional to the absolute temperature at which the observation is made. The appropriate units of measurement are absolute temperature, therefore, in the vicinity of 25°C a 1 degree centigrade change represents a change temperature change of about 0.3 percent.

As mentioned previously, each of the reported permeability measurements was based on a number of parametric measurements. To this end it is possible to assess the effect of temperature variations in the data by comparing the raw data measurements to those in which the incident temperature has been replaced with the series average temperature. The expectation is that if the initial, raw data population represents the actual conditions then replacement of one of the parameters, temperature, by a population average should not change the results of the evaluation. The results of this substitution are listed in table 3-7. All of the average temperature permeabilities are equal to the series average permeabilities. Compare the permeabilities in column k to those in column k_T . Additionally, the standard deviations of these averages are very close.

Based upon the above evaluation it appears that the variations in the recorded temperature do not significantly affect the computed permeability for the samples tested.

3.4.4.2 Effect of Variation of Mean Gas Pressure

As illustrated in the permeability equation, permeability is inversely proportional to the difference of the squares of the pressure across the sample.

Variations in the measured mean gas pressure are likely to have occurred due to one of two conditions. The first is drift in the zero point of the pressure transducer during the period of a test sequence. The second is the mechanical regulator that controlled the flow of gas from the bottle to the sample.

The impact of zero drift was accounted for, and corrected, by recording the zero (atmospheric) pressure indications at both the start and end of a test series. If substantial zero drift had occurred the data were corrected to reflect this condition.

Once the instrument drift had been corrected out of the gas pressure measurements the variability remaining was associated with the mechanical regulator. The impact of this variability on the permeability measurement was assessed by assuming that all of the gas was delivered to the sample at the average pressure for that series. The permeability at each measurement time was assessed at the mean pressure for the respective series, then the mean permeability was determined. As the column k_p shows, in table 3-7, the variations in the measure pressure had no effect on the determination of the permeability. Differences in the standard deviations of the permeability are consistent within each sample; however, the standard deviation of the constant pressure permeability are not uniformly higher or lower than that determined from the total data permeability, column k.

3.4.4.3 Effect of Variation of Mass Flow Rate

For the permeability tests conducted the mass flow rate was a measured parameter. The permeability equation indicates that the permeability is proportional to the mass flow rate. Along with the gas pressure and the sample temperature this was one of the factors in the determination of permeability that was likely to vary during the collection of a data series. The potential sources of variation in this parameter are real changes in the driving pressure, changes in temperature (both of the gas and of the sample), and measurement error. Sources of error in the driving pressure and temperature have been discussed in the relevant sections, above.

Sources of measurement error can be attributed to operator induced errors when using the automatic bubble tube flow meter. This device required that the operator squeeze the soap solution past the gas inlet to form a bubble. In fairly high flow rate conditions a series of bubbles would form, some of which could be sent past the sensor at a higher than actual speed due to displacement of the water in the bulb. It is also possible that the soap bubble was drawn backwards past the optical sensor timers as the solution bulb was released. To minimize the effects of operation of this instrument it was necessary to observe each of the flow rate measurements, only those that appeared to be “clean” were recorded and several observations were made at each time point to ensure that the measurement was consistent.

For those flow rate measurements made with by displacing water in a graduated cylinder the sources of error are also observer related. When making these measurements it was important that the observer start timing as soon as gas began to flow into the cylinder and to stop timing as soon as the gas had filled the measured volume. While slight errors in timing of these events have little impact on low flow rate conditions, at high flow rates slight discrepancies can induce fairly significant errors. For instance, for a 250 ml fixed volume, a tenth of a second error at 2 liters per minute represents about 3 milli-liters, where as the same error at 5 liters per minute represents about 8 mill-liters. Again, as with the bubble tube meter, a key factor in making the measurements was looking for consistency amongst the related data.

Another aspect to consider here is the solubility of methane in water, and whether this represents a significant source of error. Standard data⁸ for atmospheric pressure and room temperature (298.15 K) lists a mole fraction solubility of 2.552×10^{-5} in water. This indicates that at saturation 5.7 mg of methane would be dissolved in the 250 mg of water displaced from the graduated cylinder. The nominal amount of methane gas collected in the cylinder was 162.3 mg. At saturation the dissolved methane would represent 3.3 percent of the total, an value not altogether insignificant. It must be remembered here that the transport of methane from a gaseous to dissolved phase is a diffusive process requiring a finite period of time.

The transport of methane from gas to dissolved phase occurs as a result of diffusion of the gas into and through the water, as well as convective mixing as the water is displaced by the gas. It appears that the controlling rate will be that of the diffusion of the dissolved methane through the liquid water. The diffusion coefficient of methane in water is listed⁹ as $1.49 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ at 25° C. It appears that the diffusion through water is on the order of 10000 times smaller than that of the diffusion through air. This tends to indicate that the “loss” of methane to the water by molecular transport is relatively insignificant with respect to the time period of exposure.

Another point to consider is the presence of water vapor in the collected methane gas. At 25° C the partial pressure of saturated water vapor is 3.169 kPa¹⁰. Considering the collected gas to be saturated with respect to water, water vapor accounts for just over 3 percent of the collected gas. Coincidentally, this is approximately the same amount of methane that would be lost due to saturation of the liquid water with methane gas. Based on this evaluation, it is again possible to assume that the mutual transport of water and methane between the present phases is not a significant factor in the data that was collected.

The calculated permeabilities based on the average mass flow rate are listed in column k_M in table 3-7. As with the other comparisons, above, the average permeability computed in this manner is equal to that computed from each of the specific observations. Utilizing the average mass flow rate, however, seems to produce a smaller standard deviation, indicating a tighter grouping of the sample population.

3.4.5 Effect of Liquid Carbon Dioxide Treatment

Overall the liquid carbon dioxide treatment appears to have net positive effect on the permeability of the samples tested. The initial theory, as discussed above, indicated that this treatment would increase the permeability by interacting with the structure of the coal. If this were the only effect

⁸ Gevantman, L. H. (1996) *CRC Handbook of Chemistry and Physics*, 77th Edition, Lide, D. R (Editor), CRC Press, pp. 6-3 to 6-6.

⁹ *ibid.* p. 6-220.

¹⁰ Van Wylen and Sonntag 1986, p. 635.

then the sandstone sample should not have produced significant increases in permeability as a result of treatment. Figure 3-27 shows the effect of the liquid carbon dioxide treatment. In this figure the x-axis represents the permeability prior to treatment and the y-axis the permeability following treatment. Thus a point plotted above the baseline (slope = 1), as shown, indicates a net increase in permeability, conversely a point plotted below this line indicates a net decrease in permeability.

Independent data sets are plotted for three cases: 1) Initial treatment of coal samples, 2) treatment of radial sandstone samples, and 3) treatment of axial sandstone samples. An additional data set is plotted for the changes associated with the second treatment of samples PMOG05 and PMOG11; as shown these points refer to the change between the first and second treatments, rather than between the initial and final permeability.

Both the coal and the sandstone samples, tested in the radial configuration, experienced permeability increases on the same order of magnitude, about 82% and 85% respectively. Since the sandstone was expected to be inert to the carbon dioxide, it is possible to ascribe most, or all, of the enhanced permeability to cleaning of the internal surface of the borehole in the center of the sample. Such action is similar to the approach taken in the open hole cavity completion technique in coalbed methane wells.

It may be that without significant shut-in time the chemical effects which could be gained from the injection of liquid carbon dioxide are not possible.

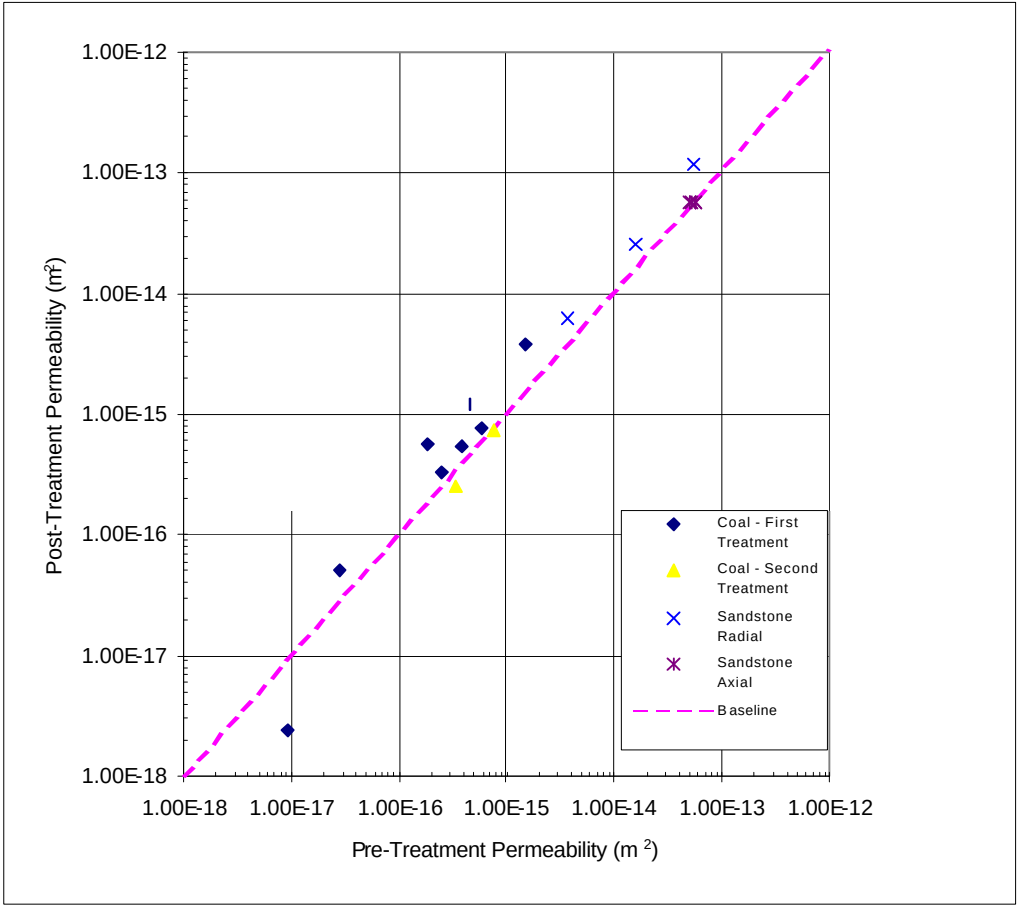


Figure 3-27: General Comparison Between Pre-Treatment and Post-Treatment Permeabilities for Sandstone and Coal Samples.

3.4.6 Effect of the Radial Flow Sample Design

The basic assumption in this exercise has been that the design of the radial flow samples does not significantly impact the measured state of the sample. In this section two elements of the sample design will be considered, flow in the annular region between the sample and the Hoek cell sheath, and flow in the vents from the sample to the lower platen.

The first point to consider is the flow in the annulus. The main assumptions here are that the flow is predominantly in the axial direction, that there is no rotation of flow in the annulus, and that the region is of uniform cross-section. The annulus was filled with a uniformly graded sand that was screened between 40 and 70 mesh, assuming a d_{50} of 50 mesh, the Shepherd method can be applied to estimate the permeability of this region. The Shepherd method equation is, again:

$$k = d_{50}^j \frac{m C_s}{r g}$$

The parameters associated with the estimation of the annulus permeability are listed in table 3-8, below.

Table 3-8: Estimation of Sample Annulus Permeability by Shepherd's Method

Parameter	Value
Mean Grain Size	$d_{50} \approx 0.297 \text{ mm}$
Effective Grain Size	$d_{10} \approx 0.240 \text{ mm}$
Shepherd Index	$j = 2$
Shepherd Coefficient	$C_s = 0.1411$
Gravity	$g = 9.81 \text{ m/s}^2$
Fluid Density	$\rho = 3.86 \text{ kg/m}^3$
Fluid Viscosity	$\mu = 1.1 \cdot 10^{-5} \text{ Ns/m}^2$
Permeability	
$P_o = 100000 \text{ Pa}$	$k \approx 2.167 \cdot 10^{-8} \text{ m}^2$
$P_o = 800000 \text{ Pa}$	$k \approx 2.74 \cdot 10^{-9} \text{ m}^2$

Consider the case in which all of the gas flows half of the length of the sample. Then for a gas flow rate of $5.5 \cdot 10^{-5} \text{ kg/s}$ (5000 ml/min) at 100 kPa the estimated pressure loss in the annulus is 6.35 Pa. This flow condition results in a Reynold's number of about 6.9. Based upon the evaluation presented by Bear (1972) Darcy's law is valid for Reynolds numbers not exceeding 1 to 10. Since such a flow condition is at the upper limit of those measured in the laboratory, it can be assumed that the flow in the annular region of the radial samples is laminar.

Considering the sandstone samples, where relatively small gradients were used compared to coal samples, with a flow rate of 5.5×10^{-5} kg/s (5000 ml/min) at a pressure of 800 kPa the pressure drop in the annulus can be estimated as 6.3 Pa. The corresponding Reynold's number is, 6.9. Again, the flow rate chosen for this example exceeds the vast majority of observed values in the laboratory, indicating that the validity of Darcy's law assumption is fair.

Turning, now, to the vent holes at the bottom of the sample their effect can be analyzed in the following manner. Assume a flow rate of 5.5×10^{-5} kg/s at atmospheric conditions. The parameters associated with this analysis are listed below in table 3-9.

Table 3-9: Parameters for Analysis of the Effect of Vent Holes in Radial Sample.

Parameter	Value
Flow Rate	$Q = 8.5 \times 10^{-5} \text{ m}^3/\text{s}$
Fluid Density	$\rho = 0.65 \text{ kg/m}^3$
Fluid Viscosity	$\mu = 1.1 \times 10^{-5} \text{ Ns/m}^2$
Hole Diameter	$d = 2.1 \text{ mm}$
Hole Length	$l = 17 \text{ mm}$
Velocity	$v = 6.1 \text{ m/s}$
Reynold's Number	$N_{RE} = 750$
Pressure Drop	$\Delta p \approx 8 \text{ Pa}$

The Reynold's number determined in this analysis, 750, is indicative of laminar flow in tubes. The above analysis does not account for the presence of the ultra fine steel wool that was used to prevent drainage of the sand from the annulus of the sample.

As the analyses above indicate, the effect of the sample design is small. Thus it is possible and reasonable to assume that the parameters measured are, for all practical purposes, within the sample being tested, rather than in the hardware and sample systems.

3.4.7 Potential for Carbon Dioxide in Coalbed Methane Stimulation

Prior to assessing the possibility that the injection of liquid carbon dioxide may be a coalbed methane well stimulant a brief review of outstanding patents may be in order. The following table 3-10 lists those patents found in the Virginia Tech data base that may be of significance.

Table 3-10: Patents Applicable to Carbon Dioxide Stimulation of Coalbed Methane Wells

Patent Number (USA)	Title	Applicable
5332036	Method of Recovery of Natural gas from underground coal formations.	Yes
5249627	Method for stimulating methane production from coal seams.	No
5229017	Method of enhancing methane production from coal seams by dewatering.	No
5147111	Cavity induced stimulation method of coal degasification wells.	Yes
5099921	Recovery of methane from solid carbonaceous subterranean formations.	Yes
5085274	Recovery of methane from solid carbonaceous subterranean of formations.	Yes
5014788	Method of increasing the permeability of a coal seam	Yes
5014785	Methane production from carbonaceous subterranean formations	No
4993491	Fracture Stimulation of coal degasification wells	No
4913237	Remedial treatment for coal degas wells	No
4883122	Method of coalbed methane production	No
4756367	Method for producing natural gas from a coal seam	No
4544037	Initiating production of methane from wet coal beds	Yes
4305464	Method for recovering methane from coal seams	Yes
4245699	Method for in-situ recovery of methane from deeply buried coal seams	No
4089374	Producing methane form coal in situ	Yes
4043395	Method for removing methane from coal	Yes

Much of the work involving the injection of carbon dioxide for hydrocarbon stimulation has been centered in the petroleum industry. In this field the carbon dioxide serves a two-fold purpose, that is to maintain reservoir pressure and to act as a solvent for the heavier hydrocarbons. Patents related specifically to the enhancement of petroleum production have not been reviewed for this document.

The most significant of these patents, with respect to this research, is number 5,147,111. This patent has been addressed previously, in the literature review section. To give brief coverage, again, the idea covered by this patent is to inject carbon dioxide, as a liquid, into the coal formation. Once the carbon dioxide has been allowed to permeate into the coal seam the well is depressurized, causing the carbon dioxide to rapidly boil off. The velocity gradients induced by

this action remove coal debris from the formation around the bottom of the well. The final result is a form of the open-hole cavity well completion method. Regarding the general practice of this technique may warrant the commentary of Holditch (1993) regarding the open-hole strategy, which is that outside of the ideal conditions it may be more expensive, with no better results, than the use of the conventional hydraulic fracture methods.

Other patents of keen interest include 5,332,026; 5,099,921; 5,014,785; 4,883,122 and 4,043,395. The first two and last of this list cover the use of a gas, which reacts with the coal, the third and fourth cover the use of an inert gas.

In the abstract to patent 5,332,026 the originators¹¹ describe injection of a more highly adsorbed fluid into the deposit followed by injection of weakly adsorbed fluid. By performing this action, between injection and recovery wells, they expect to liberate and produce the desired product gas. Based upon interpretation of the system described in this patent, it may work in this manner: (1) A gas such as carbon dioxide is injected into the target coal seam. Since carbon dioxide has a higher affinity to the coal than methane, the methane tends to be liberated as the carbon dioxide is captured. (2) A gas such as nitrogen is injected in to the well system to drive the liberated methane towards a production well. (3) At the production well the mixture of the nitrogen and methane are collected and separated. A weakness in the approach suggested by this patent is that the adsorbed carbon dioxide molecules are large enough to block capillaries in the coal matrix, thus inhibiting the flow of methane from the pore structure.

Based upon the abstract to patent 5,099,921 the technique described by the originators¹² is essentially the same as that later described in patent 5,332,026, above.

In the abstract to patent 4,043,395 the originators¹³ describe the injection of a gas containing at least 20 percent carbon dioxide into the coal seam for the purpose of desorbing the methane. The resulting gas mixture would later be drawn from the well. The process repeated until a substantial portion of the original methane had been removed from the seam. This process was intended to support the de-gassing of coal ahead of mining rather than the commercial production of the methane.

The originators¹⁴ of patent 5,014,785 describe a method in which an inert gas is injected into the coal seam through an injection well. The produced gas, a mixture of the inert gas and methane, is

¹¹ Shirley and Ramachandran, United States Patent 5,332,026, *Official Gazette*, United States Department of Commerce, Vol. 1164, July 26, 1994.

¹² Puri, Yee, and Metcalfe, United States Patent 5,099,921, *Official Gazette*, United States Department of Commerce, Vol. 1136, March 31, 1992.

¹³ Every and Dell'Osec, United States Patent 4,043,395, *Official Gazette*, United States Department of Commerce, Vol. 961, August 23, 1977.

¹⁴ Puri and Stein, United States Patent 5,014,785, *Official Gazette*, United States Department of Commerce, Vol. 1126, May 14, 1991.

withdrawn from a second, production well. The application of this technique as been discussed previously by Puri and Yee (1990), they describe that the role of nitrogen is to maintain the original pressure gradient of the production well. A secondary factor is the reduction in methane partial pressure in the fracture system, causing enhanced desorbtion of methane.

In an earlier patent, 4,883,122, the same originators¹⁵ describe the same technique. However, the illustration indicates a single injection well servicing several production wells.

The general background, as well as the results of this research, indicates a role for carbon dioxide in two areas of coalbed methane production. The first is use in the stimulation of open-hole cavity completed wells. This application is based on the consideration that carbon dioxide can be pumped into the well (possibly) as a liquid, then by dropping the well pressure it is converted to a gas and can be released directly to the atmosphere. In this process very high pressure, velocity, and temperature gradients are likely created. The physical properties of carbon dioxide are itemized in appendix A.

The second use for carbon dioxide is based on its higher affinity to the coal surface than methane. In this manner carbon dioxide gas is pumped into an injection well. The carbon dioxide tends to adsorb to the coal, displacing methane. A high pressure gradient is maintained throughout the coal seam, causing the liberated methane to flow toward one or more production wells. The produced gas is likely to contain some carbon dioxide, requiring separation prior to placing the methane in a natural gas pipeline.

Conclusions with be addressed in chapter 8, "General Conclusion of these Studies and Recommendation for Future Study."

¹⁵ Puri and Stein, United States Patent 4,883,122, *Official Gazette*, United States Department of Commerce, Vol. 1108, November 28, 1989.

3.5 Nomenclature

Symbol	Description
<u>Roman</u>	
A	Cross-sectional Area ($\mathbf{L}^2$)
a	Axial Length of Radial Flow ($\mathbf{L}$)
B	Langmuir Constant for Respective Species
b	Density Coefficient, Viscosity Equation ($\mathbf{L}^2/\mathbf{t}$)
C_H	Hazen Method Coefficient
C_S	Shepherd Method Coefficient
d	Porous Medium Matrix Particle Size ($\mathbf{L}$)
d_{10}	Effective Grain Size - 10% ($\mathbf{L}$)
d_{50}	Mean Particle Size - 50% ($\mathbf{L}$)
g	Acceleration of Gravity ($\mathbf{L}/\mathbf{t}^2$)
h	Height of Fluid Column, Pressure Head ($\mathbf{L}$)
j	Shepherd Method Index
K	Hydraulic Conductivity ($\mathbf{L}/\mathbf{t}$)
k	Intrinsic Permeability ($\mathbf{L}^2$)
k_T	Intrinsic Permeability - Temperature Fixed
k_P	Intrinsic Permeability - Pressures Fixed
k_M	Intrinsic Permeability - Mass Flow Rate Fixed
$\mathbf{L}$	Dimensional Argument for Length
l	Distance of Fluid Travel - Length ($\mathbf{L}$)
M	Mass Flow Rate ($\mathbf{M}/\mathbf{t}$)
$\mathbf{M}$	Dimensional Argument for Mass

Symbol	Description
N_{RE}	Reynolds Number (Dimensionless)
P	Pressure or Partial Pressure ($\mathbf{M/Lt^2}$)
P_i	Inlet Pressure ($\mathbf{M/Lt^2}$)
P_{mean}	Mean Gas Pressure ($\mathbf{M/Lt^2}$)
P_o	Outlet Pressure ($\mathbf{M/Lt^2}$)
Q	Volumetric Flow ($\mathbf{L^3/t}$)
R	Gas Constant ($\mathbf{L^2/t^2T}$)
r_b	Radius of Wellbore ($\mathbf{L}$)
r_s	Radius of Sample ($\mathbf{L}$)
$\mathbf{T}$	Dimensional Argument for Temperature
T	Absolute Temperature ($\mathbf{T}$)
$\mathbf{t}$	Dimensional Argument for Time
t	Relative Temperature (degrees Centigrade/Fahrenheit)

Greek

h	Coefficient of Adsorbed Species Interaction
m	Dynamic Viscosity ($\mathbf{M/Lt}$)
m°	Dynamic Viscosity at Reference Temperature ($\mathbf{M/Lt}$)
n	Fluid Bulk Velocity in Porous Medium ($\mathbf{L/t}$)
r	Density ($\mathbf{M/L^3}$)
u	Adsorbed Gas Quantity

Subscript

i	Antecedent Refers to Species i
j	Antecedent Refers to Species j
m	Monolayer Quantity - Langmuir Equation

Chapter 4. Tests of Propellant Characterization

The testing described in this section deals with the characterization of propellants intended for use in the laboratory scale experiments with an eye to characteristics necessary for field application. The use of commercial and available propellants for these experiments is considered since they are readily obtainable in small quantities. When the field tests are designed it may be necessary to consider the use of more specialized industrial propellants. It is likely that a commercial manufacturer will be needed to fabricate the propellant devices to be utilized in the field tests.

4.1 Basic Theory

Some of the principles and previous experiments relevant to tailored-pulse fracturing have been addressed in the introduction and the literature review. For thoroughness, some more detailed coverage of this material is prudent before any investigation into the application of propellants or their study is made. To this end, the basic theory presented below covers confined fracturing fundamentals (4.1.1), hydraulic fracturing (4.1.2), explosive fracturing (4.1.3), and propellant fracturing (4.1.4). In this context, the term explosive refers to high explosives such as nitroglycerin based materials; the term propellant refers to nitrocellulose based materials. A common point of separation between the classes can be made at the speed at which the reaction occurs. In an explosive the flame front through the material is moving faster than the local speed of sound, whereas the flame front in a propellant pack is moving at a velocity lower than the speed of sound.

Some of the material relevant to the study of propellant fracturing, in the laboratory, will be addressed in section 4.1.5 prior to beginning the process of conducting and analyzing the laboratory scale experiments.

4.1.1 Confined Fracturing Fundamentals

Unlike blasting in surface or underground mines, fractures generated to assist the flow of gas from a well are not intended to reach or cause a free face. These will be termed confined explosions. For this reason it is desirable to understand the conditions that cause fractures to develop in the confined rock mass. Only the explosive shock wave and the product gas pressure are at work in a confined detonation (Watson, Benson, and Fillo 1986). In the time frame of the shot duration, there is no venting of the products of the reaction nor is there any noticeable ground movement at the borehole collar.

Consider the homogenous rock mass shown in figure 4-1, with principal stresses σ_x , σ_y , σ_z , as the highest, intermediate, and lowest respectively. When the pressure in the borehole is increased to a level above the tensile strength a fracture will form normal to the lowest principal stress, or on the x-y plane. Since typical conditions are such that the least principal stress in horizontal the developing fractures will be vertical (Fjær et al. 1992).

It is desirable, during the stimulation of wells, to induce as many fractures as possible in the surrounding rock, without crushing the rock immediately adjacent to the borehole. The type of fracturing that is observed can be correlated to the rise time of the pressure in the borehole. The rise time of the pressure will determine the type of fractures obtained and the in-situ stresses determine the orientation of those fractures (Cuderman 1986). When the rise time is long hydraulic fracturing will occur along the principal stress axes, as described above. When the rise time is short explosive fracturing will occur, which may result in crushing and the generation of a stress cage around the borehole, limiting the permeability into the borehole. For a range between the extremes, multiple fracturing will occur beyond the orientations of hydraulic fracturing, but without the extreme damage of explosive fracturing. Base on empirical studies this Multiple Fracture Regime occurs when the rise time t_p is:

$$\frac{p d}{2n_s} < t_p < \frac{8p d}{n_s}$$

where d is the hole diameter, and n_s is the Raleigh surface wave velocity (Cuderman and Northrop 1986). The authors report that this equation holds well for rocks with a Poisson ratio of about 0.3. A graph of the range covered by this equation is shown in Figure 4-2. For application later in this thesis, the pressure rise-time is taken as the time interval required for a pressure to change from 10 to 90 percent of the peak value. The parameters associated with measurement of the pressure pulse are illustrated in figure 4-8.

Illustrated in figure 4-3 are typical expected fracture patterns in a borehole that is arranged parallel to one of the principal stress directions. The hydraulic fracture regime is sensitive to the orientation of the peak principal stress as described above; however, as the pressure rise time

decreases towards the explosive range the sensitivity to this orientation decreases (Cuderman 1986). When it is assumed that the maximum principal stress is parallel to the borehole, hydraulic fracturing will produce a pattern like that shown in figure 4-3a. As the pressure rise time decreases the fracture along the intermediate stress direction will become more pronounced, with smaller fractures forming along a 45 degree direction as the pressure rise time enters the multiple fracture regime, as shown in figure 4-3b. When the pressure rise time becomes explosive crushing occurs in the proximity of the borehole, as shown in figure 4-3c.

When the object of the fracturing is to provide free paths for gas or fluid to flow from the formation to the bore hole the condition shown in figure 4-3b is the most effective. The hydraulic fractures shown in figure 4-3a reach out into the surrounding rock to a limited extent in both depth and direction. The explosive fracturing shown in figure 4-3c has reduced the permeability around the hole and thereby limits the wells potential to produce. The next few sections will look at these three techniques in the order of hydraulic, explosive, and multiple fracturing regimes.

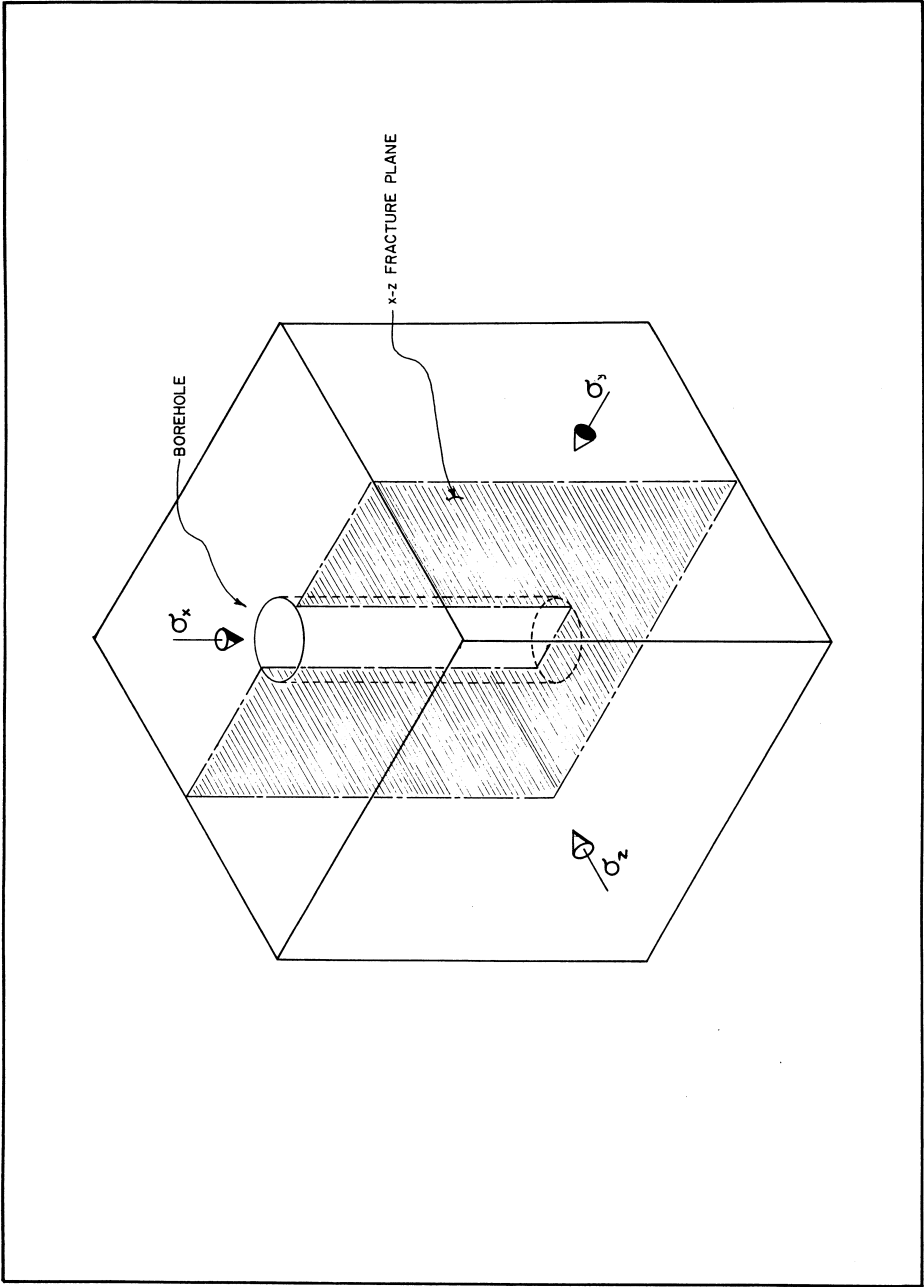


Figure 4-1: Illustration of Tri-axial Cube and Fracture Plane

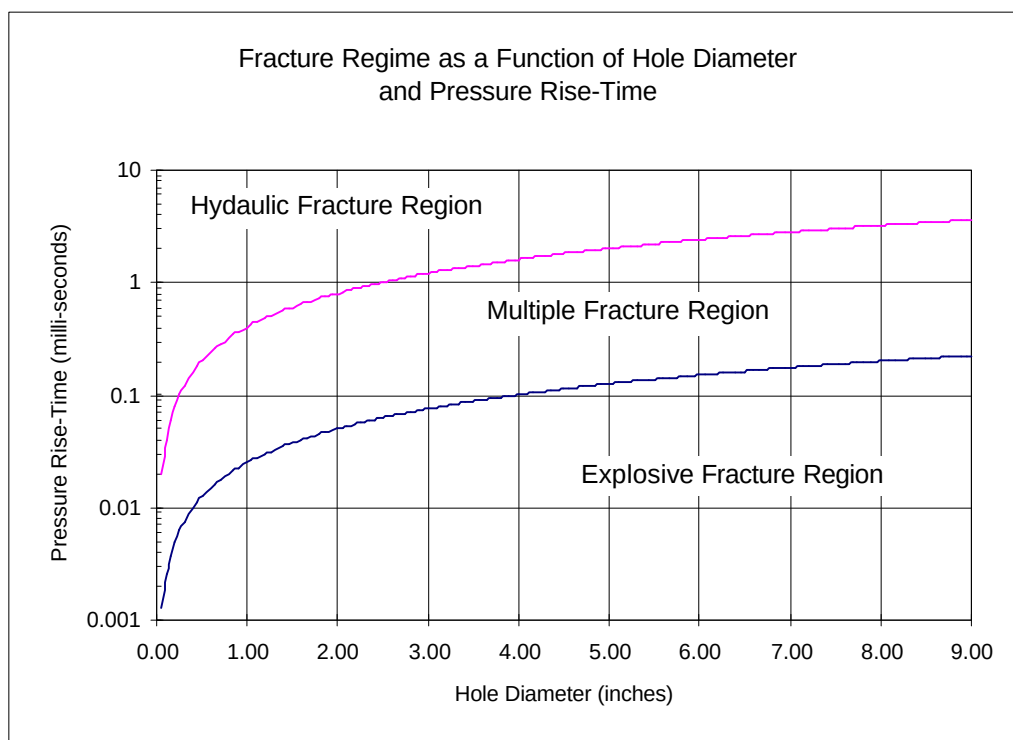


Figure 4-2: Typical Relationship of Fracture Regime as a Function of Hole Diameter and Pressure Rise Time for Sandstone (after: Cuderman and Northrop, 1986).

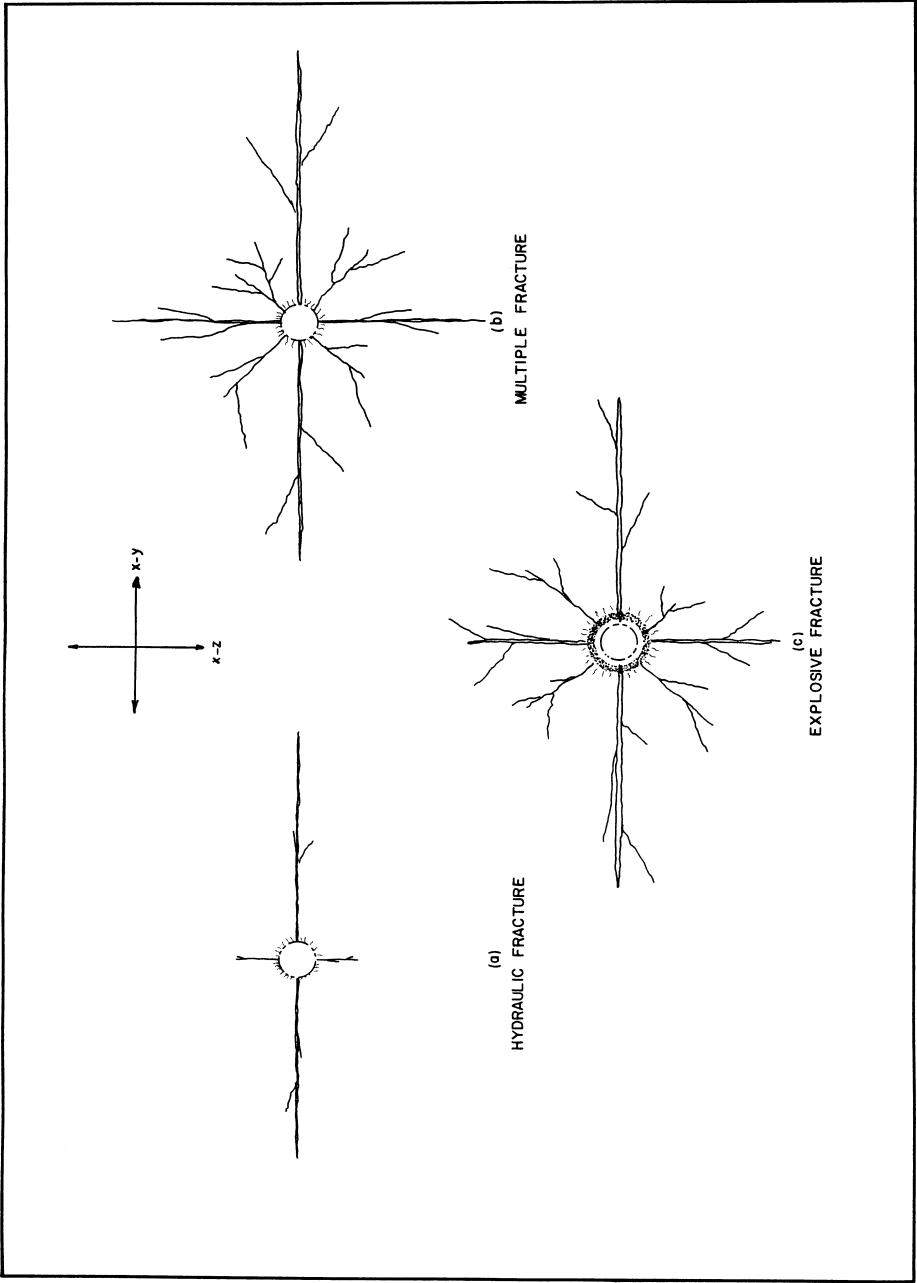


Figure 4-3: Illustration of Three Fracture Regimes (After: Swift and Kusubov 1982).

4.1.2 Hydraulic Fracturing

The technology of hydraulically fracturing a well for stimulation purposes was developed in the Oklahoma and Texas oil fields in the 1950 time frame. The technology advanced quickly as various factors affecting performance were identified. As a result of the complexity of the equipment required to perform a hydraulic fracturing job the cost of the treatment may be equal to the cost of initially drilling the well (Allen and Roberts 1982). This leads to enhanced incentives to get the job done right the first time.

Based upon the work performed by Cuderman and Northrop (1986) and Cuderman (1986) this regime of fracturing occurs when:

$$t_p > \frac{8p d}{n_s}$$

as described above. As the fracture begins to develop and enlarge, a proppant is typically inserted to prevent closure when the pressure is removed from the borehole. Fracturing may be naturally terminated when the pressure losses in the developing fractures overcome the pumping capacity, or when the fracturing rock is further confined by regions of higher tensile strength or higher in-situ stresses (Fjær, et al. 1992).

A typical “hydrofrac” job begins with the determination of the well type and the desired results of the treatment. From these data it is possible to determine if proppants, to hold the fractures open, will be required and what type will be used. The type of fracturing fluid to be employed must also be determined based on the individual characteristics of the well or strata. When the job is performed, the pumps are connected to the well head and the fluid is pumped into the well. It is preferable to monitor the pressure and flow rates down the hole rather than at the well head so that adjustments to pressures and quantities do not have to be made for column head, frictional losses and compression effects. As fracturing is initiated and propagates, the pressure on the well needs to be maintained by the continuous addition of fluid. It is necessary to backflush the fluid out of the well before it is placed into production (Allen and Roberts 1982).

4.1.3 Fracturing with High Explosives

Well stimulation fracturing can be accomplished with the use of high explosives. An explosive charge provides a very quick high-energy pulse. This regime occurs when:

$$t_p < \frac{p d}{n_s}$$

as described by Cuderman and Northrop (1986) and Cuderman (1986). A considerable weakness with this method is that the shock wave generated during the detonation may cause crushing, a stress cage, in the near vicinity of the bore hole reducing the permeability to the well. This obviously negates the effort of the stimulation. The creation of the stress cage and of fines that plug the fractures can be minimized by decoupling the charge from the hole.

Following the first well drilled specifically for oil in 1859 the application of explosive stimulation began with the use of black powder in 1864. By 1867 the use of nitroglycerin became preferable over the black powder because of its higher shattering potential, consequential to its higher detonating velocity. By 1930 liquid nitroglycerin was being replaced with more stable varieties of the product offered in gellified forms (Watson, Benson, and Fillo 1986), despite the development of Dynamite in 1866 by Alfred Nobel. Hydraulic fracturing technology, as discussed above, was developed and began to see application in the early 1950s.

Testing conducted at the University of Maryland (Fourney, Baker, Holloway 1981) investigated the problem of fracture propagation around the well bore using decoupled explosive charges. Testing was conducted in both air and water filled holes drilled into solid blocks of Plexiglas. The tests also considered the effect of notching the borehole to guide the fracture propagation. In general, these tests concluded that:

for air filled holes

- 1) the un-notched holes showed initiation of a large number of radial fractures, however, these fractures did not extend deeply into the surrounding media. Fracture depth was limited to 2-4 borehole diameters.
- 2) the notched holes showed the capacity to produce directed fractures up to 11 boreholes diameters in depth, in some cases cleaving the test samples.
- 3) noticeable and significant fracture generation was observed near the stemming material when the explosive charge was placed at the bottom of the hole. This is presumably due to the longer rise time of the pressure pulse at the top of the hole as the pulse reflects off the stem.

and for water filled holes

- 1) deeper fracturing was observed in the notched holes, although not as deep as those in the air filled holes, compared to the un-notched holes.
- 2) fracturing was not observed to begin near the stemming as it had done in the air filled tests. Regarding this the authors note that the explosive charge employed in the water filled tests were much smaller than that for the air filled tests (50-60 mg versus 175-250 mg PETN).

This research (Fourney, Barker, and Holloway 1981, 1983) was conducted using Plexiglas as the fractured medium. This material was used for its transparent properties, rather than any direct similarity to a rock mass. The authors did comment that the results could be qualitatively applied to rock masses.

The effects of water in the borehole for full scale holes are reported by Coursen (1987) concerning stressed shale with flooded joints. This research suggests that the fragmentation that occurs in flooded joints is not solely attributable to the shock wave forces. There appears to be indication that the fracture patterns are influenced by the presence of pressurized gas in the initially water-filled joints. Thus the fracturing that is occurring is closely related to the dilation of pre-existing fracture patterns. Furthermore, the evidence suggests that the flow of pressurized gases into the fractures is between what could be expected if it were not impeded and if it were highly restricted. This is likely due to the dynamic nature of the formation of the initial fracturing and crushing at the borehole itself.

Based on the research by Coursen (1987) it is possible to estimate the fracturing radii as a function of the borehole radius. The model presented considers factors such as the gas production and pressure during and after the detonation of the explosive, the resulting cavity volume ratios and the effects of isentropic cooling of the product gases. Also included are the in-situ stresses and the shear and compressive strengths of the rock mass. This model, however, does not consider the risetime of the pressure pulse, and therefore will not be addressed in this paper.

4.1.4 Propellant Fracturing

A method of initiating fracturing in the well bore that has been receiving some interest in recent times is the use of a propellant rather than an explosive. Propellants are employed for their tendency to deflagrate, rather than to detonate, when ignited. The net result is a slower build-up of pressure in the well bore. This is associated with a much lower or negligible shock wave. The use of propellants fits into the 'tailored pulse' concept of being capable of providing a pressure pulse whose rise time small enough to cause multiple fractures to form but long enough to prevent crushing around the borehole (Fourney, Barker, and Holloway 1983).

Investigations have been conducted at the University of Maryland (Fourney, Barker, Holloway 1983) into the effects of propellant charges used to initiate fracturing in small-scale test blocks. For the purpose of testing and evaluation the researchers used blocks of Plexiglas as the test media. The testing performed was similar to that conducted by the same researchers concerning explosive fracturing, discussed above. This testing considered the effects of notched and un-notched, and wet and dry boreholes. The results of the testing conducted showed that:

for air-filled holes

- 1) when the holes were not notched between 2 and 4 fractures developed in the block that extended to cleave the test samples. The researchers reported that no significant crushing was seen in the borehole.

- 2) very little damage occurred to the bore holes as a result of the propellant deflagration.

and for liquid filled holes

- 1) for holes that were not notched the effects were comparable to the air-filled holes, but with the use of only 1/2 to 1/4 of the air-filled charge.

- 2) again, very little damage occurred to the borehole as a result of the propellant deflagration.

Overall, very little energy was released in the form of stress waves from the deflagrating propellant. It is worth noting two things that are addressed in above research. First, the quantity of propellant applied in the wet holes is again significantly smaller than that of the dry holes (300-350 mg versus 1.4 grams). Second, that under certain conditions the propellants can be caused to detonate, rather than to deflagrate, resulting in a pressure pulse profile similar to that of an explosive charge. The tendency to detonate can be associated with excessive initiation energy or burning under excessively confined conditions. For these reasons solid propellants are normally ignited along the entire length of the charge (Watson, Benson, and Fillo 1986).

The applicability of designed notching of boreholes in a real well application may be of dubious value. Assuming that the targeted horizon was uniform and solid, as was the case with the Plexiglas experiments cited above, the multiple radial fracturing would begin as the tensile stress on the wellbore wall due to pressurization exceeded the strength of the material. Initial failure by this means would tend to occur at either local weakness or stress concentration points in the borehole wall, such as designed or natural “notches.” In a coalbed well the natural fracture structure of the coal provides pre-existing points of weakness and stress concentration. Furthermore, in the situation of a slotted casing well completion, communication from the well casing to the formation through cut slots should tend to focus the generated fractures along the radials of those slots. Hence, there is no reason to believe that for coalbed methane wells there is any benefit to deliberately “notching” the wellbore prior to stimulation.

One possible application of this research, noted by the researchers themselves, is that where water is undesirable in the borehole, such as clay filled rocks, propellants can produce similar results as in a water-filled hole when the charge is multiplied by a factor of between 2 and 4 (Fourney, Barker, and Holloway 1983). That is, where the propellant charge must, for some reason, be “decoupled” from the formation, the propellant charge needs to be twice to four times as large as one for a water-filled borehole to achieve the same net effect. Fortunately, the wells of

consideration in the current research are typically flooded with water. The outcome here tends to imply that for a charge in an air filled chamber the weight can be reduced by a factor of 2 to 4 when placing it in a water-filled chamber.

Tests concerning the field application of propellant based fracturing has been conducted by Sandia National Laboratories as a part of the tests at the G-tunnel on the Nevada Test Site (Cuderman and Northrop 1986, Cuderman 1986). The investigations reported deal with effects of both dry and wet boreholes. The experimental results pertaining to dry boreholes are based on the application results obtained at the Nevada Test Site to Devonian Shale in the Mid-western United States. Results concerning water-filled boreholes are limited to experiments performed on the ash fall tuff at the Nevada Test Site.

The Sandia experiments employed surplus military propellants normally designed for artillery weapons. Two variants of one type were used for the dry hole tests and two variants of another type were used for the liquid filled tests. The experimenters were able to characterize the pressure rise of the propellant variants as a function of the borehole size. It is possible by mixing the propellants to obtain pressure rise time rates between the individual rates. The following equation for blending is suggested by Cuderman and Northrop (1989):

$$f_A = \frac{\log \frac{t_B}{t_p}}{\log \frac{t_B}{t_p} + 2 \cdot \log \frac{t_p}{t_A}}$$

where f_A is the proportion of propellant A in the mixture, t_p is the desired pressure rise time, and t_A and t_B are the pressure rise times of propellants A and B respectively. This equation assumes that both rise times are taken at the same chamber volume. When the charge is decoupled from the borehole a further correction must be made to compensate for the annulus:

$$\frac{t'}{t} = \frac{V'}{V}$$

“where V' is the larger free volume [total chamber volume], t' is the larger rise time, and t and V correspond to the zero-annulus case” (Cuderman and Northrop 1986). With these techniques it is possible to customize the propellant charge for the conditions at hand and the desired degree of fracturing.

The fracture mechanism and patterns that can be generated are discussed in the relevant section, above. Use of the customizing technique can provide reproducible pressure rise time characteristics, although the peak pressure is variable dependent on the state of the in-situ stress. Propellant mixtures producing pressure rise times in excess of 1 milli-second produced fairly low

pressure peaks, around 34 to 48 MPa. However, when the pressure rise time falls below 1 millisecond the pressure peak can rise to 200+ MPa (Cuderman and Northrop 1986).

The experiments described where the propellant techniques were applied to dry boreholes in Devonian Shale produced fracture patterns that could be predicted from the pressure levels obtained by the ignition of the propellants. In one of the shots the pressure rise time was longer than predicted due to free volume in existing fractures, resulting in less overall fracturing (Cuderman and Northrop 1986).

The conditions of the fracturing media change somewhat when the hole is filled with water. The basic criteria for obtaining multiple fractures and the blending of propellants remains the same as described above, however the experimenter used a larger grained power for the wet borehole experiments.

During the experiments in liquid filled holes the experimenter found that pressure rise curve was marked with significant oscillation, and that the ultimate borehole pressure was about 1/4 of that experienced when they were determining the pressure rise characteristics in pipe tests. The oscillations are explained as being the result of the formation of multiple fractures and on an overall scale the duration suggests hydraulic fracturing (Cuderman 1986). When the resulting fractures were “mined-out” there was evidence that fracturing had occurred in all three of the regimes discussed, hydraulic, multiple and explosive. The experimenter attributes this to severe pressure gradients within the liquid filled holes that do not exist in the dry holes. He further notes that although the pressure rise times are much quicker in the fluid filled holes the peak pressures are lower than in the dry holes. To this the experimenter adds that in the liquid filled holes the fractures are generated on the shear planes about as readily as on the principal stress planes and that the reduced peak pressure is due to more efficient hydraulic fracturing. It appears that under these loading conditions the induced fractures are produced independent of the natural, static stress pattern

Some work has been performed in the use of liquid propellants, rather than the granular military surplus types used above. The liquid propellant was developed specifically for shooting wells and is of a nature to respond to the borehole water. That is when it is poured into the borehole it sinks to the bottom without forming an emulsion with the water. In the experiments conducted by Watson, Benson and Fillo (1986) it was found that at least 400 feet of water was required above the propellant to contain the deflagration for maximum efficiency. The water column could be replaced with an appropriately designed gravel tamping. The presence of a tamping material is required for any propellant, or high-explosive, shot to keep the released energy at the point where it is required, that is the target horizon. The results of the liquid propellant tests appear to be very similar in nature to those of the dry propellants.

A conceptual drawing of the test cell for propellant burn characterization is shown in figure 4-4. This cell is configured with a constant volume chamber, the actual free volume will be determined based on the volume of propellant placed in the chamber.

Monitoring of the pressure rise was accomplished using the piezoelectric transducer, as indicated in figure 4-4. The data output from the transducer was recorded and stored with a recording oscilloscope. The initiation of the recording sequence will be triggered using the initial response of the pressure transducer.

4.2 Apparatus and Test Parameters

This section addresses the apparatus and parameters associated with two types of testing conducted during this phase of the research project. Both of these are used to characterize the burning of propellants. The following section (4.3) covers measurements of the particle size distribution of the propellant powders, since this is considered to be a matter of standard practice it will not be addressed here.

Though of less importance overall, the unconfined tests were conducted to obtain values for straight gas production from the propellant burned against atmospheric pressure. These tests will be addressed briefly in subsequent sections of this chapter, but do not carry into further work in the next chapters.

The main intent of the propellant tests are covered in the confined burning tests. These tests are used to characterize the properties of the propellants burning under conditions similar to those that might be expected in a wellbore. The key exception here is that the confined volume is air filled whereas the wellbore will most likely be water-filled. The data collected in this series of experiments is used to determine the burning properties of the propellants and serves to provide the base data from which numerical modeling exercises can be based (chapter 5).

In this section the basic apparatus the confined tests are covered, as well as the measured parameters. The chemistry and make up of the propellants selected for this research is covered in section 4.2.1. Section 4.2.2 provides treatment of the various apparatuses used to conduct the confined burning series of experiments. The various systems are separated into the pressure vessel (4.2.2.1), the propellant charge design (4.2.2.2), and the data logging system (4.2.2.3). The elements associated with an individual, confined burning, test are listed, with photographs, in section 4.2.3. Brief comments on the evaluation of data collected from these tests are given in section 4.2.4.

4.2.1 Propellant Properties

During the course of conducting the propellant shots three different propellants and two variations of black powder were employed.

Black powder is, technically, an explosive. Its use in these experiments was intended as an accelerant to aid in the flame spread and pressure rise associated with the conventional propellant charges. The chemical composition of black powder is on the order of 74.0 percent potassium nitrate, 10.4 percent sulfur, and 15.6 percent charcoal. This material has been known since ancient days and was used as an artillery propellant through World War I. The advent of nitrocellulose based smokeless powders has supplanted wide spread use of black powder. Black Powder is still used in artillery propellant charges as an igniter material to carry the initial flame deep into the smokeless powder propellant pack. As an explosive, black powder has a tendency to detonate, that is to exhibit a supersonic combustion wave.

Typical propellants are a mixture of combustible materials that contain both the fuel and the oxidizer elements. Double-base propellants contain two different, primary, ingredients, usually nitrocellulose and nitroglycerin. The three propellants used in these tests were all classified, by the manufacturer, as double base. The primary composition of the propellants is listed in table 4-1. Propellants have a tendency to deflagrate, that is to exhibit a subsonic combustion wave.

Table 4-1: Primary Composition of Accurate Arms Propellants Employed.

Component	Accurate Arms Company Propellant Name		
	No. 2-Improved	No. 5	8700 ¹⁶
Nitrocellulose	83.47	78.89	7.4
Nitroglycerin	13.45	18.02	
Centralite ¹⁷	1.23	1.5	
RDX ¹⁸			73.5
CEDAC ¹⁹			11.7
DPB ²⁰			6.7

Data on No. 2-Improved and No. 5 from personal conversation with Mr. G. Grinstead, Accurate Arms Company, Inc., 20 February 1997.

Data on 8700 (WC-870) from (Freedman 1988).

Modern double-base smokeless powders are typically a mixture of nitrocellulose and nitroglycerin. Nitrocellulose, or gun cotton, is the major constituent of these mixtures. There are two primary factors that affect the energy of these types of propellants, the amount of nitrogen in the nitrocellulose, and the ratio of nitroglycerin to nitrocellulose (Urbanski 1965). The typical nitrogen content in the nitrocellulose used in smokeless propellants manufactured in the United States varies between 13.00 and 13.25 percent (Stiefel 1979). The lower percent of nitrogen in the nitrocellulose having a more negative enthalpy of formation (Freedman 1988). There is a broad range of mixtures of nitrocellulose and nitroglycerin that fill the available propellant scope. In general, higher proportions of nitroglycerin result in higher temperature products, but lower gas volumes (Urbanski 1965). For military artillery designers, higher nitroglycerin content tends to increase barrel wear, for the present research high temperature products of combustion may affect the surface of developing, and pre-existent, fractures in the coalbeds.

In the nitrocellulose/nitroglycerin propellants the compound Centralite I (Carbamite) is added during manufacture as a non-volatile inert solvent to gelatinize the powder grain surfaces. The result being a colloidal grain with enhanced progressive burning properties (Urbanski 1965).

Regarding the properties of RDX propellants, such as the 8700, Stiefel (1979) reports that compared to a nitrocellulose base the RDX is less ignitable and exhibits inferior uniformity. Conditions that were observed in the laboratory tests. The second base compound in this propellant is Cellulose Diacetate, this compound finds common use in the production of safety films, but is of a nature to be combined with RDX for the formulation of a propellant mixture. The main plasticizer in this propellant was DPB, a combustible liquid that is miscible with organic

¹⁶ Equivalent to Olin propellant WC-870

¹⁷ Centralite I [C₆H₅N(C₂H₅)₂CO

¹⁸ 1,3,5-Trinitrohexahydro-s-triazine

¹⁹ Cellulose Diacetate

²⁰ Dibutylphthalate C₆H₄(COOC₄H₉)₂

solvents. This particular propellant was selected for mixing with the nitrocellulose propellants since it was the slowest burning propellant that was readily available.

4.2.2 Confined Tests

To determine the pressure-time characteristic of the propellant, when burned in a confined system a constant volume pressure vessel was employed. This pressure vessel and the ancillary systems are illustrated in figure 4-5. The sub-units of the system are discussed in the following sections of this chapter.

4.2.2.1 Pressure Vessel

Testing of the pressure - time response of the propellants burn characteristics was conducted in a constant volume pressure vessel. The main body of this vessel was machined from cold-rolled carbon steel, other materials, such as stainless steel, brass, and Teflon were used for specific applications. Cold-rolled steel was selected for its strength characteristics and homogeneity. Design drawings and structural evaluation of the pressure vessel are provided in appendix C of this thesis.

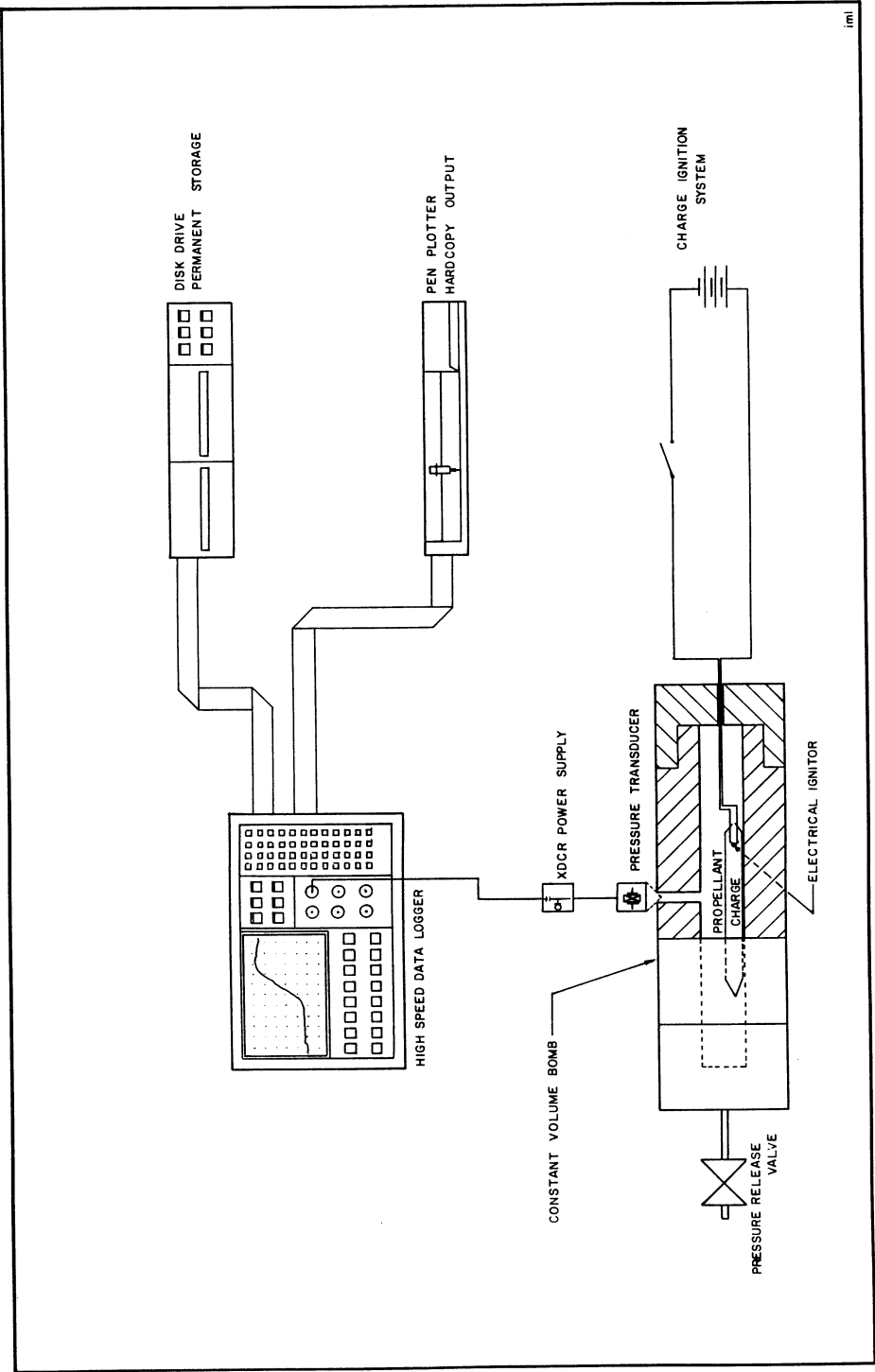


Figure 4-4: General Configuration of Small Bomb Tests

The main body of the vessel was a cylinder 3 inches in diameter with a one inch diameter bore through the axial center. Both ends were threaded to receive end caps and a seal groove was provided for gasket placement. An access hole was also prepared for the transducer, this hole was configured in accordance with the design provided by the transducer manufacturer. Placement of the transducer was set to coincide with the center of the “target” horizon of the, originally, proposed laboratory scale fracture model, see the introduction to chapter 6.

The fixed end cap was configured to provide for the release of gases generated as a result of the combustion tests. The gasket used in this joint was of machined brass. The cap was tightened on to the body to provide a compression of approximately 0.002 inches. For various tests the outlet point of this cap was equipped with either a ball valve (normally closed) or an orifice nozzle (1.3208 mm diameter, #55 drill).

The removable end cap was configured to allow for the insertion of propellant charges into the pressure vessel, and to provide for electrical connection to the charge igniter. The gasket material used in this application was machined solid Teflon. Although these gaskets did not last for more than about ten shots, they were easy to work with and did not require the very high torque associated with the brass gasket. A larger concern in the design centered around the sealing of the lead wires, on numerous occasions the wires were blown out of the vessel. Ultimately, the entire gland was filled with polyester resin, utilizing a hypodermic needle.

4.2.2.2 Charge Design

Numerous designs and configurations for the charges were tried prior to data collection. The design had to meet one simple criterion, hold together long enough to ensure that all of the propellant would be burnt. Constructions of rolled paper were tried, these worked well for charges in the range of 1 gram of propellant, however, at higher charge loads they became cumbersome and unreliable. The final design for these tests was based on a length of brass tubing. Some stainless steel tubing was evaluated, however, it proved to be too brittle to be crimped.

The basic charge was constructed in the following manner: a length of tubing suitable for the charge weight was obtained, approximately 1 inch of one end was flattened, folded and crimped closed, the opposite end was then cross-cut to a depth of about the diameter of the tube. The propellant charge was poured into the tube, the igniter inserted, and the open end crimped closed at the cross-cut. It was necessary to exercise care such that during crimping the igniter wire insulation was not damaged. A short circuit to the brass body would prevent the charge from being capable of ignition. A final check was made with an electrical multi-meter to ensure conductivity of the igniter and insulation between the igniter and the charge body.

4.2.2.3 Data Logging System

The data logger system utilized consisted of a transducer, a power supply, and a recording oscilloscope. Additionally, the oscilloscope was equipped with a plotter for hard copy generation and a floppy-disk drive for non-volatile recording of data.

The transducer employed for these experiments was a Piezotronics PCB 108A02 hydraulic pressure transducer. This transducer was not designed specifically intended for the application described here, however, discussions with the manufacturer²¹ revealed that, as used, the transducer could provide reliable data. The implications of the application are addressed in section 4.5.1, below. The specifications of the PCB 108A02 transducer are listed in Table 4-2, below.

The transducer was powered by a PCB piezotronics model 484A06 power supply. This supply was capable of multi-mode operation (either AC couple or DC couple). For the test reported here the AC couple mode was utilized. This provided for fairly quick stabilization of the output voltage following connection of the power supply to the transducer. The power supply was DC coupled to the oscilloscope.

The recording oscilloscope used for these tests was a Data Precision 6000 manufactured by Analogic. This unit is capable of providing four channel input, dual-time-base, recording at a rate of 100,000 samples per second. During these experiments a single input channel was used (the pressure transducer), and data was collected in a dual time base mode. The first time-base collected 1000 samples with a 200 micro-second period and a delay of -25 milli-seconds. The second time-base collected 1000 samples with a 40 micro-second period and no delay. The delay was in reference to the detection of the defined trigger event, in this case a positive slope voltage deviation of 0.05% of the measurable range of the oscilloscope.

A Hewlett-Packard Model 7470A plotter was connected to the oscilloscope to provide an immediate hardcopy output of the logged data. Such a record was made for all of the tests successfully conducted. Furthermore, for the tests that form the basis of the conclusions presented below, the recorded data was stored on a floppy-disk so that it could be called back later and entered into a spread sheet for evaluation. Unfortunately, the data format used by the recording oscilloscope was not compatible with personal computers, thus the relevant data points had to be entered by hand (generally between 100 and 200 points per test).

²¹Discussion with Mr. David George of TCI and Mr. Larry Depew of PCB.

Table 4-2: Manufacturer's Specifications for PCB108A02 Transducer²²

Property	Units	Range
Range, Full Scale (5 volt output)	psi	10000
Useful Range (10 volt output)	psi	20000
Maximum Pressure	psi	50000
Resolution	psi	0.4
Sensitivity	mV/psi	0.5
Resonant Frequency	kHz	300
Rise Time	μs	2
Discharge Time Constant	s	1000
Linearity (zero based BSL)	%	2
Output Impedance	ohm	100
Acceleration Sensitivity	psi/g	0.01
Temperature Coefficient	%/°F	0.03
Temperature Range	°F	-100 to +250
Vibration	g peak	2000
Shock	g peak	20000
Sealing	welded	hermetic
Excitation (constant current)	mA	2 to 20
Voltage to current regulator	VDC	+18 to 28
Case; Diaphragm	SS	17-4PH
Weight	gm	11

²²Anonymous, PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY, "Low Impedance Quartz Pressure Transducers, Series 100," publication S100993, page 13.

4.2.3 Test Assembly

Preparation and conduct of an individual test was conducted in the following manner. This sequence is illustrated in the photographs of plates 4-1 through 4-8.

1. Data logging equipment setup and properly configured (Plate 4-1).
2. Pressure vessel cleaned, paying particular attention to the sealing surfaces on the vessel body and the removable end cap.
3. With body seal in place, attach charge to lead wires (Plate 4-2). Lead wires liberally coated with ablative grease.
4. With release valve open, thread removable cap into place, snug plus 30 degrees (Plate 4-3).
5. Install pressure transducer (Plate 4-4), coat sensing element with grease.
6. Connect pressure transducer to power supply (Plate 4-5), allow to equalize for about 5 minutes, monitor on data logger.
7. Connect ignition leads to vessel lead wires and close pressure release valve (Plate 4-6).
8. Discharge shot from battery.
9. Remove debris and clean vessel (Plate 4-7).
10. Record data collected onto paper plots and to floppy disk (Plate 4-8).

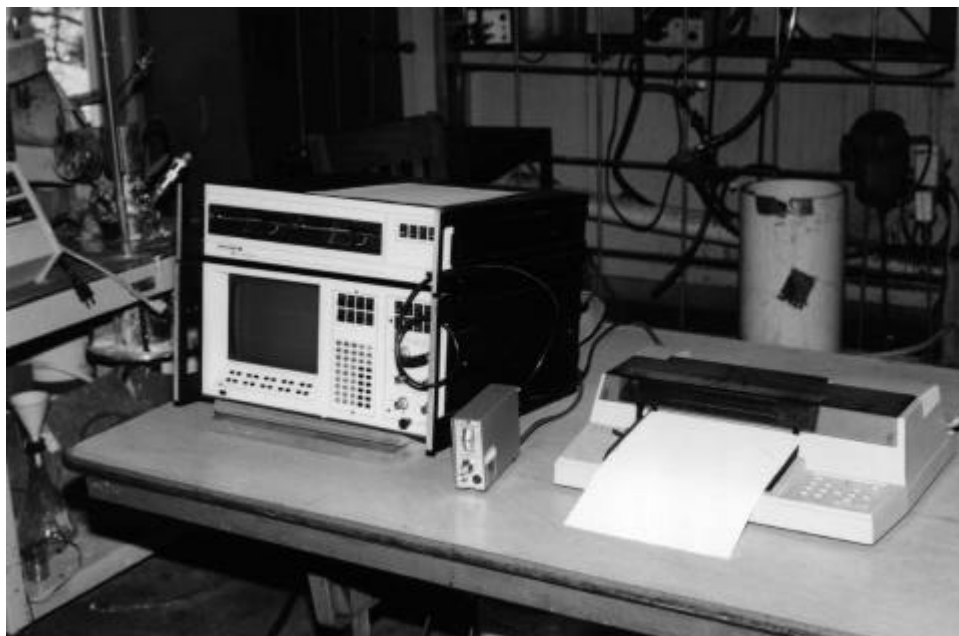


Plate 4-1: Photograph of Data Logging System Configured for Test Shot.



Plate 4-2: Inserting Test Charge into Test Vessel, Note Seal is in Place on Bomb.



Plate 4-3: Test Vessel Closed, Valve Open, Transducer not In-place.

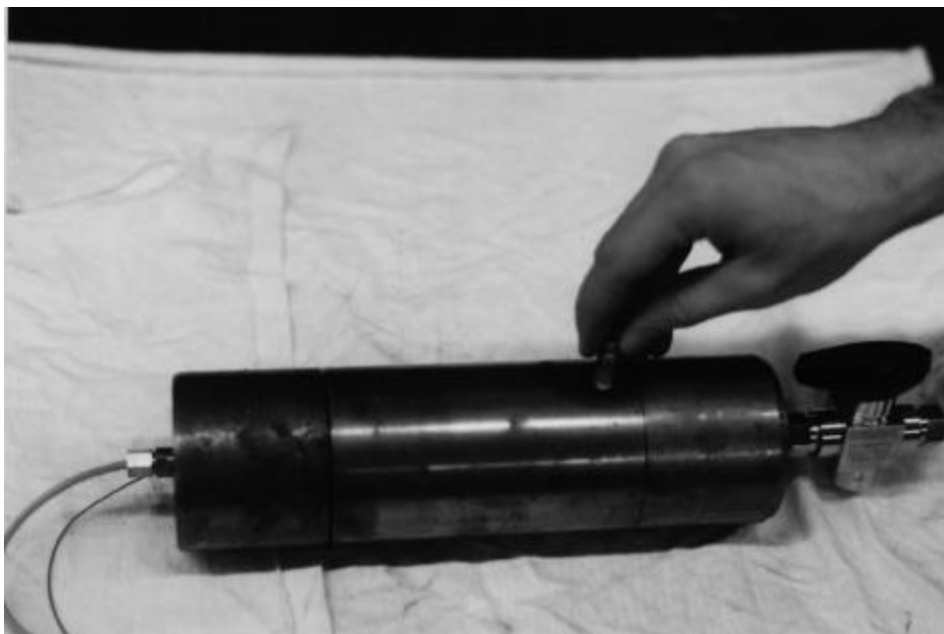


Plate 4-4: Inserting Pressure Transducer into Access Port.



Plate 4-5: Pressure Transducer Connected to Power Supply Lead.

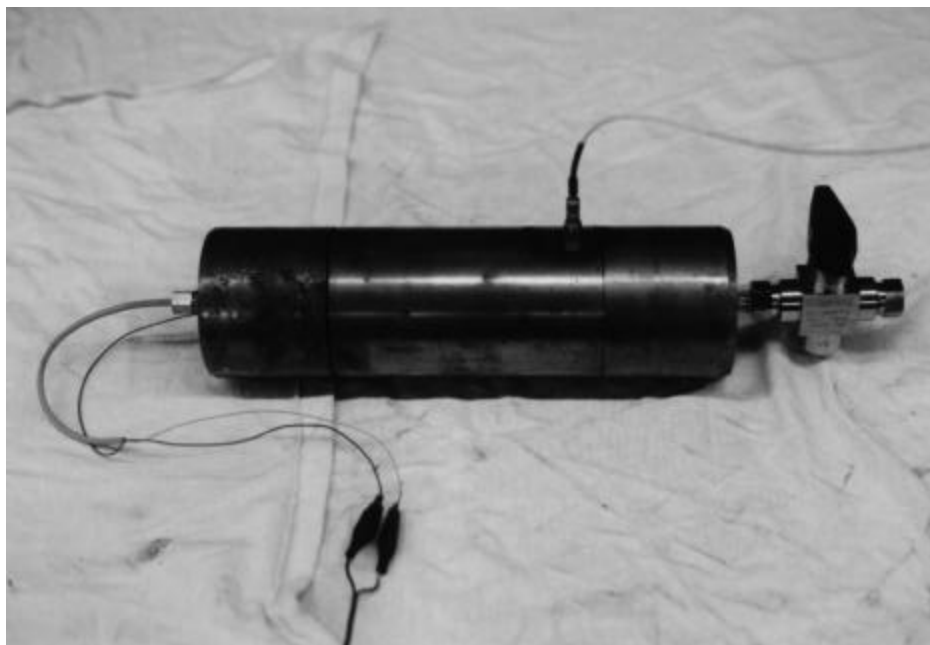


Plate 4-6: Ignition Lead Wires Connected to Vessel Leads.



Plate 4-7: Debris Removed from Test Shot.

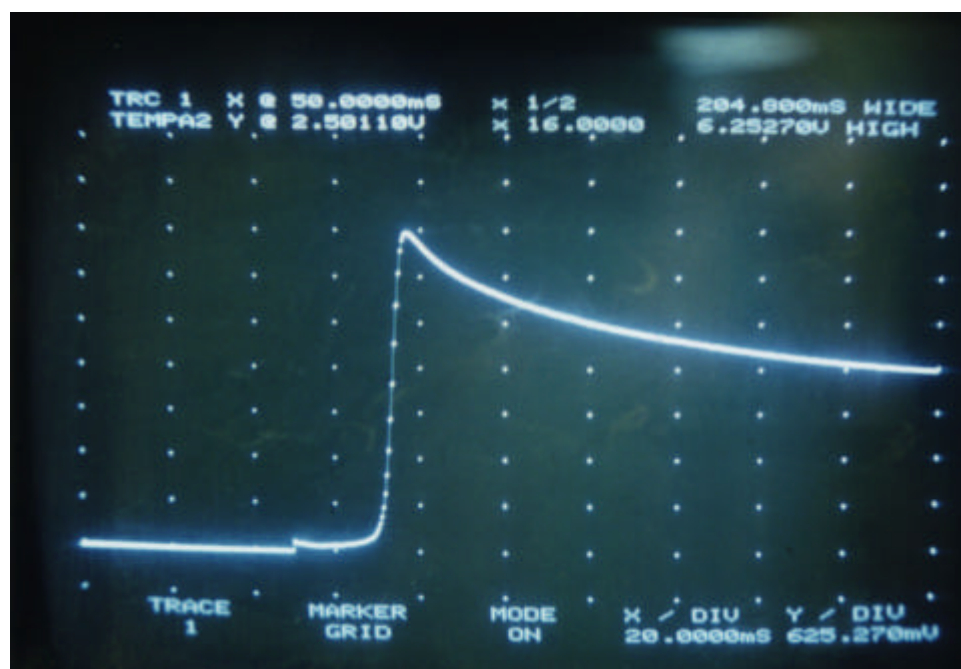


Plate 4-8: Close-up of Test Results Logged on Data Logging System.

4.2.4 Data Evaluation

For these confined burn tests there were two principal elements to the data of interest. The first was the peak pressure obtained. The second was the time in which it took to reach that pressure. From the recorded data the pressure rise-time and rise-rate were obtained for each shot. These parameters are illustrated in figure 4-8.

The peak pressure was recorded and evaluated simply as the highest pressure recorded during the burn event. This point proved to be the junction of two different curve types. The positive sloped curve was sygmoidal in shape, the negative slope side was a power function in shape.

Due to the shape of the pressure rise curve, the total pressure rise-time did not seem appropriate since it would not adequately represent the peak slope on the curve. Instead, a quite arbitrary approach was taken. The peak pressure rise-rate was defined as the average rate between 10% and 90% of the maximum pressure (Nilson, Proffer and Duff 1985). In most cases this appears to have much more closely fit the mean shape of the data since this region of the curve is the most linear part.

4.3 Results

This section addresses the results obtained from measurements of the properties of the various propellants reviewed during the course of these experiments. The results presented here follow from the apparatuses and programs addressed in the previous section (4.2). This section considers the results obtained from particle size measurement (4.3.1), and confined burning tests (4.3.2). The application of the confined burning tests to produce burn rate parameters is covered in the next section (4.4).

4.3.1 Commercial Propellant Particle Size Distribution

Prior to evaluating the burning characteristics of the commercially obtained propellants a size distribution was obtained for the speeds utilized. For these tests the propellants were of the same manufacture. That referred to as No. 8700 is the slowest burning available from the manufacturer. That referred to as No. 5 is among the fastest burning available from the manufacturer. The No. 2-Improved propellant is the fastest burning available from the manufacturer; it is, however, limited in applicability due to a bulk density about two-thirds that of the other two. All three of these propellants are identified as spherical firearm propellants (smokeless powder) intended for reloading of ammunition.

To assess the size distribution of the propellant particles, a screen stack was arranged with the following sieve sizes: 20 (0.84 mm), 30 (0.59 mm), 40 (0.42 mm), 50 (0.297 mm), 60 (0.25 mm), and 70 (0.210 mm). Table 4-3, 4-4, and 4-5 below indicates the distribution obtained for each of the powders evaluated. This data is illustrated graphically in figure 4-5. As one can see, the powders appear to be well segregated and uniform in particle size.

In addition to the size distribution analysis described above, a sample of each of the powders was subject to microscopic inspection with a Scanning Electron Microscope (SEM). Photomicrographs obtained in this manner are illustrated in plates 4-9 through 4-13. An x-ray derived chemical analysis was not possible since the samples were deposited with gold, rather than carbon, prior to placement into the microscope chamber.

As can be seen in the photomicrographs the propellant is very uniform in shape and size, this is also seen in the particle size distribution analysis cited earlier. The individual grains of propellant appear to be rather smooth, with little or no glaring imperfections. One of the grains, see plate 4-4, indicated a rather small hole that extended into the grain. As illustrated this "hole" is about 10 microns wide and 5 microns deep, compared with an estimate grain diameter of 500 microns.

Also evident in the photomicrographs is the general platelet shape of the individual grains. For both the No. 8700 and No. 5 the thickness to diameter ratio appears to be on the order of 0.56.

Table 4-3: Particle Size Distribution for Accurate Arms No. 5 Spherical Propellant

Fraction	Mass (gm)	Accumulated Mass (gm)	% of Total	% of Accumulated
+20	0	0	0	0
20-30	0	0	0	0
30-40	3.286	3.286	29.1	29.1
40-50	7.276	10562	64.4	93.5
50-60	0.648	11.21	5.7	99.2
60-70	0.066	11.28	0.6	99.8
-70	0.024	11.30	0.2	100

Table 4-4: Particle Size Distribution for Accurate Arms No. 8700 Spherical Propellant

Fraction	Mass (gm)	Accumulated Mass (gm)	% of Total	% of Accumulated
+20	2.853	2.853	23.4	23.4
20-30	9.193	12.046	75.5	98.9
30-40	0.137	12.183	1.1	100.0
40-50	0	12.183	0	100.0
50-60	0	12.183	0	100.0
60-70	0	12.183	0	100.0
-70	0	12.183	0	100.0

Table 4-5: Particle Size Distribution for Accurate Arms No. 2 - I, Spherical Propellant

Fraction	Mass (gm)	Accumulated Mass (gm)	% of Total	% of Accumulated
+20	0	0	0.00	0.00
20-30	0.6192	0.6192	3.25	3.25
30-40	9.2477	9.8669	48.55	51.80
40-50	8.1663	18.0332	42.87	94.68
50-60	0.8765	18.9097	4.60	99.28
60-70	0.1116	19.0213	0.58	99.87
-70	0.0255	19.0468	0.13	100.00

The particle size distribution is illustrated in figure 4-5.

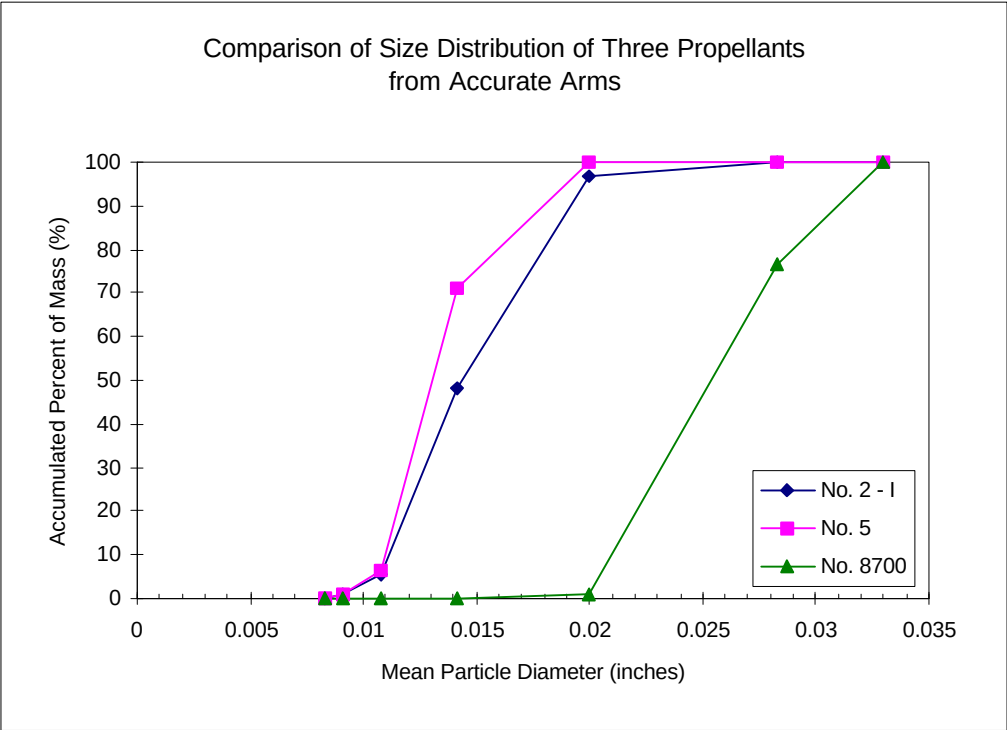


Figure 4-5: Size Distribution of Three General Propellants Considered.

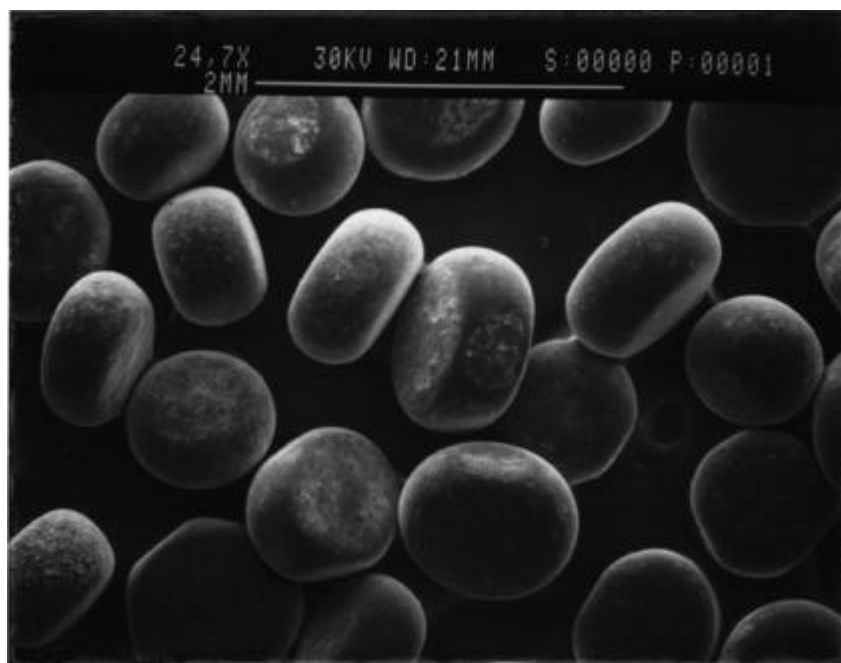


Plate 4-9: Photomicrograph of No. 8700 Propellant, 24.7x.

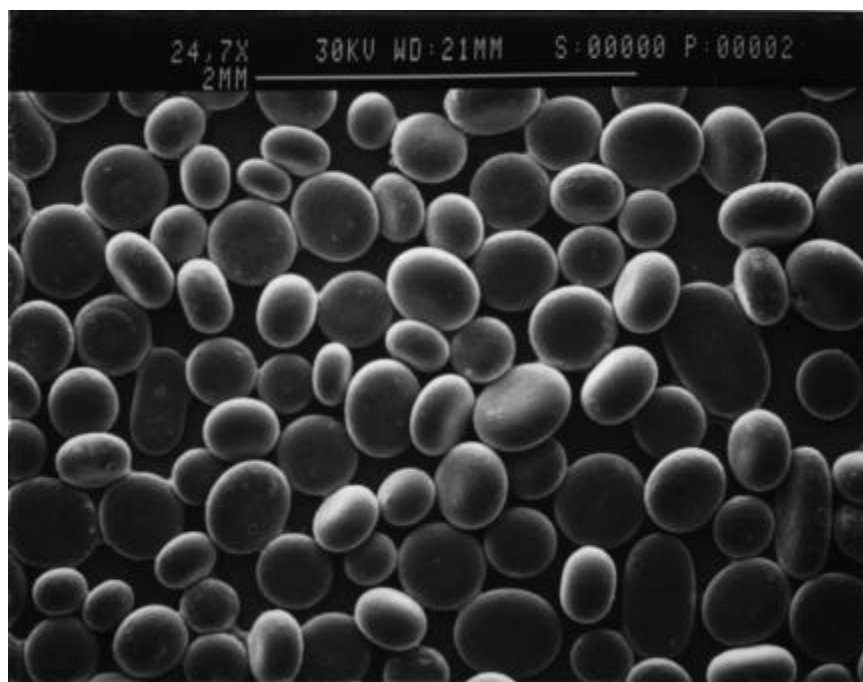


Plate 4-10: Photomicrograph of No. 5 Propellant, 24.7x

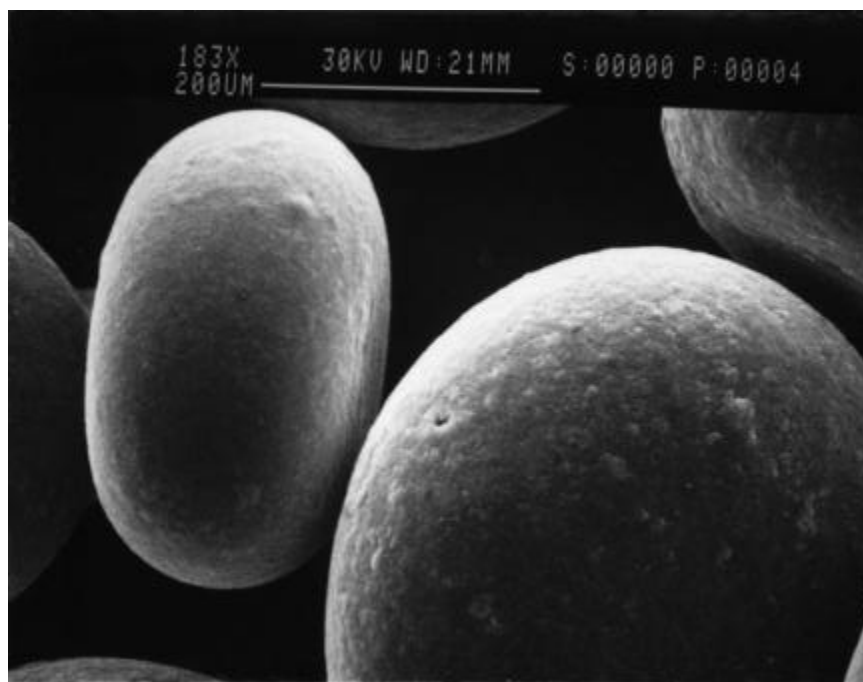


Plate 4-3: Photomicrograph of No. 5 Propellant (183x)

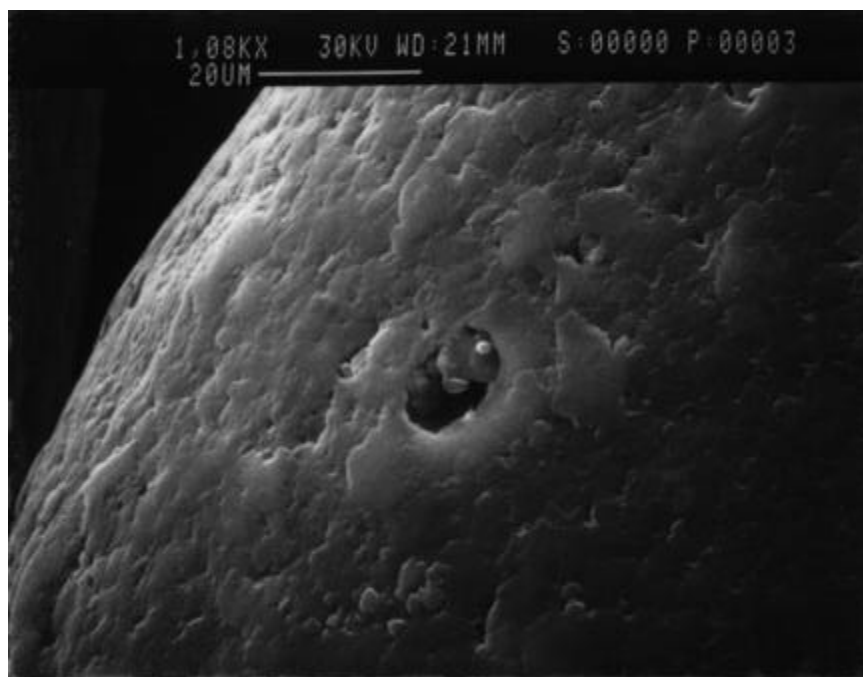


Plate 4-12: Photomicrograph of No. 5 Propellant, 1080x

4.3.2 Confined Burning Tests

The confined burning tests were conducted in a constant volume pressure vessel, as discussed above.

The most basic data collected during these tests is recorded in table 4-6. For each of the test configurations the mass of the powder, pressure rise time, pressure rise rate, and peak pressure are recorded. The pressure rise-time is defined here at the time increment between 10% and 90% of the peak pressure. The pressure rise rate is defined as the slope between 10% and 90% of the peak pressure. Here, peak pressure is based on the maximum recorded voltage, which is known to be germane to the test. (In some cases the pressure of detonation events within the vessel are recorded, the peak pressure of interest is that associated with the main deflagration event.) These features are illustrated in figure 4-6. The events associated with an entire shot, from the point of ignition, are illustrated in figure 4-7.

The data collected for the peak pressure as a function of the charge weight is shown in figure 4-8. When obvious outliers are rejected from the data set, there appears to be a very strong linear correlation between the charge weight and the maximum pressure attained. The highest level of pressure relative to the charge weight is seen for the 100% No. 5 charges. Mixtures of the No. 5 and No. 8700 show a lower peak pressure for total charge weight as the amount of No. 8700 powder is increased.

Table 4-6: Basic Propellant Burn Results for Shots Performed

Sample	Mass (gm)	Rise Time (milli-seconds)	Rise Rate (MPa/ms)	Peak Pressure (MPa)
100% No. 5				
6-13-96-D1-*	5.1045	3.2	11.75	47.93
6-13-96-D2-*	5.0932	4.0	9.07	46.31
5-29-96-A1	4.986	2.74	14.80	50.92
5-29-96-A2	5.081	3.7	10.59	49.21
5-29-96-A3	5.103	4.0	10.01	49.15
5-23-96-C	5.37	2.8	15.63	54.86
5-23-96-A	4.645	4.6	7.77	44.58
5-21-96-A	5.85	2.0	21.39	58.18
5-20-96-A	2.493	3.375	4.78	22.50
5-17-96-D	3.00	5.6 (est.)	3.78	26.47
75% No. 5; 25% No. 8700				
6-13-96-C1-*	5.2348	7.7	4.54	43.40
6-13-96-C2-*	5.25	5.1	7.00	44.82
5-31-96-A1	5.0775	4.8	7.58	46.22
5-31-96-A2	5.1327	4.6	7.49	44.02
5-21-96-B	5.85	3.6	12.20	55.02
5-20-96-E	3.85	10.6	2.45	32.12
5-20-96-B	2.413	12.0	1.28	19.29
5-17-96-B	2.0	9 (est.)	1.44	13.29
5-17-96-E	3.0	12.0	1.56	23.80
66% No. 5; 34% No.8700				
5-29-96-B1	4.959	7.4	4.81	43.89
5-29-96-B2	5.247	5.6	6.44	46.38
5-29-96-B3	2.41	4.7	7.66	45.95
5-21-96-C	5.85	6.2	6.92	53.67
5-20-96-F	3.85	8.0	3.36	33.29
5-17-96-C	2.0	12.0 (est.)	0.66 (est.)	11.70
5-17-96-E	3.0	18.75	0.98	23.11
50% No. 5; 50% No. 8700				
6-13-96-B1	5.249	9.0	3.94	45.09
6-13-96-B2-*	5.2391	0.6	0.87 (min)	0.52

Table 4-7 (Con't): Basic Propellant Burn Results for Shots Performed

Sample	Mass (gm)	Rise Time (milli-seconds)	Rise Rate (MPa/ms)	Peak Pressure (MPa)
75% No. 5; 25% Rocket Fuel (Black Powder)				
5-23-96-B	4.8	3.3	9.19	38.19
66% No. 5; 34% Rocket Fuel (Black Powder)				
5-23-96-D	5.37	2.8	11.28	39.18
50% No. 5; 50% Rocket Fuel (Black Powder)				
6-13-96-A1	5.223	4.6	5.61	32.38
6-13-96-A2	5.2321	(N/A)	4.83 (min.)	32.38
6-5-96-B1	4.251	2.0	6.36	24.21
6-5-96-B2	4.251	9.2	1.94	23.43
100% Rocket Fuel (Black Powder)				
6-5-96-A1	5.2504	0.4	28.58	17.39
6-5-96-A2	5.2501	0.7	18.36	16.40
100% No. 2 -Improved Propellant				
7-2-96-A1-*	3.400	3.0	8.69	31.47
7-2-96-A2-*	3.402	3.8	6.36	29.32
6-19-96-A2	3.346	5.5	4.20	28.20
6-19-96-A3	3.346	7.0	3.10	27.40
100% Commercial Black Powder				
7-2-96-B1	4.902	2.1	5.32	14.39
7-2-96-B2	4.965	2.6	4.77	14.57
7-2-96-B3	4.930	2.8	5.13	14.68
7-2-96-C1-*	4.926	1.8	6.24	15.27
7-2-96-C2-*	4.824	1.3	9.02	13.92

Note: * indicates that the referenced shot was discharged through the 1.3208 mm diameter nozzle (#55 drill).

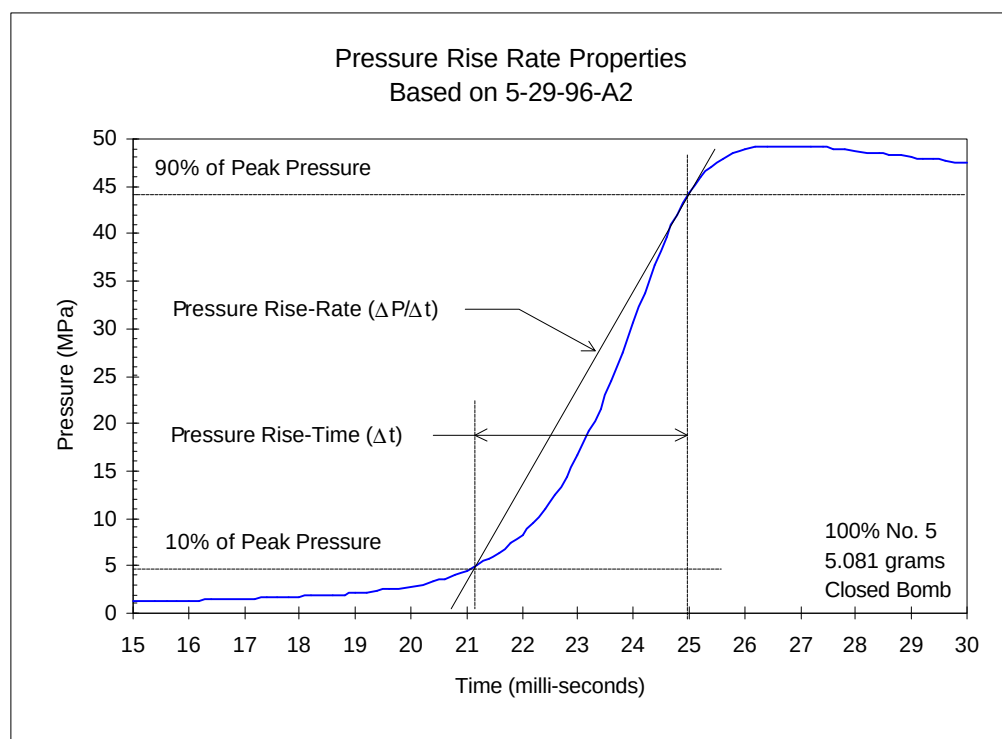


Figure 4-6: Illustration of Pressure Rise Parameters, Based on Shot 5-29-96-A2.

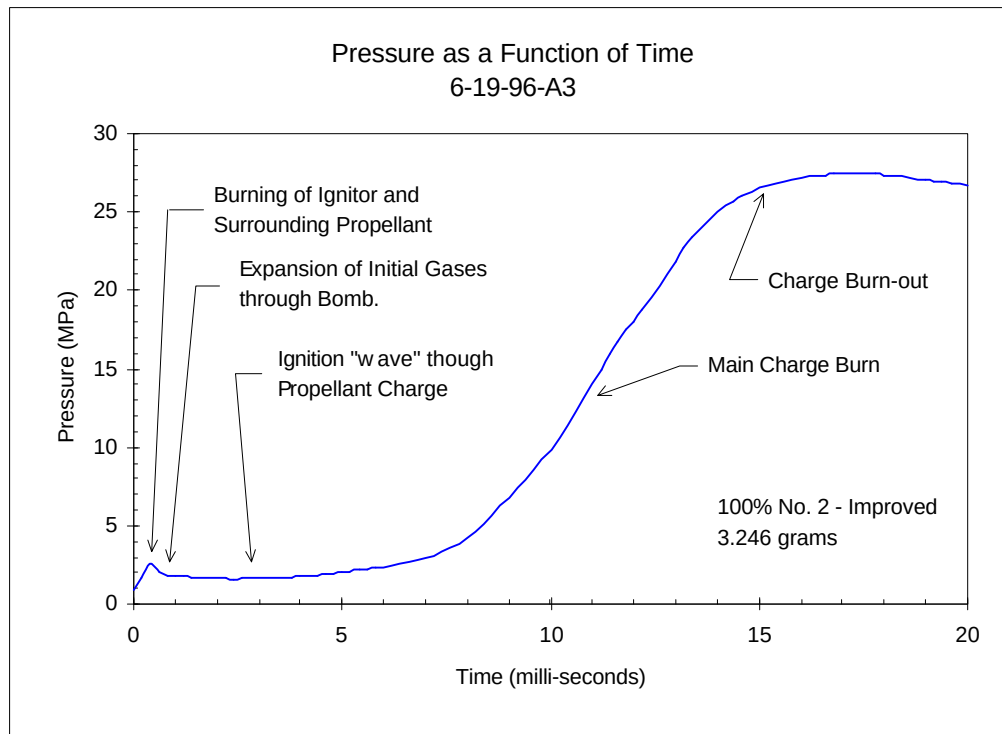


Figure 4-7a: Example of Typical Pressure-Time Profile Curve, Ignition Inclusive.

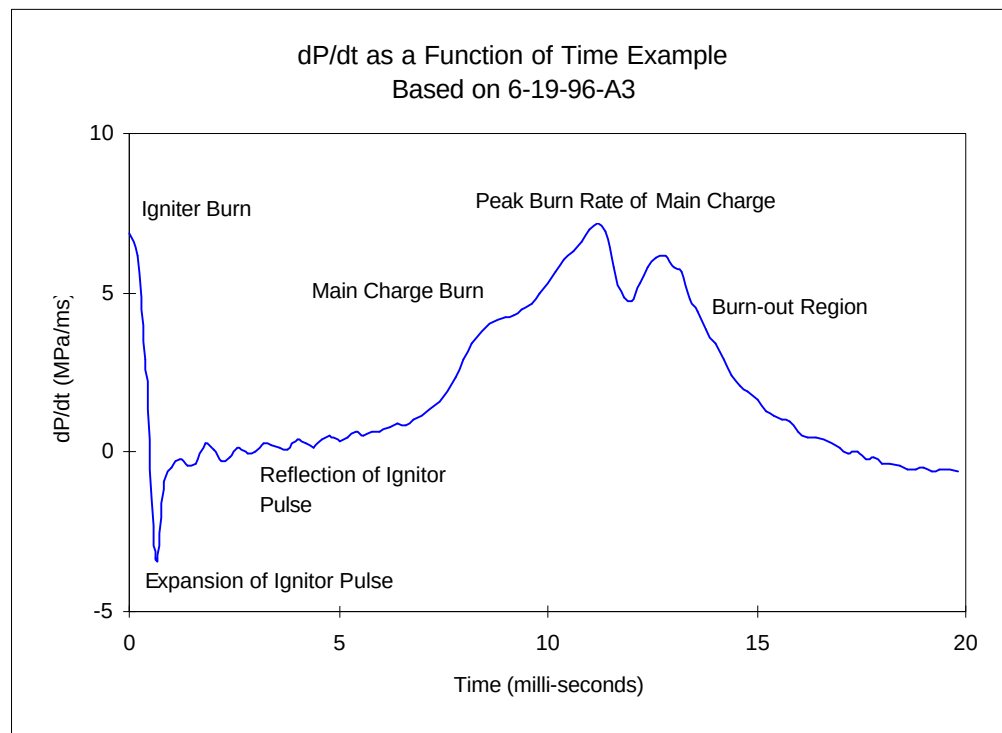


Figure 4-7b: Example of Typical dP/dt Profile Curve, Ignition Inclusive.

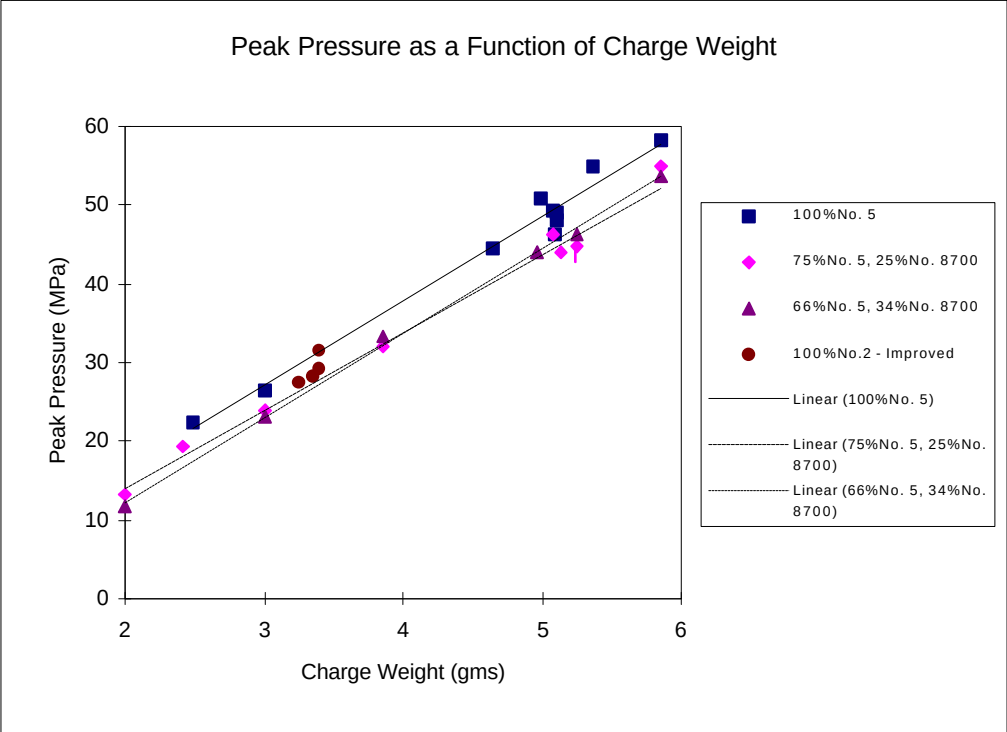


Figure 4-8: Illustration of Peak Pressure as a Function of Charge Weight.

The data illustrating the relationship between the pressure rise rate and the charge weight tends to show a greater variability than was seen for peak pressure. Overall the data trend appears to be as one would expect, that is as the charge weight is increased some increase in the rise rate is also seen. This is expected since the burn rate of the propellant is generally considered to be proportional to pressure. Any action that would tend to increase the pressure will also tend to increase the burning rate.

The general data collected for the test mixtures are addressed below, based on the propellant mixture. These sections do not include numerous tests conducted to evaluate the design of the charge and the operability of the data logging system.

Each figure for the shots reviewed is provided in two parts, the first (a) shows the pressure-time trace for the respective shot. The second (b) element illustrates the first derivative of the pressure with respect to time (dP/dt) plotted as a function of time. The evaluation of this derivative is a central difference in which the computed slope is taken as the average of the slopes immediately behind and ahead of the point of interest. This scheme is shown mathematically in section 4.4. For the sake of clarity the pressure traces shown are scaled, in pressure and in time, to illustrate the main event of the charge shot. Appendix D, of this thesis, contains the raw voltage traces made in the laboratory, which are proportional to the pressure in the bomb.

4.3.2.1 100 Percent No. 5

For this investigation 10 shots were made utilizing a straight charge of Accurate Arms No. 5 small arms propellant. These shots ranged in size between 3.0 and 5.85 grams charge weight. Two of the shots in this series were fired with the vessel open to the atmosphere through a 1.3208 mm diameter orifice, and are noted specifically. The pressure-time profiles illustrated are scaled on the time base such that the most significant portion of the curve is visible at a meaningful scale.

Figure 4-9 is the pressure-time trace of test 5-29-96-A1. This curve illustrates what appears to be a mild explosion or rapid pressure pulse within the test bomb. This assessment is based on the fluctuations in the pressure, which are particularly noticeable at the pressure reaches its peak. Strictly speaking, an explosion would result from a detonation of the propellant, direct evidence of which is not available in these data. Basically, however, the period of the pulses is consistent with the reflection of a wave within the bomb at the predicted conditions. Another noticeable factor in this figure is the immediate jump in the trace, followed by a lull prior to the one milli-second point. This phenomenon was seen in numerous tests; as well as in the numerical modeling problems where the propellant was not ignited simultaneously (see section 5.2.4.2). This jump appears to be due to the burning of the propellant surrounding the igniter, prior to the ignition of the main body of the propellant charge.

Figure 4-10 illustrates the pressure time profile of shot 5-29-96-A2. This profile is characterized by a smooth curve, which does not appear to indicate the continued reflection of a pressure wave as was seen in shot 5-29-96-A1, above. The initial pressure jump is not visible in this figure due to the limited time base. It appears that there was some pre-ignition burning that triggered the recorder prior to the accelerated burning of the charge.

Figure 4-11 is the pressure time profile of shot 5-29-96-A3. This profile shows a fairly smooth pressure growth function. This shot is also marked by a triggering spike in pressure that does not appear in the figure.

Figure 4-12 is the pressure-time profile of shot 6-13-96-D1. This shot, as well as 6-31-96-D2, was vented through an nozzle with a diameter of 1.3208 mm (drill #55). No visible evidence of detonation is seen in the pressure trace. The initiation phase of this shot, not visible in the referenced figure, does indicate pressure fluctuation for about 2 milli-seconds following the logger trigger. The pressure profile does appear to come to “steady-state” prior to the event illustrated in this figure. This shot does not indicate a peak pressure significantly different than that generated during the closed bomb tests for similar charge weights. One noticeable difference is in the general shape of the profile. The generation of the pulse appears to be slower starting and peaks more rapidly than the closed bomb tests. This phenomenon is easily explained as being related to the venting of gases and the growth of the internal pressure. The vent will very quickly

choke as the pressure builds; however, since the gas exits the system early, the growth rate of the pressure will initially be delayed due to delayed acceleration of the burn rate.

Figure 4-13 is the pressure-time profile of shot 6-13-96-D2. This shot displays characteristics similar to the previous example. A triggering spike event is recorded in the total data set for this test, which is not visible in the referenced figure. The main differences lie in the observations that the slope of the pressure rise-rate is not as steep, and that the peak of the pressure curve is not as sharp. In the tail of the pressure curve, following the peak, there does appear to be some oscillation in the pressure trace. However, based on the early portion of the profile, and the very low amplitude of the oscillations, it is doubtful that an explosive event occurred. More likely the fluctuation is due to the sensitivity of the pressure transducer and gas pressure relaxation as matter left the bomb. It is conceivable that a shock wave was disturbing flow entering the nozzle assembly.

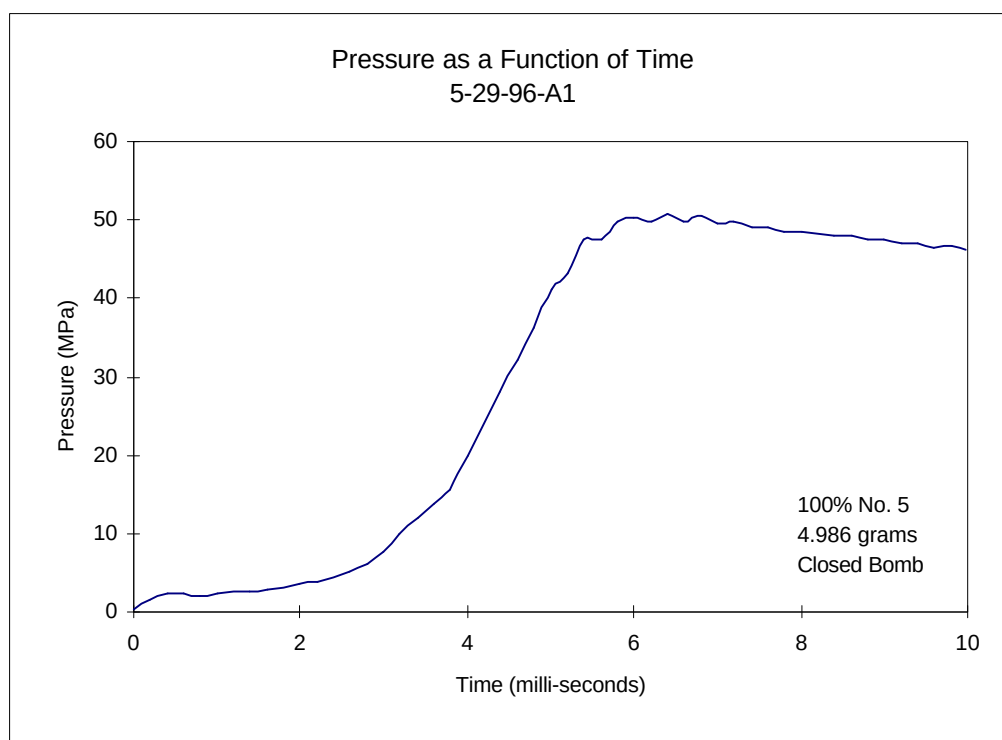


Figure 4-9a: Bomb Pressure as a Function of Time, shot 5-29-96-A1

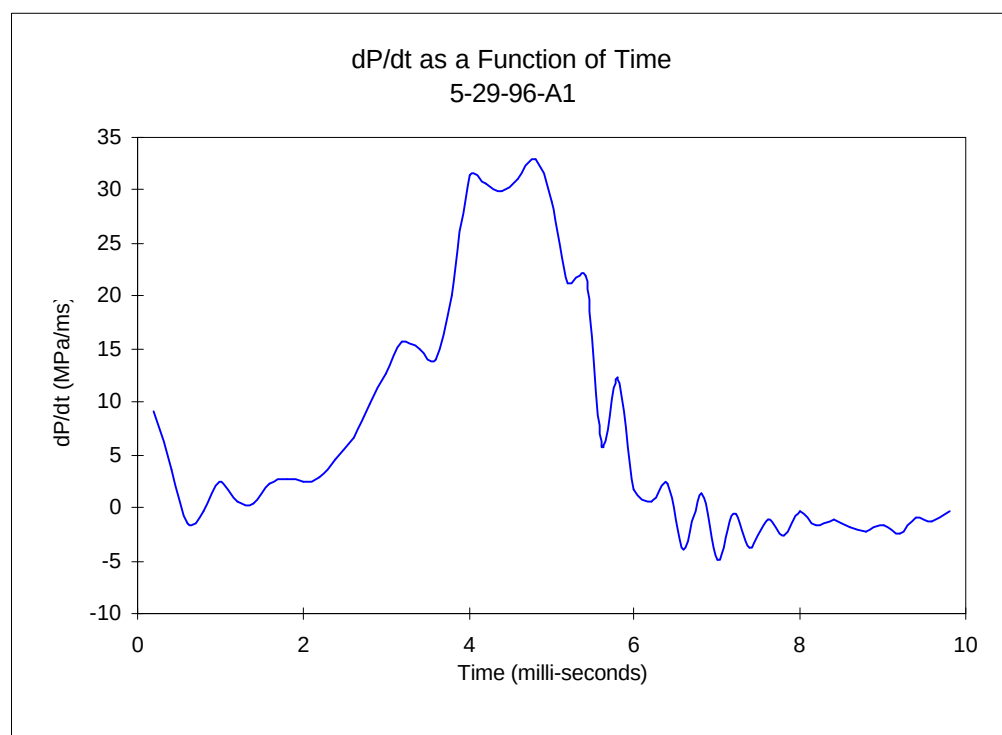


Figure 4-9b: dP/dt as a Function of Time, Shot 5-29-96-A1

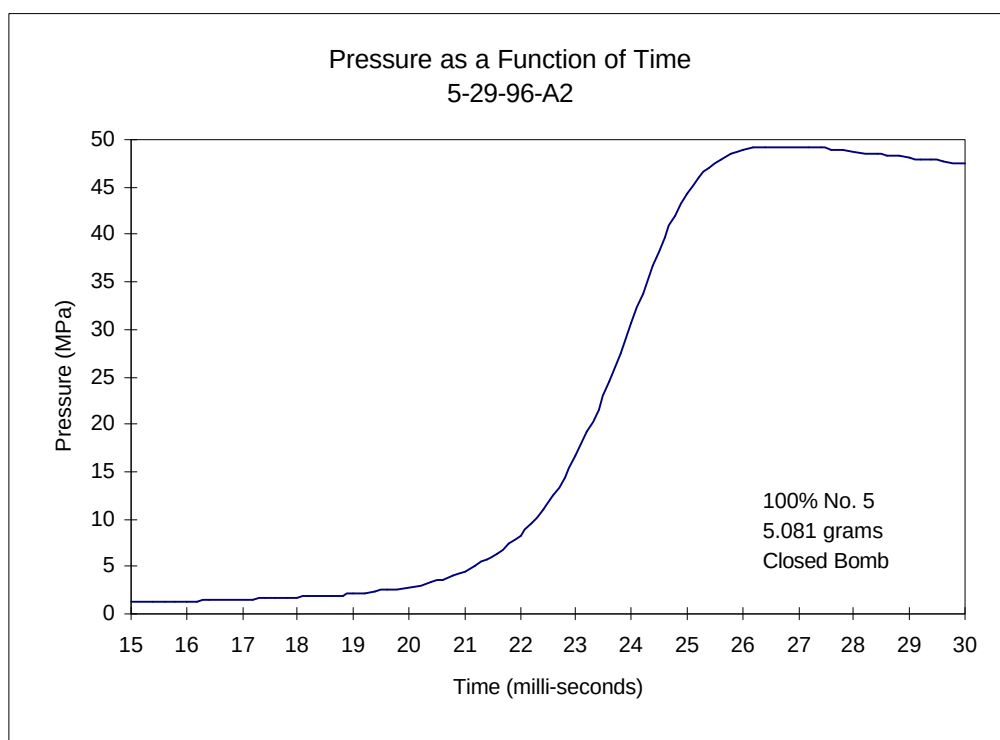


Figure 4-10a: Pressure as a Function of Time, Shot 5-29-96-A2

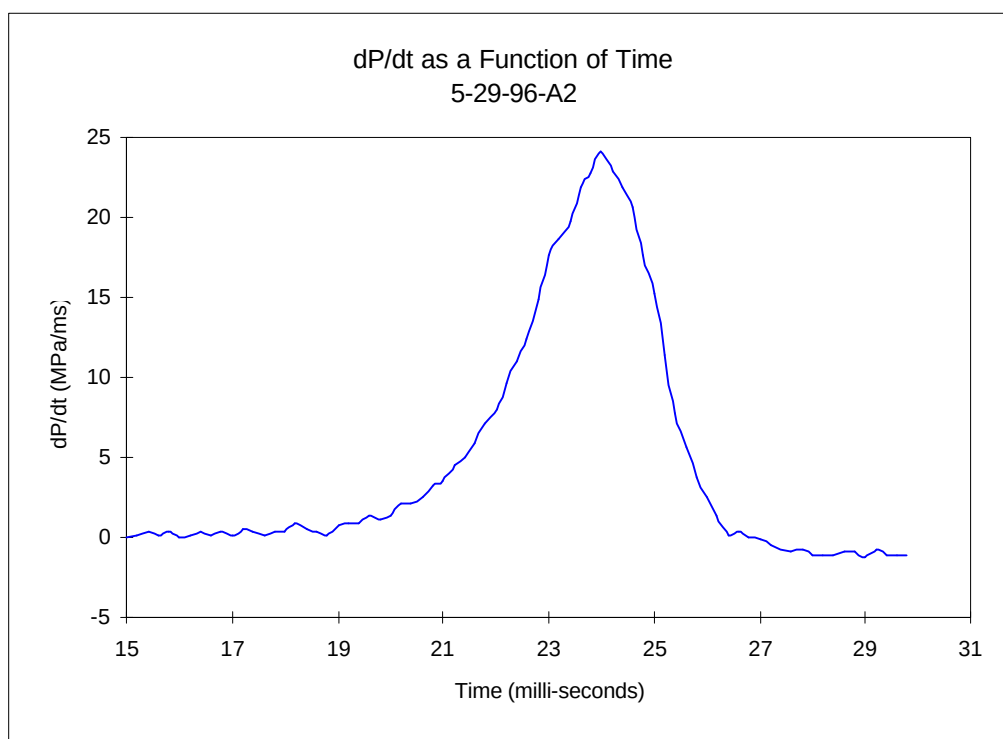


Figure 4-10b: dP/dt as a Function of Time; Shot 5-29-96-A2

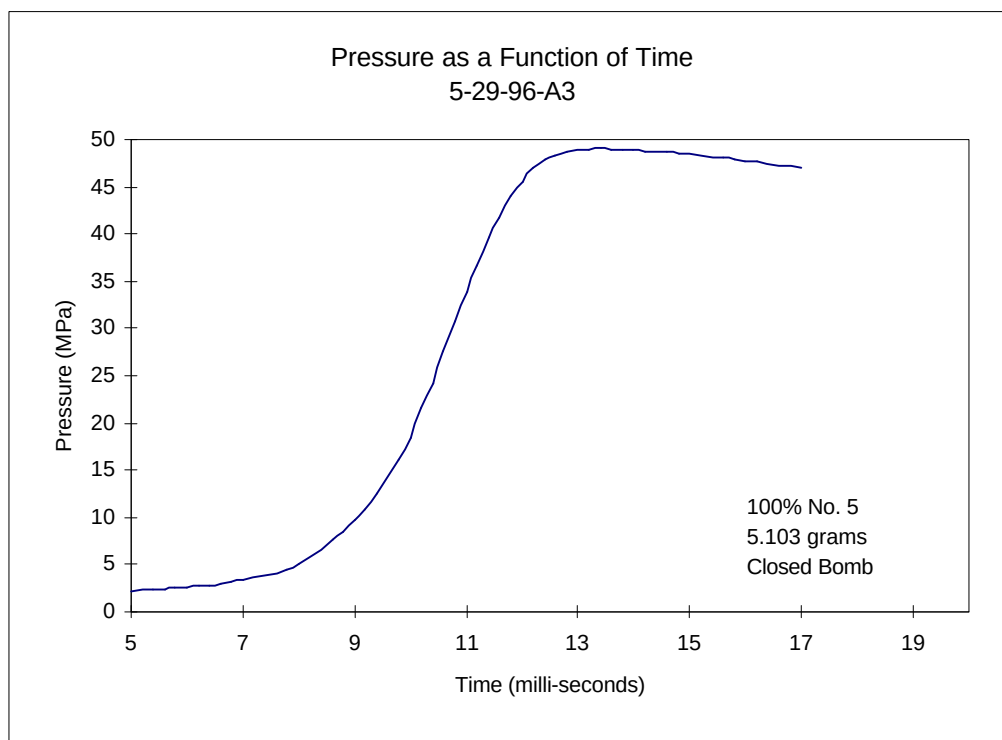


Figure 4-11a: Pressure as a Function of Time, Shot 5-29-96-A3

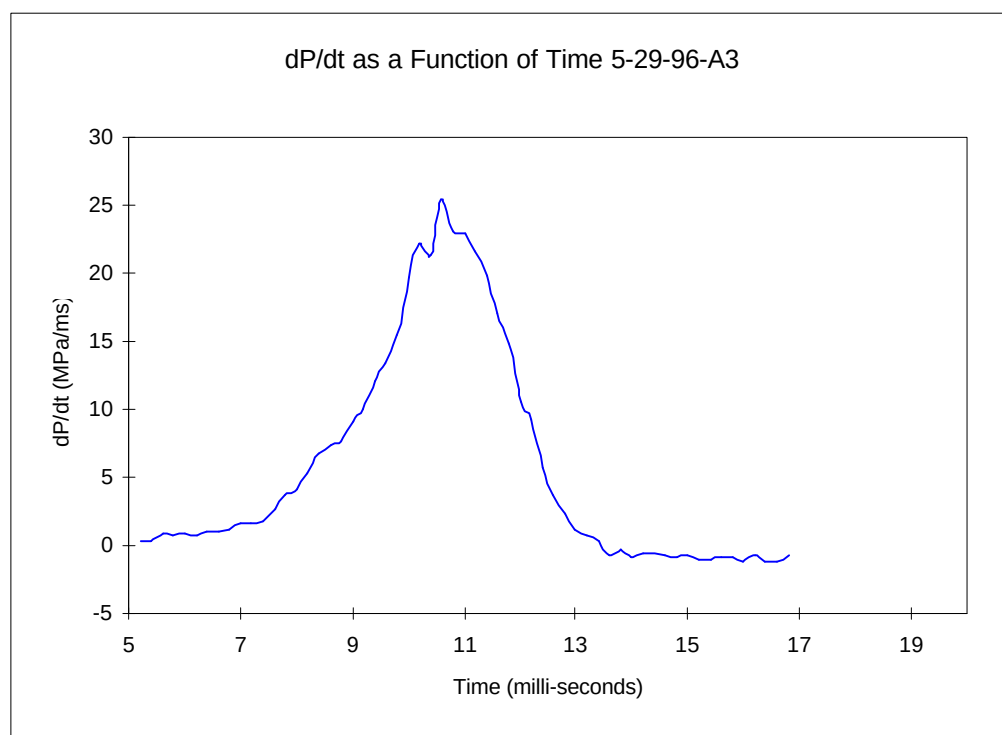


Figure 4-11b: dP/dt as a Function of Time, Shot 5-29-96-A3

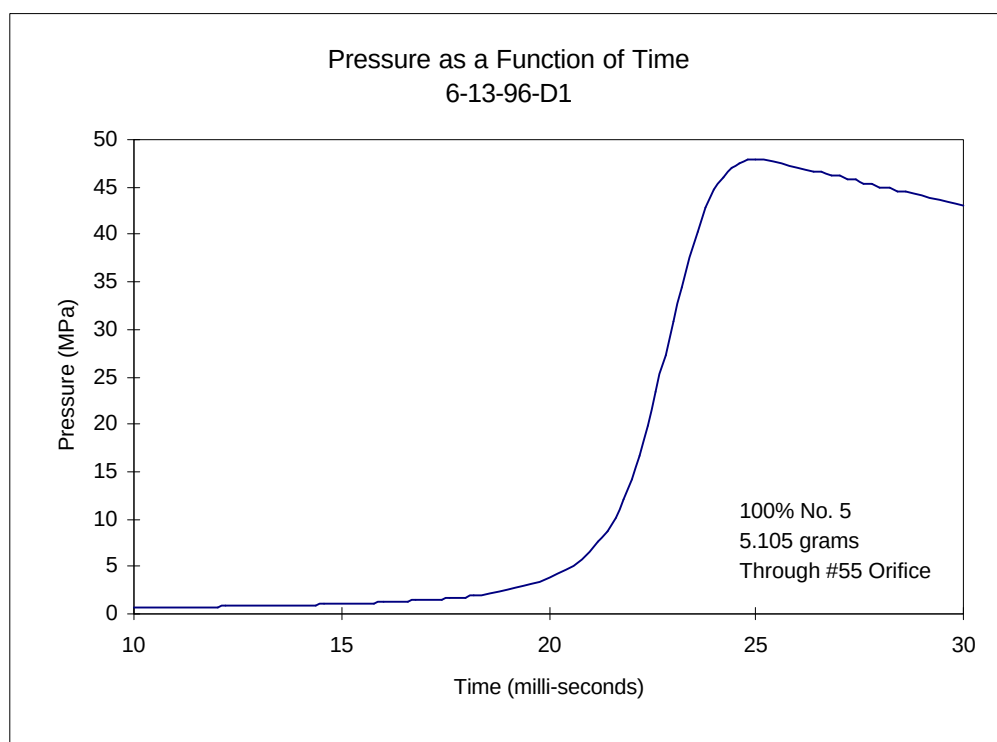


Figure 4-12a: Pressure as a Function of Time, Shot 6-13-96-D1

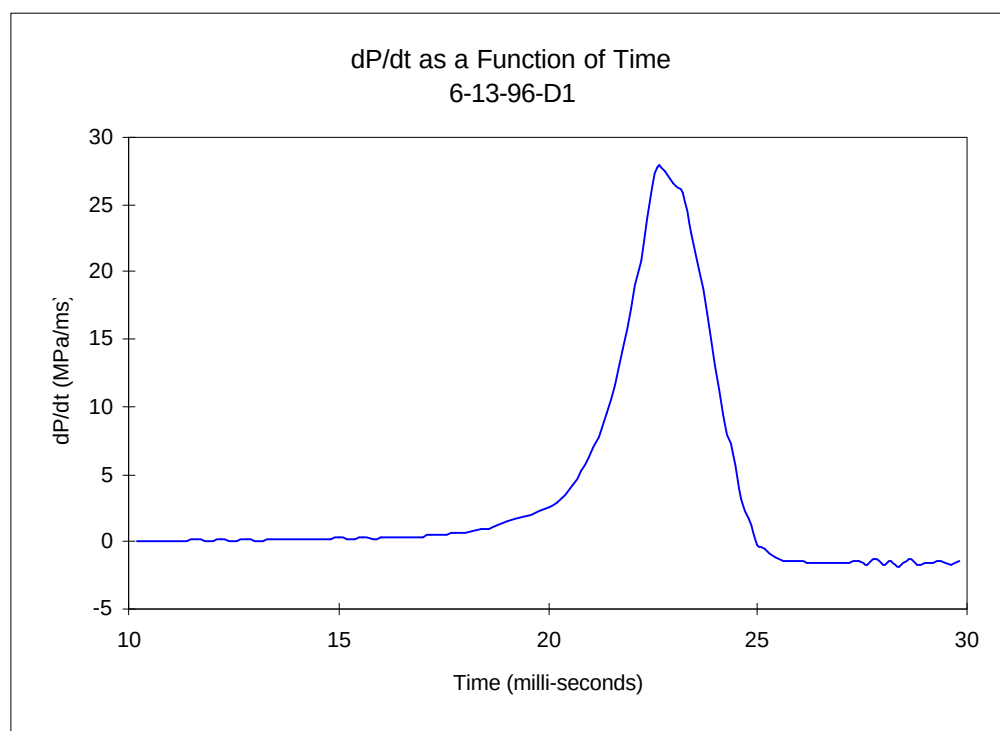


Figure 4-12b: dP/dt as a Function of Time, Shot 6-13-96-D1.

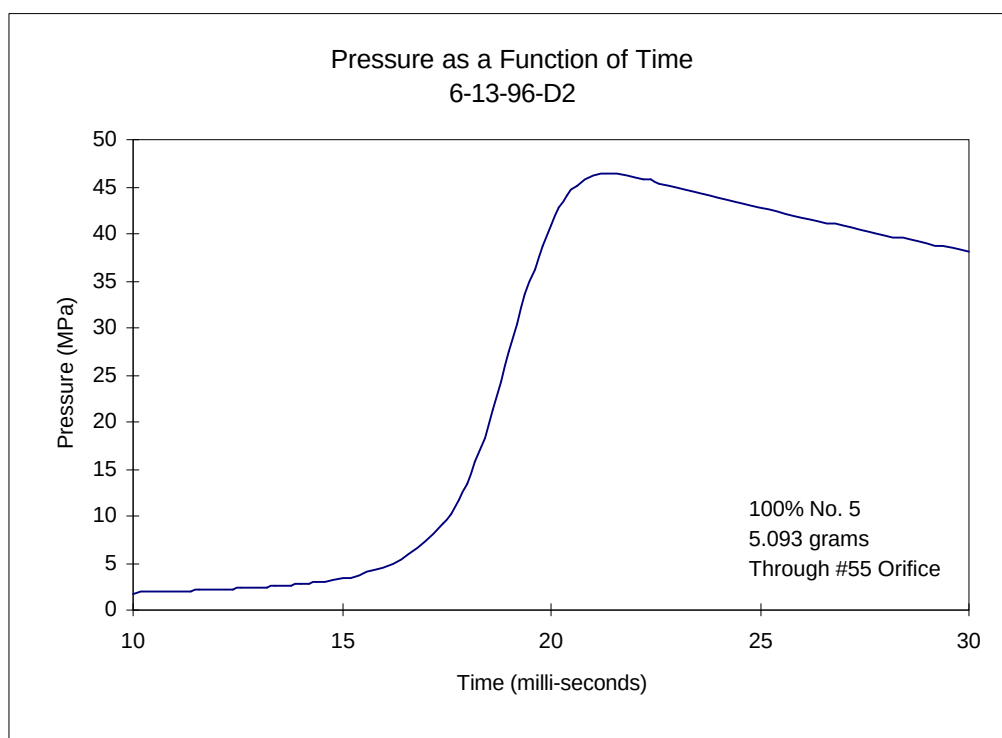


Figure 4-13a: Pressure as a Function of Time, Shot 6-13-96-D2

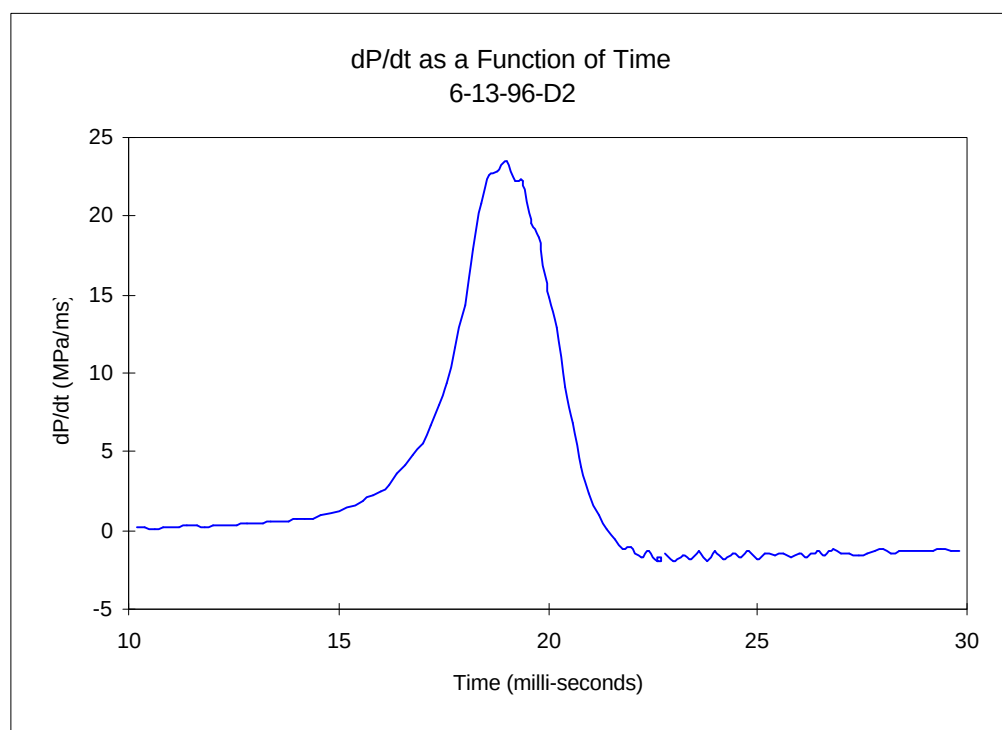


Figure 4-13b: dP/dt as a Function of Time, Shot 6-13-96-D2

4.3.2.2 75 Percent No. 5, 25 Percent No. 8700

During this phase of the project 9 shots were fired utilizing a blend of propellants 75 percent Accurate Arms No. 5 and 25 percent Accurate Arms No. 8700. The charge weights in this series varied between 2.0 and 5.85 grams. Two of these tests were conducted with the vessel open to the atmosphere through a 1.3208 mm diameter orifice. The shots described below, with appropriate pressure-time profiles, are used in the mixture burn rate equation parameters analyzed in section 4.4.2.

Figure 4-14 illustrates the pressure-time profile for shot 5-31-96-A1. In this figure the triggering pressure spike is visible. Although there appears to be some period pressure fluctuations, these events are small in magnitude and probably are not signifiers of a detonation event. A noticeable point of comparison between the general shape of this curve (and the next one, 5-31-96-A2) and those observed for the 100% No. 5 cases is the much longer period of time observed at the top of the curve following the point of inflection. This is most likely due to the differences in burning between the grains of No. 5 and No. 8700 propellants. The steep early section of the curve is most likely the result of preferential burning of the No. 5 grains. Since the No. 5 grains are much smaller than the No. 8700 grains they will burn out sooner. The greatly decreasing amount of burning propellant then causes the pressure growth rate to drop, as is visible in the figure.

Figure 4-15 shows the pressure-time curve obtained from shot 5-31-96-A2. A mild detonation echo is visible during the first 2.5 milli-seconds of this trace. Notice that the period of the spikes is fairly constant. Following the last of the spikes a “steady-state” growth is observed to the point where the pressure growth rate rapidly accelerates. The pressure appears to grow from this point without observable residual pressure pulses.

Figure 4-16 is the pressure-time trace obtained from test 6-13-96-C1. This shot and 6-13-96-C2 were of the same magnitude as the two above, except that the vessel was open to the atmosphere through the 1.3208 mm (#55 drill) nozzle. The main profile, and peak pressure, of this trace is similar to those observed in the closed bomb tests. It is observable, however, that this shot took a long period of time to accelerate. The whole shot trace does show the typical spike triggering the recorder, associated with the firing of the igniter.

Figure 4-17 shows the pressure-time profile of shot 6-13-96-C2. The general shape of this shot is similar to that of 6-13-96-C1. It is noticeable that the time interval from ignition to acceleration is shorter than for the previous shot. The full shot trace also presents the triggering event spike, not visible in figure 4-19. The magnitude of the spike in this test is, however, about 20 times that of the previous shot.

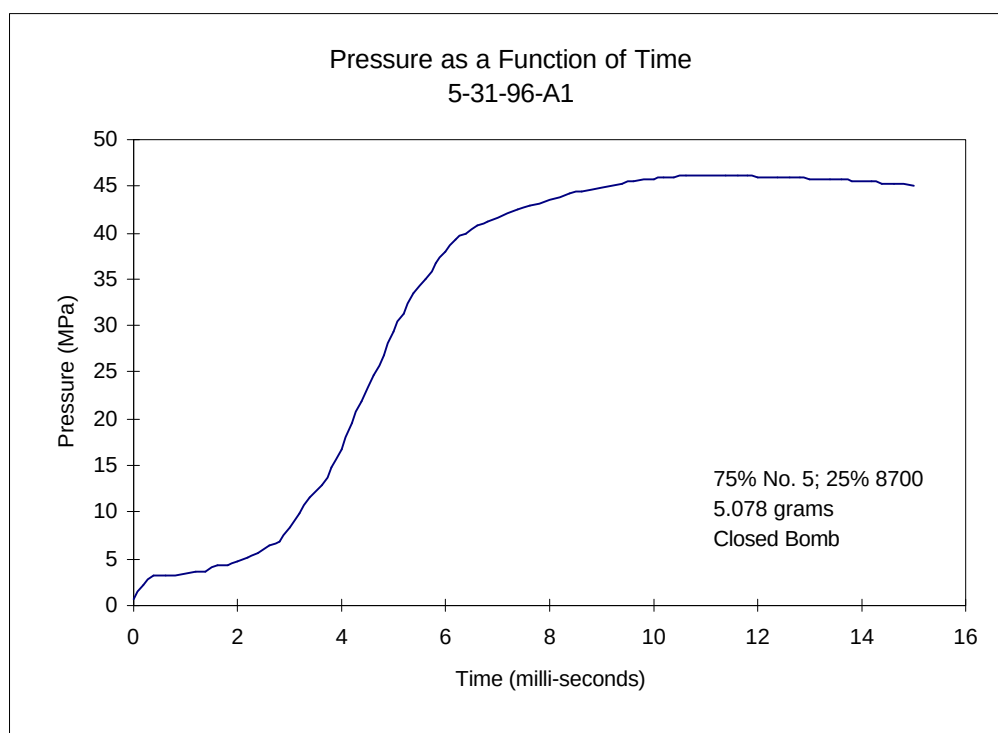


Figure 4-14a: Pressure as a Function of Time, Shot 5-31-96-A1

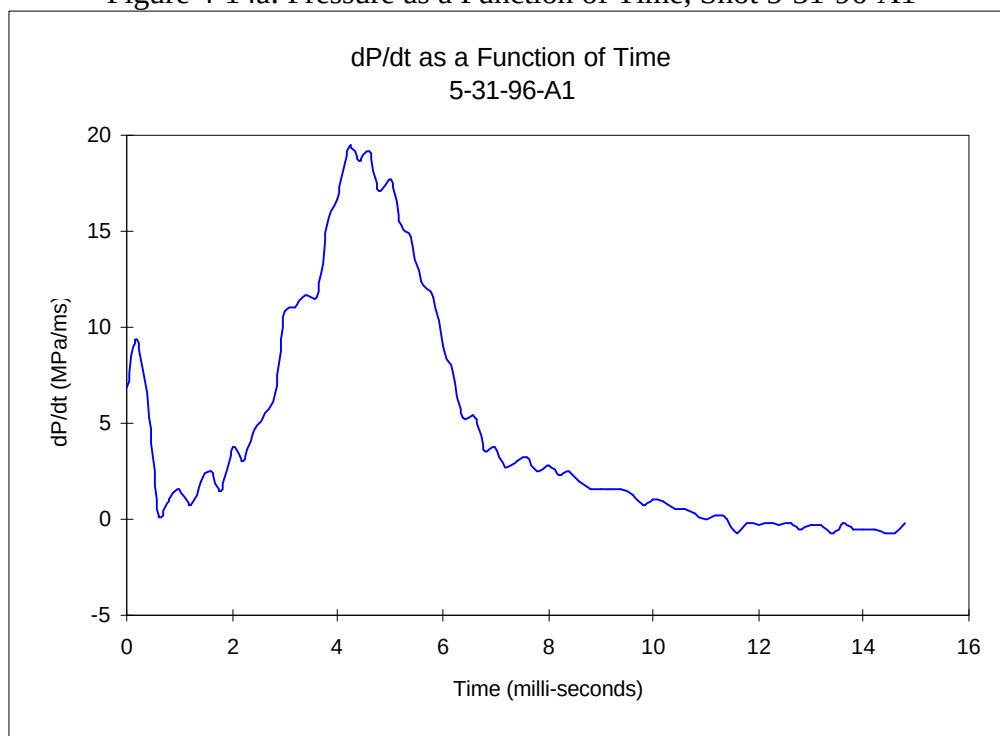


Figure 4-14b: dP/dt as a Function of Time, Shot 5-31-96-A1

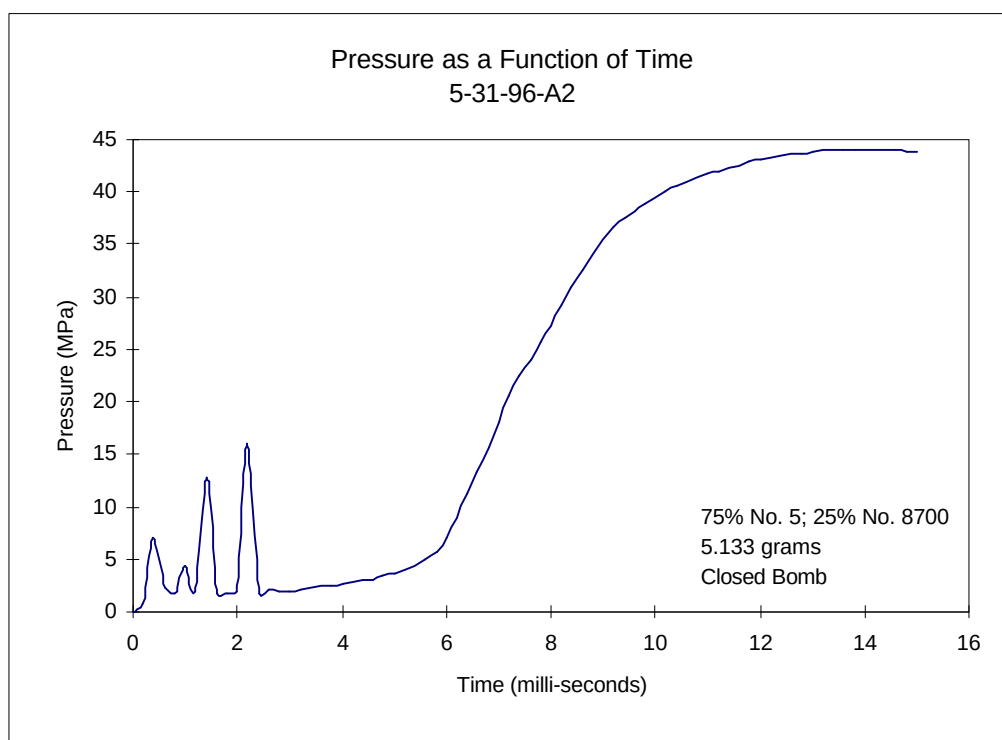


Figure 4-15a: Pressure as a Function of Time, Shot 5-31-96-A2

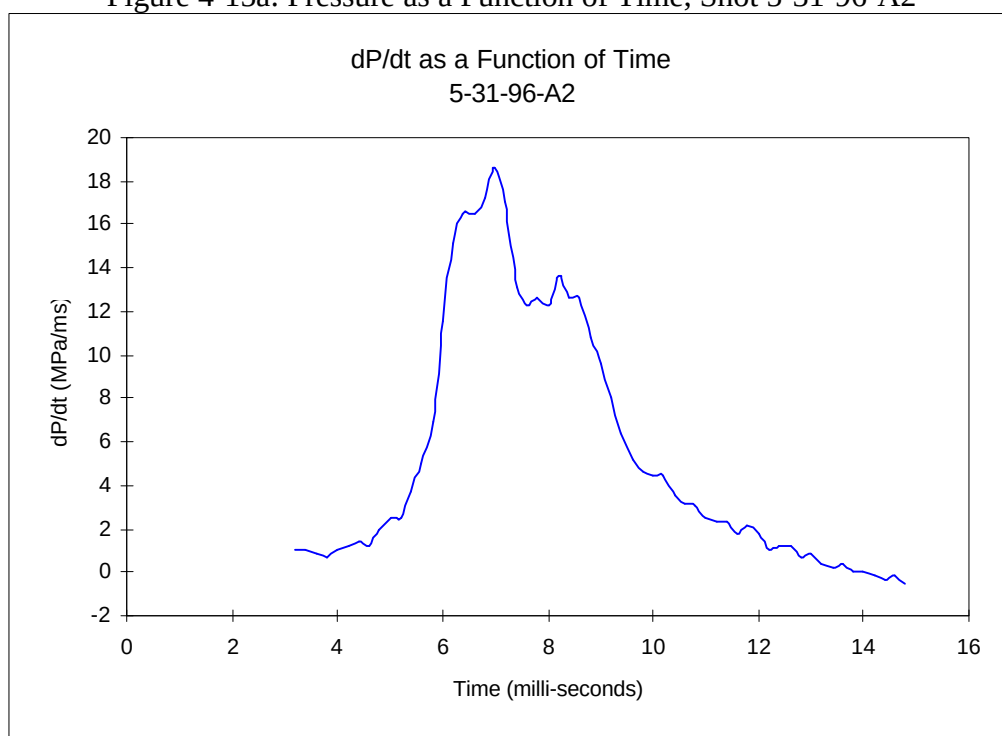


Figure 4-15b: dP/dt as a Function of Time, Shot 5-31-96-A2

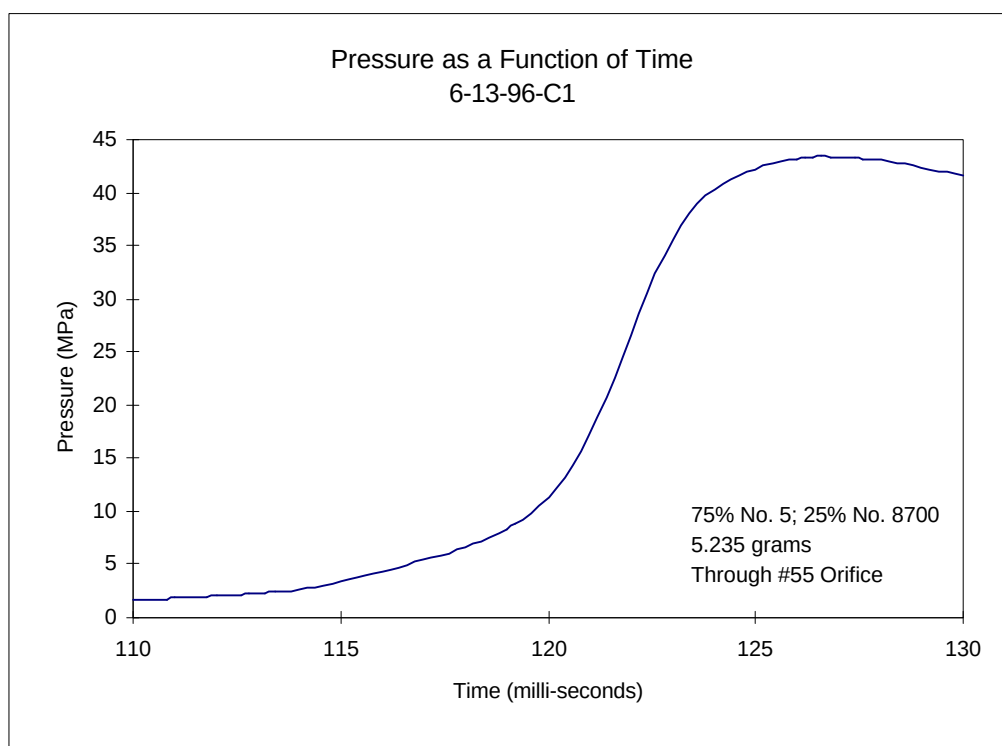


Figure 4-16a: Pressure as a Function of Time, Shot 6-13-96-C1

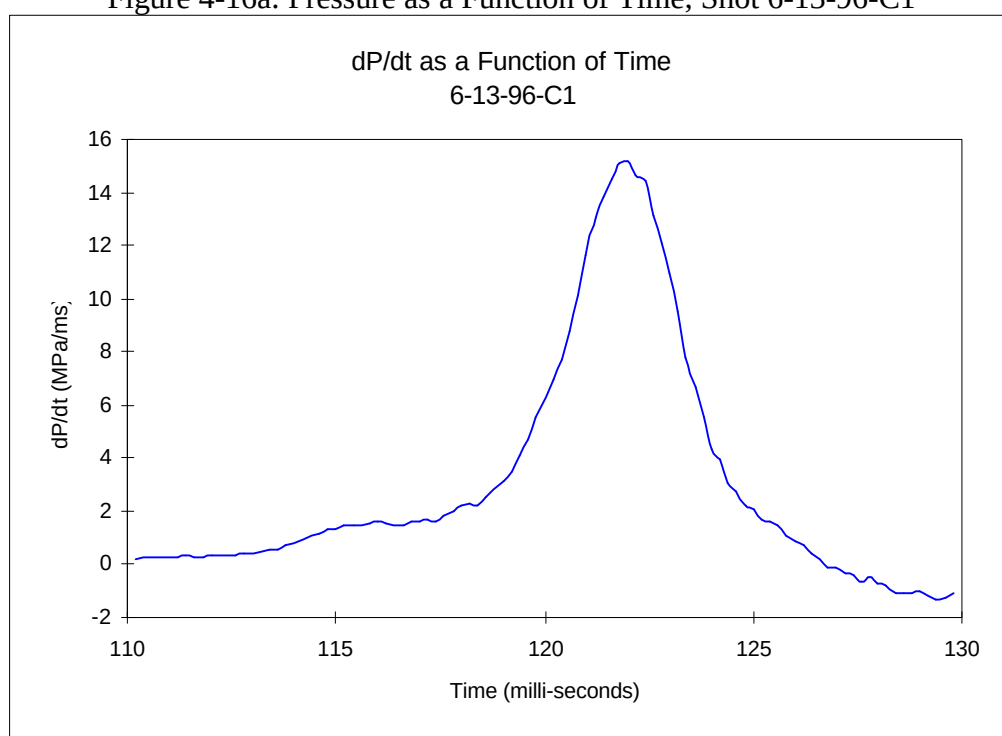


Figure 4-16b: dP/dt as a Function of Time, Shot 6-13-96-C1

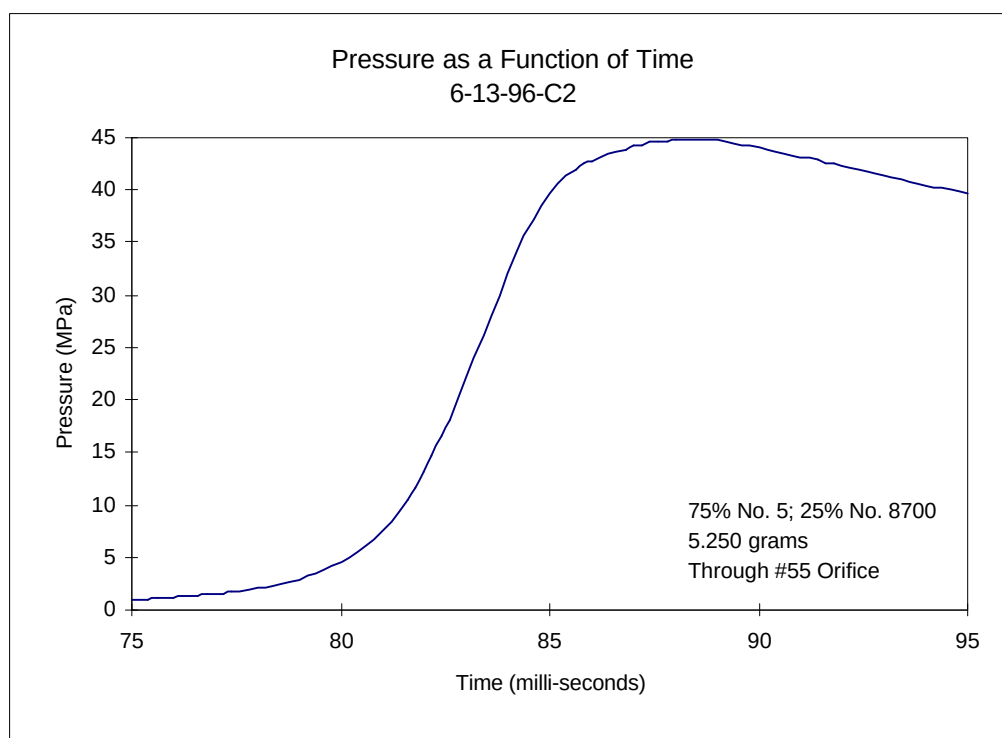


Figure 4-17a: Pressure as a Function of Time, Shot 6-13-96-C2

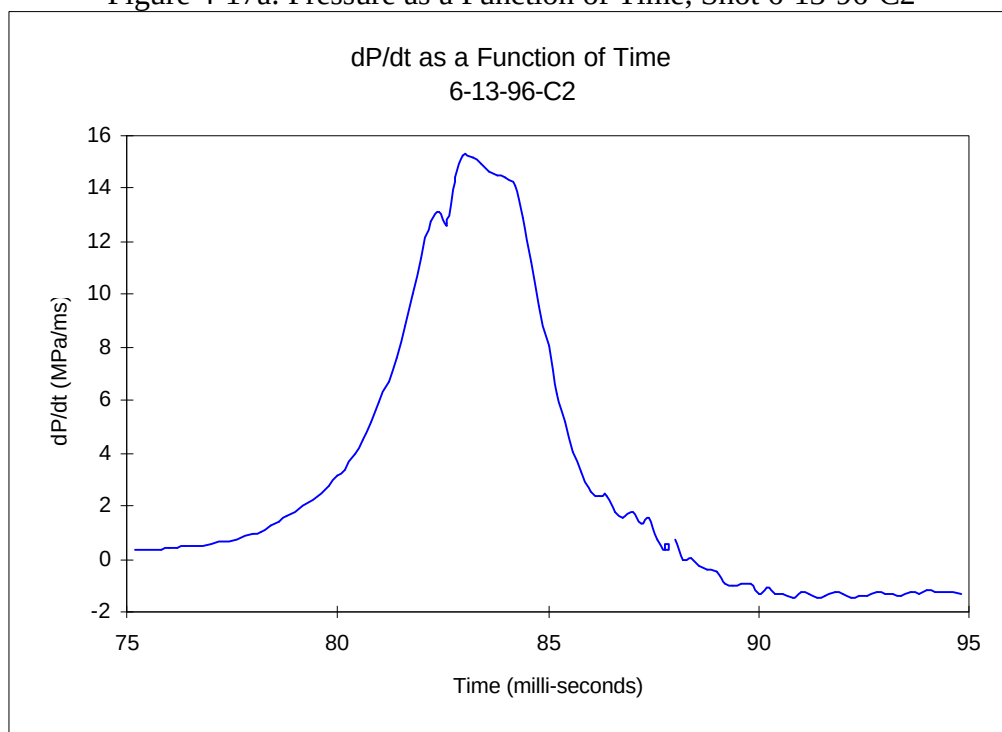


Figure 4-17b: dP/dt as a Function of Time, Shot 6-13-96-C2

4.3.2.3 66 Percent No. 5, 34 Percent No. 8700

This test series consisted of 7 shots with a mixture of 66% Accurate Arms No. 5 and 34% Accurate Arms No. 8700 propellants. The charge weights varied between 2 and 5.85 grams. The shots described below are used in the analysis of burn rate equation parameters in section 4.4.3.

Figure 4-18 illustrates the pressure-time profile of shot 5-29-96-B1. This shot shows a fairly shallow slope for the pressurization rate; although the curve does not seem to have a distinct “break” that was seen in the previous propellant mixture. This trace does not indicate that a detonation event occurred within the propellant charge. The whole shot pressure trace indicates the typical pressure spike associated with the igniter discharge.

Figure 4-19 shows the pressure-time profile of shot 5-29-96-B2. This shot indicates a pressure growth pattern similar to that of the previous test. Again there is not an indication that detonation occurred, and similarly there is a trigger spike, not visible in the figure.

Figure 4-20 is the pressure-time profile of shot 5-29-96-B3. This shot shows two features not visible in the previous shots of the series. First is the very rapid acceleration of pressure growth, with associated oscillations in the pressure trace that are indicative of a light detonation event within the charge. Second, there appears to be a significant period of time following the initial growth of pressure and when peak pressure is reached, a pattern similar to that observed in the previous propellant mixture.

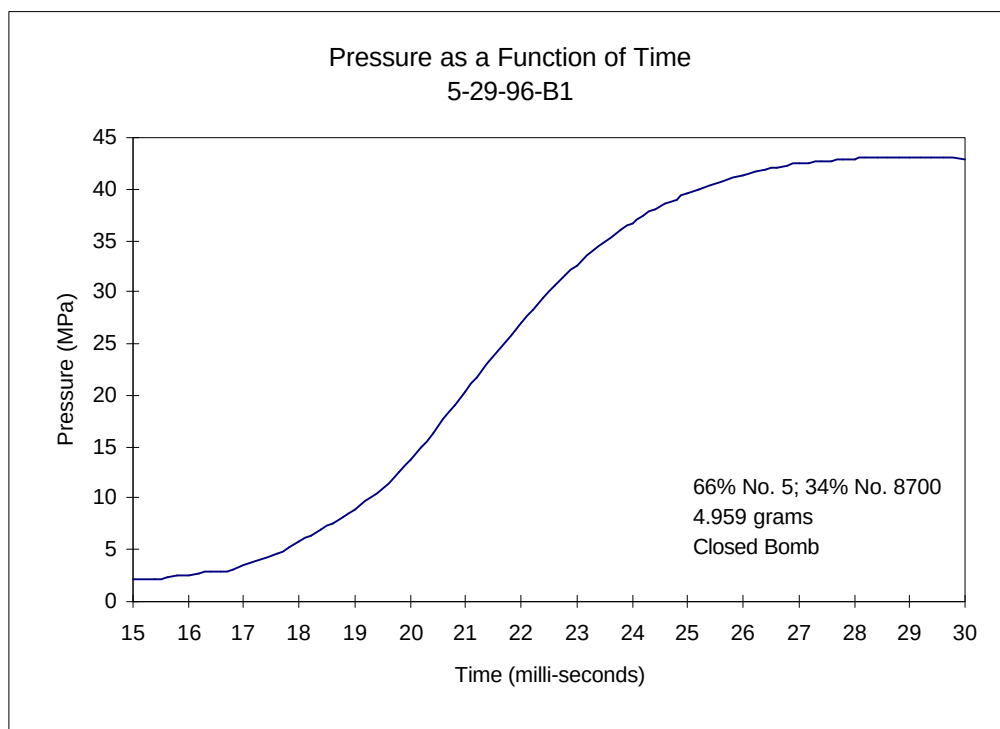


Figure 4-18a: Pressure as a Function of Time, Shot 5-29-96-B1

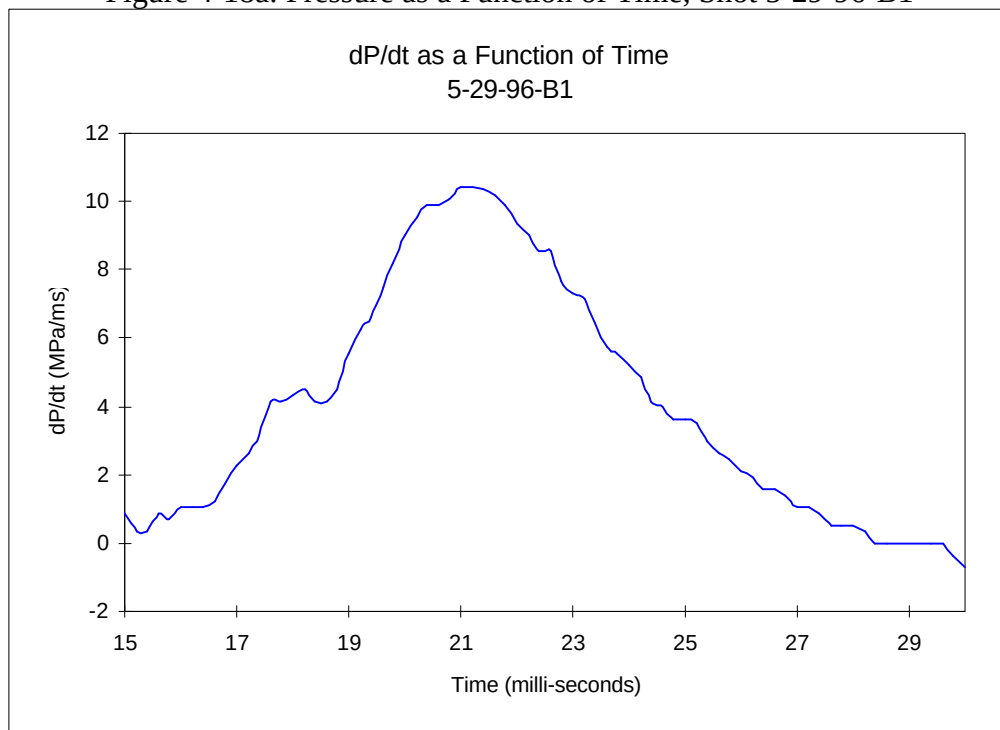


Figure 4-18b: dP/dt as a Function of Time, Shot 5-29-96-B1.

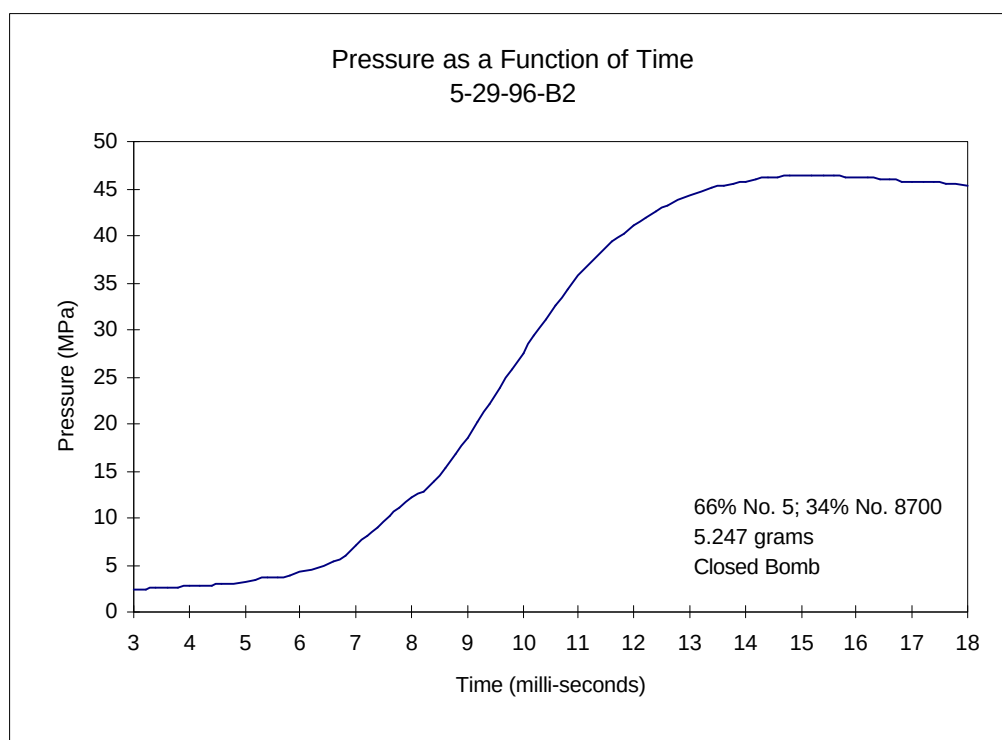


Figure 4-19a: Pressure as a Function of Time, Shot 5-29-96-B2

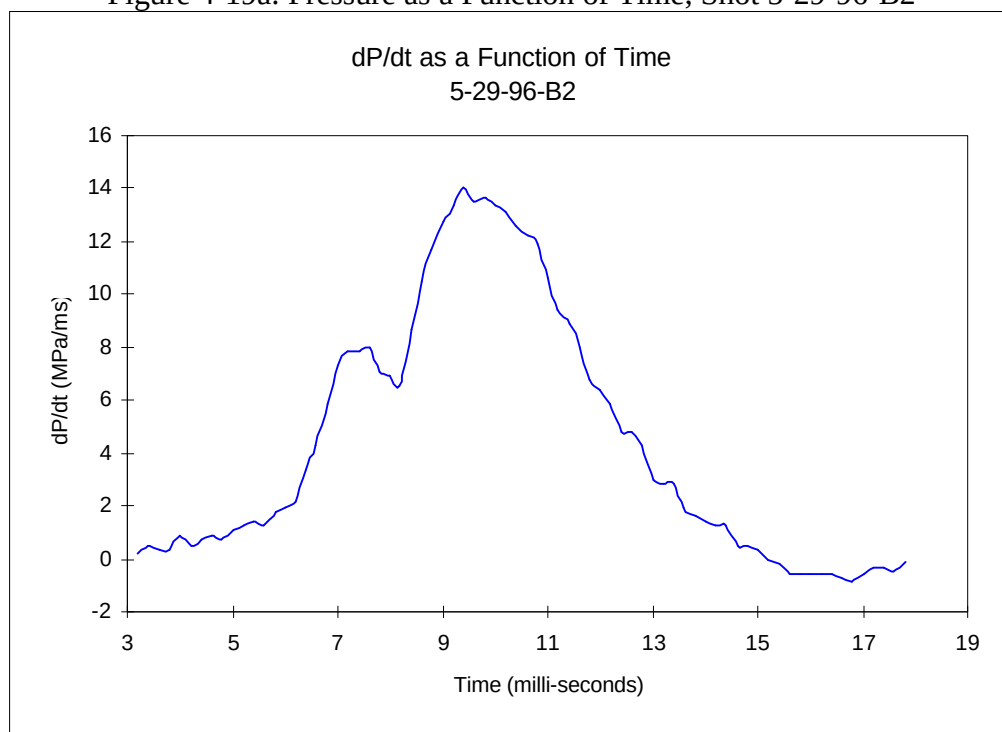


Figure 4-19b: dP/dt as a Function of Time, Shot 5-29-96-B2

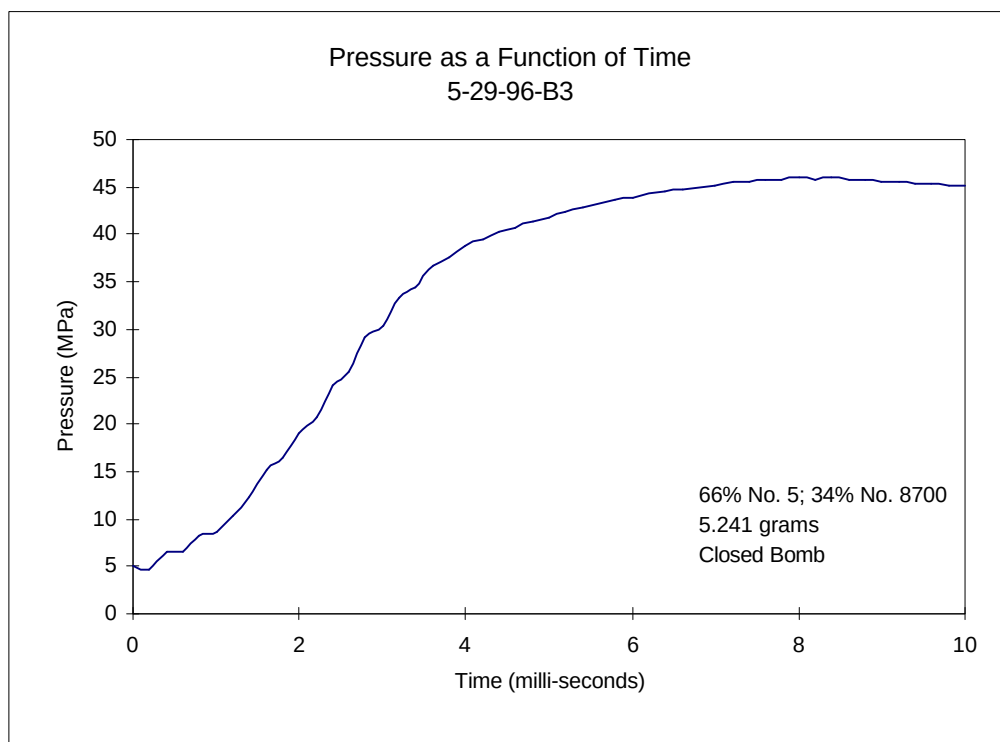


Figure 4-20a: Pressure as a Function of Time, Shot 5-29-96-B3

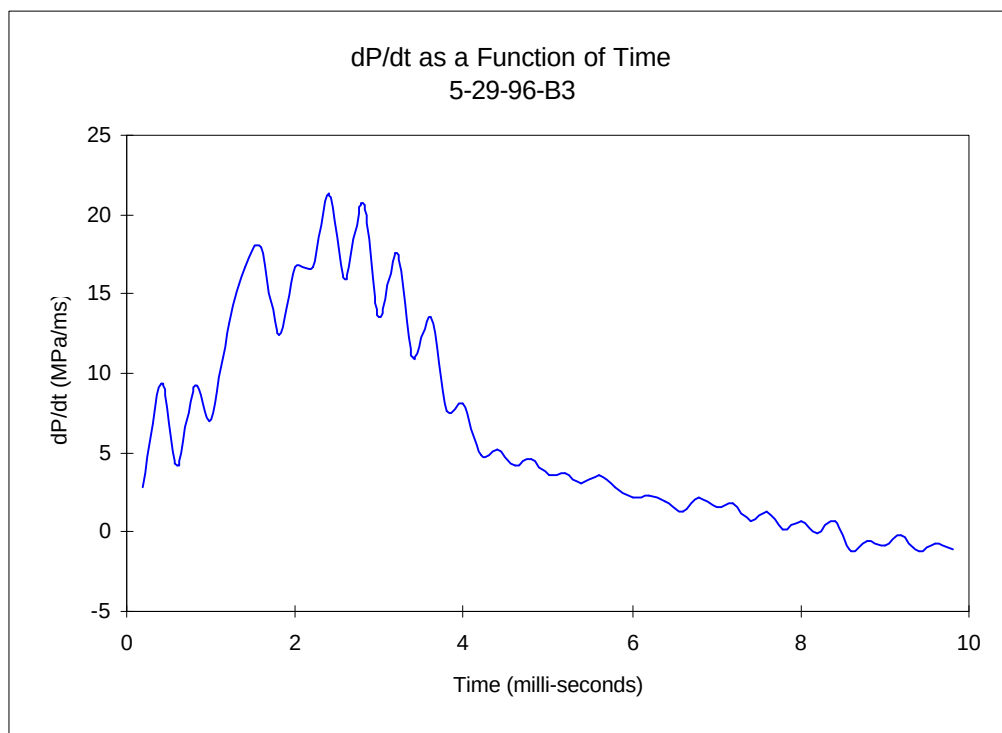


Figure 4-20b: dP/dt as a Function of Time, Shot 5-29-96-B3

4.3.2.4 50 Percent No. 5, 50 Percent No. 8700

This test series consisted of two shots with a charge mixture of 50 percent Accurate Arms No. 5 and 50 percent Accurate Arms No. 8700 propellants. Both had a charge weight of about 5.25 grams. One of the shots was fired with the pressure vessel open to the atmosphere through a 1.3208 mm diameter orifice. The first shot described below is used in the assessment of burn rate equation parameters in section 4.4.4.

The pressure-time profile of test 6-13-96-B1 is illustrated in figure 4-21. This figure illustrates a noticeable change in the pressurization rate at a point about half way along the curve. As in the case of the 75% No. 5, 25% No. 8700 mixture this is likely due to premature burn-out (consumption) of the No. 5 propellant prior to the No. 8700.

Figure 4-22 illustrates the pressure-time profile of shot 6-13-96-B2. This figure is very limited in scope, particularly with respect to the dependent variable. The figure does, however, clearly illustrate the pressure spike associated with the igniter discharge. The echo of the igniter shot is clear in the profile shown, although the peak pressure reached is less than 1 MPa. The entire record of this shot indicates that the pressure begins to grow again near the end of the record. This would indicate that a firing event did occur in which the charge was consumed, however, the recorded pressure does not exceed that recorded in the initiating event, and the pressure increase rate slope is far too low to be of significance. The misfire observed here may be accounted to a propellant mixture too rich in the 8700 propellant. The 100 percent 8700 propellant charges proved incapable of sustaining an ignition, as is addressed in section 4.3.2.5

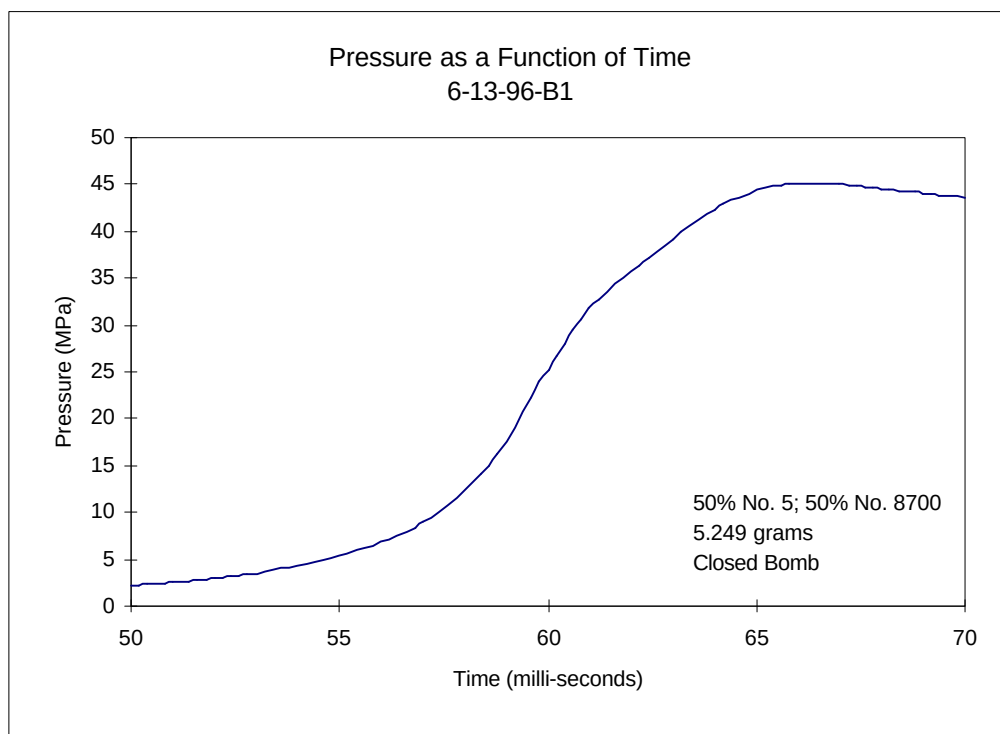


Figure 4-21a: Pressure as a Function of Time, Shot 6-13-96-B1

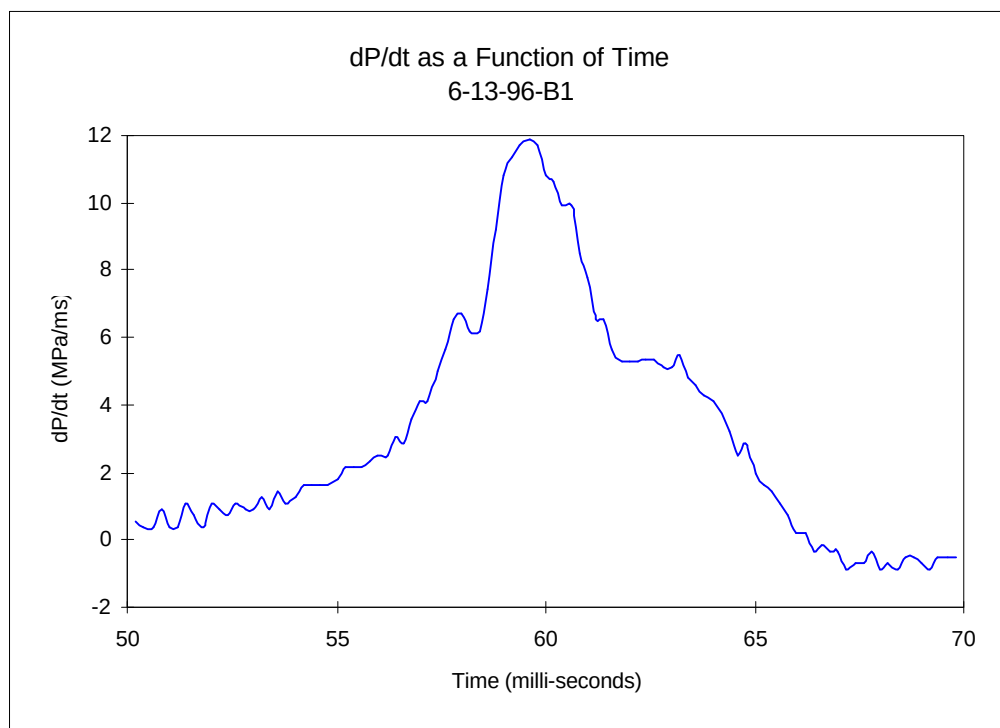


Figure 4-21b: dP/dt as a Function of Time, Shot 6-13-96-B1

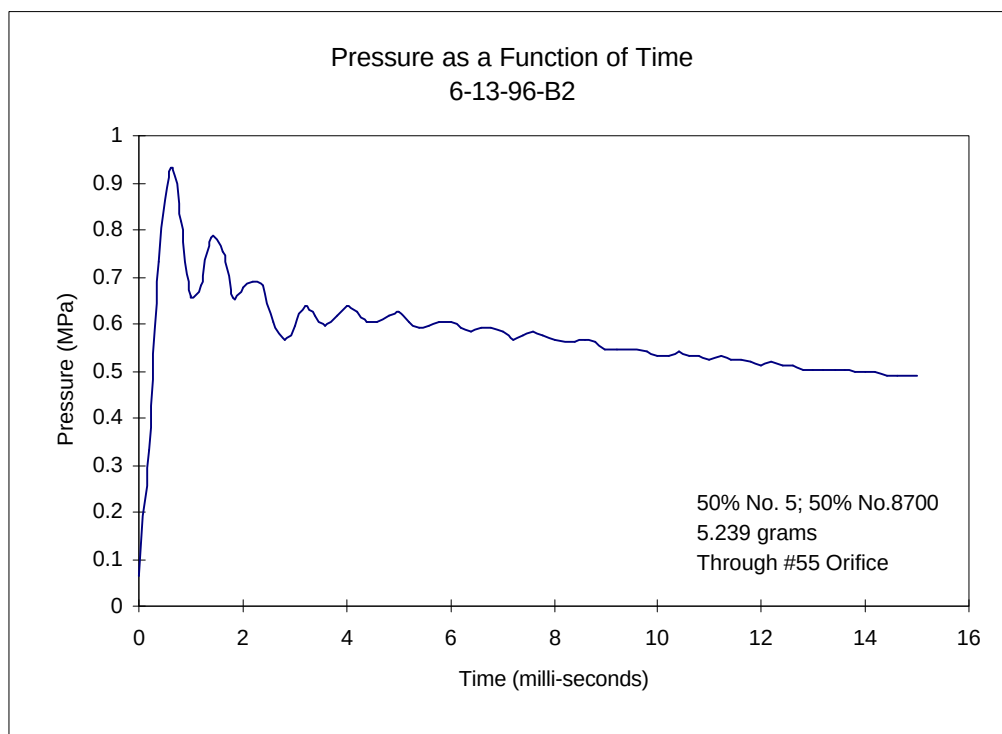


Figure 4-22a: Pressure as a Function of Time, Shot 6-13-96-B2

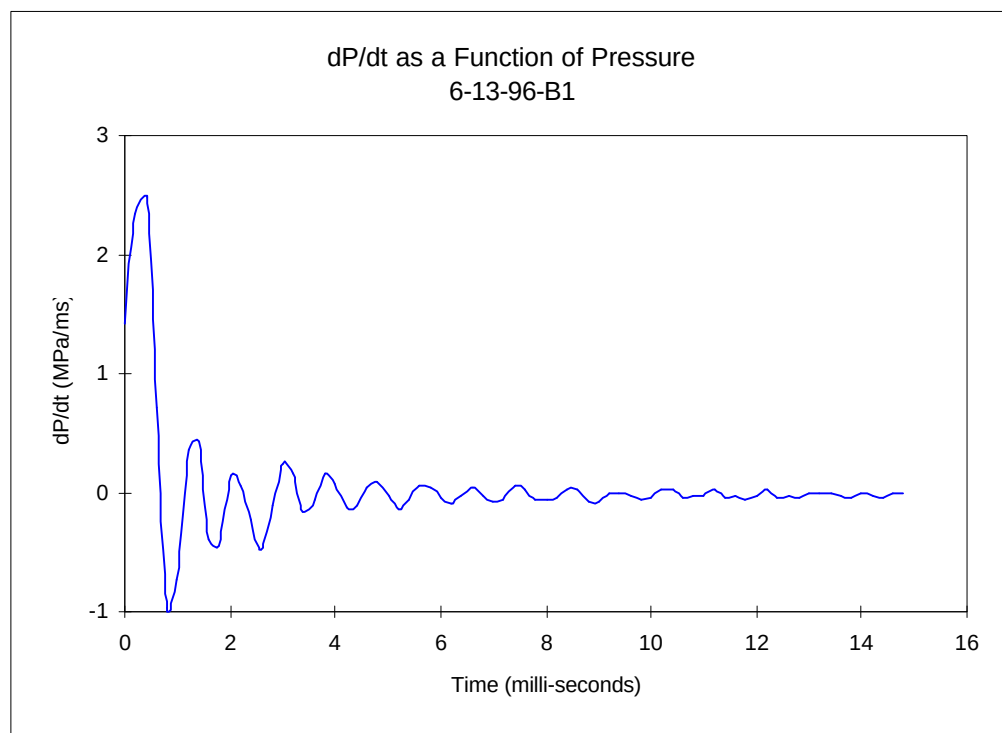


Figure 4-22b: dP/dt as a Function of Time, Shot 6-13-96-B2.

4.3.2.5 100 Percent No. 8700

To determine the lower velocity limit of the powders selected for evaluation a single shot was configured with a charge that was 100% Accurate Arms No. 8700 propellant. This charge proved to be incapable of complete combustion in the test vessel. The initial pressure response was insufficient to trigger the data recorder. When the pressure vessel was opened a significant portion of the charge had been blown out of the case, but remained unburned. Since no data was obtained for record, this test does not appear in table 4-6.

4.3.2.6 75 Percent No. 5, 25 Percent Model Rocket Fuel

A single shot was fired that consisted of a charge mixture of 75 percent Accurate Arms No. 5 propellant and 25 percent model rocket fuel (black powder), crushed to a flour. Using the more volatile black powder it was expected that the pressure rise rate would increase, with a decrease in the peak pressure, relative to the pure smokeless powder charges. Due to the shape and size variety, and the explosive nature, of the black powder no attempt has been made to correlate the linear burn rate to the ambient pressure. The shot number for this was 5-23-96-B.

This charge had a weight of 4.8 grams and produced a peak pressure of 46.38 MPa, a pressure rise rate of 11.16 MPa per milli-second, and a rise time of 3.3 milli-seconds.

4.3.2.7 66 Percent No. 5, 34 Percent Model Rocket Fuel

A single test was also conducted with charge mixture of 66 percent Accurate Arms No. 5 propellant and 34 percent black powder, crushed to a flour. This charge had a weight of 5.37 grams and produced a peak pressure of 47.58 MPa, a pressure rise rate of 13.70 MPa per milli second, and a rise time of 2.8 milli-seconds.

4.3.2.8 50 Percent No. 5, 50 Percent Model Rocket Fuel

A series of four charges were fired utilizing a mixture of 50 percent Accurate Arms No. 5 propellant and 50 percent crushed black powder. These charges varied in weight between 4.25 and 5.23 grams.

Figure 4-23 illustrates the pressure-time profile of shot 6-13-96-A1. This graph shows the typical pressure spike associated with the igniter discharge. Following ignition the pressure indicates a growth pattern of a fairly low slope, although there is evident some echo internal to the bomb. At

a time of about 4 milli-seconds, on the figure, the pressure-time profile rapidly accelerates, followed by periodic oscillation in pressure. This appears to be due to detonation of the black powder combined with the deflagration effects of the smokeless propellant.

Figure 4-24 illustrates, in shot 6-13-96-A2, a pure detonation within the bomb. The peak pressure recorded here appears to be significantly more than that recorded for the more energetic propellant mixtures. Furthermore, the steady-state pressure recorded, following 6 milli-seconds, is on the order of that recorded for similar charges utilizing black powder. The period of oscillation in the pressure wave is consistent with the predicted conditions inside of the bomb, as described in section 4.5.2.

Figure 4-25 illustrates the pressure-time profile generated during shot 6-5-96-B1. This shot illustrates two spikes that are significantly greater in magnitude than the peak pressure of the main trace event. It is interesting to observe that the lower values of the pressure spikes appear to follow in line with the main event.

Figure 4-26 shows the pressure-time record of shot 6-5-96-B2. This event appears to show the opposite of the previous shots in this mixture. It would appear that even with the black powder mixture a deflagration event occurred without evidence of detonation.

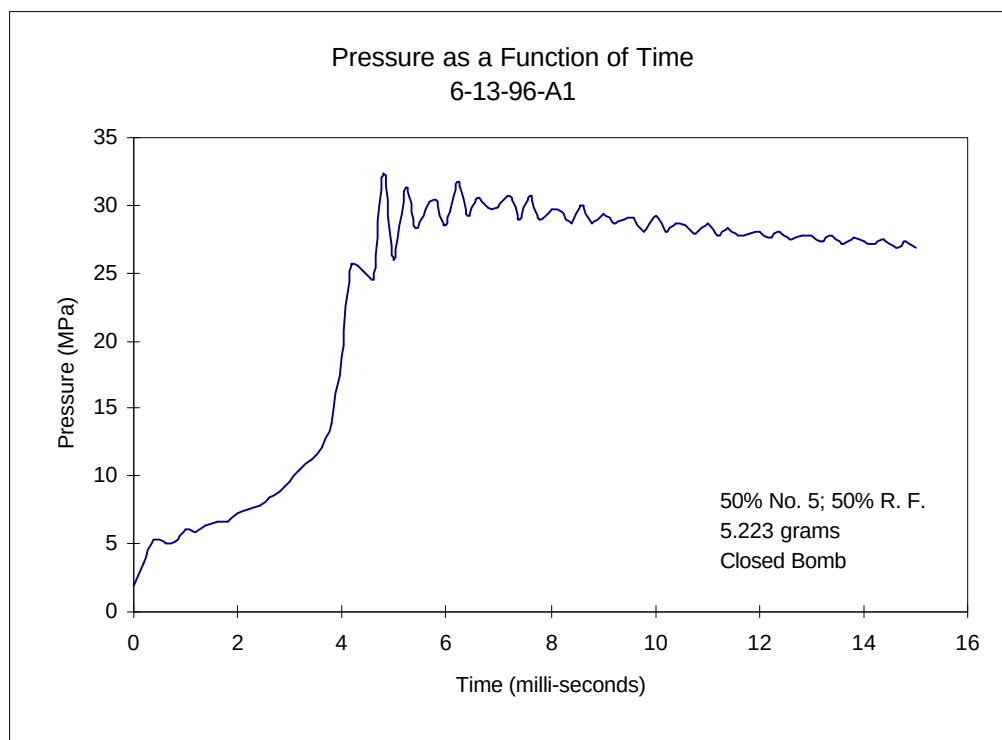


Figure 4-23a: Pressure as a Function of Time, Shot 6-13-96-A1

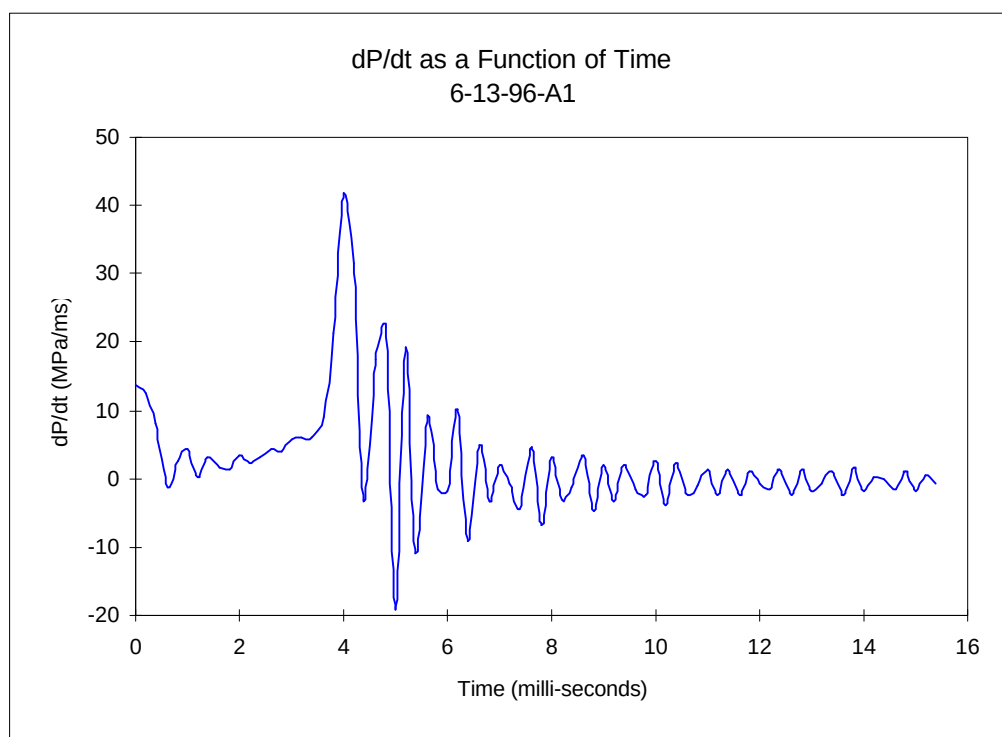


Figure 4-23b: dP/dt as a Function of Time, Shot 6-13-96-A1

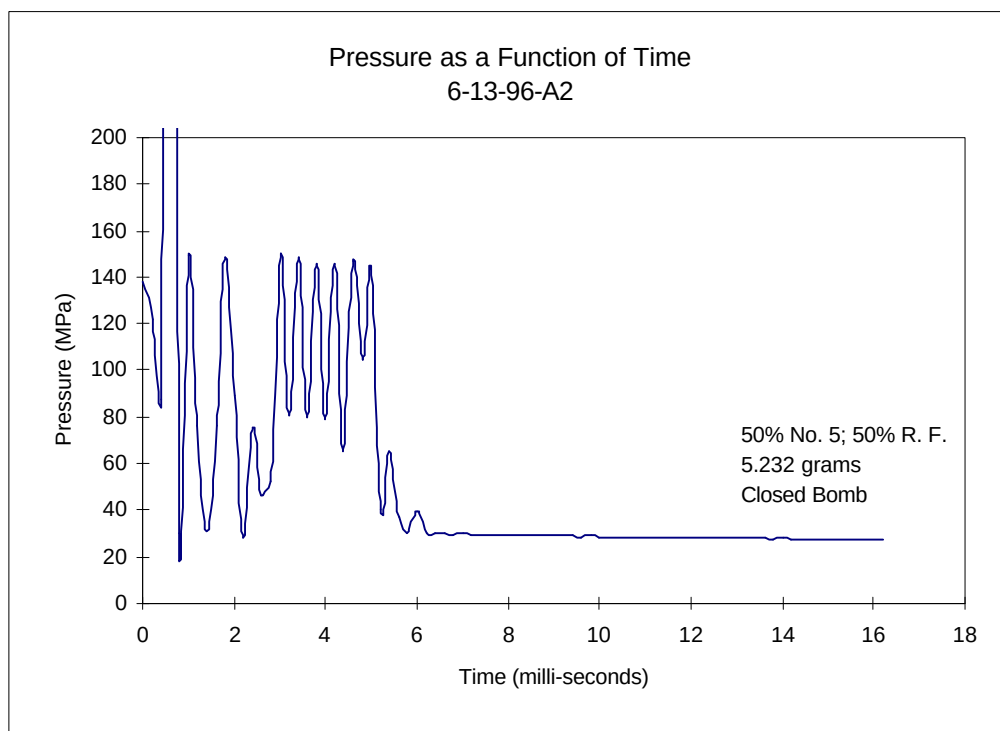


Figure 4-24a: Pressure as a Function of Time, 6-13-96-A2

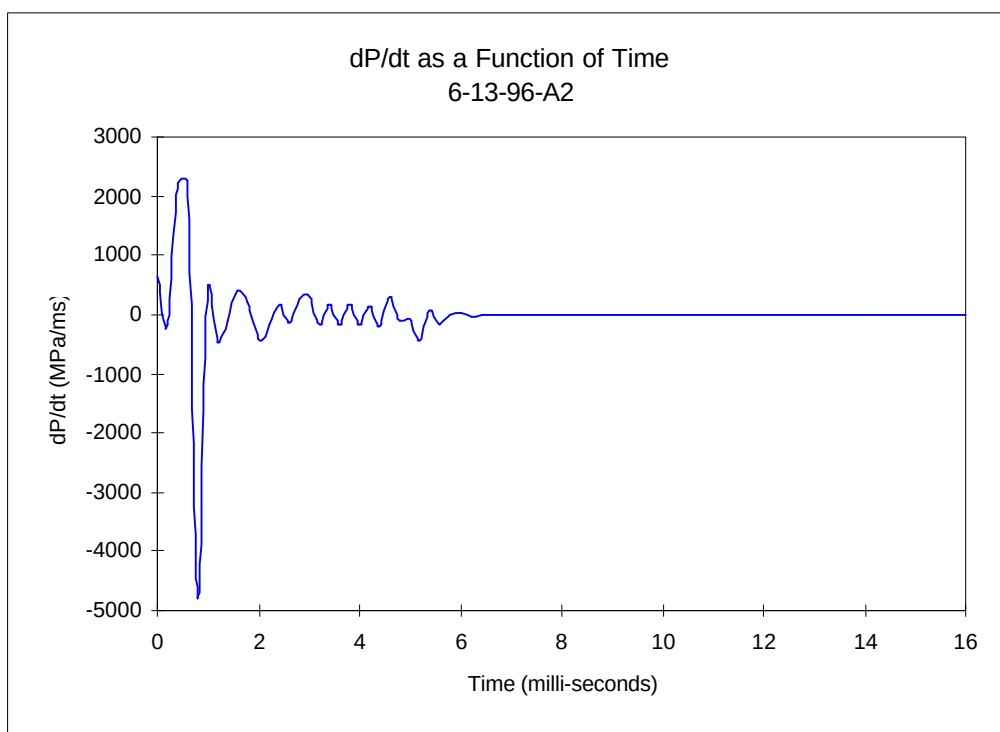


Figure 4-24b: dP/dt as a Function of Time, Shot 6-13-96-A2

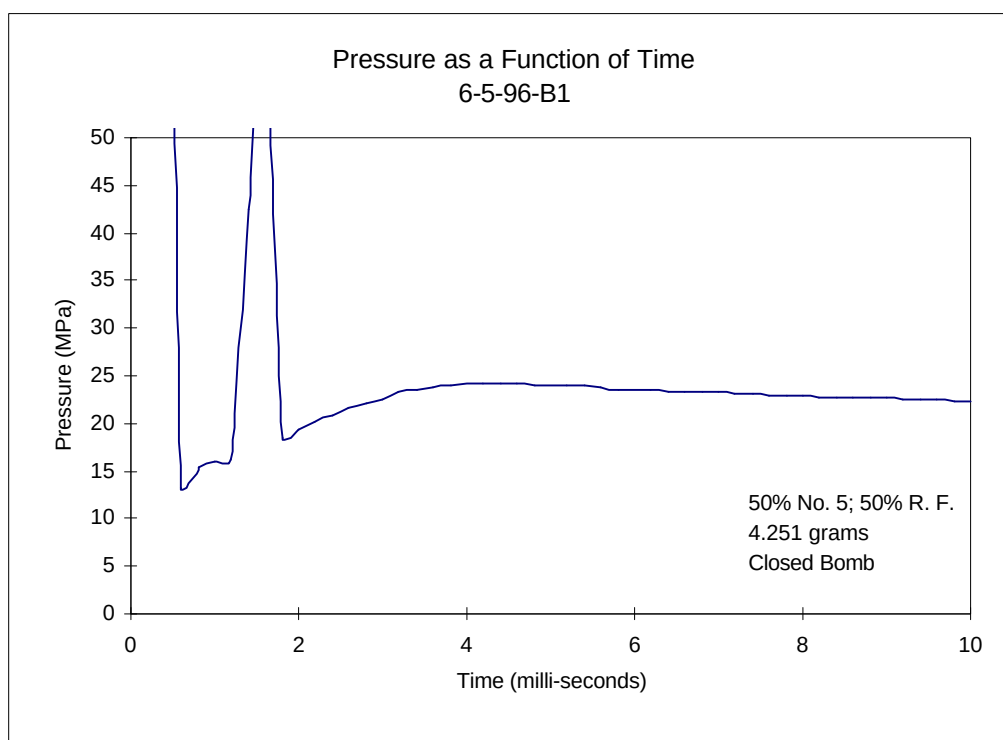


Figure 4-25a: Pressure as a Function of Time, Shot 6-5-96-B1

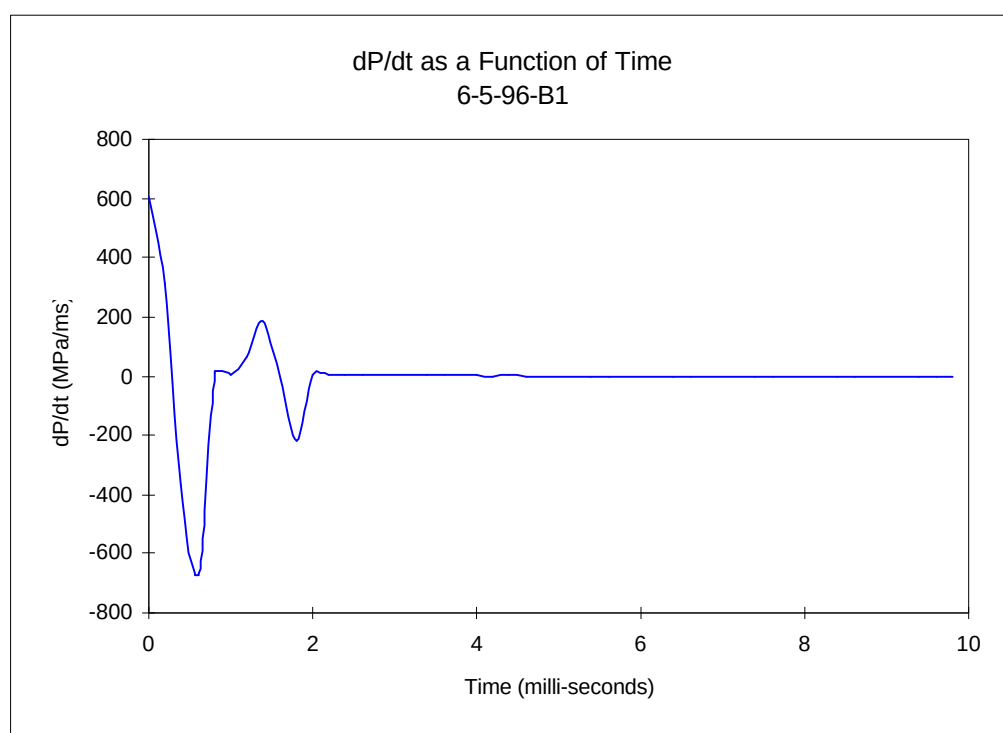


Figure 4-25b: dP/dt as a Function of Time, Shot 6-5-96-B1

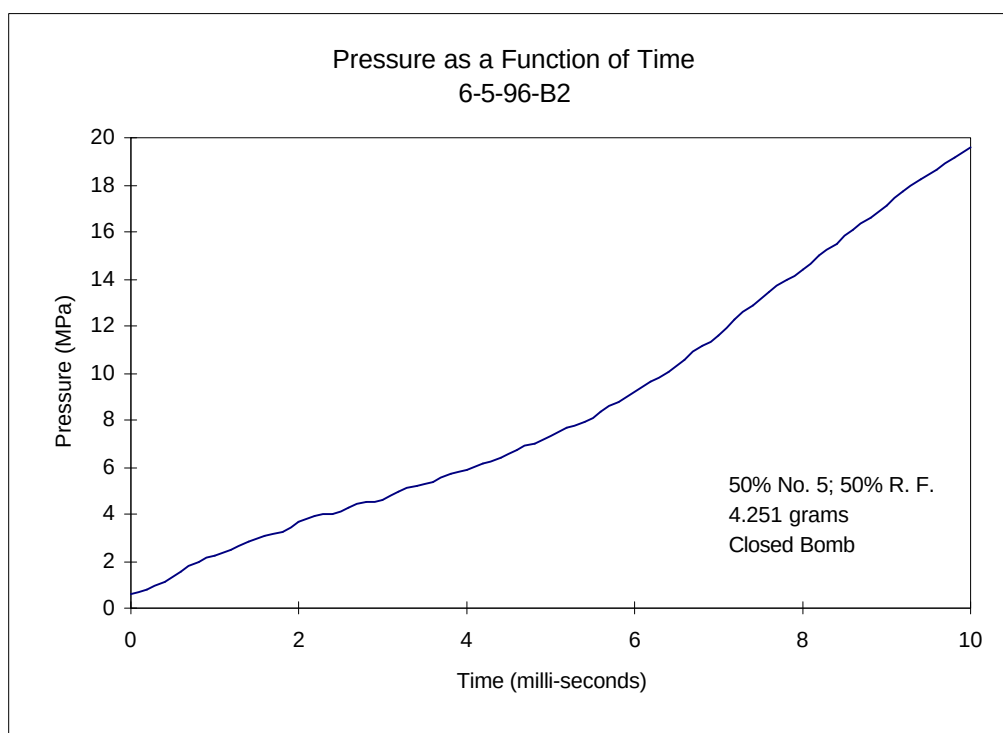


Figure 4-26a: Pressure as a Function of Time, Shot 6-5-96-B2

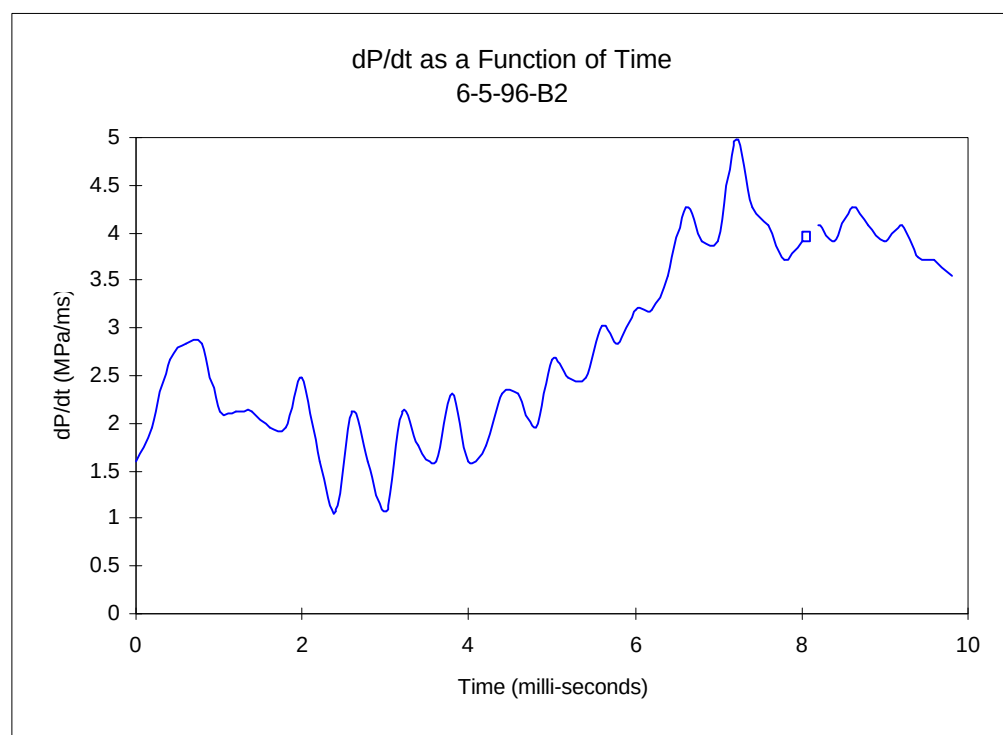


Figure 4-26b: dP/dt as a Function of Time, Shot 6-5-96-B2.

4.3.2.9 100 Percent Model Rocket Fuel

Two charges of 100 percent black powder were fired. These charges both weighed about 5.25 grams, net. Between these two samples the pressure rise time and the pressure rise rate showed a significant variation, (0.4 vs. 0.7 ms, and 34.7 vs. 22.3 MPa/ms respectively). The peak pressures obtained, however, were consistent, 21.12 and 19.91 MPa.

The lower peak pressure observed for this fuel indicates the lower amount of energy available per unit mass in the black powder relative to the propellants. Figures 4-27 and 4-28 indicate that detonations occurred in both cases. The period of the oscillations are consistent with a pressure wave reflecting in the conditions predicted in the pressure vessel.

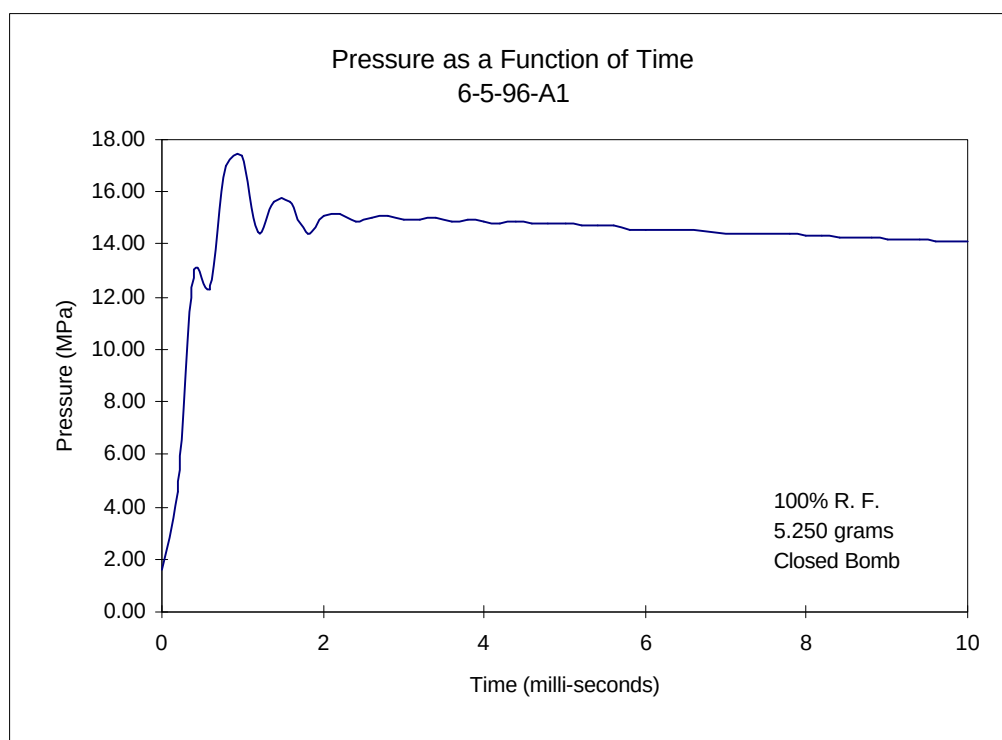


Figure 4-27a: Pressure as a Function of Time, Shot 6-5-96-A1

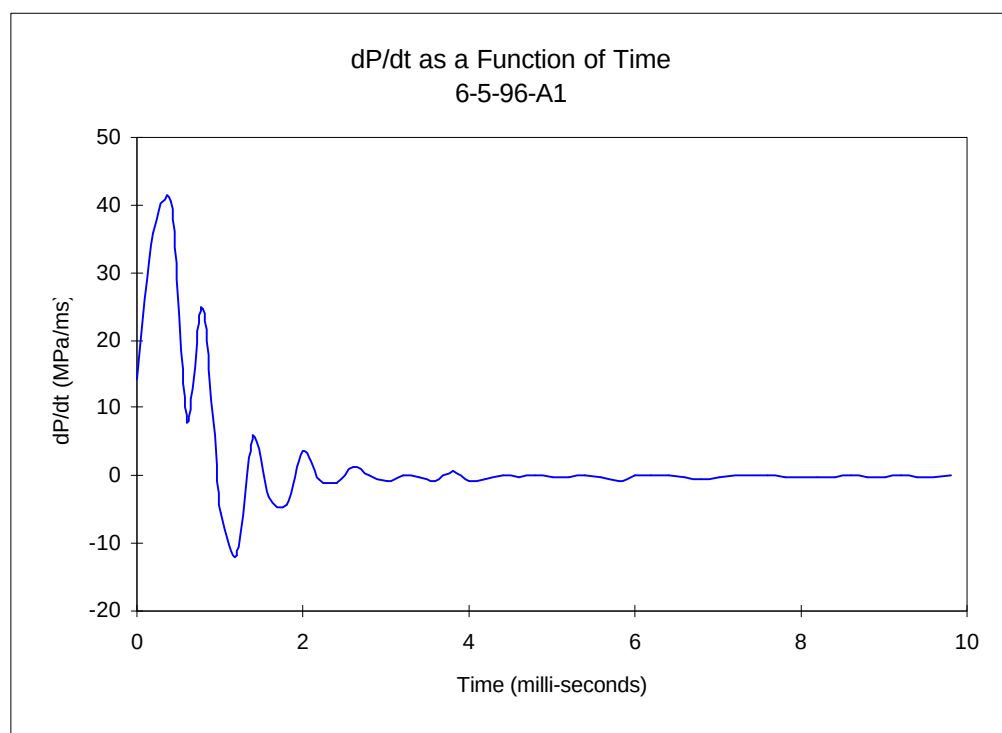


Figure 4-27b: dP/dt as a Function of Time, Shot 6-5-96-A1

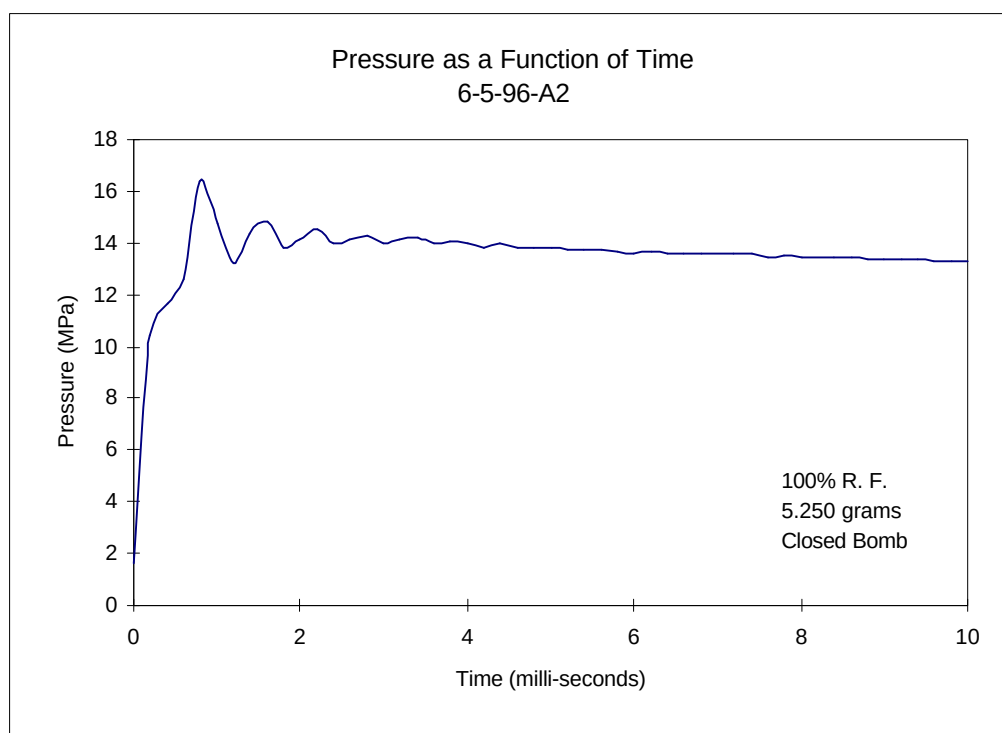


Figure 4-28a: Pressure as a Function of Time, Shot 6-5-96-A2.

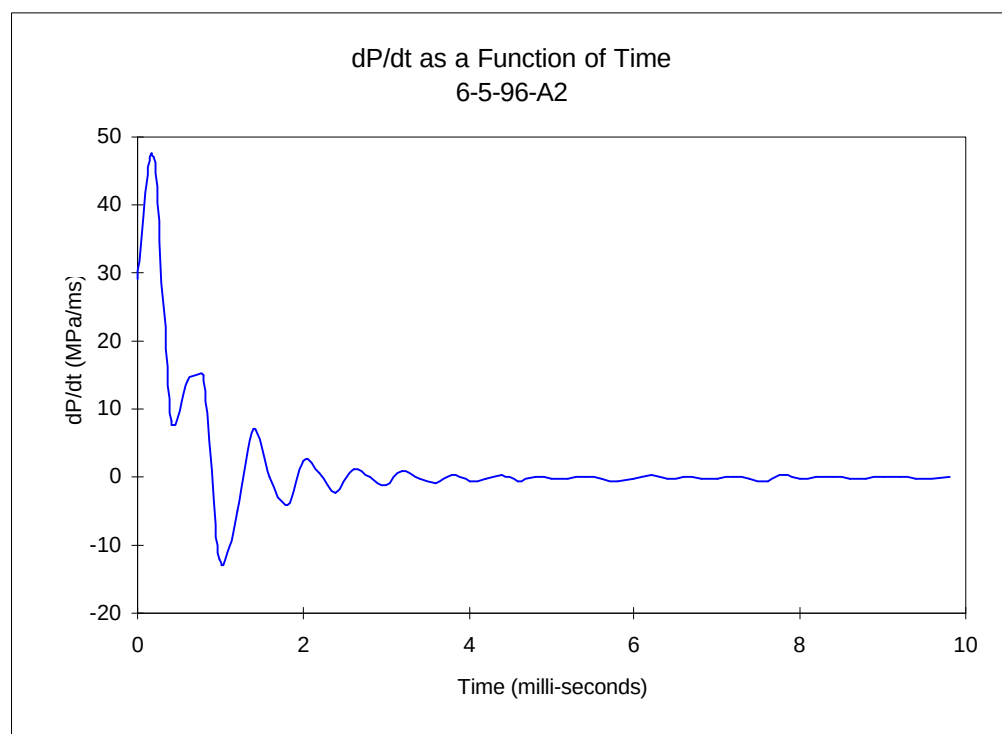


Figure 4-28b: dP/dt as a Function of Time, Shot 6-5-96-A2.

4.3.2.10 100 Percent No. 2 - Improved

Three test shots of the No. 2 - Improved powder for Accurate Arms were conducted with charge weights of about 3.3 grams. These charges had the same volume as those charges of approximately 5.25 grams of the No. 5 and No. 8700 powders. The reduced mass is consistent with differences in the bulk densities between the powders.

On a charge weight basis there appears to be little difference between the No. 2 - Improved and the No. 5 powders.

With the exception of shot 6-19-96-A3, figures 4-30a and b, all of the No. 2 - Improved charges have a very sharp pressure spike at the time of initiation; figures 4-29a and b, 4-31a and b, and 4-32a and b. For these shots the peak pressure pulse, associated with ignition is of a magnitude twice that of the pressure indicated at the charge burnout.

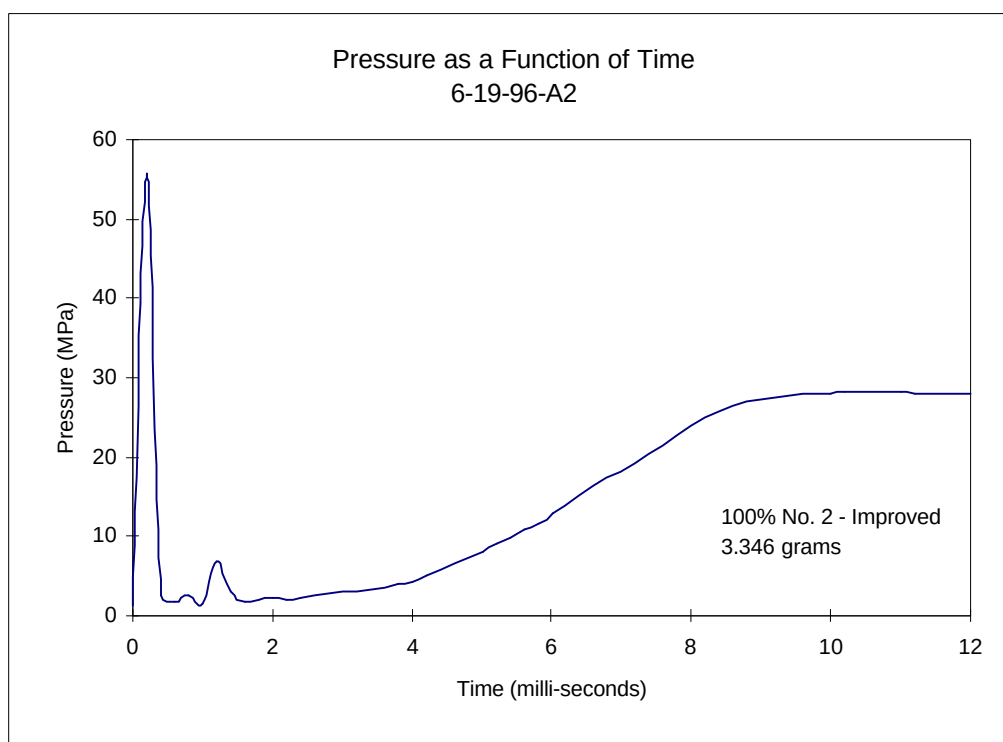


Figure 4-29a: Pressure as a Function of Time, Shot 6-19-96-A2

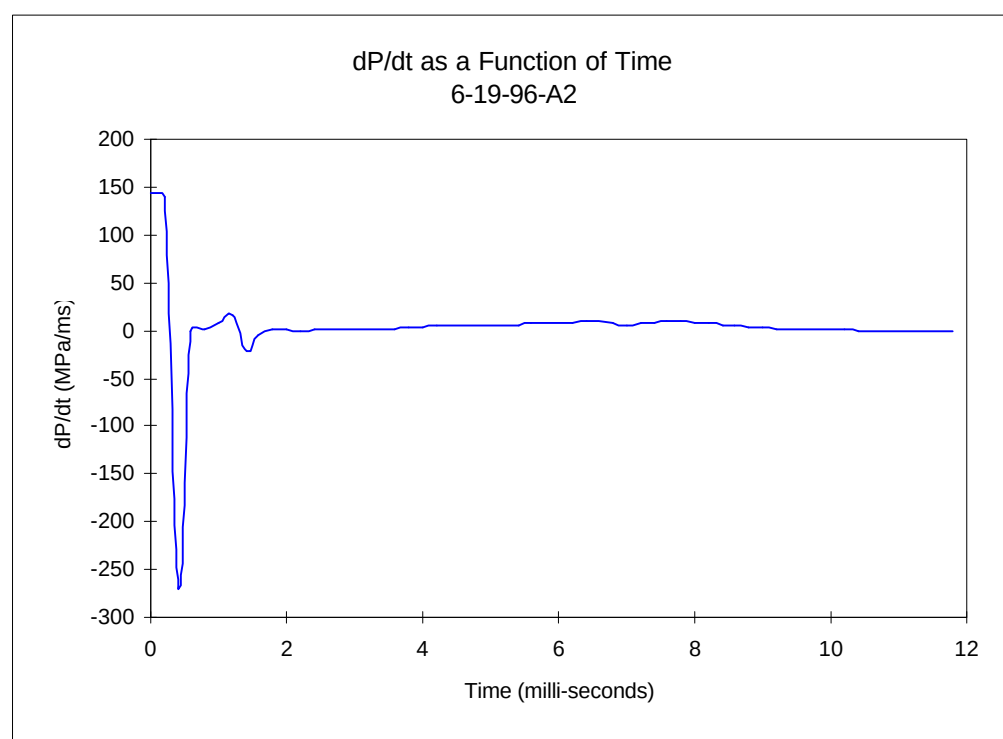


Figure 4-29b: dP/dt as a Function of Time, Shot 6-19-96-A2.

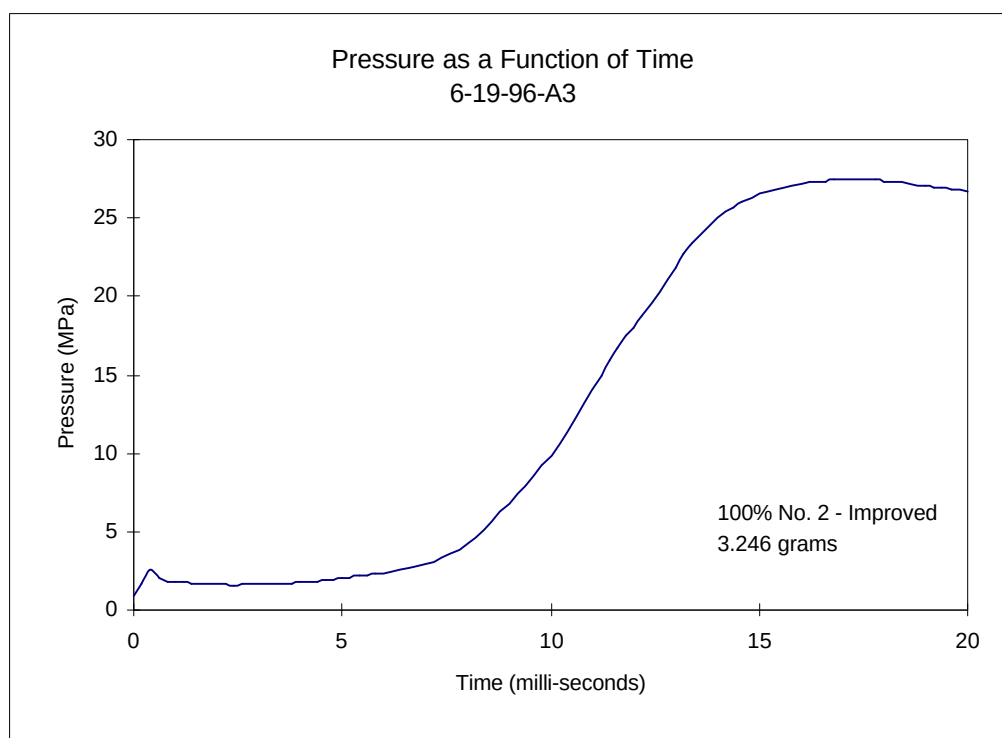


Figure 4-30a: Pressure as a Function of Time, 6-19-96-A3.

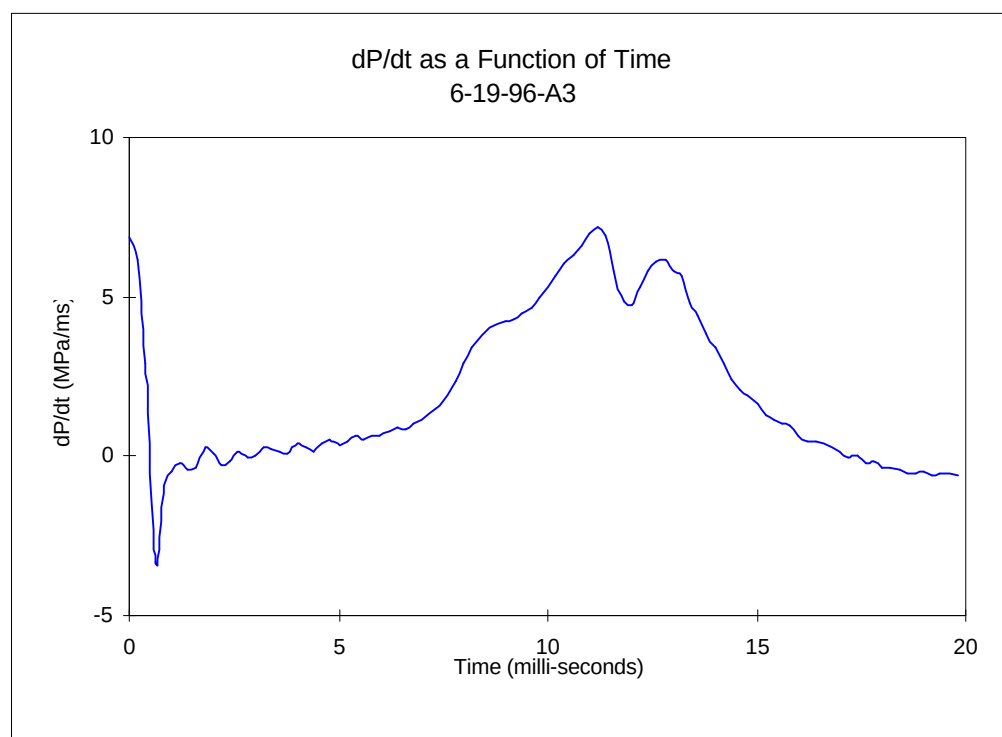


Figure 4-30b: dP/dt as a Function of Time, Shot 6-19-96-A3

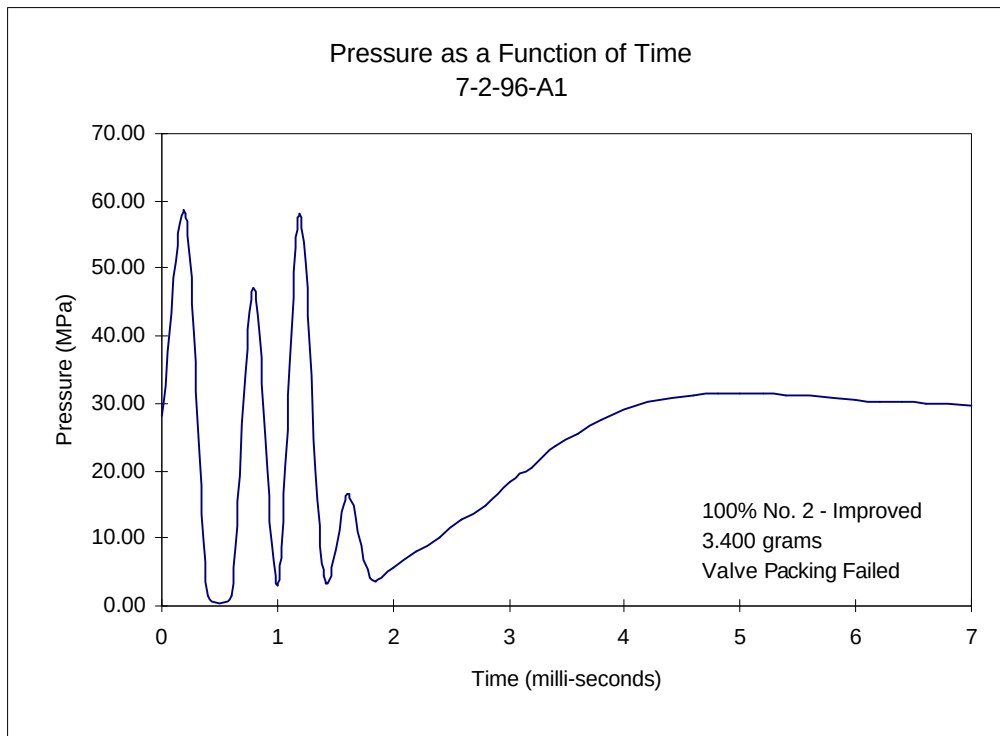


Figure 4-31a: Pressure as a Function of Time, Shot 7-2-96-A1.

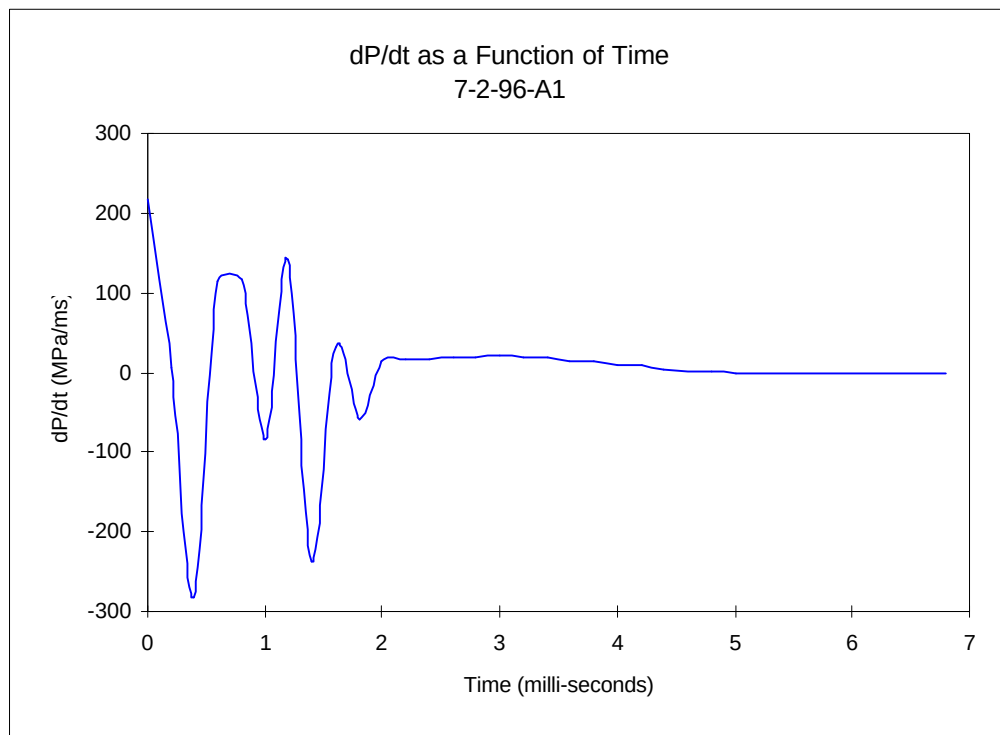


Figure 4-31b: dP/dt as a Function of Time, Shot 7-2-96-A1

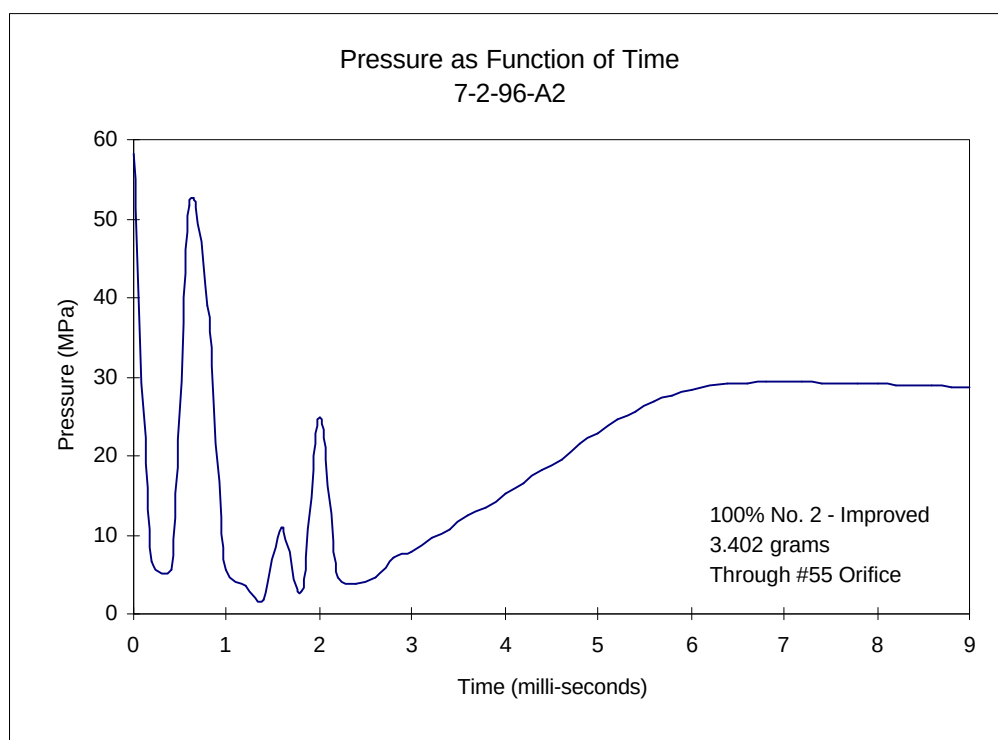


Figure 4-32a: Pressure as a Function of Time, Shot 7-2-96-A2.

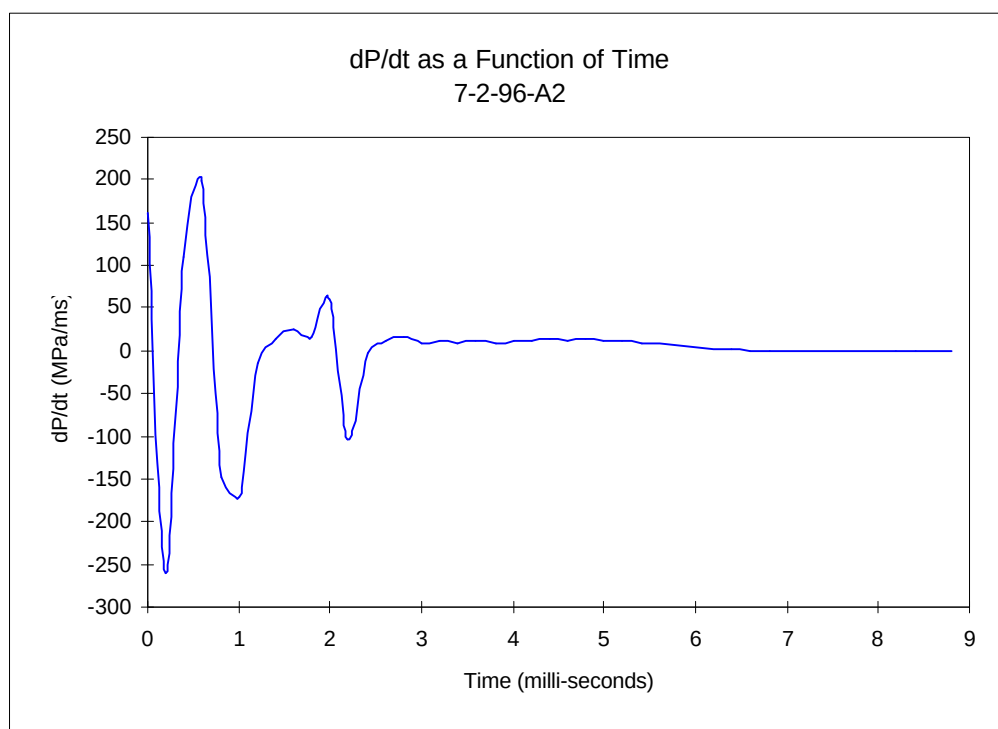


Figure 4-32b: dP/dt as a Function of Time, Shot 7-2-96-A2.

4.3.2.11 100 Percent Commercial Black Powder

Five shots were made and recorded utilizing commercial black powder. Rather than being a propellant, black powder is an explosive. Despite the much faster burn rate the black powder is far less energetic than the smokeless propellants investigated. The reduced energy is visibly indicated by the lower peak pressures observed in traces recorded during these shots.

Figure 4-33 illustrates the pressure-time and first derivative of pressure with respect to time for shot 7-2-96-B1. This trace indicates a very sharp pressure rise through the first milli-second, then following a brief decrease of pressure, the pressure slowly builds to its maximum value. There is evidence of some echoing of the initial pressure pulse in the middle stages of this pulse. These are evident on both the pressure and first derivative of pressure with respect to time curve.

Figure 4-34 shows the pressure and first derivative of pressure as a function of time for shot 7-2-96-B2. This shot was fired in a closed bomb configuration. These graphs, again, seem to indicate that the powder reacted in a detonation, rather than a deflagration. As with the previous example, this shot begins with a steep increase in pressure. Following the first echo, the rate at which the pressure increases begins to fall off and the peak pressure is approached slowly, compared to the initial pressure rise rate. From the dP/dt graph (4-34b), it appears that the magnitude of the echoes decays at an exponential (or hyperbolic) rate. This could indicate that the main wave was initiated during the detonation and slowly decays by reflection and expansion, following the burnout of the powder.

Figure 4-35 shows the pressure-time and first derivative of pressure with respect to time for shot 7-2-96-B3. This shot was conducted in a closed bomb configuration. The graphs indicate similar results to the previous cases of black powder in this configuration. The time to the initial, local maximum pressure is consistent with the previous examples, however, the shot appears to have taken a little more time in initial ignition. This is seen in 4-35b, in the initially negative slope of the dP/dt curve. The graph also indicates the consistent decaying amplitude of this parameter.

Shots 7-2-96-C1 and C2 were fired in a vented bomb configuration, utilizing a 1.3208 mm diameter (#55 drill) nozzle. Figure 4-36 illustrates the results from the C1 test. The first relative maximum occurs slightly later than those observed in the closed bomb tests, which may actually be due to the capture of the zero time very close to the initial zero pressure point. In addition the pressure trace indicates a brief step at about 0.6 milli-seconds. This could be associated with either a change in the powder burn-rate or a partial reflection of a wave within the bomb.

Figure 4-37 shows the results obtained in shot 7-2-96-C2. This shot is characterized by what appears to be a very straight pressure slope up to the first point of reflection. The first derivative of pressure with respect to time, however, shows that the slope of this line is decreasing. Again,

as with the previous examples for the black powder the pressure rises rapidly to the initial reflection, then the rate of pressure growth drops rapidly. Along with the previous shot, there is a definite decay in the rate at which the dP/dt curve is falling, however, it appears to be less bounded than those observed in the closed bomb tests.

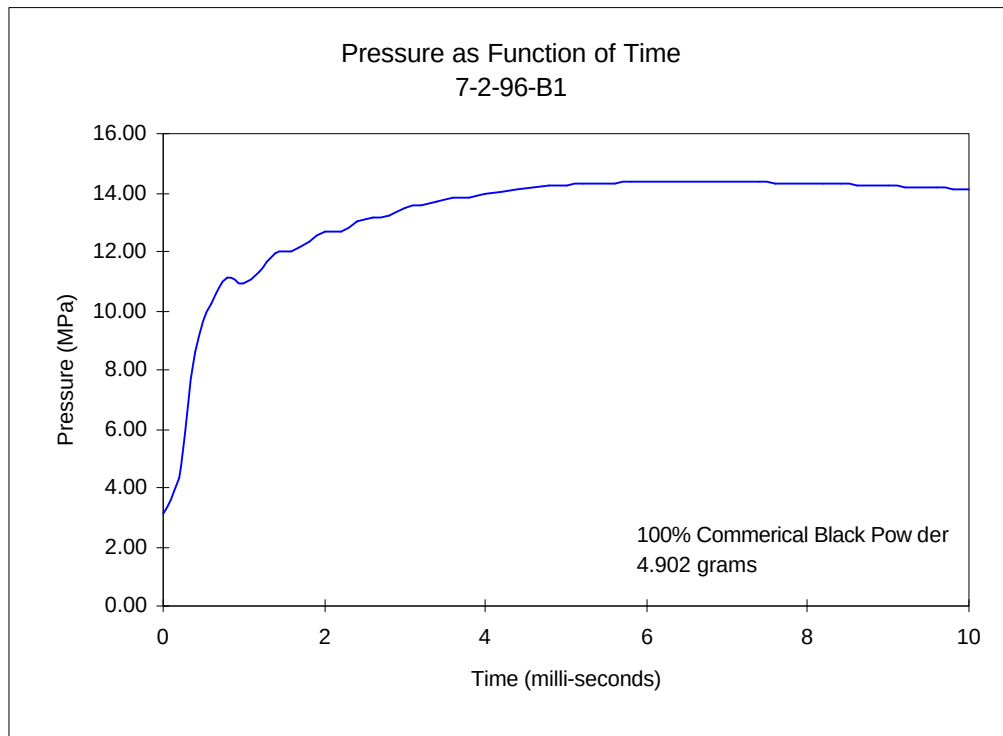


Figure 4-33a: Pressure as a Function of Time, Shot 7-2-96-B1

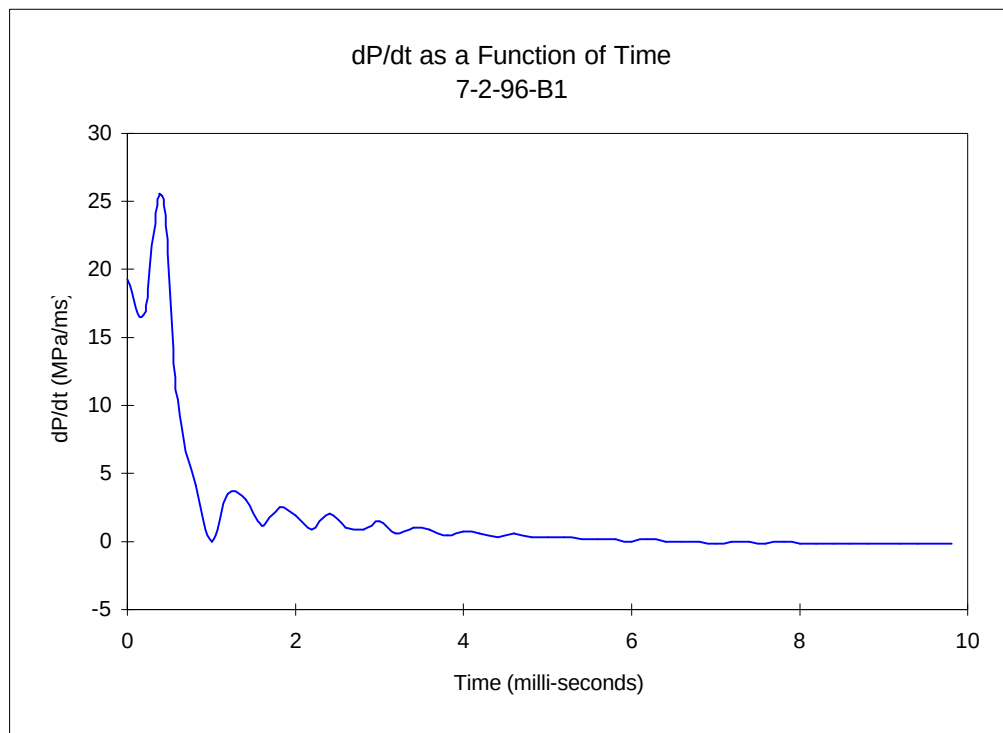


Figure 4-33b: dP/dt as a Function of Time, Shot 7-2-96-B1

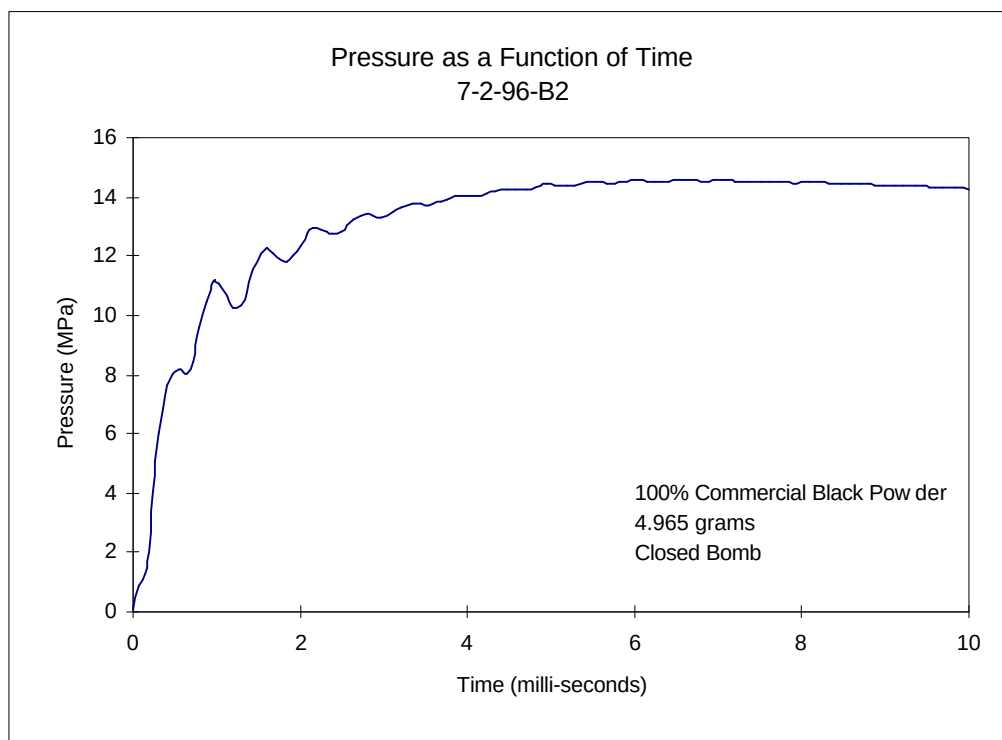


Figure 4-34a: Pressure as a Function of Time, Shot 7-2-96-B2.

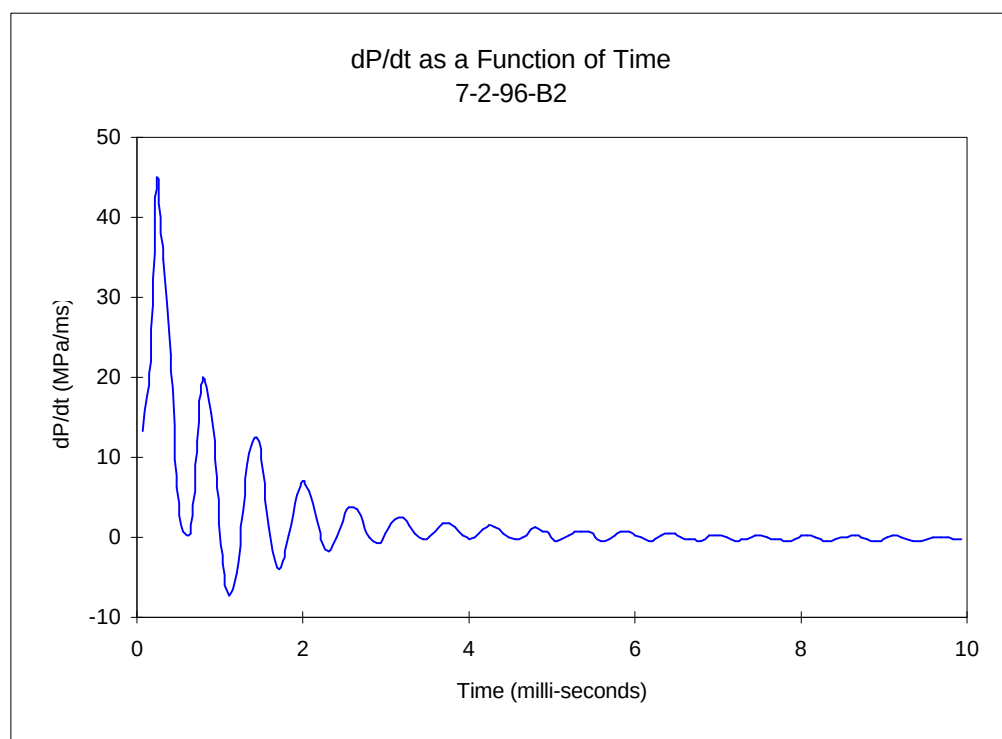


Figure 4-34b: dP/dt as a Function of Time, Shot 7-2-96-B2.

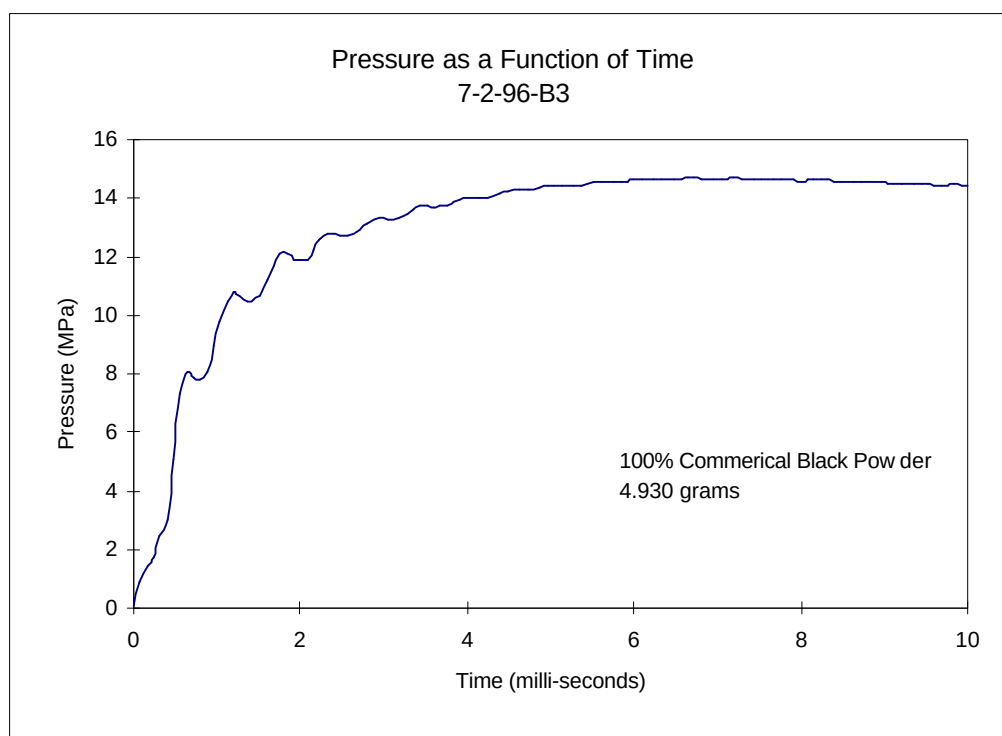


Figure 4-35a: Pressure as a Function of Time, Shot 7-2-96-B3.

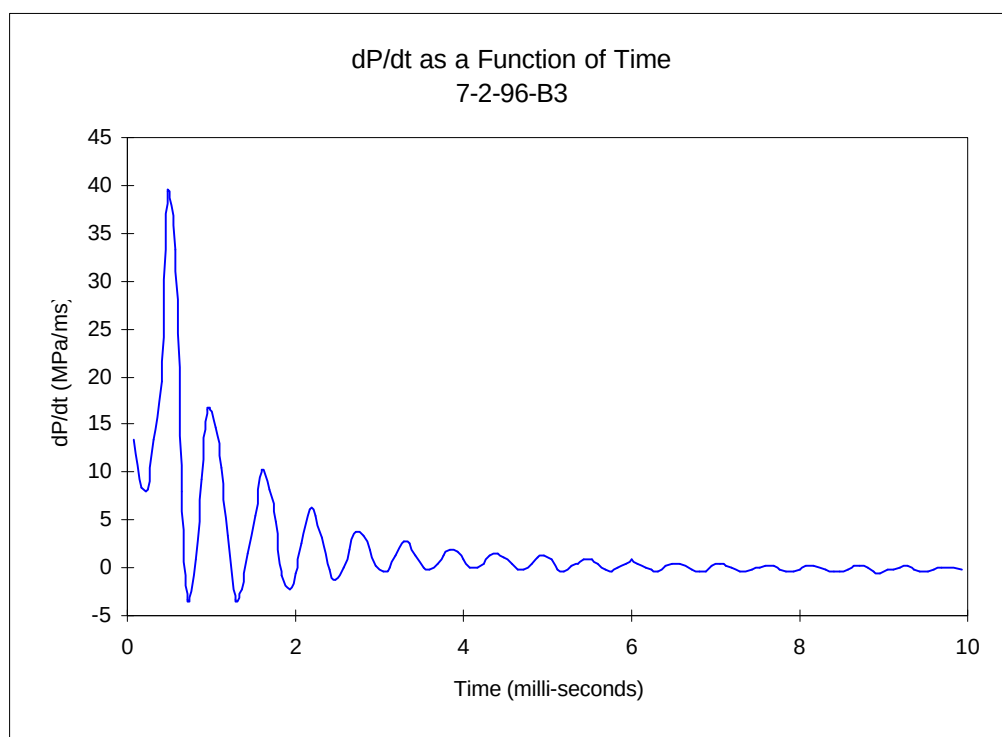


Figure 4-35b: dP/dt as a Function of Time, Shot 7-2-96-B3.

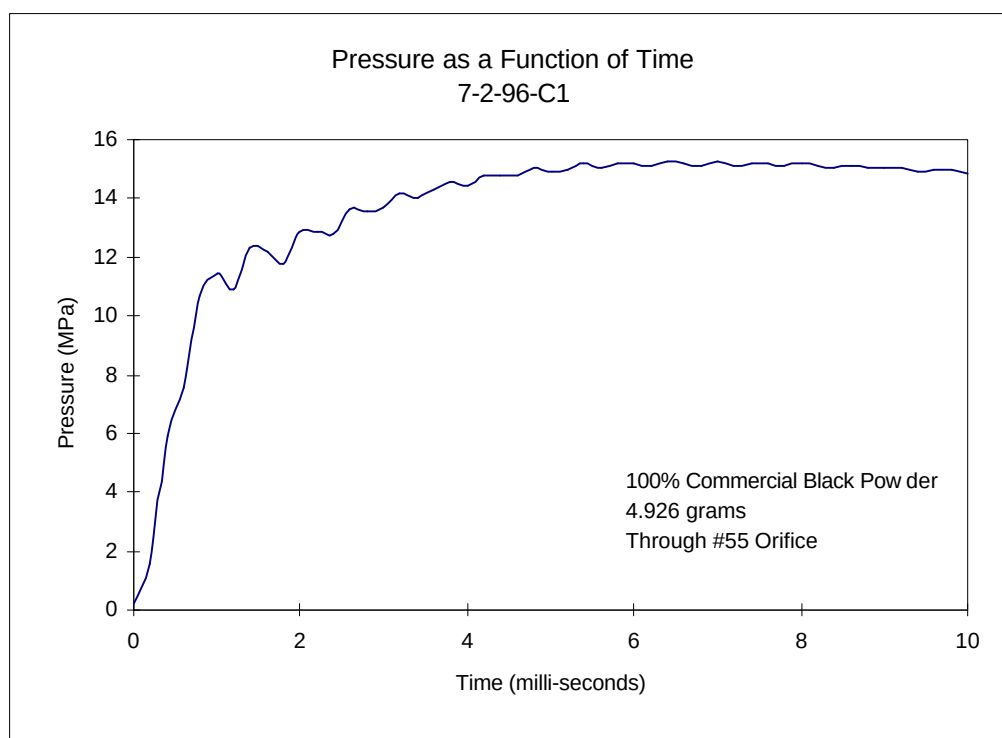


Figure 4-36a: Pressure as a Function of Time, Shot 7-2-96-C1.

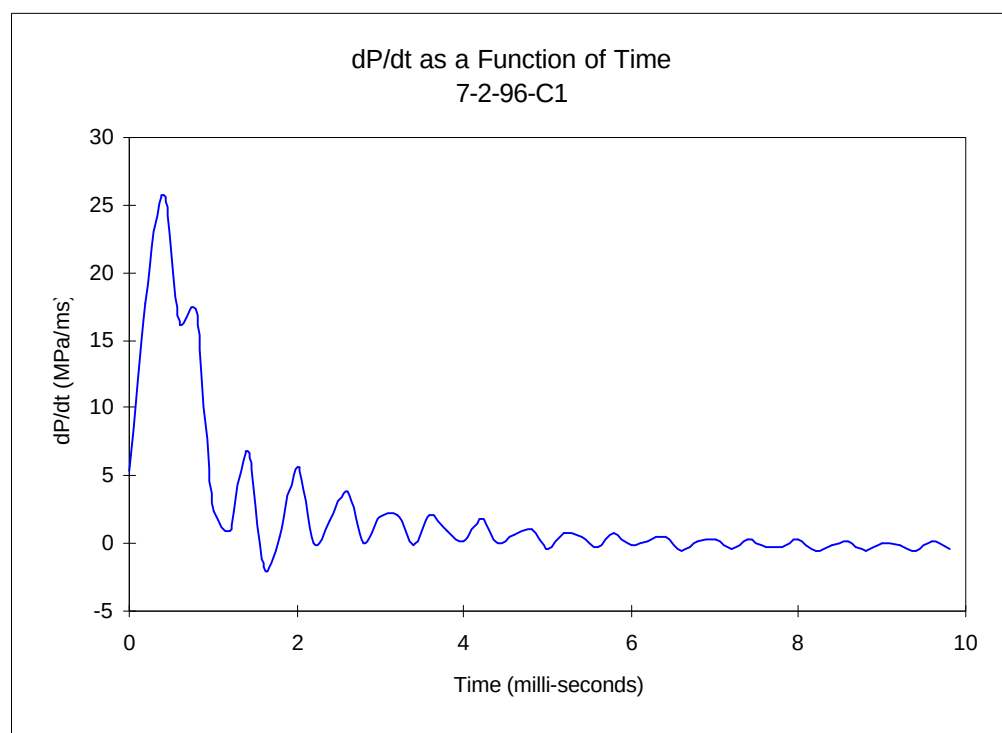


Figure 4-36b: dP/dt as a Function of Time, Shot 7-2-96-C1.

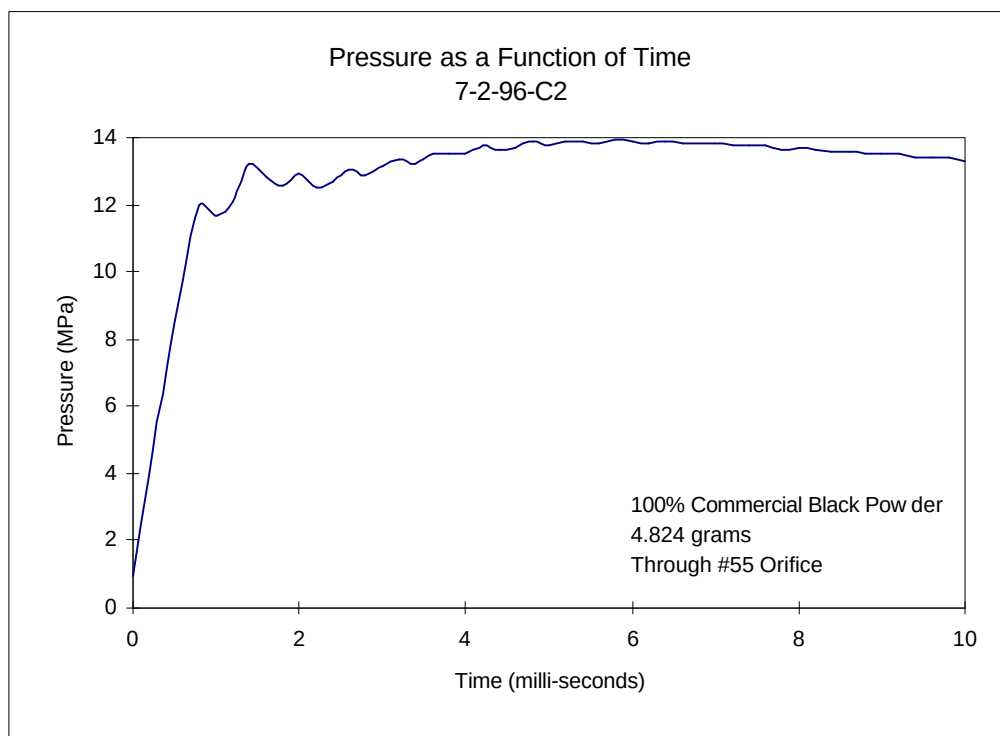


Figure 4-37a: Pressure as a Function of Time, Shot 7-2-96-C2.

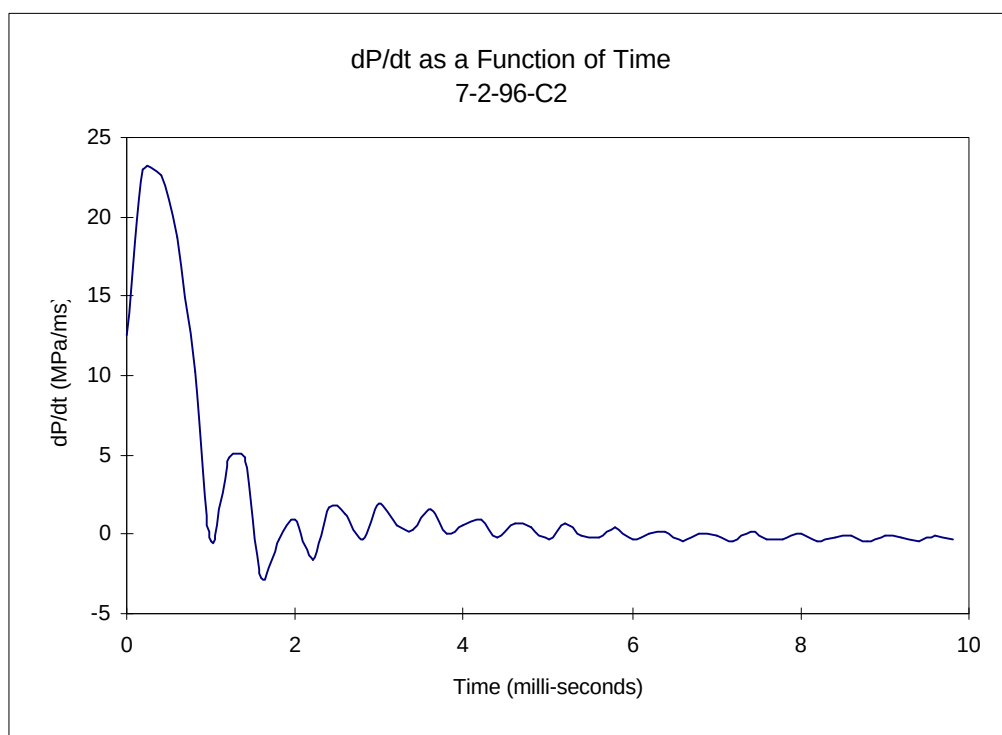


Figure 4-37b: dP/dt as a Function of Time, Shot 7-2-96-C2.

4.4 Determination of Linear Burn rates

The general assumption in interior ballistic modeling is that the linear burn rate, that is the rate of advance of the flame front into the propellant body, is proportional to the absolute pressure at the zone of combustion. This equation is generally expressed in the form:

$$\dot{X} = \frac{dr}{dt} = AP^n .$$

In which $\dot{X}$ is the linear burn rate into the propellant grain, dr/dt is the time rate of change of a propellant grain radius, A is the linear burn rate coefficient, P is the absolute pressure, and n is the linear burn rate index. The application of this equation in modeling of the propellant burn events will be covered in the next section of this thesis (chapter 5), in this section the determination of A and n , based on laboratory data will be discussed.

The best available analysis of laboratory data relating the pressure as a function of time, in a closed bomb, is that of Riefler and Lowery (1974). Regarding the burn rate model, these authors make two important observations. “If the mathematical model in which this equation occurs is being employed for a narrowly empirical purpose, the constants may be adjusted to give a good agreement between the firing data and computations with the model.” Also, “Values resulting from identical compositions used in different propellants and gun systems do not agree closely, nor is it clear how to assign values as intrinsic properties of the propellant composition.”

The authors, however, make a series of assumptions, and show that empirical constants can be derived for a propellant based on firing in a closed bomb. The assumptions that were made by Riefler and Lowery (1974) are:

- a. The charge is composed of a large number of identical grains of known shape.
- b. The grains are of uniform composition.
- c. All the grains are ignited simultaneously.
- d. All the grains burn identically.
- e. The propellant chamber is effectively isolated, i.e. neither mass nor energy are transferred into or out of the body of mixed gas and unburned propellant.

To these assumptions, the analysis in this document assumes that the effect of the igniter is negligible in comparison to the propellant charge. Therefore no account of the igniter is made in the determination of the propellant burn rate.

Neglecting the effect of the igniter, Riefler and Lowery’s (1974) analysis of the linear burn rate is expressed as:

$$\frac{dr}{dt} = \frac{dP}{dt} \frac{R_0}{3} \left[\frac{BC}{(P+B)^2} \right] \left[\frac{(P+B)}{P(C-1)+B} \right]^{2/3}$$

where:

$$B = \frac{(P_{\max} - P) \left(\frac{1}{D} - v \right)}{v - b}$$

$$C = \frac{\left(\frac{1}{D} - b \right)}{v - b} \quad .$$

$$D = \frac{W_p}{V}$$

Such that $P_{\max}$ is the maximum pressure of the burn, P is the pressure at the time of analysis, v is the covolume of the propellant gas, b is the specific volume of the propellant (solid phase), R_0 is the initial mean radius of the propellant grains, and dP/dt is the slope of the pressure versus time curve for the propellant burn. The local value of the first derivative of pressure with respect to time was estimated using the following central difference scheme:

$$\left(\frac{dP}{dt} \right)_i \approx \frac{\left[\frac{P_i - P_{i-1}}{t_i - t_{i-1}} \right] + \left[\frac{P_{i+1} - P_i}{t_{i+1} - t_i} \right]}{2}.$$

This scheme estimates the slope of P_i at t_i as the average of the slopes of P between t_{i-1} , t_i , and t_{i+1} .

The analytical background of this approach to obtaining burn rates is provided in the Riefler and Lowery reference. The basis for their approach is the Nobel-Abel equation with insignificant heat loss. Their arrangement accounts for differences in the properties between the igniter and the main charge. The burn rate parameters, A and n , are then empirically derived from the individual shot data of pressure as a function of time and time rate of change of pressure as a function of time and of pressure.

Utilizing this analytical technique, the linear burn rate (dr/dt) can be determined and when compared to the independent variable of pressure (P) the linear burn rate coefficient, a , and index, n , can be estimated. A typical dr/dt versus P graph is illustrated in figure 4-38.

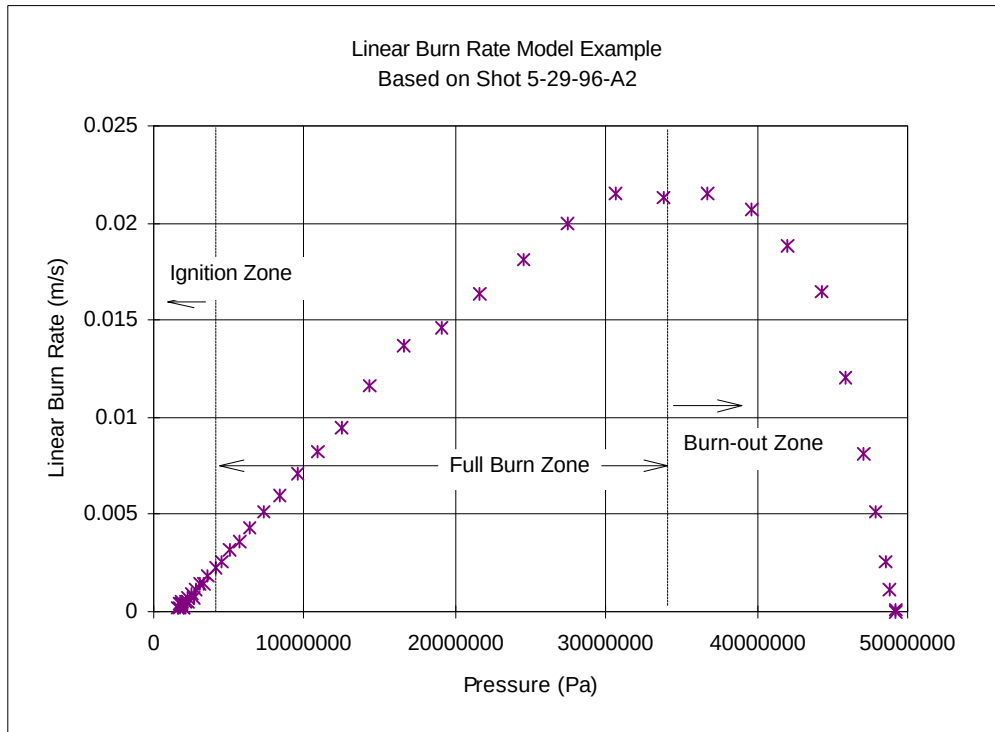


Figure 4-38a: Linear Burn Rate Model Example, Linear Axes.

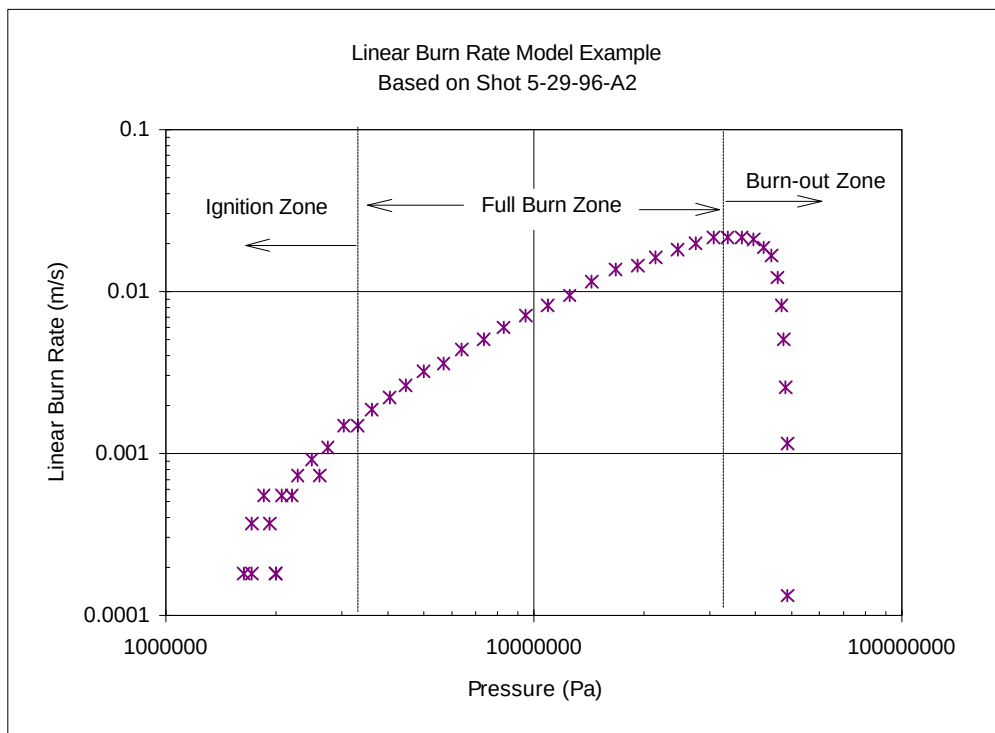


Figure 4-38b: Linear Burn Rate Model Example, Logarithmic Axes.

This graph also indicates the three zones of the propellant burn process. There is a central section of the graph that exhibits a fairly linear profile, on the log-log graph, in this section the propellant is burning uniformly proportional to the ambient pressure, hence a and n can be assumed to be constant. The section of the burn process during which the charge is being ignited and is burning out will be neglected.

To the left of the center section is the “ignition zone”, this area represents the region in which the propellant is being ignited, hence the burn rate is not necessarily observed as monotonically proportional to the pressure. This region can be explained in the contradiction to assumption “c,” above. The charges used in these experiments are ignited at a single point, rather than throughout the charge. The propellant ignition wave process by which the entire charge is ignited can occur as much as 5000 times faster than the linear burn-rate (Kuo, Vichnevetsky, and Summerfield 1971). Despite the potential for very rapid ignition there is still a finite period of time in which the proportion of propellant ignited is varying.

To the right of the linear zone is the “burn-out zone,” this region is characterized by a rapidly falling linear burn rate as the peak pressure is approached. This indication can be explained in the contradiction to the assumption “a,” above. If some of the propellant grains are larger than others, than it can be presumed that the smaller grains will burn out before the larger ones. Hence the number of grains of propellant contributing to the pressure profile is falling, thus the apparent linear burn rate also falls.

By neglecting the initiation and burn out zones it is possible to estimate the coefficient, a , and the index, n , from the full burn zone data. The data in this area is first assumed to be in the form represented as:

$$\frac{dr}{dt}(P) = aP^n.$$

By taking the logarithm of both sides the equation can be linearized as:

$$\log\left[\frac{dr}{dt}(P)\right] = \log(a) + n \log(P).$$

This now is the equation of a straight line, with a slope of n , and a y-intercept of $\log(a)$. Since both the dependent and independent variables in the above equation are available, the constant $\log(a)$ and index n can be estimated by linear regression. Considering the straight line equation: $y = mx + b$, with samples $i = 1, 2, \dots, n$:

$$m = \frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{n \sum x_i^2 - (\sum x_i)^2}$$

$$b = \frac{1}{n} (\sum y_i - b \sum x_i)$$

The Coefficient of Determination, R^2 , is determined as:

$$R^2 = \left[\frac{n \sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{[n \sum x_i^2 - (\sum x_i)^2][n \sum y_i^2 - (\sum y_i)^2]}} \right]^2$$

Analysis of the laboratory data, in the above manner, was performed using Microsoft Excel, and the Power Curve -Trend Line function provided with it. Figures 4-39 through 4-56 illustrate the entire dr/dt versus P graph and the appropriate full burn zone linear burn rate determinations. A brief discussion of each case precedes the presentation of those figures. The coefficient, index, and coefficient of determination, for the burns evaluated are listed in table 4-7.

Table 4-7: Linear Burn Rate Coefficients for Samples Indicated

Sample	A	n	R^2
100% Accurate Arms Company No. 5			
5-29-96-A(Average)	$6*10^{-11}$	1.1535	0.9879
5-29-96-A1	$1*10^{-9}$	0.9766	0.9456
5-29-96-A2	$9*10^{-11}$	1.1271	0.9914
5-29-96-A3	$6*10^{-11}$	1.1531	0.9908
6-13-96-D1	$3*10^{-13}$	1.4840	0.9970
6-13-96-D2	$2*10^{-14}$	1.6586	0.9902
75% Accurate Arms Company No. 5; 25% Accurate Arms Company No. 8700			
5-31-96-A1	$2*10^{-11}$	1.2308	0.9291
5-31-96-A2	$4*10^{-13}$	1.4990	0.9027
6-13-96-C1	$1*10^{-15}$	1.7981	0.9904
6-13-96-C2	$9*10^{-12}$	1.2875	0.9992
66% Accurate Arms Company No. 5; 34% Accurate Arms Company No. 8700			
5-29-96-B(Average)	$5*10^{-8}$	0.7536	0.9451
5-29-96-B1	$9*10^{-9}$	0.8503	0.9583
5-29-96-B2	$6*10^{-11}$	1.1544	0.8906
5-29-96-B3	$6*10^{-9}$	0.9008	0.9100
50% Accurate Arms Company No. 5; 50% Accurate Arms Company No. 8700			
6-13-96-B1	$2*10^{-13}$	1.5012	0.9895

The evaluation of each of the shot series is covered in the following paragraphs. Each individual test is covered separately and, where appropriate, group averages are also presented. Evaluation of the burn rate equation parameters determined in the section with respect to numerical modeling, and comparison between the laboratory data and numerical predictions are reserved for section 5.3, concerning the numerical model application.

4.4.1 100 Percent No. 5

Figure 4-39 illustrates the computed propellant linear burn rate with respect to pressure. Observing the data for each of the six groups presented, there does not appear to be a significant variation between those shots in the closed bomb and those vented through the orifice.

Figure 4-40a illustrates the entire linear burn rate estimates based on the average of the pressure-time data recorded during shots 5-29-96-A1, -A2, and -A3. The three zones described above, concerned with the type of burning, are visible in this profile. Figure 4-40b illustrates the relationship of linear burn rate as a function of pressure. This figure is limited to the section identified as the full burn zone.

Figure 4-41a illustrates the linear burn rate estimates for shot 5-29-96-A1. The main division in the burn zones are illustrated based on observation, rather than a physical definition. Within the full burn zone, as illustrated, there is a definite non-linearity. This “hump” appears to be associated with the pressure oscillations recorded, and visible in figure 4-9. Figure 4-41b shows the “best-fit” through the data that can be assumed as the full burn zone of this shot. The power curve form was used since that is the general form of the equation used in propellant burn rate modeling, even though the derived line does not fully fit the shape of the data.

Figure 4-42a shows the burn rate versus pressure computed for shot 5-29-96-A2. This graph clearly illustrates the shape of a “clean” curve. The data in the ignition zone appears to be highly variable, a fairly clear linear portion (in the log-log form) defines the full burn zone, and the rapidly falling burn rate, following the peak, defines the burn-out zone. Figure 4-42b illustrates the basis for the determination of the burn rate parameters for this test.

Figures 4-43a and b show the determination of the linear burn rate parameters for test 5-29-96-A3. This shot was affected by a change in the burn-rate, which is also evident in the pressure-time trace for this test, figure 4-11.

Figures 4-44a and b illustrate the linear burn rate computations of test 6-13-96-D1. This shot, and the next (6-13-96-D2) were vented through a 1.3208 mm nozzle (#55 drill). The three burn phase zones of the clearly visible in this shot.

Figures 4-45a and b show the results of the linear burn rate determination for shot 6-13-96-D2. In the shot the burn-out zone is clearly obvious, however, the transition from the ignition zone to the full burn zone is not as clear. The point of transition was based on the selection of a lower data point that maximized the R^2 of the computed linear burn-rate equation.

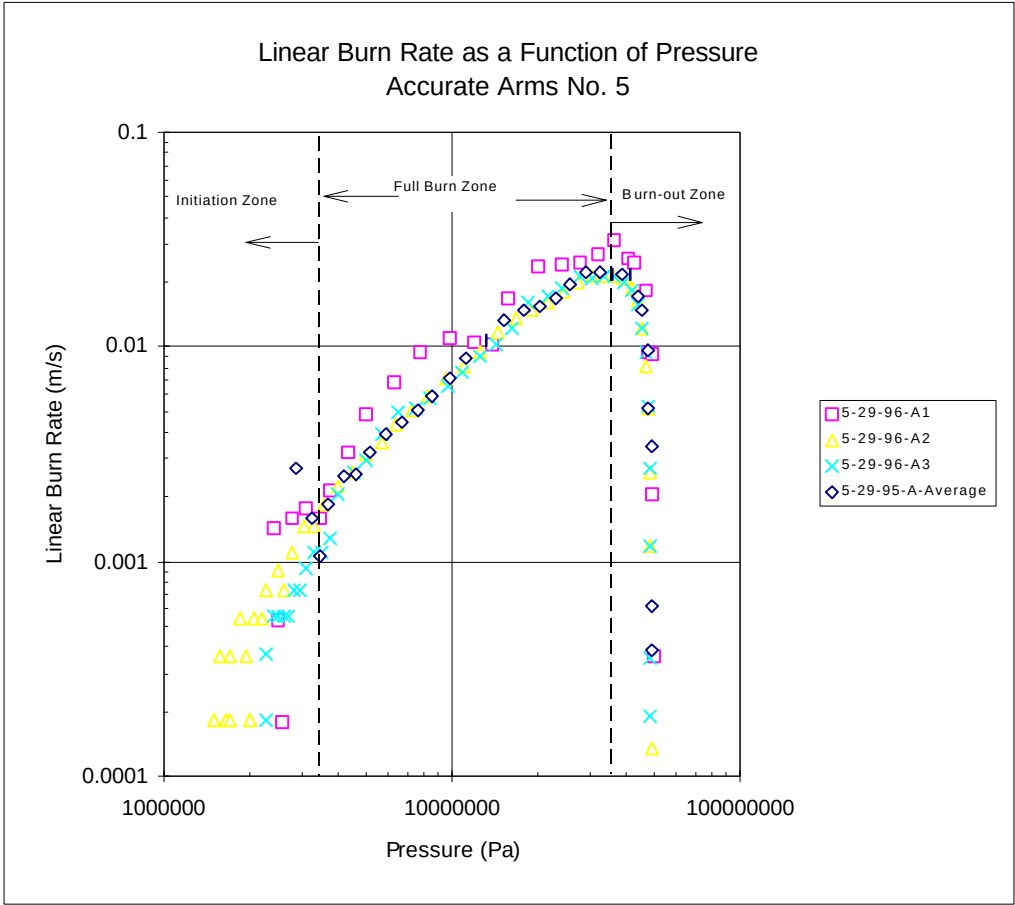


Figure 4-39: Linear Burn Rate as a Function of Pressure, for Shots of 100 Percent No. 5 Propellant.

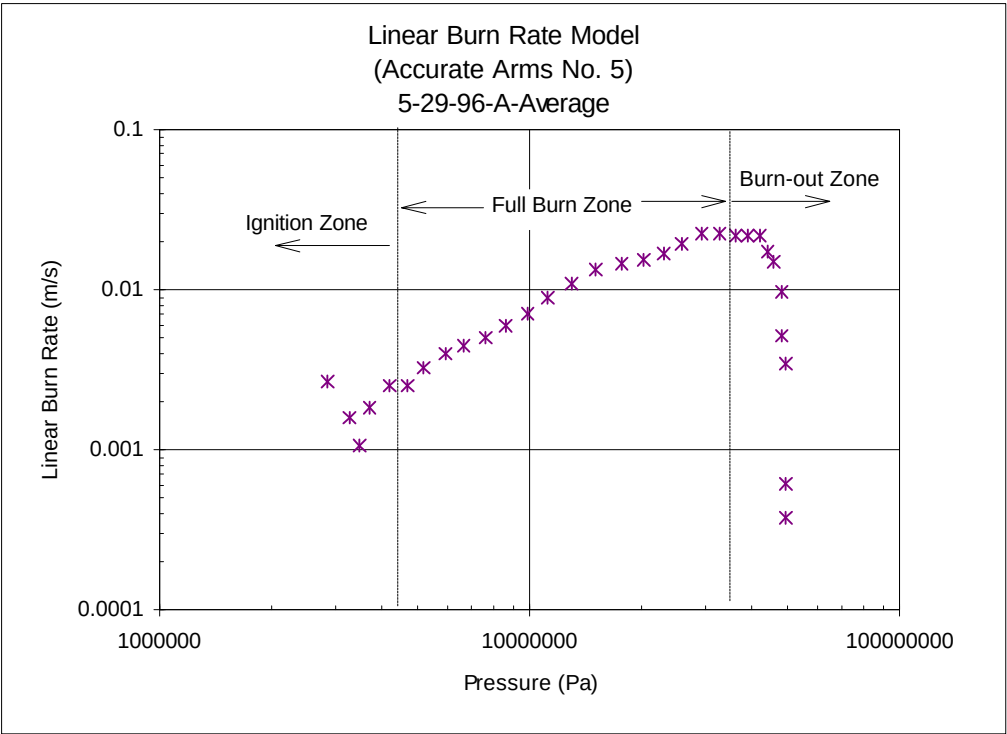


Figure 4-40a: Linear Burn Rate, Entire Model, Shot 5-29-96-A-Average

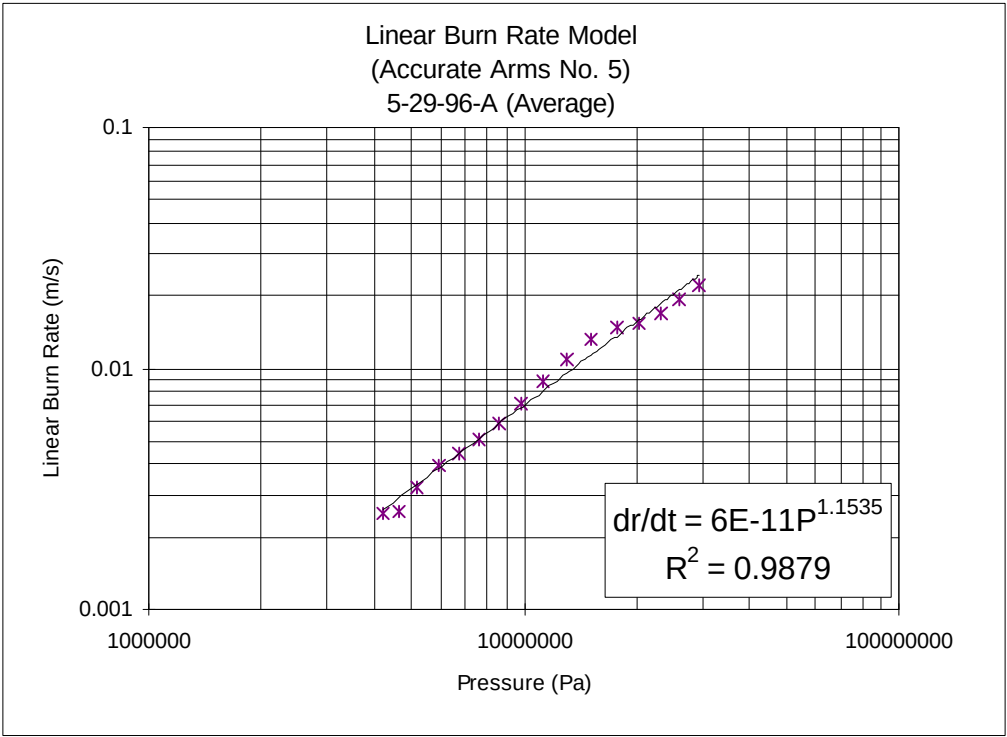


Figure 4-40b: Linear Burn Rate Model, Shot 5-29-96-A-Average

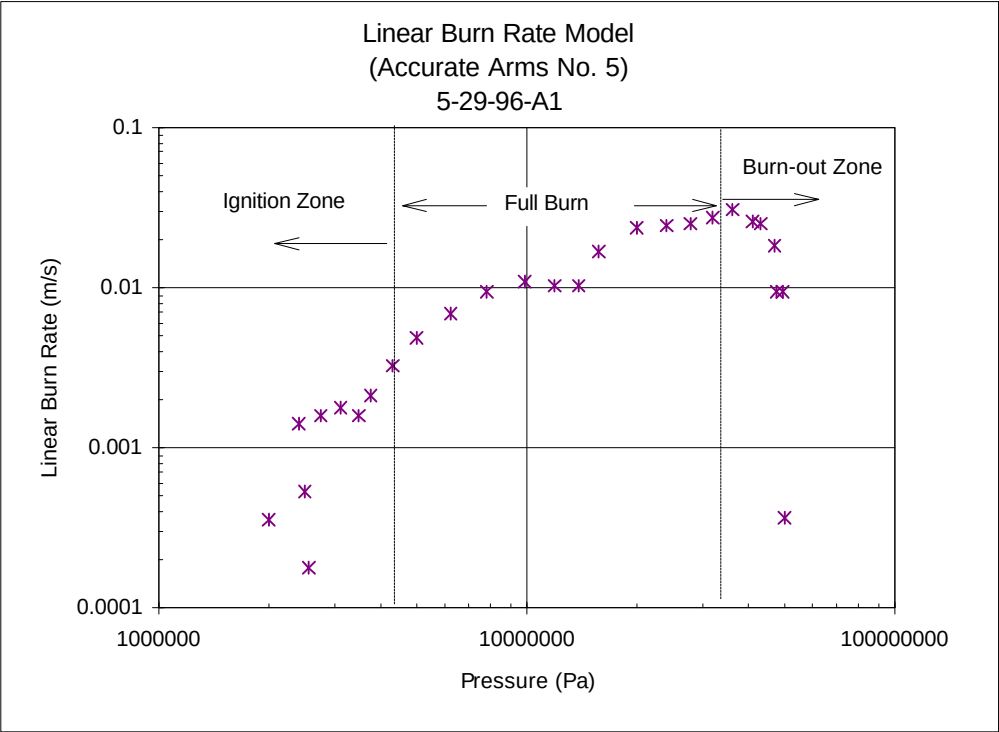


Figure 4-41a: Linear Burn Rate, Entire Model, Shot 5-29-96-A1

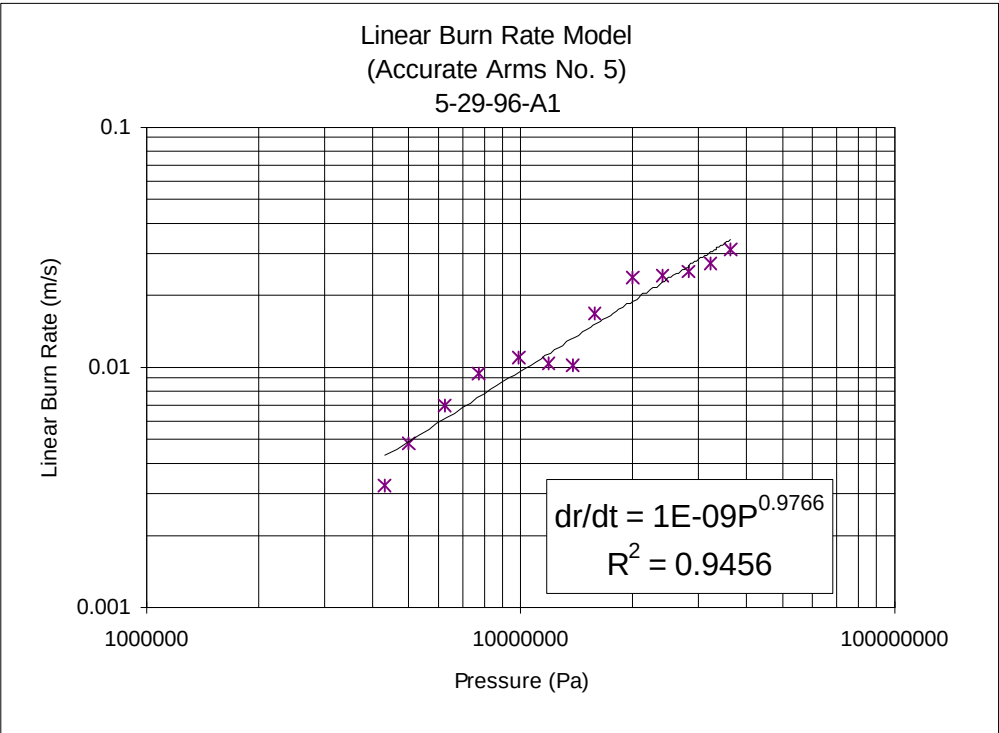


Figure 4-41b: Linear Burn Rate Model, Shot 5-29-96-A1

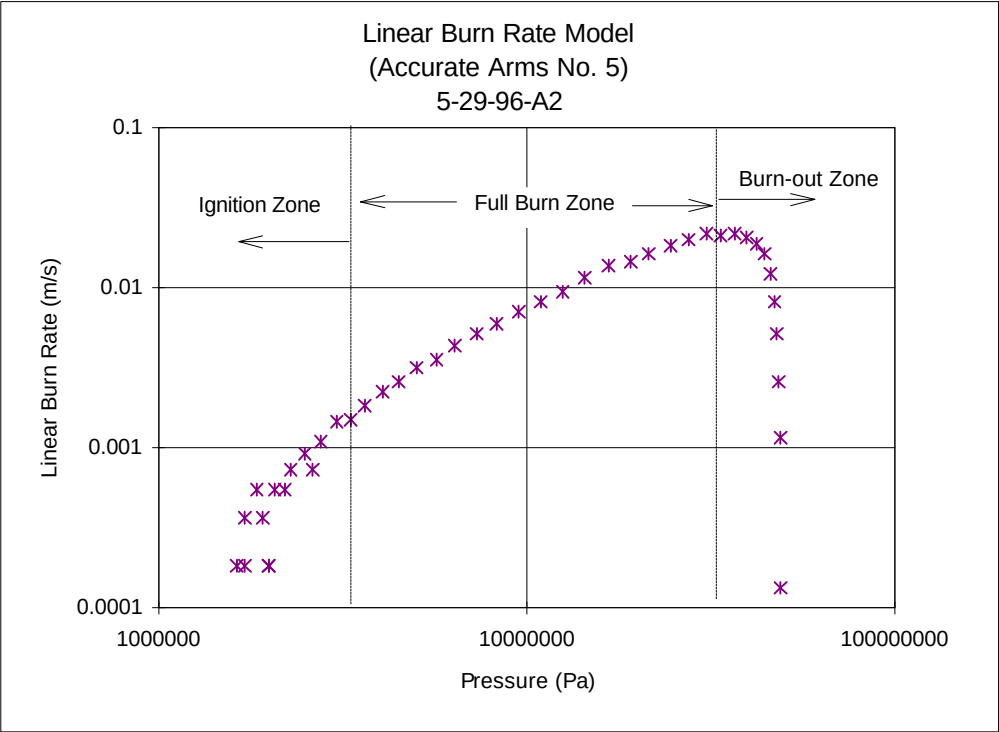


Figure 4-42a: Linear Burn Rate, Entire Model, Shot 5-29-96-A2

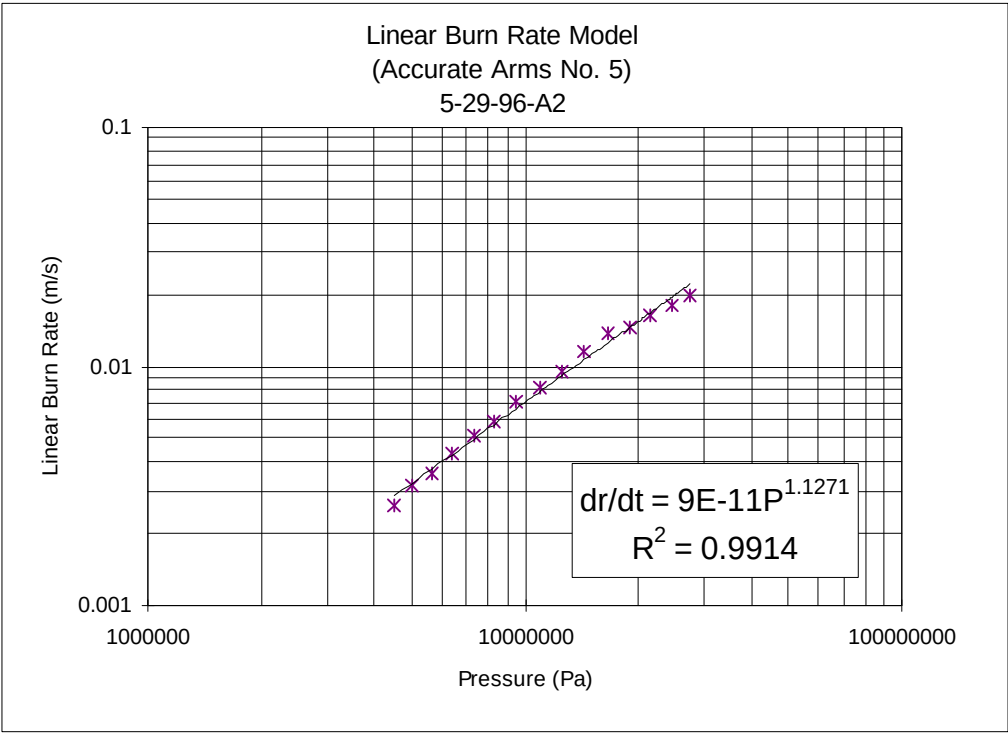


Figure 4-42b: Linear Burn Rate Model, Shot 5-29-96-A2

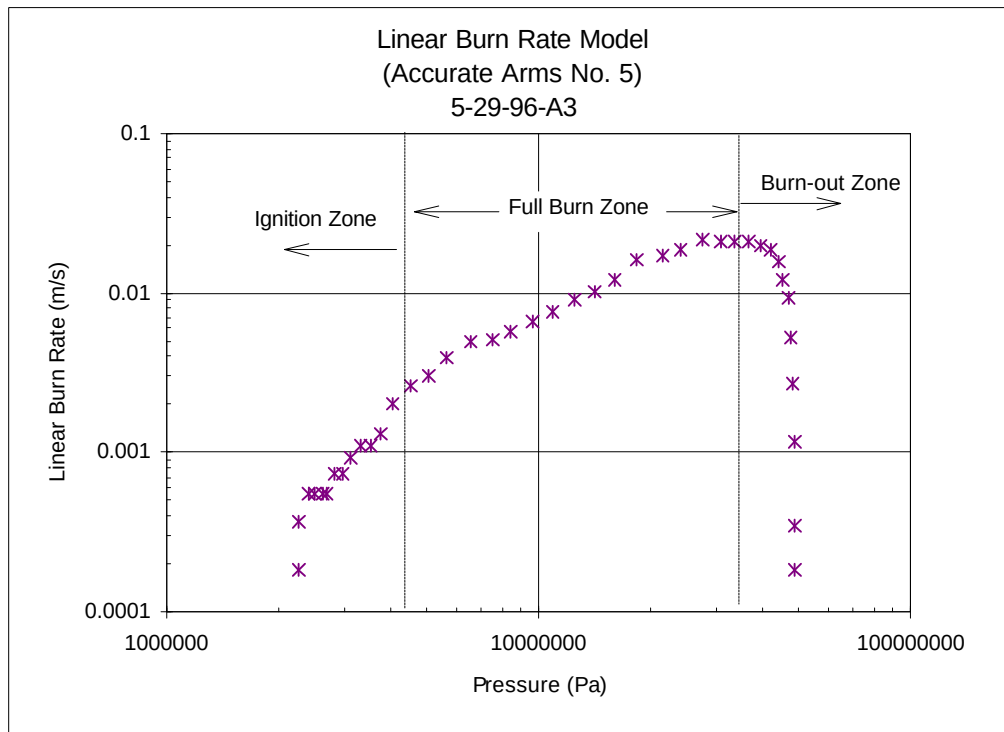


Figure 4-43a: Linear Burn Rate, Entire Model, Shot 5-29-96-A3

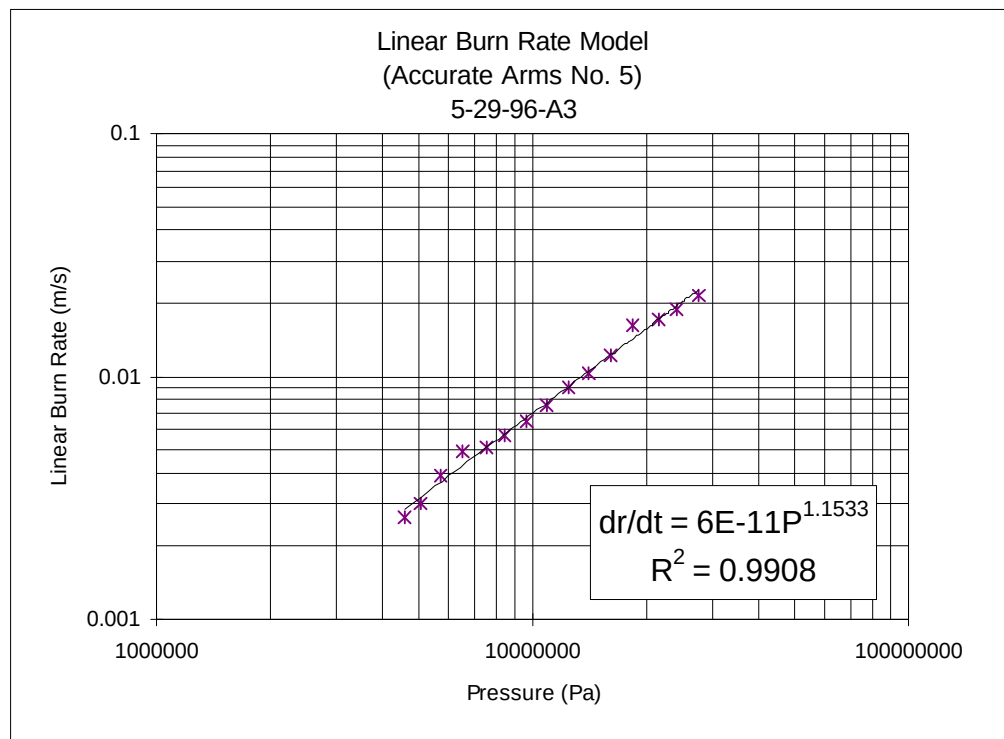


Figure 4-43b: Linear Burn Rate Model, Shot 5-29-96-A3

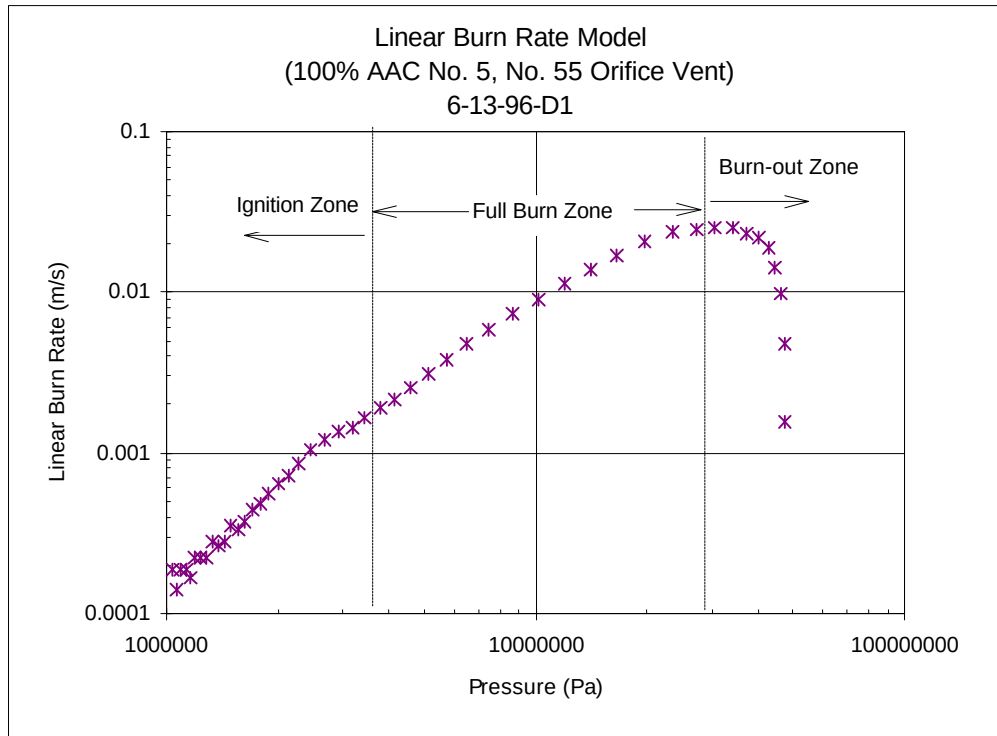


Figure 4-44a: Linear Burn Rate, Entire Model, Shot 6-13-96-D1

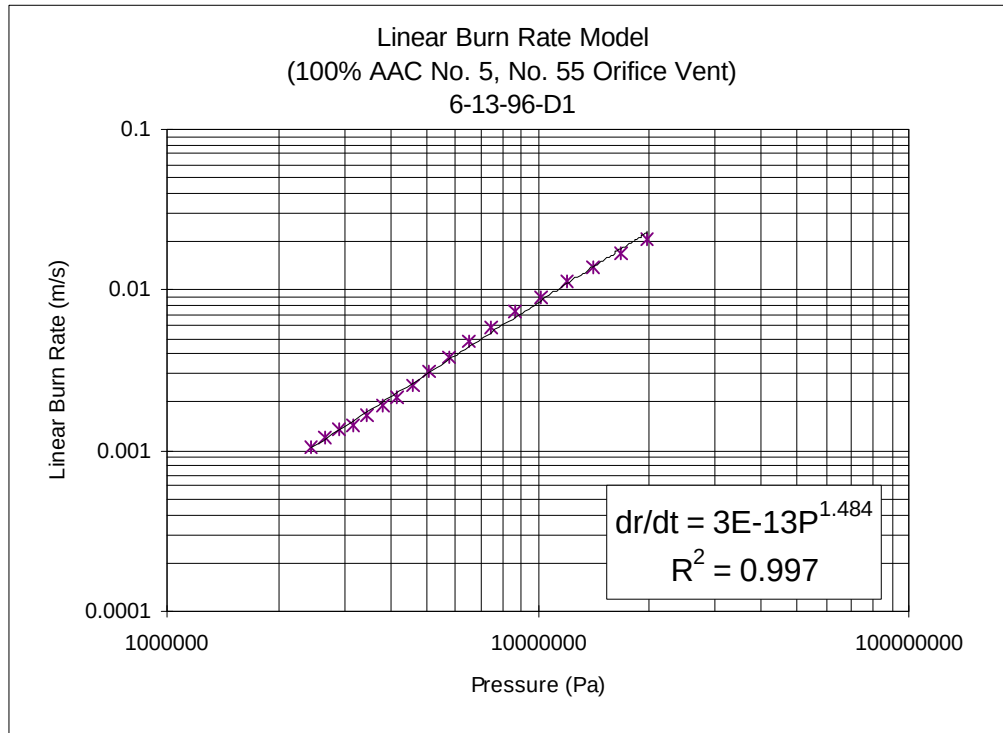


Figure 4-44b: Linear Burn Rate Model, Shot 6-13-96-D1

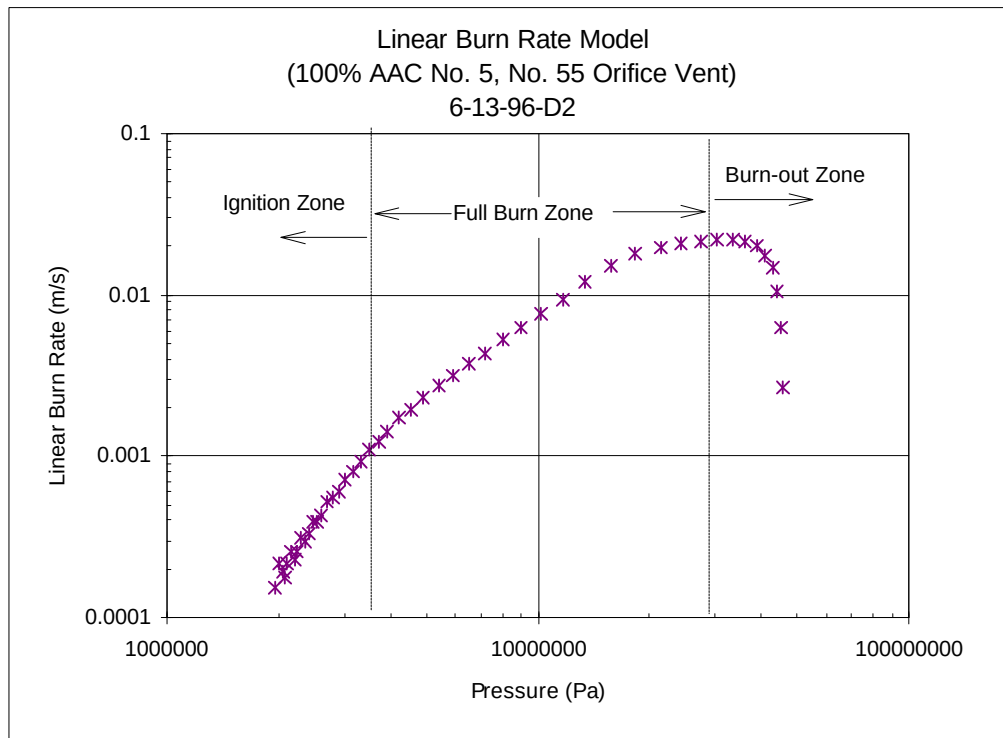


Figure 4-45a: Linear Burn Rate, Entire Model, Shot 6-13-96-D2

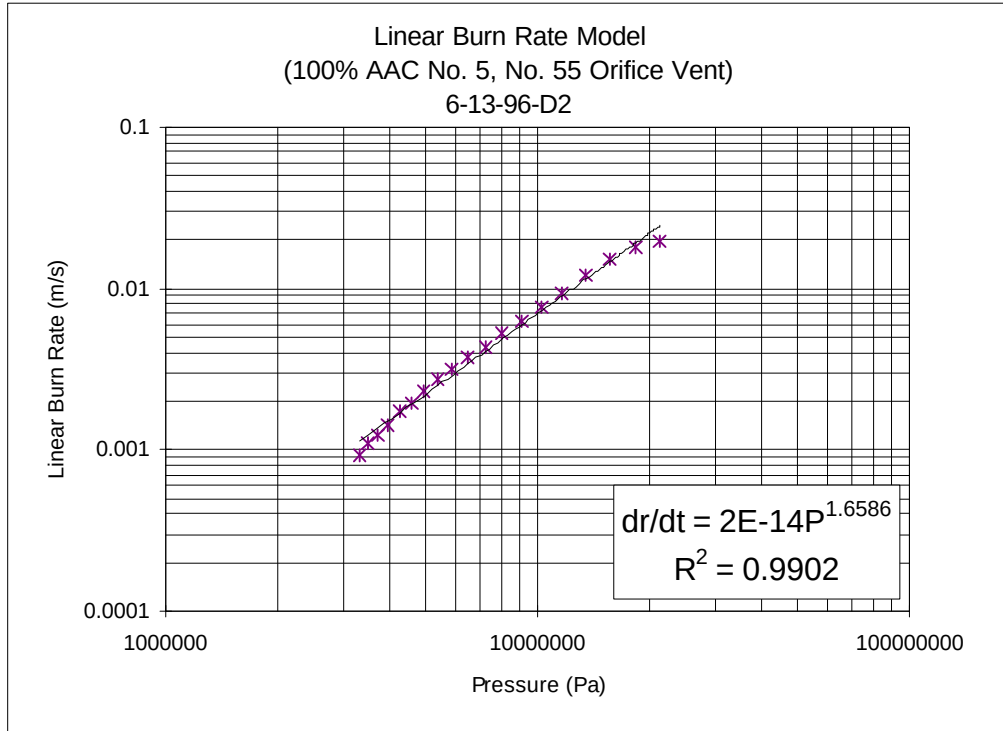


Figure 4-45b: Linear Burn Rate Model, Shot 6-13-96-D2

4.4.2 75 Percent No. 5, 25 Percent No. 8700

Figure 4-46 compares the linear burn rate as a function of pressure for the four shots evaluated previously for the propellant mixture of 75% No. 5 and 25% No. 8700. All of these shots indicate a similar peak burn rate for a similar pressure. However, the full burn zone linear burn rate paths show a great range of variability. This may be due to gradations of the individual propellants in the mixture. The effect of the differences between the individual test burn rate equations will be addressed in the section on numerical modeling, with this data.

Figure 4-47a and b illustrate the data used in the determination of the linear burn rates for sample 5-31-96-A1.

Figure 4-48a and b show the computed linear burn rate data based on shot 5-31-96-A2.

Figure 4-49a and b provide the linear burn rate estimates for shot 6-13-96-C1. Both this shot and the next (6-13-96-A2) were vented through the 1.3208 mm nozzle (#55 drill).

Figure 4-50a and b cover the linear burn rate determination of sample 6-13-96-C2. These figures show a case that moves, seemingly, continuously from the ignition zone into the full burn zone, making this point difficult to determine. The correlation of the linear burn rate function was maximized by neglecting the data that occur associated with the step that is visible in 4-50a, at a pressure of about 13 MPa. This point was chosen as the upper boundary, even though the actual linear burn rate does not begin to fall off rapidly until the pressure exceeds 35 MPa.

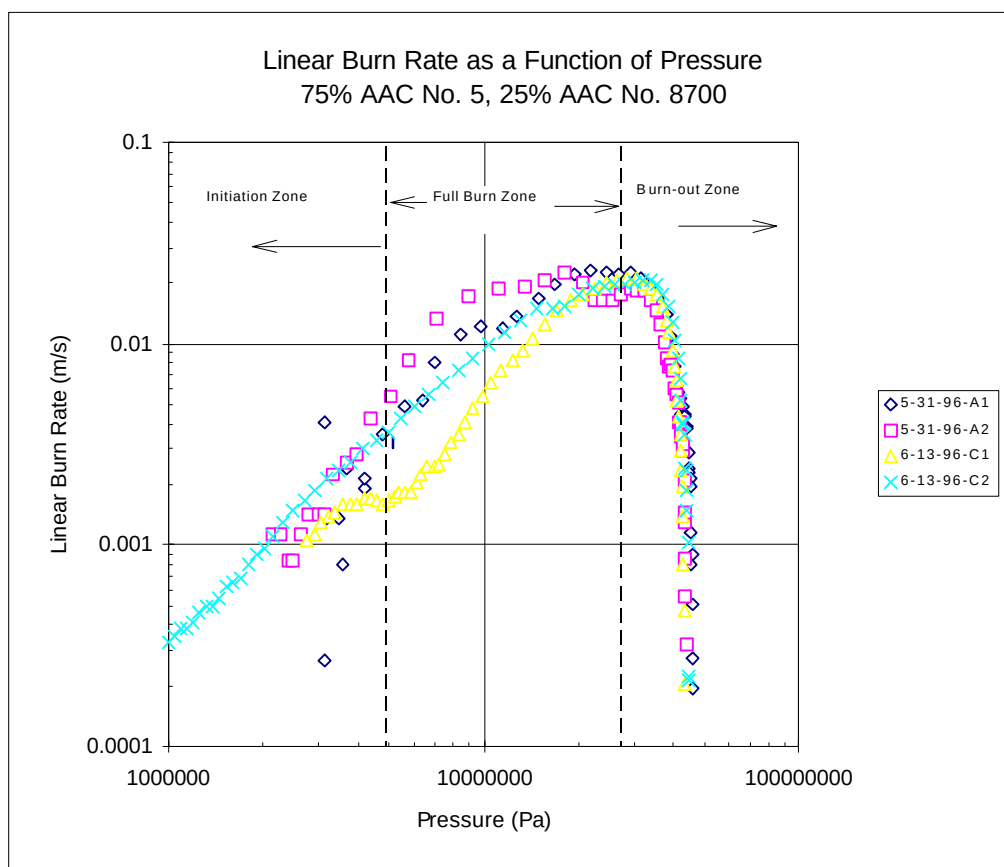


Figure 4-46: Linear Burn Rate as a Function of Pressure,
for Propellant Mixture 75% No. 5, 25% No. 8700

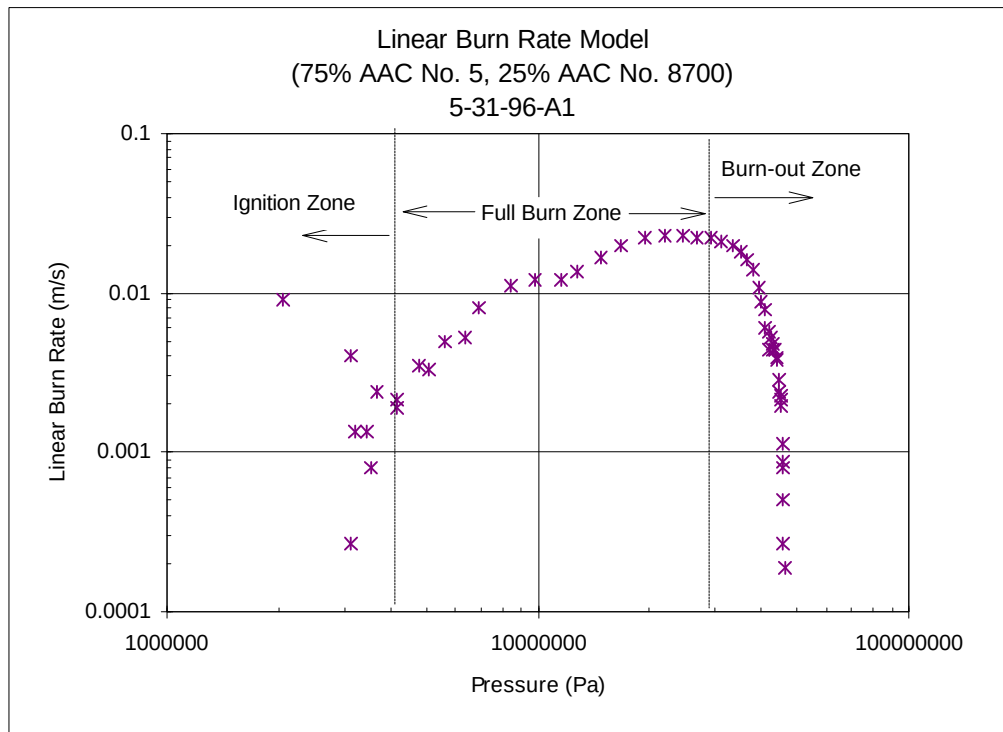


Figure 4-47a: Linear Burn Rate, Entire Model, Shot 5-31-96-A1

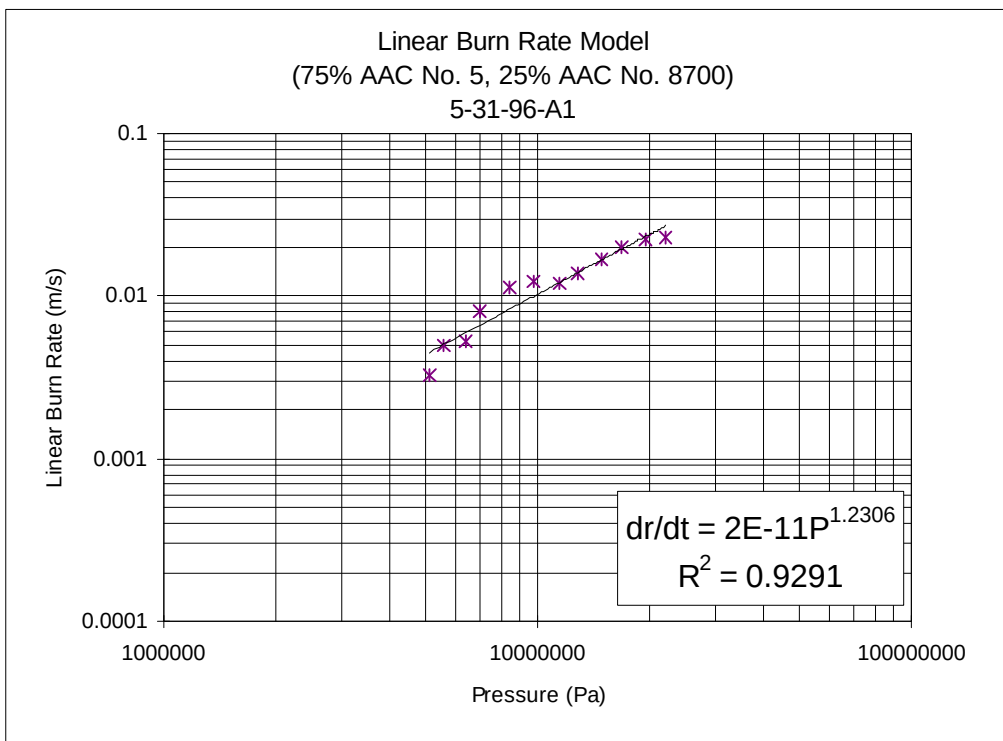


Figure 4-47b: Linear Burn Rate Model, Shot 5-31-96-A1

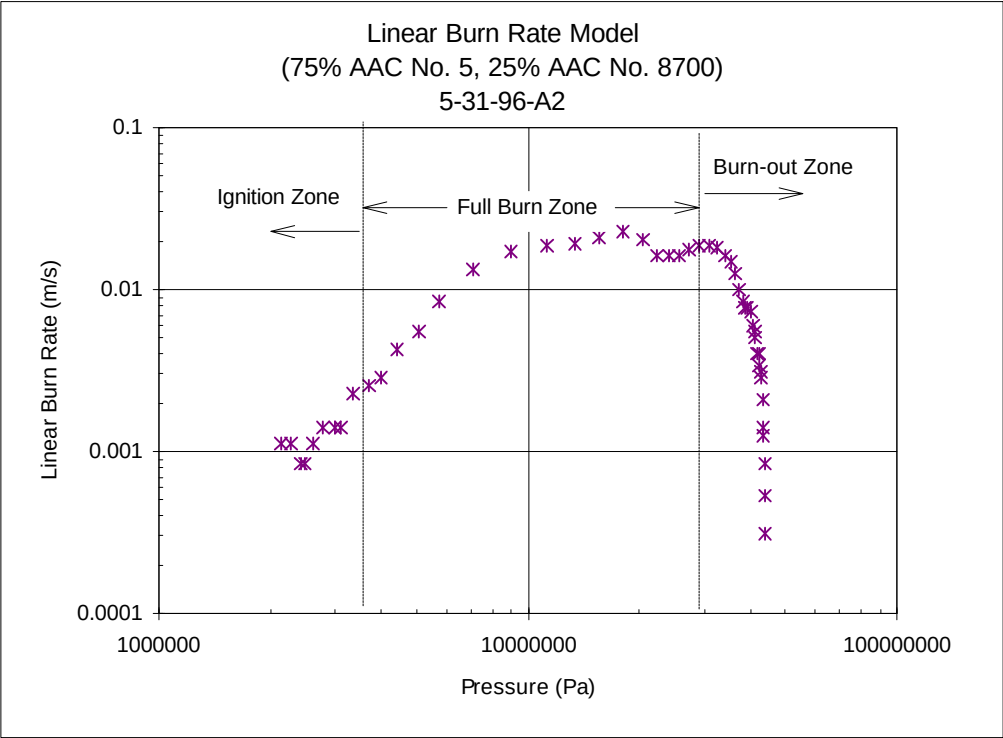


Figure 4-48a: Linear Burn Rate, Entire Model, Shot 5-31-96-A2

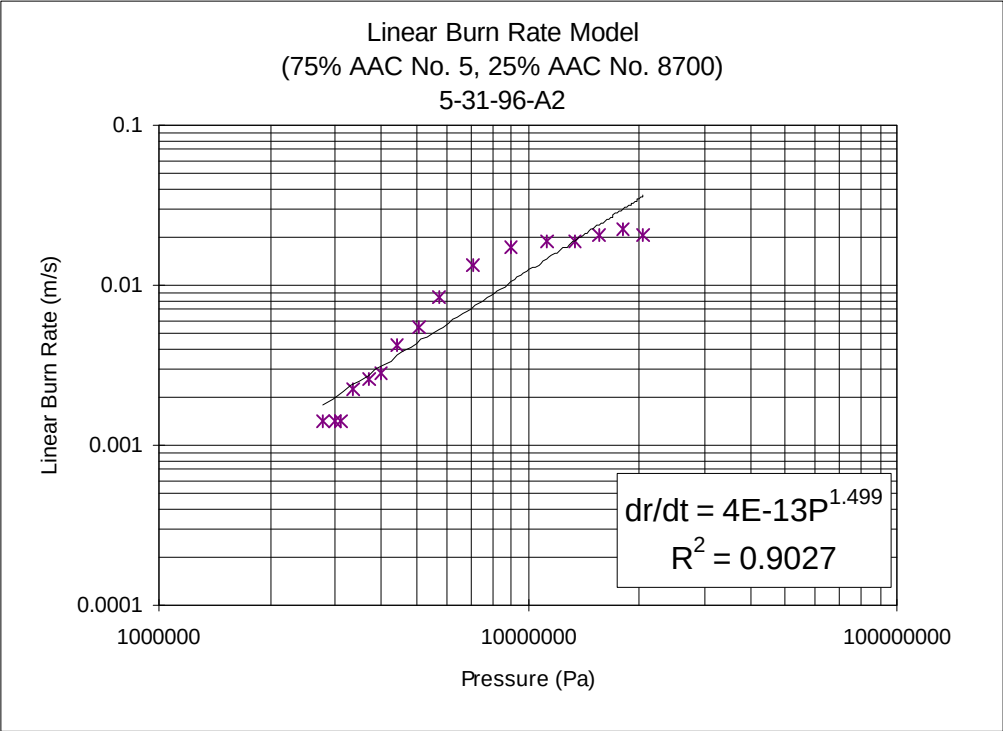


Figure 4-48b: Linear Burn Rate Model, Shot 5-31-96-A2

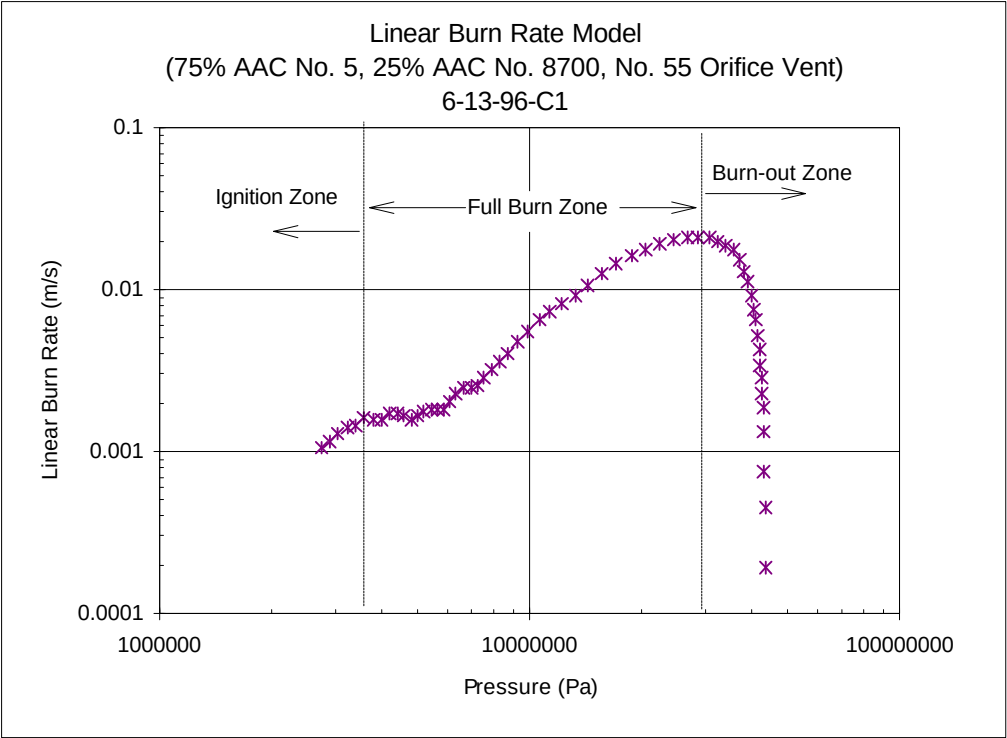


Figure 4-49a: Linear Burn Rate, Entire Model, Shot 6-13-96-C1

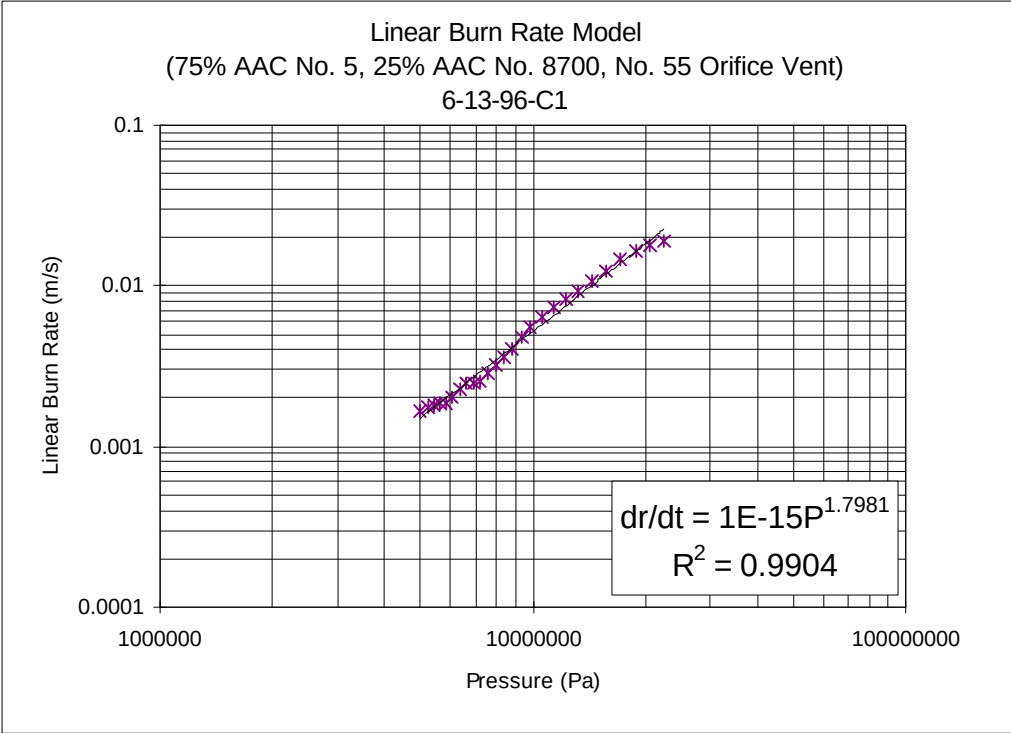


Figure 4-49b: Linear Burn Rate Model, Shot 6-13-96-C1

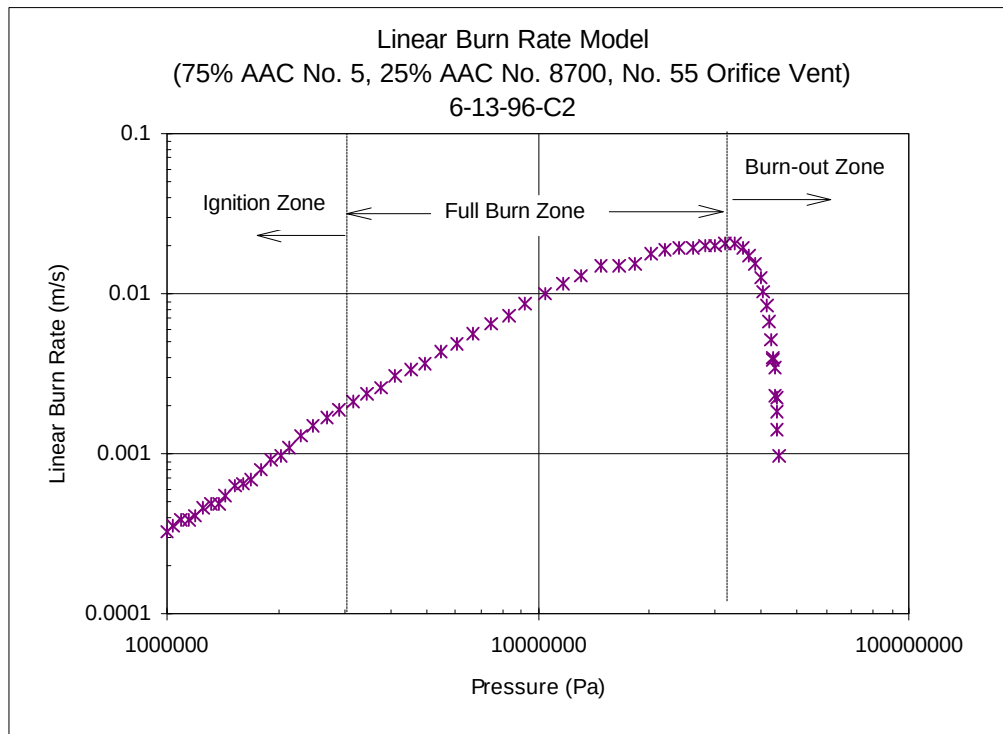


Figure 4-50a: Linear Burn Rate, Entire Model, Shot 6-13-96-C2.

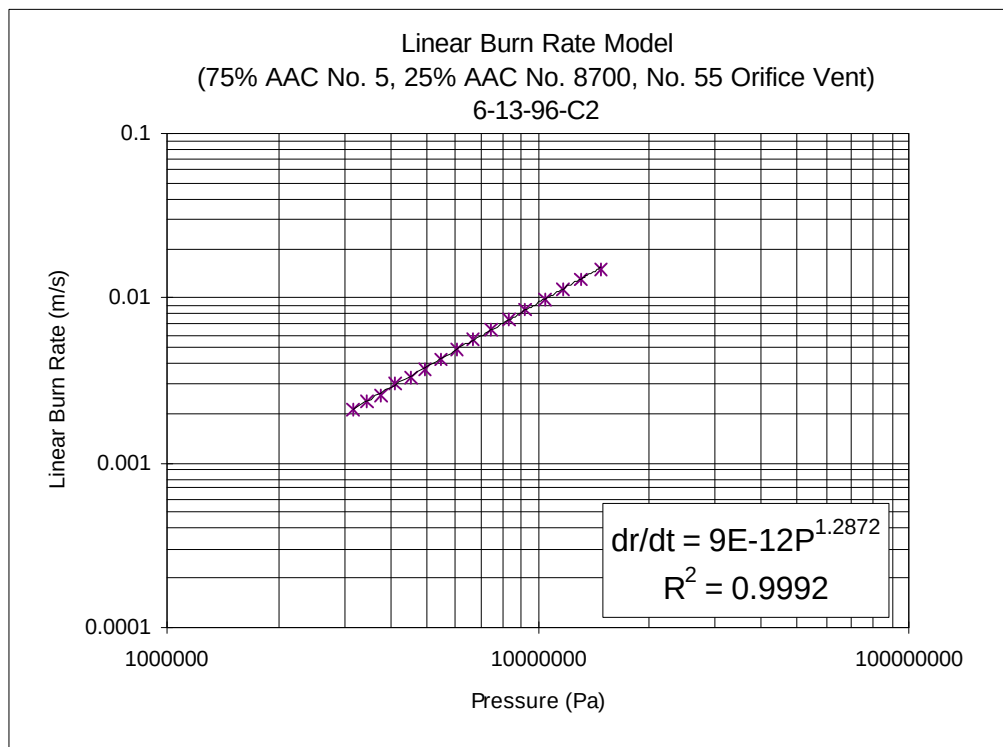


Figure 4-50b: Linear Burn Rate Model, Shot 6-13-96-C2.

4.4.3 66 Percent No. 5, 34 Percent No. 8700

Figure 4-51 illustrates the combination of the individual and average linear burn rates as a function of pressure for those tests using a mixture of 66% No. 5 and 34% No. 8700 propellants. Compared to the two previous mixtures there appears to be less consistency in the peak linear burn rate, even though there are similar peak pressures. The general trend is still evident, that during the full burn zone the linear burn rate tends to increase as the pressure increases. All three, individual, example of this mixture were fired in a closed bomb configuration.

Figures 4-52a and b, show the linear burn rate for the average conditions during the three individual tests of the 5-29-96-B series. No initiation zone, or early full burn zone data appear in the graphs due to the limited data supplied by shot 5-29-96-B3. Although there is a momentary drop in the linear burn rate, this does not appear associated with the assumed burnout of the faster propellant, as has been addressed previously in section 4.4.2. The burn rate equation parameters determined are affected by the limited data available for evaluation, although the correlation coefficient is reasonable high.

Figures 4-53a and b, show the linear burn rate model output for shot 5-29-96-B1. In figure a, the three zones are basically evident. However, a step in the burn rate in the full burn zone is also clearly obvious. The step is most likely due to the burn out of the faster (smaller grained) No. 5 propellant, and the continued burning of the larger grained No. 8700 propellant. In figure b the linear burn rate parameters are obtained using the range of full burn zone data illustrated.

Figures 4-54a and b show the linear burn rate model data obtained for shot 5-29-96-B2. In this figure the three separate zones are evident, with a similar step in the full burn zone area as has been seen in previous shot involving propellant mixtures. The peak burn rate in the initial side of the full burn zone is faster, and occurs at a higher pressure than that observed in the previous shot (5-29-96-B1). This appears to be a factor that affects the burn rate parameters, and results in a lower correlation coefficient for this data set.

Figure 4-55a and b show the linear burn rate data obtained for the shot 5-29-96-B3. This shot contains very little data through the full burn zone, and none in what is shown as the ignition zone. By reflecting on the pressure-time trace for this shot, figure 4-22a, it is observed that the first data point has a magnitude of around 5 MPa, a level consistent with the full burn zone in the previous shots. Furthermore, the echoing that is apparent in the pressure-time figure can account for the variation in the linear burn rate observed in the present figure. The linear burn rate model, in figure 4-55b, shows a reasonable random distribution of data points about the “best-fit” line, compared to the distribution observed in the previous models of this propellant mixture. However, the range of the burn rates about the line appears to affect the correlation coefficient.

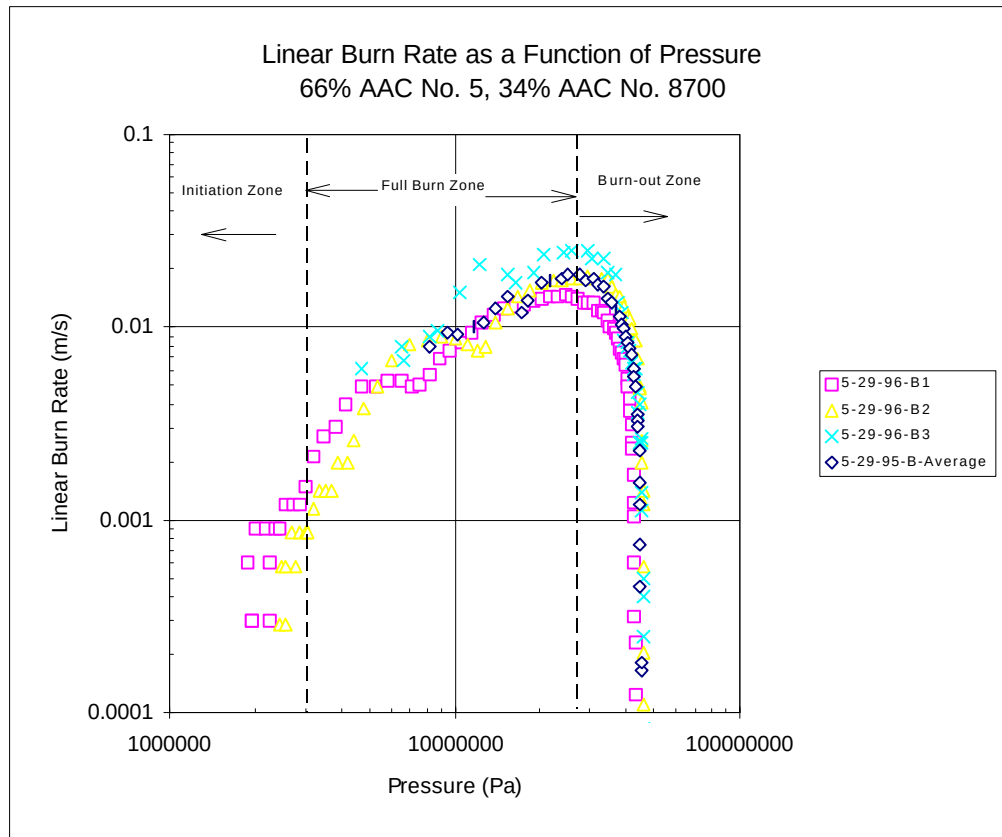


Figure 4-51: Linear Burn Rate as a Function of Pressure,
for Propellant Mixture 66% No. 5, 34% No. 8700

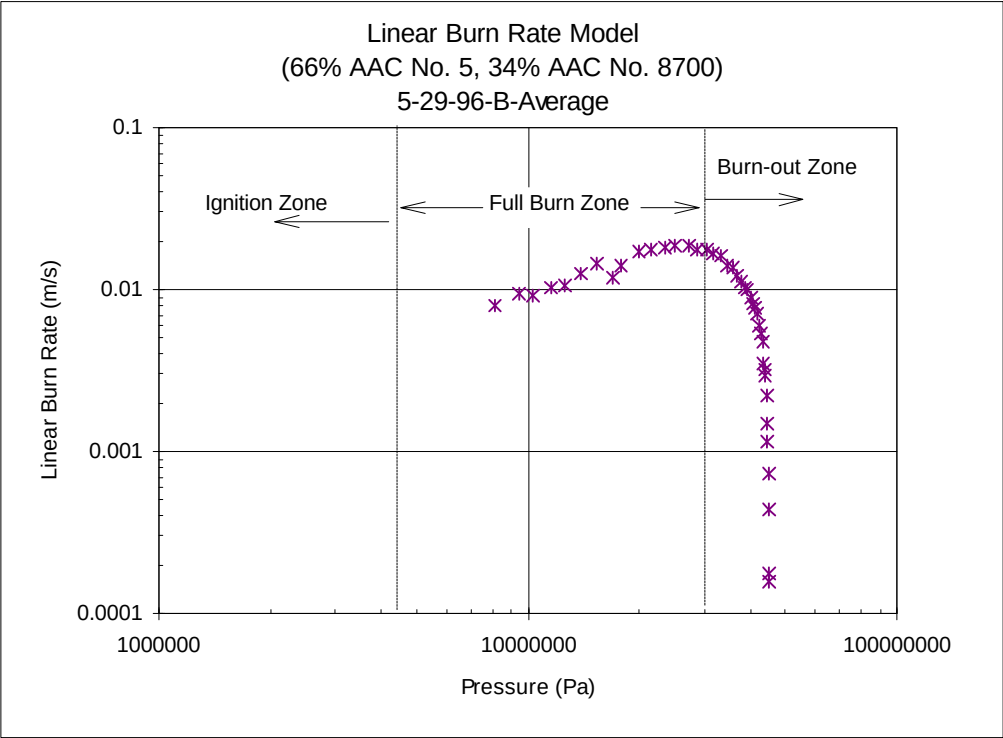


Figure 4-52a: Linear Burn Rate, Entire Model, Shot 5-29-96-B-Average.

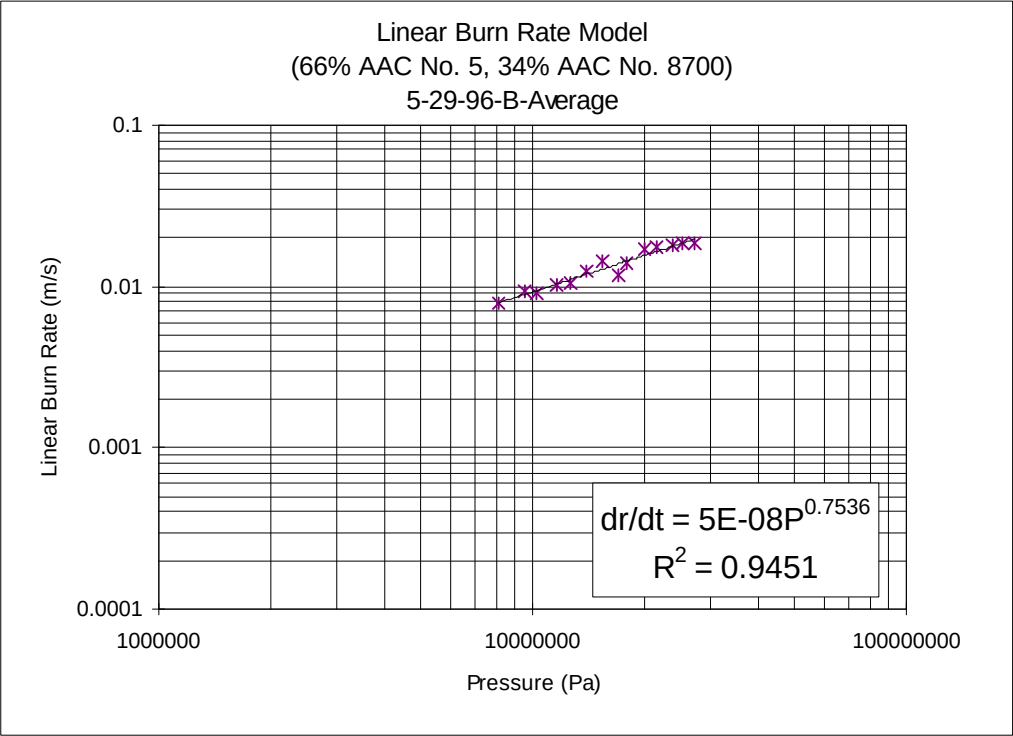


Figure 4-52b: Linear Burn Rate Model, Shot 5-29-96-B-Average.

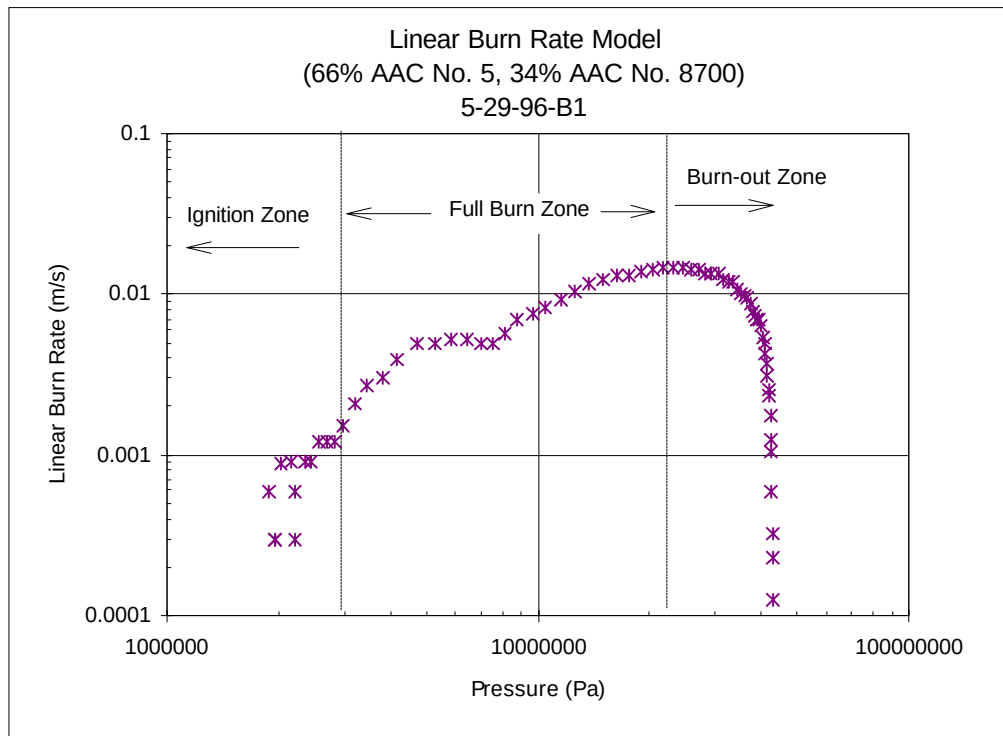


Figure 4-53a: Linear Burn Rate, Entire Model, Shot 5-29-96-B1.

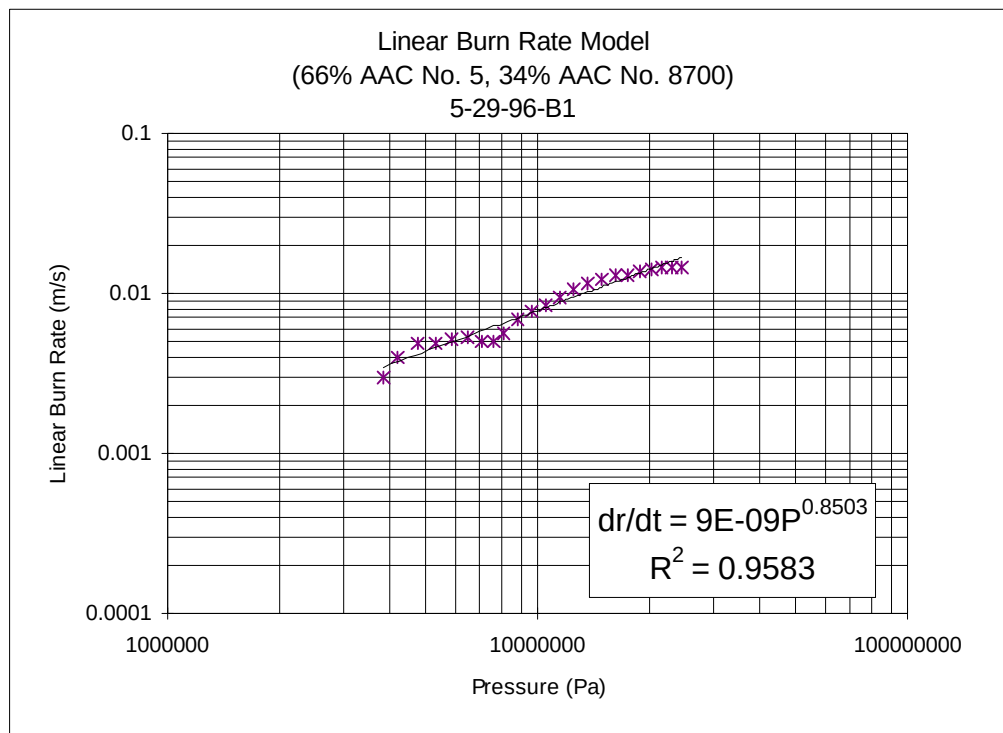


Figure 4-53b: Linear Burn Rate Model, Shot 5-29-96-B1.

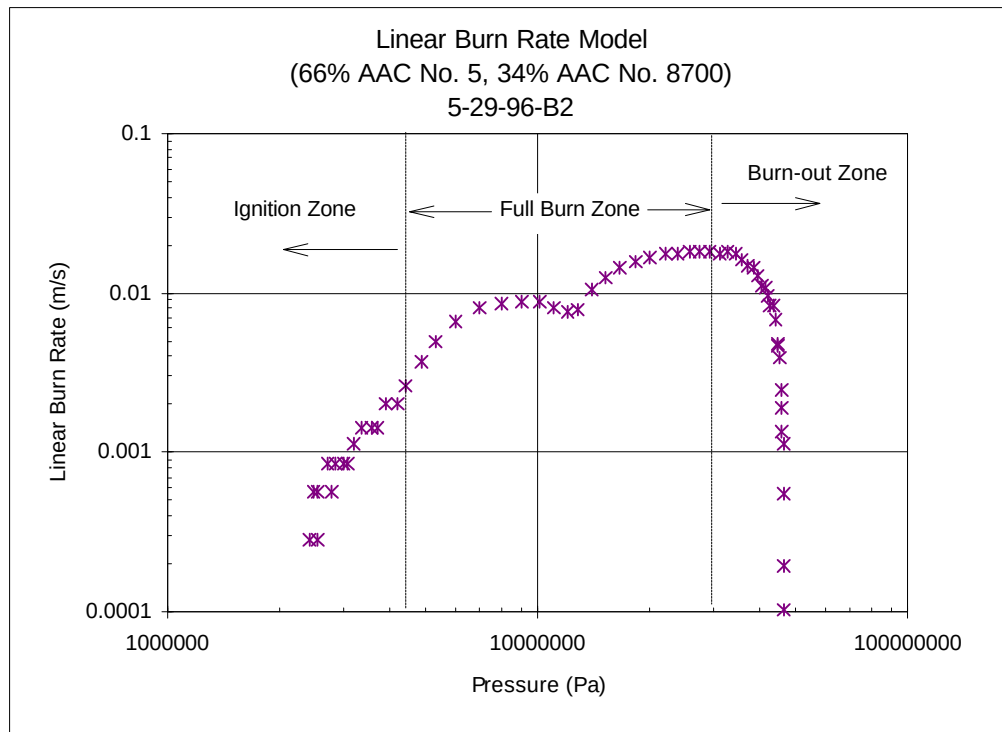


Figure 4-54a: Linear Burn Rate, Entire Model, Shot 5-29-96-B2.

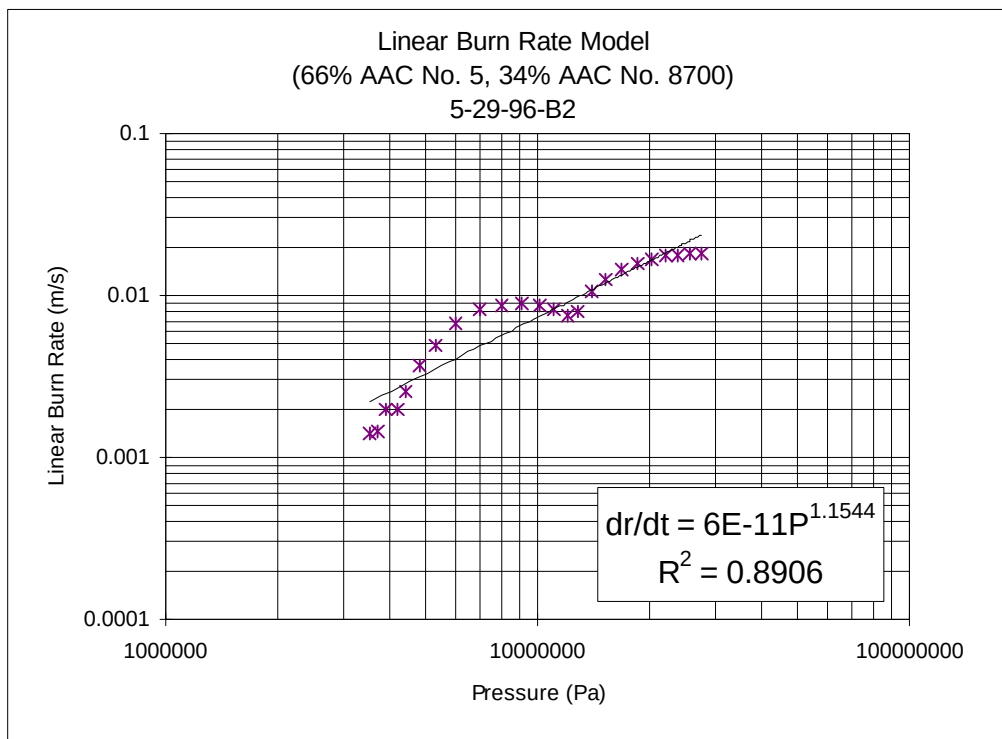


Figure 4-54b: Linear Burn Rate Model, Shot 5-29-96-B2.

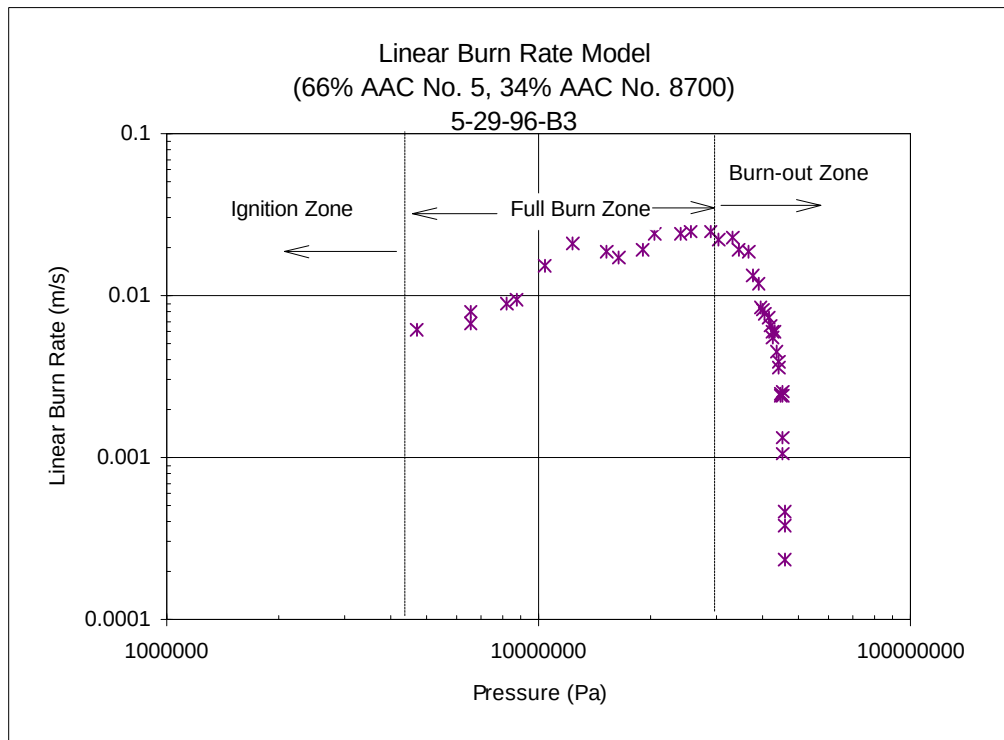


Figure 4-55a: Linear Burn Rate, Entire Model, Shot 5-29-96-B3.

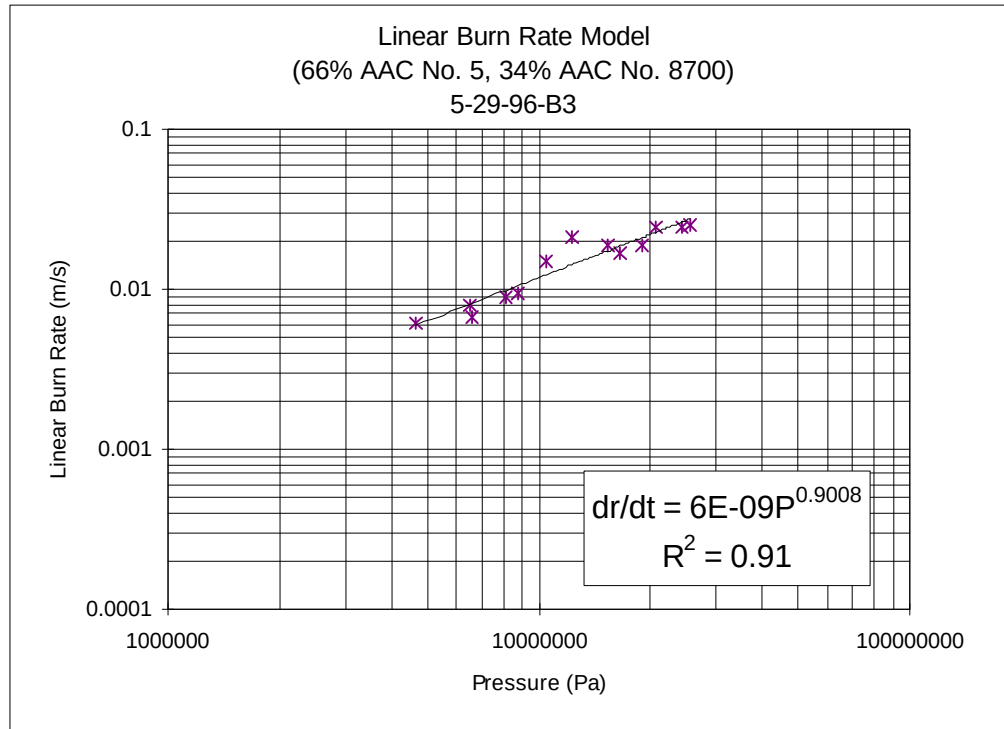


Figure 4-55b: Linear Burn Rate Model, Shot 5-29-96-B3.

4.4.4 50 Percent No. 5, 50 Percent No. 8700

Figure 4-56a and b illustrate the linear burn rate model data obtained for shot 6-13-96-B1. This shot consisted of a mixture of 50 percent No. 5 and 50 percent No. 8700 propellants. Of the shots consisting of this mixture this one was the only one in which a full shot took place, instead of a misfire. In the a figure, the ignition zone is fairly recognizable. In this evaluation the transition to the burnout zone was taken as the point of peak linear burn rate. In the full burn zone the linear burn rate data contain a point of relative maximum and relative minimum rates, in the vicinity of 12 MPa. This condition is, perhaps, associated with the consumption of the No. 5 powder, but since the condition is less than pronounced this is difficult to infer. A region of relative minimum followed by a relative maximum occurs in the burnout zone. The specifics of this case are also difficult to ascertain, however, the point can be correlated to the step, at 62 milli-seconds, seen in the dP/dt versus time plot, figure 4-21b, for this shot. The linear burn rate model, in figure 4-56b, indicates a very good fit to the full burn zone data used, as shown in that figure.

The determination of the linear burn rate for this mixture is obviously limited by the single sample available for evaluation. Although, from this condition it is evident that there is an upper limit to the quantity of No. 8700 propellant that can be, reliably, used in the very low loading density conditions employed in these tests. Not one of the shots utilizing a mixture with more than 50% of this propellant was observed to fire normally.

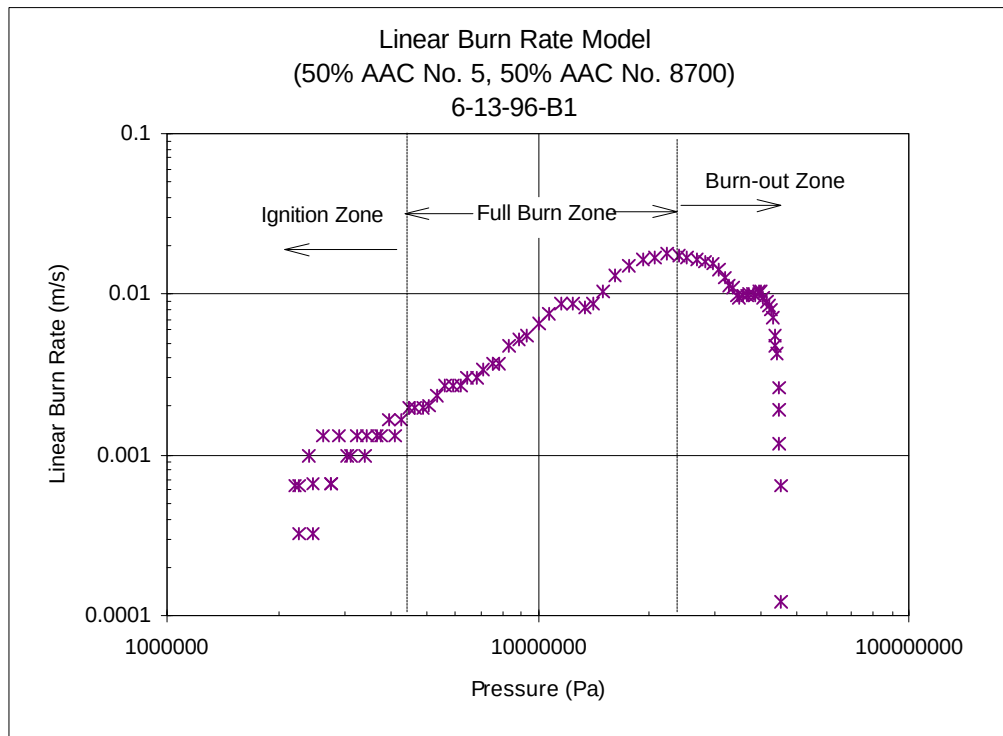


Figure 4-56a: Linear Burn Rate, Entire Model, Shot 6-13-96-B1.

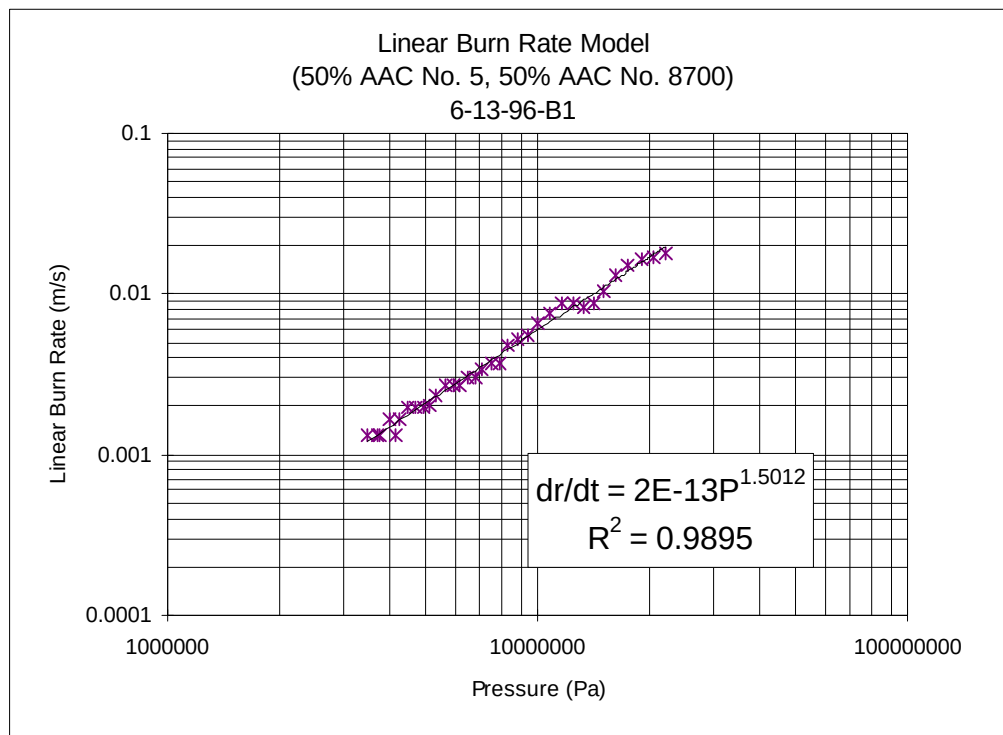


Figure 4-56b: Linear Burn Rate Model, Shot 6-13-96-B1.

4.5 Discussion

This section will cover those topics relevant for discussion and germane to the current chapter. More broad-reaching discussion will be covered in the chapter specifically addressing the general discussion of the material of this thesis (chapter 7). The topics for current discussion then are: the effect of the temperature sensitivity of the pressure transducer (4.5.1); internal reflection and end effects within the test vessel (4.5.2); effect of pressure rise-time and rise-rate relative to the predicted results (4.5.3); the effects of propellant mixtures (4.5.4), and a comparison of the linear burn rate estimates relative to those of the Ballistic Research Laboratory (4.5.5).

4.5.1 Effect of Temperature Sensitivity of the Pressure Transducer

As has been mentioned previously, see section 4.2.2.3, the PCB 108A02 pressure transducer was not ideally specified for the application and conditions experienced during these tests. The general specifications were, however, adequate for the pressure range and rate parameters of the testing. The limitation of the transducer came in its ability to respond to the temperatures presented during the course of propellant burning.

The transducer was designed for service in hydraulic systems where changes in temperature would be minimal, with respect to the time interval measurement. This was clearly not the case observed in the confined burning tests. The typical response initially observed as output from the transducer was of the following profile: the pressure would build to a recorded maximum, followed by a rapid decay; often the final indicated pressure of the recorded data would be significantly below that of a total vacuum, even in a closed system where a positive pressure was known to exist.

This condition lead an inquiry to the manufacturer regarding this phenomenon. The question was posed, was this a matter of inertia of the sensing element (considered unlikely based on the instrument specifications) or was it a temperature effect within the transducer (considered the more likely culprit). The representative from PCB²³ concluded from the description of the testing being conducted that the observation was based on temperature gradient induced into the transducer, a condition for which it had not been designed. It seems that the thermal gradient would tend to induce the following factors: (1) as the gradient increased the output voltage would decrease, (2) the peak pressure measurement (voltage output) would be attenuated, and (3) the peak measurement would be subsequently delayed. The recommended solution was to use a small dab of silicon grease on the exposed end of the transducer to insulate it from the vessel chamber.

²³ Discussion with Mr. David George of TCI and Mr. Larry Depew of PCB.

Due to the configuration of the test vessel, and the limited access to the transducer once installed, the method of placing a dab of silicon high-vacuum grease on the end of the transducer prior to placing it into the access port was developed. This method was rooted in filling the port between the transducer and the vessel chamber with the grease in such a manner as thermally insulate the transducer from the products of combustion. Once this modification to the laboratory procedure had been made the recorded data fit the pattern that was expected.

4.5.2 Internal Reflection and End Effects

In making the progression from laboratory scale tests to numerical modeling, one of the main assumptions is that the gases expand instantaneously to fill the entire volume. Based upon the tests conducted and evaluated in the above section this assumption appears to be, in general, valid. This is based on the large number of experiments conducted in the bench scale bomb, in which smooth pressure build-up curves were obtained. There are, however, a few exceptions to this. Several tests indicated very sharp pressure spikes in the initial few milli-seconds of the data. For the most part, these data settled out to the normal smooth profile. This lead to an initial estimate that the spikes were due to electrical current flow through the grounding system. A re-assessment of these spikes, spurred by small “bounces” in some of the smooth trend data, indicated that they were more than likely due to shock pulses bouncing about in the bomb.

The determination of the reflecting shock pulses is based primarily in the time differential between each of the spikes. Considering a typical case, using the properties of the products of combustion listed above; where (with round numbers) g (Ratio of Specific Heats)= 1.25, R (Gas Constant)= 368, T (Absolute Temperature)= 2500 K, the speed of sound (c) is determined as:

$$c = \sqrt{g RT} = \sqrt{1.25 \times 368 \times 2500} \approx 1070 \text{ m/s}.$$

With a reflected distance (d) of 0.30 meters, the period of pulses is expected to be d/c or 2.8×10^{-4} seconds. Based upon one of the representative tests (6-13-96-A2) the period between successive pulses is measured to be on the order of 2.7×10^{-4} seconds. The independent nature of these two determinations leads to the belief that those tests which indicated rapid pressure fluctuations immediately following ignition of the charge, were subjected to a detonation rather than a deflagration.

It might also be noted that even in some of the smooth profile records there appear be pulses occurring at a period that would indicate that a wave was reflecting within the bomb. In most cases, however, the magnitude of the pulses with respect to the current pressure, and the peak pressure, is of negligible impact. The effect of the detonation, versus a deflagration, and the resulting pressure transients is a factor that can be addressed in later refinements of the model at hand.

The general presence of wave reflection within the bomb is even more visible on the graphs that show the first derivative of pressure with respect to time. In these graphs it is clear that reflection was occurring in shots that, otherwise, appear to have a very smooth pressure growth profile.

4.5.3 Effect of Pressure Rise-Time and Rise-Rate

Based upon the work by Cuderman and Northrop (1986), it is evident that the pressure rise times observed in the laboratory are insufficient to generate a Multiple Fracture system at the 1 inch diameter scale. This does not, however, discount the ability to generate a sufficiently fast pulse, of sufficient magnitude, at a scale appropriate to the actual field conditions.

This basic conclusion changes the focus of the research at hand from that initially proposed. That is to take the propellant characterization data and charge design, and apply these lessons to fracturing in a laboratory scale tri-axial test vessel. These tri-axial tests were to investigate the effect of initial permeability path orientation to the orientation of a Multiple Fracture system generated by a tailored pressure pulse. Given that the present data indicated that such conditions could not be met at the laboratory scale, by the intended methods, more effort was directed to the field scale project. This includes the numerical modeling exercises developed in the next chapter (chapter 5), the large-scale tests addressed in chapter 6, and the recommendations for field application in chapter 8.

One factor that leads to the general supposition that the larger scale experiments may be more successful, at generated pulses of significantly short duration, is based on observations of all of the data collected in these small-scale tests. That is that as the charge weight was increased the pressure rise-rate also increased. This is easily explained in the power law relationship between linear burn rate and the surrounding pressure. For the cases under consideration, as the charge weight was increased the amount of propellant being consumed in each time step increases. This leads to a faster rate of change in the linear burn rate since the pressure is increasing in proportion to the amount of propellant consumed, in each time step. This self feeding loop causes a larger propellant charge to be burnt in a shorter period of time than a smaller charge of the same propellant.

Looking toward the large-scale experiments, several considerations relating to this are observed. First, that a larger test vessel will be required, obviating a good portion of the gain in burn rate due to the charge mass, since this is in proportion to the pressure and, hence, the vessel volume. Second, however, in a larger charge it is expected that control over the ignition sequence will be much easier to attain. That is a larger charge can be ignited along the center of the propellant body, with burning radially outward, rather than the axial burning systemic to the small charges. Third, is a consideration of the design of the large-scale test vessel. While a vessel less than 0.1 liters in volume charged with a gas at 50 MPa is easy enough to control, both in the pressurized state and during depressurization, a vessel of several liters presents more of a problem. This

factor was addressed in the design of the large-scale vessel, both in the structural elements as well as the compressed gas control.

4.5.4 Effect of Propellant Mixture

The effect of mixing two propellants, nominally equal except for the burn rate, has been addressed above referencing the work of Cuderman and Northrop (1986). Based upon this analysis it is expected that there is some difference in the pressure rise-rate of the classes of samples investigated here, related to the mixture of the two propellants involved in each case. While it is probably not fair to include the rocket fuel (black powder) samples with those using the smokeless propellant they are worth observing for trends. That the black powder should not be included in any quantitative way is relevant to the consideration of the powder as primarily an explosive, and, in any rate, it burns much faster than the standard propellants. Furthermore, the chemistry of the black powder is sufficiently different from the smokeless propellants that similarity in this respect cannot be assumed.

With respect to the smokeless propellants, even if the chemical make up of the two are not entirely identical within the class there has been assumed sufficient similarity to make a direct comparison.

Figure 4-57 illustrates the variation in pressure rise time for No. 5 propellant combined with either No. 8700 propellant or with black powder. Regarding mixtures with No. 8700 the pressure rise time tends to increase as the proportion of that propellant increases. This observation is expected due to the slower burning characteristics of the No. 8700 propellant. Also noticeable, concerning the No. 8700 mixtures, is that the variability in pressure rise time increases with the proportion of No. 8700. This is consistent with the behavior of the RDX propellant class, which is more difficult to ignite and is more variable in its properties than Nitrocellulose based propellants.

In figure 4-57 the mixtures of No. 5 propellant with black powder indicate a decreasing pressure rise-time as the proportion of black powder (Rocket Fuel) is increased. This observation is consistent with the much higher burn velocities associated with black powder, relative to the propellants. There appears to be some variation in the observed pressure rise time at the 50-50 mixture. This condition may be due to either poor mixing of the two materials, or to reduction of pressure levels in the bomb that are associated with the less energetic black powder. Lower pressures in the bomb result in slower burning of the propellants, which increase the pressure rise-time.

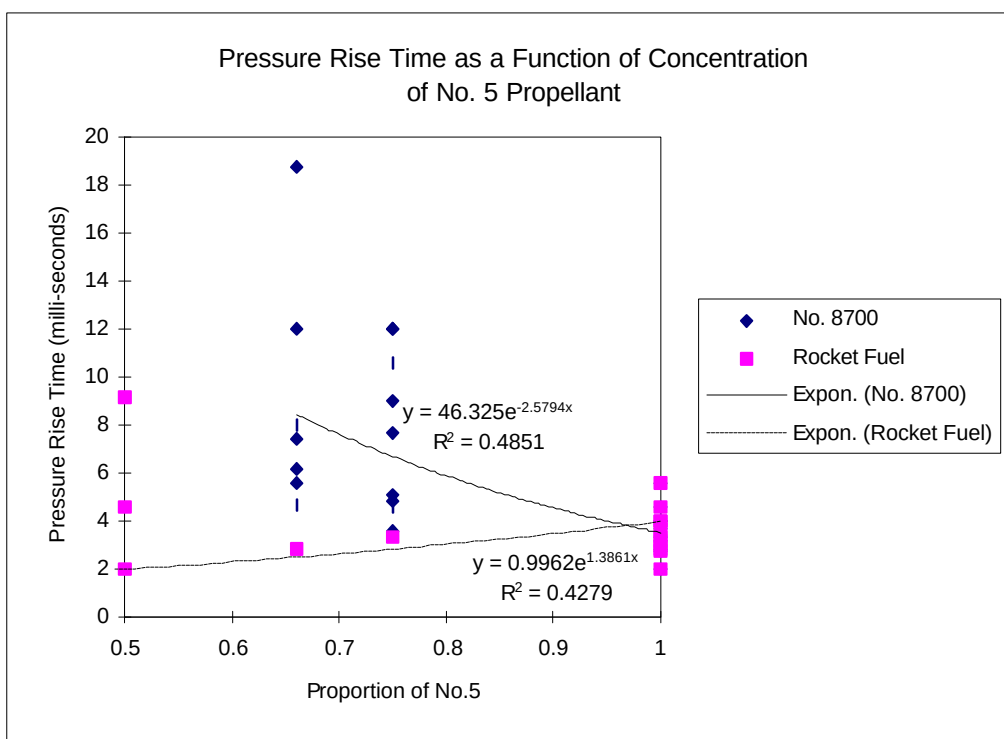


Figure 4-57: Comparison of Pressure Rise Time as a Function of Propellant Mixture.

4.5.5 Comparison of Linear Burn Rate Measurements

Some consideration of the burn rate estimates made here, versus those obtained by Riefler and Lowery (1974) is in order. This will be attempted even though there are several noticeable differences between their propellants and those used in this study. The most obvious difference is that the Riefler and Lowery propellants tended to be very lean with respect to nitroglycerin, suggesting a single base product. The propellants used in this study were all double base, primarily a mixture of nitrocellulose and nitroglycerin. The range of values estimated in this study and in the Riefler and Lowery study are presented in table 4-8.

Table 4-8: Comparison of Burn Rate Parameters.

Parameter	Minimum Value	Average Value ²⁴	Maximum Value
Riefler and Lowery Study (1974)			
Coefficient (m/s)	$1.1 * 10^{-5}$	$3.0 * 10^{-5}$	$1.1 * 10^{-4}$
Exponent	0.5986	0.7762	0.9022
Present Study			
Coefficient (m/s)	$1.0 * 10^{-15}$	$1.75 * 10^{-11}$	$5 * 10^{-8}$
Exponent	0.7536	1.2352	1.7981

The Riefler and Lowery study indicates that for similar propellant mixtures, the coefficient is inversely proportional to the initial grain diameter; and that the exponent is proportional to the initial grain diameter. The burn rate equation parameters developed in the present study do not present this trend, this may be due to a smaller shot population in the study or to the mixing of propellant chemistries in this study. In the present study, the average grain size in the shot was increased by adding an RDX based propellant. None of the propellants tested by Riefler and Lowery contained the RDX base.

The differences in the two data sets are obvious. The previous study has a coefficient that is 6 orders of magnitude larger than the present study, whereas its exponent is not quite half of that in the present study. Since both of these factors influence the shape of the pressure-time profile it is difficult to say what the actual parameters are that cause the disparity between the two sets of data, which would, at least, be expected to be of similar magnitude.

It is worth noting, however, that both of the data sets are based on physical experiments and are therefore empirical in nature. Sources of difference can arise from two main sources. The first

$$^{24} \text{Average Coefficient} = e^{\left[\frac{\sum \ln(\text{Coefficient})}{n} \right]}$$

being the size of the charge. In the Riefler and Lowery studies the charges tended to be on the order of 14.9 grams, whereas those presently were on the order of 5 grams. The other source of difference is in the configuration of the shot. In the Riefler and Lowery study a standard pressure bomb was used with an 87.5 cc volume, and a primer of length 20 mm. In their case the ideal of instantaneous ignition was probably much more closely reached than the present tests. In the present test, the focus was on the configuration of the charge and the shape of the vessel, this obviously played a part in the observed discrepancies between the data collected and reported herein and that produced on behalf of the United States Ballistic Research Laboratory.

The applicability of the data concerning the linear burn rate parameters determined in this project are addressed with respect to the Riefler and Lowery numbers in the discussion section of the next chapter (see section 5.4.1).

4.6 Nomenclature

Symbol	Description
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Roman

<i>A</i>	Linear Burn Rate Coefficient ($\mathbf{L^2t/M)^n}$
<i>B</i>	Coefficient in Burn Rate Estimation Equation
<i>b</i>	Solid Phase Propellant Specific Volume ($\mathbf{L^3/M}$)
<i>C</i>	Coefficient in Burn Rate Estimation Equation
<i>D</i>	Coefficient in Burn Rate Estimation Equation
<i>d</i>	Hole Diameter (L)
<i>f</i>	Proportion of Propellant in Mixture
L	Dimensional Coefficient for Length
M	Dimensional Coefficient for Mass
<i>n</i>	Linear Burn Rate Index
<i>P</i>	Absolute Pressure ($\mathbf{M/Lt^2}$)
<i>R₀</i>	Propellant Grain Initial Radius (L)
<i>r</i>	Propellant Grain Radius (L)
T	Dimensional Coefficient for Temperature
t	Dimensional Coefficient for Time
<i>t</i>	Bore Hole Pressure Rise Time (t)
<i>t_p</i>	Multiple Fracture Pressure Rise Time (t)
<i>v</i>	Propellant Gas Co-Volume ($\mathbf{L^3/M}$)
$\dot{X}$	Linear Burn Rate of Propellant (L/t)

Greek

η_s	Raleigh Surface Wave Velocity (L/t)
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Sub-Script

<i>A</i>	Propellant Type A
<i>B</i>	Propellant Type B
max	Series maximum value

Super-Script

'	Indicates Conditions in a Larger Free Volume, Propellant Charge Scaling
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Chapter 5. Numerical Modeling

This chapter concerns the development of a numerical model that is capable of producing adequate similarity between the computed results obtained by said model and those results obtained in laboratory experiments. The main goal of the numerical model is to be able to estimate the physical response that is expected under field conditions, prior to actually performing tests in the field.

The layout of this chapter covers the following topics: Section 5.1 presents the thermodynamic assumptions from which the model was developed. Section 5.2 lays out the development of the model and the necessary physical assumptions. Section 5.3 discusses the results of the modeling process and the application of specific cases developed from the results of the closed bomb firings presented in chapter 4.3 of this thesis. The code listing for the numerical model developed in this study is provided for the reader in appendix E of this thesis.

5.1 Thermodynamic Principles

The most basic view of the problem under consideration is that there is a conversion of stored chemical energy, in a solid, to internal energy in a compressed gas. In the problem, a quantity of granular propellant is ignited, an exothermic chemical reaction occurs, the resulting product being a gas. All of this takes place in an air-filled vessel of a constant volume.

As the following sections will address, a basic tenet of the solution is that both mass and energy are conserved. Hence valid solutions to the Continuity, Momentum, and Energy equations exist.

5.1.1 Conservation of Mass

During combustion of the propellant it is assumed that all of the solid phase mass is converted to gas phase. During the time period of interest it is also assumed that no condensation of products of combustion occurs. With this in mind the time dependent conservation of mass equation can be expressed as follows:

$$\frac{dm_s}{dt} = \frac{dm_{g,b}}{dt} + \frac{dm_{g,v}}{dt},$$

where m_s is the solid phase mass of propellant, $m_{g,b}$ is the gas phase mass remaining in the bomb, and $m_{g,v}$ is the gas phase mass vented from the bomb. It is assumed that no solid phase propellant is ejected from the bomb.

5.1.2 Conservation of Energy

The combustion phase of the propellant burn consumes the stored chemical energy. For the case of a closed bomb, all of this energy goes into internal energy of the gas phase present in the bomb. In the vented bomb case, some of the energy made available must also be used to accelerate the escaping gases and, thus, perform P - v work. The conservation of energy can thus be expressed as:

$$\frac{dm_s}{dt} = \frac{du_{g,b}}{dt} + \frac{du_{g,v}}{dt},$$

where m is the stored chemical potential and u is the internal energy of the produced gas.

5.1.3 Noble-Abel Equation of State

The Noble-Abel equation of state is based upon the ideal gas law, but includes a covolume factor that accounts for the volume occupied by the gas molecules. This equation is expressed as:

$$P = \frac{RT}{(b - v)},$$

where P is the pressure, R is the gas constant, T is the absolute temperature, b is the specific volume and v is the covolume. At low pressures the covolume is significantly less than the

specific volume and the equation degrades to the ideal gas relationship. However, as the pressure increases, resulting in a lower specific volume, the volume occupied by the gas molecules can become a significant factor, hence the deviation from ideal behavior. Powell et al. (1979) report that this equation finds application in interior ballistics due to its simplicity, even though there is the potential for error to be introduced at high temperatures.

5.1.4 Velocity of vented gases

The velocity of gases vented from the bomb are related to the difference between the internal and external pressure across the vent. At some point, however, the velocity of gas escaping the system coincides with the rate at which the gas movement is being communicated to the gas upstream of the vent, i.e. the gas velocity is equal to the speed of sound in the fluid. At this point the velocity of the escaping gas is equal to the speed of sound in the gas, regardless of the pressure difference. The speed of sound, c , in a gas is generally expressed as:

$$c = \sqrt{g RT}$$

where g is the ratio of specific heats, R is the gas constant, and T is the absolute temperature of the gas. The differential pressure ratio that will cause flow from the vent to be equal to the speed of sound is referred to as the critical pressure. Based on an isentropic consideration and ideal gas behavior the critical pressure ratio can be expressed as (Hughes and Brighton 1991):

$$\left(\frac{P_{ext}}{P_{int}} \right)_{critical} = \left(\frac{2}{g+1} \right)^{\frac{g}{g-1}}$$

where P_{ext} is the pressure exterior to the nozzle and P_{int} is the pressure interior to the nozzle. The mass flow rate for differential pressure ratios greater than the critical value, that is flow less than sonic velocity, can be expressed as (Vennard and Street 1982):

$$\frac{dm}{dt} = a \sqrt{\frac{2g}{g-1}} P_{int} r_{int} \left[\left(\frac{P_{ext}}{P_{int}} \right)^{\frac{2}{g}} - \left(\frac{P_{ext}}{P_{int}} \right)^{\frac{g+1}{g}} \right].$$

where a is the minimum nozzle area and r_{int} is the gas density interior to the nozzle. For sonic velocity flow, pressure ratios less or equal to the critical value, the mass flow rate can be expressed as:

$$\frac{dm}{dt} = \frac{aP_{int}}{T_{int}} \sqrt{\frac{g}{R} \left(\frac{2}{g+1} \right)^{\frac{g+1}{g-1}}}$$

where T_{int} is the temperature interior to the nozzle. While it may be common to assume that flow through the nozzle occurs isentropically, without special design considerations this will not be assumed here. Rather, a coefficient of discharge, C_D , will be employed to adjust the overall efficiency of the nozzle.

5.2 Model Development

The physical basis for the development of the computational model is illustrated in figure 4-4. This prototype is based in similarity to a laboratory scale fracturing experiment that had been proposed. Completion of the tri-axial fracturing experiments was supplanted in favor of performing larger scale experiments on the tailored pulse system.

This section addresses two portions of the development of the numerical model used to estimate the various bomb internal parameters as a function of time during the charge burn. The first of these is propellant burn characteristics and properties. The second is the solution algorithm developed for solution of the non-steady state burning problem.

5.2.1 Burning Rate

The steady state burning rate of a propellant is generally expressed as a power function that relates the advancing rate to the pressure at the burning face. This expression is:

$$\dot{X} = AP^n,$$

where $\dot{X}$ is the linear advance rate of burning, A is the rate coefficient, P is the ambient gas pressure and n is the burning rate index. This equation is reported as the standard means of analysis for internal ballistics at steady state.

Several refinements of this expression, relevant to non-steady burning, are available in the literature (Krier 1972, and Osborn 1973). The non-steady-state variations appear to be due to changes in the heat transported as pressure variations alter the position of the flame front relative to the propellant burning face. That is, as the pressure builds the flame front is pushed towards the propellant face. During this process heat released during the combustion reaction is directed back towards the propellant, tending to increase the reaction rate. The opposite holds true for

propellant burning during a depressurization process. Account of this phenomena is provided by Krier (1972), [corrected by Ben-Reuven (1973)]:

$$\dot{X}_{ns} = \dot{X} \left[1 + y \left(\frac{n}{P} \frac{a}{\dot{X}^2} \right) \frac{dP}{dt} \right],$$

where y is the dynamic burning rate coefficient:

$$y = \frac{\left(1 - \frac{1}{m} \right) \left(\frac{P}{p_0} \right)^{n/m}}{\left[\left(\frac{P}{p_0} \right)^{n/m} \left(2 + \frac{1}{m} \right) - 2H \right]}.$$

In this expression, a is the solid phase thermal diffusivity, m is the propellant pyrolysis index, H is the dimensionless magnitude of surface heat release, P/p_0 is the dimensionless pressure. Although there are several reports investigating the dynamic burn rate acceleration phenomenon (Kuo and Coates 1976) Stiefel (1979) indicates that there is little evidence that such theoretical approaches offer practical solutions to the effects in gun chambers. Considering Stiefel's conclusion the dynamic effect will not be considered in the models developed herein.

5.2.2 Propellant Properties

The propellant utilized in the physical experiments was a commercially available ball propellant intended for use in the reloading of civilian firearms. The type of propellant was chosen due to the availability and the fact that it would likely continue to be manufactured into the foreseeable future. It did suffer from the fact that little data were immediately available concerning its general properties. Therefore, an assumption was made that the properties would be similar to those expressed for the military small arms ball propellant M18. These basic properties are listed below, in table 5-1.

Table 5-1: Properties of Propellant M18 (after: Stiefel 1979)

Isochoric Flame Temperature (T_v)	2577 K
Impetus (F)	$9.5 * 10^5$ J/kg
Heat of Explosion	772 c/g
Gas Volume	0.04457 moles/g
Ratio of Specific Heat (γ)	1.2523
Covolume (b)	$1.09 * 10^{-3}$ m ³ /kg
Density	1620 kg/m ³
Gas Constant ²⁵	368.6 J/kg K

The steady state burn parameters were initially assumed to be, $A = 7*10^{-8}$ m/s Paⁿ, and $n = 0.9$ (Nilson, Proffer, and Duff 1985). In the absence of values directly relevant to the M18 propellant, these values for M5 propellants provided an initial data point. These parameters are based on the chemical reactions involved in the combustion process and not the geometry of the problem. A principle difference in the burning characteristics of the artillery propellants, such as the M5, and small arms propellants, such as M18, is that the small arms propellants are normally coated with a deterrent material. The deterrent is provided to slow the initial burning of the propellant, due the normally higher loading densities employed in small arms cartridges.

Goldstein (1979) addresses the role of deterrents in the rate of burning. He points out that the deterrent chemical is applied to the outside of the propellant grain and is allowed to diffuse inwards. This configuration leads to a progressive burning rate as the diameter of the propellant grain decreases. A detailed solution to the deterred burning phenomenon is given in this source. Analysis in that manner, however, requires more information than is available concerning the propellant at hand.

Since the deterrent diffuses into the grain of propellant, the analytical model includes the capability of assessing the impact of the deterrent as a function of the initial burn rate compared to the nominal burn rate. This relative burn rate is independent of the gas pressure at the propellant grain.

5.2.3 Numerical Modeling

The development of a model for estimating the properties inside the closed bomb was initially based on the assumption that all of the available propellant was ignited simultaneously. This

²⁵ Gas Constant is based on the following:

$$R = \frac{F}{T_v} = \frac{950000(\text{J / kg})}{2577(\text{K})} = 368.6 \left(\frac{\text{J}}{\text{kgK}} \right)$$

condition is clearly not the case, and in a situation wherein the loading density is very low, it is also not an implicitly valid assumption. In a condition where the propellant loading density approaches, or surpasses, the bulk density, a much greater pressure rise curve can be expected. However, in a low loading density situation the high free volume will tend to decrease the magnitude of the peak pressure, and the pressure rise rates. It is for this reason that it is not valid to freely assume that instantaneous ignition of all of the available propellant occurs. Utilization of the instantaneous ignition assumption can provide a reference point for the computational procedure, from which a more detailed analysis can be developed.

The solution approach is based on a quasi-steady-state assumption, in which the burning rate is assumed to remain constant during some finite time increment. Furthermore, it is assumed that the products of combustion from the propellant: (1) are non-condensing for the period of time considered, (2) have fixed specific heat and gas constants, (3) exhibit real gas behavior expressed by the Noble-Abel equation of state, (4) expand instantaneously to fill the bomb volume, and (5) do not transfer heat to the bomb.

5.2.4 Deterrent of Propellant Burning

The effect of deterred burning will be modeled on the basis of a proportion of the nominal burning rate. It will be assumed that the maximum inhibition of burning advance will occur at the initial surface, and that the very center of the propellant grain will be completely free of deterrent. Two approaches to the degree of deterrence are available for use in the modeling problem. The first is that the actual burn rate approaches the nominal on a logarithmic curve; and the other on a polynomial curve. For convenience, these forms have been non-dimensionalized. The deterred burn rate is expressed as the following:

$$\dot{X}_{det} = \dot{X}z .$$

Where z is the non-dimensional deterrent coefficient ($\dot{X}_{det} / \dot{X}$). This is defined for the profiles in the following manner:

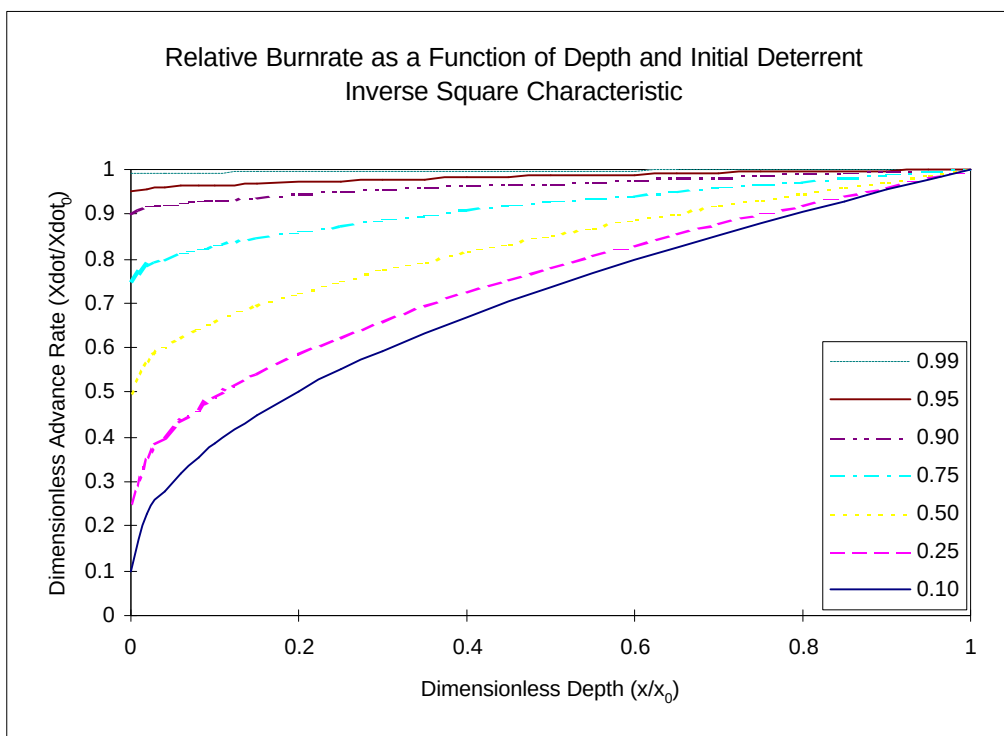
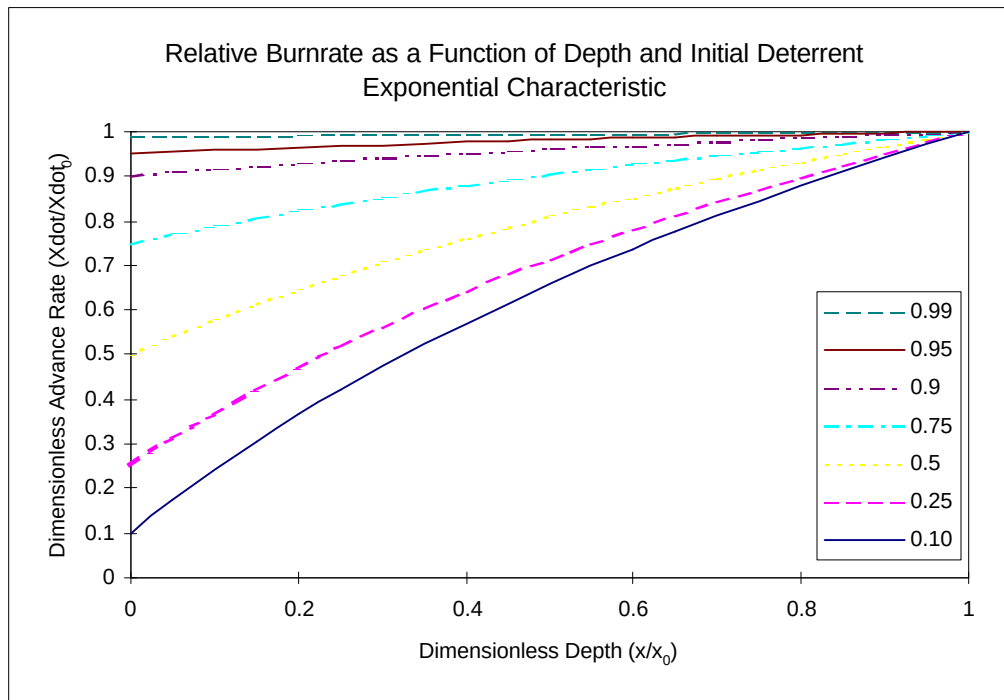
$$(1) \text{ Logarithmic Curve: } \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_x = \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_0 + \left(1 - \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_0 \right) \ln \left(1 + \frac{X}{X_0} [e - 1] \right).$$

$$(2) \text{ Polynomial Curve: } \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_x = \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_0 + \left(1 - \left. \frac{\dot{X}_{det}}{\dot{X}} \right|_0 \right) \left(\frac{X}{X_0} \right)^z.$$

Figures 5-1 and 5-2 illustrate the above families of curves, respectively. As illustrated, the polynomial characteristic is shown as a cubic, the model in actuality allows for the user to select

the degree, z . To simplify the programming only the highest order element of the polynomial, along with the y -intercept are used. A physical justification for this is that the degree of deterrence should decrease monotonically as the burning progresses toward the center of the grain, a condition not guaranteed when other coefficients of the polynomial are considered to be non-zero.

Figure 5-3 illustrates the effect of deterrence on the time required for the propellant charge to burn.



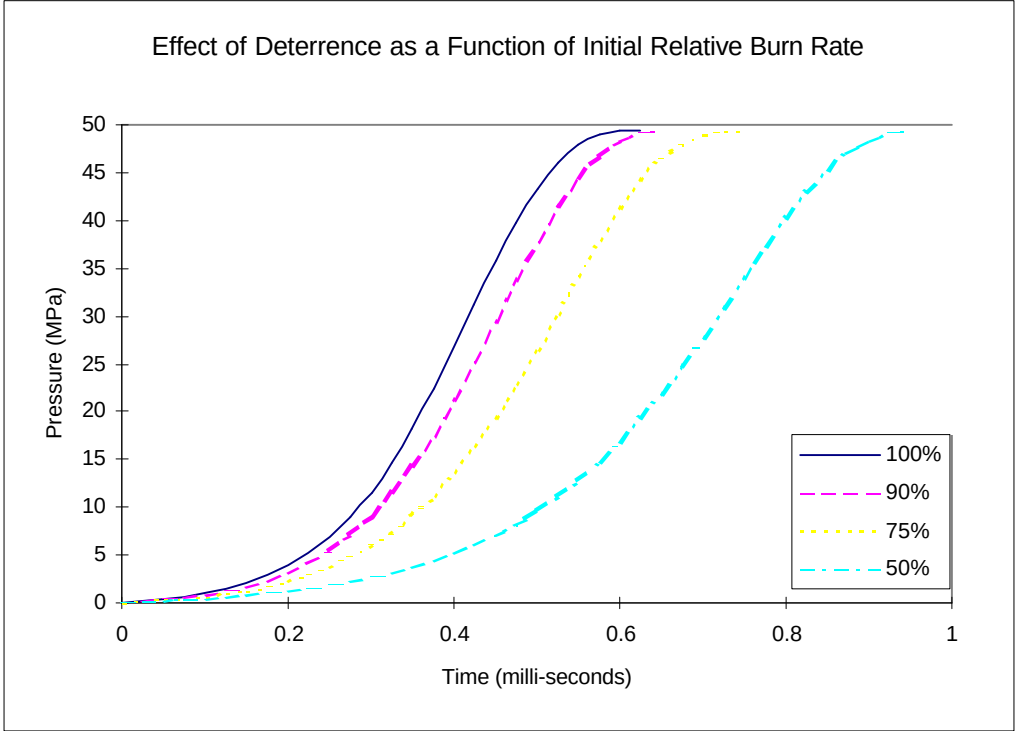


Figure 5-3: Effect of Deterrent on Time to Reach Peak Pressure.

5.2.4.1 *Instantaneous Ignition of Propellant*

The first problem addressed was to model the instantaneous ignition of the propellant charge within the bomb. To begin the process of developing a computational scheme it is helpful to evaluate, qualitatively, the likely outcome. The final temperature, pressure, specific volume, etc. are easily estimated given the confines of the problem. However, that still leaves the task of evaluating the path from the pre to post burn state.

If the propellant is assumed to be truly spherical in shape and has a steady state burn rate, then, a few characteristics can be determined. First, since the burn rate is a function of the pressure, the pressure will build fairly slowly, accelerating as the pressure increases. While the propellant is burning, however, the surface area available for reaction is decreasing. Thus, despite the ever increasing progression velocity, the rate of pressure increase begins to fall as a result of the disappearing propellant surface area. The outcome, and estimated shape of the pressure versus time curve, should exhibit a sigmoidal shape.

The general algorithm utilized for the computation of the instantaneous burn problem in a constant volume bomb is illustrated in figure 5-4. The initial routine did not account for the volume initially occupied by the solid phase propellant. This weakness was corrected in a later iteration of the code. Examples given as output in this thesis consider the effect of the transfer of volume inside the pressure vessel from solid propellant to products of combustion.

Figure 5-5 illustrates relationship of (a) pressure, (b) temperature, (c) specific volume, and (d) mean grain diameter as functions of time for a typical test. The problem illustrated in this figure was based on an undeterred propellant. Table 5-2 compares the peak pressure outcome of burns conducted in the laboratory to those estimated using the M18 propellant parameters listed above. These data are illustrated in figure 5-6. Since the reaction was assumed to occur in the bomb without heat transfer the peak pressure results are unaffected by the time duration element of the model.

Table 5-2: Experimental and Estimated Peak Pressures

Propellant Mass (grams)	Peak Pressure	
	Experimental (MPa)	Estimated (MPa)
5.85	58.2	58.2
5.37	54.9	53.2
5.06	49.8	50.0
4.65	44.6	45.8
3.00	26.5	29.3
2.49	22.5	24.2

There appears to be a very good correlation between the peak pressures observed in the laboratory scale experiments and those predicted by the numerical model. Based on this conclusion, there appear to be no significant problems with the propellant properties assumed in table 5-1.

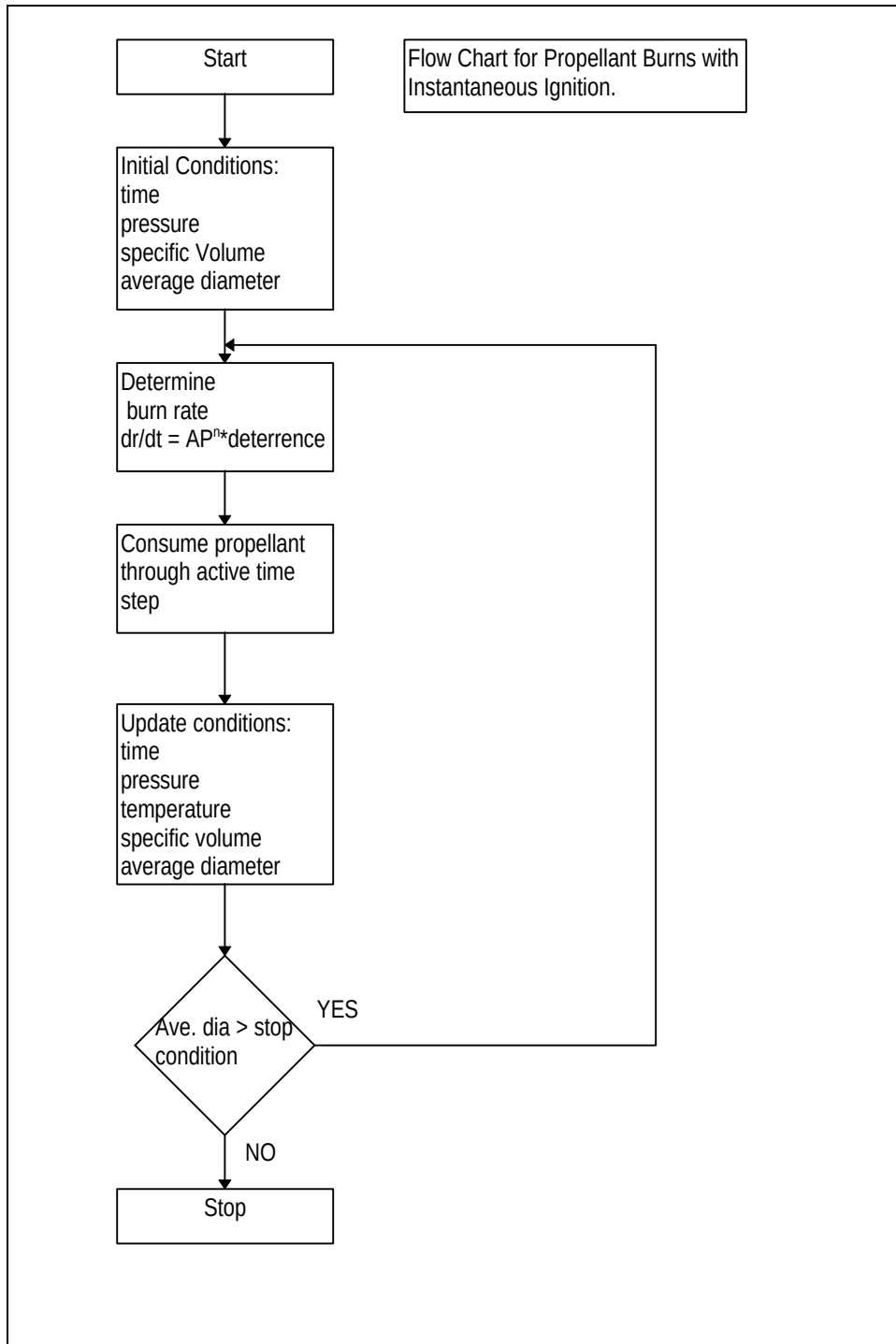


Figure 5-4: Instantaneous Ignition Profile, General Algorithm.

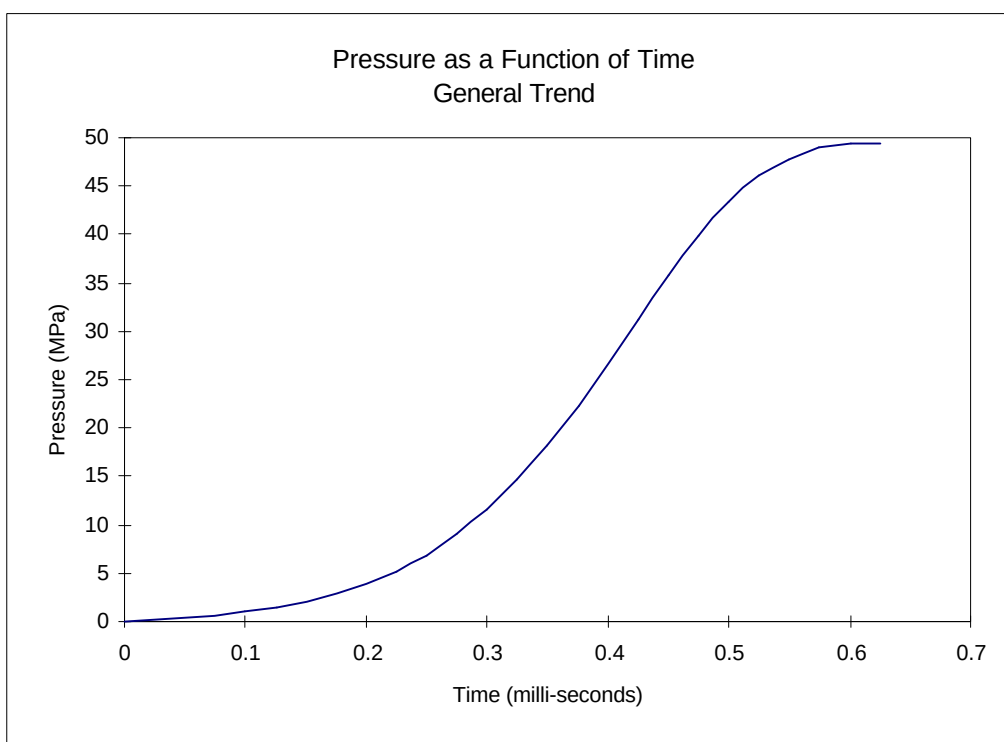


Figure 5-5a: Relationship of Pressure with Time During Modeled Propellant Burn.

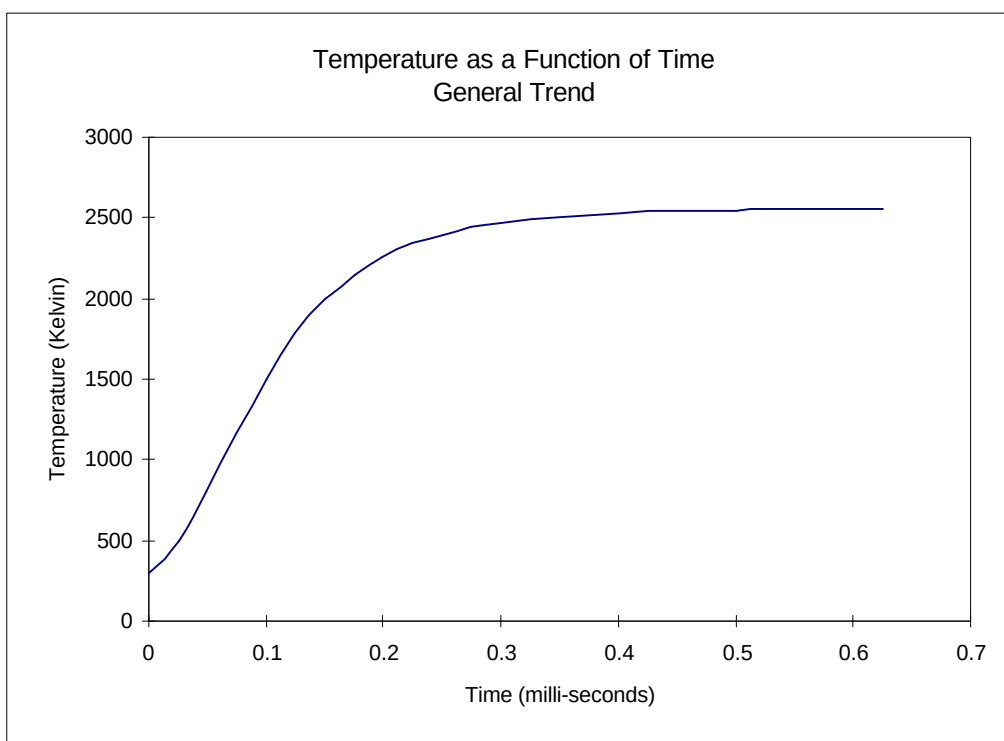


Figure 5-5b: Relationship of Temperature with Time During Modeled Propellant Burn.

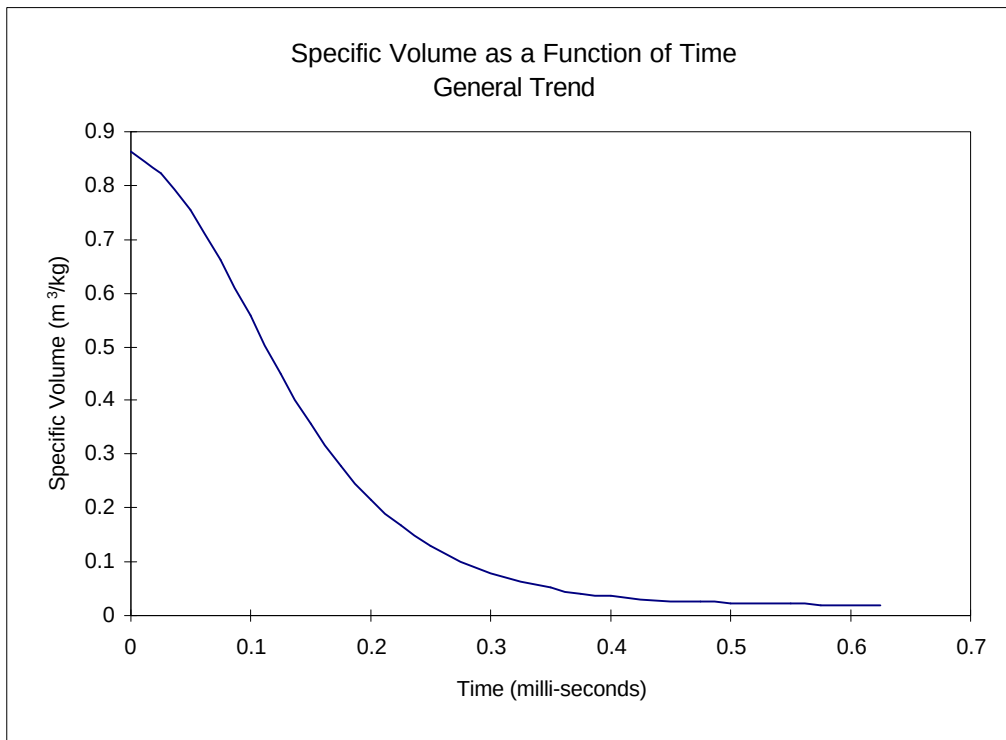


Figure 5-5c: Relationship of Specific Volume to Time During Modeled Propellant Burn.

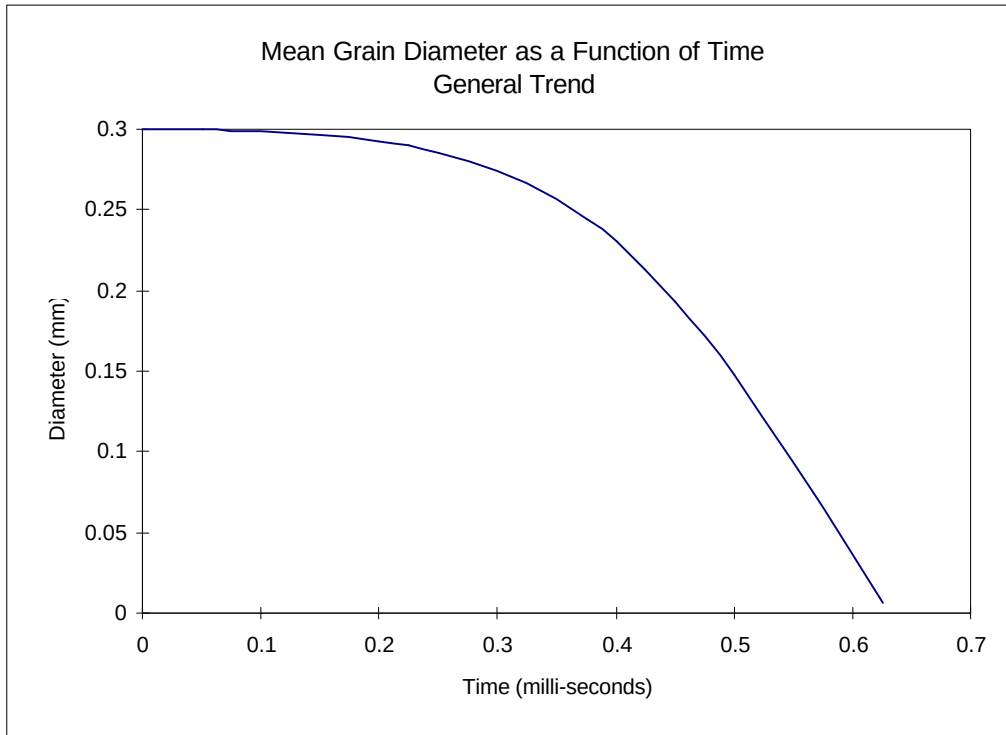


Figure 5-5d: Relationship of Grain Size with Time During Modeled Propellant Burn.

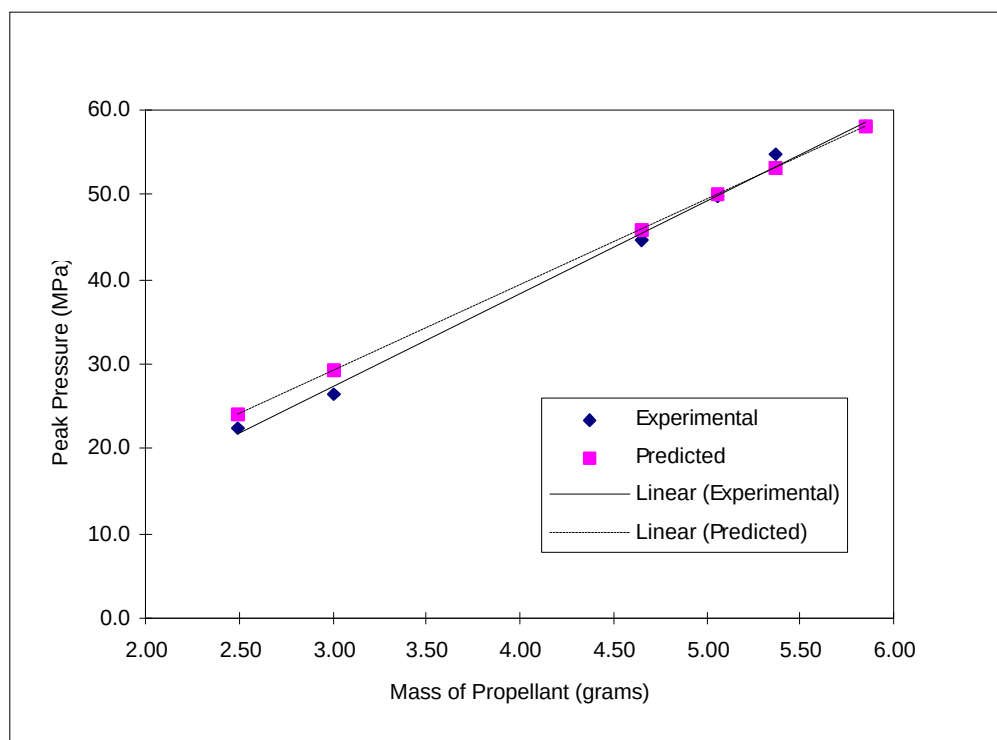


Figure 5-6: Experimental and Estimated Peak Pressures of Various Charge Weights in Closed Bomb Tests.

5.2.4.2 Axial Burn Profile

An attempt to increase the accuracy of the model to the experimental conditions meant approaching the propellant ignition phenomenon in two dimensions. First, is the problem addressed above, wherein the propellant burn is progressing normally inward to the individual propellant grain. The second is the advancement of the propellant burn along the axial length of the propellant charge. The basis for this problem is illustrated in figure 5-7. The computational flow chart is illustrated in figure 5-8.

This burn profile turns out to be a substantially slower path than that seen in the instantaneous ignition assumption. The reason for this is that the advancement of the burn from the point of ignition is taken as a function of the rate at which the propellant is burning into an individual grain. Based upon the model used for computations, this leads to the situation wherein a small number of increments are actually active for each time step. As the pressure increases, a point is reached where the entire grain of propellant is consumed during the time step. Thus, what is observed is the summing of numerous individual and complete propellant burn steps. This explains why the pressure - time profile exhibits the increasing slope behavior, rather than the sigmoidal behavior seen in the instantaneous model. A typical output curve for pressure versus time is shown in figure 5-9.

An interesting phenomenon of this burn model is the initial step associated with consumption of the ignition zone, figure 5-10a and b. This region exhibits the sigmoidal shape seen in the instantaneous ignition model. A step of this nature is visible in many of the laboratory tests. That is, a brief step is observed to occur at the time of initiation, with the slope of the P-t curve tracing the s-shaped path before climbing to the peak pressure.

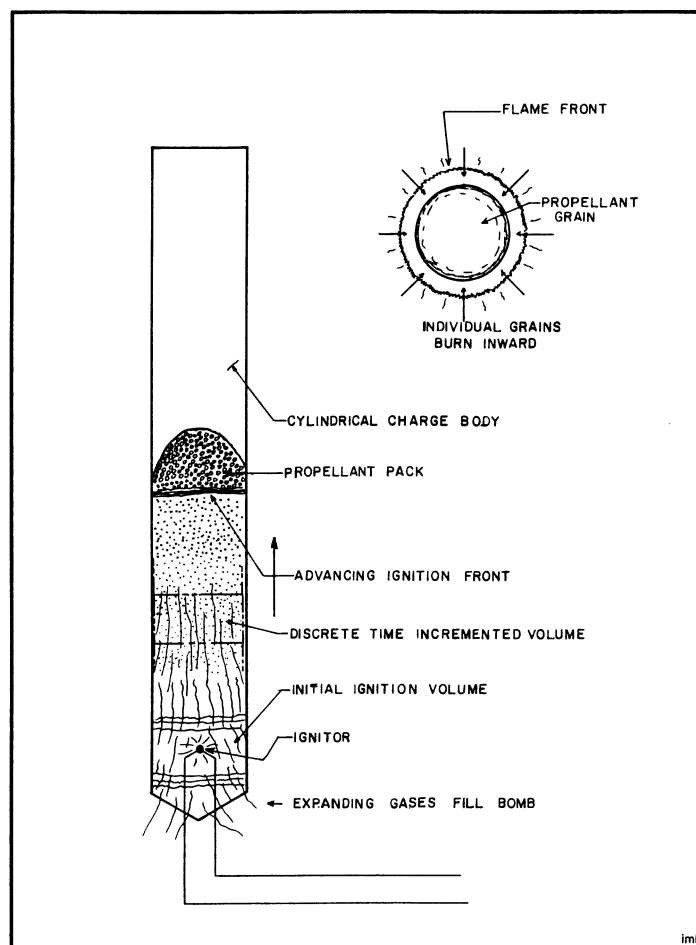


Figure 5-7: Diagrammatic Basis for Axial Burn Profile Problem.

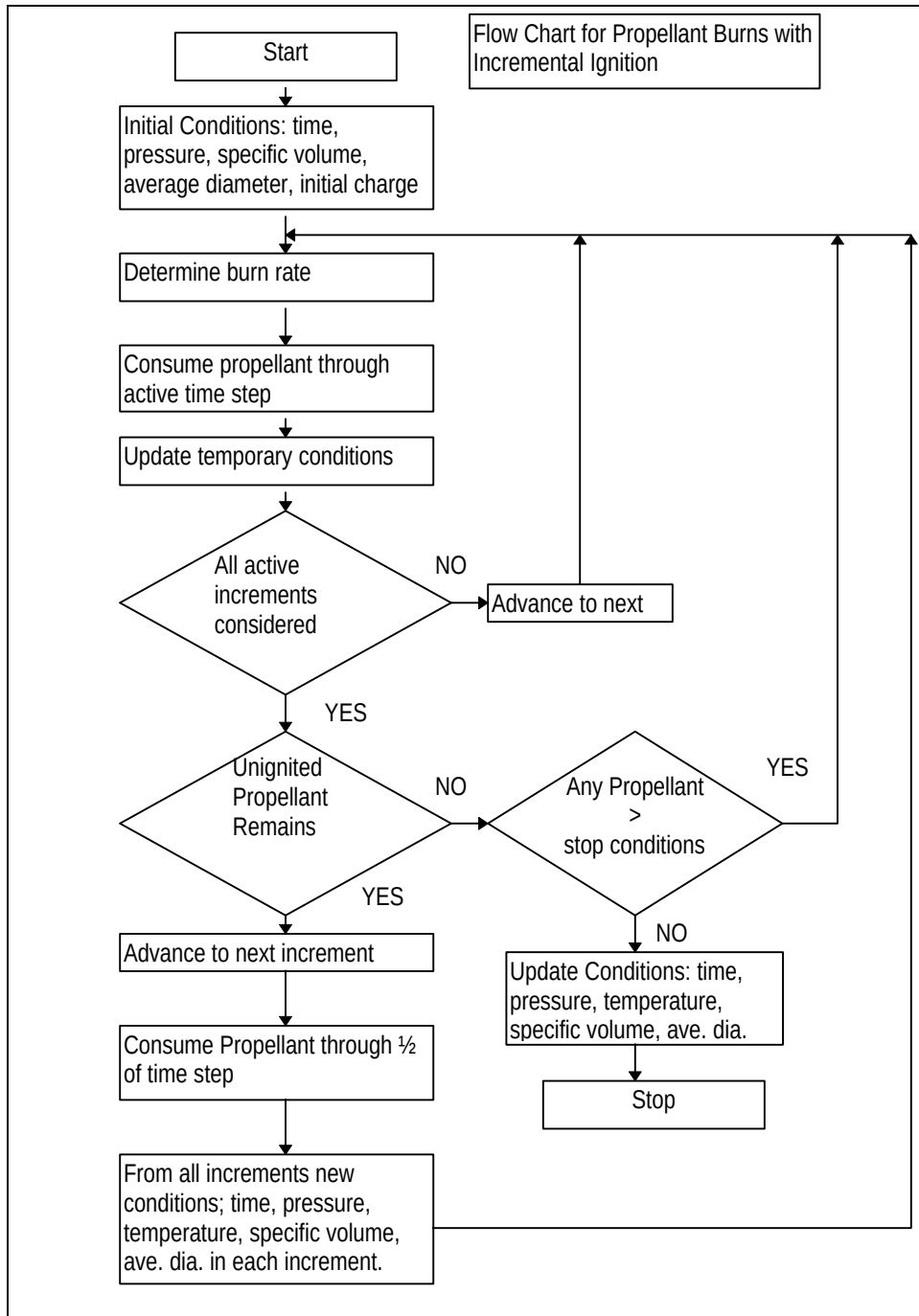


Figure 5-8: Computational Algorithm for Axial Burn Profile Problem.

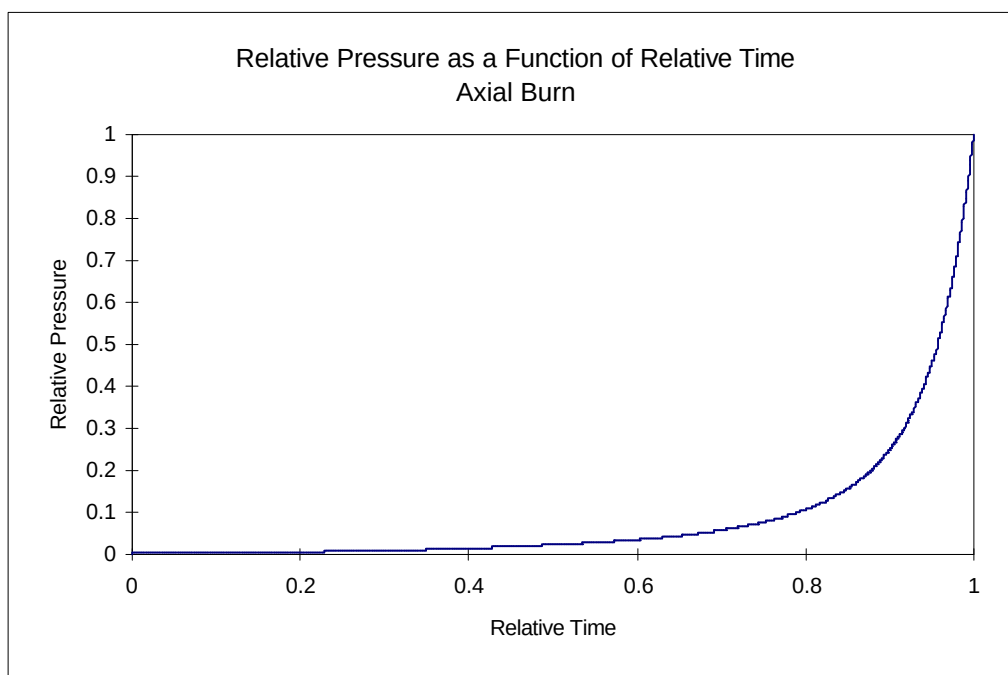


Figure 5-9: Typical Pressure-Time Output from Axial Burn Model.

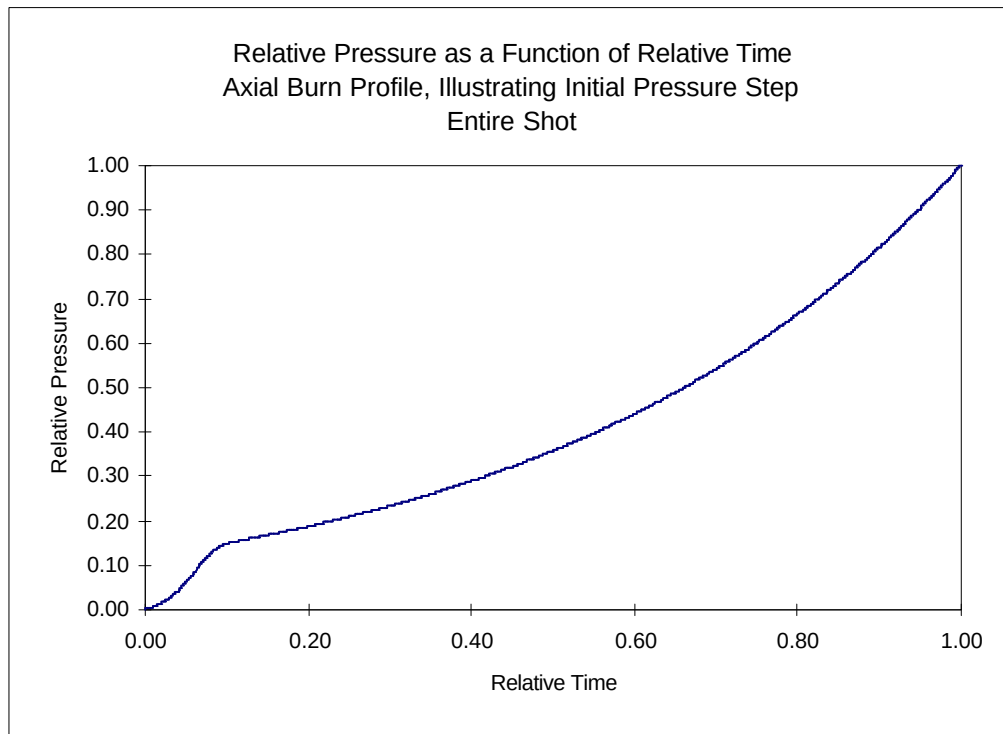


Figure 5-10a: Illustration of Pressure Step, Entire Shot.

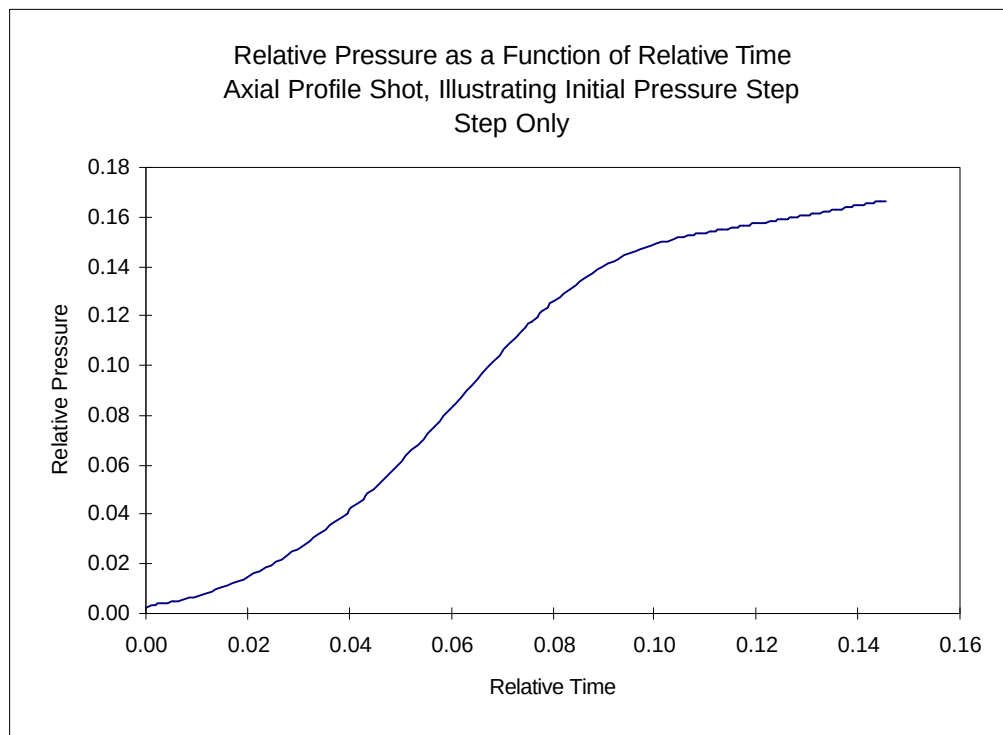


Figure 5-10b: Illustration of Initial Pressure Step, Step Only.

5.2.4.3 Radial Outward Burning

This section of the problem is based on the configuration shown in figure 5-11. In this case the propellant charge is considered to be ignited at the center axis of a cylindrical shaped charge. The advancement direction is then radially outward. The algorithm flowchart for the numerical approach is similar to that illustrated in figure 5-8, except that the direction of advancement is radially outward rather than axially.

The consumption of propellant in this model is substantially faster than the axial burn model. This is due to the configuration, where the distance traveled by the flame front is much less, for identical quantities of propellant, even when similar quantities of propellant are used in the initiation. Figure 5-12 illustrates typical output from the radial outward burning model, where the flame front is advancing about 4000 times faster than the linear burn rate.

Again, the rate at which the flame front is progressing is a function of the instantaneous advance rate into the propellant grain. The result is the same as seen in the axial burn model. Following the first several time steps, propellant is burning in only a small number of the increments behind the advancing flame front. As the pressure increases the propellant grains are consumed in only a few time steps. This leads to the steep slope at the end of the propellant burn phase.

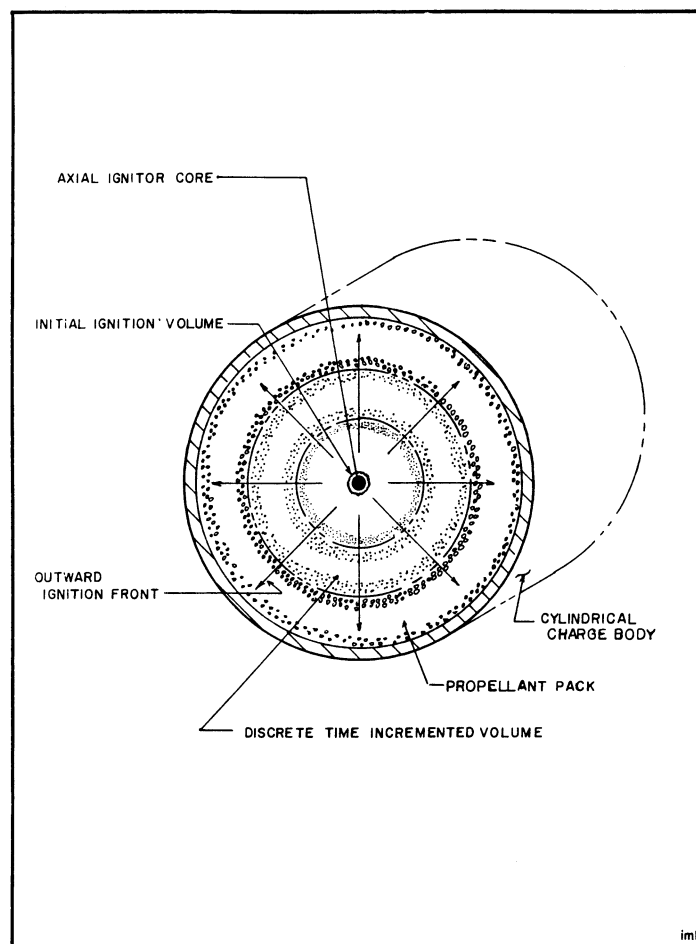


Figure 5-11: Problem Basis for Radial Outward Burning Configuration.

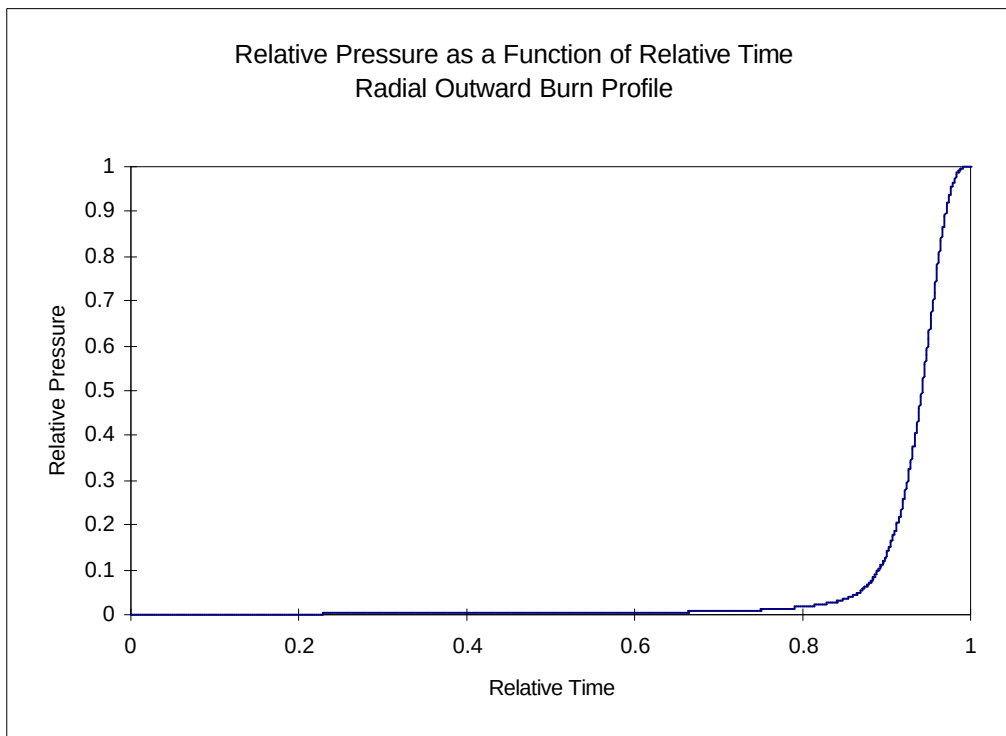


Figure 5-12: Typical Pressure as a Function of Time for Radial Outward Burn Profile.

5.2.4.4 Altered Models

Thus far, with the models that have been investigated, only the Instantaneous Ignition model produces a curve that, overall, is similar in shape to those observed in the laboratory experiments. Before addressing the problem of a vented bomb system it would be desirable to have a closed bomb model that does predict the decreasing slope at burnout that is observed in the laboratory experiments. One possible solution to this problem is a two-step instantaneous burn model.

In the two step model the initiation and burn phases will be handled separately, but both utilizing the instantaneous burn model. The first step will be the ignition. Ignition occurs due to the input of sufficient energy to activate the exothermic reaction of burning. Within the charge, two fronts associated with the initiation result. The first, that has been covered already, is the flame front. The flame front has been assumed to progress at a rate associated with the rate at which the flame is progressing into the individual grains of propellant. This rate has been shown to be as high as 60 times the consumption rate, for the explosive black powder (Taylor 1959), and as much as 5000 times the linear burn rate for smokeless propellants (Kuo, Vichnevetsky, and Summerfield 1971).

The second front, which has not been considered to this point is the pressure pulse associated with the expanding products of combustion. This pressure pulse can be assumed to travel along the propellant charge at the local speed of sound. This pressure wave results in local heating of the propellant due to heat transfer from the compression of the surrounding air. The work of Kuo and Coates (1976) suggests that the ignition of a propellant pack can occur several thousand times faster than the linear burn rate. Such a reaction may account for the use of the instantaneous ignition assumption in the interior ballistics of guns.

5.2.4.5 Effect of Venting of the Products of Combustion

This section of the numerical modeling program was prepared to investigate the effect that a vented bomb would have on the estimated burn profile. Due to the small size orifices used during the tests, for both the small and large-scale shots, venting of the shots appears to have little impact on the progression of the shot.

The algorithm for the vented bomb case is essentially identical to that used for the instantaneous ignition case. The key difference lies in the inclusion of computing the mass of products lost through the vent. The closed bomb case utilizes a forward stepping approach where the initial pressure is assumed to be fixed for the entire time step. Analysis of the output data indicates that for a sufficiently small time step this approach is sufficient. In the vented bomb case a segmented forward stepping approach is used, wherein each time step is broken into 10 sub-steps, for which

conditions are computed, both propellant consumed and mass lost. Event records are maintained only for the standard, user defined, time step.

Consistent with the field experience, the predicted results indicated that mass loss during the burn phase of the shot was not a significant factor that produces results different than that of the closed bomb case. It appears, as was observed in the laboratory, that the most significant mass loss occurs after the combustion event has concluded.

5.3 Results of Modeling Bench Scale Experiments

Utilizing the burn rate equation parameters obtained in the previous chapter, 4.4, a series of modeling exercises were conducted to evaluate the numerical model system, against those tests considered in chapter 4.4. All of the models discussed below were performed using the instantaneous ignition assumption. There are two primary reasons that this approach has been taken: first, that the burn rate parameters were determined with this assumption implicit. Second, that in general interior ballistic computation this assumption is made.

A third motive for using the instantaneous ignition model is that it provides the closest general curve form to those observed in the laboratory test shots. That is, this model is the only one that provided results consistent with the sigmoidal shape of the pressure-time profile. The other models generated in the numerical model package tend not to indicate a decaying burn rate as all of the propellant is finally consumed. The other models, since they assume a finite ignition source volume, do tend to generate the initial step, from atmospheric pressure to about 2.5 MPa, that is observed in most of the laboratory data. Few of the pressure-time traces in chapter 4 show this step since it occurs too early to be of significant interest with respect to the rest of the pressure growth curve. Its presence is seen in the total event logs for these tests, see appendix D.

As was the approach in chapter 4, the modeled output will be evaluated with respect to the propellant mixture used. Furthermore, where appropriate the pressure-time profiles generated by the numerical model are compared, on the same graph, with the same profiles generated in the laboratory experiments. For comparison, the basic burn data is listed in table 5-3. Within that table the values obtained during the bench scale shots are presented in normal text, the model values are in bold text. The number below the test number is the coefficient of determination (R^2) obtained for each test in section 4.4, above.

Considering the 5 columns of data obtained from each test, the mass and the peak pressure are independent of the linear burn rate expression. Hence they should not bear on the coefficient of determination. The peak pressure is a function of the propellant chemical properties and the correlation between the peak pressure measured in the laboratory and that reported by the model will be addressed separately, below. This leaves three of the output parameters that will be

related to the coefficient of determination, the rise-time, the rise rate, and the time of peak pressure.

In the following figures (5-13 through 5-17) the error values reported are determined as:

$$error = \left[\frac{(model - lab)}{lab} \right] * 100\% .$$

Thus an over-prediction by the model indicates a positive error with respect to the laboratory measurement and *visa versa*.

Figure 5-13 illustrates the relationship between the Rise-Time Error and the Coefficient of Determination. For clarity the various propellant mixtures are identified by data sets. In this graph a positive error indicates that the pressure rise-time predicted by the model is greater than that observed in the laboratory. Taken as a whole, the data appear to indicate that there is no clear relationship between the variables. The mean error appears to be in the vicinity of zero percent over the range of R^2 s.

Figure 5-14 shows the relationship between the pressure Rise-Rate Error and the Coefficient of Determination for the various laboratory experiments and numerical models. Again, the propellant mixtures are identified in data sets. On this graph a positive error indicates that the model is over-predicting the pressure rise-rate (a parameter inversely proportional to the rise time). Therefore if a positive rise time error was observed a negative rise rate error is expected. A condition that is generally observed. It does appear in this figure, however, that the mean rise rate error is in the neighborhood of 10%, and independent of the R^2 .

Figure 5-15 shows the reciprocal nature that exists between the rise-rate and the rise-time. Based on the distribution of data in this graph, it is possible to predict a hyperbolic curve that is asymptotic to the values of -100% on both the horizontal and the vertical axes.

Figure 5-16 illustrates the relationship between the Time to Peak Error and the Coefficient of Determination. In this graph, the dependent variable is the error between the time to peak pressure observed in the laboratory and that predicted by the numerical model. As noted, the error for shot 6-13-96-C1 is 787%, this value appears to be anomalous, and has not been shown in this figure. It is generally observed in this figure that the numerical model tends to predict occurrence of the peak pressure at an earlier time than observed in the laboratory. This appears to be between 20 and 30% sooner. This observation is not surprising based on the manner in which the linear burn rate parameters were evaluated and that only the full burn zone was considered in the evaluation of these values. This implies that the power function through the full burn zone was applied to the entire burn problem in the numerical model. As the figures in section 4.4 illustrate, there can be a great degree of variability within the ignition zone. The “ignition factor” in the individual shots has not been considered in the numerical modeling. The

individual characteristics will be covered in the following section detailing each test in this comparison.

Figure 5-17 compares the error in peak pressure to the charge mass in each of the tests under evaluation. It can be observed that the peak pressure for the 100% No. 5 charges tend to fall within $\pm 3\%$. However, the peak pressure seems to be fairly significantly over predicted for those charges containing increasing proportions of the No. 8700 propellant. It would appear that the peak pressure is most significantly over predicted for the charge containing 25% No. 8700.

This figure (5-17) can also be observed to show an increasing pressure error as the charge mass is increased. With the zero error point occurring at about the five gram charge. This observation is consistent with the relationship between the predicted and experimental lines shown in figure 5-6, addressed previously. The consideration that all of the No. 5/No. 8700 mixture errors lie above a line drawn through the 100% No. 5 points (un-vented) tends to indicate that the gas production of the No. 8700 propellant may be less than that of the No. 5. Based on the limited evidence, this cannot be supported by either the pattern observed in this figure, or that observed in section 4.3.2, of this thesis.

Table 5-3: Comparison Between Laboratory and Modeled Shots, Small-scale

Sample (R ²)	Mass	Rise-Time	Rise Rate	Peak Pressure	Time of Peak
	(gm)	(ms)	(MPa/ms)	(MPa)	(ms)
100% No. 5 Propellant					
5-29-96-A-Ave (0.9879)	N/A 5.0567	N/A 4.45	N/A 8.91	N/A 49.99	N/A 12.3
5-29-96-A1 (0.9456)	4.986 4.986	2.74 5.20	14.80 7.56	50.92 49.26	24.8 11.55
5-29-96-A2 (0.9914)	5.081 5.081	3.7 4.6	10.59 8.76	49.21 50.24	21.2 12.1
5-29-96-A3 (0.9908)	5.103 5.103	4.0 4.45	10.01 9.12	49.15 50.47	6.4 12.15
6-13-96-D1 (0.9970)	5.1045 5.105	3.2 3.7	11.75 10.86	47.93 50.49	26.6 19.0
6-13-96-D2 (0.9902)	5.0932 5.093	4.0 3.2	9.07 12.72	46.31 50.36	13.4 25.25
75% No. 5, 25 % No. 8700 Propellants					
5-31-96-A1 (0.9291)	5.0775 5.078	4.8 5.05	7.58 7.95	46.22 50.21	126.6 15.6
5-31-96-A2 (0.9027))	5.1327 5.133	4.6 3.0	7.49 13.58	44.02 50.78	88.4 15.7
6-13-96-C1 (0.9904)	5.2348 5.235	7.7 8.2	4.54 5.07	43.40 51.83	11.4 101.1
6-13-96-C2 (0.9992)	5.25 5.250	5.1 4.2	7.00 9.91	44.82 51.99	13.6 14.4
66% No. 5, 34% No. 8700 Propellants					
5-29-96-B-Ave (0.9451)	N/A 5.149	N/A 6.1	N/A 6.67	N/A 50.94	N/A 11.7
5-29-96-B1 (0.9583)	4.959 4.959	7.4 7.05	4.81 5.57	43.89 48.98	28.2 14.05
5-29-96-B2 (0.8906)	5.247 5.247	5.6 6.1	6.44 6.83	46.38 51.96	15.0 16.75
5-29-96-B3 (0.9100)	5.241 5.241	4.7 4.25	7.66 9.78	45.95 51.9	8.4 9.0
50% No. 5, 50% No. 8700 Propellants					
6-13-96-B1 (0.9895)	5.249 5.249	9.0 6.5	3.94 6.43	45.09 51.98	66.2 35.1

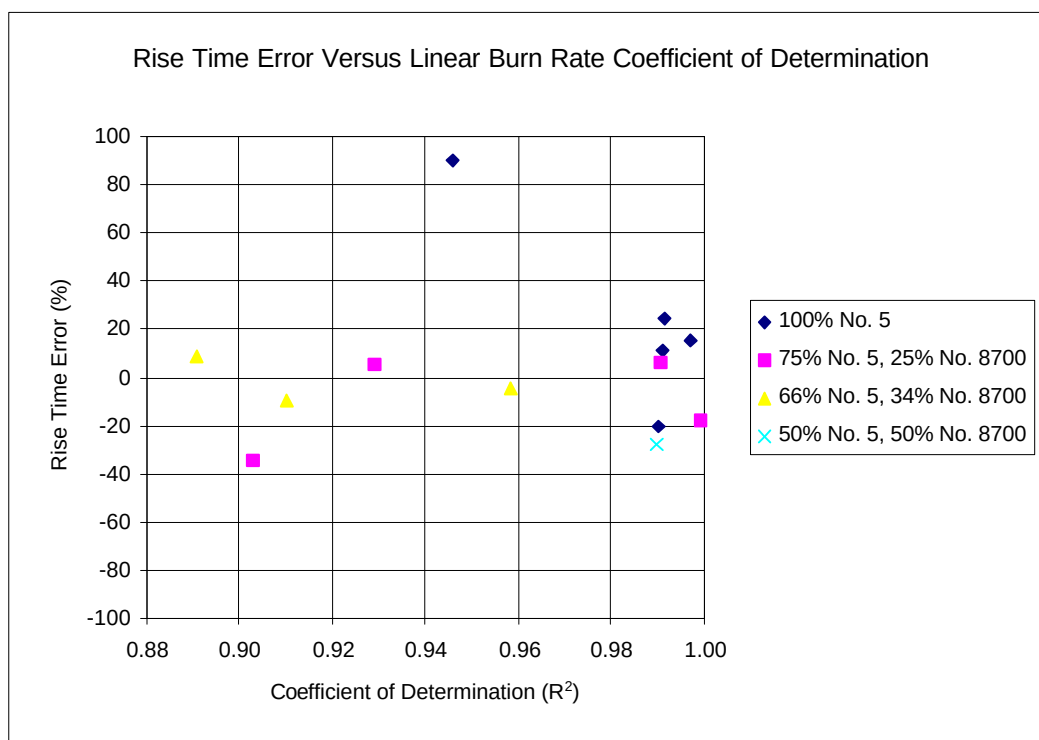


Figure 5-13: Rise Time Error Versus Linear Burn Rate Coefficient of Determination.

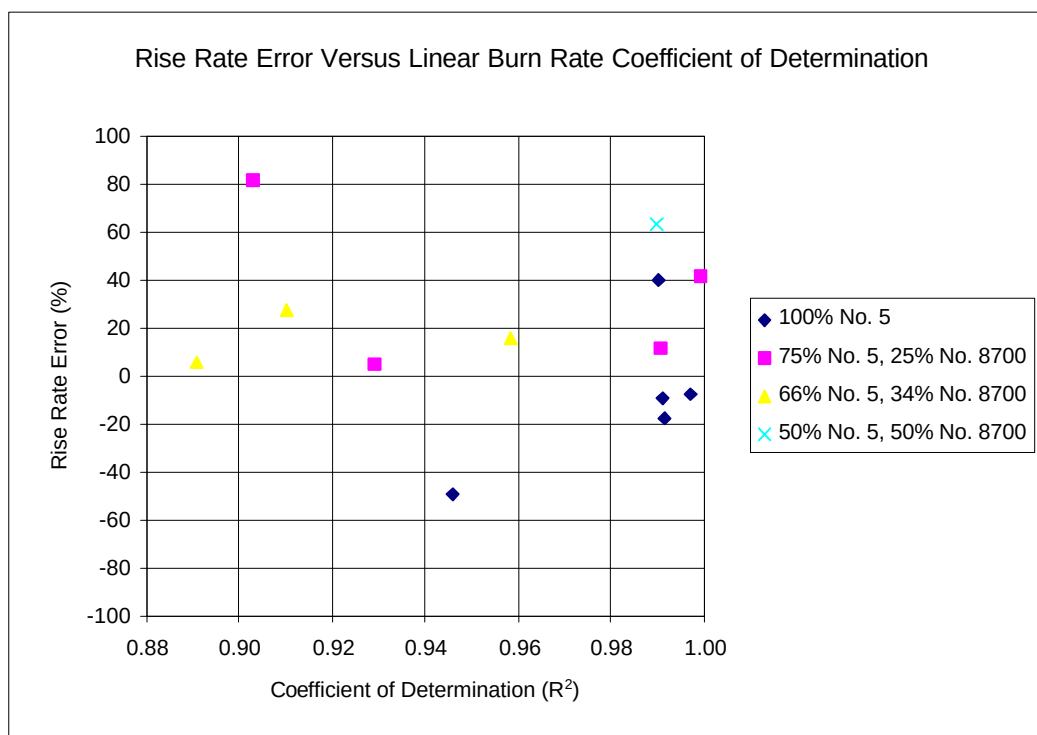


Figure 5-14: Rise Rate Error Versus Linear Burn Rate Coefficient of Determination.

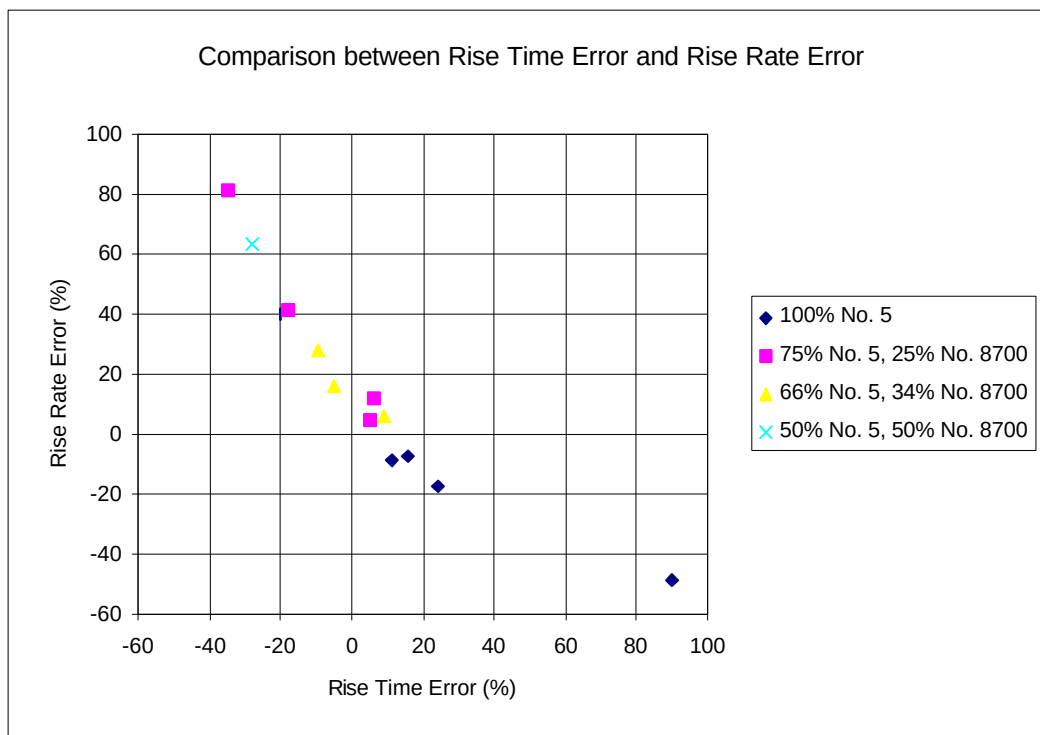


Figure 5-15: Comparison Between Rise Time Error and Rise Rate Error.

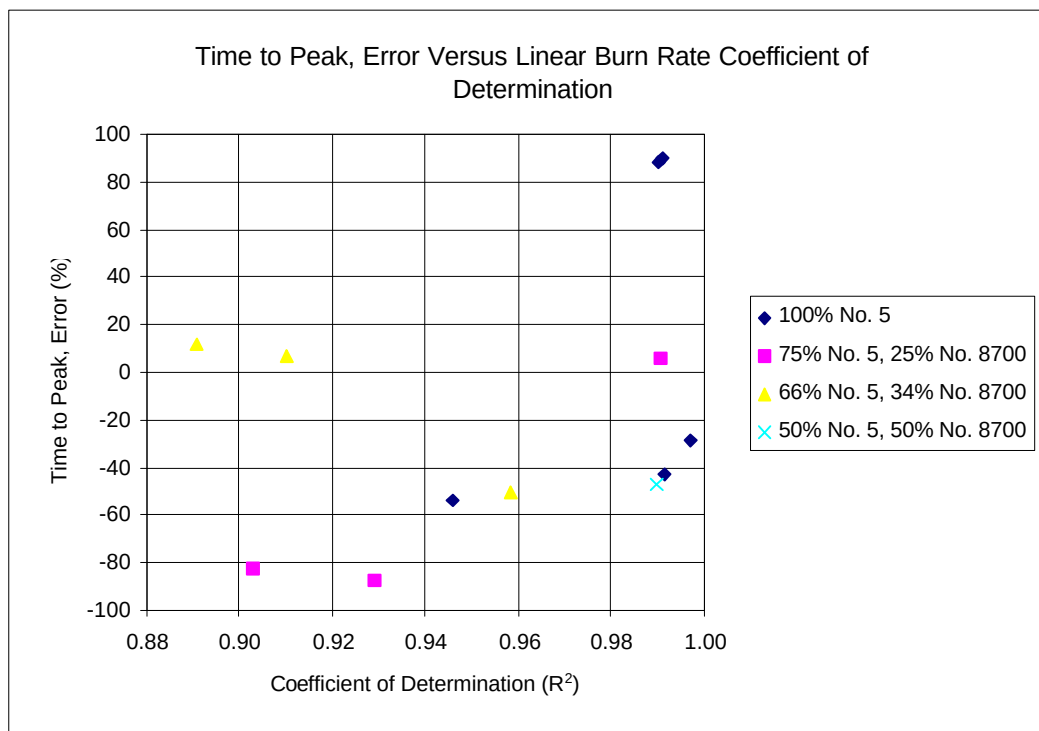


Figure 5-16: Time to Peak Error Versus Linear Burn Rate Coefficient of Determination.

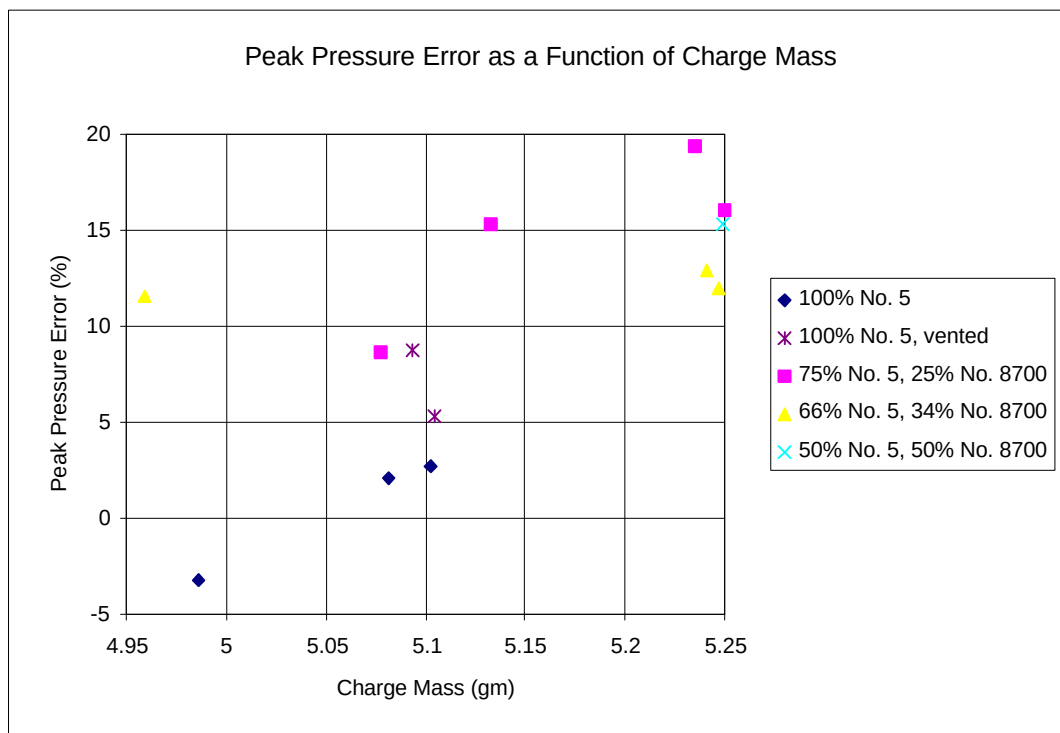


Figure 5-17: Peak Pressure Error as a Function of Charge Mass.

5.3.1 100% No. 5 Propellant

Figure 5-18 illustrates the results of the model of 5-29-96-A-Average. This model merely assesses the average conditions of the 5-29-96-A series of shots.

The model of 5-29-96-A1 is shown, compared with the laboratory data, and the series average, in figure 5-19. The numerical model predicts the peak pressure about 3% below that measured in the laboratory. The pressure-time trace does not indicate as steep a pressure pulse as was measured in the laboratory, nor as steep as that of the average of the series; although, the time to peak pressure is faster in the model than of the average data.

The model of 5-29-96-A2 is shown, compared with the laboratory data, and the series average in figure 5-20. The numerical model depicts a peak pressure that is about 2% above that observed in the laboratory. The pressure-time trace is very consistent with the series average trace. While the general shape of the model and laboratory data traces is very similar, the laboratory data is significantly delayed relative to the modeled case. This may be due to a delayed ignition in the laboratory charge, and does not, in general, appear to be terribly significant.

The model of 5-29-96-A3 is shown, compared with the laboratory data, and the series average data in figure 5-21. The numerical model depicts a peak pressure that is about 2.7% greater than that measured in the laboratory experiment. Again, the numerical model and the series average pressure-time traces are very similar. The general shape is also very similar between the model and the individual shot pressure-time trace. The actual event time is also much closer than that observed in the previous review (5-29-96-A2).

The model of 6-13-96-D1 is shown, compared with the individual shot pressure-time profile in figure 5-22. The general shape of the two curves appear to be similar, with the principle difference being in the event time, the actual data being somewhat delayed from the numerical model. The model also predicts a peak pressure that is about 6 percent greater than that measured in the laboratory. This condition, along with the similar situation in the next test, appears to be related to the loss of mass from the system through the orifice. This being the case, it is interesting to observe that the continuously vented system does not appear to have been a significant impacting factor on the peak pressure or on the pressure rise-rate.

The model of 6-13-96-D2 is shown, compared with the individual shot pressure-time profile in figure 5-23. In this case, the model predicts a peak pressure that is about 9 percent greater than that measured in the laboratory. The general shape of the two pressure-time traces appear to be similar, although in this case the modeled event is occurring later in time than the physical event.

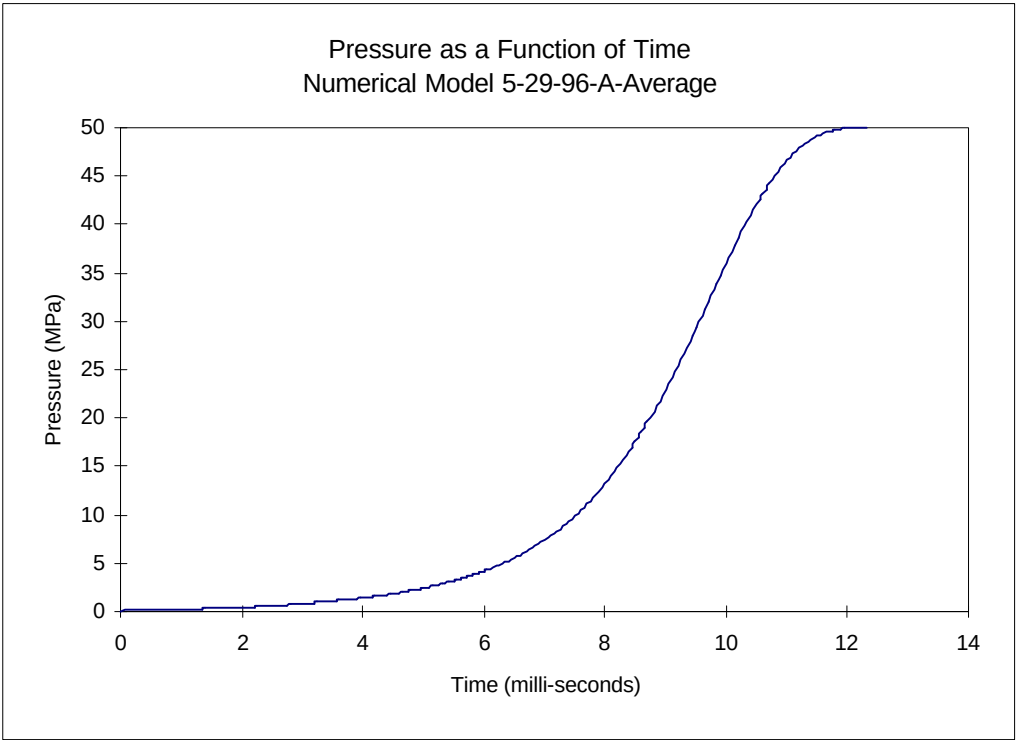


Figure 5-18: Pressure as a Function of Time, Model of 5-29-96-A-Average.

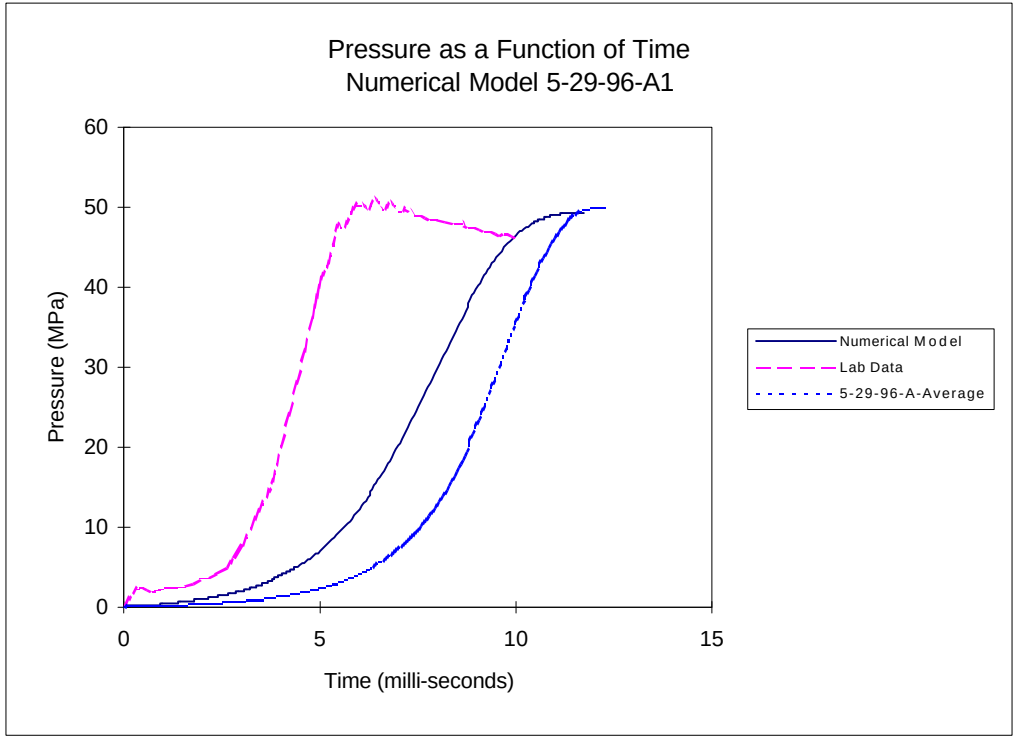


Figure 5-19: Pressure as a Function of Time, Model of 5-29-96-A1.

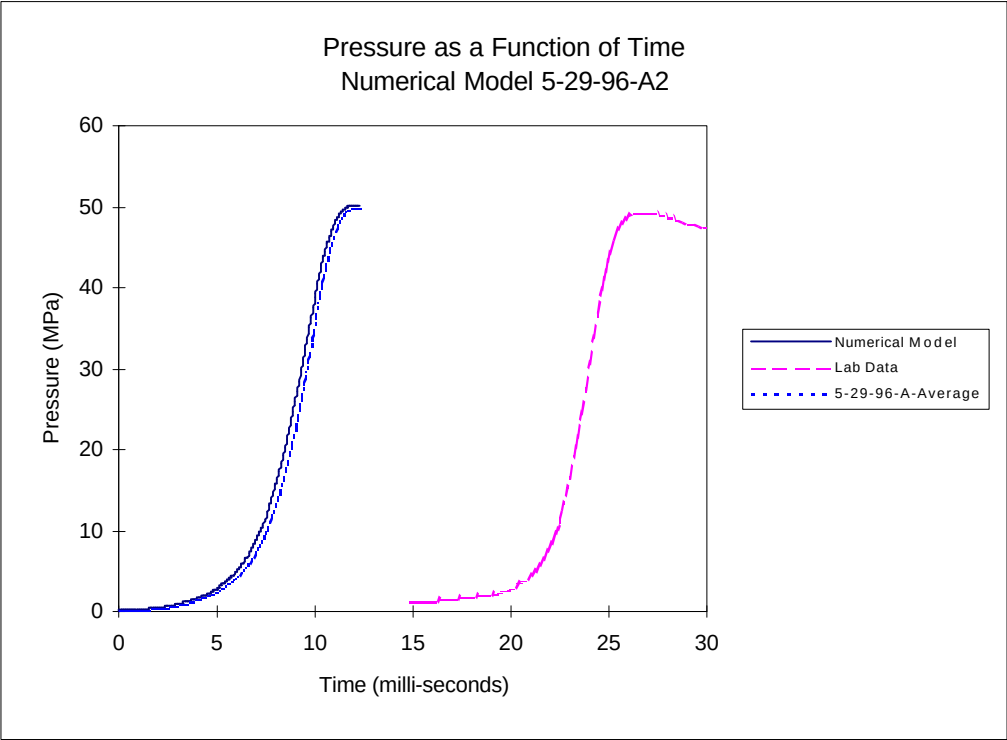


Figure 5-20: Pressure as a Function of Time, Model of 5-29-96-A2.

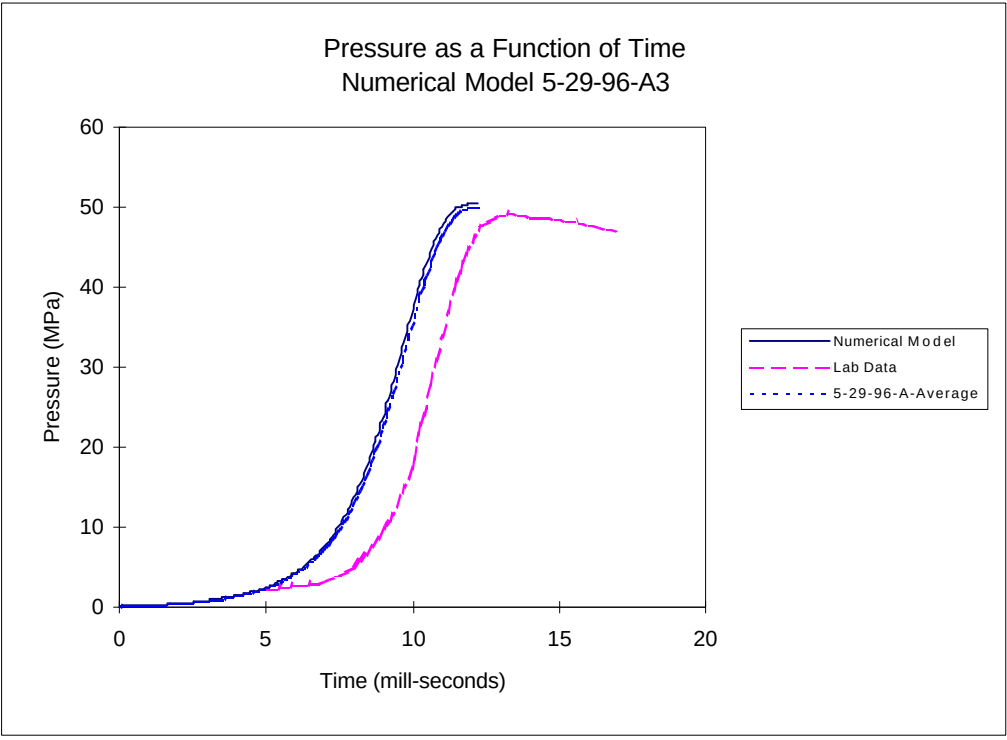


Figure 5-21: Pressure as a Function of Time, Model of 5-29-96-A3.

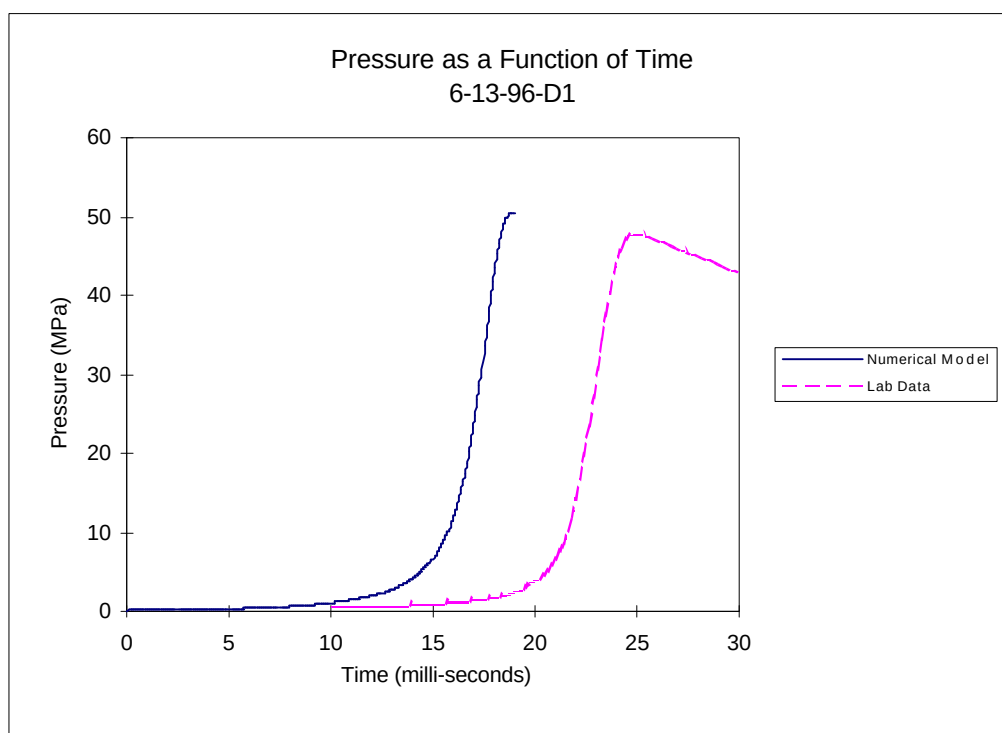


Figure 5-22: Pressure as a Function of Time, Model of 6-13-96-D1.

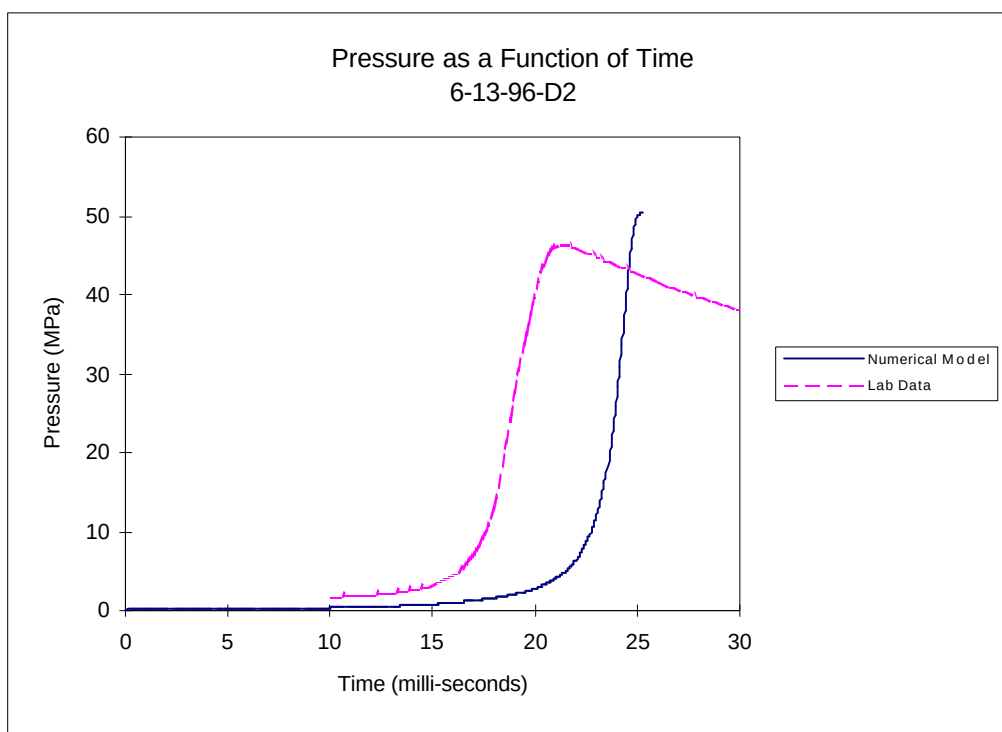


Figure 5-23: Pressure as a Function of Time, Model of 6-13-96-D2.

5.3.2 75% No. 5, 25% No. 8700 Propellants

The model of 5-31-96-A1, along with the laboratory test data is illustrated in figure 5-24. In this example the model predicts a peak pressure that is about 9 percent greater than that observed in the laboratory. The overall shapes of the curves vary greatly. The model curve shows, as expected, a smooth sigmoidal with a lower rate of change at the low pressure end. On the other hand the laboratory data exhibit a sigmoidal shape with a delay in the rate as the pressure reaches its peak. This can be explained in the very rapid burning of the smaller diameter constituent of this mixture, followed by the delayed burnout of the larger diameter particles.

The model of 5-31-96-A2, along with the laboratory test data is illustrated in figure 5-25. This model exhibits similar characteristics, relative to the basis experiment, as described for the previous model (5-31-96-A1). In this case the model predicts a peak pressure that is about 13 percent greater than that measured in the physical experiment.

The model of 6-13-96-C1, along with the laboratory test data, is illustrated in figure 5-26. The numerical model produces a pressure-time trace that is slightly steeper than the laboratory measurements. The numerical model indicates a peak pressure that is about 16 percent higher than that measured in the laboratory. The model data also shows the occurrence of the event to occur somewhat earlier than measured in the physical experiment.

The numerical model of 6-13-96-C2 and the associated physical experiment results are shown in figure 5-27. In this case the predicted event occurs much sooner than the physical experiment indicates. This may be due to a “delayed ignition” during the physical event. The peak pressure predicted by the model is about 14% higher than that measured in the laboratory.

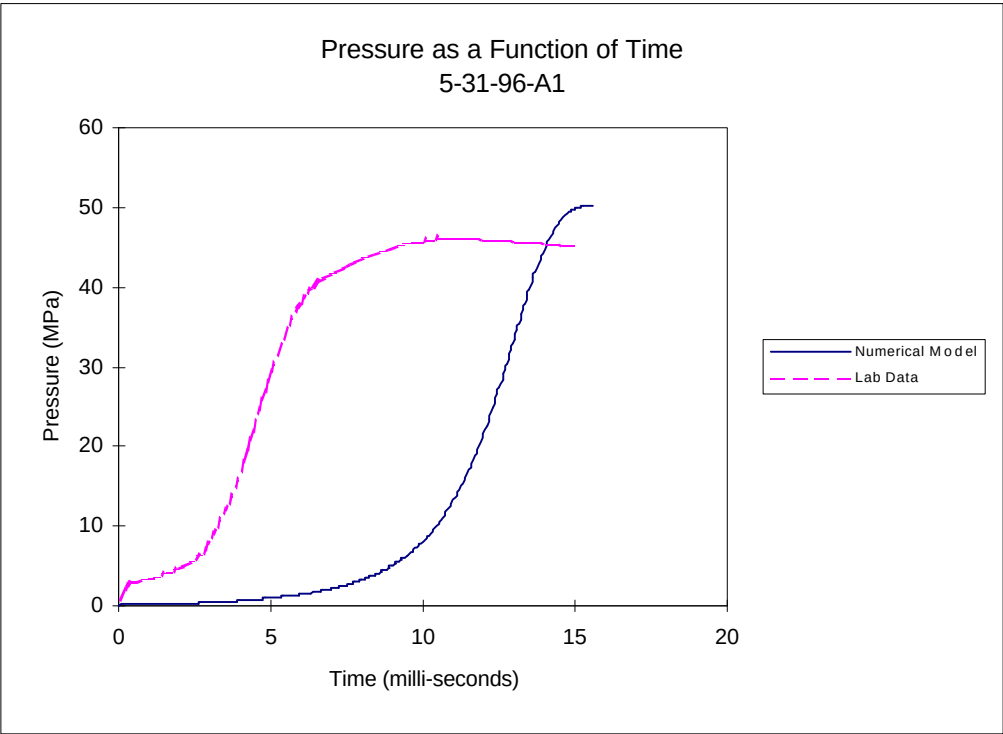


Figure 5-24: Pressure as a Function of Time, Model of 5-31-96-A1.

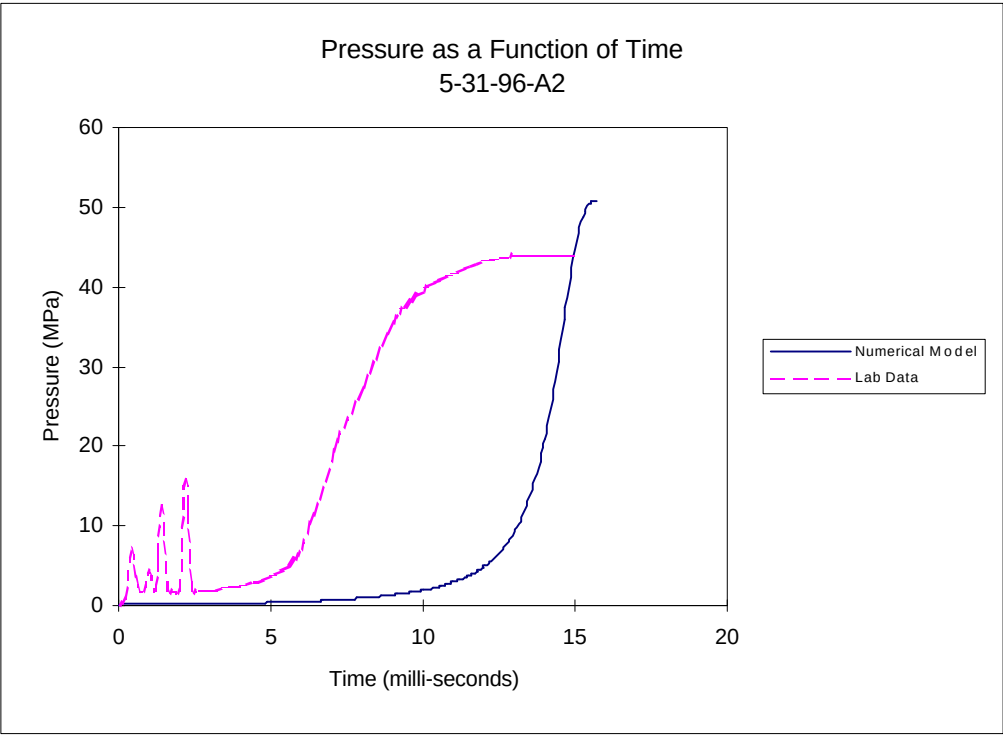


Figure 5-25: Pressure as a Function of Time, Model of 5-31-96-A2.

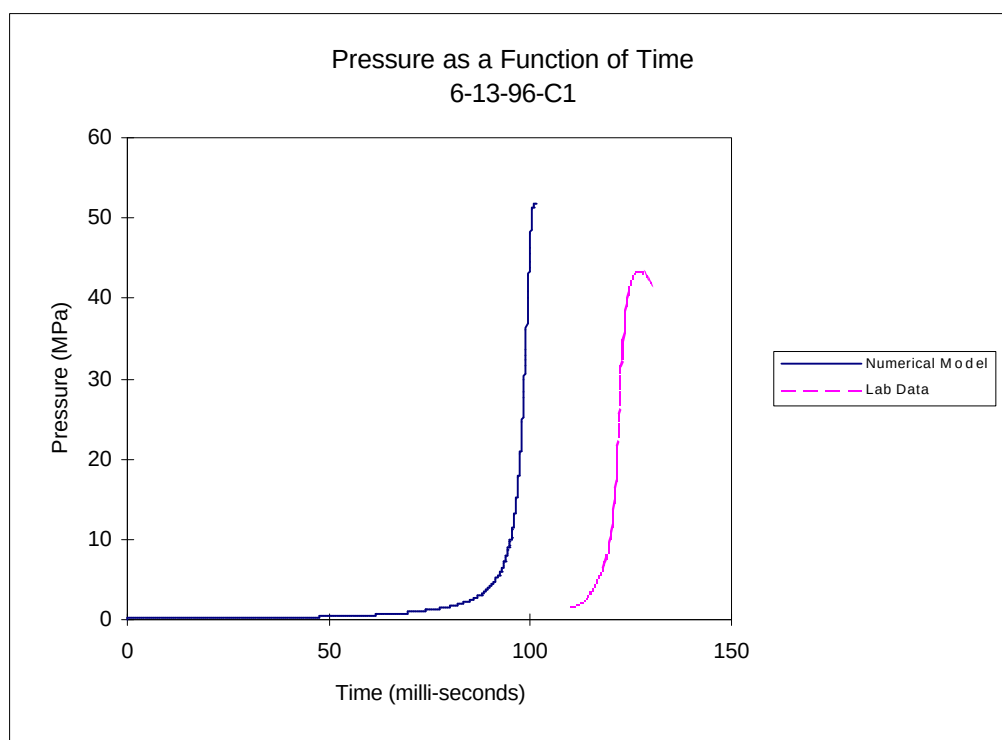


Figure 5-26: Pressure as a Function of Time, Model of 6-13-96-C1.

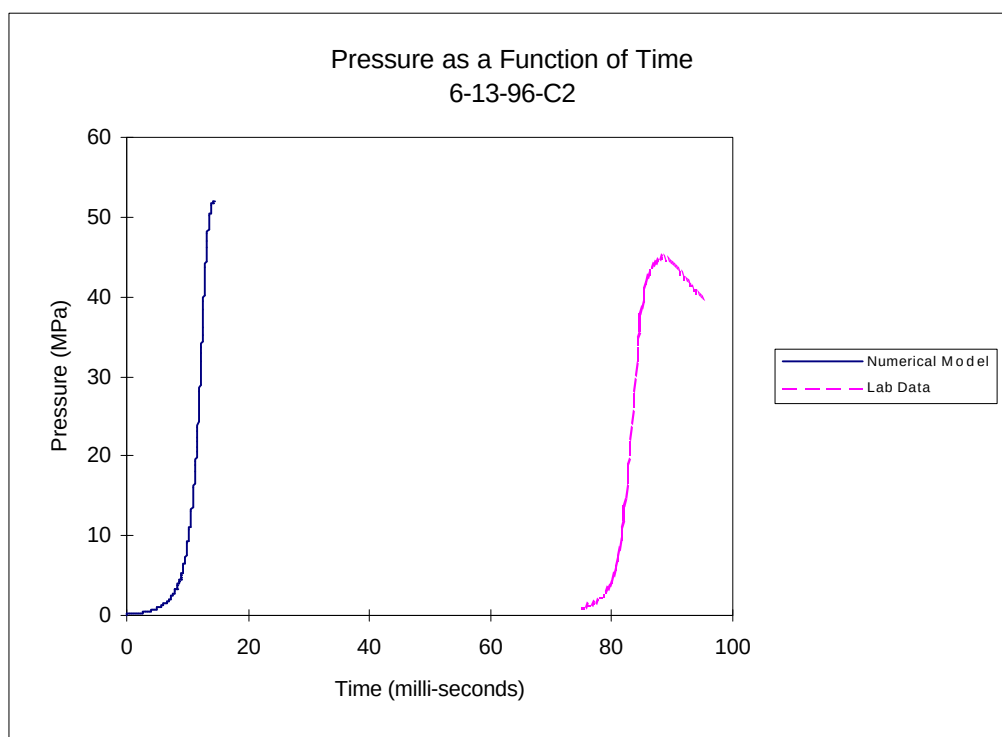


Figure 5-27: Pressure as a Function of Time, Model of 6-13-96-C2.

5.3.3 66% No. 5, 34% No. 8700 Propellants

Figure 5-28 illustrates the output of modeling the 5-29-96-B-Average conditions.

The numerical model of the shot 5-29-96-B1, along with the data from the physical experiment, and the model output from the average case for this series, are shown in figure 5-29. In this case the numerical model is slower than the average case. The physical case appears to be delayed in time, due to a delay in the main charge initiation following the igniter burn. The pressure rise times are similar between the model and the experimental data, the rise rates, however, exhibit a greater variation, probably due to the lower pressure observed in the physical case. The numerical model predicted a peak pressure that is about 10 percent greater than that observed in the laboratory.

The output of the numerical model of 5-29-96-B2, along with the physical laboratory data and the modeled average of this series, is illustrated in figure 5-30. In this case the physical case falls between the times predicted by the series average and the individual case models. The numerical model of this event predicts a peak pressure that is about 11 percent higher than that observed in the laboratory.

The numerical model of 5-29-96-B3 along with the laboratory results and series average model data are shown in figure 5-31. The physical experiment illustrates a step in the data at time zero, a fairly normal main pressure growth stage, followed by a long burnout phase. Both the model of the case average, and the specific event model both indicate a longer time duration than actually observed in the laboratory. The relatively small disparity between the physical experiment and the numerical model is due to the long burnout phase seen in the laboratory data. The model predicts a peak pressure that is about 11 percent greater than that observed in the laboratory.

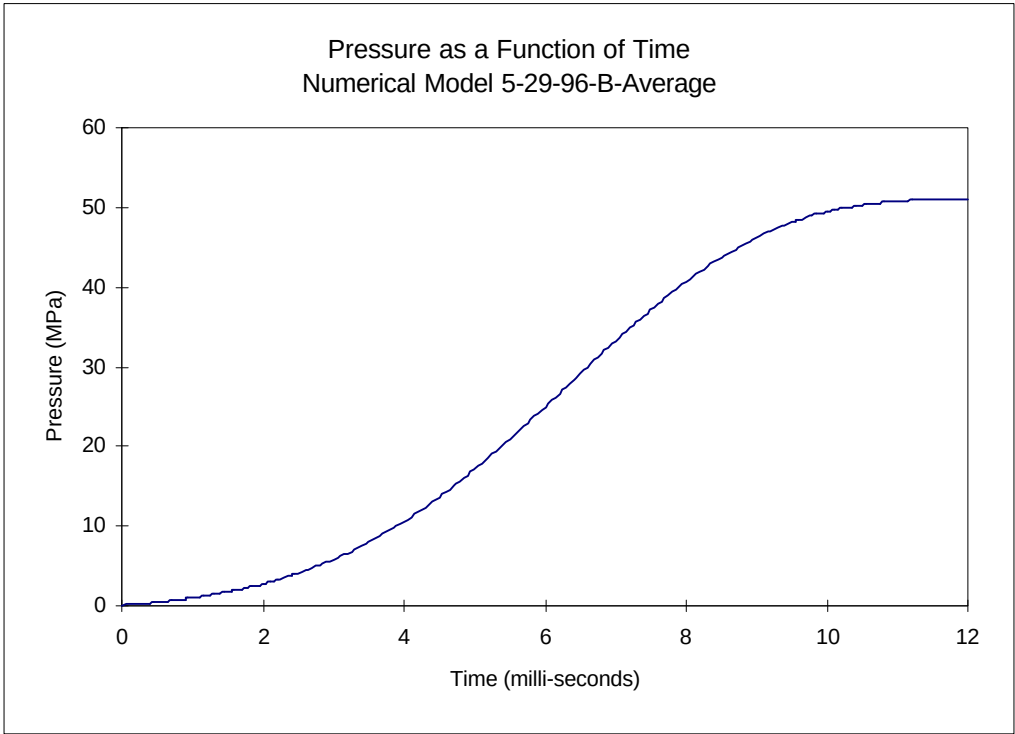


Figure 5-28: Pressure as a Function of Time, Model of 5-29-96-B-Average.

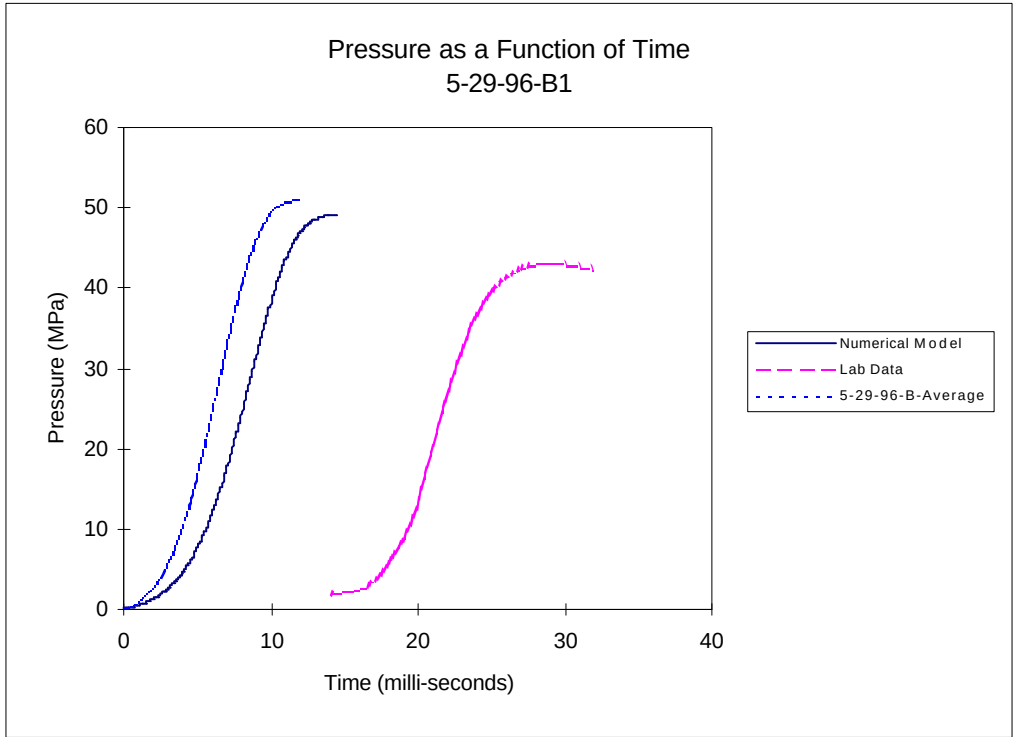


Figure 5-29: Pressure as a Function of Time, Model of 5-29-96-B1.

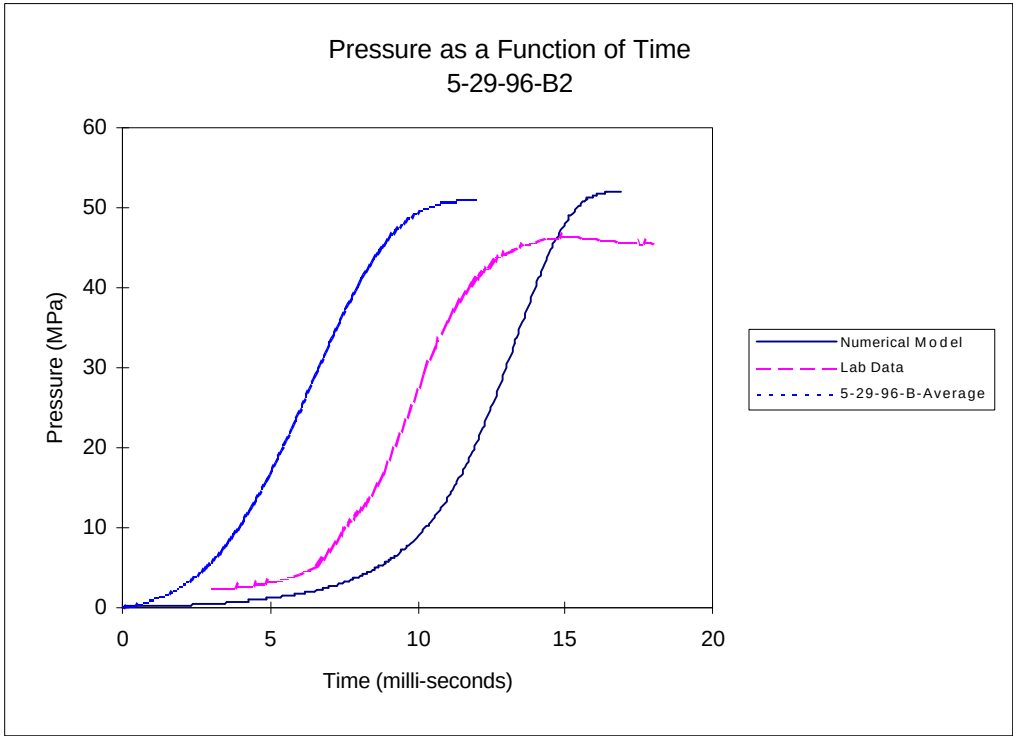


Figure 5-30: Pressure as a Function of Time, Model of 5-29-96-B2.

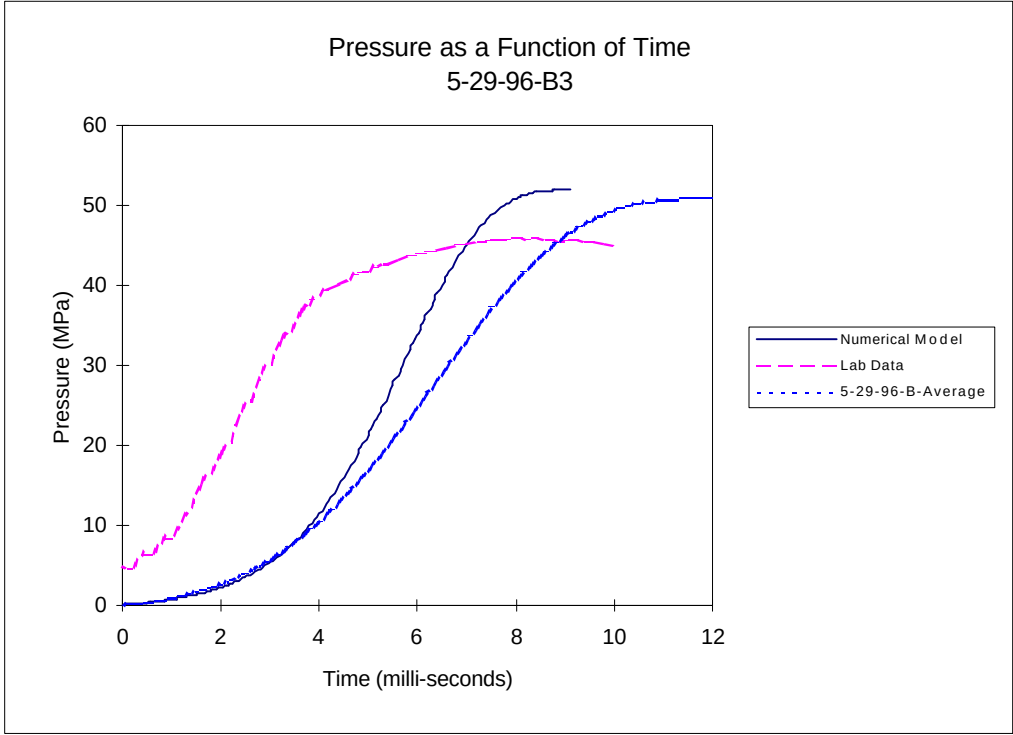


Figure 5-31: Pressure as a Function of Time, Model of 5-29-96-B3.

5.3.4 50% No. 5, 50% No. 8700 Propellants

The numerical model of 6-13-96-B1 along with the physical experiment data are shown in figure 5-32. The model predicts a peak pressure that is about 13 percent higher than that measured in the laboratory. The general shape of the pressure-time profile curves appear to be very similar, except that the model event occurs much sooner than the physical event. This may be due to the fact that the laboratory test was conducted with a vented bomb, and a delay in ignition of the main charge following the burn of the igniter.

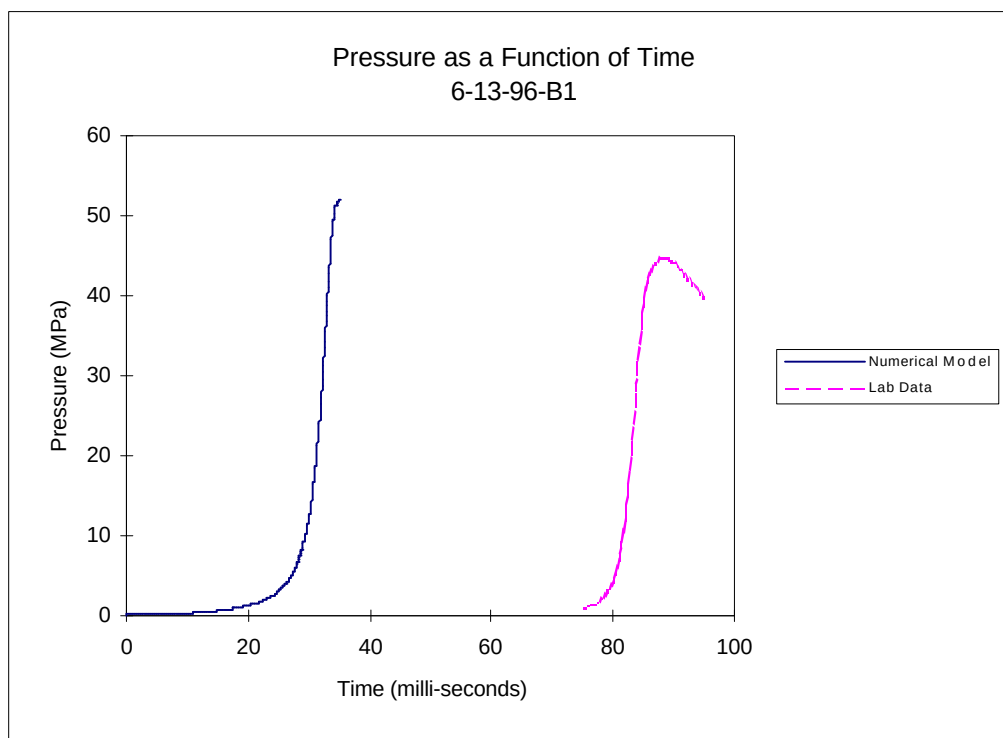


Figure 5-32: Pressure as a Function of Time, Model 6-13-96-B1.

5.4 Discussion

Overall, it appears that the observation of Riefler and Lowery (1974) that individual cases can be adequately represented by the power law relationship is applicable and practical to the cases at hand. This is true, in general, for the main shape of the pressure time profile. However, as has been observed previously in this chapter, a close match to the general shape does not imply that the timing of the events, model and physical, will occur in close approximation. This appears to be due to variations in the overall ignition timing of the individual shots. The numerical model assumes that all of the propellant is ignited simultaneously, whereas the physical case involved an ignition wave progressing through the charge. Although the progress of the ignition wave can be much faster than the combustion of the individual grains this is a factor that tends to slow down the apparent ignition of the main charge.

Conclusions based on the numerical modeling effort will be addressed in the general conclusions and recommendations for future work section, chapter 8.

5.5 Nomenclature

Symbol	Description
<u>Roman</u>	
A	Linear Burn Rate Coefficient ($\mathbf{L/t(M/Lt^2)^n}$)
a	Minimum Nozzle Area ($\mathbf{L^2}$)
B	Coefficient in Burn Rate Estimation Equation
b	Solid Phase Propellant Specific Volume ($\mathbf{L^3/M}$)
C	Coefficient in Burn Rate Estimation Equation
C_D	Nozzle Discharge Coefficient
c	Speed of Sound ($\mathbf{L/t}$)
D	Coefficient in Burn Rate Estimation Equation
d	Hole Diameter ($\mathbf{L}$)
f	Proportion of Propellant in Mixture
H	Surface Heat Release
$\mathbf{L}$	Dimensional Argument for Length
$\mathbf{M}$	Dimensional Argument for Mass
m	Propellant Pyrolysis Index
m	mass ($\mathbf{M}$)
n	Linear Burn Rate Index
P	Absolute Pressure ($\mathbf{M/Lt^2}$)
(P/p_0)	Dimensionless Pressure
R	Gas Constant ($\mathbf{(ML^2/t^2)/MT}$)
R_0	Propellant Grain Initial Radius ($\mathbf{L}$)
r	Propellant Grain Radius ($\mathbf{L}$)
$\mathbf{T}$	Dimensional Argument for Temperature
$\mathbf{t}$	Dimensional Argument for Time
T	Absolute Temperature ($\mathbf{T}$)
T_v	Isochoric Flame Temperature ($\mathbf{T}$)
t	Bore Hole Pressure Rise Time ($\mathbf{t}$)
t_p	Multiple Fracture Pressure Rise Time ($\mathbf{t}$)
u	Internal Energy ($\mathbf{(ML^2/t^2)/M}$)
v	Gas Covolume ($\mathbf{L^3/M}$)
$\dot{X}$	Linear Burn Rate of Propellant ($\mathbf{L/t}$)

Symbol	Description
--------	-------------

Greek

a	Solid Phase Thermal Diffusivity
g	Ratio of Specific Heats
m	Stored Chemical Energy ($(\mathbf{ML}^2/\mathbf{t}^2)/\mathbf{M}$)
n_s	Raleigh Surface Wave Velocity ($\mathbf{L}/\mathbf{t}$)
r	Density ($\mathbf{M}/\mathbf{L}^3$)
y	Dynamic Burning Rate Coefficient
z	Dimensionless Deterrent Coefficient

Sub-Script

<i>b</i>	Retained in Bomb
<i>critical</i>	Conditions at which Sonic Flow is Achieved in Nozzle
<i>det</i>	Deterred Condition
<i>ext</i>	Conditions External to Nozzle
<i>g</i>	Gas Phase
<i>int</i>	Conditions Internal to Nozzle
max	Series maximum value
<i>ns</i>	Dynamic Acceleration Condition
<i>s</i>	Solid Phase
<i>v</i>	Vented From Bomb

Chapter 6. Laboratory Large-scale Propellant Shots

This chapter address those tests conducted in the 0.88m long by 0.10m diameter test vessel. In comparison to the small-scale tests these shots exceeded the mass by at least 20 times. The smallest shot in this series was 98 grams (100 gram nominal mass). The largest shot in this series to be successfully fired was 694 grams. The designed maximum shot was to 750 grams. In comparison to the laboratory small-scale shots covered in chapter 4, the tests covered here represent both lower and higher loading densities. For a 5 gram shot in the small-scale bomb the loading density was 48.6 kg propellant per m³ of chamber volume. In this large-scale series the nominal shots were 100, 250, 500, and 750 grams representing loading densities of 14.2, 35.9, 72.7, and 110.5 kg per m³ respectively.

Since the general theory surrounding the tailored pulse concept has already been discussed in chapter 4 it will not be covered in this chapter.

6.1 Apparatus and Test Parameters

This section addresses three main portions of this set of experiments. The design of the test vessel, the design of the shots, and the evaluation of the data collected.

6.1.1 Test Vessel

The test vessel in this experiment was designed and fabricated specifically for this project. The general configuration is illustrated in figure 6-1. Design drawings are given in Appendix F of this thesis.

The main tube of the bomb was fabricated from a piece of 4 inch (0.1016m) inside diameter seamless pipe with a 1 inch (0.0254m) wall thickness. The end caps were machined from a piece of 6 inch (0.1524m) diameter cold-rolled steel bar. The bomb support system and stress cage was

cut from a piece of 1 inch thick (0.0254m) A36 steel plate. The theoretical strength of the bomb is listed in Appendix F.

Both end caps were vented with a nozzle 2.3749mm (#42 drill) in diameter. This was based on a mass flow rate of 0.25 kg/s at about 80 MPa, assuming isentropic flow. This would give a nominal mass flow of 0.50 kg/s considering a vent hole at each end of the vessel.

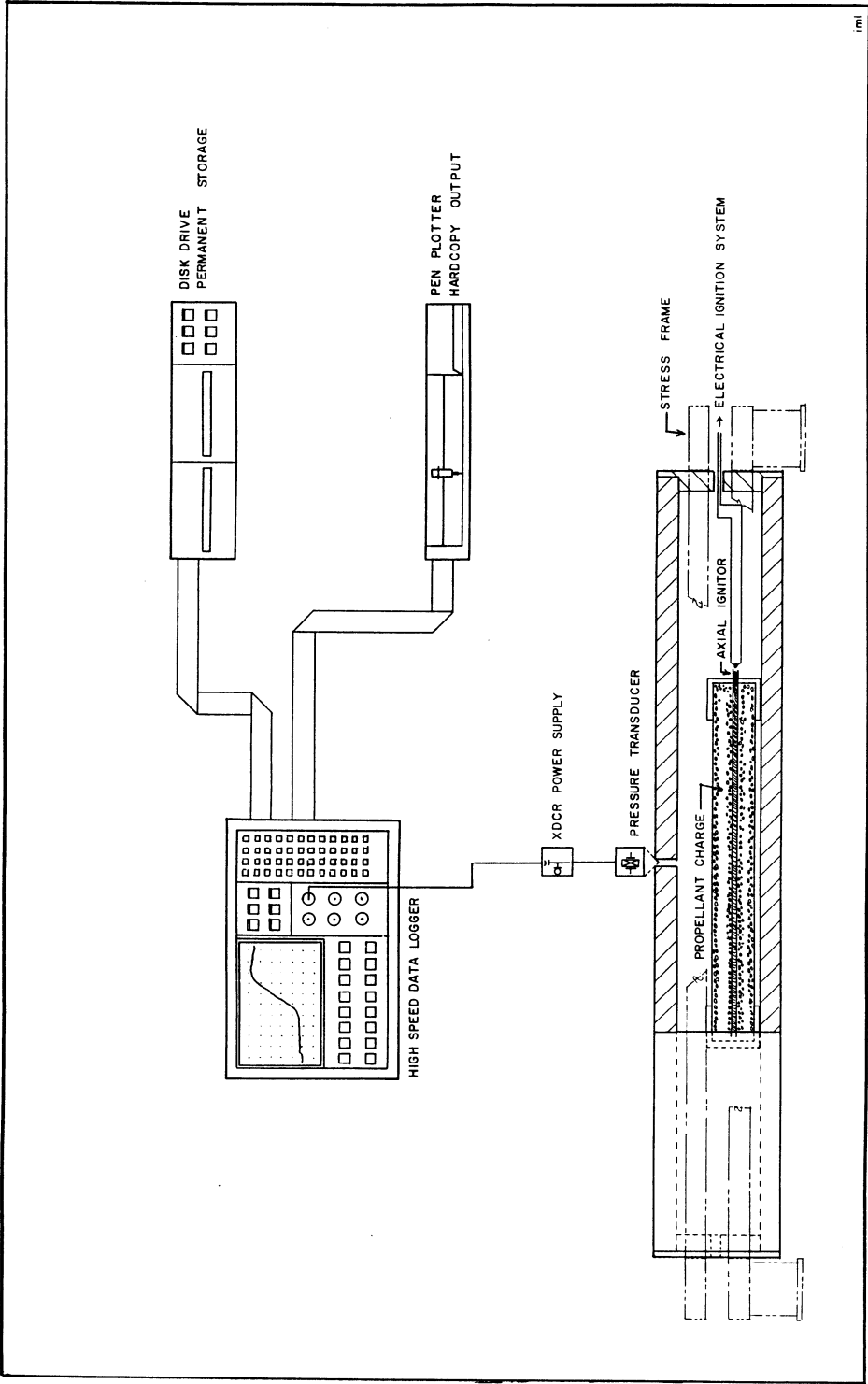


Figure 6-1: General Configuration of Large Scale Test Vessel.

6.1.2 Data Collection

The data collection system used during these tests has already been addressed, see section 4.2.2.3.

6.1.3 Shot Configuration

The basic shot configuration utilized during these tests is illustrated in figure 6-2. The use of the black powder core carried the ignition down the length of the charge much faster than the burn rate of the main propellant charge. In this way the main charge body was burning radially outward rather than axially.

The test sequence for these shot is illustrated in photographs, see plates 6-1 through 6-6.

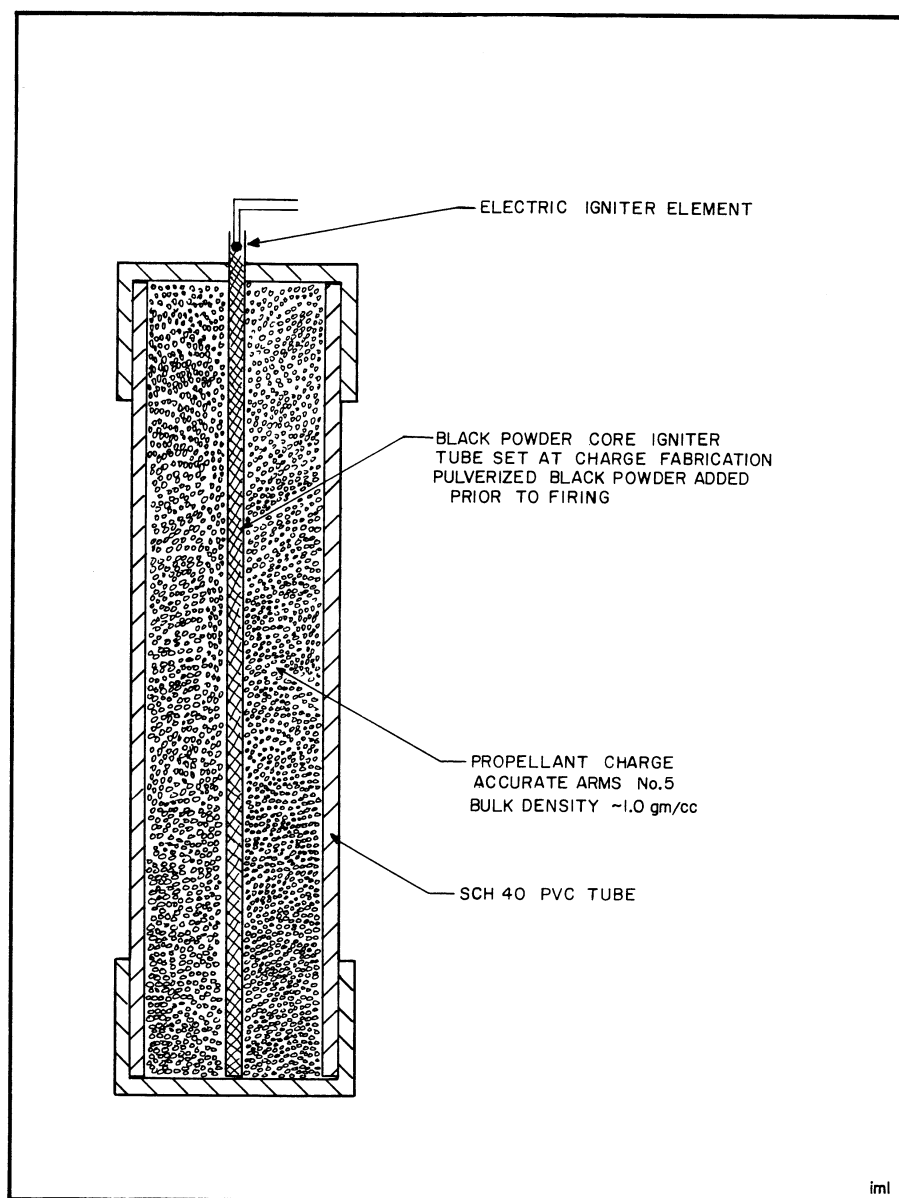


Figure 6-2: General Shot Configuration for Large-scale Shots.

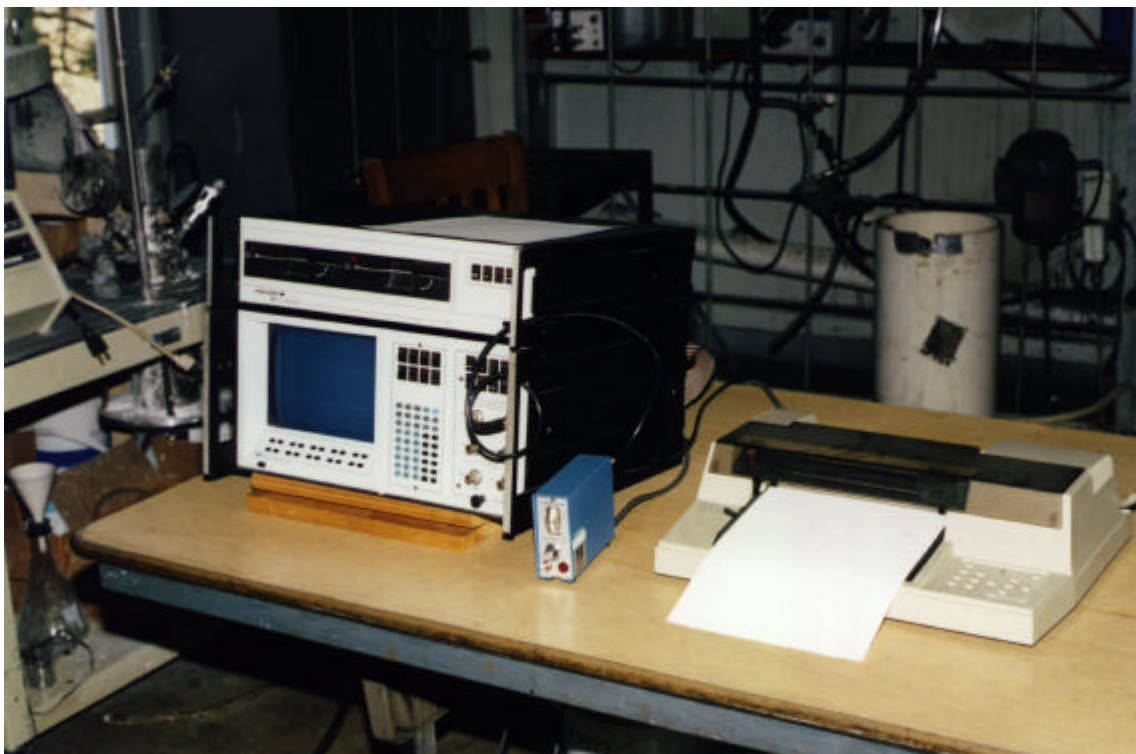


Plate 6-1: Data Logger Table, with Logger, Disk Drive, Plotter, and Pressure Transducer Power Supply.



Plate 6-2: Preparing to Arm Propellant Charge with Igniter Charge.



Plate 6-3: Loading Ignition Charge into Igniter Tube.



Plate 6-4: Installing Pressure Transducer into Large-scale Bomb.



Plate 6-5: View of Bomb Covered Prior to Shot Firing.



Plate 6-6: View of Covered Bomb After Firing, Notice Smoke Plume.

6.1.4 Data Evaluation

The general data evaluation used for these tests is the same as was applied in the small-scale shots. This is presented in section 4.3.3 of this thesis. There are elements of this technique that are not directly amenable to this analytical approach, a case that arises from the high degree of noise experienced in the laboratory large-scale tests.

In order to evaluate the observed trend in several of the shots of this series a significant degree of filtering of the data was required. In the test descriptions that follow the use of filtering is pointed out for those tests where it was used. Figures 6-3a and b compare the typical case of unfiltered and filtered data. As shown in the graph of filtered data, no attempt is made to predict the actual value of data points that were filtered out due to exceeding the filter criteria. The normal approach used to filter data points was to remove those that represented pressure values well above the predicted peak pressure, as well as those that did not appear to be consistent with the nominal pressure growth profile. Once these data points were filtered the standard “smoothing” function for graphs in the Microsoft Excel package was used to fill in the gaps based on the surrounding data.

The overall value of the dp/dt graphs becomes questionable for the severely filtered data, but no less questionable for the data in its original state with the recorded noise. It appears that the presence of pressure wave reflection within the test vessel greatly overshadows the main pressurization event. This is seen in the dp/dt graphs by the rapidly fluctuating values superimposed on what, otherwise, may be a much smoother pressure growth rate curve. All of the dp/dt graphs have been included with their source pressure-time profile, this is done for completeness and consistency with chapter 4, even when the respective pressure growth rate curve appears to be of no analytical value.

A systematic condition was observed in these large-scale tests. Due to the length of the coaxial cable between the pressure transducer and its power supply, and the cool ambient temperatures the initial voltage reading is about 25 milli-volts negative. When the absolute value of the voltage swing is considered the peak pressure results are consistent with the calculated estimated values.

Propellants, in general are affected by their temperature at the time of ignition. The fact that these shot were fired during cool ambient condition should not present a concern since the charges were maintained at room temperature until loaded into the test vessel.

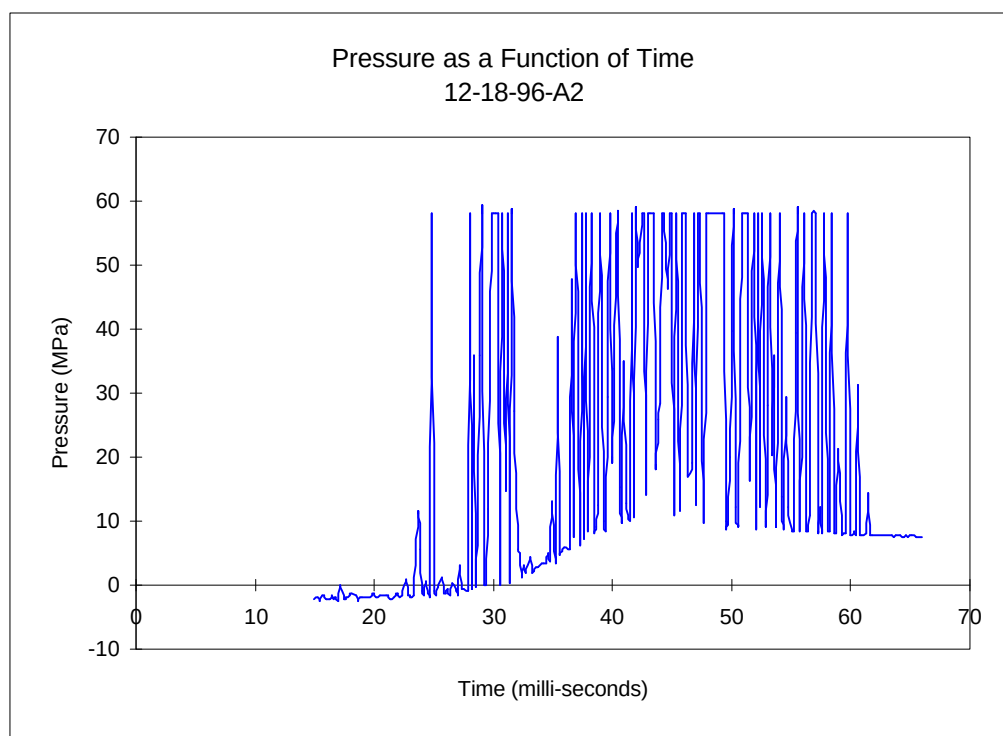


Figure 6-3a: Raw Pressure-Time Data, Example from 12-18-96-A2.

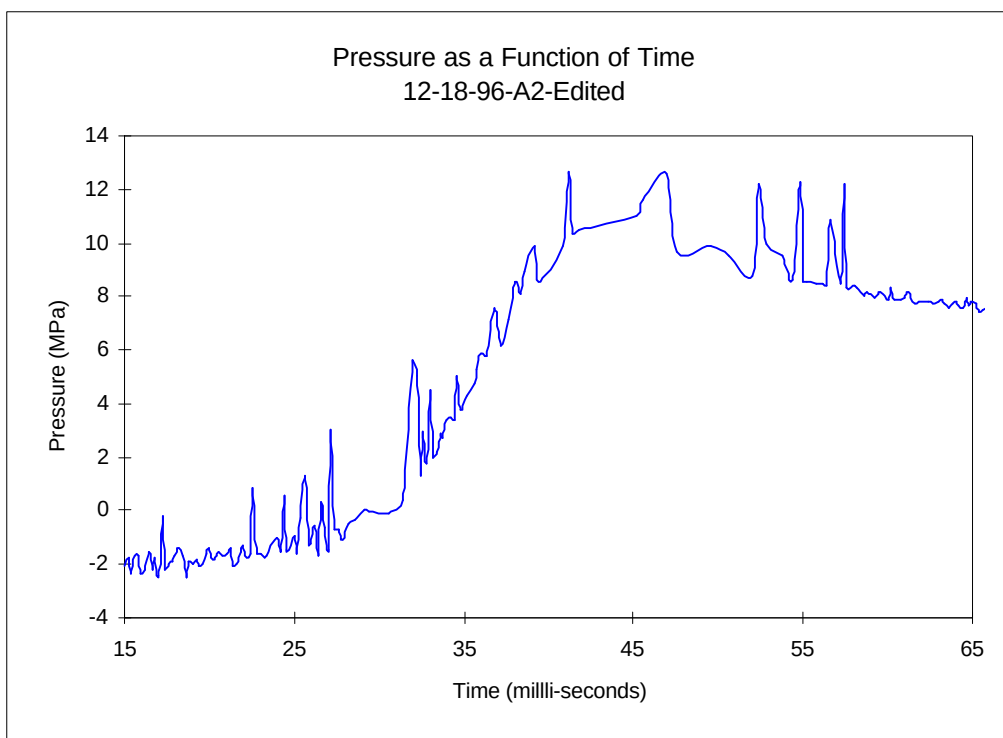


Figure 6-3b: Filtered Pressure-Time Data, Example from 12-18-96-A2.

6.2 Results

Based on the results obtained during the small-scale shots the large-scale shots are limited to tests utilizing only the 100% Accurate Arms Company, Inc. No. 5 propellant. The data logs of these tests tend to indicate a very dynamic event with numerous echoes and peaks that are superimposed on the main pressure rise trace.

Throughout this test series the shots produced some very large echoes within the test vessel, as observed by the large pulses recorded by the pressure transducer. Similar pressure transients were observed in the small-scale bomb tests. These transients appear to be related to the gases expanding away from the burning charge as they reflect off of the interior surfaces of the bomb. This has been addressed previously in this thesis, see section 4.5.2. It is unclear why some of the shots are recorded with a very large degree of echoing, whereas others exhibit very little. Such a case may be due to the overall efficiency of the charge burn. In any case, it must be remembered that the pressure measurement is made at a single, discrete point in the pressure vessel, which is generally applied to the entire vessel for analysis. In reality, the pressure distribution within the vessel, with respect to both time and position, becomes very complex very quickly as the shot is fired. For this reason, the appearance of a lower boundary of the echoes is assumed as the pressure within the vessel at any given time during the shot, see figure 6-3a.

6.2.1 100 gram Shots

Three shots were configured and fired with a 100 gram nominal charge. The numerical model estimation of peak pressure (for a closed vessel) for this charge size was 14.4 MPa.

Figures 6-4a and b illustrate the pressure-time and dP/dt -time profiles for shot 12-18-96-A1. This shot indicates a fairly smooth pressure growth profile up the peak recorded pressure of about 11.5 MPa, this pressure is about 80 percent of that predicted by the closed vessel numerical model. The rate of pressure growth is fairly low for this series, (100 gram shots) which is clear in figure 6-4b. This graph indicates that the fluctuations during the pressure growth rate are on the same order of magnitude at the peak growth rate.

The data collected for the above shot suffer from an error in setting the data logging parameters. The intended condition was to record the 25 milli-seconds preceding the triggering event (a positive slope pressure change passing through 15 milli-volts [0.17 MPa]). Due to a setup error, the data logger did not start recording until 25 milli-seconds after the triggering event. The possible effects of this error are addressed in section 6.3.2, below.

Figures 6-5a and b illustrate the pressure-time and dP/dt as a function of time for shot 12-18-96-A2. The complete data set for this shot is illustrated in appendix D, the graphs shown contain

data from this shot that has had points over 12 MPa filtered out. This filtering produces the data illustrated, which shows the overall trend of the shot without having the extraneous peaks that are observed in the entire data set. This data set also indicates a negative starting pressure. This can be attributed to the ambient temperature at which the shot was conducted and the length of the coaxial cable used for transmitting the signal from the transducer. With this in mind, it is practical to take the lower values as the zero reference, hence the actual peak pressure is the absolute difference between the practical peak pressure and the practical minimum pressure, in this case approximately 12 MPa. This peak pressure value is about 83 percent of the estimated peak based on the numerical simulation in a closed bomb. Due to the significant amount of noise in the data set the dP/dt graph indicates very little regarding the overall progress of the combustion reaction in this test.

Figures 6-6a and b show the pressure-time and dP/dt as a function of time profiles for shot 12-18-96-A3. The recorded data for this shot contains a significant amount of noise, that appears to be reflections within the test vessel. To clarify the interpretation the data set has been filtered so that all pressures over 12 MPa have been removed from the data series. This is in the same manner as the previous example, shot 12-18-96-A2. This shot also indicates a negative starting pressure, a condition that is corrected in the same manner as above, that is the pressure is taken as the absolute difference. In this case the peak practical pressure is on the order of 11.6 MPa, a value that is about 80% of the peak pressure predicted by modeling the shot in a closed vessel. Again, as in 12-18-96-A2, the dP/dt graph reveals very little in the pressure growth pattern of this shot, due to the significant amount of noise present in the data.

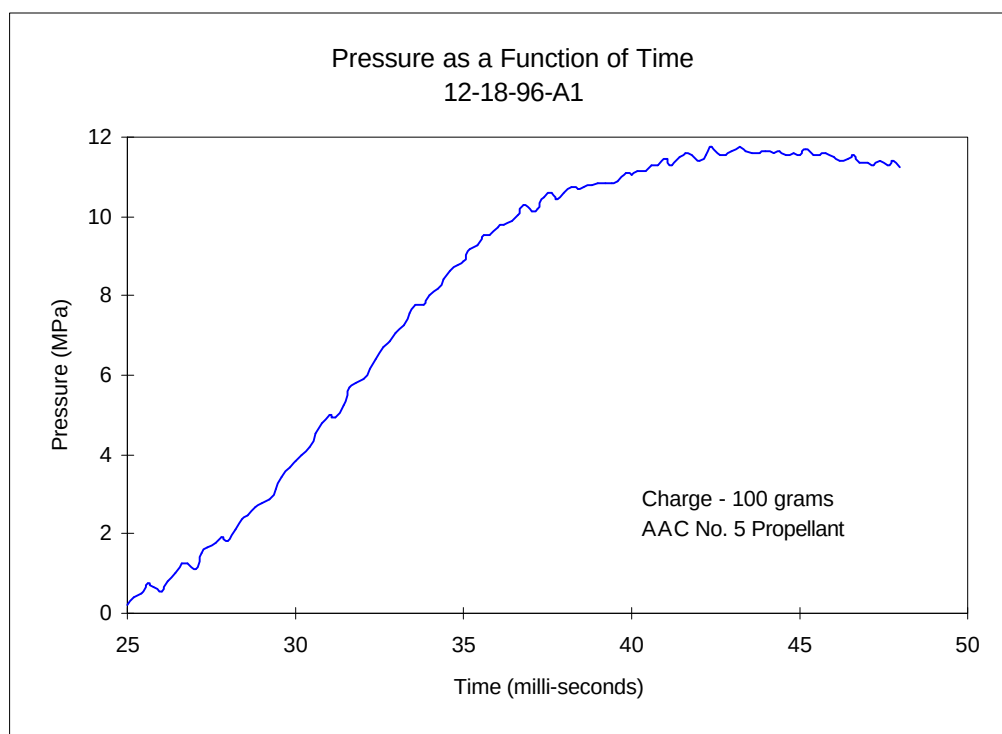


Figure 6-4a: Pressure as a Function of Time, Shot 12-18-96-A1.

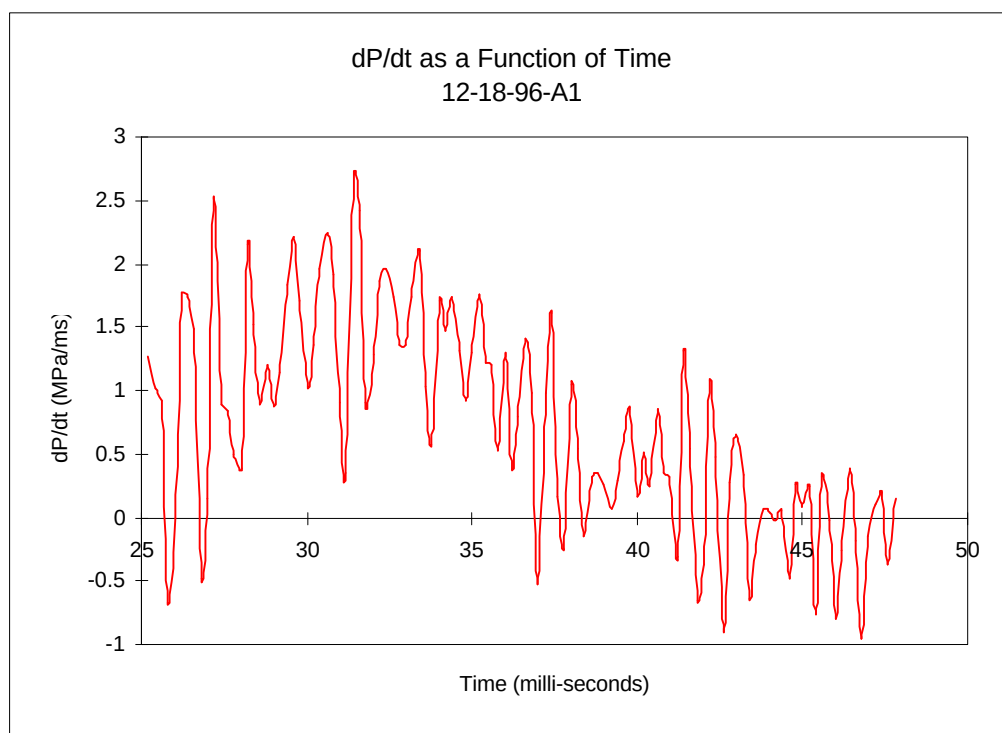


Figure 6-4b: dP/dt as a Function of Time, Shot 12-18-96-A1.

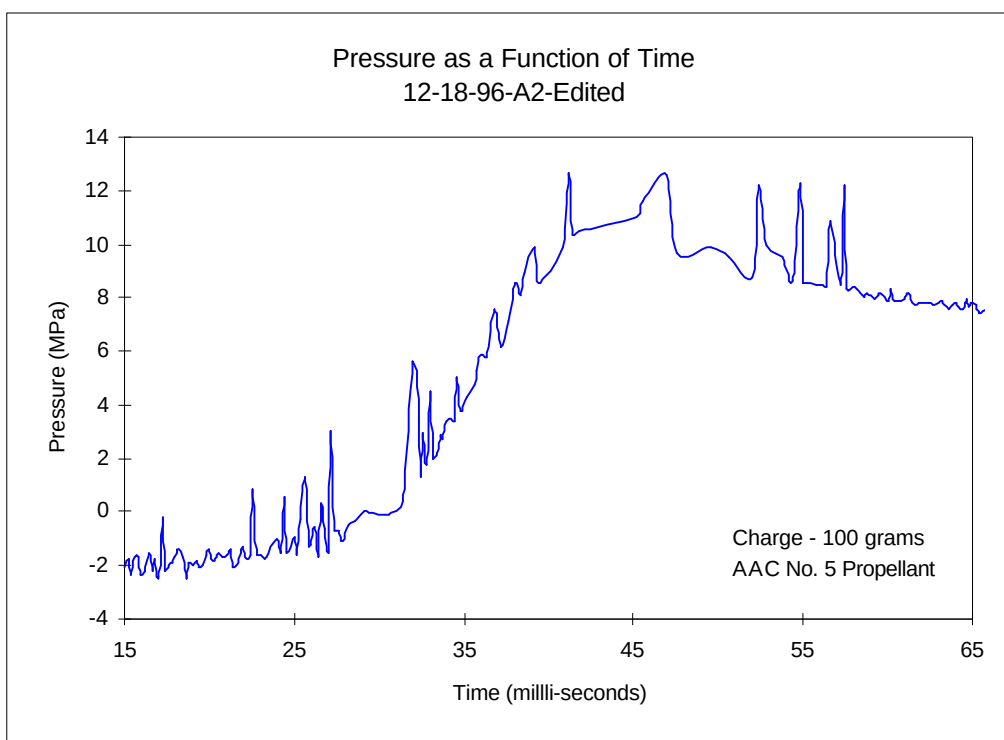


Figure 6-5a: Pressure as a Function of Time, Shot 12-18-96-A2.

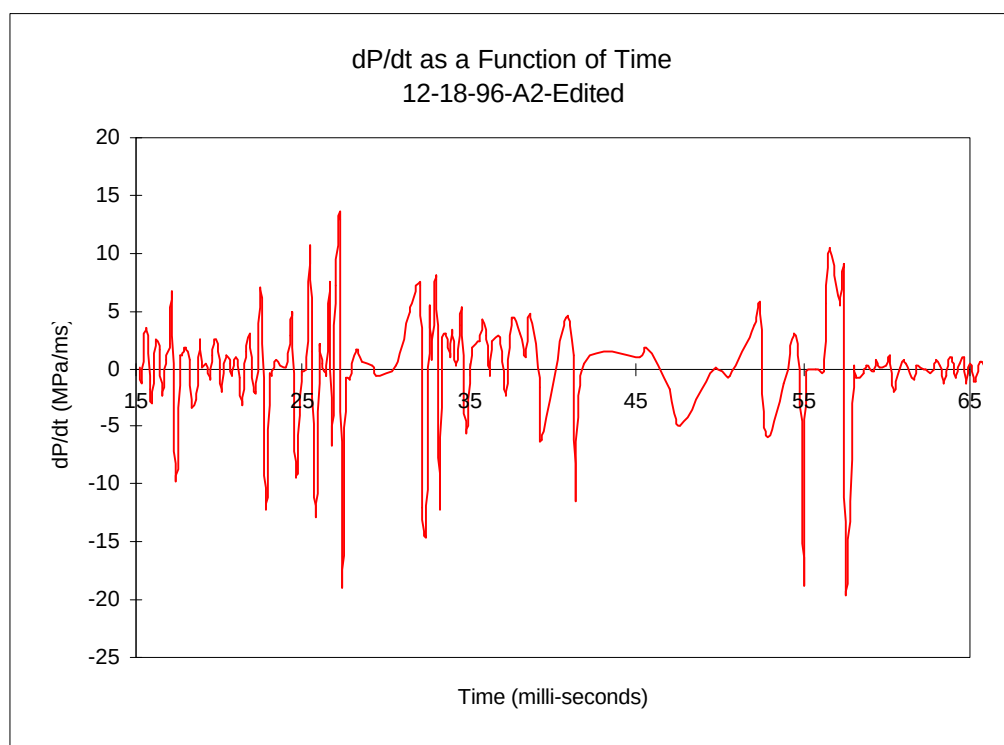


Figure 6-5b: dP/dt as a Function of Time, Shot 12-18-96-A2.

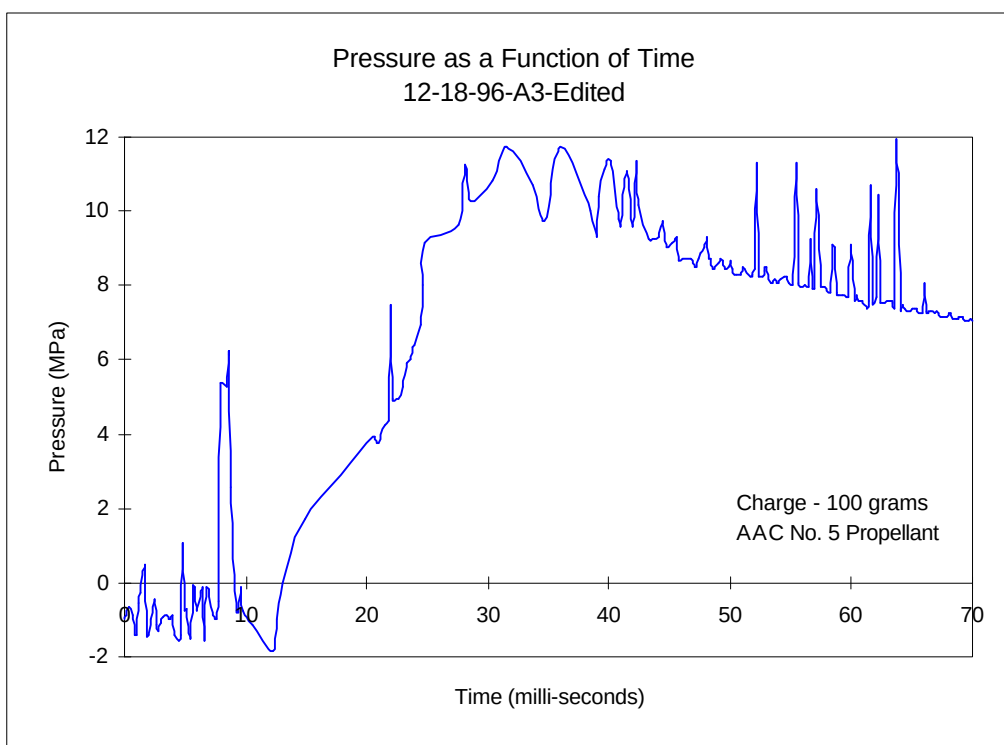


Figure 6-6a: Pressure as a Function of Time, Shot 12-18-96-A3.

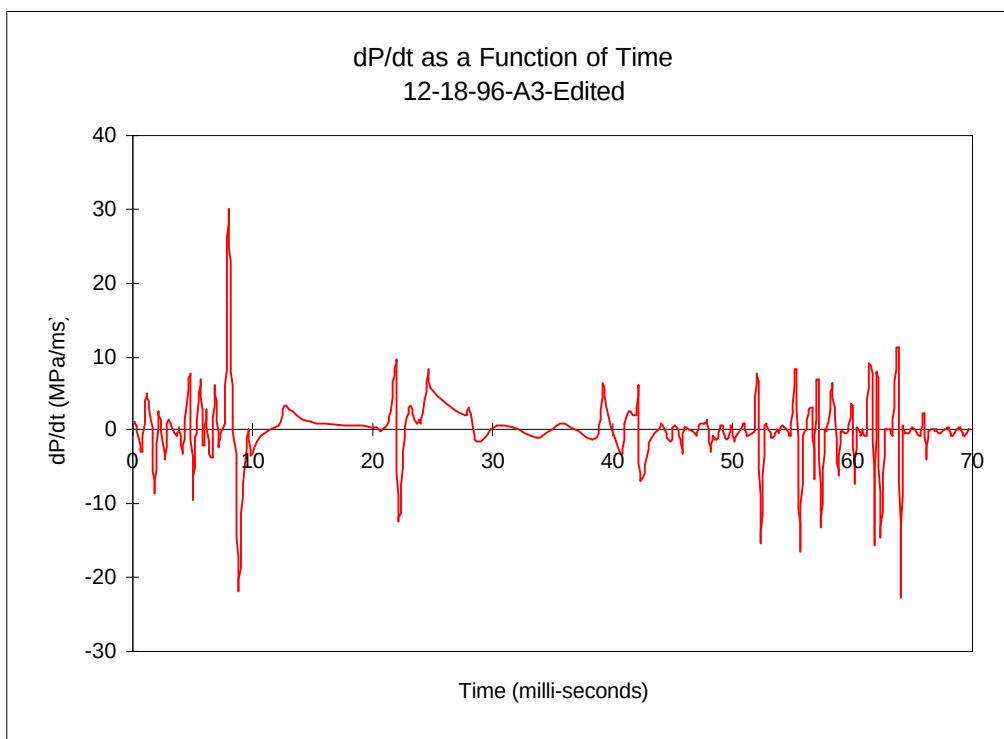


Figure 6-6b: dP/dt as a Function of Time, Shot 12-18-96-A3.

6.2.2 250 gram Shots

Three shots were configured and fired with a 250 gram nominal charge. The numerical model estimation of peak pressure (for a closed vessel) was 36.1 MPa. These shots appear to be the “cleanest” of the large-scale series, that is that there are very few anomalous spikes in the pressure-time traces. It is unclear why these shots tended to produce smoother pressure-time traces than the other shots within the large-scale series. Some suggestions include, cartridge placement within the test vessel, loading density near some “ideal” value for the loading configuration, efficiency of initial pressure confinement within the cartridge resulting in a better burn. In the overall results of this test series the data of these shots are consistent with the other large-scale shots, thus specific evaluation of these possibilities is beyond the scope of this research.

Figures 6-7a and b illustrate the pressure-time and dP/dt as a function of time traces for shot 12-18-96-B1. The pressure-time trace shows a fairly smooth pressure increase, with only a small step at about half of the peak pressure. The peak pressure measured for this test was about 38.4 MPa, or about 106 percent of the estimate peak. The dP/dt trace appears to show some fluctuations that may be consistent with the presence of echoes within the test vessel.

Figures 6-8a and b illustrate the pressure-time and dP/dt as a function of time traces for shot 12-18-96-B2. These graphs show gaps in the data, near the peak of the pressure-time trace. The data from these locations has been edited out to show the main trend to the pressure data. The peak pressure measure in this test was 39.1 MPa, or about 108 percent of the predicted peak pressure. The dP/dt trace appears to show fluctuations that are consistent with the time associated with echoes inside the test chamber.

Figures 6-9a and b illustrate the pressure-time and dP/dt as a function of time traces for shot 12-18-96-B3. Due to, what appears to have been, a delay in the ignition process the burn data collected at a 0.2 milli-second period was not recorded. The data presented here is taken from the second group of the 40 micro-second period data. The graphs in these figures are based on every 5th data point in this series, or at 200 micro-second intervals. This data shows a consistent growth in the pressure-time trace, although some pressure fluctuation is clear during this shot. The timing of these local variations is consistent with echoing within the pressure vessel. These fluctuations are also visible in the dP/dt graph.

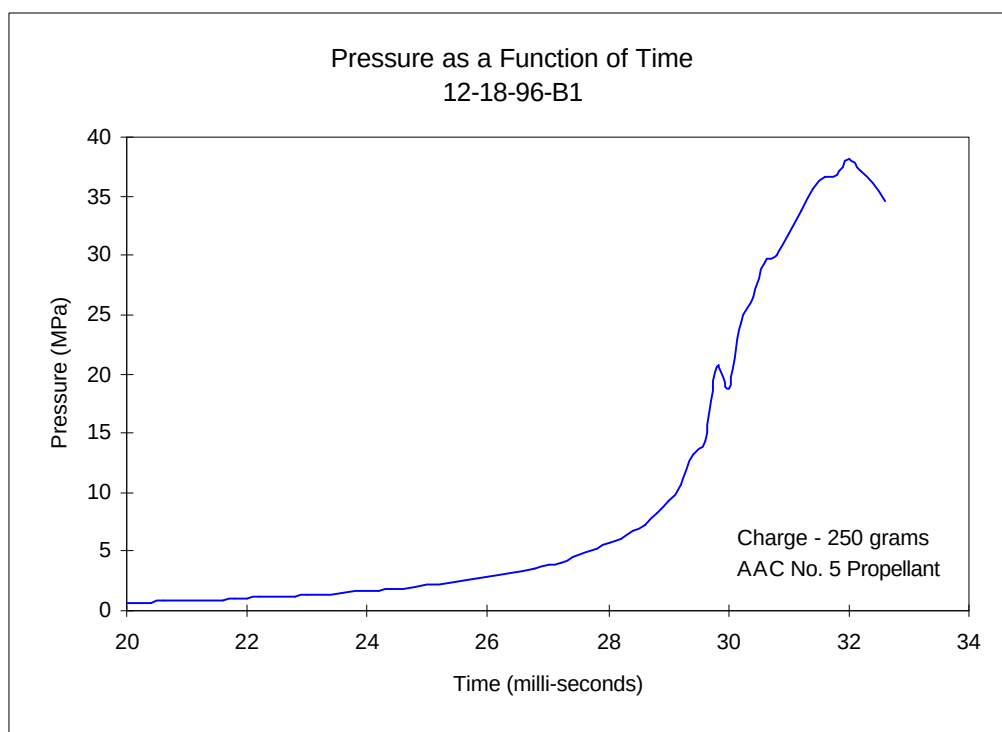
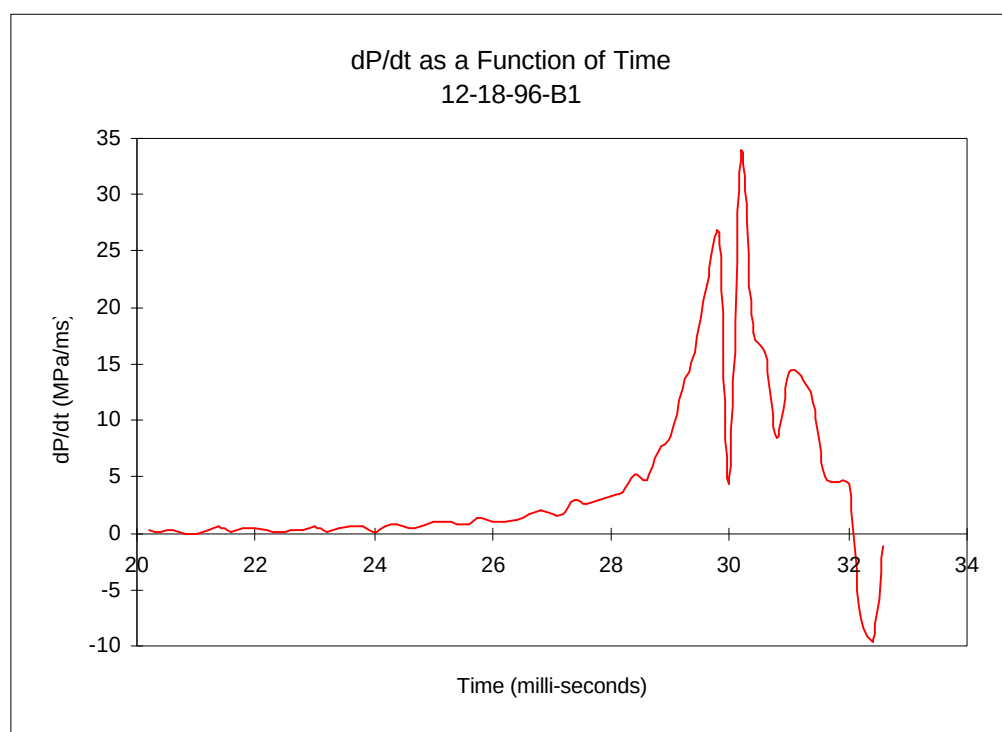


Figure 6-7a: Pressure as a Function of Time, Shot 12-18-96-B1.

Figure 6-7b: dP/dt as a Function of Time, Shot 12-18-96-B1.

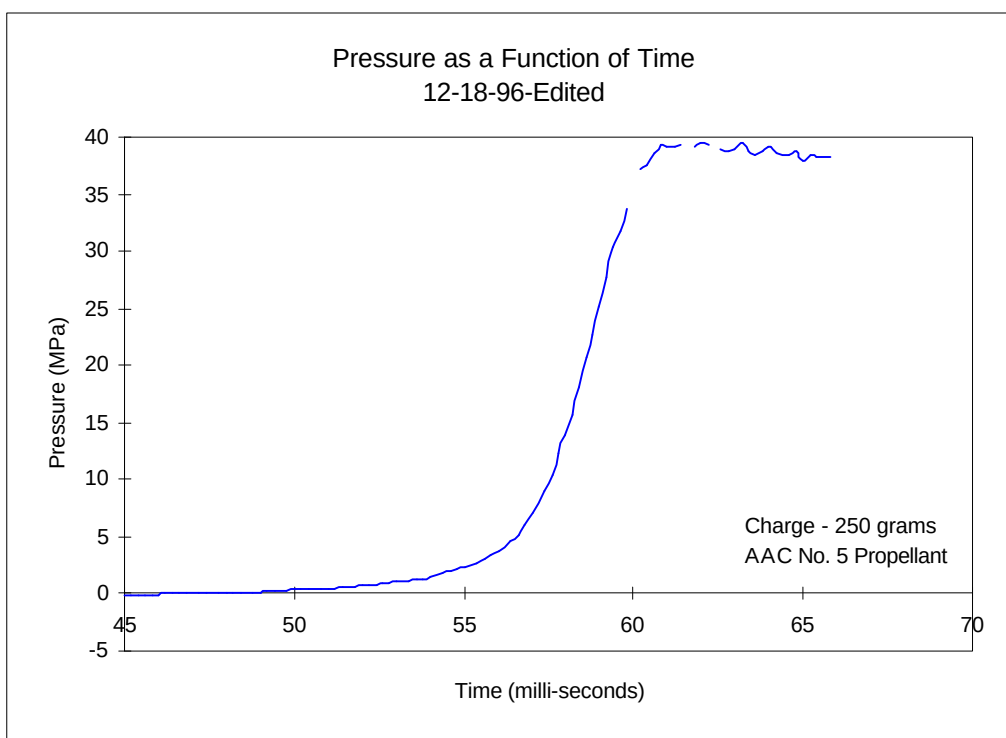


Figure 6-8a: Pressure as a Function of Time, Shot 12-18-96-B2.

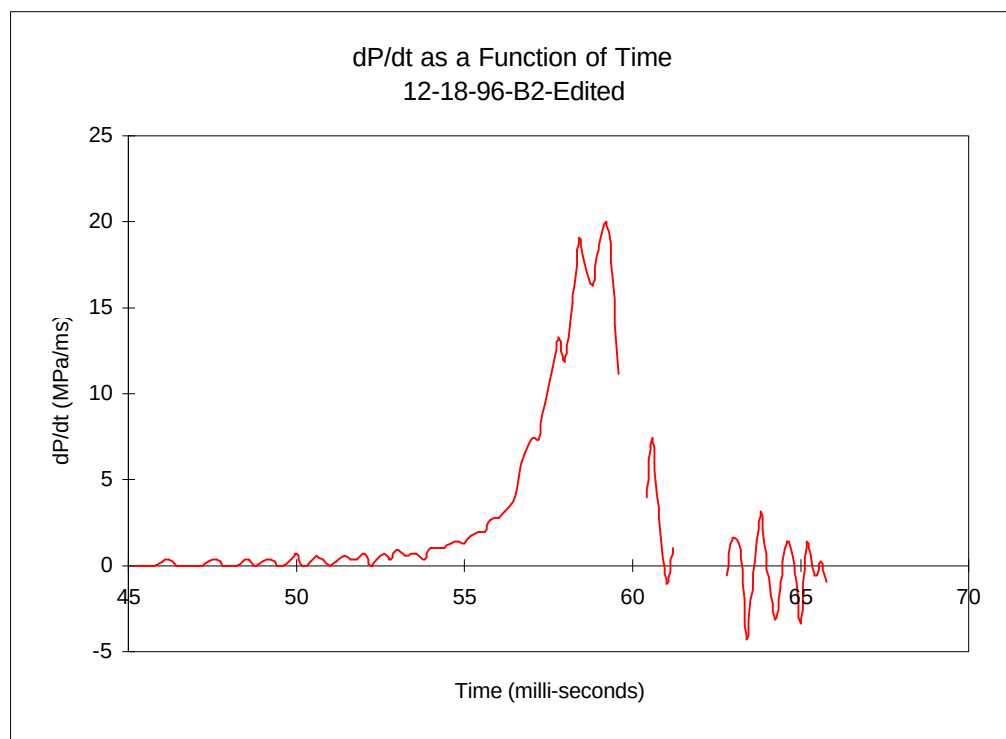


Figure 6-8b: dP/dt as a Function of Time, Shot 12-18-96-B2.

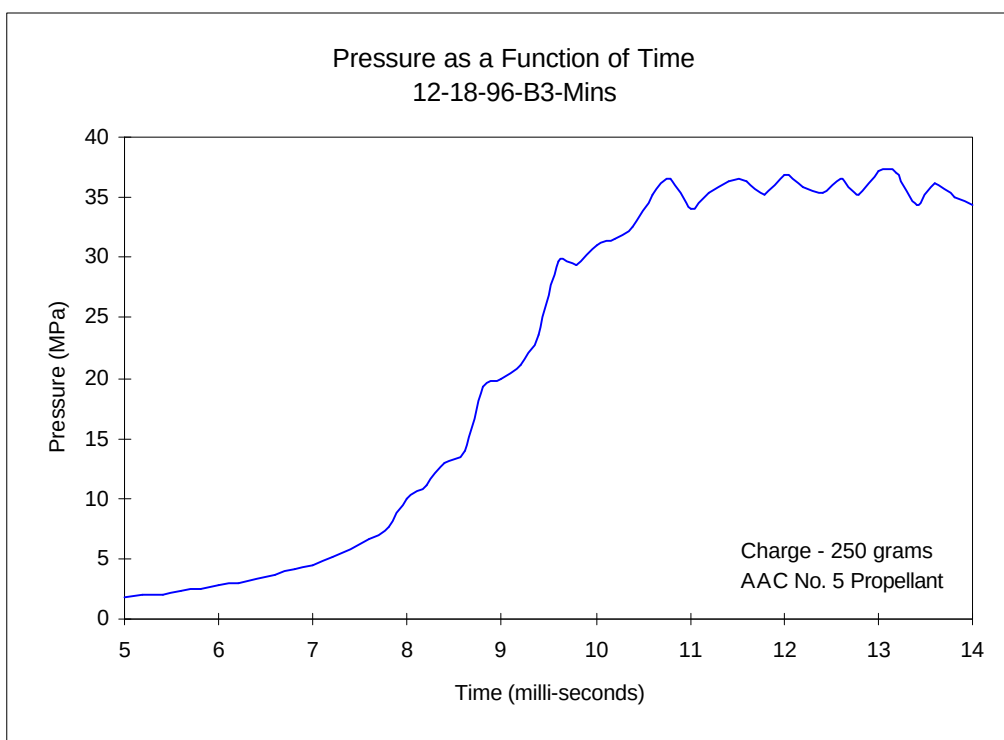


Figure 6-9a: Pressure as a Function of Time, Shot 12-18-96-B3.

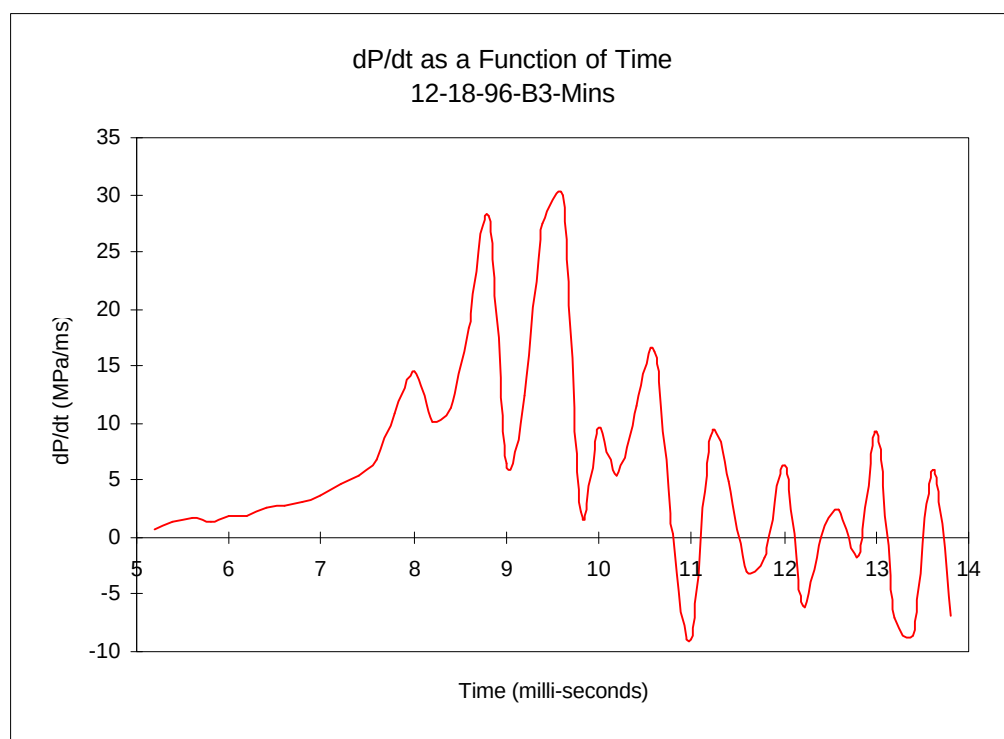


Figure 6-9b: dP/dt as a Function of Time, Shot 12-18-96-B3.

6.2.3 500 gram (Nominal) Shots

Due to unexpected variation in the size of the 1-1/2 inch tube the nominally 500 gram shots fell short of the mass target by about 7%. The theoretical peak pressure (for a closed vessel) was 74.8 MPa, for the 500 gram charge.

Figures 6-10a and b show the pressure-time and dP/dt as a function of time profiles for shot 12-18-96-C1. The pressure growth profile for this shot shows a brief step occurring about halfway up the pressure pulse. This step appears to be consistent with the passage of an echo within the test vessel. The initial practical peak pressure is on the order of 80 MPa, this is based on the relative minimums of the reflections following the initial measured peak of 96 MPa. The practical peak pressure is about 107 percent of the modeled peak pressure for a sealed system. The dP/dt curve shows a fairly smooth initial growth, up to the point where the step occurs in the pressure-time data. Following this point the dP/dt data shows a rapid fluctuation in the pressure rate that is consistent with reflections of the pressurization pulse within the bomb.

Figures 6-11a and b illustrate the pressure-time and dP/dt -time profiles for shot 12-18-96-C2. This shot shows a very sharp pressure rise to the first of numerous pressure spikes that appear to associated with reflection within the bomb. Based upon the lower data in the reflection sequence the practical peak average pressure in the bomb was on the order of 78 MPa, or about 104 percent of that estimated by the numerical model. Furthermore, a practical evaluation of the data appears to indicate that the rise to the peak average pressure occurred between about 20 and 21.6 milli-seconds, rather than the very sharp rise seen at about 20.4 milli-seconds. The 1.6 milli-second period is also more consistent with the pulse duration observed in the previous shot. The dP/dt profile for this shot shows very rapid oscillation of the pressurization rate, which is consistent with reflection of a pressure pulse within the test vessel.

Figures 6-12a and b show the pressure-time and dP/dt -time profiles for shot 12-18-96-C3. During the main pressure rise of this shot several minor pulses are evident. The practical peak pressure of this shot appears to be on the order of 70 MPa, or about 94 percent of the estimated peak pressure based on the modeled example for a sealed vessel. The dP/dt profile for this shot reveals relatively little as the data is heavily biased by the intense reflection of the pressure waves within the bomb.

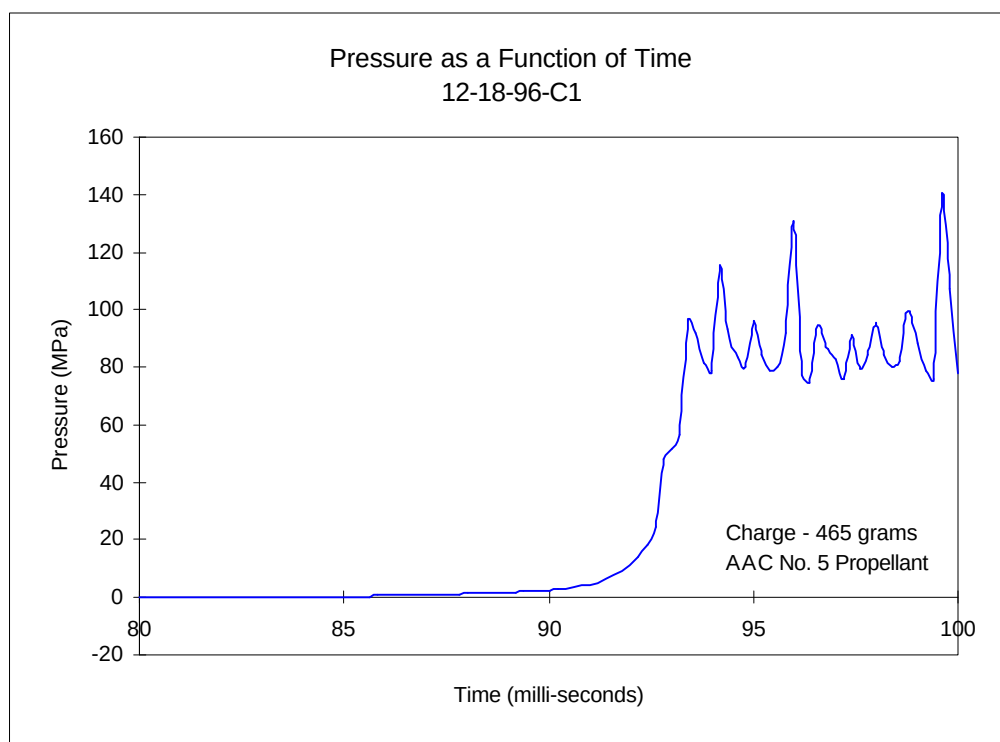


Figure 6-10a: Pressure as a Function of Time, Shot 12-18-96-C1.

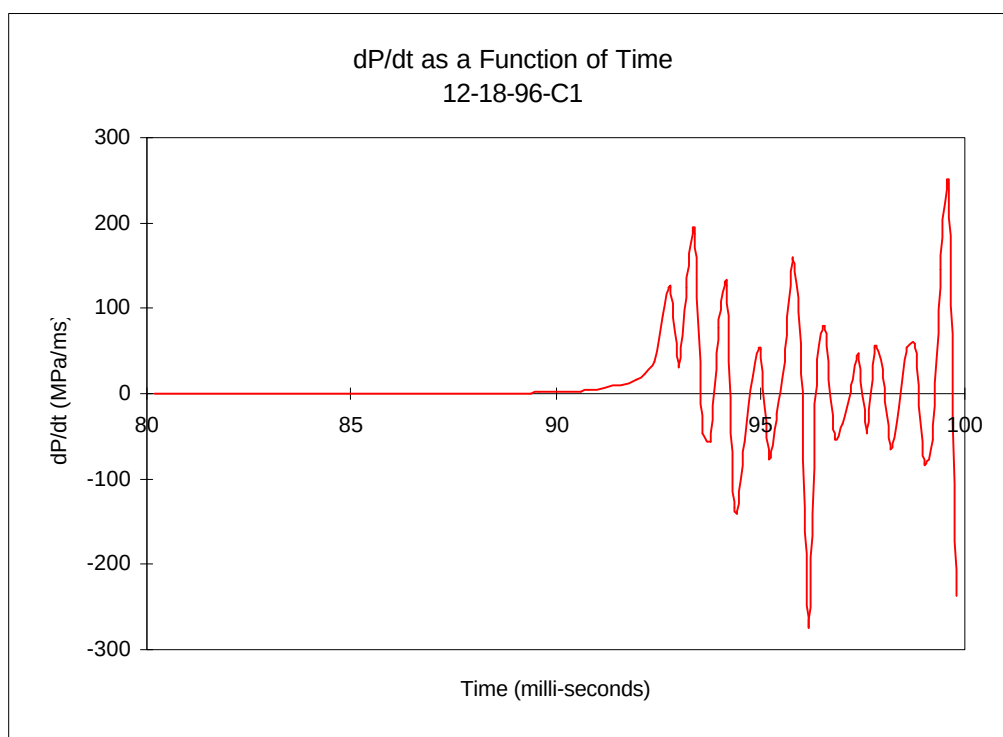


Figure 6-10b: dP/dt as a Function of Time, Shot 12-18-96-C1.

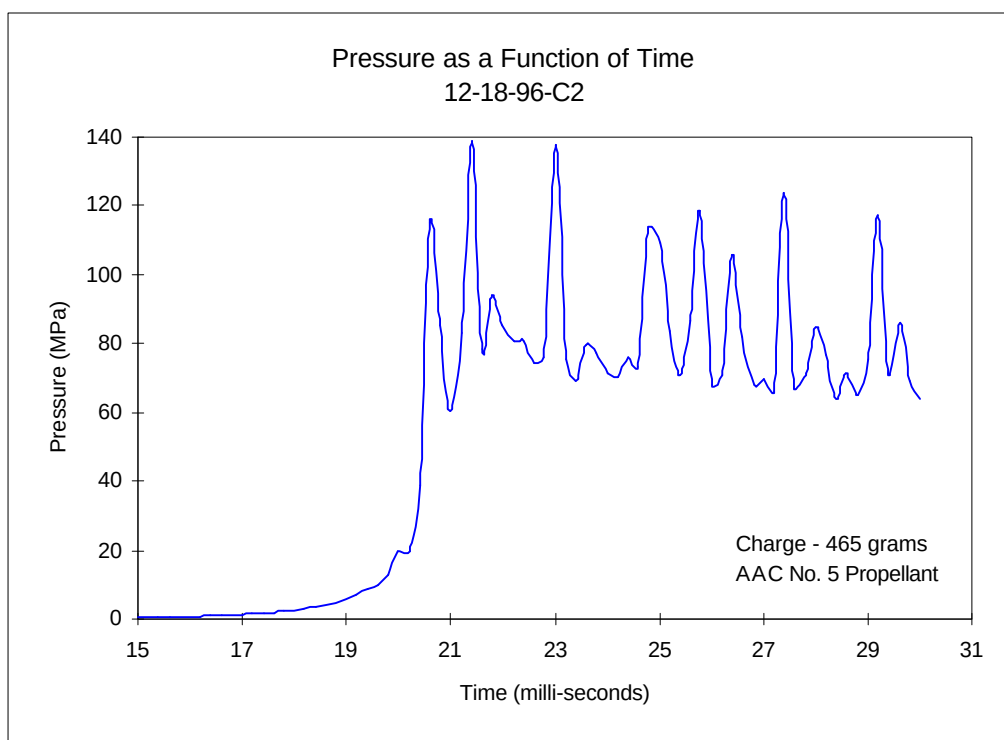


Figure 6-11a: Pressure as a Function of Time, Shot 12-18-96-C2.

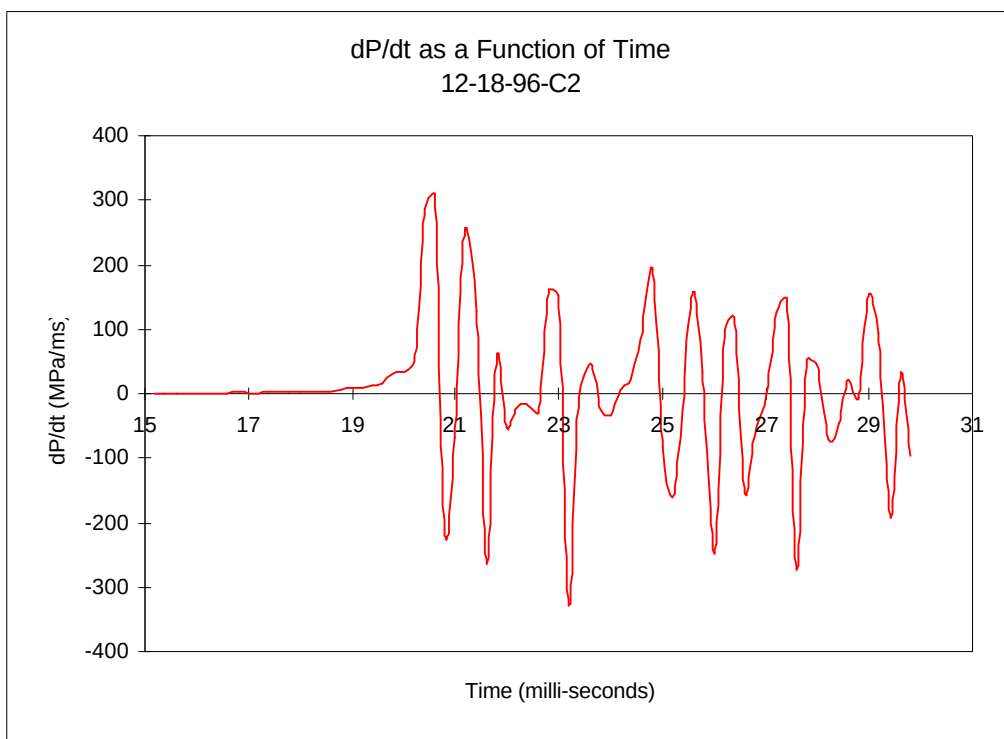


Figure 6-11b: dP/dt as a Function of Time, Shot 12-18-96-C2.

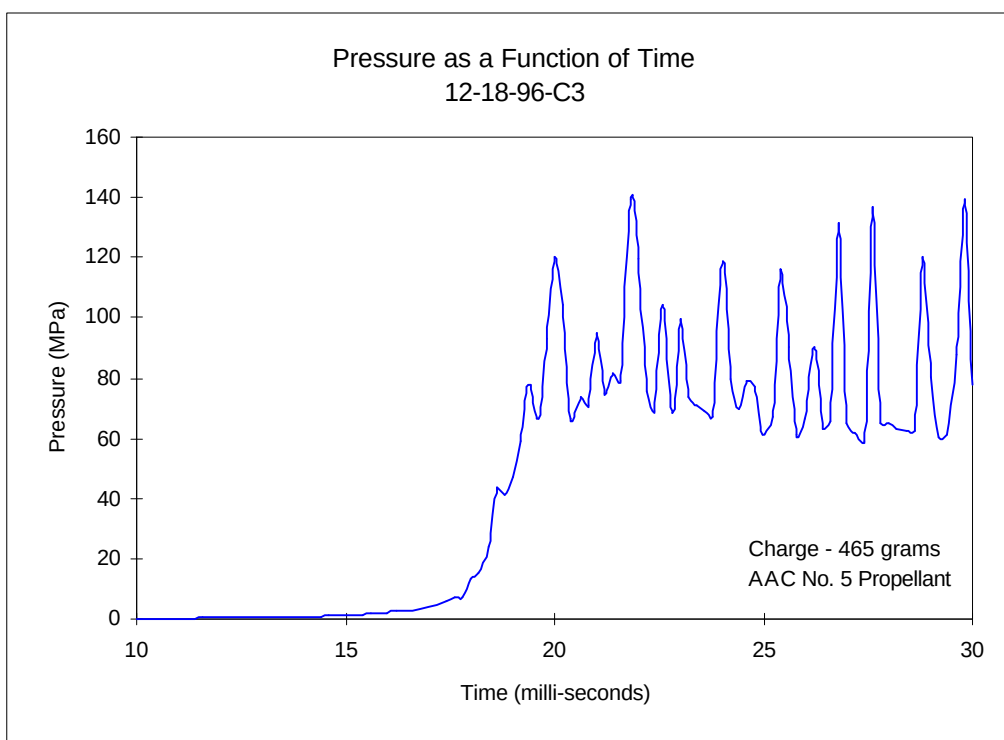


Figure 6-12a: Pressure as a Function of Time, Shot 12-18-96-C3.

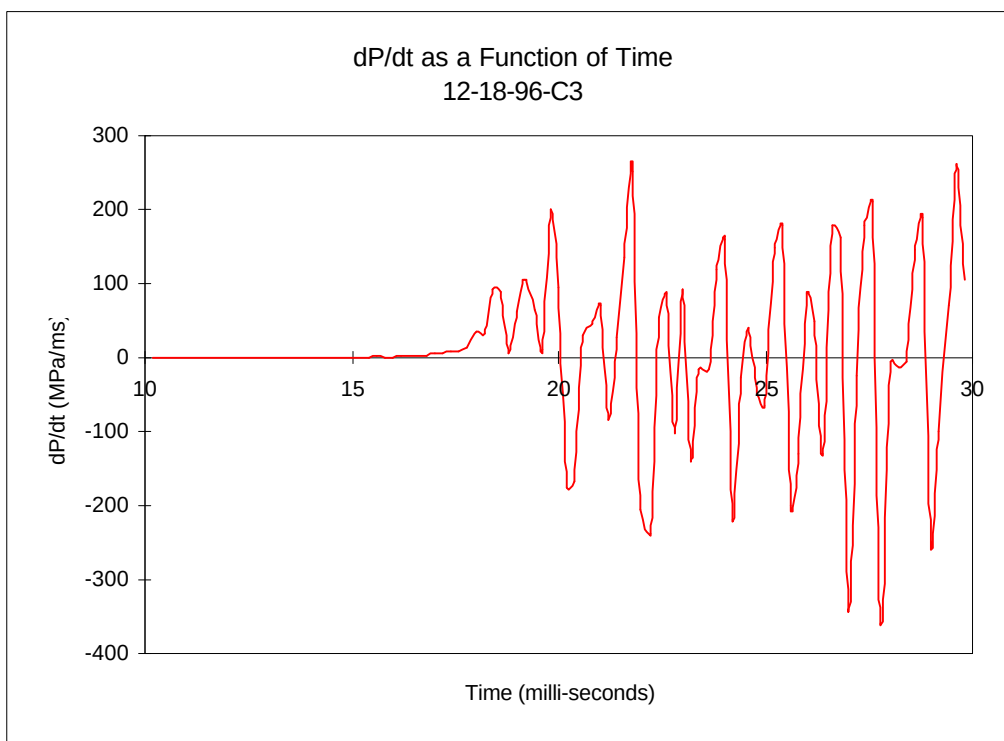


Figure 6-12b: dP/dt as a Function of Time, Shot 12-18-96-C3.

6.2.4 750 gram (Nominal) Shots

Due to unexpected variation in the size of the 1-1/2 inch tube the nominally 750 gram shots fell short of the mass target by about 7.5%. A single shot at this charge was conducted, the other two planned shots could not be performed because of the unplanned failure of the test vessel.

The theoretical peak pressure of a 750 gram charge, in a closed vessel, was 119.0 MPa. Based on the 10 volt nominal peak output of the pressure transducer by about 3 percent, however, experience with this particular transducer has shown a peak voltage output on the order of 12.5 volts. Assuming that the output continues on the linear relationship beyond 10.0 volts the maximum expected pressure is about 84 percent of the maximum output from the transducer. [Compare also the designed pressure response of the transducer 2 psi per milli-volt (140 MPa at 10 Volts output) to the actual case of 1.64 psi per milli-volt (114 MPa at 10 Volts output).

Figure 6-13a and b illustrate the pressure-time and dP/dt-time profiles for shot 12-18-96-D1. The first of these graphs illustrate the pressure-time characteristic of this shot. The initial pressure rise indicates a smooth increase in the pressure as the charge burned. The shape of this portion of the trace (from -0.2 to 0.6 milli-seconds) is fairly typical of the expected shape, with the exception that the time duration is significantly less than observed in the previous series of tests (250 and 500 gram charges). The dP/dt-time profile also indicates the very rapid change in pressure that occurred as the pressurization wave was reflecting about in the test bomb. Due to the fairly smooth pressure profile in the time defined above the initial pressure peak appears to be a valid point for evaluation of the peak pressure. In this case the initial peak pressure of about 134 MPa appears to be reasonable representative, this pressure is about 113 percent of the peak pressure estimated by the numerical model.

The relative “flatness” of the tops illustrated in figure 6-_a also seem to indicate a limit of the pressure sensor. The voltage associated with the flattened peaks is about 11.8 Volts, a peak limit observed previously. The sigmoidal shape of the initial pressure front is consistent with the expected results, as noted previously. It appears to be coincidental that the peak measured pressure is of the same order of magnitude as the upper limit of the pressure transducer. This condition does not appear to significantly affect the interpretation of the data.

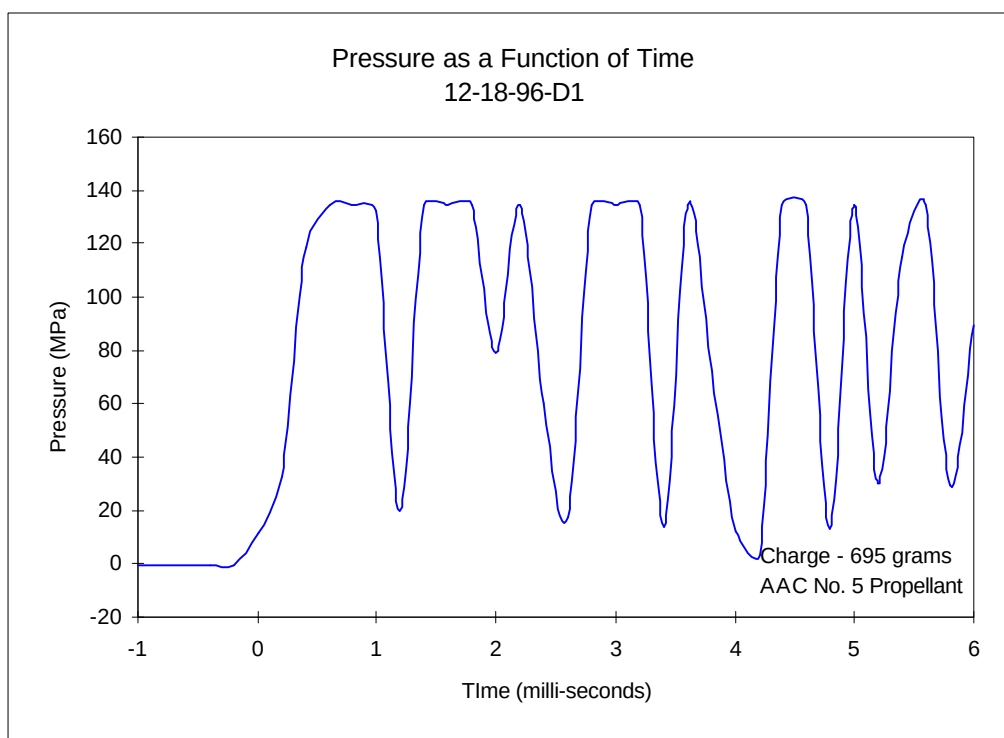


Figure 6-13a: Pressure as a Function of Time, Shot 12-18-96-D1.

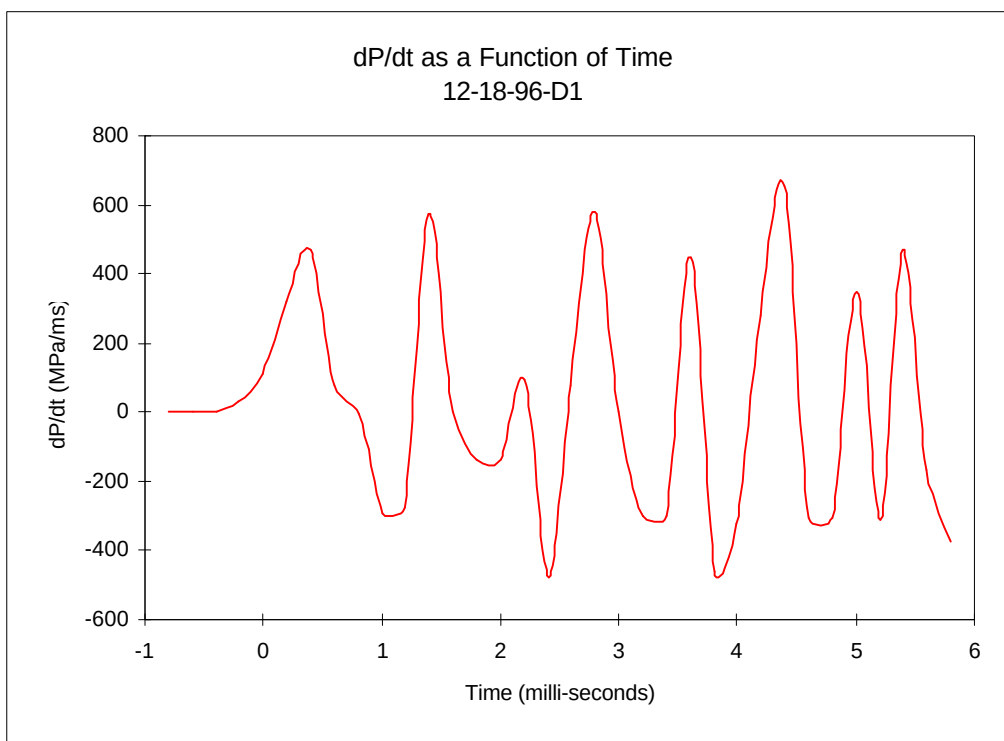


Figure 6-13b: dP/dt as a Function of Time, Shot 12-18-96-D1

6.3 Discussion

The basic data for the large-scale tests is presented in table 6-1, below. As in the previous, small-scale, tests this table presents the charge mass, the pressure rise-time, the rise-rate, the peak pressure, and the time of peak pressure.

Table 6-1: Basic Propellant Burn Results for Large-scale Shots and Numerical Models.

Sample	Mass	Rise-Time	Rise-Rate	Peak Pressure	Time of Peak
	(gm)	(ms)	(MPa/ms)	(MPa)	(ms)
100 Gram Series					
12-18-96-A1	100 ± 0.5	12.15	0.77	12.4	43.2
12-18-96-A2	100 ± 0.5	10.29	0.94	12.0	45.2
12-18-96-A3	96 ± 0.5	13.14	0.72	11.6	31.6
Num. Model	100	18.20	0.63	14.4	37.4
250 Gram Series					
12-18-96-B1	250 ± 0.5	4.92	6.2	38.4	32.0
12-18-96-B2	250 ± 0.5	3.93	8.2	39.1	60.8
12-18-96-B3	250 ± 0.5	3.68	8.0	37.5	11.0*
Num. Model	250	6.45	4.5	36.2	16.35
500 Gram Series					
12-18-96-C1	468 ± 0.5	1.43	41.8	82.0	93.4
12-18-96-C2	464 ± 0.5	1.97	29.8	74.0	21.6
12-18-96-C3	459 ± 0.5	2.66	20.8	68.0	21.2
Num. Model	465	3.08	18.3	70.1	38.2**
Num. Model	465	3.05	18.4	70.1	8.98
Num. Model	500	2.78	21.7	75.8	8.38
750 Gram Series					
12-18-96-D1	694 ± 0.5	0.43	249	134.0	0.6
12-18-96-D2	N/A				
12-18-96-D3	N/A				
Num. Model	694	1.85	47.5	110.0	6.05
Num. Model	750	1.68	57.2	120.2	5.58

* - This time value recorded on second pass of 40 micro-second period time-base, hence value is more likely 51 milli-seconds.

** - Based on Radial Burn Model, advance ratio = 2500 times linear burn rate.

In the case of the 500 gram shot, modeled using the radial outward burn model and the 5-29-96-A(Average) properties, it can be observed that as the advance ratio increases the pressure rise-

time, rise-rates stabilize at 3.05 ms, and 18.4 MPa/ms respectively, and that the time of peak pressure reduces to 28 ms at an advance ratio 5000 times the linear burn rate.

6.3.1 Linear Burn Rates

The general background to the development of linear burn rate parameters has been addressed in chapter 4.4 of this thesis, therefore it will not be repeated here. As a reminder, in the context expressed here, *linear burn rate* refers to the advance of the flame front into the propellant grain, as opposed to the advance of the flame front through the propellant pack. The form of this equation is a power function based on the ambient pressure in the vicinity of the burning propellant.

The determination of linear burn rates specifically from these tests is very limited. This condition is due to the high degree of filtering that is needed with most of the data in order to arrive at a reasonably smooth pressure growth profile from which the linear burn rates can be estimated. Linear burn rate estimates will be made based on the following shots, 12-18-96-A1, -B2, and -C1. The merit of the results based on these three tests will be addressed in relation to the outcomes covered below.

Figure 6-14 illustrates the linear burn rate estimates for the shot 12-18-96-A1. This data does not indicate a clear distinction between the ignition, full burn, and burn-out zones that are typically associated with propellant burns. Without a clearly defined “full-burn” zone it is not practical to attempt to derive a the linear burn rate parameters for the power law function.

Figures 6-15a and b show the linear burn rate estimates for shot 12-18-96-B2. The burn rate estimates from this shot appear to show the three regions associated with the propellant burn. Utilizing the linear burn rates in the “full-burn” zone the burn rate equation parameters are estimated, and shown, in figure 6-15b.

Figures 6-16a and b illustrate the linear burn rate estimates for shot 12-18-96-C1. The burn rate estimates from this shot show distinct ignition and full-burn zones. The presence of the burn-out zone is not as distinct as was observed in previous analyses. The lack of the clear burn-out zone may be due to the echo associated with the peak pressure of this shot, see figure 6-10. The echo affects the linear burn rate estimate as the pressure peaks, this is observable in figure 6-16a between the last two points shown to be in the full-burn zone; notice also the scatter of points in the burn-out zone. For the purpose of estimating the burn rate equation the last data point within the full-burn zone was deleted from the relevant data set. The estimated burn rate equation is shown in figure 6-16b.

Both of the linear burn rate equations produce coefficients of determination (R^2) values in excess of 0.95, indicating a very good correlation between the data and the estimated function. The parameters (coefficient and index) for the burn rate equation, for both the 12-18-96-B2 and 12-

18-96-C1 shots are consistent with values determined for the small-scale shots. This comparison is shown in table 6-2. Notice in this table the consistency between the values of n and R^2 for the respective values of A , across the spectrum of those values. That is to say that as A increases n and R^2 tend to decrease, the values estimated for the large-scale tests fall into the overall range of the small-scale shots. The linear burn rate parameters from the 5-29-96-A(Average) series has been used to estimate the behavior of the large-scale shots. A comparison between these parameters and those estimated for shots 12-18-96-B2 and -C1 is shown, for a 465 gram charge, in figure 6-17. The basic relationship between these three models is illustrated in table 6-3, below.

Table 6-2: Comparison of Linear Burn Rate Coefficients for Samples Indicated.

Sample	A	n	R^2
100% Accurate Arms Company No. 5 Propellant			
5-29-96-A(Average)	6×10^{-11}	1.1535	0.9879
5-29-96-A1	1×10^{-9}	0.9766	0.9456
5-29-96-A2	9×10^{-11}	1.1271	0.9914
5-29-96-A3	6×10^{-11}	1.1531	0.9908
6-13-96-D1*	3×10^{-13}	1.4840	0.9970
6-13-96-D2*	2×10^{-14}	1.6586	0.9902
12-18-96-B2*	8×10^{-11}	1.1507	0.9744
12-18-96-C1*	3×10^{-14}	1.6096	0.9963

* - indicates that the covered shot was fired in a vented test vessel.

Table 6-3: Relationship Between Three Models of 465 Gram Shot.

Model	Rise Time (ms)	Rise Rate (MPa/ms)	Time of Peak Pressure (ms)
465 Gram Shot; 67.6 kg/m^3 loading density			
12-18-96-B2	2.42	23.15	7.05
5-29-96-A(Average)	3.05	18.35	8.98
12-18-96-C1	2.78	20.25	23.9

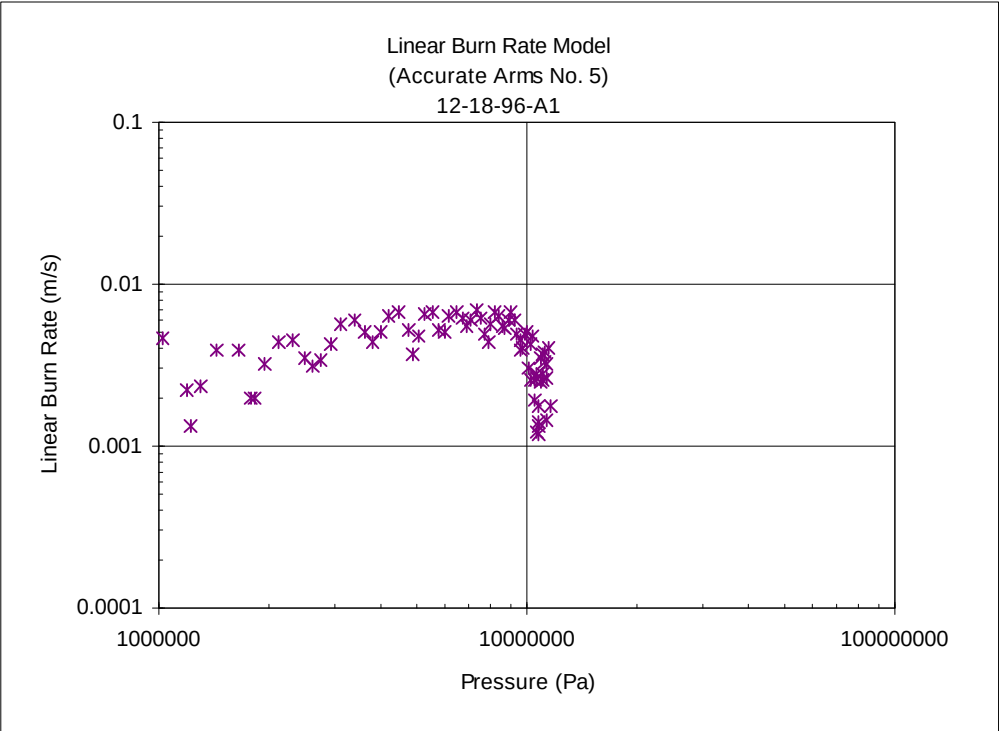


Figure 6-14: Linear Burn Rate, Entire Model, Shot 12-18-96-A1.

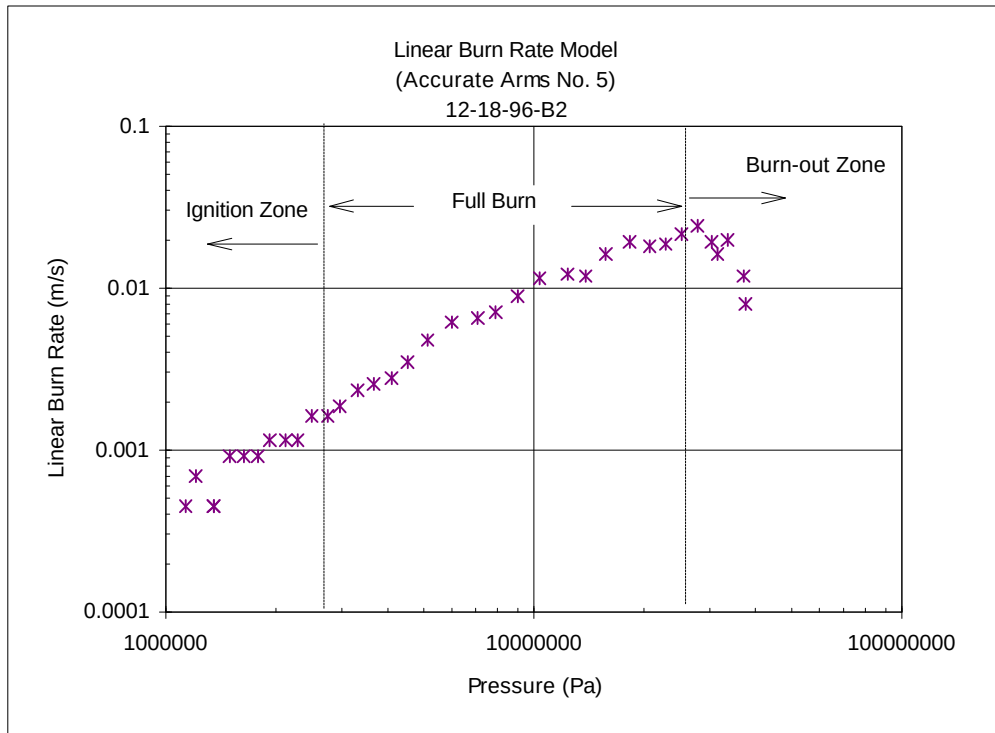


Figure 6-15a: Linear Burn Rate, Entire Model, Shot 12-18-96-B2.

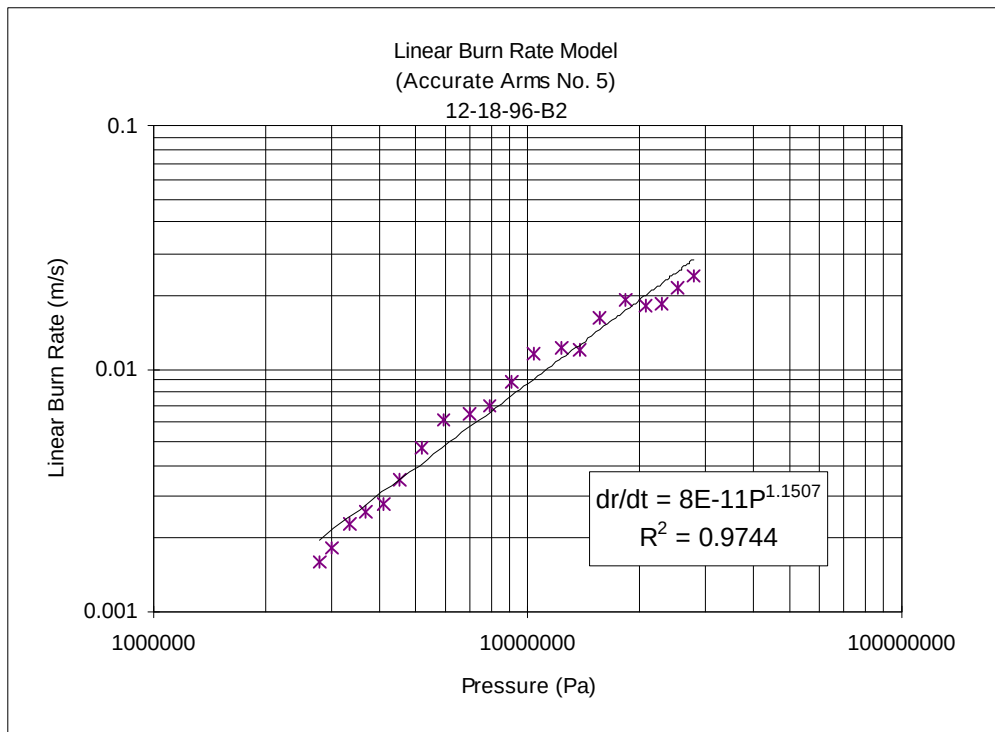


Figure 6-15b: Linear Burn Rate Model, Shot 12-18-96-B2.

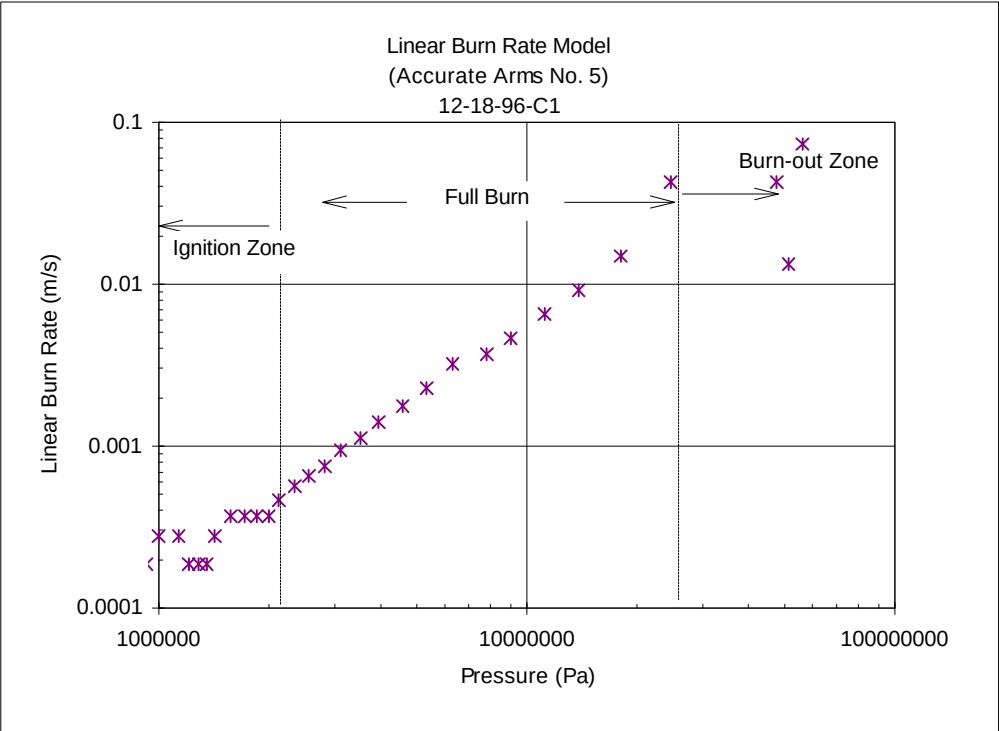


Figure 6-16a: Linear Burn Rate, Entire Model, Shot 12-18-96-C1.

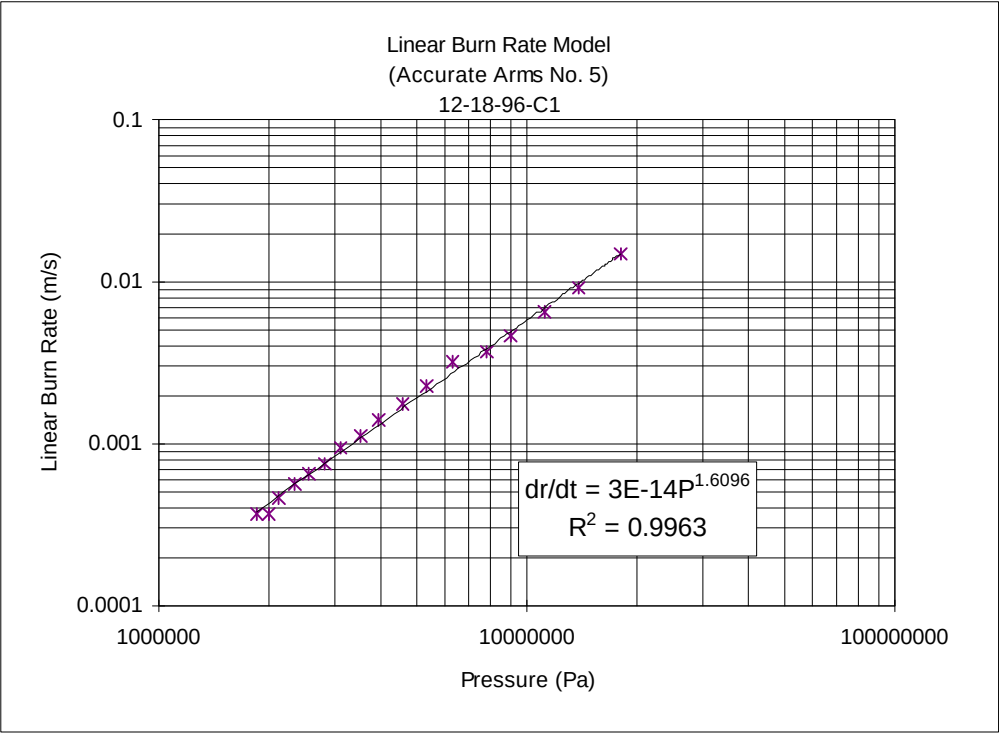


Figure 6-16b: Linear Burn Rate Model, Shot 12-18-96-C1.

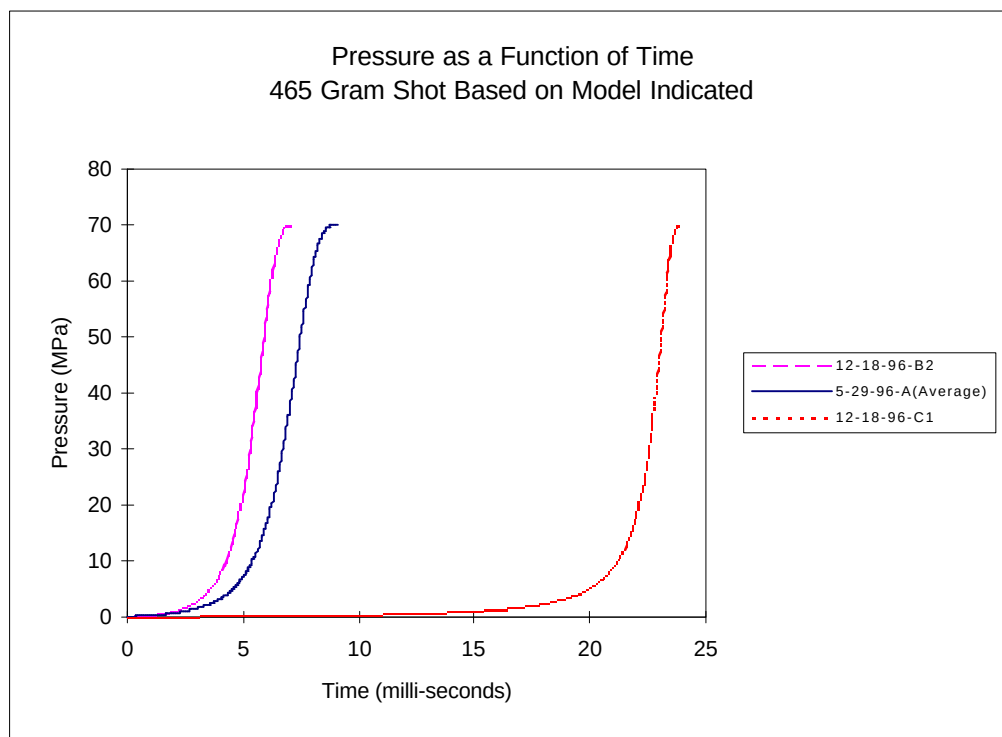


Figure 6-17: Comparison of Modeled Shots, 465 grams No. 5 Propellant.

6.3.2 Numerical Model Comparison

The general trend of the numerical model output is shown in figure 6-18. This figure illustrates the nominal charge weights, as well as the actual charge weight used in the heavier shots. For the 100 and 250 gram series the actual mass was the same as the nominal weight.

The propellant burn rate parameters for these models are based on the average conditions for the 5-29-96-A shot series. In the power law burn rate equation:

$$\dot{X} = AP^n,$$

a value of $6 \cdot 10^{-11}$ was used for the coefficient A , and a value of 1.1535 was used for the index n . The numerical model used in this assessment was the instantaneous ignition model, a factor that accounts, in part, for the disparity in time between the modeled conditions and the laboratory results.

Figure 6-19 illustrates the comparison between the numerical model and the laboratory data of test 12-18-96-A1. While there is some obvious similarity between the curves, indicating a general agreement between the model and the lab data, the lab data shows a significantly lower peak pressure than was predicted. Such a case may be accounted for in two ways. First is that the numerical model assumes that the vessel was sealed, which was not the case in the laboratory; this, along with the relatively long burn time, can account for loss of mass from the system, hence a reduced peak pressure. The second consideration arises from the shape of the recorded laboratory data curve. The trend of this curve at its point of initiation suggests that the origin is at a negative pressure value, a case observed in the other shots of the 12-18-96-A series. Considering this, the actual peak pressure may be as much as 2 MPa higher than actually recorded. This would not change the shape of the laboratory data curve, it would merely translate the data up by 2 MPa. Similar analysis can be applied to the other 100 gram shots, 12-18-96-A2 and -A3, with consistent results.

Figure 6-20 compares the differences between the laboratory data for the shot 12-18-96-B1 and the numerical model of this shot size. The laboratory data indicates a rise-rate that is about 150% of that of the modeled results. The peak pressure predicted by the model is somewhat less than that observed in the lab, a condition consistent with all cases tested in this series (12-18-96), except for the 100 gram charges (12-18-96-A1, A2, A3). The pressure rise event in the modeled data occurs significantly sooner than the physical event. This is likely due to a delay in the ignition of the main propellant charge following the ignition of the black powder igniter charge. This would be accounted within the ignition wave progressing through the propellant pack, whereas the model assumes that the charge is ignited simultaneously.

Figure 6-21 shows the comparison between the numerical model and physical experiment for test shot 12-18-96-C2. The laboratory data in this shot appears to be delayed by the propagation of the ignition wave through the charge pack, as was observed in the previous test set (12-18-96-B1, B2, B3).

Figure 6-22 illustrates the differences between the laboratory shot of 12-18-96-D1 and the numerical model of this event. Unlike the previous comparisons, in this shot the laboratory data precedes, in time, that of the numerical model. This case, along with the physical evidence gained in the laboratory supports the conclusion that this test resulted in a detonation of the propellant charge rather than the expected, and modeled, deflagration. This point leads to an upper limit on the charge configuration and loading density, which will be addressed in some detail in the following chapters concerning General Discussion (chapter 7) and Conclusions and Recommendations (chapter 8).

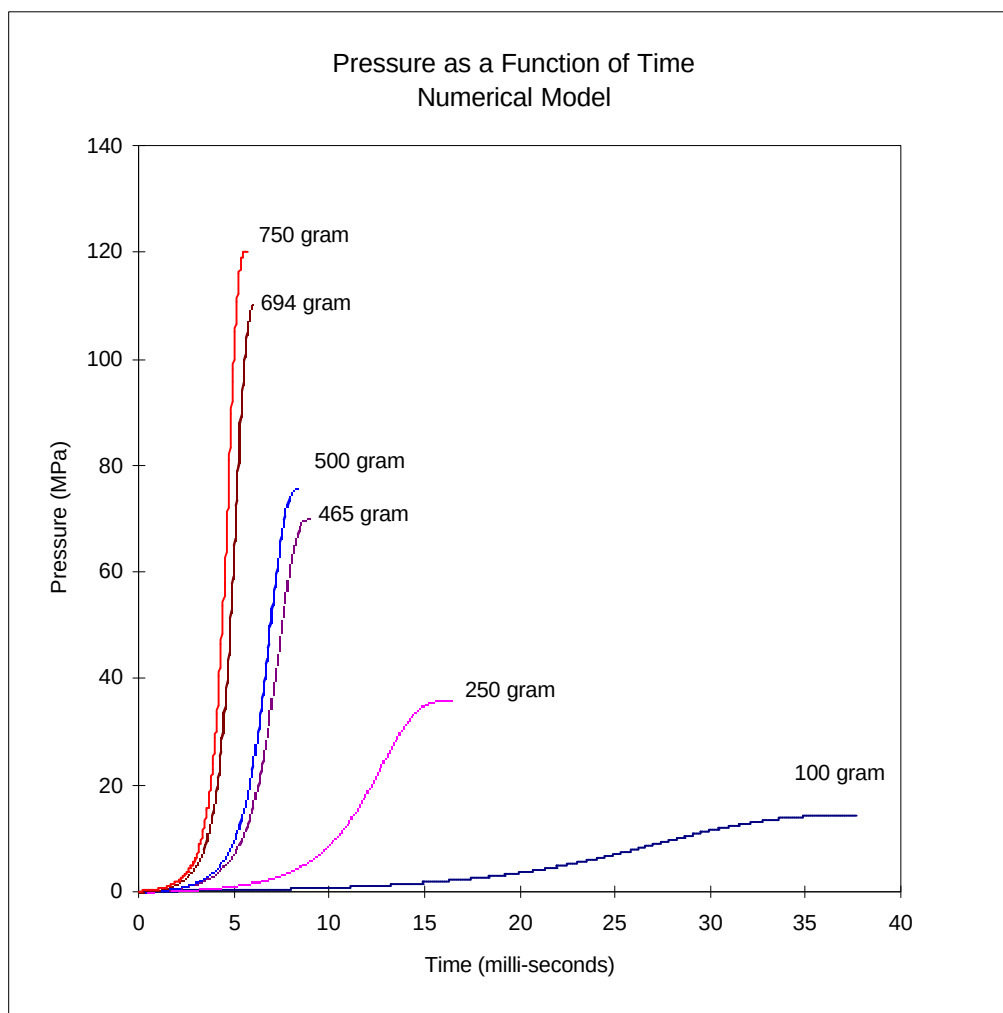


Figure 6-18: General Comparison in Pressure-Time Profiles for 12-18-96 Shot Series.

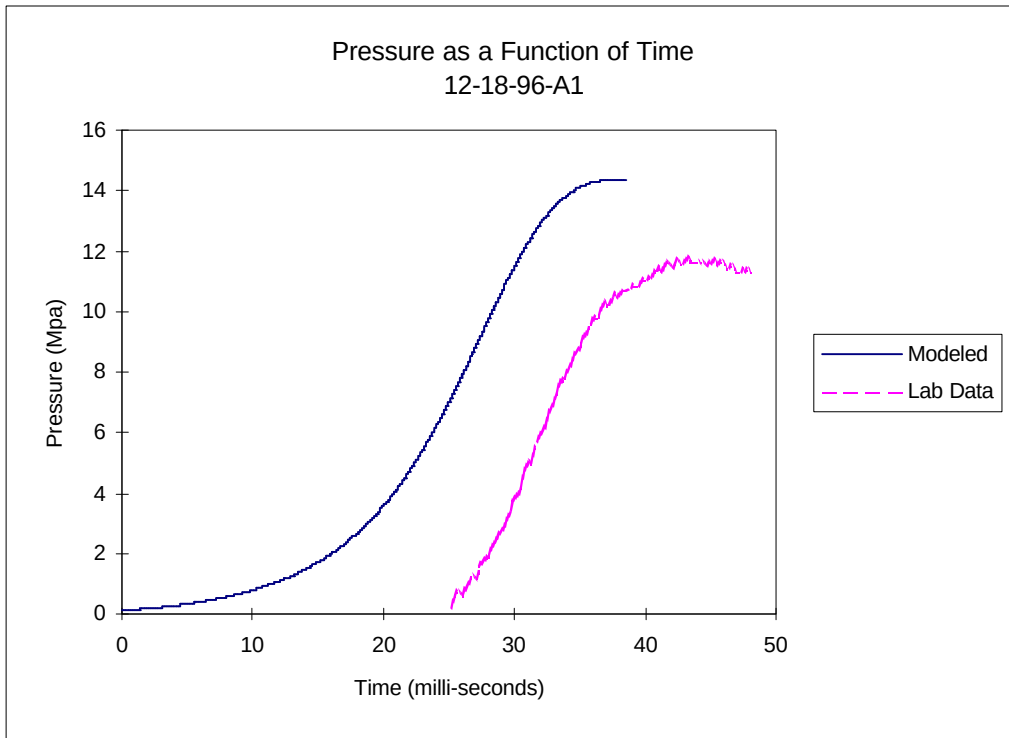


Figure 6-19: Pressure as a Function of Time Comparison, Shot 12-18-96-A.

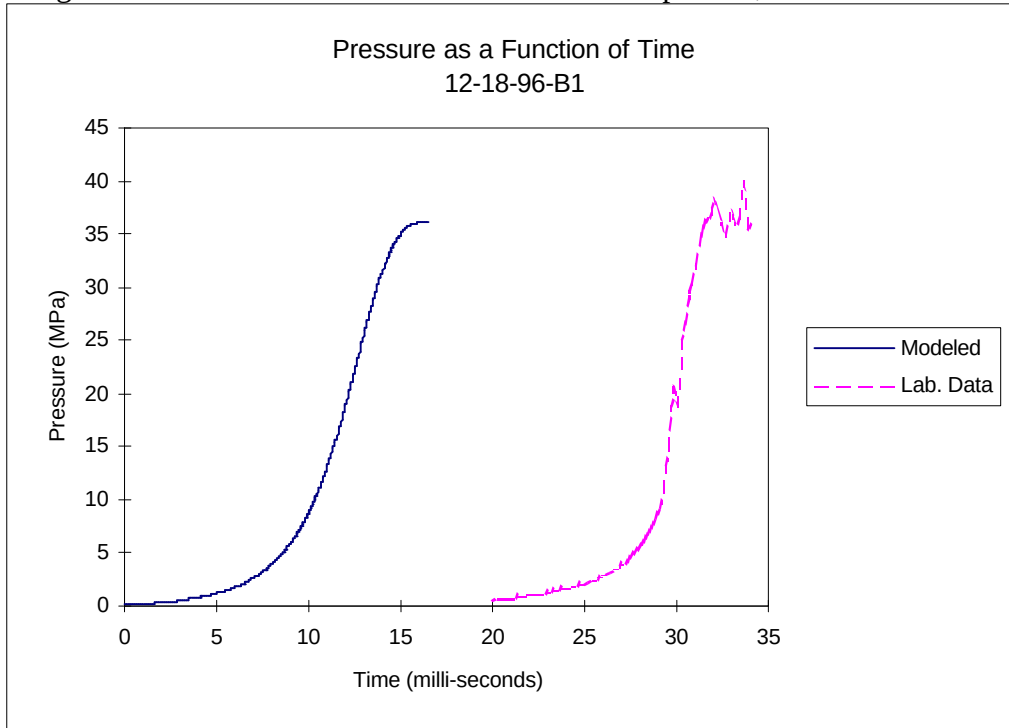


Figure 6-20: Pressure as a Function of Time Comparison, Shot 12-18-96-B.

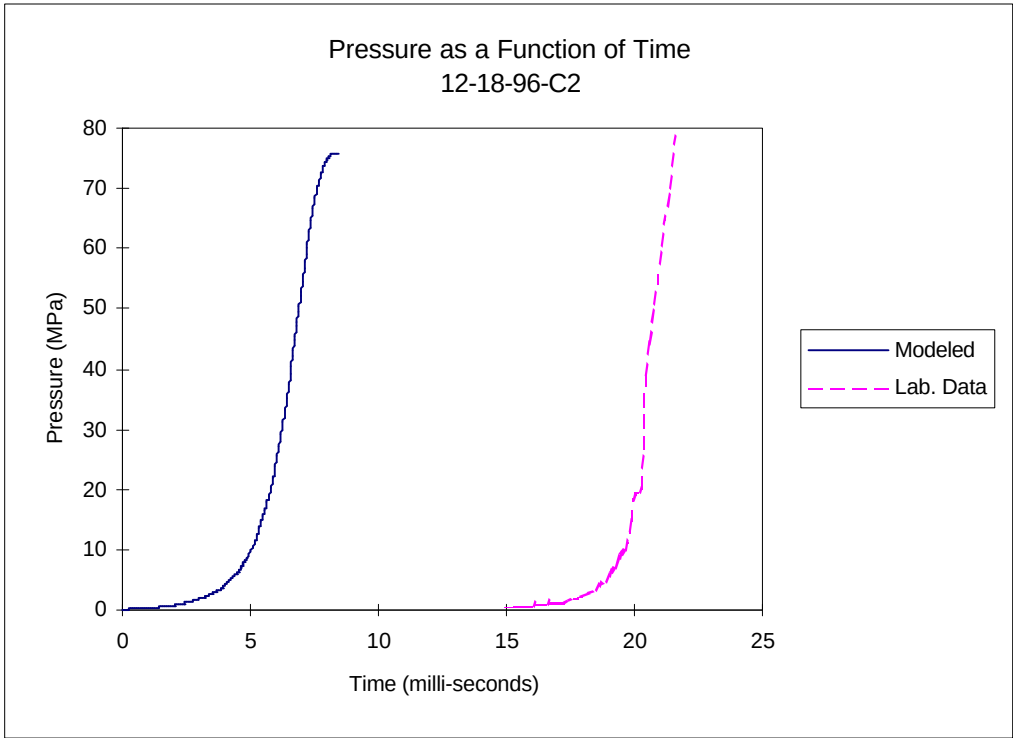


Figure 6-21: Pressure as a Function of Time Comparison, Shot 12-18-96-C.

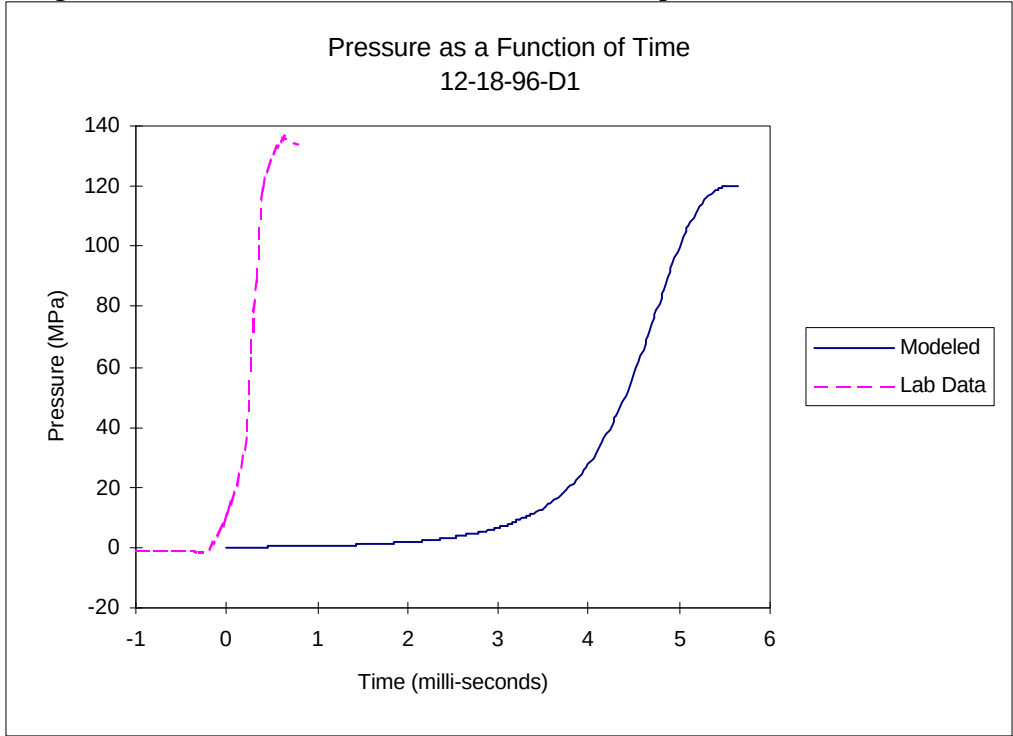


Figure 6-22: Pressure as a Function of Time Comparison, Shot 12-18-96-D.

6.3.2.1 *Predicted Behavior*

In using the numerical model to estimate the behavior of the charges a number of assumptions have been made, these include:

1. That the entire charge is ignited simultaneously, rather than using the configuration specific algorithm.
2. That the test vessel is closed, rather than assuming that mass was lost from the system during the progress of the propellant burn.
3. That the propellant must burn in accordance with the power law behavior, that is, a detonation is not accounted for in the modeled propellant burn system.

Given the limitations of the modeling, addressed in chapter 5, the prediction model seems to have adequately predicted the general behavior of the physical tests. A general comparison between the instantaneous ignition model and the radial outward burn model for the tests modeled exhibit a good similarity. This factor has been addressed in a small degree in a previous section. Based on the physical parameters of the models evaluated, similar to the 465 gram charges, the two model approaches produce similar results in the area of pressure rise-times, and rise-rates, as the ignition front approaches a practical rate (greater than 2500 times the linear burn rate). The key difference that arises with an increase in the ignition front advance ratio is the time to peak pressure. As the advance ratio becomes very large, the pressure-time profile of the outward burn configuration approaches that of the instantaneous ignition model.

At practical values of the ignition front advance ratio, the propellant burn between 10 percent and 90 percent of the peak pressure is unaffected by the advance rate. This case is shown in figure 6-23. In this figure, the condition of increasing the flame front advance through the propellant pack can be observed. Notice that shape of the main pressure pulse event is mainly the same, except for the time to the peak pressure.

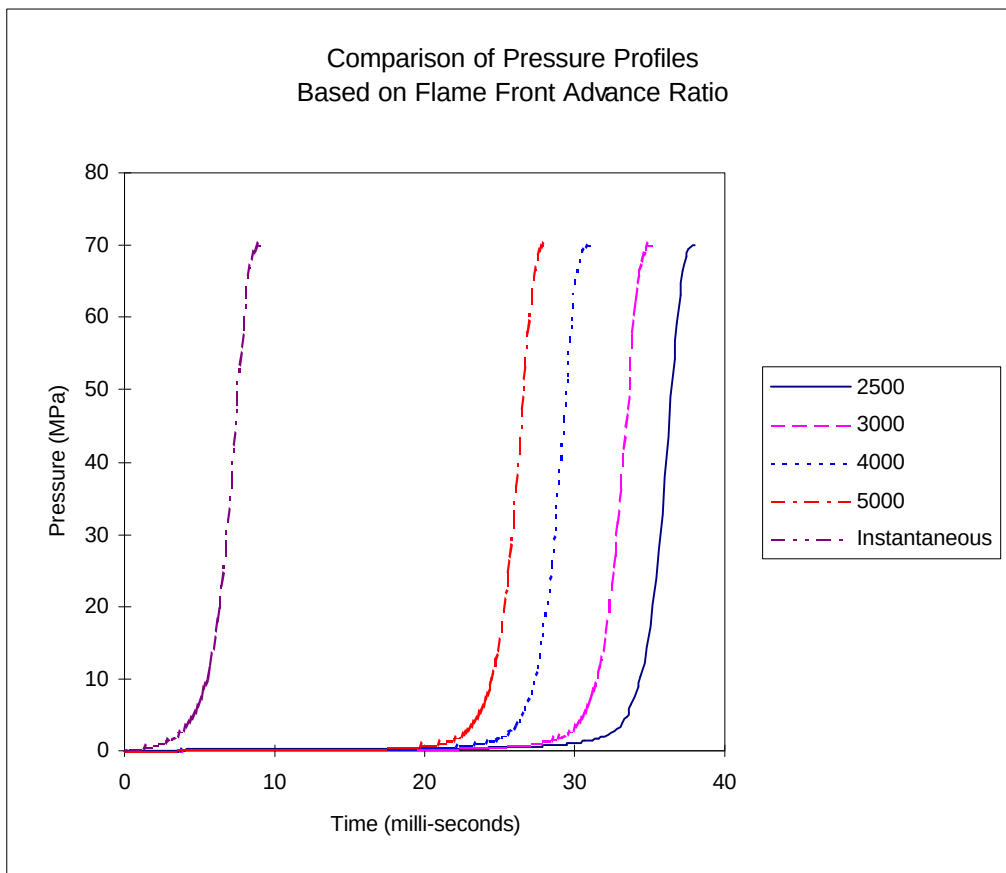


Figure 6-23: Comparison of Differences in Ignition Front Advance Ratio.

6.3.2.2 *Laboratory Behavior*

The behavior of the shots fired in the laboratory seem to indicate that the pressure rise-times and the rise-rates are greater than those estimated by the numerical model approach. These two parameters are controlled by the burn rate of the propellant, thus errors in the burn rate equation parameters will be translated into the numerical estimates of the pressure profile.

Within the laboratory test at the 100 gram level the pressure rise-time between 10 and 90 percent of the practical peak pressure appears to be on the order of 12 milli-seconds. The average slope through this range is about 0.81 MPa/ms.

For the 250 gram shot the pressure rise-time falls to the order of 4 milli-seconds for the 10-90 percent pressure change. The rise-rate, however, increases to be on the order of 7.47 MPa/ms.

For the 500 gram shots the pressure rise-time is about 2 milli-seconds for the 10-90 percent pressure change. The pressure rise-rate for this charge is at a level of 30.8 MPa/ms.

In the single 750 gram shot the pressure rise-time was 0.43 milli-seconds through the 10 to 90 percent of peak pressure range. The pressure rise-rate for this case was recorded as 249 MPa/ms. The general evidence presented by this situation, relative to the previous shots, and the numerical model data is that the propellant burn made a transition for deflagration to detonation.

Figure 6-24 compares the pressure rise-rate and the peak pressure based on the loading density. The small-scale shot series is identified specifically. Both data sets appear to have a fairly consistent trends. The peak pressure exhibits a linear trend. The Pressure Rise Rate is consistent with an exponential trend. The Coefficient of Determination (R^2) for these trends both exceed 0.95. The data presented are based on the laboratory shots, rather than the numerical estimates. Due to the good fit of the small-scale to the large-scale data, in both categories, the loading density appears to be a good scaling parameter for the propellant shots.

The location of the pressure rise-rate point associated with the highest loading density does produce a good fit of the data in an exponential form ($y = ae^x$). The fit is slightly better than that produced by a power law fit ($y = ax^n$) [not shown]. The power law fit would be expected if the power law burn rate equation or its parameters were valid throughout the loading density range. The exponential trend seems to suggest that the power law rate equation is not constant for variations in loading density. This may be a factor wherein the parameters selected for the rate equation can vary for the same propellant, as suggested by Riefler and Lowery (1975). The shape of this curve seems to suggest that there is a tendency for the propellant burn to transition from a deflagration event to a detonation event as the loading density increases.

The laboratory behavior of the propellant charges tested is consistent with the desired impulse to be applied within a coalbed methane well bore system.

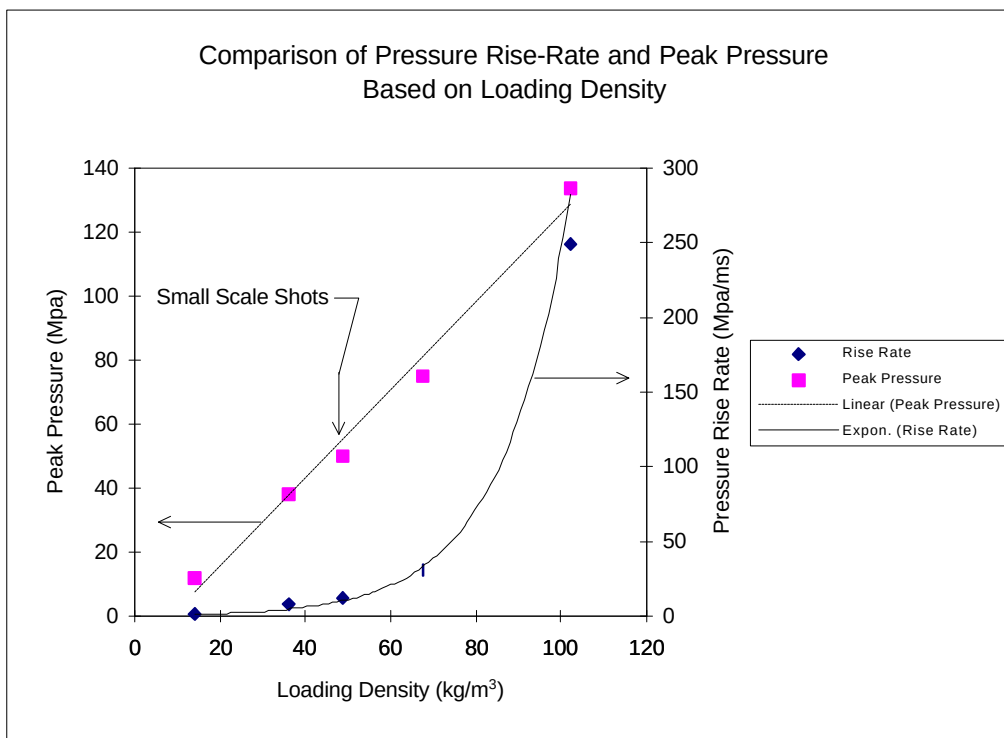


Figure 6-24: Comparison of Rise-Rate and Peak Pressure Based on Loading Density.

Chapter 7. General Discussion

Within each of the major sub-headings of this thesis there is a separate discussion section. This chapter, General Discussion, simply puts forward some of the discussion material covered in the previous chapters.

7.1 Results of Tests with Liquid Carbon Dioxide

The conventional approach to measuring the permeability of a rock core sample is illustrated in figure 3-2, in this method the permeability is measured on the cylindrical axis. The approach works well for samples that are reasonably isotropic, or where the sample can be obtained with the desired orientation of the cylinder axis. This method and configuration is limited when the sample orientation does not coincide with the desired orientation respective to sample features. The specific case is samples of coal that have been cored vertically. In these samples the desired direction of flow is perpendicular to the cylindrical axis of the sample. In this way, vertical coal samples do not lend themselves to the appropriate permeability measurement in a conventional approach. A sample preparation method was prepared, as a part of this study, in which the radial permeability of a vertically cored sample could be obtained using a standard Hoek cell apparatus. The sample configuration is illustrated in figure 3-7, and the Hoek cell test configuration is shown in figure 3-8. The background review of applicable literature and patent applications indicates that this approach has not been reported in the past.

The computation of permeability was based on four monitored variables, inlet pressure, differential pressure, gas flow rate, and temperature. The other parameters from the permeability equation, length, bore radius, sample radius, and gas constant were considered to be fixed values. By knowing the inlet and differential pressures it was possible to determine the mean gas pressure and the pressure gradient. Mass flow of the gas was computed from the gas volumetric flow rate. The sample temperature was estimated to be the temperature at the interface between the sample package and the tri-axial cell gland wall.

During the course of the testing program none of the variations of these parameters, during the monitoring cycle, proved to be affective to the computed results. An analysis was performed that indicates a fairly high degree of confidence in the computed permeability values reported as they relate to a specific sample. There are several limitations to the application of laboratory permeability value to a seam or series of seams. The most over-riding, however, is that those samples that are able to be tested in this manner tend to be the strongest, most solid, pieces from an individual core. Thus, it stands to reason that the tested specimens are among the lowest permeability regions of a particular seam. The more highly fractured, higher permeability, sections are simply too friable to be tested without total failure of the physical sample.

It is clear, based on the comparison between the baseline samples and the test samples that the principal outcome of the liquid carbon dioxide treatment was the cleaning of the borehole skin. This effect is similar to that used in open cavity well completions, wherein a very high flow rate of gas from the well, either natural or artificial, is used to clear debris from the well bore.

7.2 Results of Propellant Characterization Testing

The goal behind the propellant characterization testing was to establish a mixture of propellants that would be suitable for fracture testing in the anisotropic media. To accomplish this task a special test vessel was designed and fabricated, which provided a constant volume container.

The series of pressure as a function of time tests were conducted using a variety of readily available propellants, as well as black powder. The commercial propellants, all intended for use in standard firearms, proved to be capable of giving pressures exceeding 10000 psi, however, the rise-time to that pressure exceeded the maximum to ensure that the multiple fracture regime was attained. The black powder charges that were tested proved to be capable of providing the necessary rise-time, however, the use of the explosive black powder was not desired for further applications of the tailored pulse approach.

Using the method recommended by Riefler and Lowery (1974) fifteen of the propellant shots were evaluated to determine the linear burn rate parameters.

The work of Cuderman and Northrop (1986) indicate that the necessary pressure rise-time to develop the multiple radial fracture regime is proportional to the borehole diameter. Considering this, it was possible to ascertain that a propellant charge that was too slow in a small diameter wellbore could be of sufficient speed in a larger borehole.

7.3 Results of Numerical Modeling Exercises

The small-scale shots proved to be amenable to the derivation of linear burn rate parameters from the pressure-time data. The lower degree of internal reflection in the small-scale bomb, compared to the large-scale bomb, appears to have had an impact on the ability to determine the burn progress.

7.3.1 Burn Rate Equation and Parameters

The development of the linear burn rate equation parameters was based on the approach of Riefler and Lowery (1974). As these researchers pointed out, the parameters appear to be more appropriate to the individual test on which the derived parameters are based rather than on wide scale general application. There was observed some variation in the coefficients (A) of the linear burn rate equation, the total variation was 6 orders of magnitude. However, some of the variation in the coefficient is accounted for by variation in the index (n), such that the index tends to increase the pressure sensitivity as the constant decreases.

7.3.2 Comparison of Predictions to Laboratory Behavior (Small-scale)

Of the shots that were modeled, the largest discrepancy appears in the mixture of 75% No. 5, 25% No. 8700 propellants, for the closed bomb cases. The numerical results, using individual burn rate parameters, indicate that the shot should exhibit the expected smooth, sigmoidal pressure growth. The laboratory data, however, indicates that the individual shots experience a period of very rapid burning followed by a period of reduced combustion activity. These results are clearly evident in figures 5-24 and 5-25. The shot 5-29-96-B3 (66% No. 5, 34% No. 8700) also exhibits this same behavior, as well as similar modeling results.

Overall, the modeling results are reasonably close to the actual laboratory data in so far as the 10 to 90 percent of the peak pressure is concerned. Thus, in the program of the test conditions used here the pressure rise-time and rise-rates can be predicted to within 30 percent. This is illustrated in figure 5-13 and 5-14. That the variation is less than a factor of 2 between the laboratory and modeled cases suggests that the variation could be worked out through slight modification of the burn rate equation parameters. Figure 5-16 illustrates that the time to peak pressure is far more difficult to predict, this may be due to physical parameters that are not considered in the numerical model. Since the interest is in the rise-time and rise rate the time to peak pressure is of little consequence.

7.4 Observations from Large-scale Tests

The series of large-scale tests was conducted using only charges of 100% No. 5 propellant composition. While this limited comparison between the propellant mixtures the 100% No. 5 charge appears to be most practical to the field application. Furthermore, the scale and loading density behavior appears to be directly applicable to the propellant mixtures tested in the small-scale pressure vessel.

7.4.1 Linear Burn Rates

Based on the linear burn rates computed for the small-scale and large-scale tests there appears to be very little difference in the implications of using one set of parameters over another. Table 6-2 illustrates that, in the tests conducted here, the index n varies inversely to the coefficient A . There appears as though there may be some variation in the burn rate parameters based on the loading density. The smaller of the two large-scale shots (12-18-96-B2) has the third largest coefficient (A) and the larger of the large-scale shots (12-18-96-C1) has the sixth largest coefficient. For these cases the smaller shot had a lower loading density than the associated small-scale shots and the larger shot had a higher loading density. These indications are clearly insufficient evidence to base an empirical conclusion. However, the relationship to loading density appears to be independent of scale, as shown in figure 6-24.

7.4.2 Numerical Modeling Results

An area worthy of some note here is the outcome of the attempts to model the propellant burn with an advancing flame front, both in the axial and radially outward directions of advance. The numerical modeling predictions of the large-scale tests indicate that at sufficiently realistic flame front advance rates, 3000 to 5000 times the linear burn rate (Kuo and Coates 1976), the pressure pulse is practically indistinguishable from that predicted by the instantaneous ignition approach. This is not to say that the peak pressures occur at equivalent times, rather that the pressure rise-time and rise rates between 10 and 90 percent of the peak pressure become identical. This case is clearly illustrated in figure 6-23. The difference between each of the curves illustrated in that figure is the time that is required for the pressure to reach 10% of the peak value.

The traditional approach used by those in the field of interior ballistics is to assume that the entire propellant package is ignited simultaneously (Mayer and Hart 1945; Joglekar, Phadke, and Wu 1973). The comparison between the radially outward and instantaneous ignition conditions lends some validation to the use of the much simpler model, particularly where one is interested in the main pressure pulse of the propellant burn, that is the region between 10 and 90 percent of the peak pressure.

The sample configured for radially outward ignition is an ideal application of the linear ignition source. Where there is a fairly low ratio of charge diameter to length, the charge burn profile is very similar to that of instantaneous ignition of the entire charge. The alternative, a point ignition of the cylindrical charge is not so ideal. Research at the U. S. Army Ballistic Research Laboratory suggests that the a pressure front advancing ahead of the flame front can lead to premature detonation of the propellant charge (Soper 1973). The “premature” ignition appears to be associated with the pressure spike that occurs as the pressure front reflects off of the base of the projectile in the artillery shell. The possibility of detonation of the propellant charge in a wellbore is addressed by Cuderman and Northrop (1986) who attribute the axial ignition design of their propellant to explosion prevention by minimizing the time required for total ignition of the charge.

Chapter 8. Conclusions and Future Work

The research that has been accomplished for the development of this thesis is divided into 2 separate fields. The first involves the use of liquid carbon dioxide injected into and released from the coal as a means to increase formation permeability. The second aspect considers the application of a pressure pulse especially tailored to the coal formation to produce an extensive fracture network. The conclusions based on these research projects are presented in the following sections of this chapter.

The experimental work involving liquid carbon dioxide is separated into two sections within this chapter. Section 8.1 covers conclusions regarding the applicability of the modified permeability measurement method, in which the permeability is measured radially to the cylindrical axis of the sample. Section 8.2 gives the general conclusions regarding the effect of the liquid carbon dioxide treatment on the samples tested. The samples covered in these sections include both coal and sandstone. Sandstone samples were used to provide a general baseline of comparison between permeability measurements made in the conventional (axial) configuration and in the modified (radial) configuration.

Experimental work relevant to the generation of tailored pulses are covered in sections 8.3 and 8.4. The first of these is associated with small-scale propellant shots conducted in a laboratory scale constant volume bomb. These shots were used to evaluate the propellant burn characteristics, in particular the relationship between the propellant linear burn rate and the ambient pressure. Included in this section are brief conclusions made on the numerical model program developed during this research. The later section covers those propellant shots that investigated propellant cartridge burn behavior of shots of the same scale as those that would be applied in actual field test.

Section 8.5 addresses the application and recommended design of a field test of the propellant based well stimulation approach. Finally, section 8.6 presents a few comments for the direction of future research in these fields.

8.1 Radial Permeability Methods

At a very early stage of this research, the recognition that conventional permeability measurement techniques would be inadequate for the coal core samples provided led to the design and development of a custom approach to the radial flow permeability measurement problem. The technique used was based on a conventional Hoek cell method, but with a specially prepared sample. The standard approach using the Hoek cell is illustrated in figure 3-2, the limitation here is that the flow is along the cylindrical axis of the sample. The modified approach is shown in figures 3-7 and 3-8. The basis of this approach is that the central bore of the sample is pressurized with the testing fluid causing flow radially outward to the sand-filled annulus of the sample “package.”

This approach proved adequate for the tests conducted herein. That is to say that the tests conducted on samples configured in this manner appear to be consistent for each sample tested. Using Berea sandstone a series of samples were tested to make a comparison of the results of the conventional and modified approaches. The measured permeability of the conventional samples was consistent, between 5×10^{-14} and $5.5 \times 10^{-14} \text{ m}^2$, for all three of these samples. A higher variability was observed in the pre-treatment permeability of the radial flow samples, ranging between 3.5×10^{-15} and $4 \times 10^{-14} \text{ m}^2$ for the four samples tested. The three conventional samples were obtained from a single core sample, taken parallel to the bedding planes. The four radial flow samples were obtained from a single core sample, taken perpendicular to the bedding planes. Both of these core samples had the same permeability, as reported by the source quarry.

The results of permeability measurements, on the sandstone samples, taken for comparison using the conventional and modified approaches appear to be consistent within an order of magnitude. The main deviation of the modified configuration is associated with two samples, in particular SSRAD1 and SSRAD4, the other two samples exhibit a measured permeability much closer to that of the conventional samples. There are several possible explanations for the deviation associated with the modified permeability measurement approach.

The first, and most obvious, is variability associated with differences in the core itself. This is a valid concern since all three of the conventional samples contained the same bedding planes within the sample. Hence, it is expected that the measured permeabilities would be very similar. On the other hand the radial flow configuration samples are taken across numerous bedding planes, which were not repeated sample to sample. Thus, some variability can be expected in the results, even though the measured permeabilities should be consistent with that reported by the quarry.

The second source of variability within the results is the “skin” effect associated with drilling the central bore hole through the radial flow samples. This effect is the result of damage to the sample as the bore hole used for gas inlet is drilled. The source of the skin, in these samples, can be attributed to drill cuttings pressed into the sample matrix as the hole was drilled and to general break down of the sample in the vicinity of the drill hole. An effort was made during sample

preparation to clear debris from the drill hole prior to permeability testing. However, it was inevitable that some debris would remain within the pore spaces of the sample prior to testing. This was evidenced by presence of fine dust, from the sample, in the test system inlet manifold following liquid carbon dioxide blow down.

Both of these sources of variability appear to cause a decrease in the permeability measured for the sample. With this limiting factor kept in mind, the radial permeability measurement approach developed and presented in this thesis appears to provide consistent measurements within the limits of the type of testing performed. That is to say that the technique is reliable on a sample by sample basis. However, one must bear in mind that the samples that are likely to be used for this method may not be representative of the entire coalbed in question. Therefore, some skepticism must be maintained in reporting the permeability of samples measured in the laboratory compared to those that would be obtained through the application of field methods.

8.2 Liquid Carbon Dioxide Stimulation

Tests to evaluate the effect of injecting liquid carbon dioxide into a sample, and rapidly releasing the pore pressure were conducted on both sandstone and coal samples. The key objective in these tests was to determine if this method of treatment resulted in a significant increase in sample permeability.

The results of this series of tests do show a general increase in the sample permeability. These data are shown, graphically, in figure 3-27. The degree of permeability modification due to an initial treatment of liquid carbon dioxide, on coal samples, varies between a decrease (in one sample) of 75% to an increase of over 200 percent. The three radial flow sandstone samples treated in the same manner exhibited an increase in permeability on the order of 60 to 120 percent. The axial flow samples (Berea sandstone) treated did not show significant change due to treatment.

In consideration of the results, the enhanced permeability that is associated with the liquid carbon dioxide treatment is general in nature. That is, it is not specific to the coal samples. This tends to indicate that the modification of the sample that occurs through the treatment process is one in which the skin effect in the sample bore is reduced. Most likely this occurs through the removal of cuttings and other debris from the wall of the hole, through the sample, used as the gas inlet point. It is not practical, based on these results, to assume that the carbon dioxide has a measurable affect on the physical structure of the coal itself. Due to the adsorptive nature of carbon dioxide to coal, if the changes the coal sample were primarily due to interaction between these two then there should have been a noticeable difference compared to the sandstone specimens.

Two special conditions should be noted here. The first is that one of the coal samples tested, not reported in the above paragraph, became completely impermeable, using the current technique, following the liquid carbon dioxide treatment. Examination of this particular sample showed no peculiar physical anomalies following removal from the test system. Following the realization that the sample had been rendered impermeable a series of pressurization/depressurization cycles were made to observe the differences between using liquid and gas phase carbon dioxide. The general results of these cycles are presented in section 3.3.3. Through these pressurization/depressurization cycles several differences between the two different carbon dioxide phases are evident and are presented were covered in the main text.

The second special consideration to be covered is that two of the coal samples were treated with carbon dioxide a second time. Both of these samples exhibited a loss in permeability, relative to that after the first treatment, following the second treatment. This effect may be due to the higher permeability, in the region of the sample borehole, allowing higher flow rates within the sample. Since the fluid would be moving faster as it is vented from the sample, it could have the opportunity to move debris in from the sand filled annulus of the sample package, or to dislodge debris within the physical sample itself. This may lead to caking within the sample matrix, resulting in the lower measured following the second treatment.

The application of liquid carbon dioxide as a means to affect the near well bore area of actual coalbed wells has already been proposed by other researchers (Puri and Yee 1990). It appears likely that the most applicable area for this type of treatment would be those formations that would also be conducive to open cavity completion methods. The very factors that render the coalbed methane fields in southwest Virginia not amenable to stable cavity completion will tend to minimize potential gain through the application of liquid carbon dioxide treatment. The general basis of the approach presented by the above mentioned researchers, indicates use of an open well completion method, rather than the cased well techniques used in the southwest Virginia region.

As a final note with respect to the injection of liquid carbon dioxide into a coalbed formation the physical properties of carbon dioxide are such that it is unlikely that the carbon dioxide would exist in the liquid phase once it reached the formation. The maximum temperature at which carbon dioxide can exist as a liquid is 31.01 °C (87.8 F) irrespective of the pressure applied. Above this temperature carbon dioxide exists as a super-critical fluid that is neither true liquid nor true gas.

Since the effect of carbon dioxide treatment appears to be of minimal impact to the production of methane gas from the coalbed formations of southwest Virginia no further consideration is given in this thesis.

8.3 Propellant Characterization

To investigate the potential of using solid granular propellants as an energetic material to generate a pressure pulse tailored to the formation of interest a series of laboratory small-scale shots were fired. This series of tests required that a constant volume bomb be designed and fabricated in which to conduct the shots. The bomb is covered, in detail, in section 4.2.2.1 and appendix C of this thesis. The propellant shots that constitute this portion of testing were conducted with the bomb closed and, in some cases with the bomb vented.

8.3.1 Pressure-Time

The basis of the propellant characterization exercise was the development of the pressure-time profiles for small shots conducted in the closed bomb. These curves were obtained for a series of propellants and mixtures of propellants. Typical curves of the pressure as a function of time and the rate of change in pressure as a function of time are illustrated in figures 4-9a and b. These curves are annotated to illustrate the progression of the shot process.

8.3.2 Linear Burn Rate

Using the basic, empirical method suggested by Riefler and Lowery (1975) the linear burn rate parameters were developed from the pressure-time data. The method employed was suggested for spherical granular propellants, hence shots of straight black powder and mixtures including black powder were not evaluated.

General interior ballistic practice employs a power law function for the linear burn rate behavior of the propellant. In this case the linear burn rate is referring to the rate at which the flame front is advancing into an individual propellant grain, not the rate at which the flame front is advancing through the propellant charge. Development of the parameters of this non-linear ambient pressure to burn rate relationship is covered in section 4.4 of this thesis.

For each of the shots, for which linear burn rate parameters were evaluated, a good to excellent fit was obtained between the laboratory data and the estimated values. These evaluations were based on the full burn zone of the combustion process; the burn rates in the ignition and burn-out phases were neglected in this analysis, as suggested by Riefler and Lowery (1974).

8.3.3 Numerical Model Development and Output

The burn rate equations employed by interior ballistics researchers have traditionally assumed that all grains of the propellant charge are ignited simultaneously. There are several factors that attest

to the validity of this approach, the key point being, however, that the ignition wave front through a propellant charge is usually much faster than the burn rate of an individual grain. The ratio of flame front advance through the charge to the linear burn rate of an individual grain can exceed 5000 times. With this in mind, the first approach in the numerical modeling of the charge shots was based on the instantaneous ignition assumption. Refinements of the model were made to allow investigation of the effects of the ignition wave moving axially along a cylindrical charge, as well as radially through a cylindrical charge.

Using the thermodynamic properties for standard military small arms propellants the model accurately, and consistently, predicted the peak pressure output for shots fired in a closed bomb. The results from this comparison are illustrated in figure 5-6. The thermodynamic properties utilized were: the products of combustion covolume, the isochoric flame temperature, the ratio of specific heats, and the gas constant. While the general parameters of the initial air in the bomb were carried in the computations, the effect of the air quickly becomes insignificant during the course of the propellant burn.

The other key output from the numerical model was the pressure versus time data. This data was the primary output from the numerical modeling program. It was this data that could be compared with the laboratory tests to determine how well the model predictions of the bomb time dependent parameters would fit with the physical experiments. Utilizing the linear burn rate equation parameters developed for each shot evaluated model appears to reasonably predict the pressure rise rate and rise times. These parameters are illustrated graphically in figure 4-6 of this thesis. The data is tabulated in table 5-3.

As a whole, the predictions of pressure rise-time and rise-rate were fairly close to the values measured in the laboratory. The observation that the predicted pressure rise-times and rise-rates vary by less than a factor of two from the measured results suggests good agreement between the model and the physical environment. Due to variations in the ignition process, there were much larger variations in the ability to predict the time to reach the peak pressure.

8.4 Laboratory Large-scale Tests

In order to estimate the pressure and time behavior of propellant shots to be fired in actual coalbed methane wells a series of test shots were fired in a large-scale bomb. Unlike the small-scale tests, all of the large-scale tests shots were fired in a vented bomb. The configuration of this vessel is covered in section 6.1.1 and appendix F of this thesis. The coalbed methane wells developed by Pine Mountain Oil and Gas, Inc. are completed with a casing that has a 4.25 inch (0.108 m) nominal inside diameter. For these tests the vessel tube had an inside diameter of 4 inches (0.102 m). Comparison of the small and large-scale laboratory data suggests that the change in scale is relatively insignificant.

8.4.1 Predicted Behavior

Using the propellant linear burn rate data developed from the small-scale shots a series of numerical model exercises were conducted to predict the behavior of the shots in the large-scale vessel. The numerical output of these estimations is shown in figure 6-18. This graph illustrates several of the factors that were expected to be observed. First, that the peak pressure is proportional to the charge mass. Second, that the pressure rise-time is inversely proportional to the charge mass.

The original predictions were based on the instantaneous ignition of all of the propellant model. This ensured that the fastest possible pressure pulse would be predicted. Later modeling was performed using the radial outward staged ignition model. At realistic flame front advance rates, 3000 to 5000 times the linear burn rate (Kuo and Coates 1976), the model predicts pressure rise time estimates similar to those of the instantaneous ignition model with the exception that there is a time off-set during the ignition phase, this is illustrated in figure 6-23. At these flame front advance rates, the radial outward model also predicts the sigmoidal shape observed in the laboratory shots.

8.4.2 Laboratory Behavior

The laboratory large-scale test shots were configured such that the nominal shot would be ignited on a line extending along the cylindrical axis of the charge. The direction of flame front advance would then be radially outward through the propellant pack. This burn profile is suggested by Northrop and Cuderman (1986) to reduce the possibility of a deflagration to detonation transition, the likelihood of which increases as the duration of the burn increases.

Four sets of shots were conducted in the laboratory large-scale bomb. Each of these sets of three shots stepped up in total charge weight from 100, 250, 465 through 694 grams of propellant. The results from the small-scale tests and from the numerical modeling indicated that the most prudent approach was to investigate charges limited to straight Accurate Arms Company No. 5 propellant. Only one of the 694 gram shots was fired, due to failure of the test vessel support system.

Within each of the charge weight groups the pressure rise-time, rise-rate, and peak pressures were consistent. When compared to the numerical predictions the peak pressures, pressure rise-times and rise-rates were also reasonable consistent. As with the small-scale tests the large-scale tests appear temporally delayed. This can be explained in the derivation of the burn rate parameters, which are based on the entire propellant charge burning and does not account for the ignition phase of the burn profile. Fortunately, the time lag does not appear to have an effect on the

pressure rise-rate and rise-time, which along with the peak pressure are the principal factors related to the generation of multiple radial fractures.

8.5 Consideration and Design of Field Test

The main focus of experiments involving propellants in this thesis has been to the evaluation of their properties in the laboratory environment. In order for the laboratory research to be of particular value, there must be a means to transfer what is gained there into the field for practical application. This final section is intended, therefore, to provide the basic means for technology transfer from laboratory to coalbed methane gas wells. Section 4.1 of this thesis addresses the theory behind the development of the multiple fracture regime wherein numerous radial fractures are generated and driven from the wellbore independent of the pre-existing stress field. By tailoring the pressure pulse generated by a propellant based charge it should be possible to increase the productivity of a coalbed methane well by enhancing the communication between the well and the surrounding formation. This is accomplished by the presence of fractures created that extend into the least principal in-situ stress, a fracture orientation not considered to be feasible using conventional hydraulic fracturing. Furthermore, by limiting the pressure rise-rate, of the propellant charge, excessive damage adjacent to the wellbore is prevented during the fracturing process. Treatment of coalbed methane wells in this manner has the potential to enhance the performance of the well by increasing the volume of the gas bearing formation that has high-permeability communication with the well.

The current method of coalbed methane well stimulation provides a reliable means to attain profitable levels of production. Any competition to the current method should be evaluated on the potential merit of the idea, the real enhancement to outcome, or to the actual cost savings for comparable outcome. In other words new approaches need to be rationally considered, rather than blindly accepted because they appear to be novel or exciting.

8.5.1 Field Test Considerations

There are many factors to be considered as relevant to the conduct of a propellant based coalbed methane well stimulation. Those that are generally applicable will be addressed in this section.

The communication between the wellbore and the coalbed formation is an important factor in the stimulation program. In the standard hydraulic fracture approach a number of individual spots are perforated through the casing and casing cement to provide the primary communication paths. The concern with this approach, with regards to the propellant based stimulation, is that the area of contact to the formation as well as the fluid flow paths may be insufficient to effectively transfer the energy pulse into the coalbed. A more desirable approach would be to slot the well casing with eight to ten vertical slots over the extent of the target formation.

Prior to and following stimulation the well permeability should be established utilizing a standard technique for aquifers. The method selected should be consistent with the properties of the region of interest, the selection method is addressed in ASTM D 4043-91 (anon. 1991a).

8.5.2 Pre-existing Well

The use of a pre-existing well presents a less than ideal situation for testing a new stimulation approach. This does not mean, however, that a suitable approach for evaluation cannot be devised. If a pre-existing well, which is currently, or has previously been, in production is used some special considerations should be made.

The well should be reworked to replace the standard perforations through the casing with slots. The use of slots will increase the total communication between the well and the formation at large. In addition, a full pattern of slots around the well will ensure that fractures can develop in “all” directions extending radially away from the bore. Since the slots will have a much larger open area than the perforations currently employed, the pressure drop across them will be significantly less than for the perforations.

Once slotting of the casing has been accomplished the target horizon, for the propellant stimulation, should be isolated and its permeability assessed. This would involve the application of a STEP or slug test to determine the pretreatment permeability of the well. In addition, the gas make of the target horizon should be established. The current methane production method is by reservoir pressure depletion, thus the production may be significantly less than expected from a new well. Determination of the formation permeability and gas make prior to stimulation will provide a baseline of comparison for the stimulation results that cannot realistically be expected to match levels associated with new wells that have not been subject to production.

8.5.3 New Well

The most ideal situation for a test well is one that has not been previously stimulated nor produced. This condition is desired for several reasons: First, a more complete evaluation of the effect related to the propellant based stimulation could be measured since no other well states would be overlaying factors. Second, a water saturated formation would be better to affect a coupling of the charge to the target formation as well as carrying the charge energy into the pre-existing and developing fracture network. Third, the formation water existing in the coal would help in cooling gases produced by the charge, thus minimizing the potential of formation damage due to “cauterization” of the fracture faces. Fourth, by having a full head of water in the well the need for packing above the target horizon may be obviated.

8.5.4 Evaluation of Enhancement

The evaluation of any enhancement process should be conducted in such a means as to allow for a realistic comparison based on statistical proof. The most ideal method of conducting such a program would be to identify a test region containing a statistically significant number of individual wells intended to produce, or producing, from a common seam or formation of seams. The stimulation method of each well would be randomly assigned such that half of the wells were treated by the new method, the remainder by the old method. As each of the wells comes on line the production parameters could be evaluated, on a population basis, for both of well groups. An added note here is that the selection of such a site must minimize the effects of known factors that account for anomalous wells, in particular those that have been identified by the statistical analysis of Holman (1996), i. e. structural high and Jawbone elevation, as well as certain aspects of the initial treatment conditions.

Considering the situation of initial field testing, where the number of wells may not be statistically significant, the evaluation of real gain, or loss, due to the recommended approach presented in this thesis may be a challenge in and of itself. The nature of this task can be approached with respect to the type of well, or wells, provided for evaluation. Separate test program approaches may be needed depending upon whether new or pre-existing wells are used as the basis of the test program. Furthermore, the wells treated using the tailored-pulse approach may be augmented by a conventional hydraulic fracturing treatment following the propellant based stimulation. Table 8-1 lists a few of the differing well characteristics that must be considered in the evaluation of production data taken from the treated wells. Deviation of actual test well conditions from average values of these properties should be indication of the possibility of bias introduced into the test well evaluation.

Table 8-1: Affective Properties of Coalbed Methane Wells (after: Holman 1996)

Rank	Property
1	Jaw Bone seam elevation at well.
2	Well located on a structural high.
3	Well water production.
4	Total amount of nitrogen used in foam fracture treatment.
5	Volume of water injected into well prior to application of proppant.

Two areas are practical for evaluation of the effect associated with a modified stimulation program. The first, and most obvious, is the gas production. Clearly, if the modified stimulation approach results in a significantly higher gas production from the average well, and there are no special considerations, then there is reason to believe that progress has been made. Although there is no specific reason to believe that a higher total gas production over the life of the well will be attained, higher production rates would shorten the pay-back time possibly off-setting any added cost. The second consideration is that of the cost of putting the well into production. If the new stimulation approach does not produce a significant gain in production rates, but can be done at a lower cost the approach may still be a valid and profitable means to well stimulation.

8.5.5 Basic Design of Propellant Charge

The basic design of the propellant charge system suggested for further evaluation is presented in the following paragraphs. While certain assumptions have been made regarding the target horizon for beginning a field test program, it is imprudent to be totally specific in these results so that the approach may remain reasonably general. In this way, the approach and conditions presented can be considered as those parameters that are independent of wells in the intended gas field of southwest Virginia. Application of the system presented here should be individually tailored to the well under consideration, to which the intended seam, and surrounding seams, can be applied.

8.5.5.1 Necessary Rise Time

In designing the propellant charge package, the first task is to determine the appropriate pressure rise-time that is predicted to produce multiple fracturing within the coal target horizon. The relevant properties are listed in table 8-2.

Table 8-2: Propellant Charge Pressure Rise-Time, Basic Parameters.

Parameter	Value
Compressive Wave Velocity (Bit. Coal)	2539 m/s (8333 ft/s) ²⁶
Surface (Raleigh) Wave Velocity, n_s	1270 m/s (4166 ft/sec)
Hole Diameter (d)	0.108 m (0.354 ft)
Minimum Rise Time (Explosive limit) $t_{p,min}$	0.134 milli-second
Maximum Rise Time (Hydraulic limit) $t_{p,max}$	2.14 milli-second
Target Rise Time, $t_{p,target}$	1.20 milli-second

In the above table the Raleigh wave velocity is taken as about one-half of the compressive wave velocity (Kolsky 1963, Cuderman and Northrop 1986). The time limits for t_p are based on the upper ($t_{p,max}$) and lower ($t_{p,min}$) limits of the inequality (Cuderman and Northrop 1986):

$$\frac{p d}{2n_s} < t_p < \frac{8p d}{n_s}.$$

The target rise time ($t_{p,target}$) is based on the average of the framing time limits, with a slight preference to the slower end of the scale. Selection of a slower rise-time is preferable to offset some of the effects associated with the presence of wellbore fluids.

8.5.5.2 Estimated Charge Weight

The work of Nilson, Proffer, and Duff (1985) and Cuderman (1986) suggest that the optimum loading density, in dry holes, is on the order of 500 kg/m³. Considering the results obtained by Fourney, Barker, and Holloway (1986) that the presence of water in the well can amplify the effects by at least a factor of 2, the optimum loading density in a liquid filled hole would be on the order of 250 kg/m³.

8.5.5.3 Charge Layout

The general layout of the charge is definitely limited by the size and shape of the wellbore. Consideration should be given to using the axial ignition system with a radially outward burning profile. Rather than using the black powder igniter system, that was used for the laboratory, the main charge ignition should be accomplished using a PETN based “det-cord” or similar product.

²⁶ Ransom, R. C. (1995) *Practical Formation Evaluation*, John Wiley and Sons, Inc., p. 189.

The suggested design of a system for application is illustrated in figure 8-1. The main features are:

- 1) A charge weight of 2.25 kg per meter of treated length. In a 4.25 inch (0.108 m) inside diameter well casing this results in a loading density of nearly 250 kg propellant per cubic meter of casing volume.
- 2) The propellant mixture suggested, based on the estimations developed in chapter 4 of this thesis, is 66% No. 5 propellant and 34% No. 8700 propellant, both products are from Accurate Arms Company, Inc.
- 3) A det-cord igniter aligned axially down the center of the charge package.
- 4) A PVC tube casing for the charge package, the size of this tube is based on commercially available schedule 80 pipe.
- 5) Initiation of charge package is by means of an electric blasting cap coupled to the det-cord. The blasting cap is energized via an electric timer package. This configuration does not require any type of blasting leads or trunk lines from the surface down to the charge package.
- 6) In cases where the charge cannot be placed at rest in the wellbore, some means of suspension must be provided to hold the charge at the desired depth.
- 7) A head of at least 400 feet of water above the charge package.

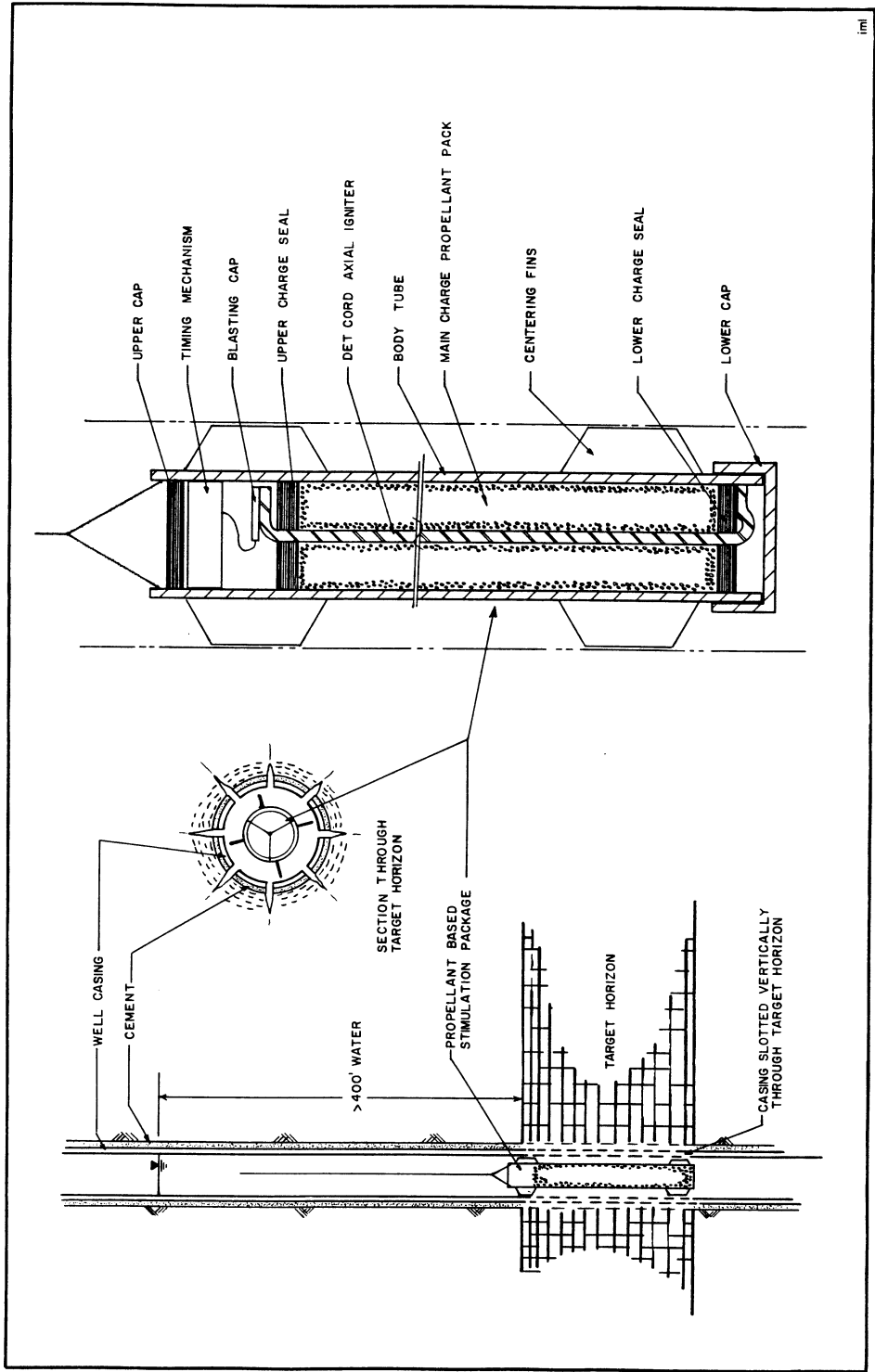


Figure 8-1: Schematic Diagram of Recommended Propellant Based Stimulation Package.

8.6 Future Testing

The research that has been presented thus far has been divided into two primary fields; (a) permeability assessment of samples treated with liquid carbon dioxide, and (b) the development of propellant burn parameters that can be applied to tailored pulse well stimulation in coalbed methane reservoirs. While these efforts have been presented as complete unto themselves, it is inevitable that more questions can be raised following the research than were possible at the beginning. Just a few of the future possibilities are presented in the concluding paragraphs of this thesis.

8.6.1 Radial Permeability

The outcome of the radial permeability measurement approach suggests that there may be the potential for application in a commercial laboratory setting. Due to the relatively simple nature of this experimental technique, it could be applied by virtually any laboratory that currently conducts permeability studies on rock using the axial flow approach in a Hoek cell.

The potential of investigating the permeability of core samples in the planes perpendicular to the core axis in this manner should be the subject of patent protection. As a part of seeking this protection, the technique should be subjected to another round of scrutiny, comparing the results of axial and radial flow cases in similar materials. The testing that was performed as part of the current research was conducted in a BX size (42 mm) Hoek cell. Consideration should be given to utilizing an NX size (54.7 mm) cell. When considering the initial coal samples provided (approximately 50.8 mm) this larger size Hoek cell would require no size reduction of the coal for suitable application. By not having to make size reductions of the sample, assuming that the 50.8 mm size is typical of exploration core, there is a higher probability of finding samples for evaluation, since further trauma to the coal would be minimized.

8.6.2 Propellant Based Stimulation

A key aspect of the research that has been reported in this thesis is that of analyzing, and predicting the behavior of propellant shots fired in an air filled chamber. The results of the small-scale experimental work, numerical estimating, and subsequent large-scale shots suggest that good correlation can be established between the physical and modeled realms. The potential for factors affecting the large-scale, wellbore application, of these results provides a source of continued investigation. Some possible areas for continued research include:

- 1) Application of numerical code, such as that of Sandia National Laboratories (Nilson, Proffer and Duff 1985), which contains the fracture growth element to the field conditions of the coalbed methane fields of southwest Virginia.
- 2) Investigation of the real effect of tailored-pulse fracturing in coalbed reservoirs through “mine back” methods where a well is drilled, treated, produced, and eventually mined out in an active underground coal mine. Such an approach should consider the factors of the shape, direction, and extent of the fracture system around the wellbore. Another aspect to investigate in the mine back is the effect of thermal stress on the coal fracture surfaces during treatment.
- 3) Further laboratory studies to investigate the transfer of energy from the burning charge, through the wellbore liquids and the well casing, outward to the formation should be considered. These could be performed at both a small and large-scale. Consideration should be given to the use, or development, of an off-campus research facility, or test range, for charges much larger than 500 grams.

Chapter 9. Summary

9.1 Introduction

Current estimates predict the presence of some 400 trillion cubic feet of natural gas, principally methane, held in the coalbeds of the United States. Due to the nature of coal, most of this gas is held adsorbed to the surfaces of pores within the coal matrix. Using current technology the recoverable portion of this gas is less than 25 percent (Puri and Yee 1990). In 1990, Schraufnagel, McBane and Kuuskraa (1990) presented what they considered to be the six key challenges facing the coalbed methane industry. This thesis focuses on methods of affecting three of those challenges, namely: measuring coal seam permeability, well completions and stimulations in new settings, and reducing the cost of production.

The work that has been described in this thesis arose out of an effort to enhance the production of methane gas from wells drilled into coal seams in southwest Virginia. Two general approaches were considered. The first was the use liquid carbon dioxide injected into coal seam to affect the structure of the coal matrix, increasing the communication between the micro-pores thus increasing the rate at which the methane can desorb from the matrix. This first approach produced enhanced permeability of the samples, in the laboratory. However, the enhancements do not appear to be specific to the coal, therefore no claim to permeability increase due to alteration of the coal itself can be made.

The second approach taken in this research to increasing the permeability of the coalbed in the vicinity of a production gas well was the application of a “tailored-pulse” technique. This method involves using a specifically designed propellant based charge to develop a pressure pulse capable of extending fractures from the wellbore into the coal formation. Testing of the tailored pulse approach indicated that sufficient control of the propellant burn could be made such that prediction of the multiple fracture regime could be made. By stimulating a gas well in this fracturing range production of gas from coalbed methane wells should be enhanced by increasing communication from the wellbore to the formation in all directions from the well.

9.2 Carbon Dioxide Tests

The investigation into the application of liquid carbon dioxide as a means to stimulate a coalbed methane well was conducted in two basic steps. One set of tests was conducted on coal specimens obtained from wells drilled in southwest Virginia and eastern Kentucky. These tests merely investigated the effect of the prescribed liquid carbon treatment on the radial permeability of the sample to methane gas. A second set of tests were conducted with Berea sandstone wherein the samples were configured, separately, for conventional permeability testing and for the modified radial permeability testing. These tests were conducted to verify the radial permeability testing method that was developed as a part of this research project. The test apparatus used of these experiments is illustrated in figure 9-1.

The use of sandstone samples also provided a baseline for the effects of the liquid carbon dioxide treatment. Ideally, the sandstone should have been reasonably inert to the adsorption of carbon dioxide and methane on the matrix surfaces. Coal on the other hand exhibits a tendency to adsorb methane on the exposed pore surfaces, and more preferentially so to carbon dioxide.

The coal samples obtained for this phase of the research were cores taken during exploration of the coalbeds. This condition presented an obstacle to measuring the permeability of the sample to methane, or any other, gas. The core axis was vertical through the coal seam, a direction in which there would no significant pressure gradient, thus no flow, in the field. It was desired that the permeability be measured in the coalbed horizontal plane. A technique to achieve this objective was developed wherein the sample was encapsulated such that the test fluid could be caused to flow from a central bore, radially through the sample, and be collected for flow rate measurement.

A brief comparison of the radial flow permeability measurement system to that of the conventional method was conducted using Berea sandstone as the sample medium. In this section the samples were selected such that the direction of flow within the sample, while being tested, would be similar. This was done to minimize any anisotropic flow behavior that might have been present in the bedded sandstone samples. Permeability measurements were made on a series of samples in which the Hoek cell permeameter was configured in the conventional manner, with gas flow axially along the cylindrical sample. This provided a baseline measurement of the expected permeability based on a standard practice technique of permeability measurement. Following these measurements, another series of permeability measurements were made with the samples configured so that the gas would flow from a hole drilled axially in the center of the sample radially outwards to a sand packed annular region between the sample and the Hoek cell gland.

The general results of the permeability enhancement tests are illustrated in figure 9-2. This figure shows the pre-treatment and post-treatment permeabilities, plotted on the abscissa ordinate axes respectively, for each sample. An increase in permeability was observed for all but one of the coal samples treated with liquid carbon dioxide. One sample exhibited a loss of permeability following

treatment. The possible explanation for this is based on adsorption of carbon dioxide molecules to the coal restricting the flow of methane through the micro-pore structure of the sample. Two of the samples were treated for a second time, after having been held in a loaded state, following the second treatment both of these samples were measured to have a permeability near to the value prior to the initial treatment. This response may be due to movement of debris from the sand annulus or from within the sample matrix into primary permeability paths by the escaping liquid carbon dioxide. It is presumed due to a higher permeability near the borehole the average speed of the escaping carbon dioxide was faster, allowing for solid material to be moved with the vented liquid/gaseous carbon dioxide.

The axial flow (conventional approach) sandstone samples that were treated with liquid carbon dioxide did not appear to have a significant change in permeability following treatment. The radial flow (modified approach) samples did demonstrate a degree of permeability enhancement following treatment with liquid carbon dioxide. This observation implies that the permeability enhancement observed in the coal samples was due to reduction in the “skin” of the center drilled borehole in the samples, rather than any significant modification of the structure of the coal sample matrix.

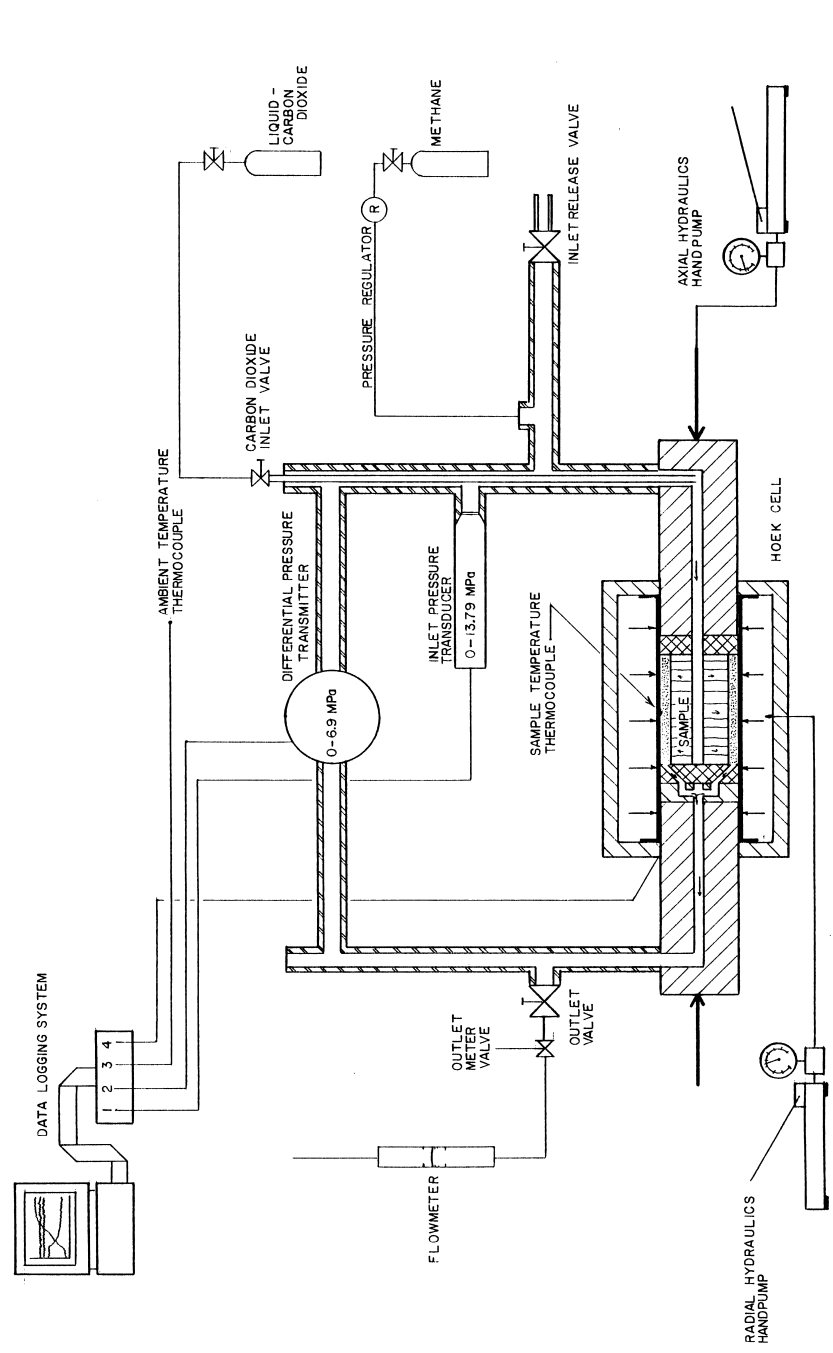


Figure 9-1: Schematic Drawing of Hoek Cell and Ancillary Systems.

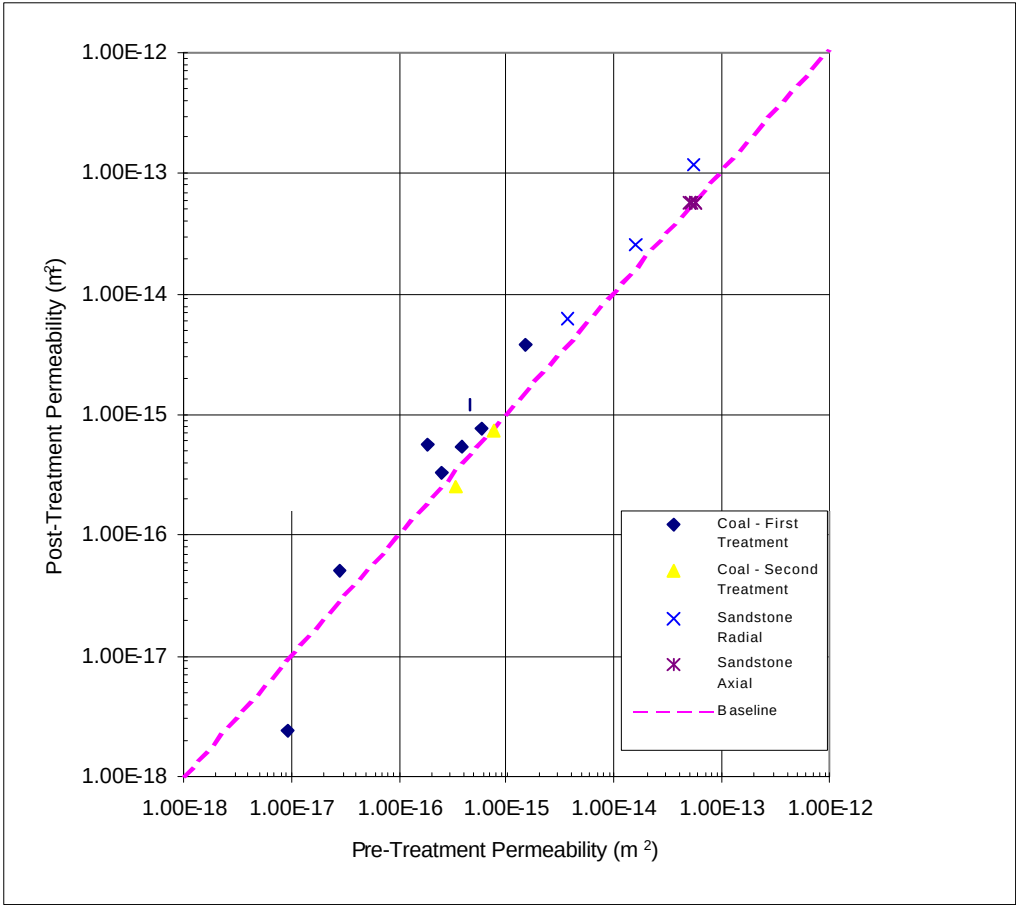


Figure 9-2: Comparison of Pre-treatment and Post-treatment permeability of samples tested.

9.3 Propellant Characterization

For the propellant based “tailored-pulse” fracturing methods it was necessary to determine the burn rate parameters of the selected propellants. Measurement of the propellant burn rate, for several propellants and their combinations, was made in a custom designed and fabricated constant volume bomb. The general configuration of this system is shown in figure 9-3.

In these shots the propellant cartridges were ignited at a single point with the ignition flame front then advancing axially along the propellant pack. Contrary to this real situation, the ideal case, used in internal ballistic calculations, considers that all of the propellant charge is ignited simultaneously. Each individual grain of propellant is assumed to be spherical and that the direction of combustion is normal to the burning surface. The rate at which the flame front is advancing into the propellant grain is referred to as the Linear Burn Rate. This rate is related to the ambient pressure surrounding the burning propellant by a power law relationship, given as:

$$\dot{X} = AP^n$$

where $\dot{X}$ is the linear burn rate, A is the burn rate coefficient, P is the ambient pressure, and n is the burn rate index.

The data collected during each of these shots was limited to the pressure in the vessel with respect to time. During the course of the combustion event the pressure was measured by a piezoelectric pressure transducer coupled to a high speed data logger. This data could then be analyzed to determine the rate at which the propellant would need to be burning to generate the measured pressure pulse. The method suggested by Riefler and Lowery (1974) was used to evaluate the burn rate equation parameters. When the linear burn rate is plotted against the pressure three distinct zones of the shot can be identified. The first is the ignition zone. In this section the flame front is advancing through the propellant pack and is characterized by oscillation in the estimated burn rate. Once the full propellant charge has been ignited the burn rate becomes much more consistent with respect to the ambient pressure. On a log-log plot this condition is ideally observed as a straight line (when the power law index is close to 1 the plot will also appear straight on a linear plot). It is this section of the total plot that is the basis of the power law function parameters. As the propellant charge begins to burn out the “apparent” burn rate with respect to pressure drops off rapidly. A typical set of propellant burn curves developed in this manner are illustrated in figures 9-4a and b.

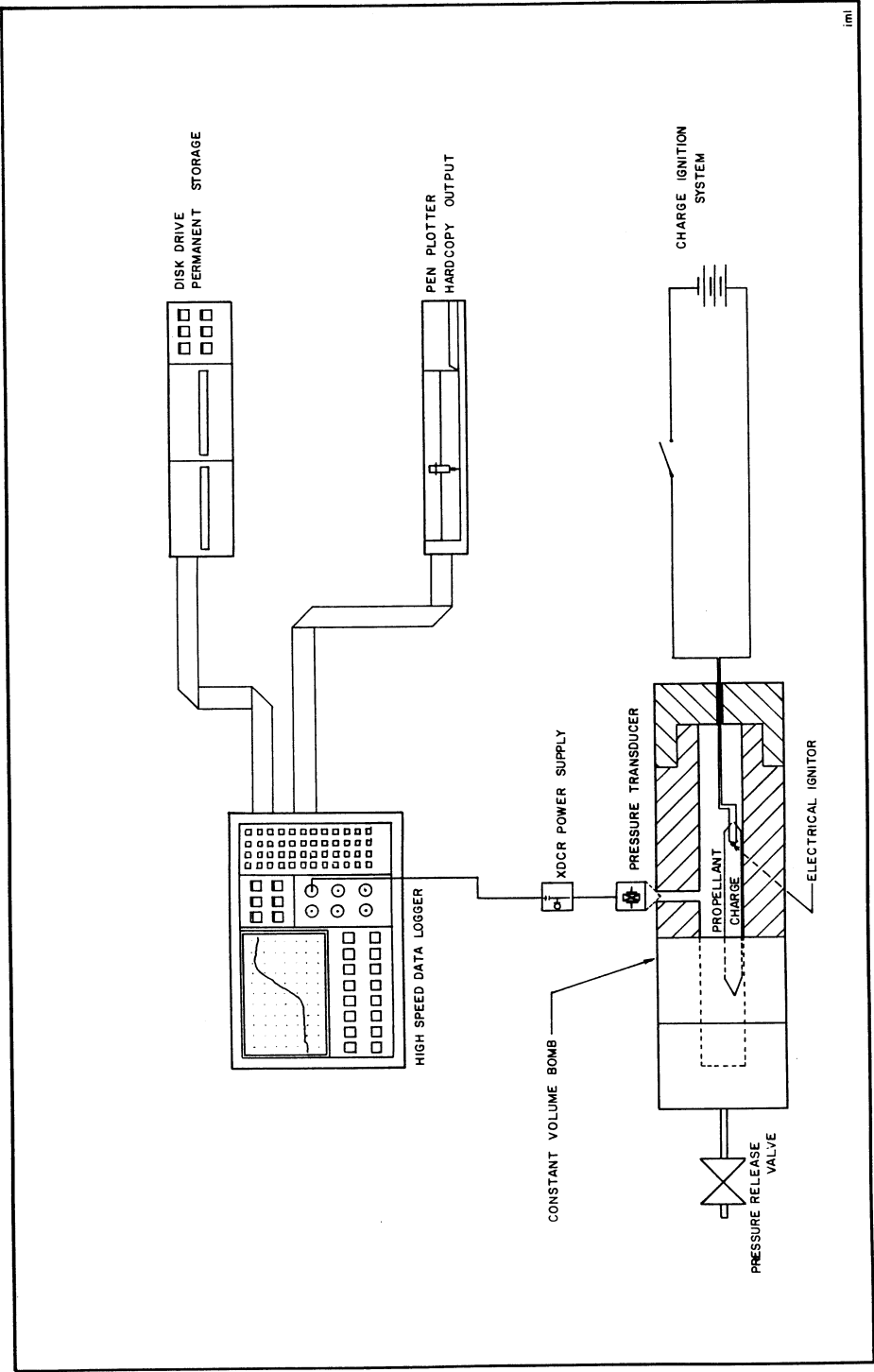


Figure 9-3: General Configuration of Small Bomb Tests

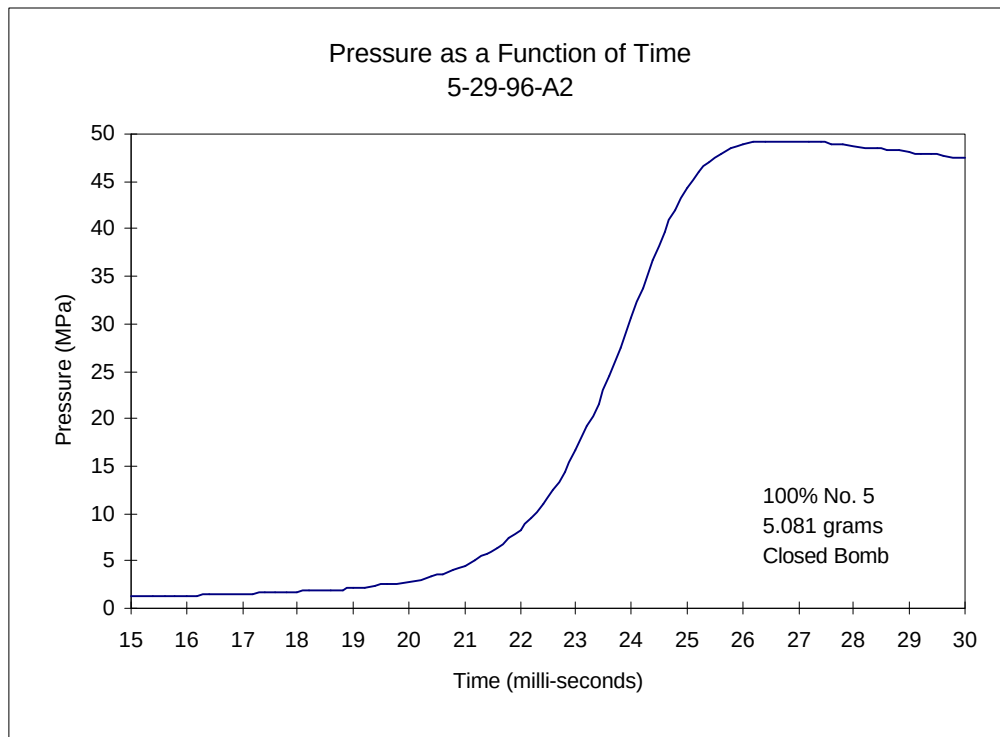


Figure 9-4a: Typical Pressure versus Time Profile for a Small-scale Shot.

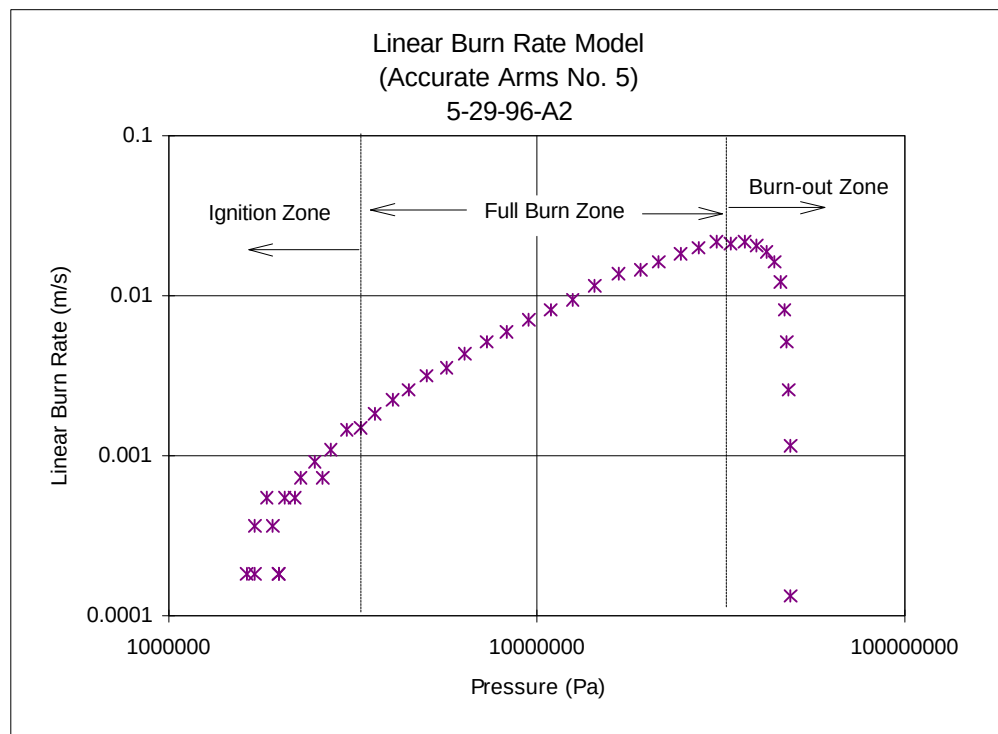


Figure 9-4b: Typical Linear Burn Rate versus Pressure for a Small-scale Shot.

9.4 Numerical Modeling

Using the basic power law linear burn rate equation a numerical model system was developed to predict the propellant burn behavior on larger scale tests. Application of the numerical model was based on the linear burn rate equation expressed above. The numerical model determines the propellant linear burn rate from a list of physical parameters provided by the user. These include the product gas properties, the specific energy released by the propellant during combustion, the propellant grain size, and the linear burn rate parameters. The model consumes the propellant in discrete time steps, estimating the surrounding gas pressure, temperature, specific volume, and amount of propellant remaining. The program assumes that the mass in the system remains constant, that there is no heat transfer from the gases to the bomb, and that there are no condensed products from combustion.

Figure 9-5 illustrates a typical comparison between laboratory data and model output. The model, based on burn parameters developed from the laboratory test, predicts the pressure rise-time, between 10 and 90 percent of the peak pressure, with a factor of two of the laboratory data. This indicates that the model is accurately reproducing the propellant burn in so much as the desired pressure pulse is concerned. The laboratory data is generally delayed in time, with respect to the model output, since the model assumes that the propellant charge is instantaneously and totally ignited.

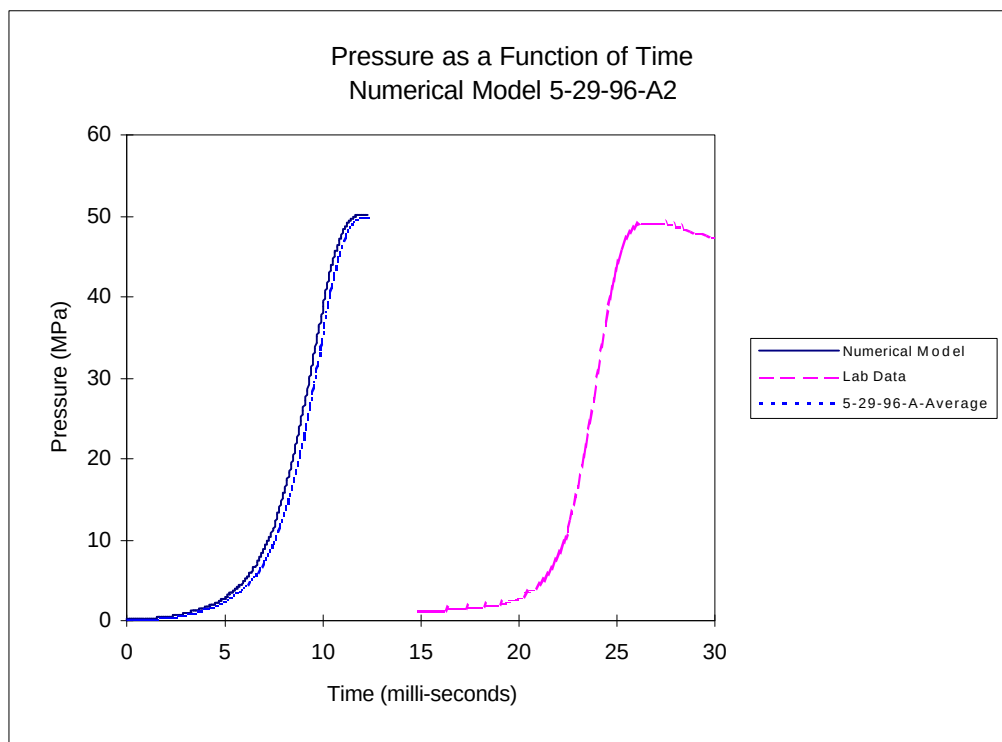


Figure 9-5: Comparison of Physical and Modeled Small-scale Shot.

9.5 Large-scale Tests

A series of large-scale shots were fired to observe the behavior of the propellant cartridges in a setting more appropriate to the actual field conditions. Predictions of the propellant burn behavior were made using the numerical model developed above. The test shots were fired in a vented bomb designed specifically for this experimental series. A typical comparison between the predicted and measured shot pressure-time profiles is illustrated in figure 9-6.

The data logs of two of the large-scale shots, both at different charge weights, proved to be amenable to evaluation of the linear burn rate parameters. In order to obtain the burn rate parameters, the pressure-time profiles must be fairly smooth. Most of the tests in this series were subject to intense echoing within the test vessel. Although this condition did not prevent the determination of the overall pressure versus time profile, it did prevent determination of reasonable burn rate parameters. Figure 9-7 illustrates the linear burn rate as a function of pressure for the data illustrated in figure 9-6. Linear burn rate parameters are attained from the section of the data identified in the “Full Burn Zone.”

The linear burn rate parameters that were derived from the large-scale shot data were consistent with those obtained for the small-scale shots. Based on the loading density the peak pressures measured for the large-scale tests are consistent with those of the small-scale tests. Additionally, considering the loading density, the pressure rise-rate of the small-scale shots are consistent with the observations of the large-scale shots

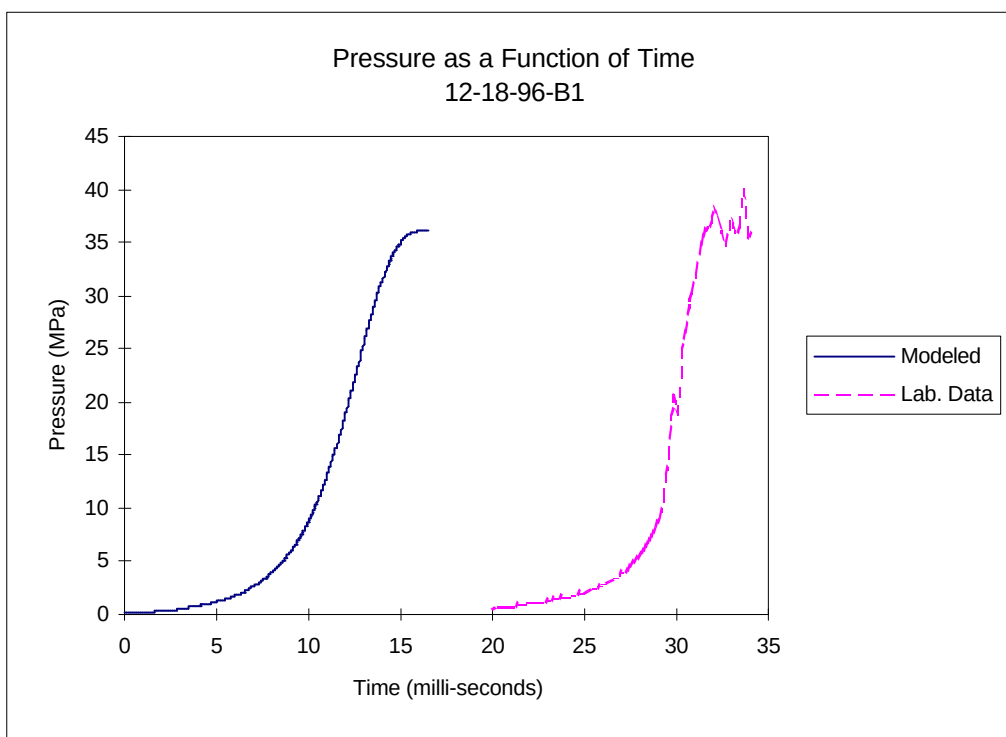


Figure 9-6: Relationship between Predicted and Physical Large-scale Propellant Burn, 250 grams No. 5 propellant, loading density 35.9 kg propellant per cubic meter of chamber.

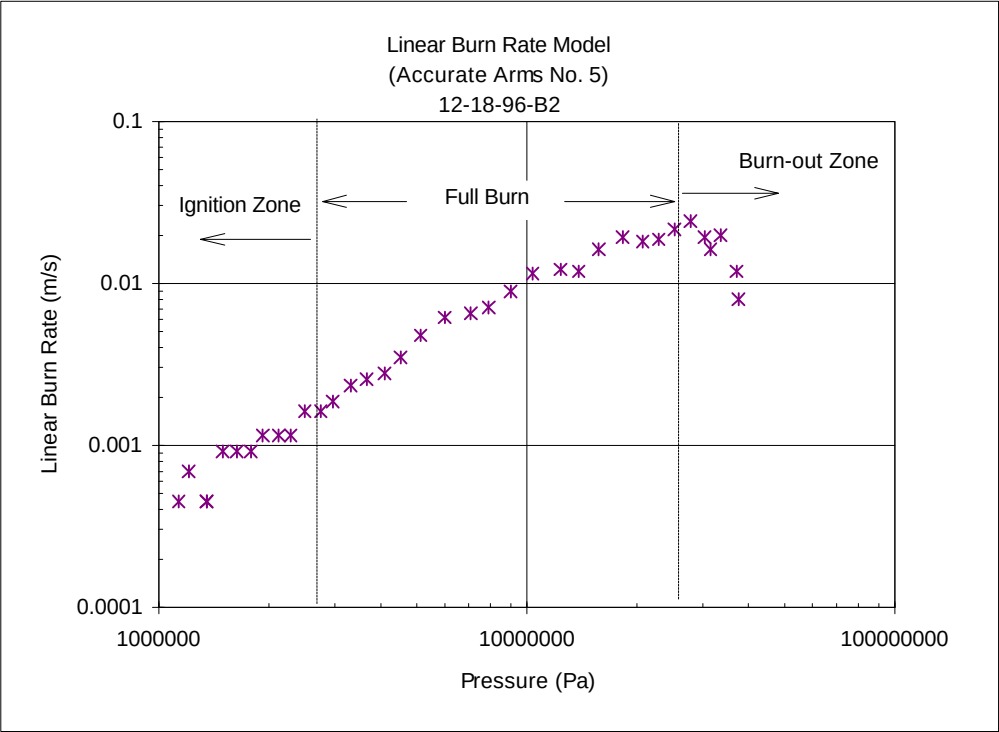


Figure 9-7: Linear Burn Rate as a Function of Pressure, Large-Scale Shot Example.

9.6 Conclusions

9.6.1 Permeability Testing

The method developed during the course of this research project to measure the permeability in planes normal to the cylindrical axis of core samples proved to be suitable for the testing conducted. This conclusion is based on reasonable similarity between the permeabilities of samples measured using a conventional, axial flow approach and the modified, radial flow approach. The total spread of the measurements made was an order of magnitude, however, a majority of the samples were within a factor of 5. Overall the radial samples exhibited a lower permeability than the axial flow samples. This condition is most likely associated with “skin” effects in the drill hole on the cylindrical axis of the sample.

9.6.2 Effect of Liquid Carbon Dioxide Treatment

The liquid carbon dioxide treatment enhance the permeability of over 90 percent of the samples, both coal and sandstone, tested. The enhancement to the permeability of the coal samples was between -75% to over 200%. The same treatment on the radial flow sandstone samples produced permeability enhancements on the order of 60 to 120 percent. The analogous treatment of the axial flow sandstone samples indicated a positive change in permeability, although the effect is arguably negligible. The indication is that the liquid carbon dioxide injection/release treatment affects the borehole skin by clearing out drilling debris, rather than altering the physical structure of the coal matrix.

9.6.3 Small-scale Propellant Characterization

The small-scale propellant characterization effort provided a series of test shots of various commercially available propellants, and mixtures of those propellants. The output from each of the tests was the pressure inside of the constant volume bomb with respect to time. From a series of the individual shots, the linear burn rate equation parameters were reduced using the U. S. Army Ballistic Research Laboratory approach (Riefler and Lowery 1974). The burn rate parameters obtained represent the burn properties of the associated mixtures of propellants evaluated. These parameters, then, account for the applicable mixture of Nitrocellulose/Nitroglycerin and RDX based propellants.

9.6.4 Numerical Modeling of Propellant Burns

All of the propellant shots, for which linear burn rate parameters were obtained, were also evaluated using a numerical model for propellant burns developed during the course of this research. Utilizing the individual shot parameters, the model output of pressure rise-time and rise-rate were within a factor of two compared with the physical data. This indicates that overall the parameters are a good fit to the laboratory data, and that minor adjustments to those values could be made without significantly altering the relationship to that data, if so desired.

9.6.5 Large-scale Propellant Tests

The series of large-scale tests proved to be consistent with the numerical model output using the appropriate scale and propellant parameters. Although these tests were conducted in a vented bomb, rather than a constant volume bomb, the shot data was similar to that predicted for the sealed cases. This can be attributed to the highly restrictive vents used on the large-scale bomb. The most significant difference between the laboratory and model data was for the largest, 694 gram, charge. In this case the actual pressure rise-rate was approximately 5 times that predicted numerically.

9.7 Recommendations

9.7.1 Radial Permeability Test Procedure

The radial permeability test method developed for the earlier research in this project proved to be a valuable technique of assessing gas flow in core samples. The general procedure is reasonably simple to implement and could be a useful tool for commercial testing laboratories. Therefore, some consideration should be given to the future of this approach, further evaluation of the physical means involved in the tests, and development for practical application.

9.7.2 Future Work Involving Propellant Testing

Despite the positive results obtained for propellant burns and prediction of behavior there are still many questions that could be raised regarding propellant burns in water filled boreholes, energy transfer in those holes, and interaction between the pressure pulse and the breakdown of the target formation. Testing and evaluation of these cases, in coal, will require the application of a fairly large-scale program which should include the opportunity to “mine-back” to the wellbore following treatment.

9.7.3 Application of Propellant Stimulation Methods

When application of propellant stimulation methods are considered, for the southwest Virginia region, the conceptual energetic package should exhibit the following properties:

- 1) Pressure rise time (0 - 95 MPa above ambient) between 0.134 and 2.14 milli-seconds.
- 2) A loading density of 250 kg propellant per cubic meter of casing volume, in target horizon.
- 3) A head of at least 120 m (400 ft) of water above the propellant charge package.
- 4) Propellant ignition by means of a det-cord strung axially through the center of the propellant pack.
- 5) A PVC tube container for the charge pack, ignition system, and seals.

Use of this approach to well stimulation has the potential of enhancing gas production by providing more extensive flow paths from the reservoir formation to the wellbore. This improvement arises from the generation of fractures away from the well along paths that are not usually generated during the hydraulic fracture process. That is, fractures driven in the direction of the least principal stress direction.

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Appendix A

Carbon Dioxide Properties

Table A-1: Physical Properties of Carbon Dioxide (Airco R687 A)

Chemical Formula	CO ₂
Molecular Weight	44.01
Specific Gravity (Air = 1; 21°C, 1 Atm.)	1.53
Density	
Liquid - 16.8°C, 2.07 MPa	1015 Kg/m ³
Liquid - 21.1°C, 5.78 MPa	758.5 Kg/m ³
Heat of Vaporization	
Liquid - 16.8°C, 2.07 MPa	277.2 kJ/kg
Liquid - 21.1°C, 5.78 MPa	148.6 kJ/kg
Specific Heat	
Constant Pressure, 1 Atm., 21 °C	465.2 kJ/kg
Constant Volume	248.9 kJ/kg
Viscosity	
Gas: 1 Atm., 21°C	1.5 * 10 ⁻⁵ Ns/m ²
Liquid: -17.7°C	1.4 * 10 ⁻⁴ Ns/m ²
Critical Temperature	31.01°C
Critical Pressure	7.39 MPa
Triple Point Temperature	-56.57°C
Triple Point Pressure	0.518 MPa
Gas Constant R *	0.18892 kJ/kg K
Heat Capacity - Constant Pressure (C _p); 26.85°C *	0.8418 kJ/kg K
Heat Capacity - Constant Volume (C _v); 26.85°C *	0.6529 kJ/kg K
Heat Capacity Ratio (γ); 26.85°C *	1.289

* - Van Wylen and Sonntag (1986), pg. 687

Further information regarding the viscosity of liquid carbon dioxide is given by Reid, Prausnitz, and Poling (1987). They present an equation for viscosity based on temperature, the general form is given as:

$$(\ln \eta)_{SL} = A + \frac{B}{T} + CT + DT^2,$$

with the virial constants for carbon dioxide being given as:

$$A = -3.097 \times 10^0$$

$$B = 4.886 \times 10^1$$

$$C = 2.381 \times 10^{-2}$$

$$D = -7.840 \times 10^{-5}$$

T is the temperature in degrees Kelvin, this equation assumes that the conditions are a saturated liquid at the prevailing pressure, indicated by the $_{SL}$ subscript. These authors also provide a correction for pressure effects on viscosity:

$$\frac{\eta}{\eta_{SL}} = \frac{1 + D(\Delta P_r / 2.118)^A}{1 + CW \Delta P_r}.$$

Where $\Delta P_r = (P - P_r)/P_c$, ω is the acentric factor (0.239 for CO₂), and the coefficients A, D, and C are given as:

$$A = 0.9991 - \left[4.674 \times 10^{-4} / \left(1.0523 T_r^{-0.03877} - 1.0513 \right) \right]$$

$$D = \left[0.3257 / \left(1.0039 - T_r^{2.573} \right)^{0.2906} \right] - 0.2086$$

$$C = -0.07921 + 2.1616 T_r - 13.4040 T_r^2 + 44.1706 T_r^3 - 84.8291 T_r^4 + 96.1209 T_r^5 \\ - 59.8127 T_r^6 + 12.6719 T_r^7$$

The reduced temperature, T_r is obtained as T/T_c . The pressure effect on viscosity is becomes pronounced at high values of T_r .

[illegible]

Table A-3: Thermodynamic Properties of Carbon Dioxide.

CARBON DIOXIDE											
Properties of Saturated Carbon Dioxide (After: Stewart, Jacobson, and Penoncello 1986)											
Temp	Press	Volume		Density		Enthalpy (above 0 C)			Entropy (from 0 C)		
deg K	Mpa	liquid m3/kg	vapor m3/kg	liquid kg/m3	vapor kg/m3	liquid kJ/kg	latent kJ/kg	vapor kJ/kg	liquid kJ/kg K	Evap kJ/kg K	Vapor kJ/kg K
243.2	1.428	0.00093	0.0269	1076.1	37.11	436.78	303.08	739.85	2.869	1.246	4.115
244.3	1.482	0.00093	0.0260	1071.4	38.53	439.01	300.96	739.97	2.878	1.232	4.110
245.4	1.538	0.00094	0.0250	1066.5	40.00	441.27	298.80	740.06	2.888	1.217	4.105
246.5	1.595	0.00094	0.0241	1061.6	41.52	443.54	296.59	740.13	2.897	1.203	4.099
247.6	1.653	0.00095	0.0232	1056.7	43.08	445.82	294.36	740.18	2.906	1.188	4.094
248.7	1.714	0.00095	0.0224	1051.7	44.70	448.13	292.08	740.20	2.915	1.174	4.089
249.8	1.775	0.00096	0.0216	1046.7	46.37	450.43	289.80	740.23	2.924	1.159	4.083
250.9	1.839	0.00096	0.0208	1041.6	48.09	452.76	287.47	740.23	2.933	1.145	4.078
252.0	1.904	0.00096	0.0201	1036.4	49.86	455.11	285.07	740.18	2.942	1.131	4.073
253.2	1.970	0.00097	0.0193	1031.3	51.70	457.45	282.68	740.13	2.951	1.116	4.068
254.3	2.039	0.00097	0.0187	1026.1	53.59	459.83	280.24	740.06	2.961	1.102	4.062
255.4	2.109	0.00098	0.0180	1020.8	55.55	462.20	277.77	739.97	2.970	1.087	4.057
256.5	2.180	0.00098	0.0174	1015.4	57.56	464.60	275.26	739.85	2.979	1.073	4.052
257.6	2.254	0.00099	0.0168	1010.0	59.65	467.01	272.70	739.71	2.988	1.058	4.046
258.7	2.329	0.00100	0.0162	1004.5	61.80	469.46	270.07	739.53	2.997	1.043	4.041
259.8	2.406	0.00100	0.0156	999.0	64.03	471.90	267.44	739.34	3.007	1.029	4.035
260.9	2.485	0.00101	0.0151	993.4	66.33	474.36	264.75	739.11	3.016	1.014	4.030
262.0	2.566	0.00101	0.0146	987.7	68.71	476.83	262.02	738.85	3.025	0.999	4.025
263.2	2.649	0.00102	0.0141	982.0	71.17	479.34	259.23	738.57	3.035	0.985	4.019
264.3	2.734	0.00102	0.0136	976.2	73.71	481.85	256.39	738.25	3.044	0.970	4.014
265.4	2.821	0.00103	0.0131	970.3	76.34	484.39	253.51	737.90	3.053	0.955	4.008
266.5	2.909	0.00104	0.0126	964.3	79.06	486.92	250.60	737.53	3.062	0.940	4.002
267.6	3.000	0.00104	0.0122	958.2	81.87	489.51	247.60	737.11	3.072	0.925	3.997
268.7	3.093	0.00105	0.0118	952.0	84.80	492.11	244.56	736.67	3.081	0.910	3.991
269.8	3.188	0.00106	0.0114	945.8	87.82	494.72	241.46	736.18	3.091	0.894	3.985
270.9	3.285	0.00106	0.0110	939.4	90.96	497.37	238.28	735.64	3.100	0.879	3.979
272.0	3.384	0.00107	0.0106	932.9	94.21	500.02	235.04	735.06	3.110	0.864	3.973
273.2	3.485	0.00108	0.0102	926.3	97.59	502.72	231.74	734.46	3.119	0.848	3.967
274.3	3.588	0.00109	0.0099	919.6	101.10	505.44	228.34	733.78	3.129	0.832	3.961
275.4	3.694	0.00110	0.0095	912.8	104.75	508.18	224.90	733.09	3.139	0.816	3.955
276.5	3.802	0.00110	0.0092	905.7	108.55	510.95	221.37	732.32	3.148	0.800	3.948
277.6	3.913	0.00111	0.0089	898.6	112.51	513.77	217.74	731.50	3.158	0.784	3.942
278.7	4.025	0.00112	0.0086	891.3	116.63	516.60	214.02	730.62	3.168	0.768	3.935
279.8	4.140	0.00113	0.0083	883.8	120.94	519.49	210.20	729.69	3.178	0.751	3.929
280.9	4.258	0.00114	0.0080	876.1	125.44	522.42	206.27	728.69	3.188	0.734	3.922
282.0	4.378	0.00115	0.0077	868.2	130.15	525.40	202.22	727.62	3.198	0.717	3.915
283.2	4.500	0.00116	0.0074	860.1	135.09	528.40	198.06	726.46	3.208	0.699	3.907
284.3	4.626	0.00117	0.0071	851.7	140.27	531.47	193.76	725.22	3.218	0.681	3.900
285.4	4.753	0.00119	0.0069	843.1	145.72	534.58	189.31	723.90	3.229	0.663	3.892
286.5	4.884	0.00120	0.0066	834.3	151.48	537.75	184.73	722.48	3.239	0.645	3.884
287.6	5.017	0.00121	0.0063	825.0	157.56	541.00	179.94	720.94	3.250	0.625	3.876
288.7	5.153	0.00123	0.0061	815.5	164.01	544.31	175.01	719.32	3.261	0.606	3.867
289.8	5.292	0.00124	0.0059	805.5	170.86	547.73	169.80	717.52	3.272	0.586	3.858
290.9	5.434	0.00126	0.0056	795.1	178.18	551.22	164.38	715.59	3.284	0.565	3.849
292.0	5.579	0.00128	0.0054	784.2	186.02	554.80	158.70	713.50	3.295	0.543	3.839
293.2	5.726	0.00129	0.0051	772.7	194.47	558.52	152.68	711.20	3.307	0.521	3.828
294.3	5.877	0.00131	0.0049	760.5	203.64	562.36	146.33	708.69	3.320	0.497	3.817
295.4	6.031	0.00134	0.0047	747.6	213.65	566.38	139.54	705.92	3.333	0.472	3.805
296.5	6.189	0.00136	0.0045	733.7	224.68	570.59	132.23	702.82	3.346	0.446	3.792
297.6	6.349	0.00139	0.0042	718.6	237.00	575.03	124.32	699.36	3.361	0.418	3.778
298.7	6.514	0.00142	0.0040	702.1	250.95	579.78	115.60	695.38	3.376	0.387	3.763
299.8	6.681	0.00146	0.0037	683.6	267.15	584.92	105.86	690.78	3.392	0.353	3.745
300.9	6.853	0.00151	0.0035	662.4	286.51	590.64	94.62	685.26	3.410	0.314	3.725
302.0	7.029	0.00157	0.0032	637.1	310.97	597.20	81.13	678.33	3.431	0.268	3.700
303.2	7.208	0.00165	0.0029	604.7	345.28	605.29	63.45	668.75	3.457	0.209	3.666
304.2	7.384	0.00215	0.0021	466.0	465.96	637.09	0.00	637.09	3.560	0.000	3.560

Appendix B

Patent Abstracts

5,297,420
 APPARATUS AND METHOD FOR MEASURING
 RELATIVE PERMEABILITY AND CAPILLARY
 PRESSURE OF POROUS ROCK
 Ronnie E. Gilliland, New Orleans, La., and Daniel R. Maloney,
 Bartlesville, Okla., assignors to Mobil Oil Corporation, Fair-
 fax, Va.

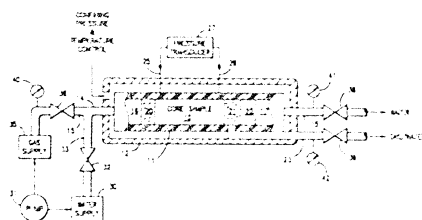
Filed May 19, 1993, Ser. No. 64,390
 Int. Cl.⁷ G01N 15/03

U.S. Cl. 73—38

11 Claims

1. Apparatus for measuring porous rock properties at subter-
 ranean reservoir conditions, comprising

- a) a sleeve containing a core sample of a porous rock satu-
 rated with a first fluid,
- b) a fluid inlet positioned in a first end of said sleeve through
 which a second fluid is injected under pressure into a first
 end of said core sample for displacing said first fluid from
 a second end of said core sample, said second fluid being
 immiscible with said first fluid,
- c) a first member positioned adjacent a second end of said
 core sample within said sleeve and which is permeable to
 said first fluid and impermeable to said second fluid,
- d) a second member positioned between said first member
 and the second end of said core sample which is permeable
 to both said first fluid and said second fluids,
- e) a first fluid outlet positioned in a second end of said sleeve
 through which said first fluid flows from said sleeve after
 having been discharged from the second end of said core
 sample through said first and second members,
- f) a second fluid outlet positioned in said second end of said
 sleeve through which said first and second fluids flow
 from said sleeve after having been discharged from the
 second end of said core sample through said second mem-
 ber,
- g) a first valve positioned in said first fluid outlet for control-
 ling the discharge of said first fluid from said core sample
 through said first and second members,



- h) a second valve positioned in said second fluid outlet for
 controlling the discharge of both said first and second
 fluids from said core sample through said second member,
- i) means for applying a confining pressure through said
 sleeve to said core sample,
- j) a pair of pressure taps contacting the outer surface of said
 core sample at spaced-apart positions along the length of
 the core sample, and
- k) a pressure transducer connected to said pressure taps for
 measuring pressure across said core sample.

Gilliland, R. E. and D. R. Maloney, U.S. Patent 5,297,420, "Apparatus and Method for Measuring Relative Permeability and Capillary Pressure of Porous Rock," *Official Gazette*, United States Department of Commerce.

5,261,267

METHOD AND APPARATUS FOR ROCK PROPERTY
DETERMINATION USING PRESSURE TRANSIENT
TECHNIQUES AND VARIABLE VOLUME VESSELS

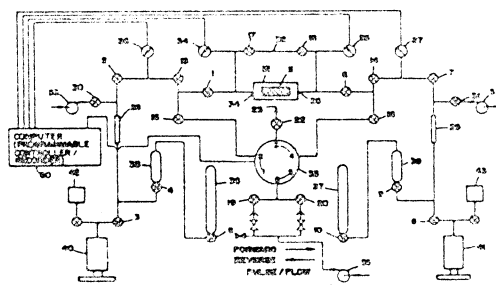
Jairam Kamath, Redondo Beach; Russ E. Boyer, and Frank M.
Nakagawa, both of Fullerton, all of Calif., assignors to Che-
vron Research and Technology Company, San Francisco, Calif.

Filed Sep. 29, 1991, Ser. No. 763,082

Int. Cl.⁵ G01N 15/08

U.S. Cl. 73—39

24 Claims

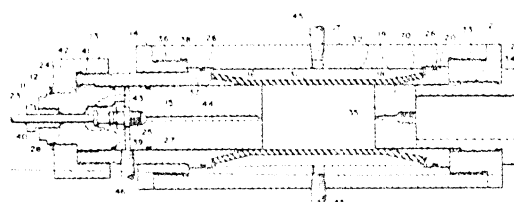


1. A method of determining properties of a core sample, comprising the steps of:

- (a) applying a predetermined upstream pressure to a first closed vessel in fluid communication with the upstream end of a core sample, said upstream pressure being greater than a predetermined system pressure existing in said core sample and the downstream pressure of a second closed vessel to which the downstream end of said core sample exits, one of said closed vessels having a β ratio sufficiently high to cause a measurable variance between an actual pressure transient response for the system and a theoretical pressure transient response for said system;
- (b) allowing said upstream pressure to dissipate into said downstream end of said core sample;
- (c) measuring the pressure at a preselected end of said core sample at predetermined time intervals during said dissipation of said upstream pressure; and
- (d) analyzing said variance to detect non-homogenous rock properties of said core sample.

Kamath, J., R. E. Boyer, and F. M. Nakagawa, U.S. Patent 5,261,267, "Method and Apparatus for Rock Property Determination Using Pressure Transient Techniques and Variable Volume Vessels," *Official Gazette*, United States Department of Commerce, Vol. 1156, November 16, 1993.

4,599,891
TCH--TRI-AXIAL CORE HOLDER
 Paul R. Brauer, Tulsa; Thomas J. Barnickel, and Gary C. Mast,
 both of Broken Arrow, all of Okla., assignors to Temco, Inc.,
 Tulsa, Okla.
 Filed Jun. 7, 1984, Ser. No. 618,039
 Int. Cl.³ G01N 15/08
 U.S. Cl. 73—38 6 Claims



1. A tri-axial core holder comprising:
 a hollow housing;
 a resilient sleeve within said housing;
 first means closing one end of said sleeve;
 second means closing the other end of such sleeve and movable therein;
 first pressure means for applying radial pressure on said sleeve;
 second pressure means for applying pressure on said second means in a direction of the longitudinal axis of said sleeve independently of the radial pressure on said sleeve;
 fluid passages through said first and second means including concentric tubings so that fluid can be inserted through the smaller of such concentric tubings and returned through the annulus between the tubings, two different fluids can be inserted simultaneously or pressure can be monitored at the face of the core when inserted.

Brauer, P. R., T. J. Barnickel, and G. C. Mast, U.S. Patent 4,599,891, "TCH - Tri-Axial Core Holder," *Official Gazette*, United States Department of Commerce, July 15, 1986.

4,555,934

METHOD AND APPARATUS FOR NONSTEADY STATE TESTING OF PERMEABILITY

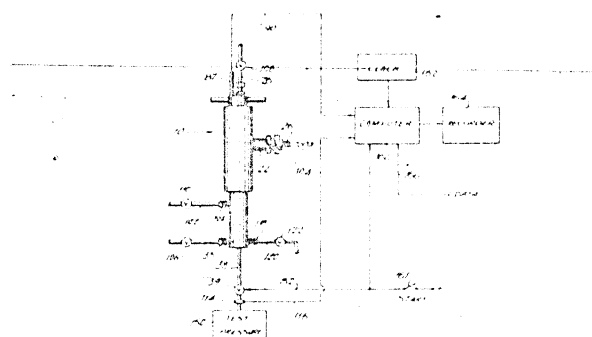
David L. Freeman, Garland, and Darrell C. Bush, Colleyville, both of Tex., assignors to Core Laboratories, Inc., Dallas, Tex.

Filed Sep. 29, 1982, Ser. No. 426,798

Int. Cl.⁴ G01N 15/08

U.S. Cl. 73—38

20 Claims



18. Apparatus for use in measuring the permeability of a core sample, comprising a core sample holder having an internal chamber for containing said core sample; a source of constant, predetermined confining pressure; means for supplying said confining pressure to said internal chamber; a source of predetermined test pressure substantially less than said confining pressure; a first channel communicating between said source of test pressure and said internal chamber for supplying said test pressure to an upstream end of said core sample; a second channel communicating with a downstream end of said core sample in said internal chamber and comprising at least a portion of a fixed closed volume; pressure transducer means disposed in said closed volume for producing electrical pressure signals representing the downstream pressure of said core sample; time sampling means for producing time samples, representing the passage of time; valve means coupled between said source of test pressure and said first channel and operative to apply said test pressure to said first channel; means for initiating said time sampling means when said valve means commences operation; means coupled to said pressure transducer means for detecting when the downstream pressure reaches a predetermined proportion of said test pressure; means for selecting a portion of the electrical pressure signals and time samples produced prior to said downstream pressure reaching said predetermined proportion; and means for determining the permeability of said core samples as a function of said selected electrical pressure signals and time samples.

Freeman, D. L., and D. C. Bush, U.S. Patent 4,555,934, "Method and Apparatus for Nonsteady State Testing of Permeability," *Official Gazette*, United States Department of Commerce, December 3, 1985.

5,332,036

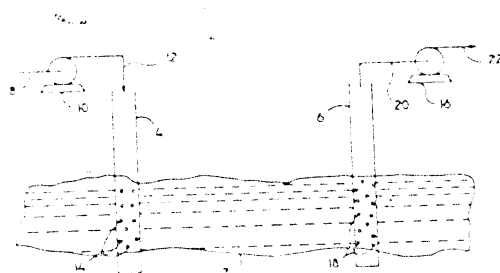
METHOD OF RECOVERY OF NATURAL GASES FROM
UNDERGROUND COAL FORMATIONSArthur I. Shirley, Piscataway, and Ramakrishnam Ramachan-
dran, Allendale, both of N.J., assignors to The BOC Group,
Inc., Murray Hill, N.J.Continuation-in-part of Ser. No. 883,504, May 15, 1992,
abandoned. This application Dec. 4, 1992, Ser. No. 986,842
Int. Cl. E21B 43/00

U.S. Cl. 166—268

12 Claims

1. A process for recovering an adsorbed fuel gas from an
underground deposit comprising:

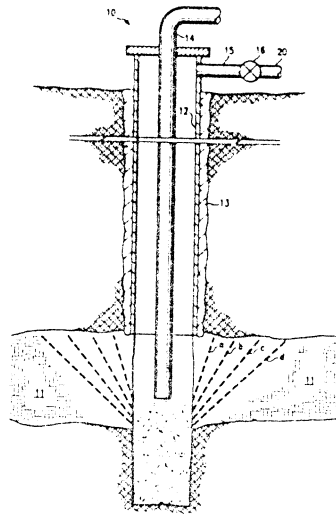
- (a) injecting a first stream comprising as major components
one or more strongly adsorbable fluids into said deposit;
- (b) injecting a second stream comprising one or more
weakly adsorbable gases into said deposit, thereby causing
said one or more strongly adsorbable components to flow



- through said deposit and desorb said fuel gas therefrom;
and
- (c) withdrawing said fuel gas from said deposit

Shirley, A. I., and R. Ramachandran, U.S. Patent 5,332,036, "Method of Recovery of Natural Gases from Underground Coal Formations," *Official Gazette*, United States Department of Commerce, Vol. 1164, July 26, 1994.

5,147,111
**CAVITY INDUCED STIMULATION METHOD OF COAL
 DEGASIFICATION WELLS**
 Carl T. Montgomery, Plano, Tex., assignor to Atlantic Richfield
 Company, Los Angeles, Calif.
 Filed Aug. 2, 1991, Ser. No. 739,939
 Int. Cl.⁵ E21B 43/26; E21C 37/14
 U.S. Cl. 299—16 7 Claims



1. A cavity induced stimulation method for improving the production of fluids from a subterranean coal seam, said method comprising:

- drilling a wellbore to a point substantially at the top of the coal seam;
- casing said wellbore;
- drilling below the cased wellbore to extend the wellbore into said coal seam;
- lowering a tubing into the wellbore to a point adjacent the wellbore; said tubing forming an annulus with the wall of the wellbore;
- flowing liquid CO₂ down said tubing while maintaining a backpressure on said annulus at about the critical temperature of liquid CO₂ until the tubing has been cooled by the liquid CO₂ to the critical temperature of liquid CO₂ and is then increased to from about 1500 psia to 2000 psia;
- displacing said liquid CO₂ into said coal seam;
- shutting in the wellbore and allowing the pressure to build on the coal seam; and
- releasing said pressure quickly to thereby cause at least a portion of the coal seam to fail and fragment into coal particles in said wellbore.

Montgomery, C. T., U.S. Patent 5,147,111, "Cavity Induced Stimulation of Coal Degasification Wells," *Official Gazette*, United States Department of Commerce, Vol. 1142, September 15, 1992

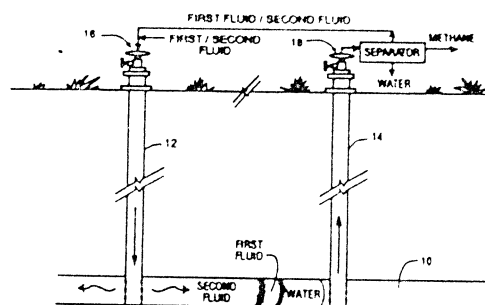
5,099,921
**RECOVERY OF METHANE FROM SOLID
 CARBONACEOUS SUBTERRANEAN FORMATIONS**
 Rajen Puri; Dan Yee, and Robert S. Metcalfe, all of Tulsa,
 Okla., assignors to Amoco Corporation, Chicago, Ill.
 Filed Feb. 11, 1991, Ser. No. 653,826
 Int. Cl.⁵ E21B 43/16, 43/24, 43/40

U.S. Cl. 166—266

14 Claims

1. A method of recovering methane from a solid carbonaceous subterranean formation, penetrated by at least one injection well and at least one production well, the method comprising:

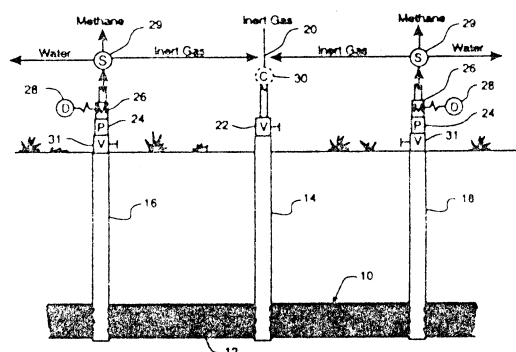
- (a) injecting a first fluid that desorbs methane into the subterranean formation through at least one injection well;
- (b) injecting a second fluid that desorbs methane into the subterranean formation through at least one injection well, the second fluid having a desorbing efficiency less a desorbing efficiency of the first fluid; and



- (c) recovering methane through the at least one production well.

Puri, R., D. Yee, and R. S. Metcalfe, U.S. Patent 5,099,921, "Recovery of Methane from Solid Carbonaceous Subterranean Formations," *Official Gazette*, United States Department of Commerce, Vol. 1136, March 31, 1992.

5,085,274
**RECOVERY OF METHANE FROM SOLID
 CARBONACEOUS SUBTERRANEAN OF FORMATIONS**
 Rajen Puri, and Dan Yee, both of Tulsa, Okla., assignors to
 Amoco Corporation, Chicago, Ill.
 Filed Feb. 11, 1991, Ser. No. 653,827
 Int. Cl.⁵ E21B 43/16, 43/40
 U.S. Cl. 166—252 20 Claims



1. A method of recovering methane from a solid carbonaceous subterranean formation penetrated by an injection well and first and second production wells, the method comprising the steps of:

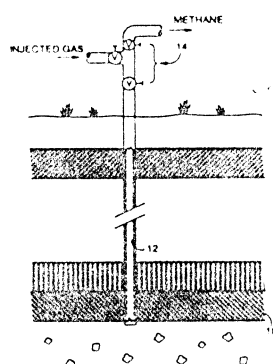
- (a) injecting a gas that desorbs methane into the subterranean formation through the injection well in a manner to cause methane to be desorbed and move towards first and second production wells;
- (b) monitoring a ratio of injected desorbing gas-to-methane recovered from the first and the second production wells; and
- (c) restricting a flow of recovered fluids from the first or the second production well with the highest monitored ratio.

16. A method of recovering methane from a solid carbonaceous subterranean formation having a first layer and a second layer, both layers being penetrated by an injection well and one or more production wells, the method comprising the steps of:

- (a) injecting a gas that desorbs methane through the injection well into the first layer and the second layer of the subterranean formation;
- (b) monitoring a rate of recovery of injected desorbing gas for the first and second layers of the subterranean formation; and
- (c) restricting a flow of recovered fluids from the first or second layer with the highest monitored recovery rate of injected desorbing gas.

Puri, R., and D. Yee, U.S. Patent 5,085,274, "Recovery of Methane from Solid Carbonaceous Subterranean Formations," *Official Gazette*, United States Department of Commerce, Vol. 1135, February 4, 1992.

5,014,788
METHOD OF INCREASING THE PERMEABILITY OF A
COAL SEAM
Rajen Puri; Dan Yee; Thomas S. Buxton, all of Tulsa, Okla., and
Om Majahan, Wheaton, Ill., assignors to Amoco Corporation,
Chicago, Ill.
 Filed Apr. 20, 1990, Ser. No. 511,497
 Int. Cl.⁵ E21B 43/25, 43/26, 43/27
 U.S. Cl. 166—308 31 Claims



1. A method of increasing the rate of methane production from a subterranean coal seam penetrated by a wellbore, the method comprising:

- (a) introducing fluid that causes coal to swell into the subterranean coal seam through the wellbore at a pressure above ambient reservoir pressure at the wellbore and below a fracture pressure of the coal seam;
- (b) maintaining the injected fluid in the coal seam in a pressurized condition so that the fluid will contact the coal seam; and
- (c) relieving the pressure within the coal seam by permitting the fluid to flow out from the wellbore prior to the pressure within the coal seam decreasing to a stabilized pressure.

Puri, R., D. Yee, and T. S. Buxton, U.S. Patent 5,014,788, "Method of Increasing the Permeability of a Coal Seam," *Official Gazette*, United States Department of Commerce, Vol. 1126, May 14, 1991.

4,544,037
 INITIATING PRODUCTION OF METHANE FROM WET
 COAL BEDS

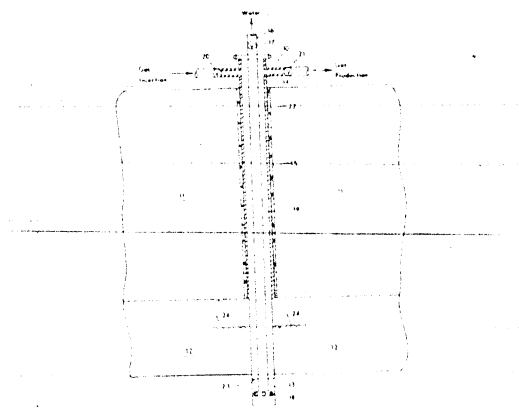
Ruel C. Terry, Denver, Colo., assignor to In Situ Technology,
 Inc., Golden, Colo.

Filed Feb. 21, 1984, Ser. No. 581,733
 Int. Cl.⁴ E21B 43/25

U.S. Cl. 166—369 7 Claims

1. A method of producing methane from a gassy underground coal seam that also is an aquifer, wherein the aquifer contains hydraulic head that impedes free flow of methane from the fracture system within the coal and free flow of the methane contained within the pore system of the coal, comprising the steps of:

drilling a well from the surface of the earth into the underground coal, the well being cased with casing cemented in place, and the well having means to permit injection of fluids into the underground coal, means to withdraw fluids from the underground coal, and means to terminate



injection of fluids into and withdrawal of fluids from the underground coal,
 injecting a gas into the well and into the coal under sufficient pressure to displace water from the coal within the vicinity of the wellbore,
 terminating injection of the gas, then
 opening the well to the flow of fluids and producing first the injected gas, followed by producing a mixture of the injected gas and methane, and then by producing methane.

Terry, R. C., U. S. Patent 4,544,037, "Initiating Production of Methane from Wet Coal Beds," *Official Gazette*, United States Department of Commerce, Vol. 1059, October 1, 1985.

4,305,464

METHOD FOR RECOVERING METHANE FROM COAL SEAMS

Denes G. Masszi, Calgary, Canada, assignor to Algas Resources Ltd., Calgary, Canada

Filed Mar. 7, 1980, Ser. No. 128,469

Claims priority, application United Kingdom, Oct. 19, 1979, 36634/79

Int. Cl.³ E21B 43/26, 43/263

U.S. Cl. 166—370 9 Claims

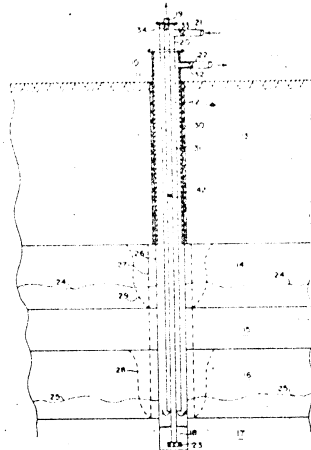
1. A process for recovering from an underground coal seam methane gas which occurs in adsorbed form in said coal seam, said process comprising providing a borehole which extends from the surface of the earth underground through overburden to a terminal point, providing at said terminal point an underground cavity at least partly in or immediately adjacent to said coal seam, said cavity being located such that the pressure of said overburden is greater than the crushing strength of said cavity, said cavity having a radius at least five times the radius of said borehole at said terminal point, said cavity being unsupported, non-self-protecting and, hence, collapsible and constructed and arranged such that under the influence of triaxial compression coal from said coal seam will move toward and into said cavity, thereby fracturing and converting methane gas adsorbed in the coal into methane gas in free form, and recovering said free form methane gas from said cavity via said borehole.

Masszi, D. G., U.S. Patent 4,305,464, "Method for Recovering Methane from Coal Seams," *Official Gazette*, United States Department of Commerce, Vol. 1013, December 15, 1981.

4,089,374
PRODUCING METHANE FROM COAL IN SITU
 Ruel C. Terry, Denver, Colo., assignor to In Situ Technology,
 Inc., Denver, Colo.
 Filed Dec. 16, 1976, Ser. No. 751,135
 Int. Cl.² E21B 43/24, 43/26

U.S. Cl. 166—259 12 Claims

1. A method of withdrawing methane from an underground coal deposit comprising the steps of establishing a first communication passage between the surface of the earth and an underground coal deposit, setting a casing in the said first communication passage, establishing a hermetic seal between the surface of the earth and the underground coal deposit, establishing three conduit means within the said first communication passage, the first of the said three conduit means being the annulus between the said casing and a tubing installed within the said casing, the second of the said three conduit means being the annulus between the said tubing and a pipe installed within the said tubing, and the third of the said three conduit means being the conduit within the said pipe, establishing a fracture radially outward from the said communication passage and into the said underground coal deposit,



deepening the said first communication passage through the lowermost portion of the said underground coal deposit and into the underburden to form a sump, installing pump means in fluid communication with the said pipe, positioning the said pump means within the said sump, removing accumulated liquids from the said first communication passage through the said third conduit means and delivering the said liquids to the surface of the earth, and withdrawing methane from the said underground coal deposit through the said first conduit means.

Terry, R. C., U.S. Patent 4,089,374, "Producing Methane from Coal In Situ," *Official Gazette*, United States Department of Commerce, Vol. 970, May 16, 1978.

4,043,395

METHOD FOR REMOVING METHANE FROM COAL
 Richard L. Every, Warrington, Pa., and Luino Dell'Osec, Jr.,
 Washington, D.C., assignors to Continental Oil Company,
 Ponca City, Okla.

Continuation-in-part of Ser. No. 558,099, March 13, 1975,
 abandoned, which is a continuation-in-part of Ser. No. 252,072,
 May 10, 1972, abandoned. This application June 7, 1976, Ser.
 No. 693,561

Int. Cl.² E21B 43/00

U.S. Cl. 166—263

5 Claims

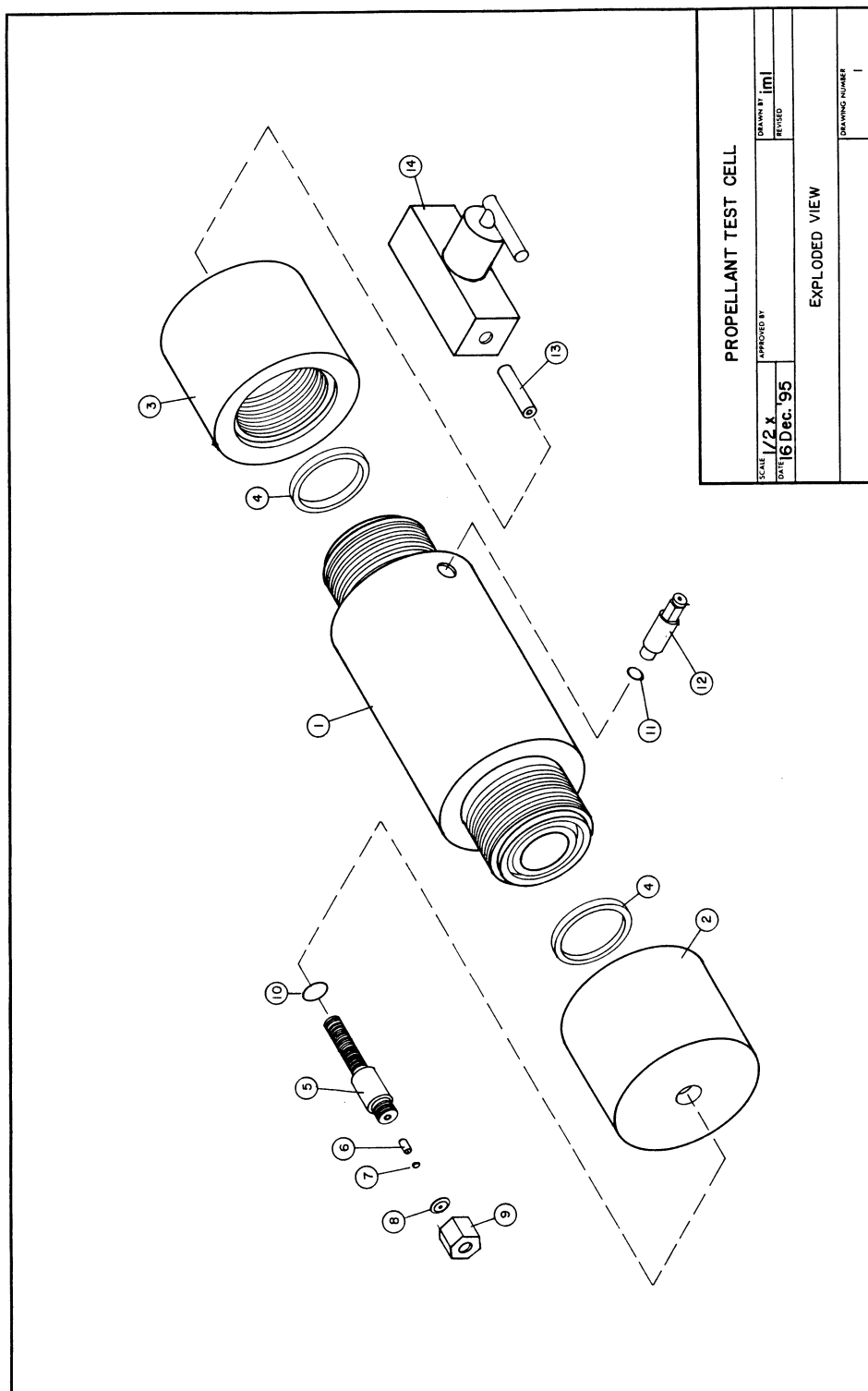
1. A process for removing methane from a subterranean coal
 deposit comprising:

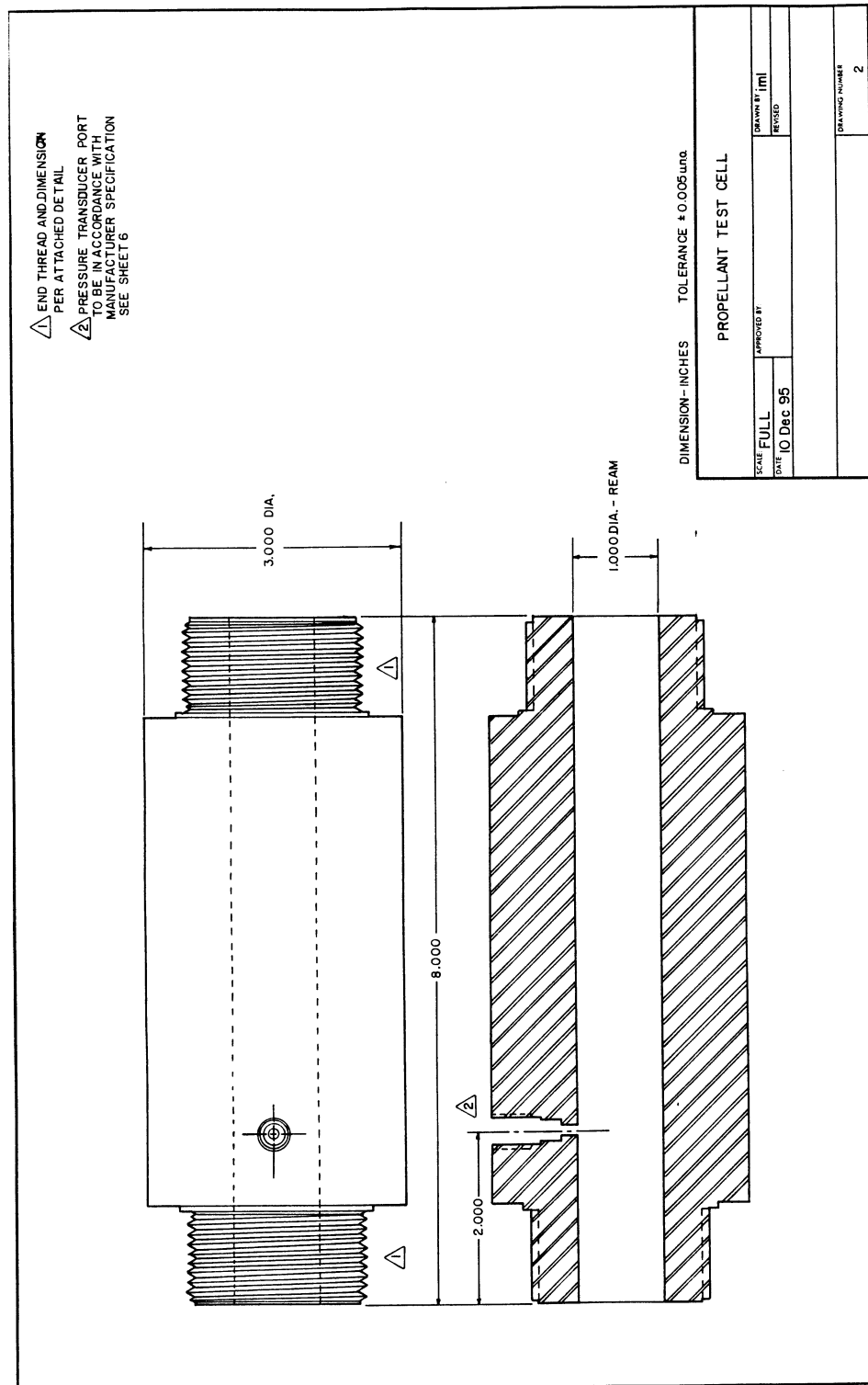
- a. providing at least one injection well and at least one re-
 covery well spaced therefrom, said wells extending from
 the surface to said coal deposit;
- b. pressurizing said coal deposit by injecting a gaseous fluid
 containing at least about 20 percent by weight carbon
 dioxide through said injection well at a pressure not ex-
 ceeding the cracking pressure of said deposit into said coal
 deposit while maintaining said recovery well closed;
- c. stopping said injection and maintaining said deposit in a
 pressurized condition for a period of time sufficient to
 enable a substantial amount of methane which is adsorbed
 on said coal deposit to be desorbed therefrom;
- d. opening said recovery well after step (c) to recover in-
 jected fluid and desorbed methane from said coal deposit;
- e. closing said recovery well after step (d); and
- f. repeating steps (b) through (e) until enough methane has
 been removed from said coal deposit to enable the deposit
 to be worked safely.

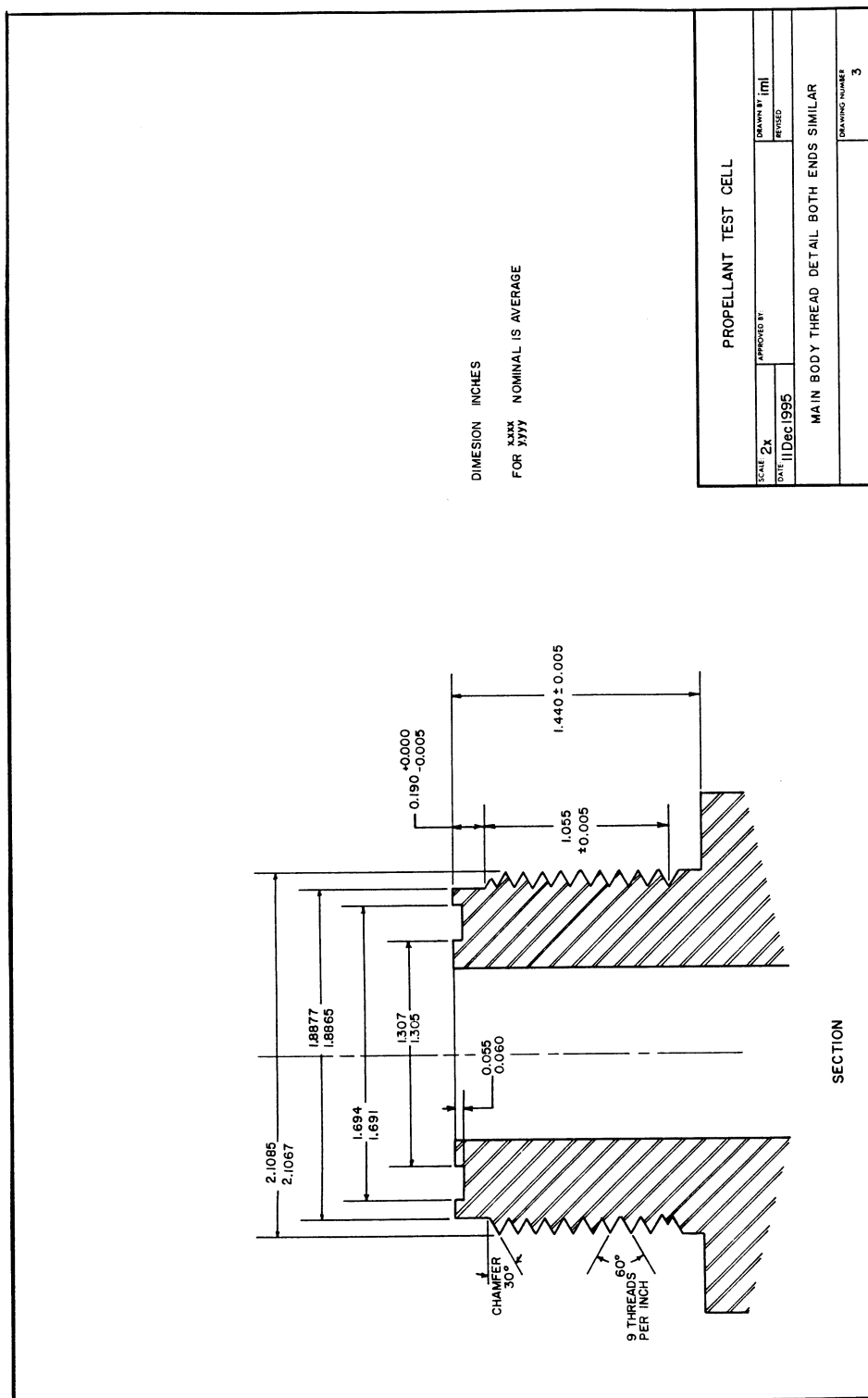
Every, R. L., and L. Dell'Osec, Jr., U.S. Patent 4,043,395, "Method for Removing Methane from Coal," *Official Gazette*, United States Department of Commerce, Vol. 961, August 23, 1977.

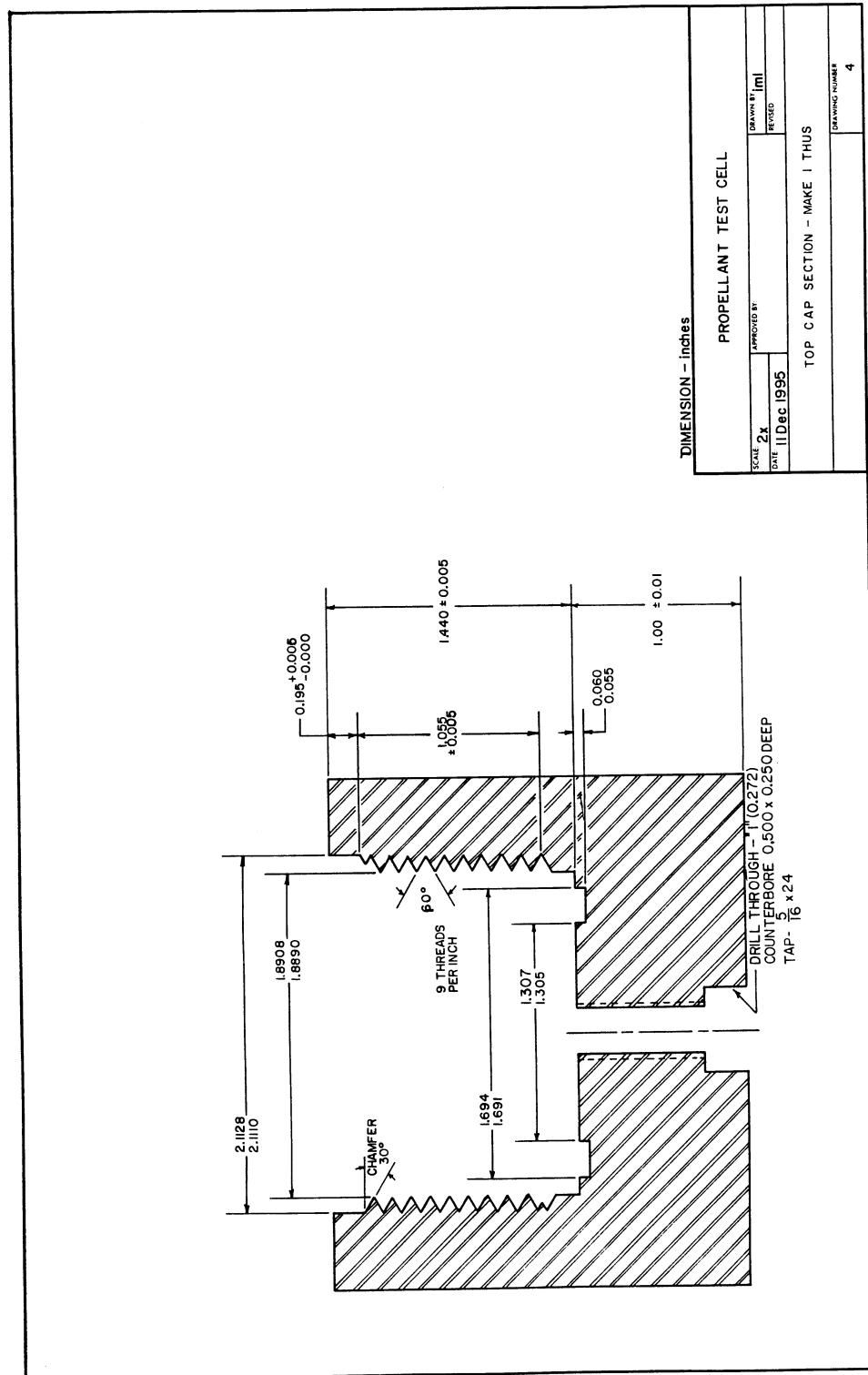
Appendix C

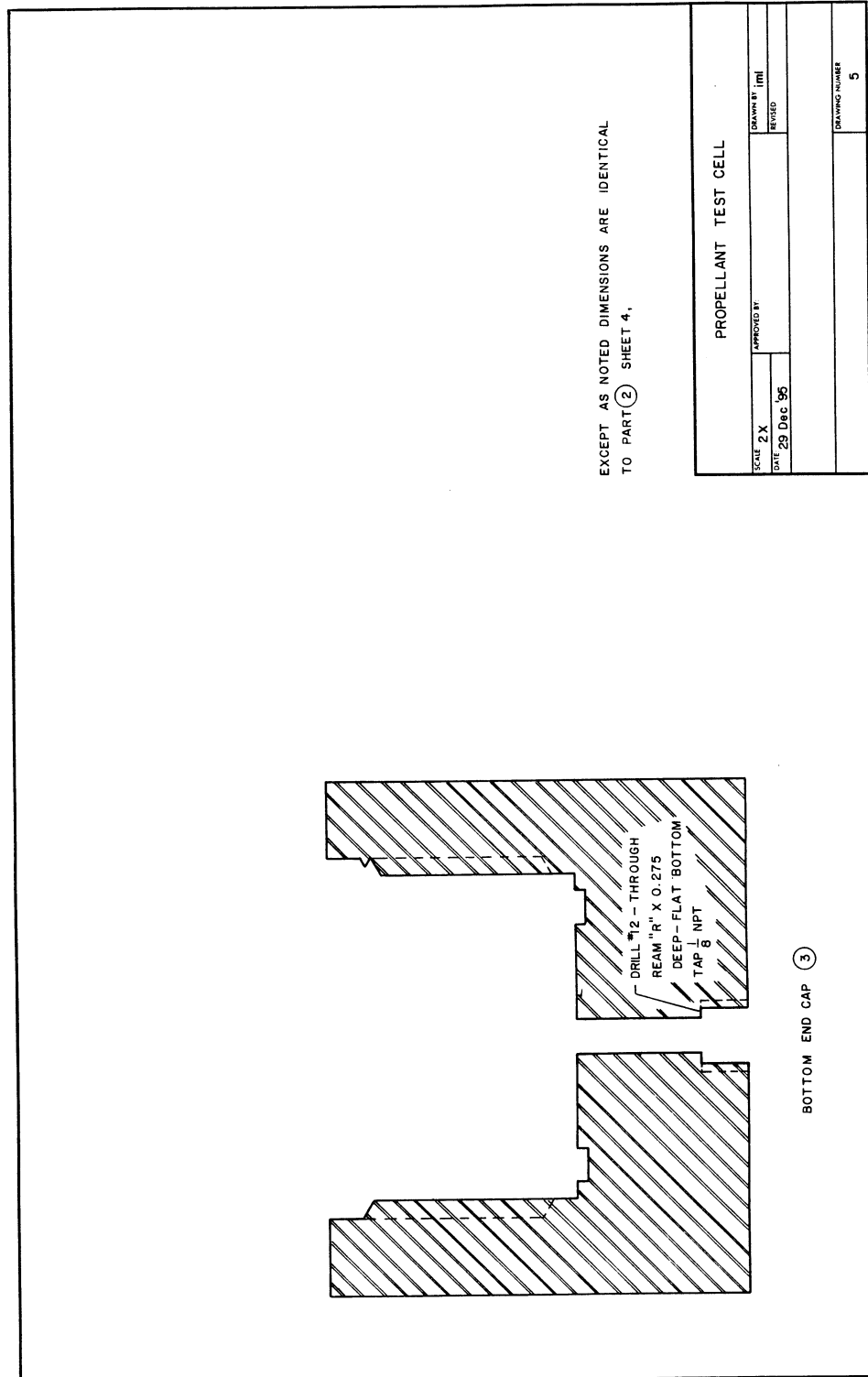
Small Scale Vessel Design

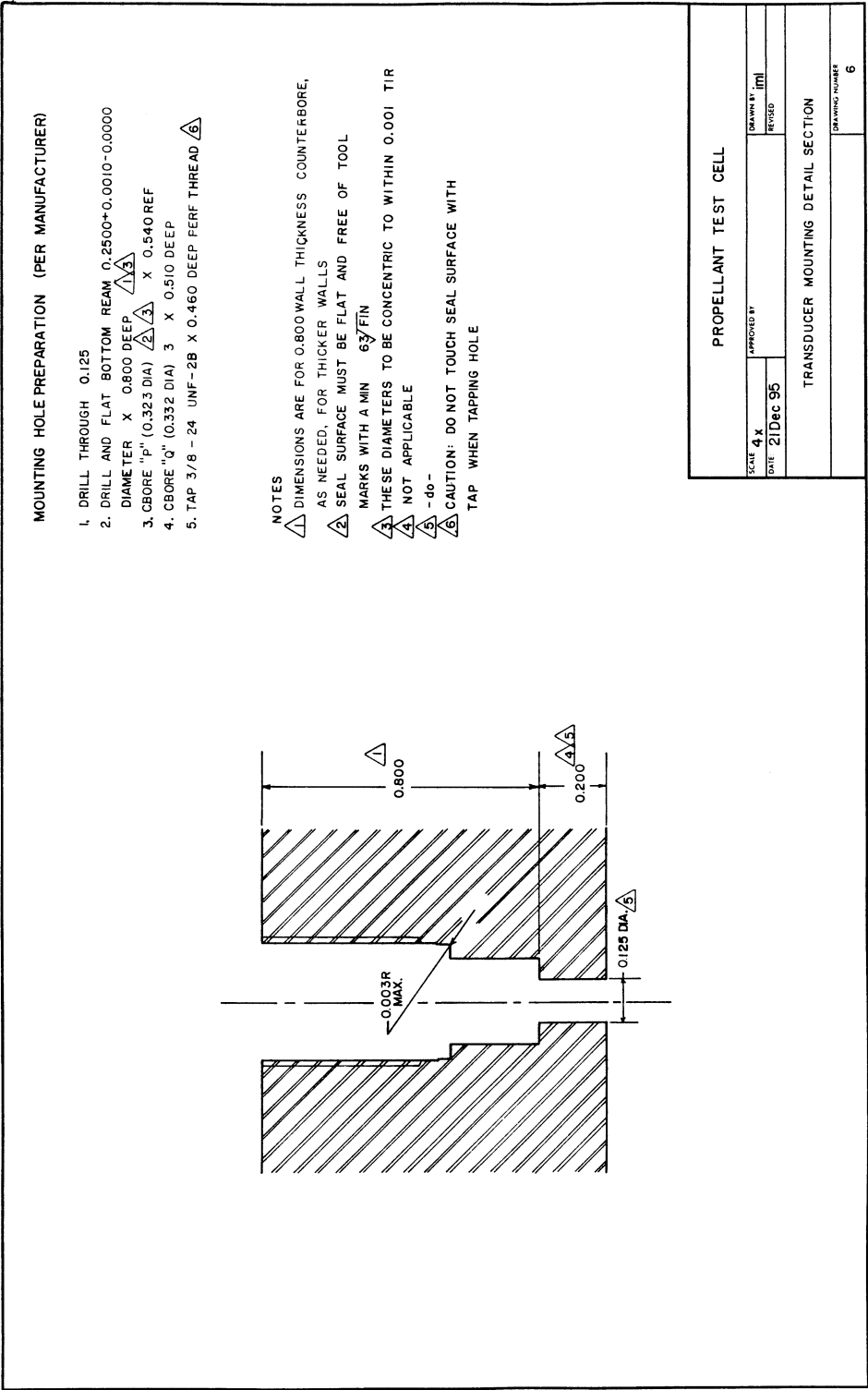


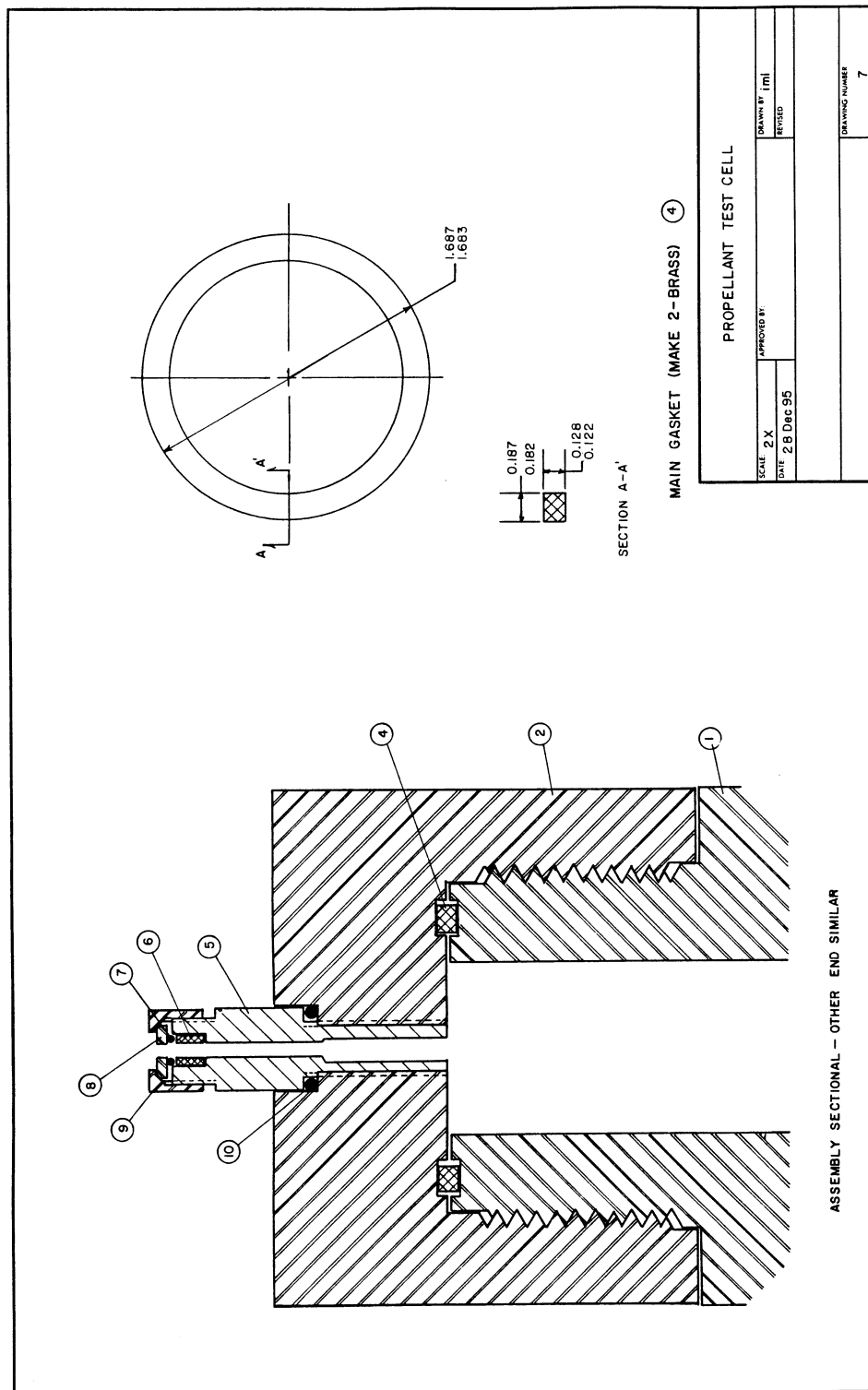


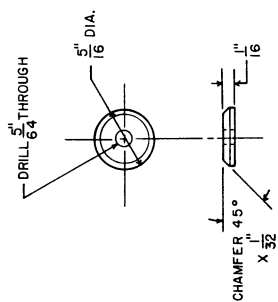






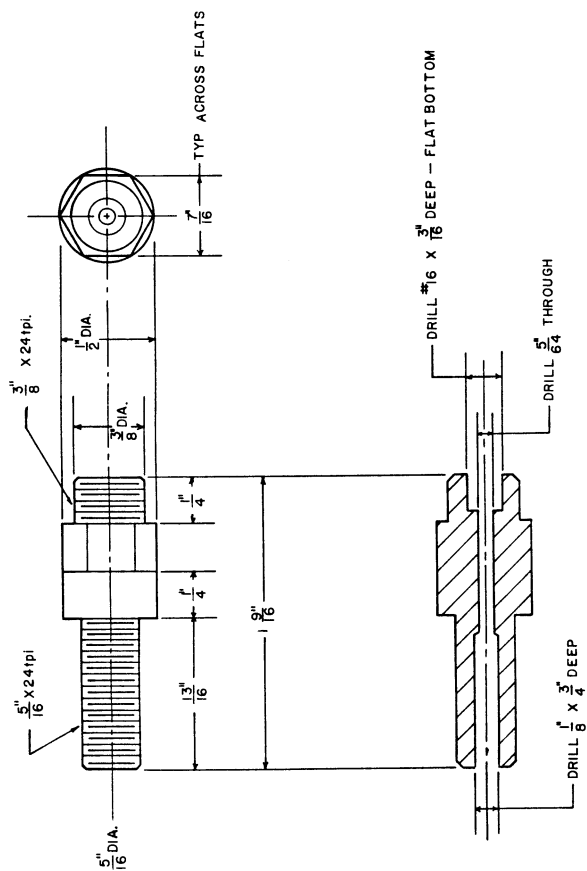






IGNITER GLAND PAD (MAKE 1)

⑧



IGNITER GLAND BODY (MAKE 1)

⑤

PROPELLANT TEST CELL		
2 X		
28 Dec 95		imi
		8

PROPELLANT TEST CELLMATERIAL: CARBON STEEL

ALLOWABLE STRESS	
TENS./COMP.	24000 psi
SHEAR	14500 psi

YOUNG'S MODULUS	
TENS./COMP	$29 * 10^6$ psi
SHEAR	$12 * 10^6$ psi

POISSON'S RATIO	0.30
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COEF. THERM. EXPAN	$6.5 * 10^{-6} / ^\circ F$
	$1.17 * 10^{-5} / ^\circ C$

<u>MAX. STATIC LOAD:</u>	5000 psi
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<u>EST. DYNAMIC COEF.:</u>	2
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<u>DESIGN LOAD:</u>	10000 psi
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ANALYSIS PROTOCOL

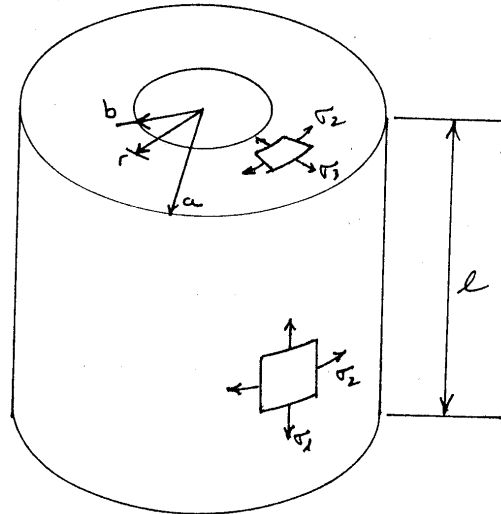
VERIFY STRESSES FOR THICK-WALLED CYLINDER
UNDER INTERNAL LOAD w/ ENDS CAPPED.

VERIFY THREAD DESIGN FOR SHEAR

VERIFY SHEAR "PUNCH-OUT" OF END-CAP.

ESTIMATE DIMENSION CHANGES.

ESTIMATE ENERGY NEEDED TO SHEAR-OFF
END CAP

THICK-WALLED CYLINDER

From: (Warren 1989, pp. 636 - 640.

$$\sigma_1 = \frac{q b^2}{a^2 - b^2}$$

$$\sigma_2 = \frac{q b^2 (a^2 + r^2)}{r^2 (a^2 - b^2)} \quad \max \sigma_2 = q \frac{a^2 + b^2}{a^2 - b^2} \quad \text{at } r = b$$

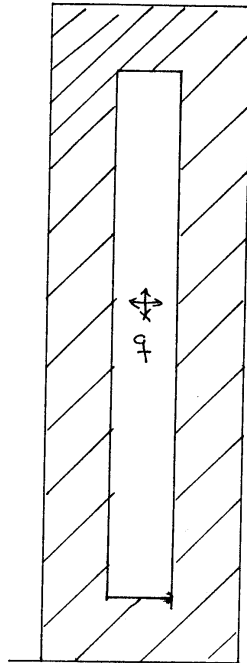
$$\sigma_3 = -q \frac{b^2 (a^2 - r^2)}{r^2 (a^2 - b^2)} \quad \max \sigma_3 = -q \quad \text{at } r = b$$

$$\text{Max SHEAR STRESS} = \frac{\sigma_2 - \sigma_3}{2} = q \frac{a^2}{(a^2 - b^2)} \quad \text{at } r = b$$

$$\Delta a = \frac{q a}{E} \frac{b^2 (1 - \nu)}{a^2 - b^2}$$

$$\Delta b = \frac{q b}{E} \frac{a^2 (1 + \nu) + b^2 (1 - 2\nu)}{a^2 - b^2}$$

$$\Delta l = \frac{q l}{E} \frac{b^2 (1 - 2\nu)}{a^2 - b^2}$$



CONSIDER:

$$\begin{aligned} l &= 8 \text{ in} \\ a &= 1.5 \text{ in} \\ b &= 0.5 \text{ in} \\ q &= 10000 \text{ psi} \end{aligned}$$

$$\begin{aligned} \sigma_1 &= \frac{q b^2}{(a^2 - b^2)} = \frac{10000 * (0.5)^2}{(1.5^2 - 0.5^2)} \\ &= \underline{\underline{1250 \text{ psi}}} \end{aligned}$$

$$\begin{aligned} \sigma_{2(\max)} &= \frac{q (a^2 + b^2)}{(a^2 - b^2)} \\ &= \frac{10000 (1.5^2 + 0.5^2)}{(1.5^2 - 0.5^2)} \\ &= \underline{\underline{12500 \text{ psi}}} \end{aligned}$$

$$\sigma_{3(\max)} = -q = \underline{\underline{-10000 \text{ psi}}} \text{ (compressive)}$$

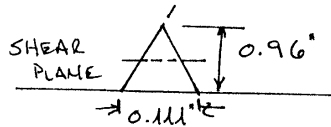
$$\text{Shear (Max)} \quad \tau_{23} = \frac{12500 - (-10000)}{2} = \underline{\underline{11250 \text{ psi}}}$$

ALLOWABLE STRESS CONDITIONS MET.

THREADS

60° ; 9 THREADS PER INCH

SHEAR PLANE CONSIDERED AT 1/2 THREAD HEIGHT.



DIAMETER AT SHEAR PLANE = 2.00" ϕ

AREA OF SHEAR PLANE = $\frac{0.111}{2}$ in²/in OF LENGTH

LENGTH OF FULL THREAD = 8.5 rev. * 2 * π
 = 53.4 inches

SHEAR AREA OF THREAD = 53.4 inches * 0.055 in²/in
 = 2.96 in²

SHEAR LOAD (ASSUME to ϕ OF GASKET):

10000 psi * (0.750)² π = 17671 lbf

SHEAR STRESS ON THREADS = $\frac{17671 \text{ lbf}}{2.96 \text{ in}^2}$

= 5970 psi

ALLOWABLE SHEAR ON THREADS ACCEPTABLE.

ESTIMATE MAX. ALLOWABLE PRESSURE
FOR SHEAR STRESS CONDITION ON THREAD

CONSIDER ENTIRE NORMAL SURFACE AREA

$$= \left(\frac{2.111''}{2} \right)^2 * \pi = 3.5 \text{ in}^2$$

$$\text{SHEAR AREA OF THREADS} = 2.96 \text{ in}^2$$

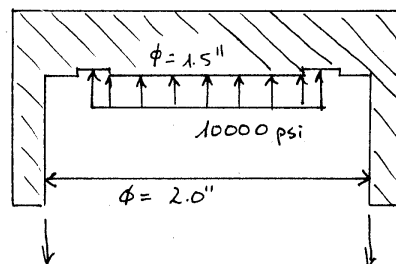
$$\text{MAX Allowable pressure} = \frac{14500 \text{ psi} * 2.96 \text{ in}^2}{3.5 \text{ in}^2}$$

$$= 12,263 \text{ psi}$$

WITH 8.0 PERFECT THREADS ENGAGED FIGURE SHEAR
STRESS BASED ON LOAD TO ϕ OF ~~OR~~ GASKET (DIAMETER)
($\phi = 1.5''$)

$$\text{LOAD} = 10000 \text{ psi} * (1.5/2)^2 * \pi = 17,670 \text{ lb}_f$$

$$\text{SHEAR STRESS} = \frac{17,670 \text{ lb}}{2 \text{ in} * \pi * 8.0 * 0.055 \text{ in/in}} = 6400 \text{ psi}$$

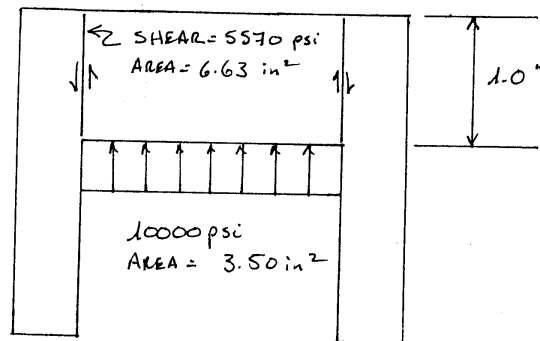


SHEAR ON THREAD = 6400 psi

SHEAR - "PUNCH-OUT" - LOAD ON END CAP

MAX SHEAR STRESS WOULD OCCUR IN THE
EVENT OF GASKET FAILURE; WITH 10000 psi
OVER ENTIRE NORMAL CROSS-SECTION (2.11" ϕ)

$$\begin{aligned} \text{SHEAR STRESS} &= \frac{10000 \text{ psi} * (1.055)^2 * \pi}{2.11 \text{ in} * 1 \text{ in} * \pi} \\ &= \underline{\underline{5,570 \text{ psi}}} \end{aligned}$$



SHEAR "PUNCH-OUT" CONDITIONS ACCEPTABLE

ESTIMATE DIMENSION CHANGES

OUTER RADIUS

$$\Delta a = \frac{q a}{E} \frac{b^2(2-\nu)}{a^2 - b^2} = \frac{10000 * 1.5}{29 * 10^6} * \frac{0.5^2(2-0.3)}{(1.5^2 - 0.5^2)}$$

$$= 1.1 * 10^{-4} \text{ inches}$$

INNER RADIUS

$$\Delta b = \frac{q b}{E} \frac{a^2(1+\nu) + b^2(1-2\nu)}{a^2 - b^2} = \frac{10000 * 0.5}{29 * 10^6} * \frac{1.5^2(1+0.3) + 0.5^2(1-2(0.3))}{1.5^2 - 0.5^2}$$

$$= 2.6 * 10^{-4} \text{ inches}$$

LENGTH (INTERNAL)

$$\Delta l = \frac{q l}{E} \frac{b^2(1-2\nu)}{a^2 - b^2} = \frac{10000 * 8}{29 * 10^6} * \frac{0.5^2(1-2*0.3)}{1.5^2 - 0.5^2}$$

$$= 1.4 * 10^{-4}$$

CHANGE IN VOLUMEVOLUME AT ATM. PRESSURE

$$8" \times (12")^2 \pi = 6.2832 \text{ in}^3$$

VOLUME AT 10000 psi

$$8.00014 \text{ in} \times (0.50026 \text{ in})^2 \pi = 6.2898 \text{ in}^3$$

ABSOLUTE VOLUME CHANGE

$$6.2898 - 6.2832 = 0.0066 \text{ in}^3$$

RELATIVE VOLUME CHANGE

$$\left[\frac{6.2898 - 6.2832}{6.2832} \right] * 100 = \underline{\underline{0.11 \%}}$$

ESTIMATE OF SHEAR ENERGY

$$\text{Energy} = \text{Force} \times \text{dist.}$$

$$\text{Ultimate strength shear} = 48000 \text{ psi}$$

$$\begin{aligned} \text{let ultimate shear stress} &= 0.8 \times 48000 \text{ psi} \\ &= 38,400 \text{ psi} \\ &= 264.8 \times 10^6 \text{ Pa} \end{aligned}$$

SHEARING FORCE ON THREADS FOR FAILURE

$$\begin{aligned} &264.8 \times 10^6 \frac{\text{N}}{\text{m}^2} \times \left(\frac{\pi \times 1.055 \times 2.54 \times 2 \times 2.54}{10000} \right) \\ &= 1.13 \text{ m} \\ &= 5.82 \times 10^6 \text{ N} \end{aligned}$$

WORK DONE SHEARING OF END CAP

$$\begin{aligned} &\frac{1.13}{5.82} \times 10^6 \text{ N} \times \left(\frac{0.055 \times 2.54}{100} \right) = \frac{1580}{8.13} \text{ J} \\ &= 8.13 \text{ kJ} \\ &1.58 \end{aligned}$$

INTERNAL PRESSURE CAUSING SHEAR FAILURE OF END CAP THREADS.

$$F = \overset{1.13}{5.82} \times 10^6 \text{ N} ; \text{Area} = 3.5 \text{ in}^2 \quad \text{assumes failure of main gasket.}$$

$$= 2.3 \times 10^{-3} \text{ m}^2$$

$$P = \frac{F}{A} = \frac{\overset{1.13}{5.82} \times 10^6 \text{ N}}{2.3 \times 10^{-3} \text{ m}^2} = \frac{\overset{49.13}{2.58} \times 10^6 \text{ Pa}}{\mu}$$

$$= \begin{matrix} 373,800 \text{ psi} \\ 71,260 \text{ psi} \end{matrix}$$

Determine Max pressure causing shear failure in Cylinder

$$\tau_{ult} = 48000 \text{ psi}$$

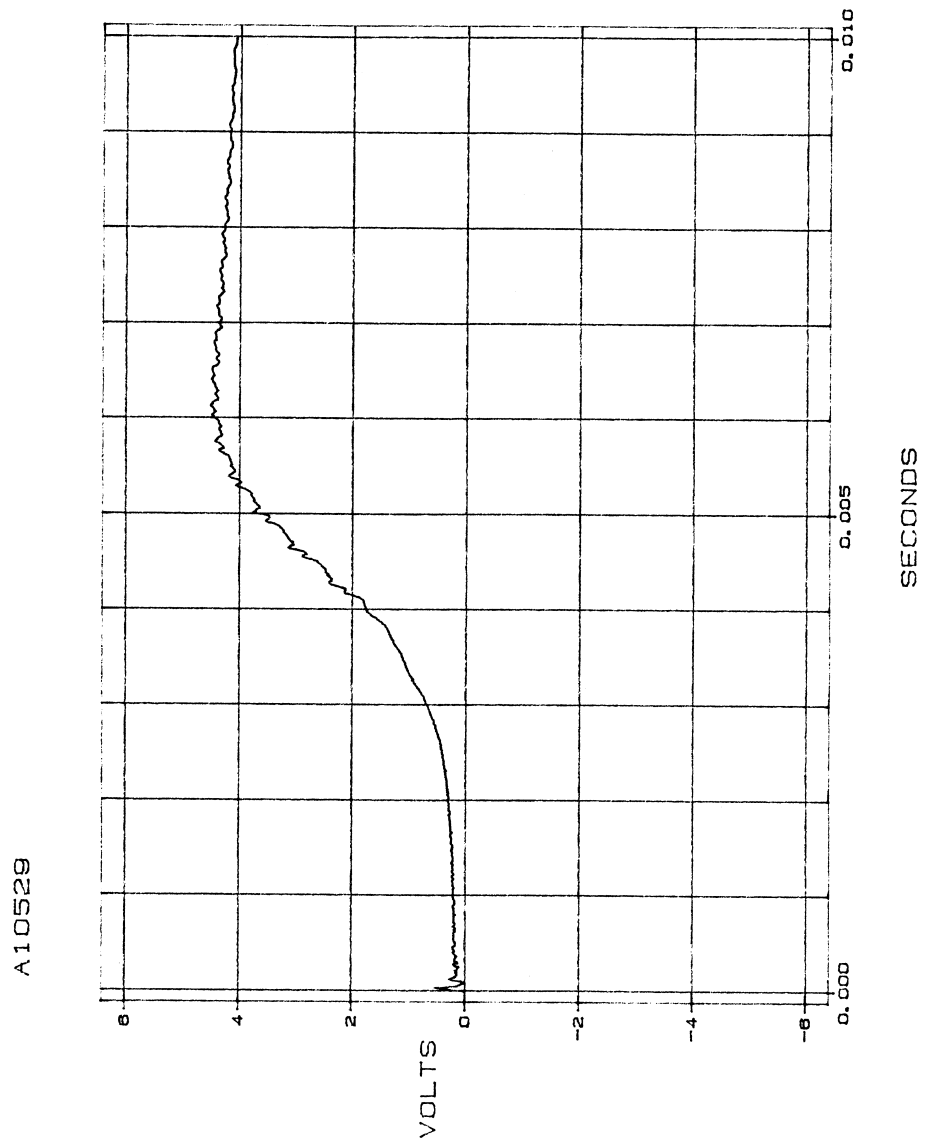
$$\tau = \eta \frac{a^2}{a^2 - b^2} \Rightarrow \eta = \frac{\tau_{ult} (a^2 - b^2)}{a^2}$$

$$= \frac{48000 \times (2)}{2.25} = \underline{42,700 \text{ psi}}$$

From this analysis the internal wall of the Cylinder will fail in shear prior to the shearing of an end cap.

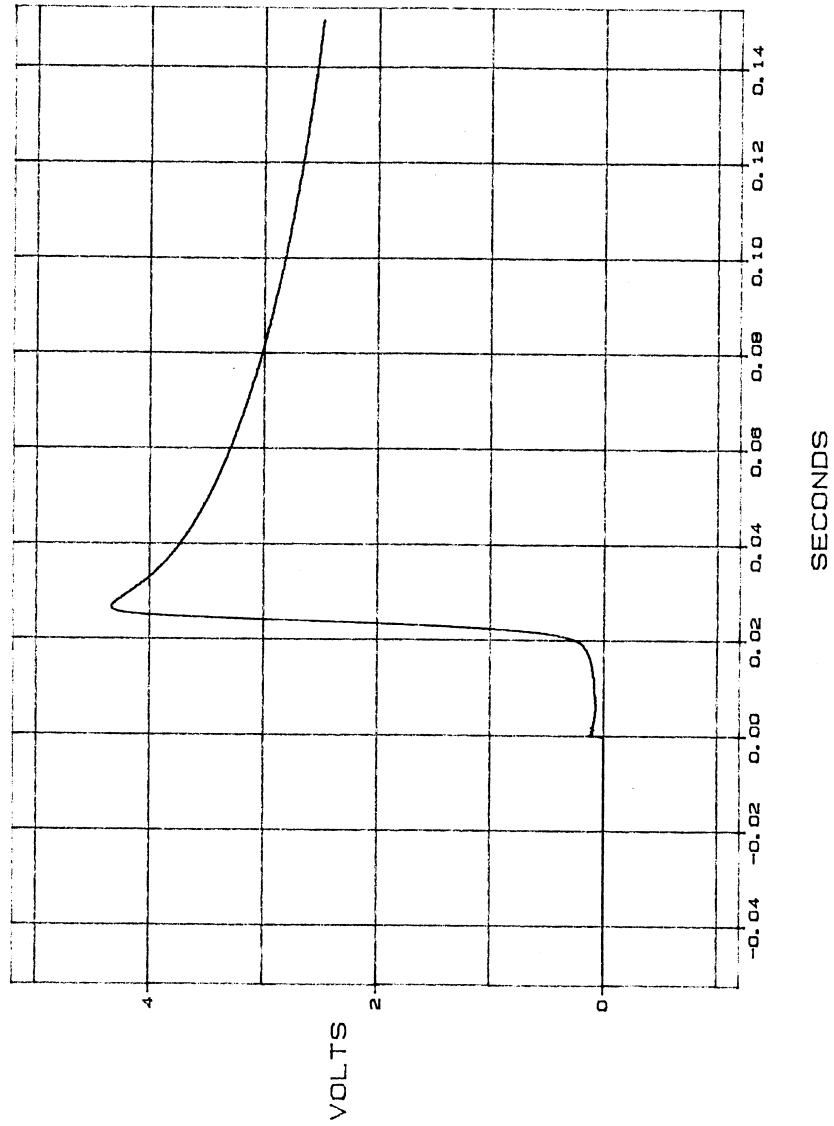
Appendix D

Propellant Shot Pressure-Time Traces

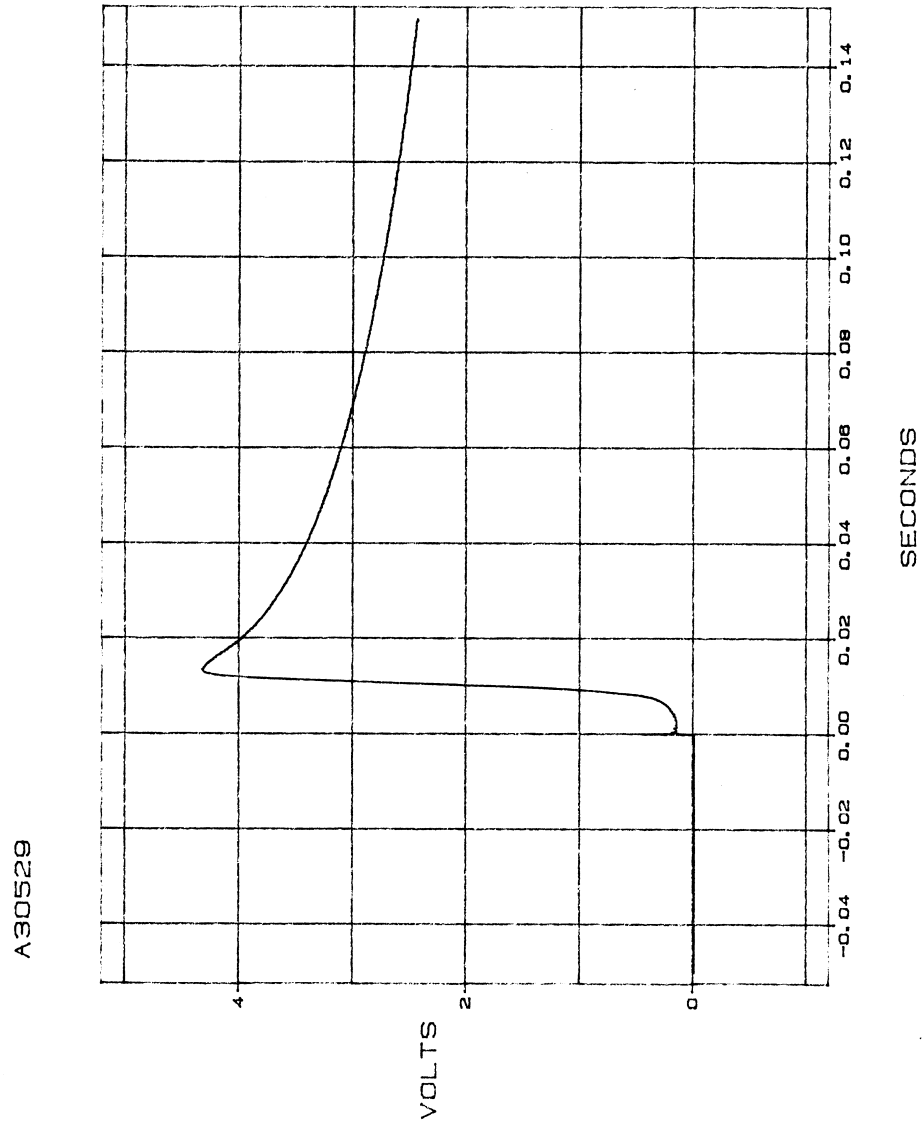


05-29-96-A1

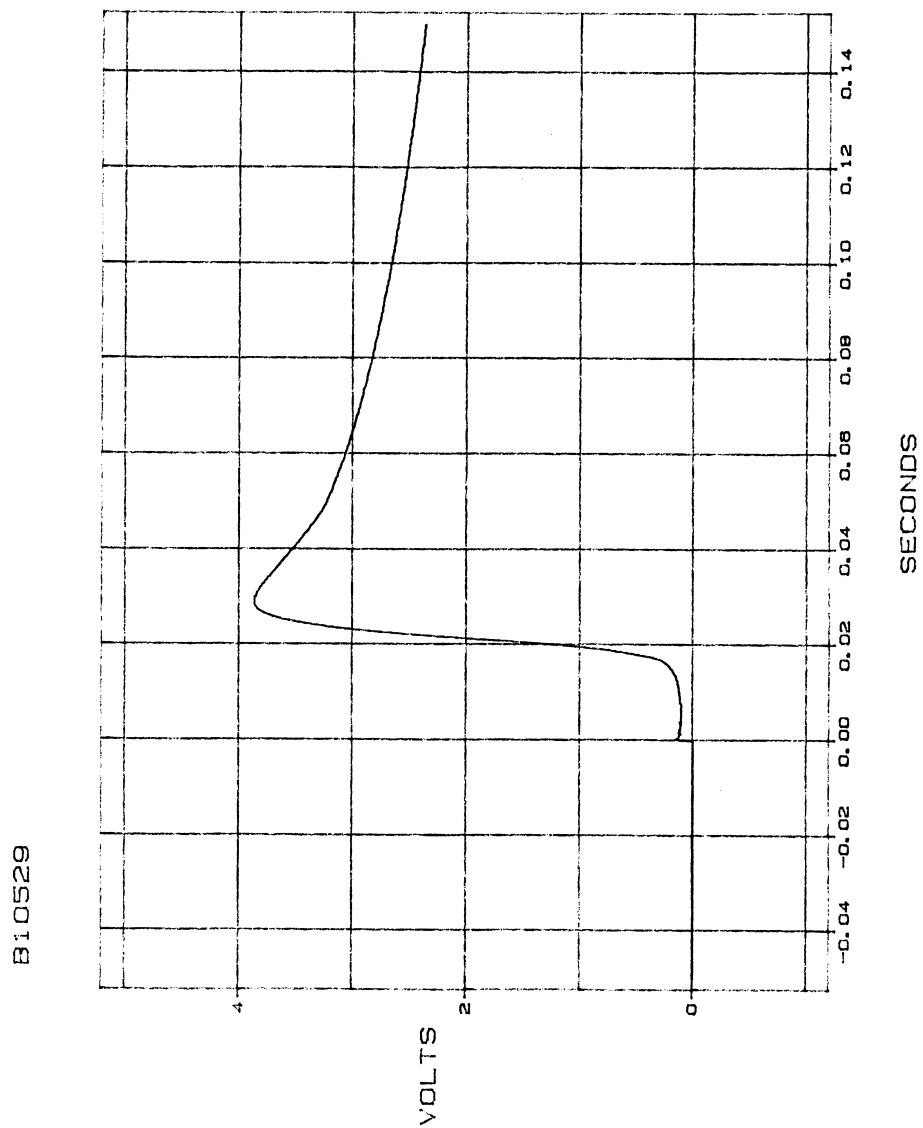
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05-29-96-A2

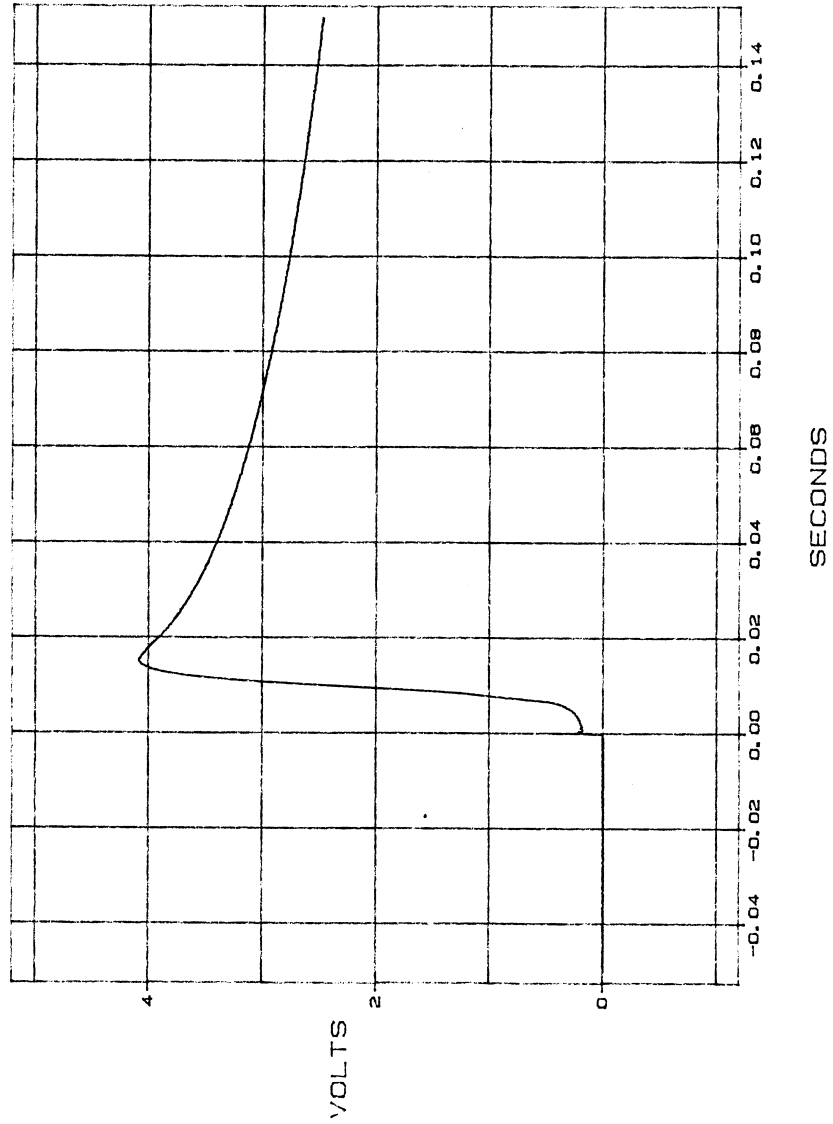


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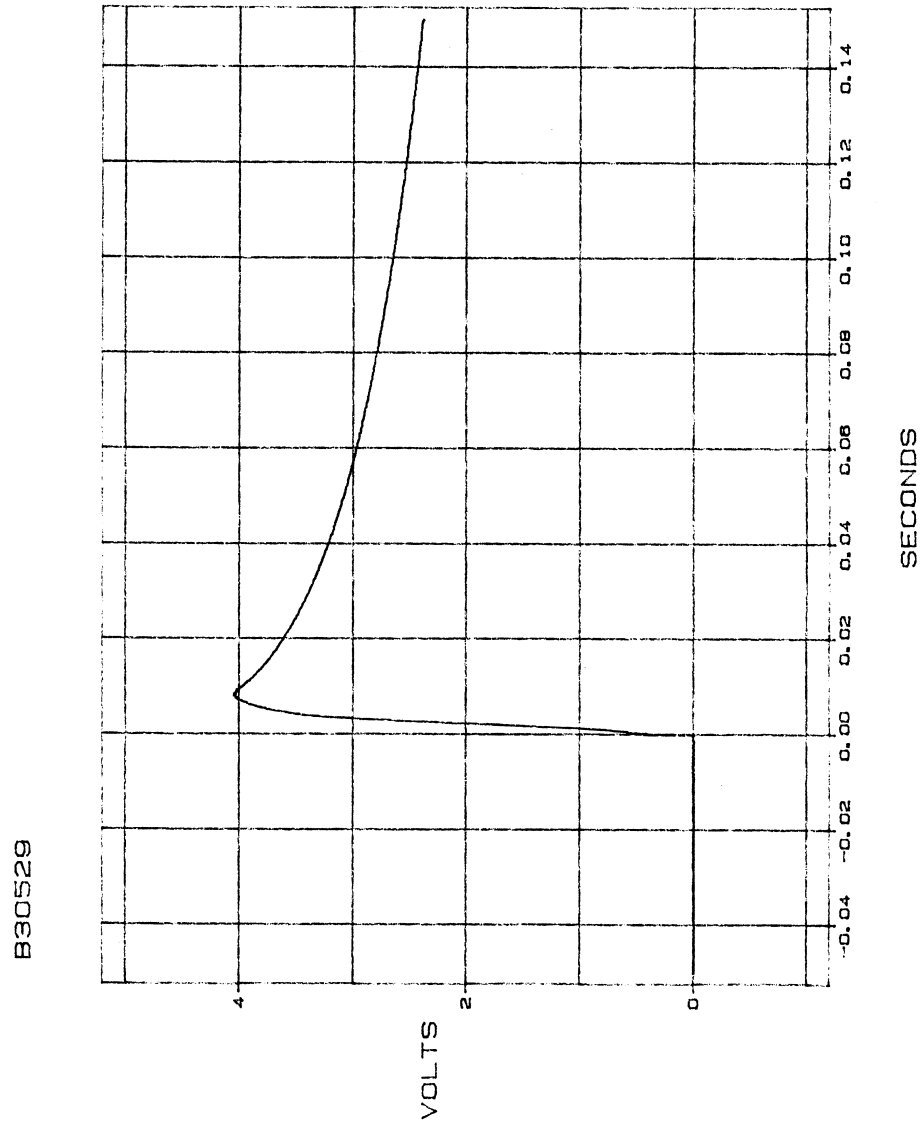


05-29-96-B1

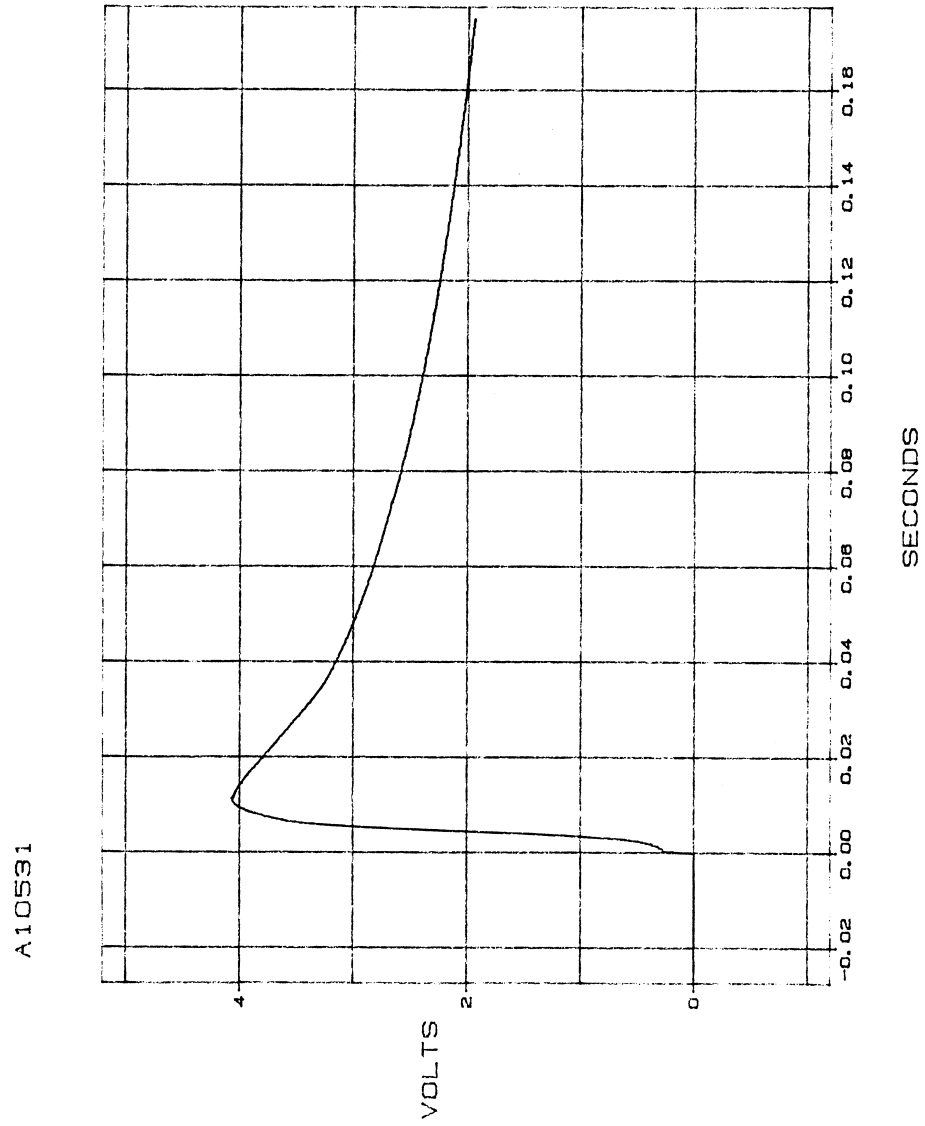
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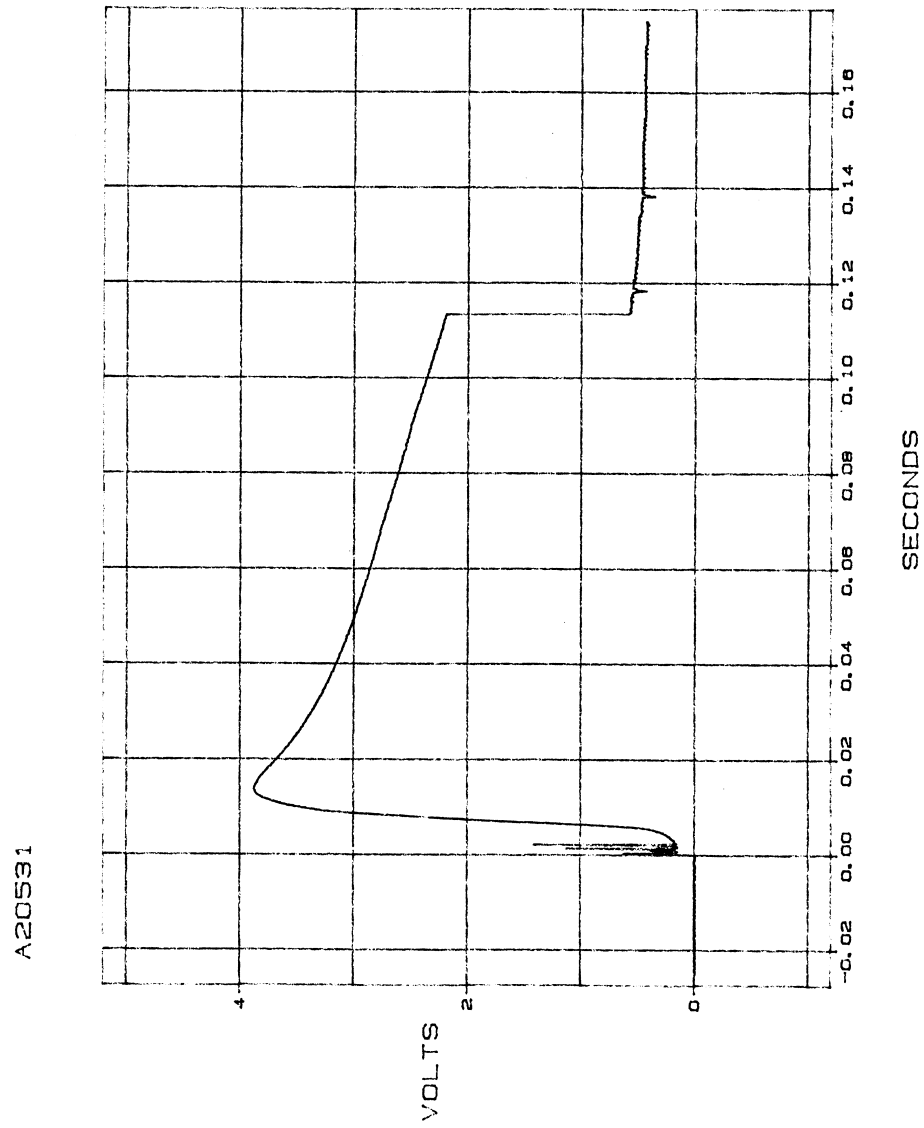
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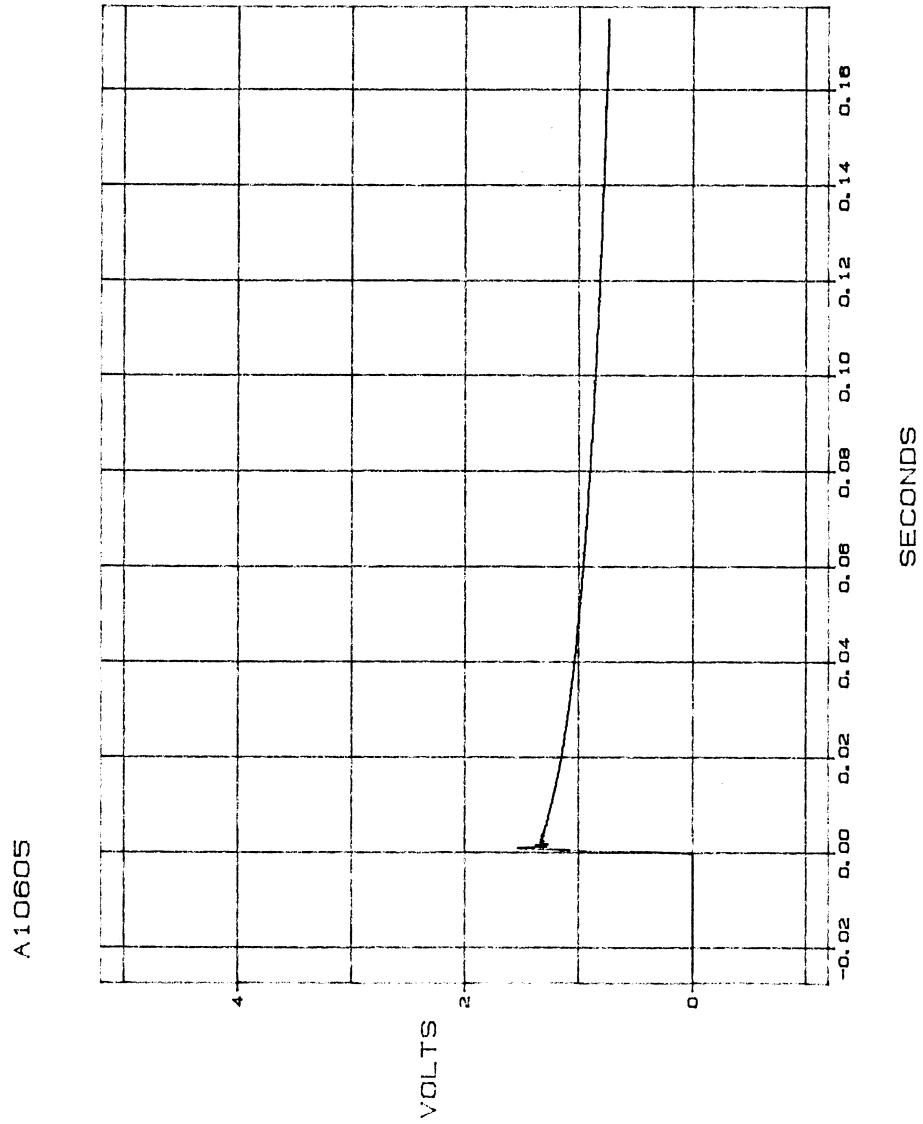
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05-31-96-A1

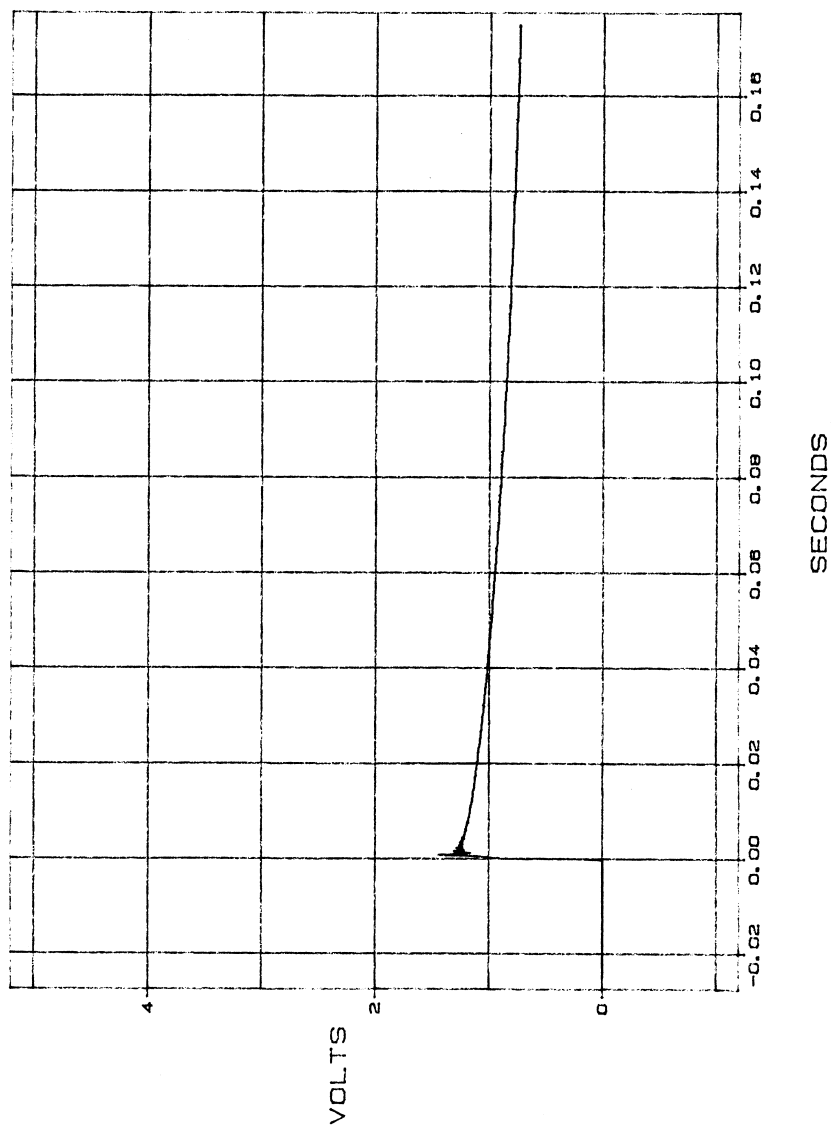


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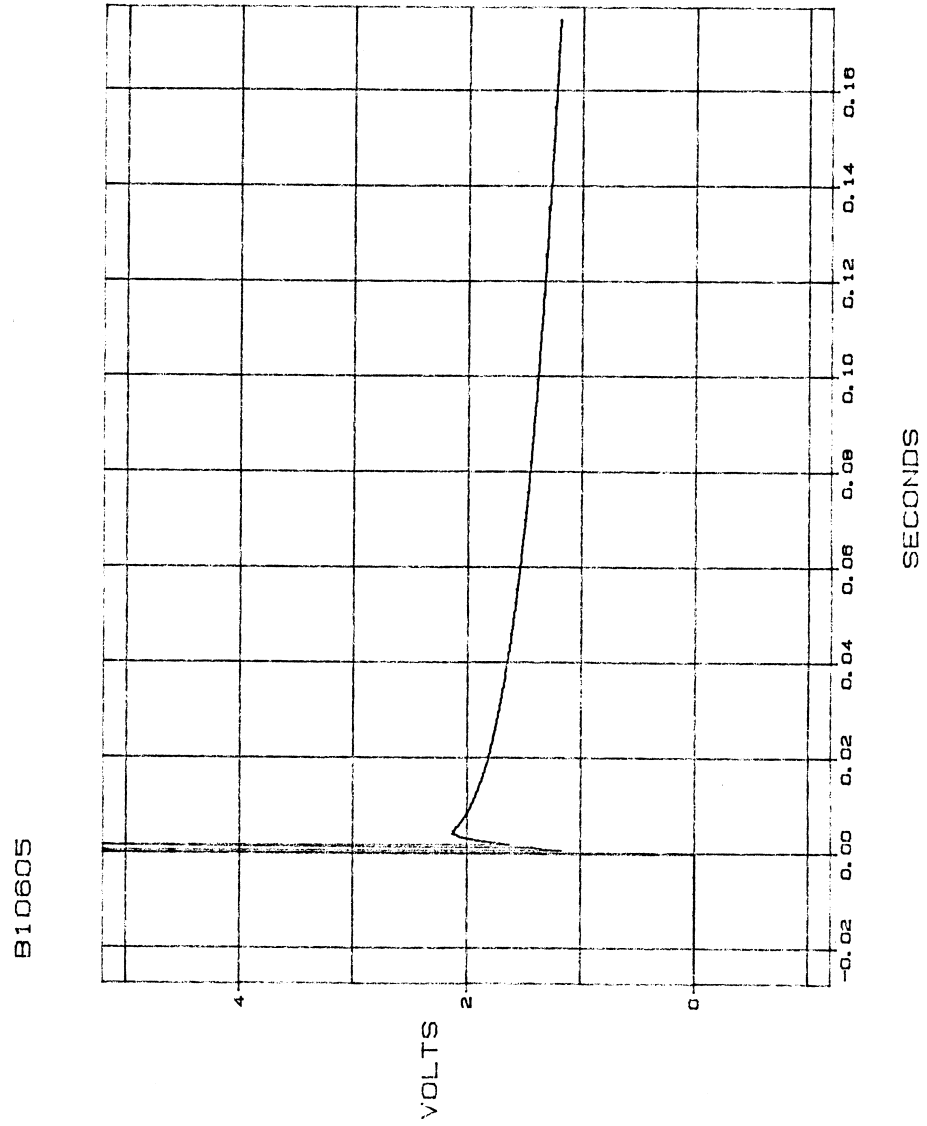


06-05-96-A1

A20605

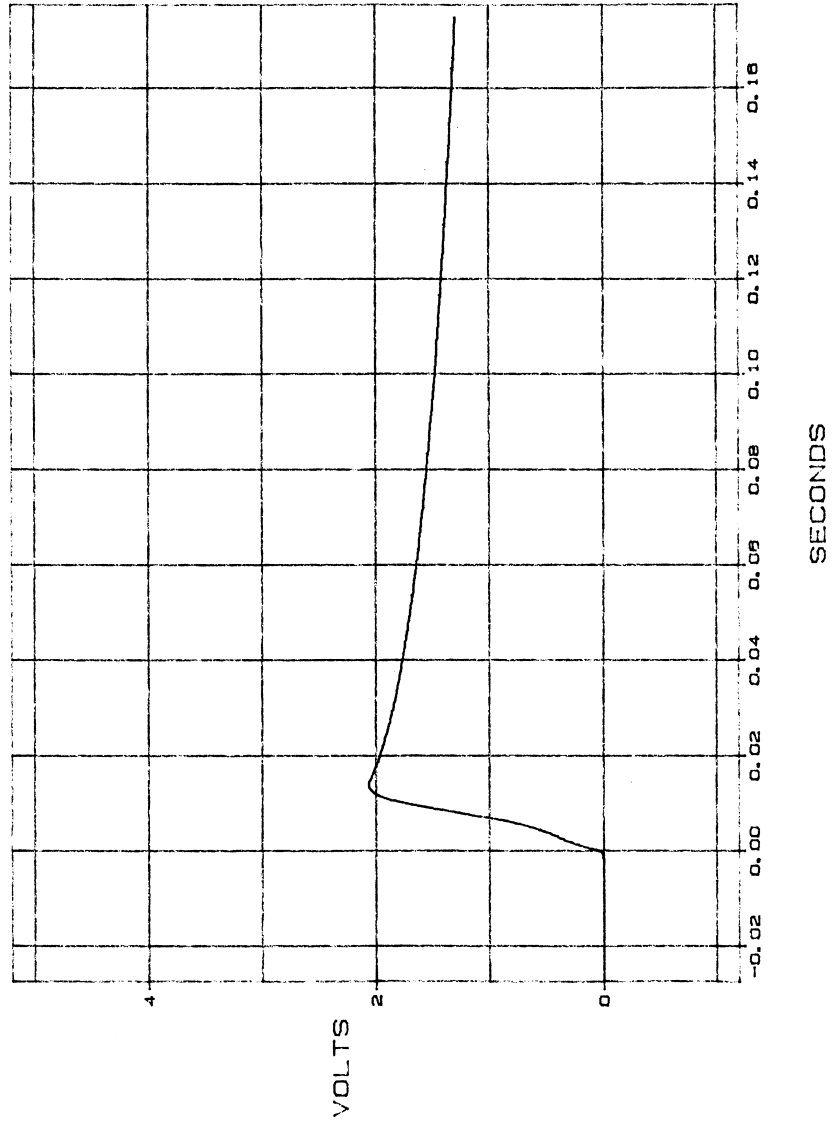


06-05-96-A2

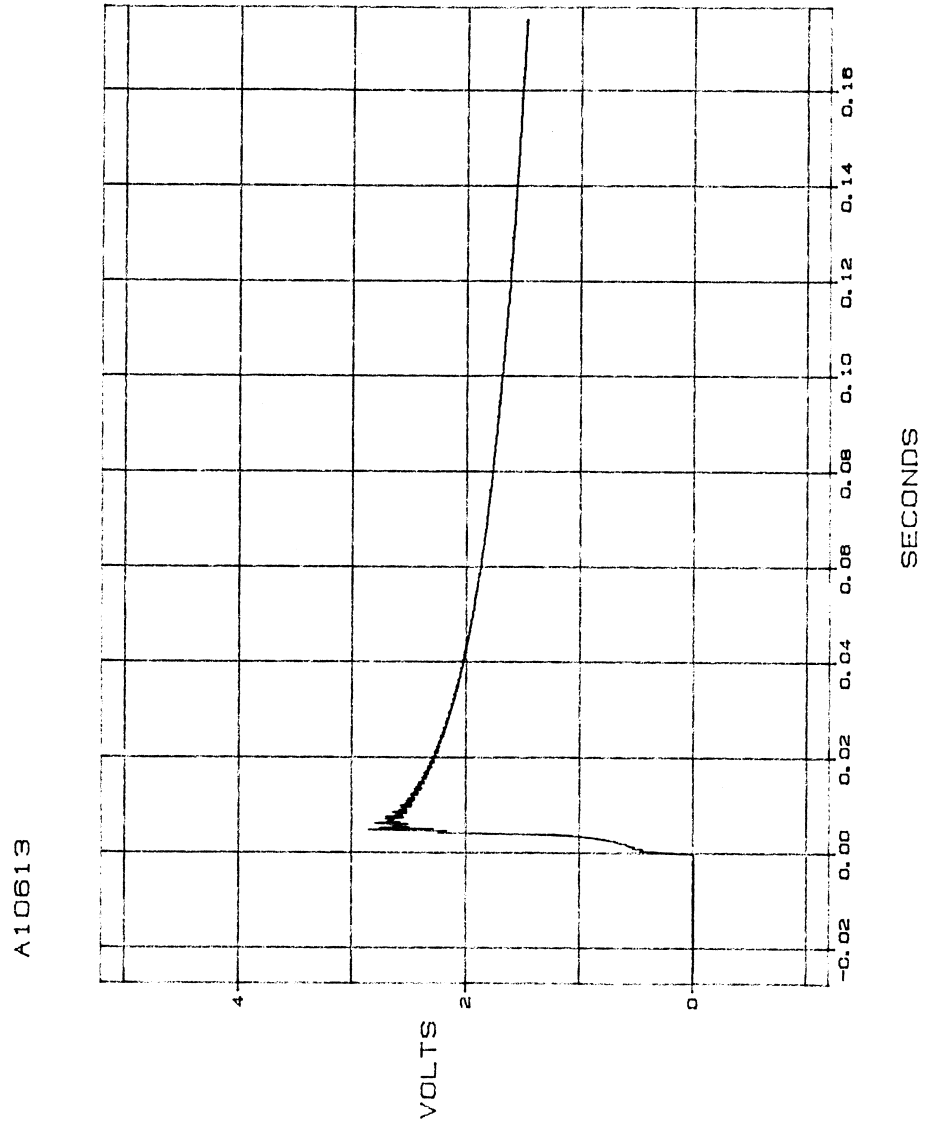


06-05-96-B1

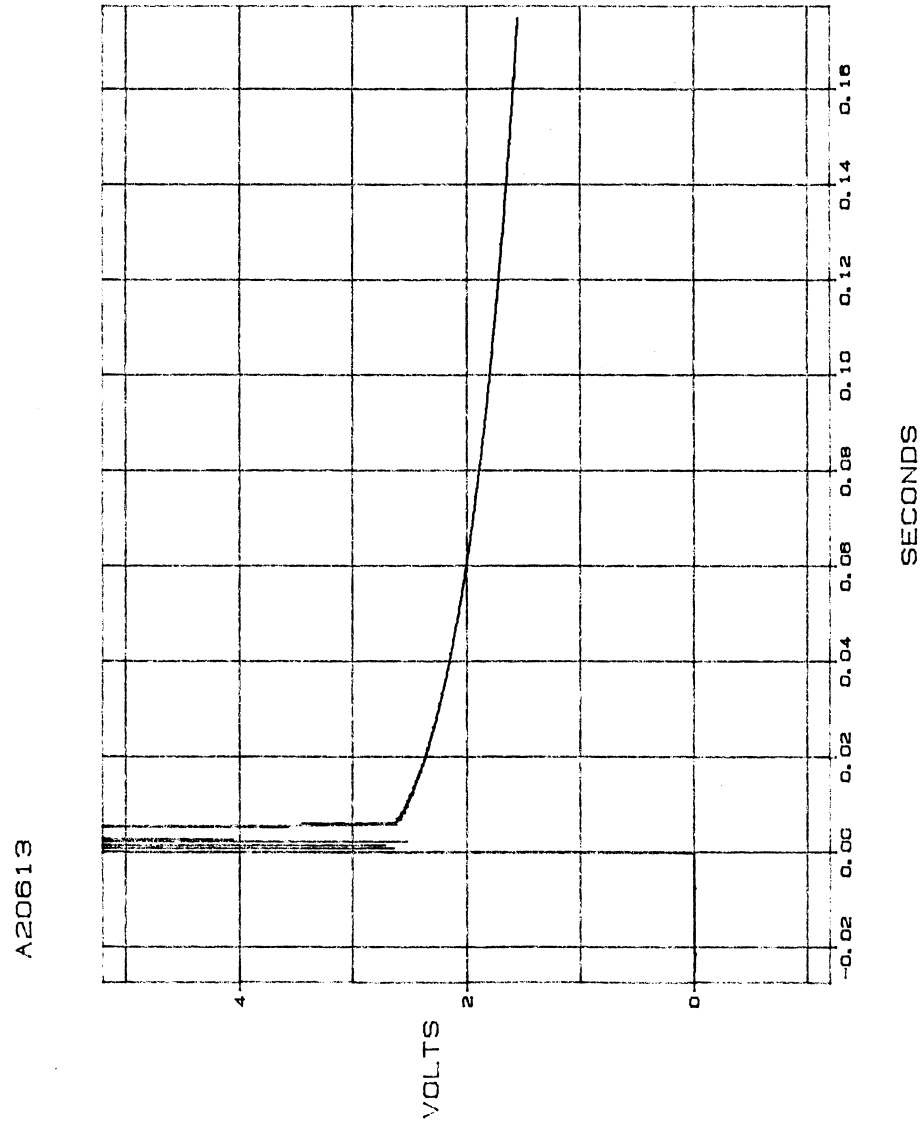
B20605



06-05-96-B2

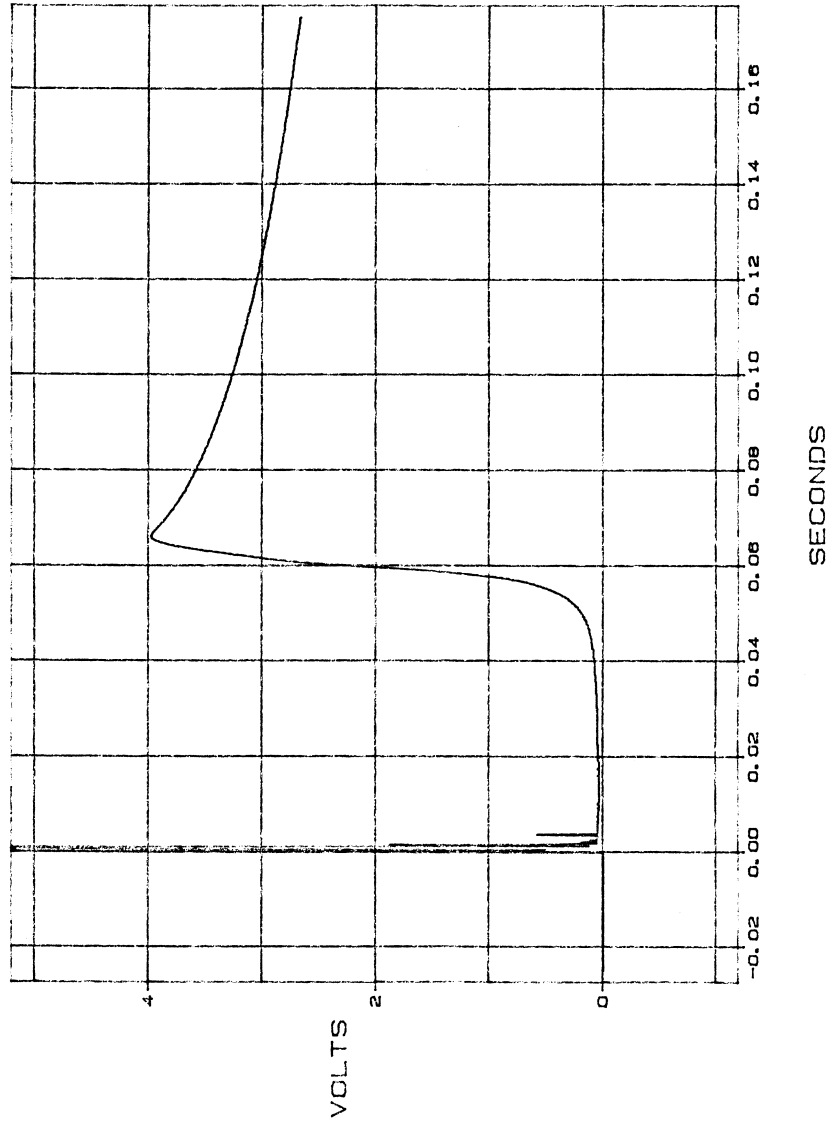


06-13-96-A1



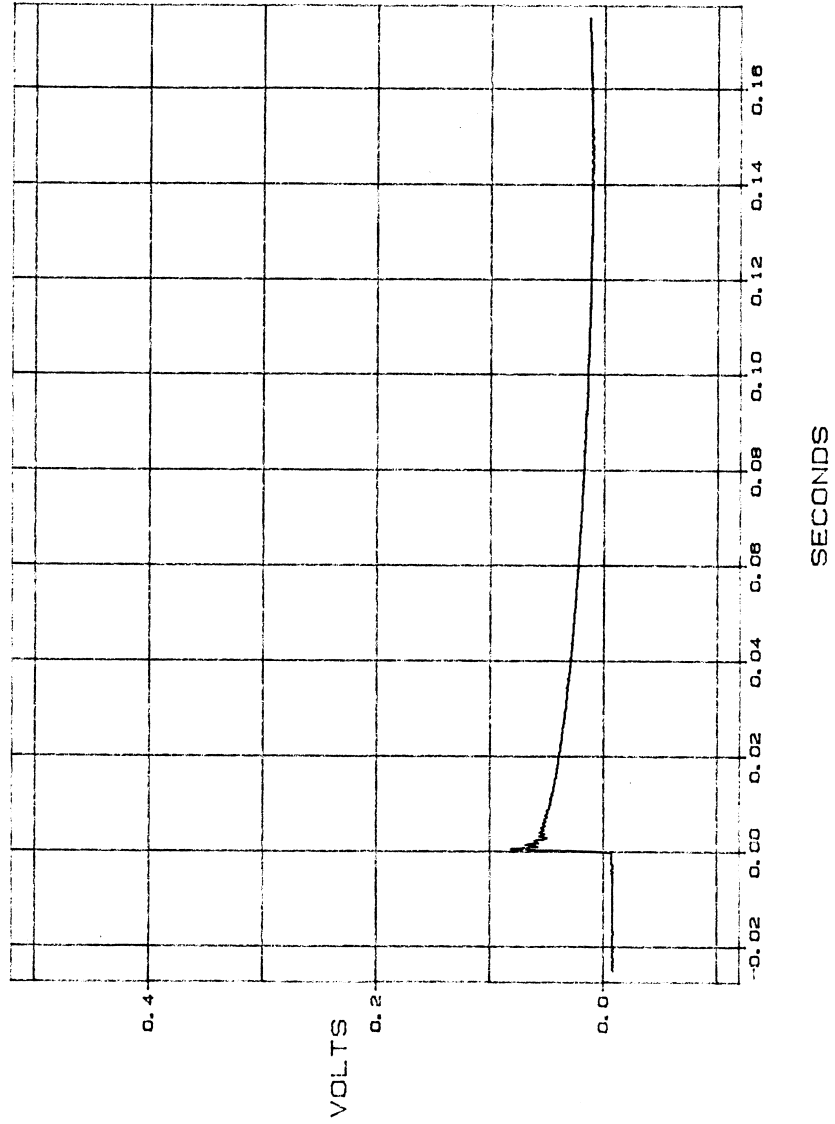
06-13-96-A2

B10613

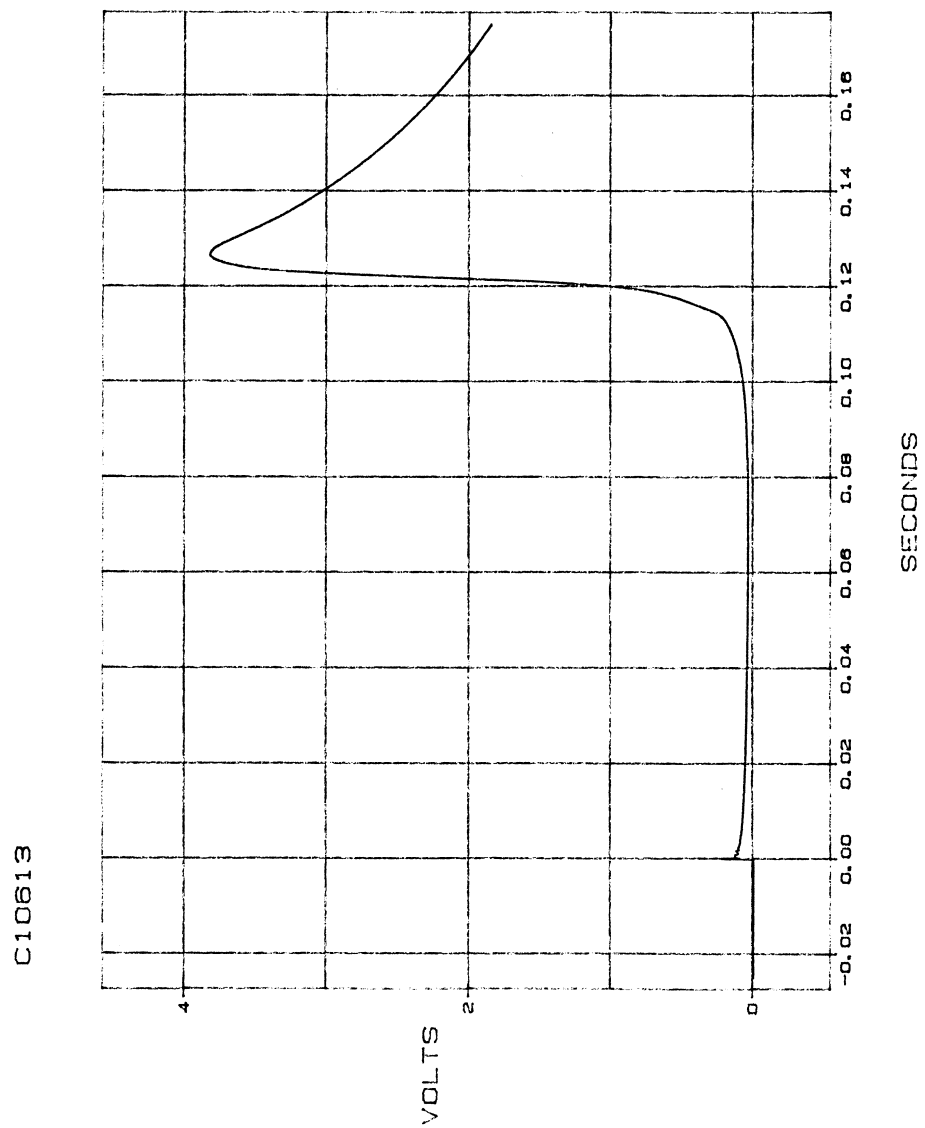


06-13-96-B1

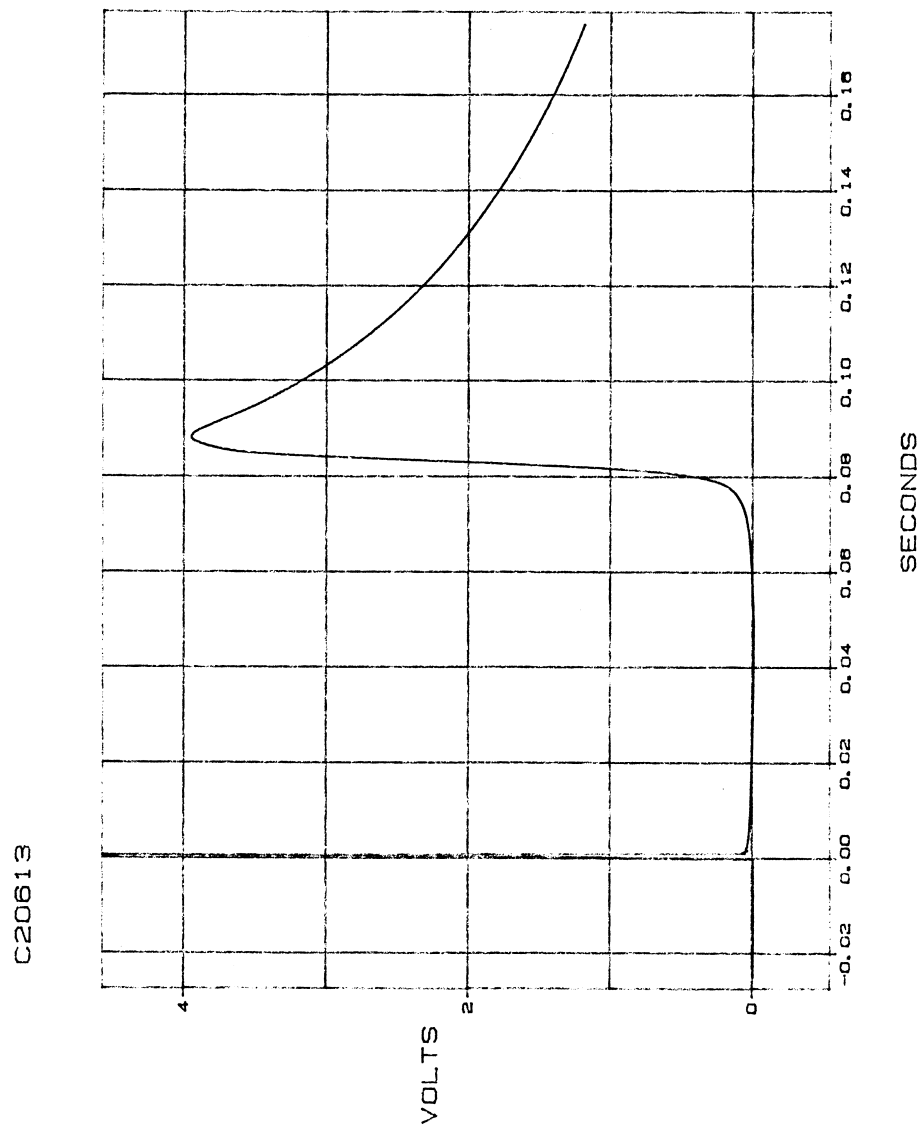
B20613



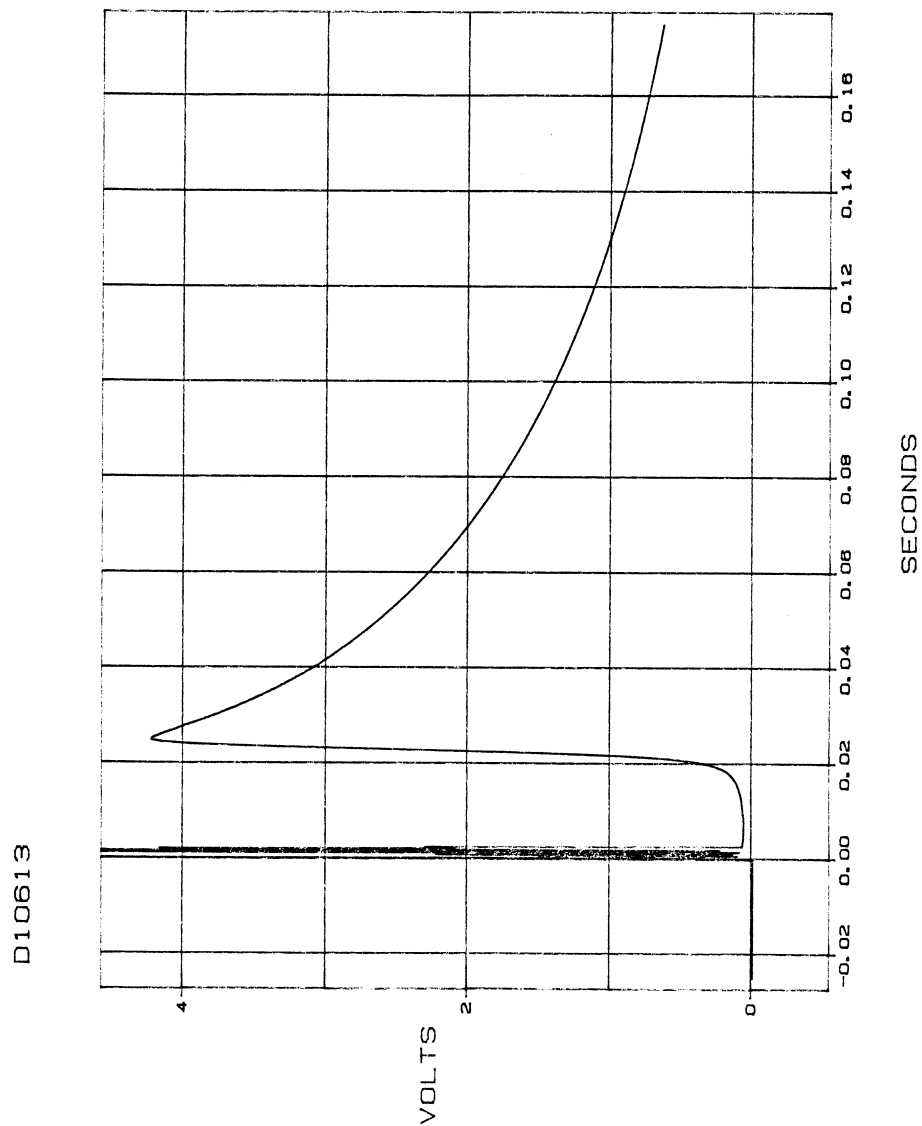
06-13-96-B2



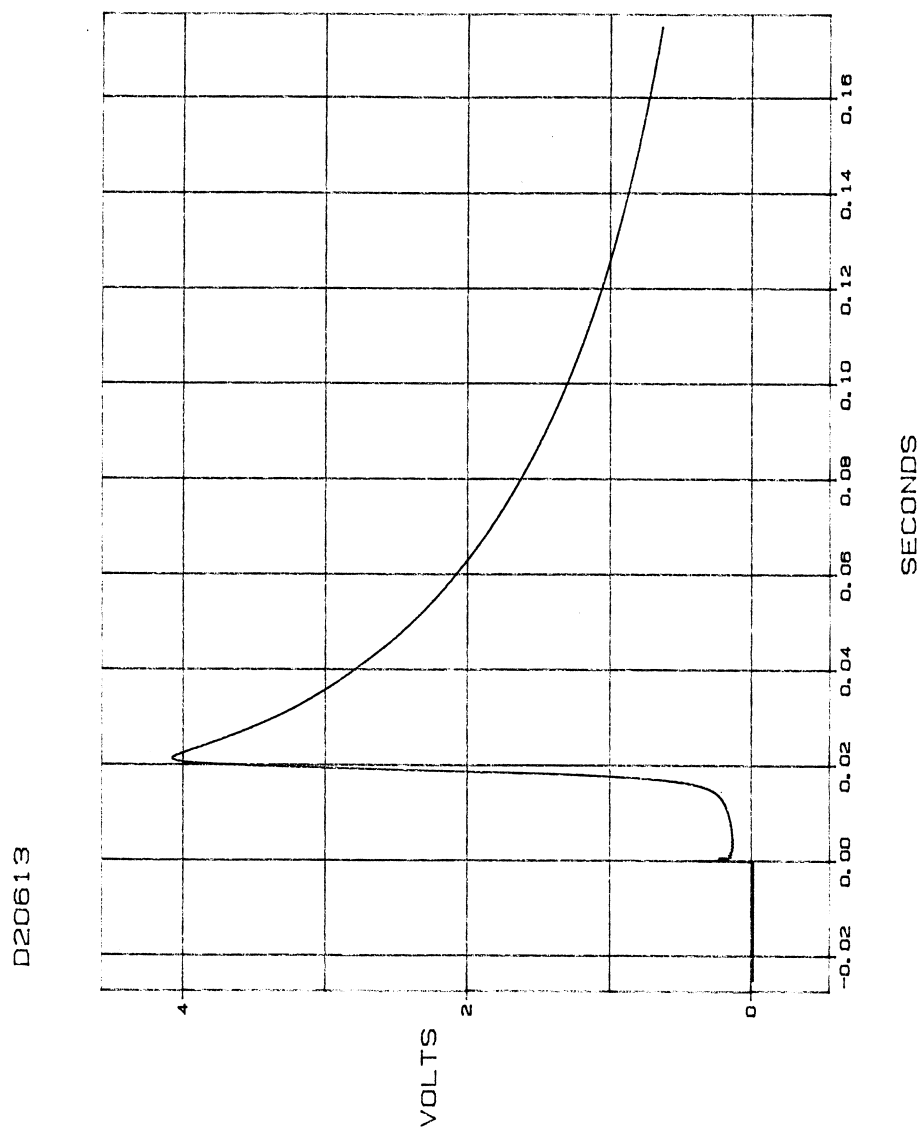
06-13-96-C1



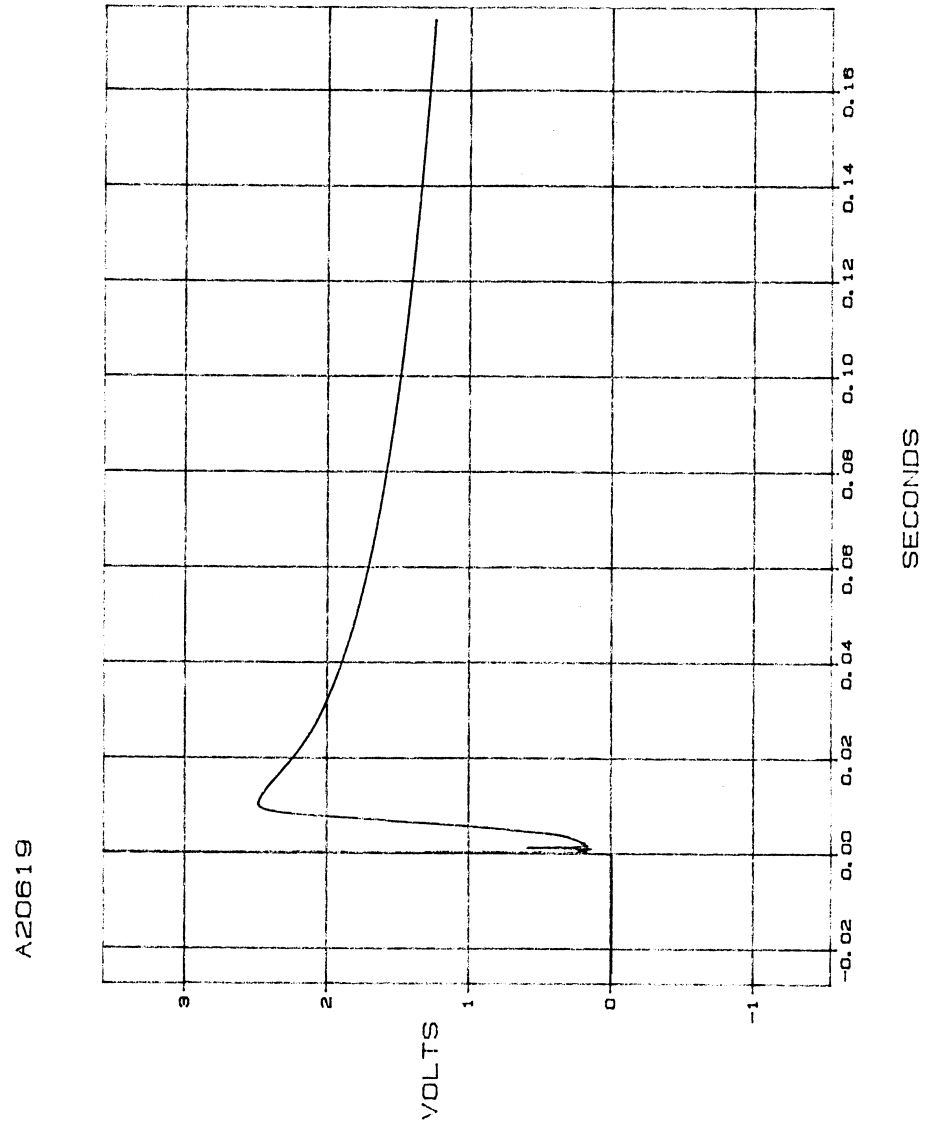
06-13-96-C2



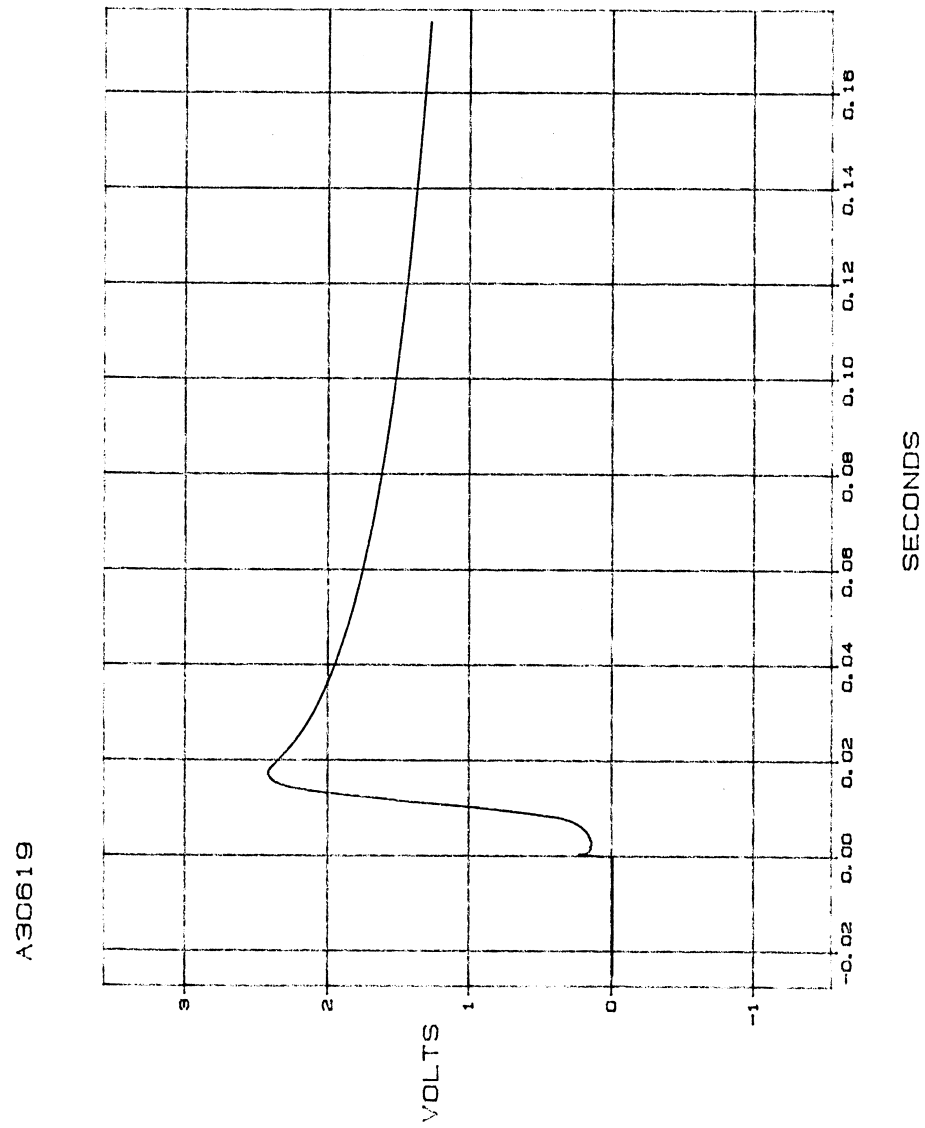
06-13-96-D1



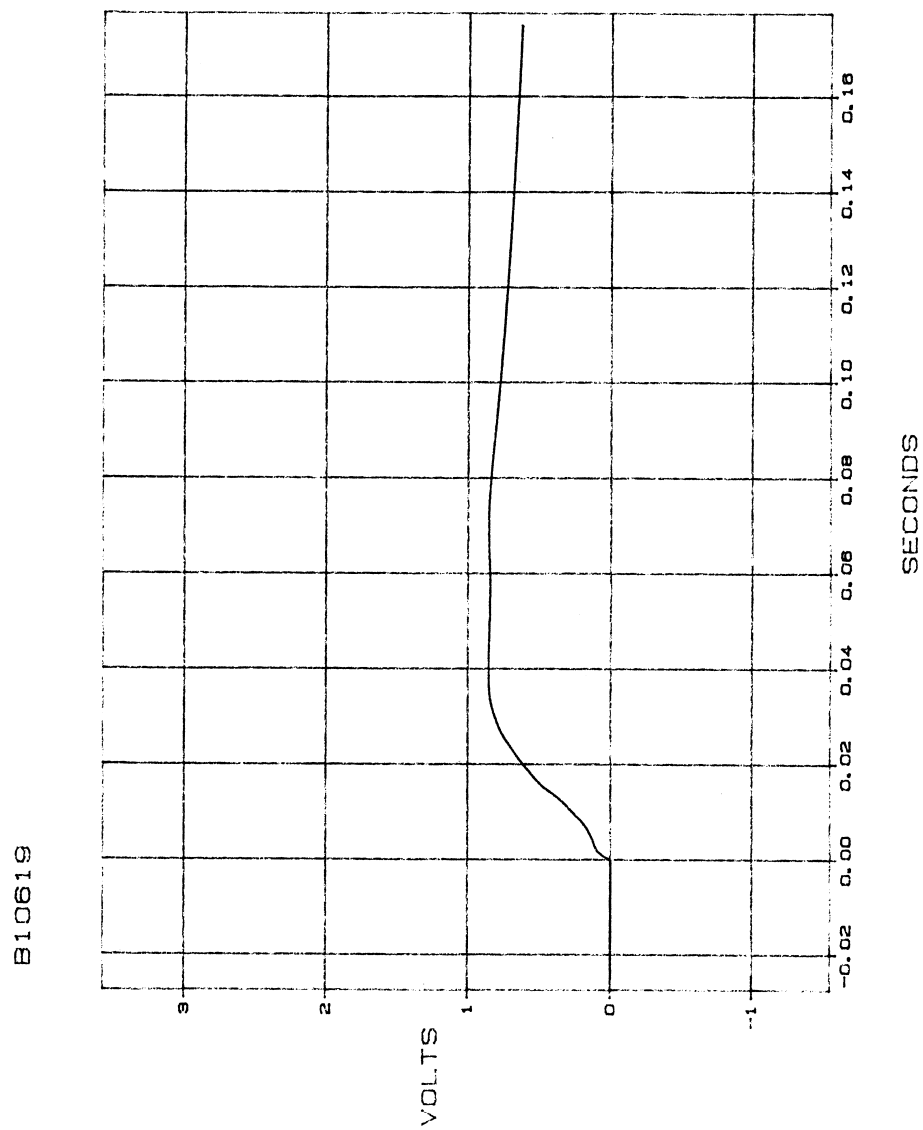
06-13-96-D2



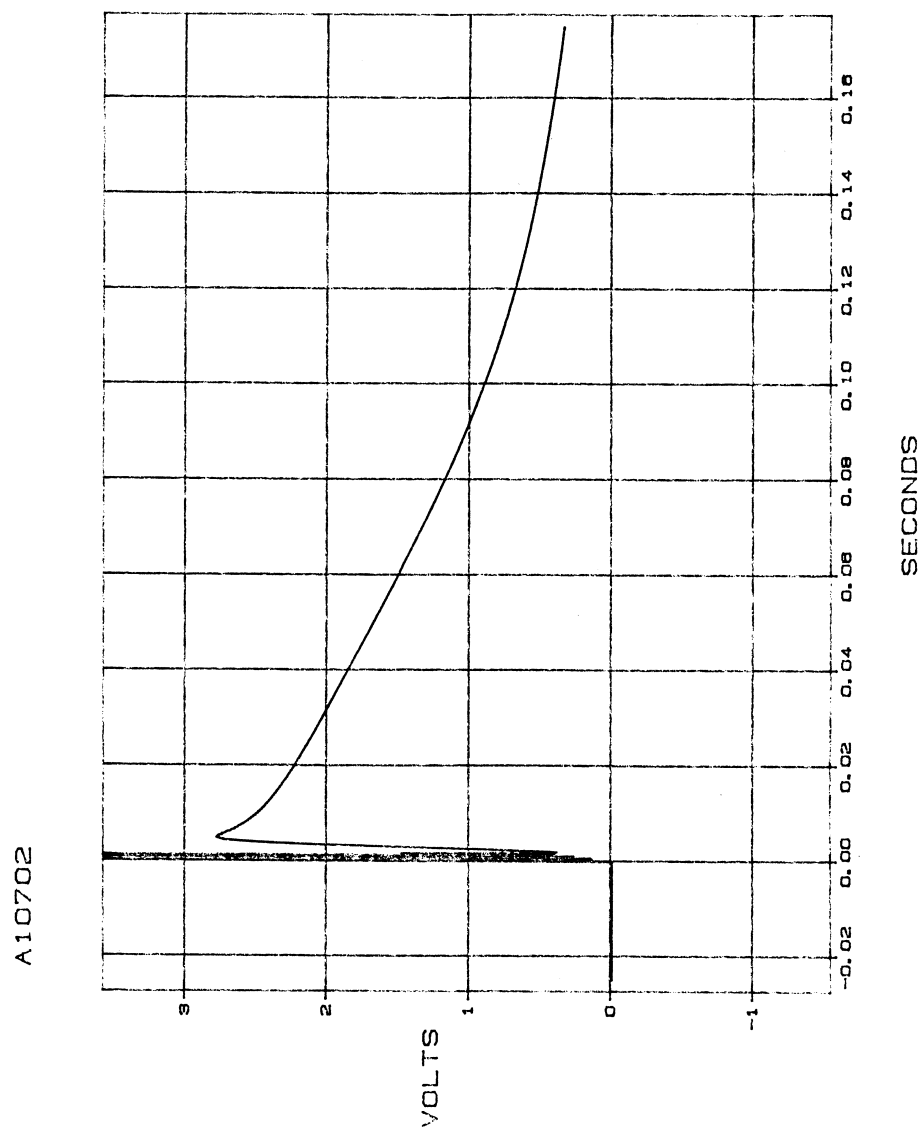
06-19-96-A2



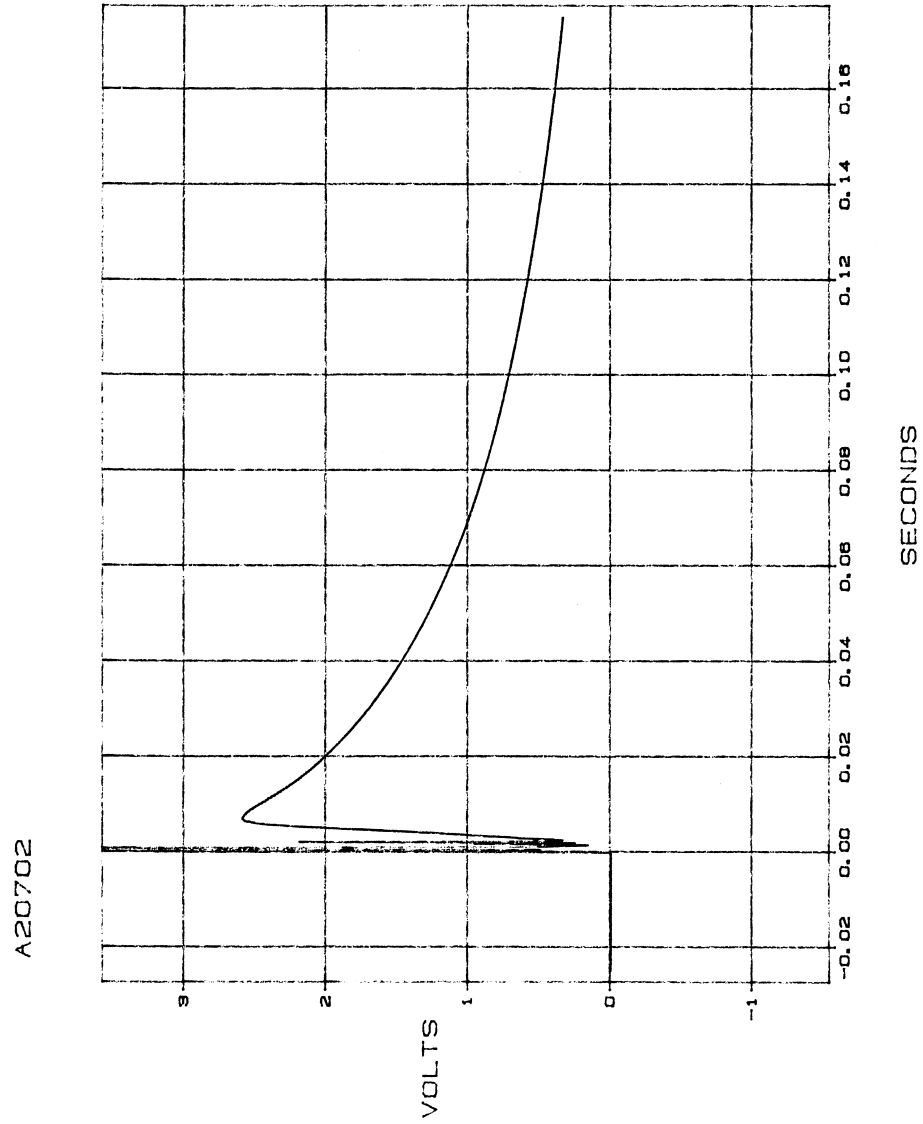
06-19-96-A3



06-19-96-B1

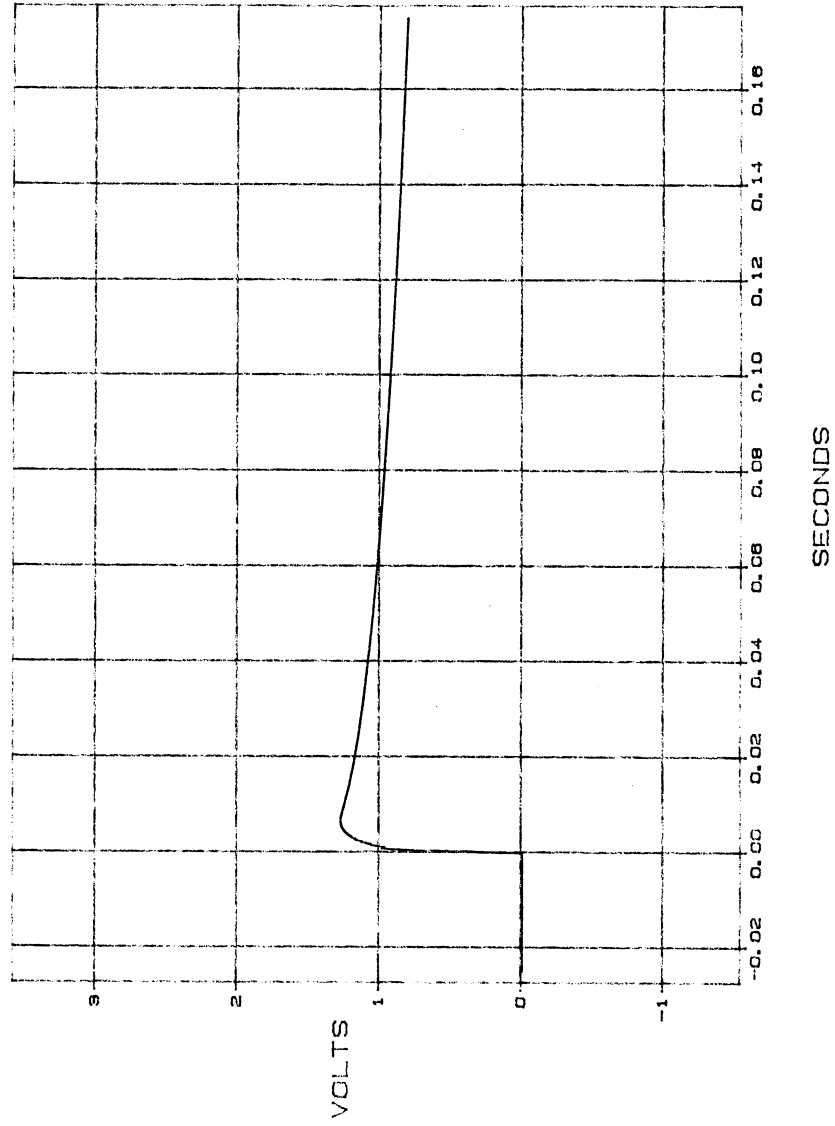


07-02-96-A1

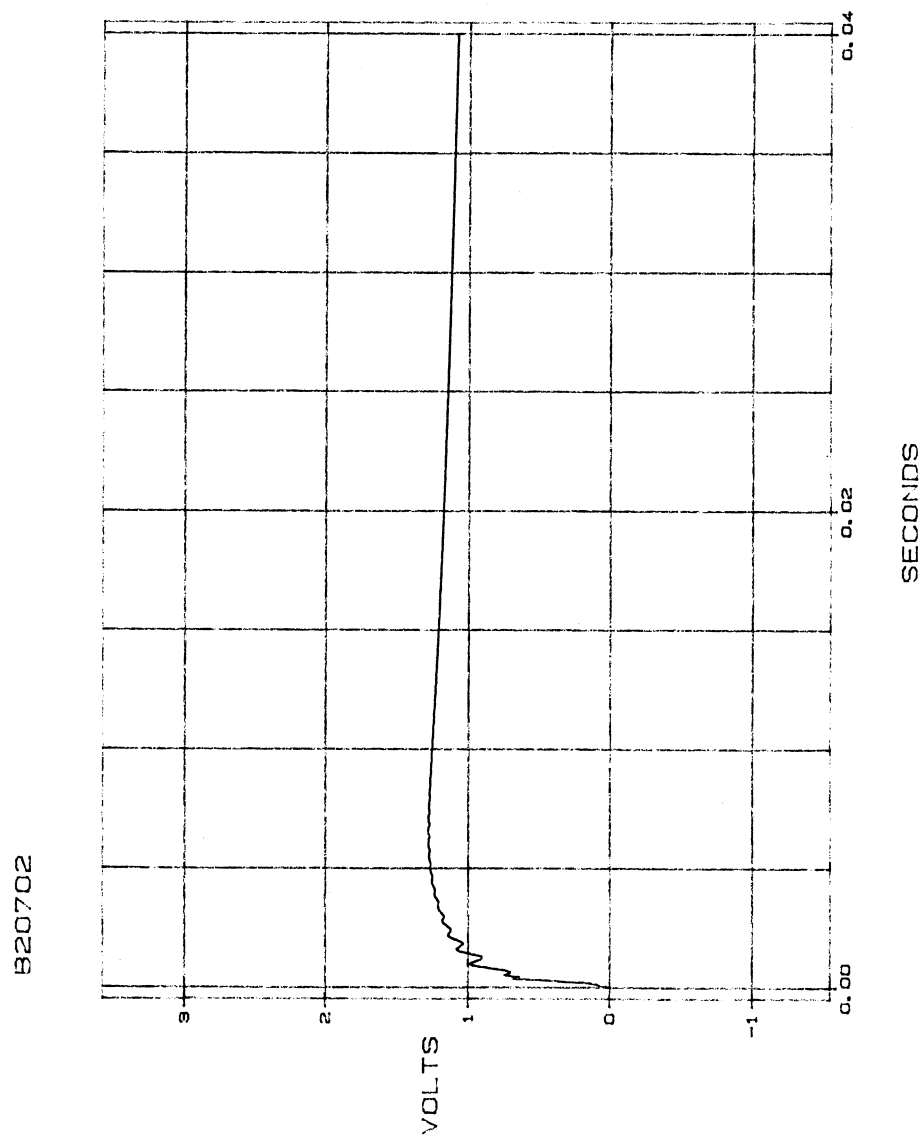


07-02-96-A2

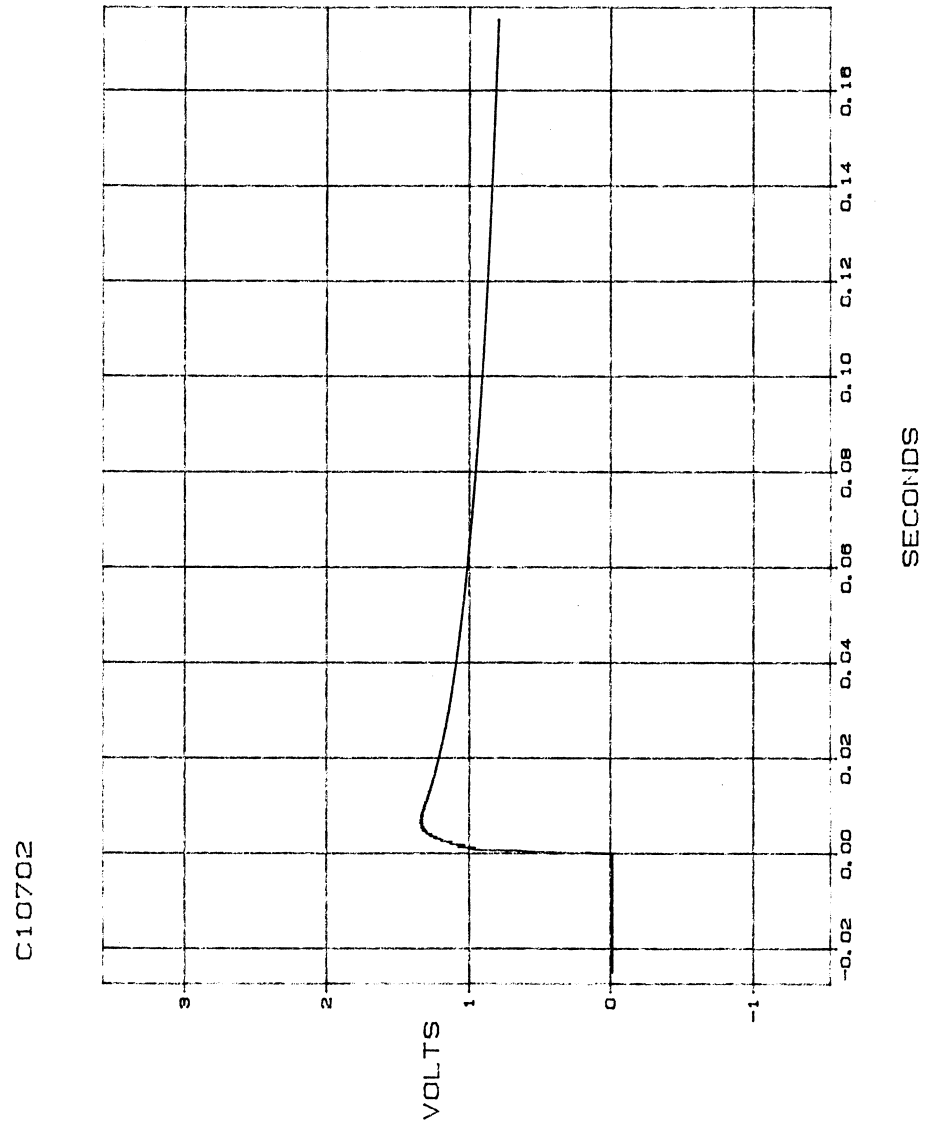
B10702



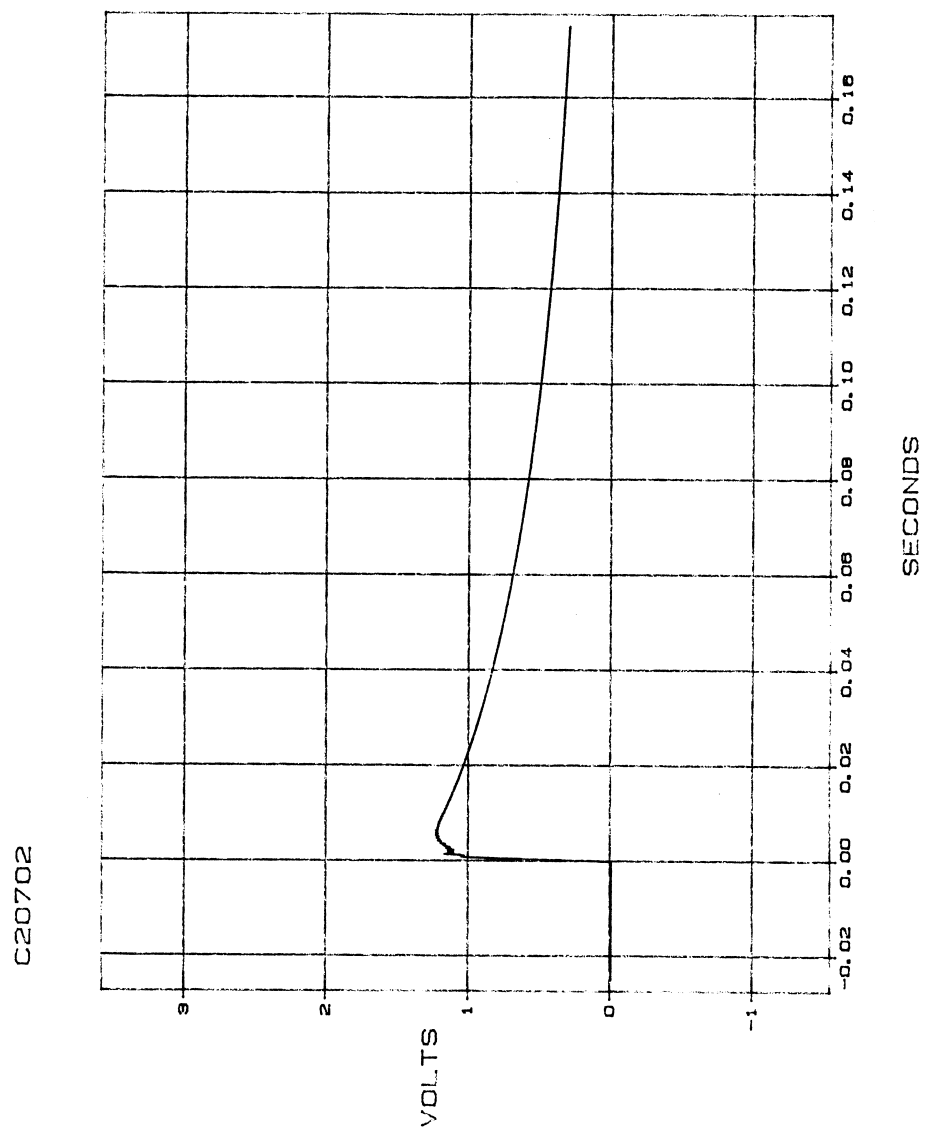
07-02-96-B1



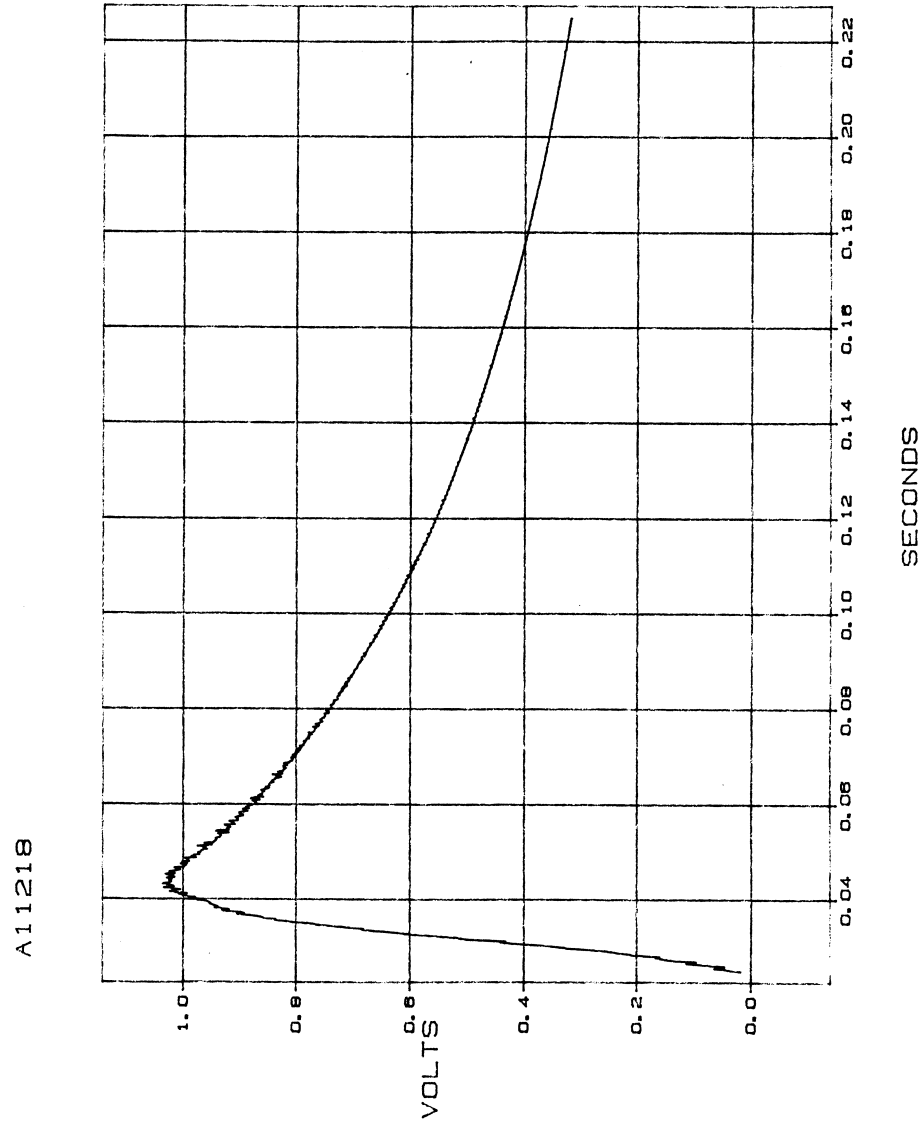
07-02-96-B2



07-02-96-C1

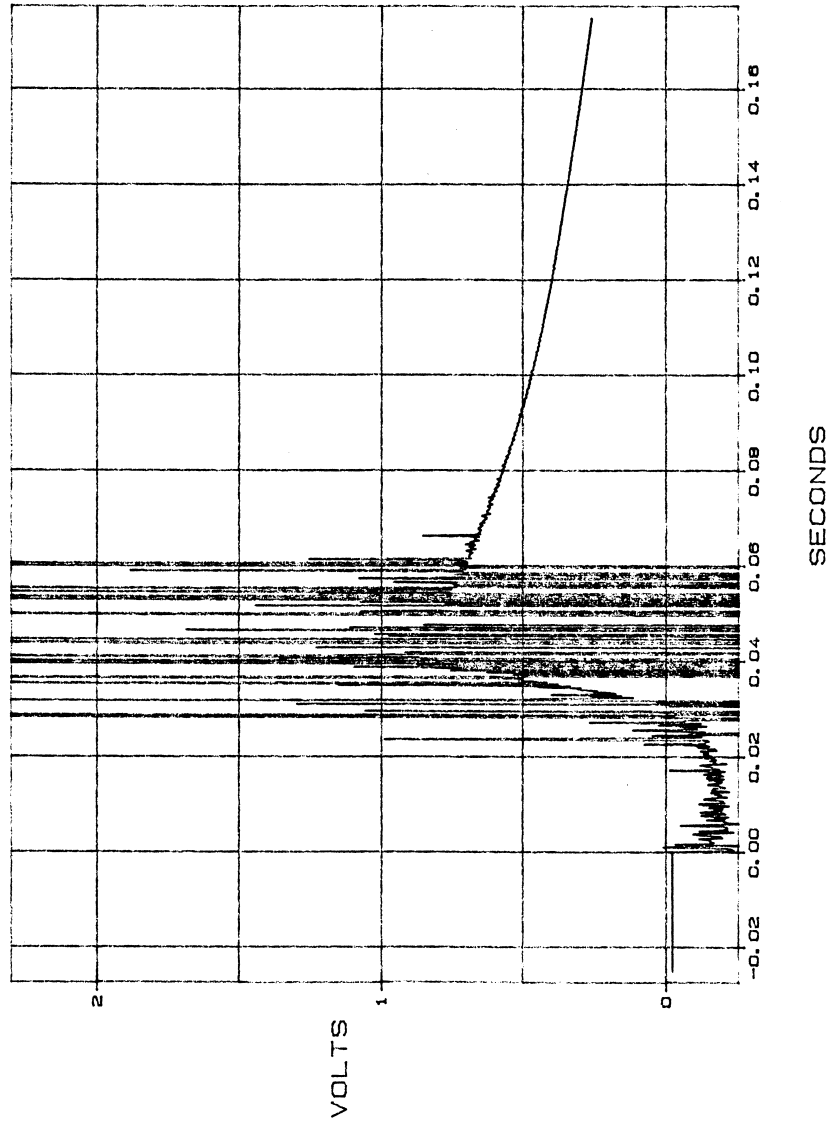


07-02-96-C2

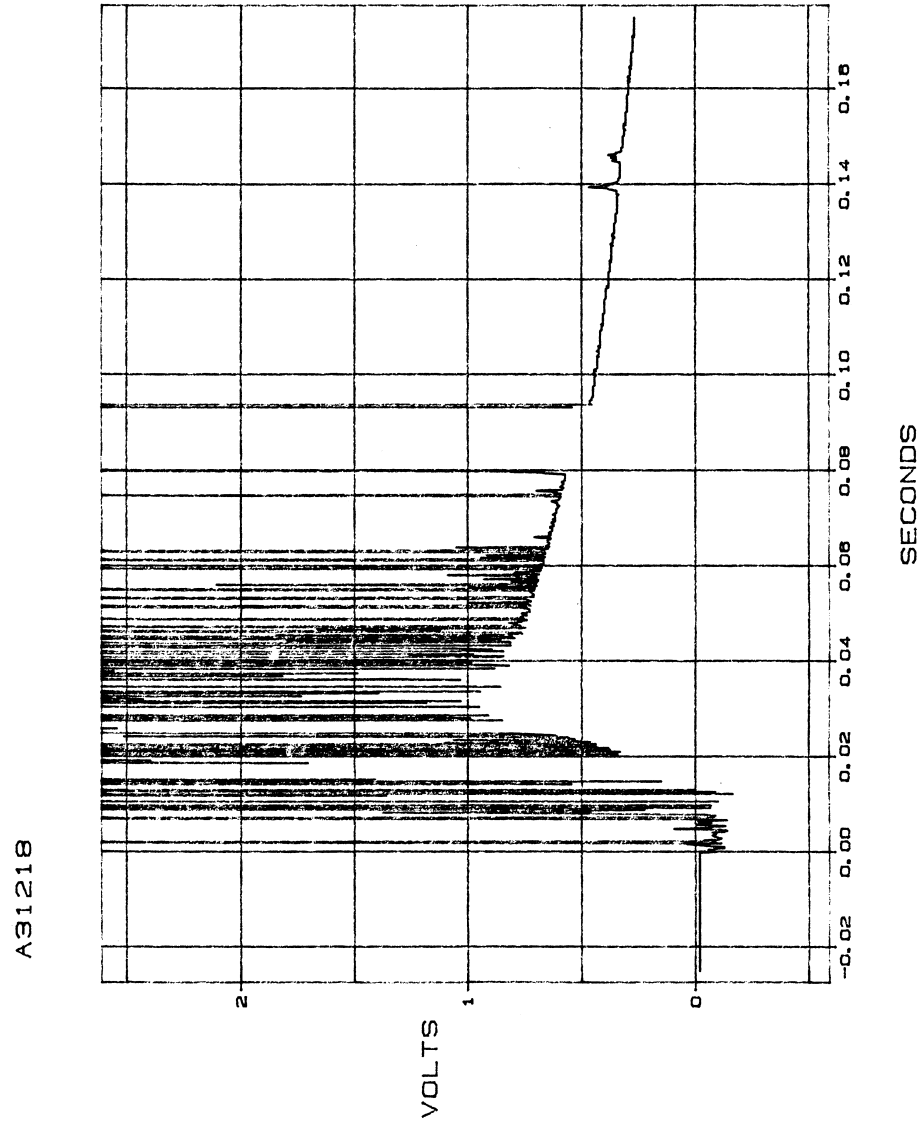


12-18-96-A1

A21218

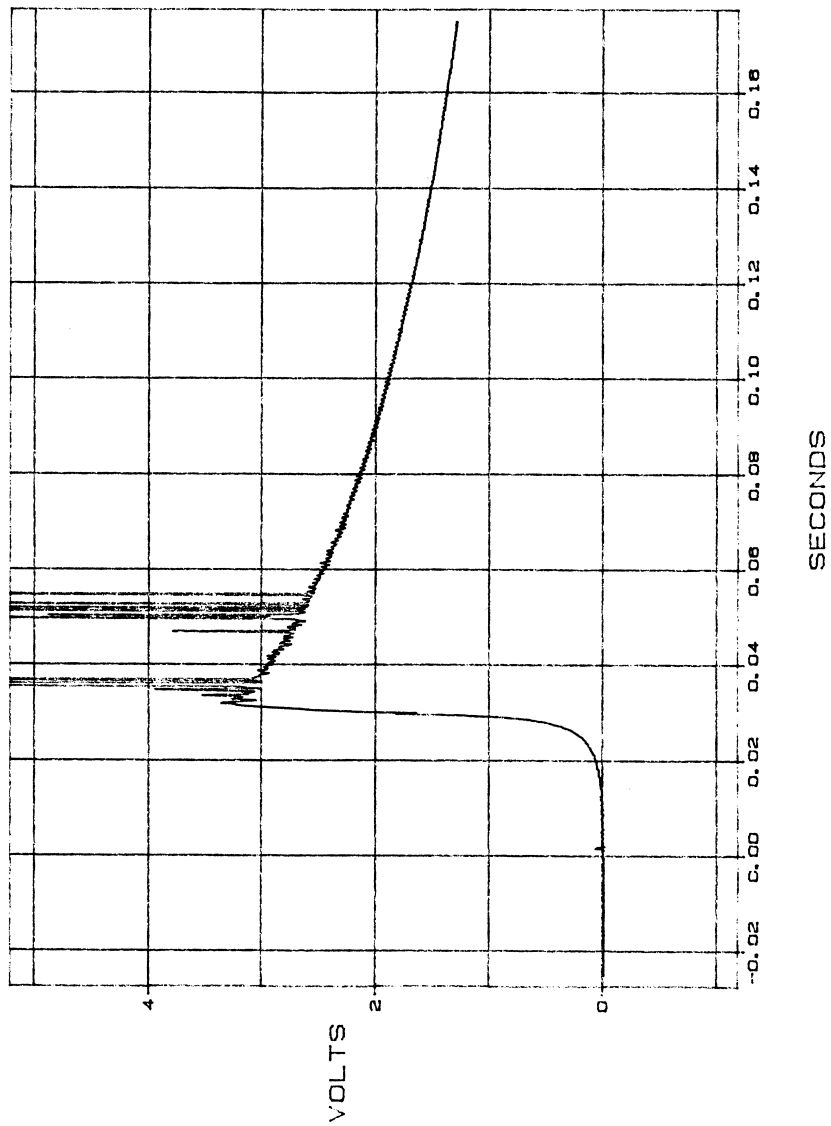


12-18-96-A2

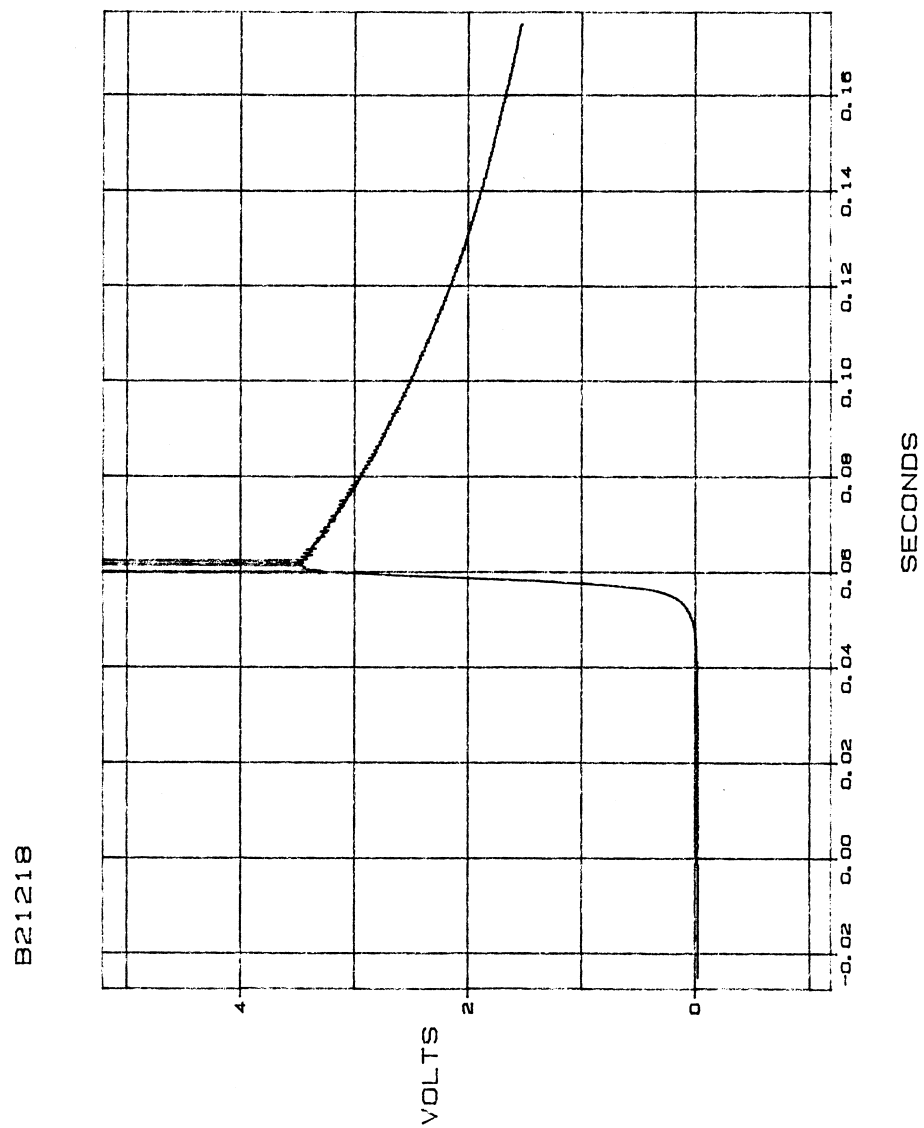


12-18-96-A3

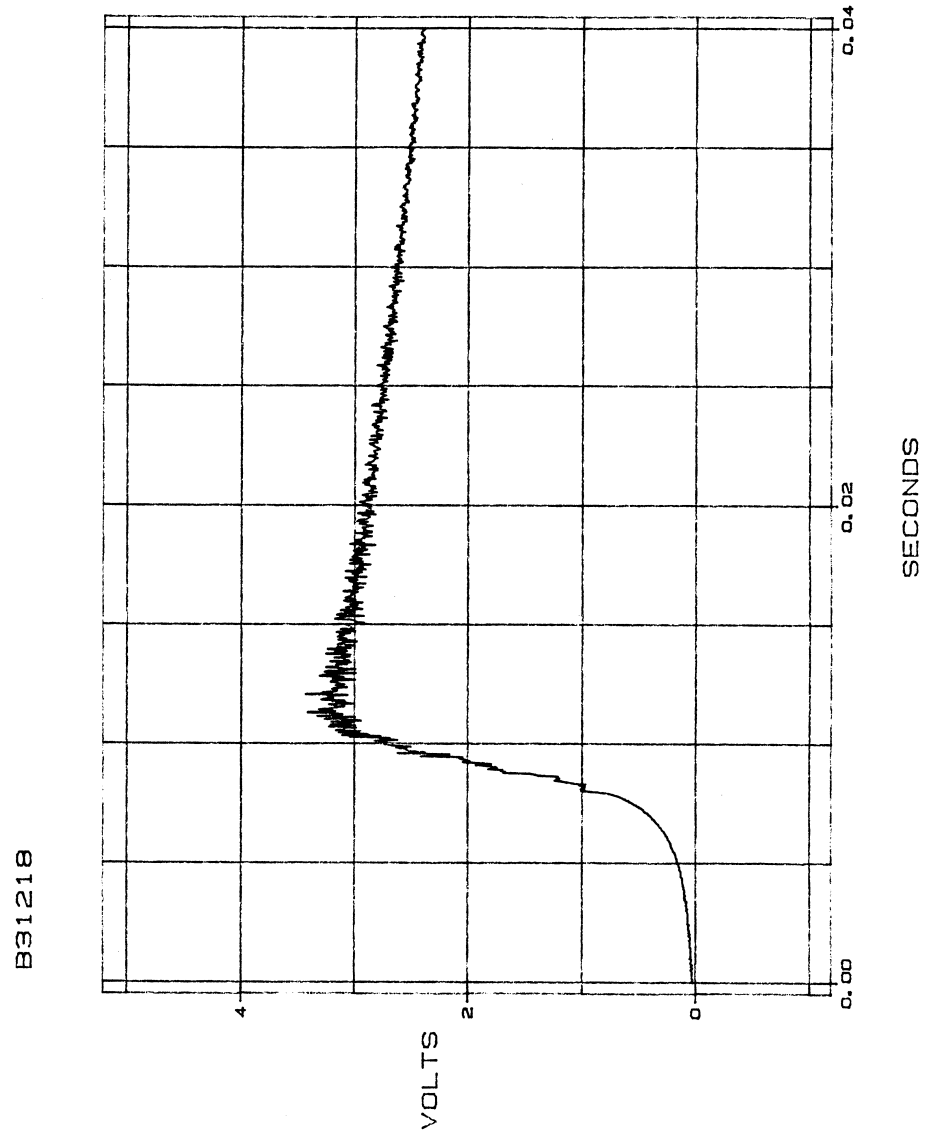
B11218



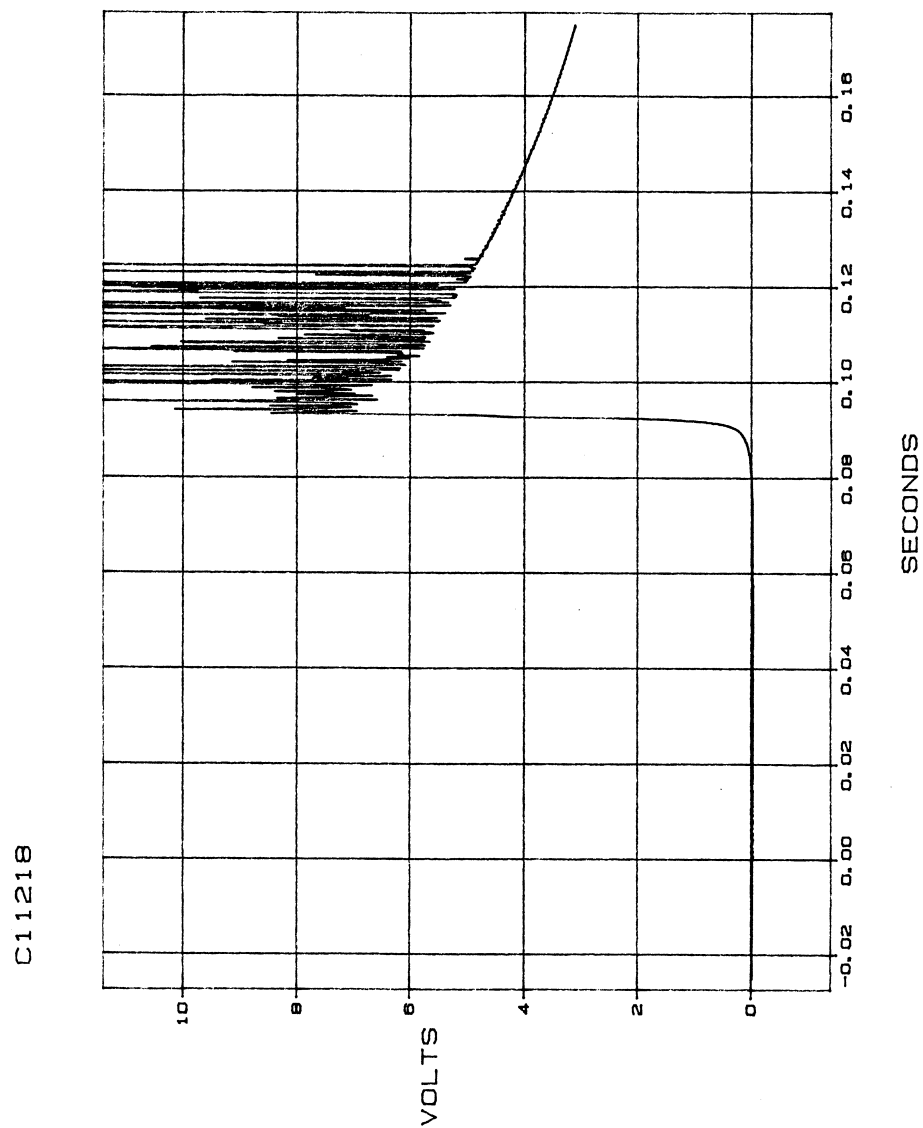
12-18-96-B1



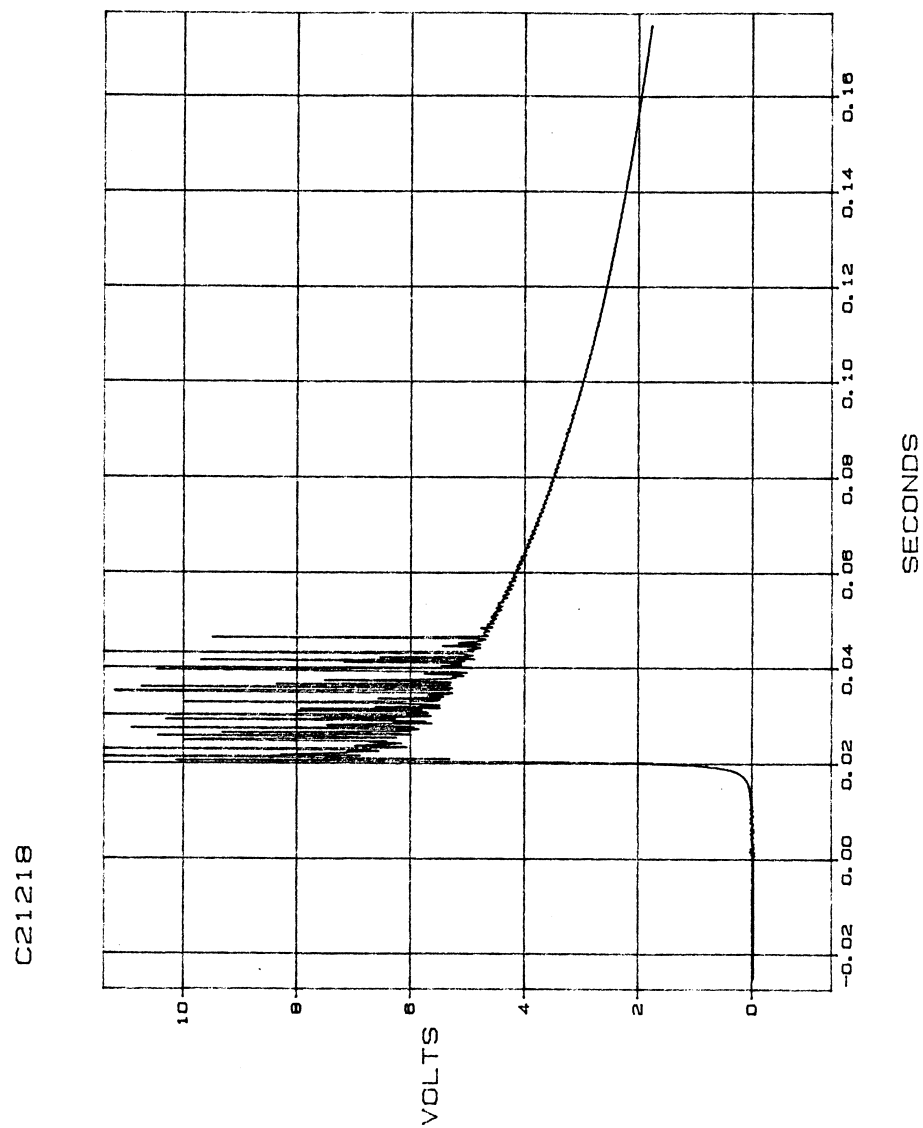
12-18-96-B2



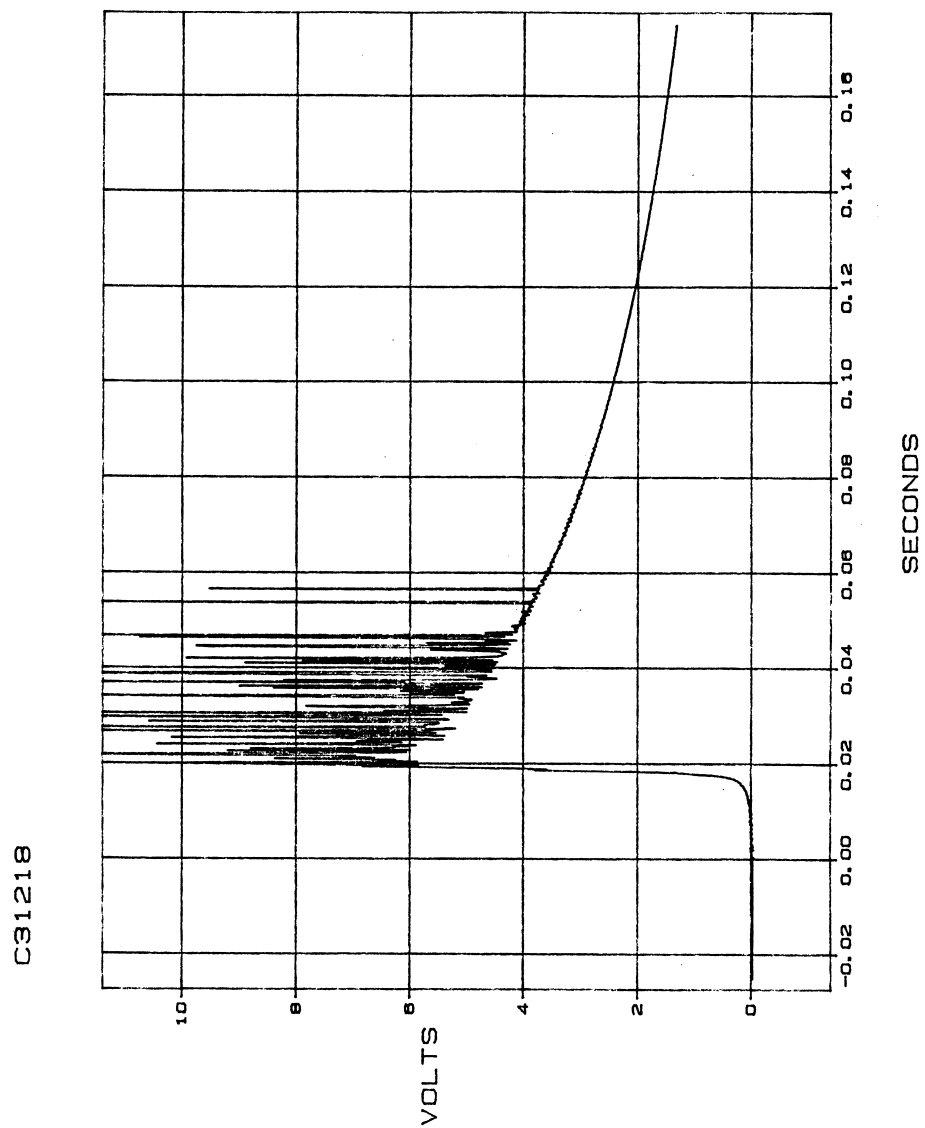
12-18-96-B3



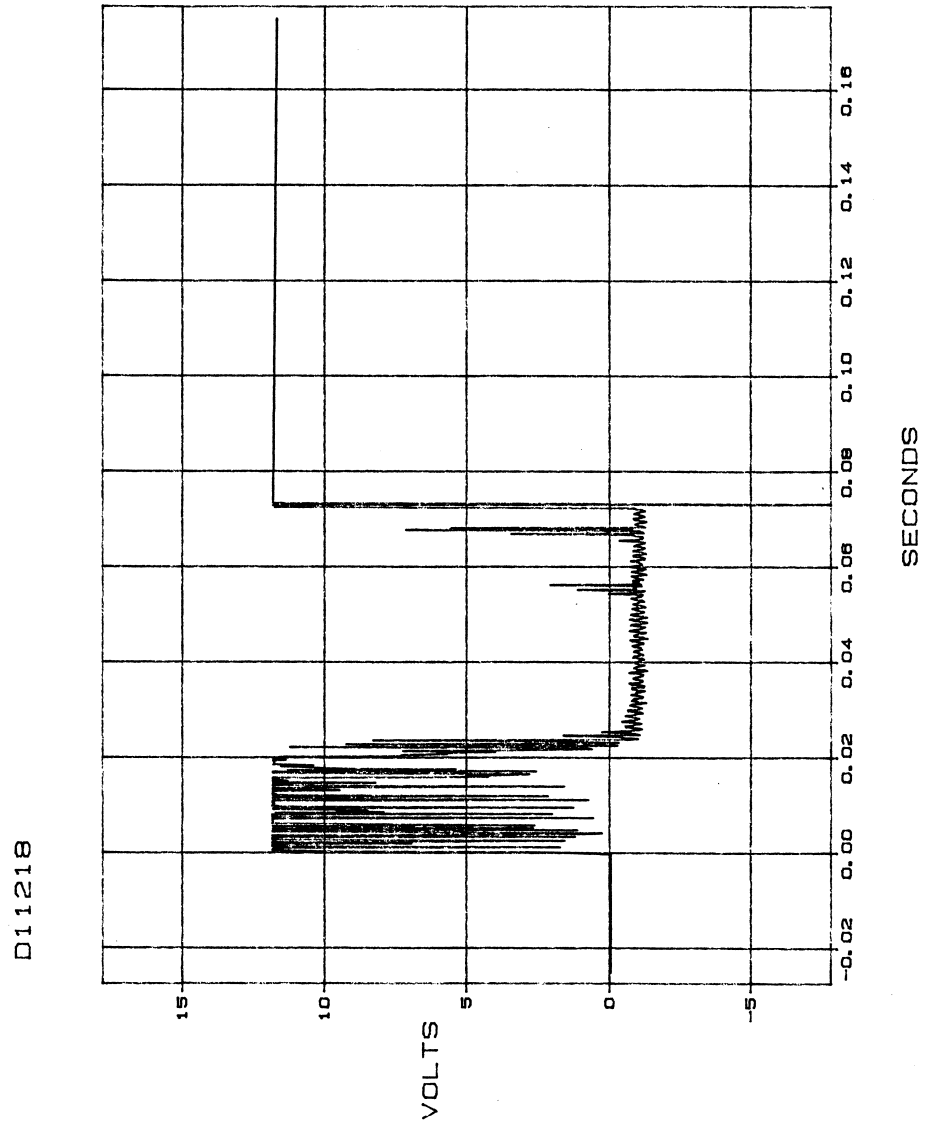
12-18-96-C1



12-18-96-C2



12-18-96-C3



12-18-96-D1

Appendix E

Code Listing For BURNIT.FOR Program

PROGRAM BURNIT

```

C *****
C *PROGRAM by Ian M. Loomis *
C *****
C * Program for computation of test vessel pressure parameters associated*
C * with the combustion of a propellant charge. *
C *****

C *****
C MODIFICATIONS TO CODE
C 30 SEPT 1996 - ADDED COVOLUME CORRECTION TO THE PRESSURE
C COMPUTATIONS  $P=(RT/v*COVOLUME)$ 
C 7 OCT 1996 - ADDED BURNRATE MODIFIERS EXPONENTIAL, POWER LAW
C AND POLYNOMIAL
C 11 OCT 1996 - ADDED BURNING MODEL 3, RADIAL OUTWARD
C 14 OCT 1996 - ADDED BURNING MODEL 4, RADIAL INWARD
C MASS FLOW RATE FUNCTIONS FOR SUBSONIC AND SONIC
C FLOW OF GAS FROM NOZZLES, BURNING MODEL 5
C 22 OCT 1996 - MODIFY MODEL2 SUBROUTINE TO DROP SEGMENTS FROM
C COMPUTATIONAL CYCLE AFTER ALL PROPELLANT HAS BEEN
C CONSUMED IN THAT SEGMENT; AXIAL MOVEMENT RATE AS A
C FUNCTION OF THE NOMINAL BURNRATE, RATHER THAN
C THE DETERRED BURNRATE.
C 27 NOV 1996 - ADDED OPTION FOR VENTED BOMB, BURNING MODEL 5
C MODIFIED INSTANTANEOUS IGNITION MODEL TO ACCOUNT FOR
C VOLUME OF REMAINING PROPELLANT IN THE SPECIFIC VOLUME
C AND PRESSURE COMPUTATIONS.
C *****

C Definition of Variables
C
C Burn Rate
C A - Burn Rate Coefficient
C P - Chamber Pressure
C n - Burn Rate index
C  $\dot{X}$  - Burn Velocity ( $\dot{X} = A*P^n$ )

C Propellant Characteristics
C den - grain density
C bden - bulk density
C mdia - mean grain diameter
C imass - initial mass of propellant
C impetus - impetus of propellant
C covol - propellant gas covolume

C Products Characteristics
C TC = Temperature of Combustion
C R = Gas Constant of Products
C Cv = Specific Heat at Constant Volume

C Initial Conditions

```

```

C      BV = Bomb Volume
C      mair = initial mass of air
C      Cvair = specific heat of air at Constant Volume
C      T0 = initial temperature of air
C      Pint = initial pressure (absolute)
C      Rair = gas constant of air
C      dt = time step

C      Computed Values
C      mair = initial mass of air
C      gvol = grain volume
C      gmass = grain mass
C      spart = specific particles (grains per cubic meter)
C      garea = surface area of grains
C      ivol = initial volume of propellant
C      iarea = initial surface area of propellant
C      numg = approx. number of grains of propellant involved

C      Definition of Array COMPX elements
C      COMPx(1) = time step
C      COMPx(2) = Initial pressure of time step
C      COMPx(3) = Initial temperature of time step
C      COMPx(4) = Initial specific volume at time step
C      COMPx(5) = Initial particle diameter at time step
C      COMPx(6) = Burn Velocity at beginning of time step
C      COMPx(7) = Particle diameter at end of time step
C      COMPx(8) = Volume consumed during time step
C      COMPx(9) = Total volume consumed through time step
C      COMPx(10) = Mass consumed during time step
C      COMPx(11) = Total mass of propellant consumed through step
C      COMPx(12) = Total gaseous phase mass in bomb through step
C      COMPx(13) = Specific Volume at end of time step
C      COMPx(14) = Temperature at end of time step
C      COMPx(15) = Pressure at end of time step
C      where x is the basic model number.

C      MODEL2 SPECIFIC VARIABLES
C      LENGTH = LENGTH OF PROPELLANT CHARGE
C      CAREA = CROSS-SECTIONAL AREA OF PROPELLANT CHARGE
C      ARATIO = ADVANCEMENT RATIO TO GRAIN BURN RATE
C      ADV = AMOUNT OF ADVANCEMENT IN CURRENT TIME STEP
C      IGZONE = LENGTH OF IGNITION ZONE
C      TLENGTH = LENGTH OF CHARGE INVOLVED IN BURN

C      UNIT DEFINITION
C
C      UNIT 3 = DOS PRINTER
C      UNIT 6 = STANDARD INPUT OUTPUT DEVICE
C      UNIT 21 = OUTPUT DATA FILE
C      UNIT 22 = INPUT DATA FILE

C      DETERRENT PARAMETERS
C

```

```

C   DET = DETERRENT MODEL NUMBER
C       1 = LOGARITHMIC MODEL
C       2 = POWER LAW MODEL
C       3 = POLYNOMIAL LAW
C       9 = NONE
C   irate = INITIAL RELATIVE BURN RATE (Xdot/Xdot(0))
C   lc = POWER LAW COEFFICIENT
C   li = POLYNOMIAL INDEX

C   define character variables

CHARACTER YN*1, INFILE*64, OUTFILE*64

C   define real variables

REAL pi, nc
REAL A, P, n, Xdot
REAL den, bden, mdia, imass, impetus, covol
REAL TC, R, Cv, BV, mair, Cvair, T0, Pint, Rair
REAL dt
C   REAL COMP1(15)
REAL gvol, gmass, spart, garea, ivol, iarea, numg
c   REAL V1, V2
REAL li, lc, irate

C   define integer variables

INTEGER i, j, k, l
INTEGER DET

C   define matrix variables

C   COMMON BLOCK OF DATA NECESSARY FOR MODEL NUMBER 1, INSTANANEOUS
C   IGNITION OF ALL PROPELLANT.

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A TC,R,Pint,mdia,covol

C   COMMON BLOCK OF DATA NECESSARY FOR MODEL NUMBER 2, AXIAL
C   BURNING OF THE PROPELLANT.

COMMON/MOD2/spart,bden

C   COMMON BLOCK OF DATA NECESSARY FOR DETERMINING THE BURN RATE
C   DETERRENT PROPERTIES.

COMMON/DETER/DET,lc,li,irate,nc

C   Define data constants

DATA pi/3.1415926536/
DATA nc/2.7182818284/

```

```

3  FORMAT(I1)
4  FORMAT(A64)
5  FORMAT(A1)

C   open access to DOS printer
    OPEN(UNIT=3,FILE='PRN')

CALL CSCREEN

WRITE(6,*)'DO YOU WANT TO USE A PREPARED DATA FILE? '
READ(6,5)YN

C   *****
C   DATA INPUT IF STATMENT
C   USES A PREPARED DATA FILE IF THE USER DESIRES
C   OTHERWISE THE USER MUST ENTER ALL OF THE DATA FROM THE KEYBOARD
C   ONCE KEYBOARD ENTRY IS COMPLETE THE USER CAN SAVE THE DATA
C   AS A DATA FILE, UPTO 64 CHARACTERS IN LENGTH.
C   *****

IF((YN.EQ. 'Y') .OR. (YN.EQ. 'y')) THEN
    WRITE(6,*)'WHAT IS THE NAME OF YOUR INPUT FILE? '
    READ(6,4) INFILE
    OPEN(UNIT=22,FILE = INFILE)
        READ(22,*) A
        READ(22,*) n
        READ(22,*) den
        READ(22,*) bden
        READ(22,*) mdia
        READ(22,*) imass
        READ(22,*) impetus
        READ(22,*) TC
        READ(22,*) R
        READ(22,*) Cv
        READ(22,*) BV
        READ(22,*) Cvair
        READ(22,*) T0
        READ(22,*) Pint
        READ(22,*) Rair
        READ(22,*) dt
        READ(22,*) covol
    REWIND(22)
    CLOSE(22)

ELSE

C   obtain initial data values

    WRITE(6,*)'INPUT PROPELLANT CHARACTERISTICS'

    WRITE(6,*)'WHAT IS THE PROPELLANT COEFFICIENT, (A)? '
    READ(6,*) A

```

```

WRITE(6,*)'WHAT IS THE PROPELLANT INDEX, (n)? '
READ(6,*) n

WRITE(6,*)'WHAT IS THE PROPELLANT GRAIN DENSITY? '
READ(6,*) den

WRITE(6,*)'WHAT IS THE PROPELLANT BULK DENSITY? '
READ(6,*) bden

WRITE(6,*)'WHAT IS MEAN GRAIN DIAMETER (d50)? '
READ(6,*) mdia

WRITE(6,*)'WHAT IS THE INITIAL MASS OF PROPELLANT (kg)? '
READ(6,*) imass

WRITE(6,*)'WHAT IS IMPETUS OF IGNITION FOR THE PROPELLANT? '
READ(6,*) impetus

WRITE(6,*)'WHAT IS THE PROPELLANT TEMPERATURE OF COMBUSTION? '
READ(6,*) TC

WRITE(6,*)'WHAT IS THE PRODUCTS OF COMBUSTION GAS CONSTANT? '
READ(6,*) R

WRITE(6,*)'WHAT IS THE Cv SPECIFIC HEAT OF THE POCs? '
READ(6,*) Cv

WRITE(6,*)'WHAT IS THE BOMB VOLUME? '
READ(6,*) BV

WRITE(6,*)'WHAT IS THE CONSTANT VOLUME SPECIFIC HEAT OF AIR? '
READ(6,*) Cvair

WRITE(6,*)'WHAT IS THE INITIAL AIR TEMPERATURE? '
READ(6,*) T0

WRITE(6,*)'WHAT IS THE INITIAL AIR PRESSURE? '
READ(6,*) Pint

WRITE(6,*)'WHAT IS THE GAS CONSTANT FOR AIR? '
READ(6,*) Rair

10  WRITE(6,*)'PLEASE ENTER YOUR DESIRED TIME INCREMENT '
    READ(6,*) dt
    IF (dt .LT. 0.1) THEN
        dt = dt*(1E-6)
        WRITE(6,*)'YOUR TIME STEP IS, ',dt,' SECONDS.'
        WRITE(6,*)'ARE YOU SURE THAT YOU WANT IT THIS SMALL? '
        WRITE(6,*)'PLEASE ENTER A VALUE AT LEAST 0.1 MICRO-SECONDS.'
        GOTO 10
    ELSE
        dt = dt*(1E-6)

```

```

END IF

WRITE(6,*)'WHAT IS THE PROPELLANT GAS COVOLUME? '
READ(6,*)covol

WRITE(6,*)'DO YOU WISH TO SAVE THIS DATA IN A FILE?'
READ(6,5)YN
IF((YN .EQ. 'Y') .OR. (YN .EQ. 'y')) THEN
  WRITE(6,*)'NAME TO SAVE FILE AS? '
  READ(6,4) INFILE
  OPEN(UNIT=22, FILE = INFILE)
  WRITE(22,*) A
  WRITE(22,*) n
  WRITE(22,*) den
  WRITE(22,*) bden
  WRITE(22,*) mdia
  WRITE(22,*) imass
  WRITE(22,*) impetus
  WRITE(22,*) TC
  WRITE(22,*) R
  WRITE(22,*) Cv
  WRITE(22,*) BV
  WRITE(22,*) Cvair
  WRITE(22,*) T0
  WRITE(22,*) Pint
  WRITE(22,*) Rair
  WRITE(22,*) dt
  WRITE(22,*) covol
  REWIND (22)
  CLOSE (22)
ELSE
  CONTINUE
END IF

END IF
C *****
C ENDS IF STATEMENT ASSOCIATED WITH DATA INPUT
C *****

C COMPUTE THE MASS OF AIR IN THE TEST VESSEL
mair = ((Pint*Bv)/(Rair*T0))

C COMPUTE THE VOLUME OF PROPELLANT GRAIN
gvol = ((pi*(mdia**3))/6)

C COMPUTE THE MASS OF A GRAIN OF PROPELLANT
gmass = gvol*den

C COMPUTE THE SPECIFIC PARTICLE
spart = bden/gmass

C COMPUTE INITIAL VOLUME OF PROPELLANT
ivol = imass/bden

```

```

C   DETERMINE INITIAL NUMBER OF GRAINS OF PROPELLANT
      numg = spart*ivol

C   DETERMINE INITIAL SURFACE AREA OF PROPELLANT
      iarea = pi*(mdia**2)*numg

C   COMPUTE INITIAL BURN RATE
      Xdot = A*(Pint**n)

C   OPEN THE OUTPUT DATA FILE.

      WRITE(6,*)'PLEASE ENTER THE NAME FOR YOUR OUTPUT FILE.'
      READ(6,4) OUTFILE
      OPEN(UNIT=21,FILE=OUTFILE)

      CALL DATESTAMP

      WRITE(21,100)'TIME','PRESSURE','TEMPERATURE',
A   'SPECIFIC VOLUME','DIAMETER'
C   WRITE(6,100)'TIME','PRESSURE','TEMPERATURE',
C   A   'SPECIFIC VOLUME','DIAMETER'

      WRITE(21,101)'(SECONDS)','(Pa)','(K)','(m3/kg)','(m)'
C   WRITE(6,101)'(SECONDS)','(Pa)','(K)','(m3/kg)','(m)'

100  FORMAT(5A17)
101  FORMAT(5A17)
102  FORMAT(5E17.4)

C   PAUSE

109  CALL MENU1
      READ(6,*) j

C   DETERMINE WHICH MODEL FOR DETERRENT IS DESIRED

      IF (j .EQ. 1) THEN
        DET = 1
        WRITE(6,*)'WHAT IS INITIAL RELATIVE BURN RATE? '
        READ(6,*)irate
      ELSE IF (j .EQ. 2) THEN
        DET = 2
        WRITE(6,*)'SORRY, THIS MODEL IS NOT AVAILABLE.'
        PAUSE
        GOTO 109
C      WRITE(6,*)'WHAT IS INITIAL RELATIVE BURN RATE? '
C      READ(6,*)irate
C      WRITE(6,*)'WHAT IS THE POWER LAW COEFF.? '
C      READ(6,*)lc
      ELSE IF (j .EQ. 3) THEN
        DET = 3

```



```

        WRITE(6,*)'WHAT IS INITIAL RELATIVE BURN RATE? '
        READ(6,*)irate
        WRITE(6,*)'WHAT IS POLYNOMIAL INDEX? '
        READ(6,*)li
    ELSE IF (j .EQ. 9) THEN
        irate = 1.0
        DET = 9
    ELSE IF (j .EQ. 0) THEN
        GOTO 99999
    ELSE
        WRITE(6,*) '
        WRITE(6,*)'INVALID SELECTION, PLEASE CHOOSE AGAIN.'
        WRITE(6,*) '
        PAUSE
        GOTO 109
    END IF

C    CONTROL THE IRATE BETWEEN 0 AND 1

    IF ((irate .LT. 0) .OR. (irate .GT. 1)) THEN
        WRITE(6,*)'RELATIVE BURN RATE BETWEEN 0 AND 1.'
        PAUSE
        GOTO 109
    END IF

200  CALL MENU2
    READ(6,3) I

C    DETERMINE MODEL DESIRED AND MAKE NECESSARY CALL TO SUBROUTINE

    IF (I .EQ. 1) THEN
        CALL MODEL1
    ELSE IF (I .EQ. 2) THEN
        CALL MODEL2
    ELSE IF (I .EQ. 3) THEN
        CALL MODEL3
    ELSE IF (I .EQ. 4) THEN
        CALL MODEL4
    ELSE IF (I .EQ. 5) THEN
        CALL MODEL5
    ELSE IF (I .EQ. 6) THEN
        CALL MODEL6
    ELSE IF (I .EQ. 0) THEN
        GOTO 99999
    ELSE
        WRITE(6,*)'INVALID SELECTION - PLEASE CHOOSE A MODEL.'
        PAUSE
        GOTO 200
    END IF

99999  STOP 'PROGRAM NORMALLY TERMINATED'
11111  END

```

```

C *****

SUBROUTINE MODEL1

C *****
C COMPUTATIONAL SCHEME NUMBER 1
C THIS SCHEME ASSUMES THAT ALL OF THE PROPELLANT IS IGNITED SIMULTANEOUSLY
C *****
REAL V1,V2,COMP1(15)
REAL imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,TC,R
REAL Pint,mdia,covol
REAL lc, li, irate, relpos, deterr,nc

INTEGER DET

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A TC,R,Pint,mdia,covol

COMMON/DETER/DET,lc,li,irate,nc

C INITIALIZE COMPUTATIONAL ARRAY

COMP1(1) = 0
COMP1(2) = Pint
COMP1(3) = T0
COMP1(4) = BV/mair
COMP1(5) = mdia
COMP1(6) = 0
COMP1(7) = 0
COMP1(8) = 0
COMP1(9) = 0
COMP1(10) = 0
COMP1(11) = 0
COMP1(12) = 0
COMP1(13) = 0
COMP1(14) = 0
COMP1(15) = 0

C COMPUTATIONAL LOOP

102 FORMAT(5E17.4)

CALL CSCREEN

DO 200 WHILE ((imass - COMP1(11)) .GE. 0.00)

```

```

      WRITE(21,102)COMP1(1),COMP1(2),COMP1(3),COMP1(4),COMP1(5)
C      WRITE(6,102)COMP1(1),COMP1(2),COMP1(3),COMP1(4),COMP1(5)

C      determine burn velocity at time step

      relpos = 1 - (COMP1(5)/mdia)

      if (DET .EQ. 1) then
        CALL EXPLAW(irate, nc, relpos, deterr)

      else if (DET .EQ. 3) then
        CALL POLYLAW(irate, li, relpos, deterr)

      else

        deterr = 1
      end if

      COMP1(6) = (A*(COMP1(2)**n))*deterr

c      determine diameter at end of time step

      COMP1(7) = COMP1(5) - (2*COMP1(6)*dt)

c      determine volume of propellant consumed in time step.

      V1 = ((pi*(COMP1(5)**3))/6)
      V2 = ((pi*(COMP1(7)**3))/6)

      COMP1(8) = (V1 - V2)*numg

c      determine the total volume of propellant consumed

      COMP1(9) = COMP1(9)+COMP1(8)

C      determine mass of propellant consumed in time step

      COMP1(10) = COMP1(8) * den

c      determine total mass of propellant consumed

      COMP1(11) = COMP1(11) + COMP1(10)

C      determine total gas phase mass in pressure vessel

      COMP1(12) = COMP1(11) + mair

c      compute specific volume at end of time step

```

```

COMP1(13) = ((BV-((imass-comp1(11))/den))/COMP1(12))

C      compute temperature at end of time step

TVAR1 = mair * Cvair * T0
TVAR2 = COMP1(11) * Cv * TC
TVAR3 = mair * Cvair
TVAR4 = COMP1(11) * Cv

COMP1(14) = ((TVAR1 + TVAR2)/(TVAR3 + TVAR4))

C      compute pressure at end of time step

COMP1(15) = ((R * COMP1(14))/(COMP1(13)-covol))

C      advance initial conditions in array for next time step.

COMP1(1) = COMP1(1) + dt
COMP1(2) = COMP1(15)
COMP1(3) = COMP1(14)
COMP1(4) = COMP1(13)
COMP1(5) = COMP1(7)

200  CONTINUE
REWIND(21)
CLOSE(21)

RETURN
END

C      *****

C      *****

SUBROUTINE MODEL2

C      *****

C      COMPUTATIONAL SCHEME NUMBER 2
C      USED TO COMPUTE BURN RATE FOR AXIAL PROGRESSION OF BURNING
C      IN PROPELLANT CHARGE
C      *****

REAL V1,V2,COMP2(15),LENGTH,CAREA,ARATIO,IGZONE,CDIA,SEGVOL
REAL INC(10,1500)

```

```

REAL imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,TC,R
REAL Pint,mdia,covol
REAL spart,bden
REAL lc, li, irate, nc

```

```

INTEGER DET, M

```

```

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A TC,R,Pint,mdia,covol

```

```

COMMON/MOD2/spart,bden

```

```

COMMON/DETER/DET,lc,li,irate,nc

```

```

C   DEFINITION OF VARIABLES IN INC(10,1500) ARRAY

```

```

C       INC(1,I)= PARTICLE DIAMETER
C       INC(2,I)= LENGTH OF SEGMENT
C       INC(3,I)= NUMBER OF PARTICLES IN SEGMENT
C       INC(4,I)= PARTICLE DIAMETER AT END OF TIME STEP
C       INC(5,I)= VOLUME CONSUMED IN TIME STEP
C       INC(6,I)= MASS CONSUMED IN TIME STEP
C       INC(7,I)= TOTAL LENGTH OF CHARGE INVOLVED
C       INC(8,I)= LOCAL BURN RATE
C       INC(9,I)=
C       INC(10,I)=

```

```

C   INITIALIZE THE BASIC PROPELLANT BURN ARRAY

```

```

COMP2(1) = 0
COMP2(2) = Pint
COMP2(3) = T0
COMP2(4) = BV/mair
COMP2(5) = mdia
COMP2(6) = 0
COMP2(7) = 0
COMP2(8) = 0
COMP2(9) = 0
COMP2(10) = 0
COMP2(11) = 0
COMP2(12) = 0
COMP2(13) = 0
COMP2(14) = 0
COMP2(15) = 0

```

```

C   OBTAIN ADDITIONAL DATA REQUIRED FOR THIS GEOMETRY

```

```

CALL CSCREEN

```

```
WRITE(6,*)'WHAT IS THE CHARGE DIAMETER (m)? '
READ(6,*)CDIA
```

```
CAREA = (pi*((CDIA/2)**2))
```

```
LENGTH = (imass/(bden*CAREA))
```

```
WRITE(6,*)'WHAT IS THE ADVANCEMENT RATIO? '
READ(6,*)ARATIO
```

```
WRITE(6,*)'WHAT IS THE IGNITION ZONE LENGTH? '
READ(6,*)IGZONE
```

```
C    COMPUTATIONAL LOOP 1
```

```
C    INITIALIZE INCREMENT DATA ARRAY
```

```
DO 150 j=1,1500,1
    INC(1,j)= mdia
    INC(2,j)= IGZONE
    INC(3,j)= (CAREA*IGZONE)*spart
    INC(4,j)= mdia
    INC(5,j)= 0
    INC(6,j)= 0
    INC(7,j)= IGZONE
    INC(8,j)= 0
    INC(9,j)= 0
    INC(10,j)= 0
```

```
150  CONTINUE
```

```
201  FORMAT(6E17.4)
```

```
M = 1
```

```
I = 1
```

```
WRITE(21,201)COMP2(1),COMP2(2),COMP2(3),COMP2(4),inc(7,I),
```

```
A  COMP2(11)
```

```
DO 500 WHILE (((imass - COMP2(11)) .GT. 0.00)
```

```
A  .AND. (INC(7,I) .LT. LENGTH))
```

```
DO 400 k=M,I
```

```
C    DETERMINE LOCAL BURN RATE FOR EACH INCREMENTAL ELEMENT
```

```
relpos = 1 - (INC(1,k)/mdia)
```

```
if (DET .EQ. 1) then
```

```
    CALL EXPLAW(irate, nc, relpos, deterr)
```

```
else if (DET .EQ. 3) then
```

```

        CALL POLYLAW(irate, li, relpos, deterr)
    else
        deterr = 1
    end if

    INC(8,k) = (A*(COMP2(2)**n))*deterr

C   WRITE(6,*)'INSIDE LOOP 400, ITERATION = ',k
    IF (INC(1,k) .GT. 0.0) THEN

C   determine diameter in segment k at end of time step.

    INC(4,k) = (INC(1,k) - (2*INC(8,k)*dt))

C   set lower limit on particle diameter

    IF (INC(4,k) .LE. 0.0) THEN
        INC(4,k) = 0
        M = M + 1
    END IF

C   determine volume of propellant consumed in segment k
C   in this time step.

    IF (INC(1,k) .GT. 0.0) THEN

        V1 = ((pi*(INC(1,k)**3))/6)
        V2 = ((pi*(INC(4,k)**3))/6)

        INC(5,k) = (V1-V2)*INC(3,k)

C   determine mass of propellant consumed in segment k
C   in this time step.

        INC(6,k) = INC(5,k)*den

    ELSE
        INC(5,k) = 0
        INC(6,k) = 0
    ENDIF

    COMP2(11) = COMP2(11) + INC(6,k)

C   set initial diameter for next time step to current diameter

    INC(1,k) = INC(4,k)

```

```

ELSE

INC(5,k) = 0.0
INC(6,k) = 0.0

END IF

400  END DO

IF(INC(7,l) .LT. LENGTH) THEN

C   increment segment index

I = I+1

C   determine length of next segment in reaction

relpos = 0

if (DET .EQ. 1) then
    CALL EXPLAW(irate, nc, relpos, deterr)
else if (DET .EQ. 3) then
    CALL POLYLAW(irate, li, relpos, deterr)
else
    deterr = 1
end if

INC(8,l) = (A*(COMP2(2)**n))*deterr

INC(2,l) = (A*(COMP2(2)**N))*dt*ARATIO


C   determine total length of charge involve in reaction

INC(7,l) = INC(7,(l-1))+INC(2,l)

IF (INC(7,l) .GT. LENGTH) THEN
    INC(7,l)=LENGTH
    INC(2,l)=INC(7,l) - INC(7,(l-1))
ELSE
    CONTINUE
END IF

c   WRITE(6,*)'TOTAL IGNITED LENGTH IS NOW: ',INC(7,l)

C   determine number of particles in the new segment

SEGVOL=CAREA*INC(2,l)
INC(3,l) = SEGVOL*spart

```


- C determine diameter at end of time segment
- $$INC(4,I) = INC(1,I) - (INC(8,I) * dt)$$
- IF (INC(4,I) .LE. 0.0) THEN
 INC(4,I) = 0
 END IF
- C determine amount of propellant burned in the next segment
 C figure at 1/2 of full rate
- $$V1 = ((pi * (INC(1,I) ** 3)) / 6)$$
- $$V2 = ((pi * (INC(4,I) ** 3)) / 6)$$
- $$INC(5,I) = (V1 - V2) * INC(3,I)$$
- C compute mass burned in segment during this time increment
- $$INC(6,I) = INC(5,I) * den$$
- $$INC(1,I) = INC(4,I)$$
- C sum up the mass consumed in through time step
- $$COMP2(11) = COMP2(11) + INC(6,I)$$
- C end of upper portion of if statement for inc(7,i) .ie. length
- END IF
- $$COMP2(12) = COMP2(11) + mair$$
- C COMPUTE SPECIFIC VOLUME AT END OF TIME STEP
- $$COMP2(13) = (BV / COMP2(12))$$
- C COMPUTE TEMPERATURE AT END OF TIME STEP
- $$TVAR1 = mair * Cvair * T0$$
- $$TVAR2 = COMP2(11) * Cv * TC$$
- $$TVAR3 = mair * Cvair$$
- $$TVAR4 = COMP2(11) * Cv$$
- $$COMP2(14) = ((TVAR1 + TVAR2) / (TVAR3 + TVAR4))$$
- C COMPUTE THE PRESSURE AT THE END OF THE TIME STEP.

```
COMP2(15) = ((R * COMP2(14))/(COMP2(13)-covol))
```

```
C   ADVANCE INITIAL CONDITIONS FOR THE NEXT TIME STEP
```

```
COMP2(1) = COMP2(1) + dt
COMP2(2) = COMP2(15)
COMP2(3) = COMP2(14)
COMP2(4) = COMP2(13)
```

```
WRITE(21,201)COMP2(1),COMP2(2),COMP2(3),COMP2(4),INC(7,I),
A  comp2(11)
```

```
500  END DO
      REWIND(21)
      CLOSE(21)
```

```
RETURN
END
```

```
C   *****
```

```
SUBROUTINE MODEL3
```

```
C   *****
```

```
C   COMPUTATIONAL SCHEME 3
```

```
C   SUBROUTINE TO MODEL BURNING OF PROPELLANTS RADially OUTWARD
C   FROM AN IGNITION ALONG THE CENTER.
```

```
C   *****
```

```
REAL V1,V2,COMP3(15),LENGTH,CAREA,ARATIO,IGZONE,CDIA,SEGVOL
REAL IGDIA, IGVOL
REAL IN3(10,1500)
```

```
REAL imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,TC,R
REAL Pint,mdia,covol
REAL spart,bden
REAL lc, li, irate, nc
```

```
INTEGER DET
```

```
COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A  TC,R,Pint,mdia,covol
```

```
COMMON/MOD2/spart,bden
```

```
COMMON/DETER/DET,lc,li,irate,nc
```

C DEFINITION OF VARIABLES IN INC(10,1500) ARRAY

C IN3(1,I)= PARTICLE DIAMETER
 C IN3(2,I)= LENGTH OF SEGMENT
 C IN3(3,I)= NUMBER OF PARTICLES IN SEGMENT
 C IN3(4,I)= PARTICLE DIAMETER AT END OF TIME STEP
 C IN3(5,I)= VOLUME CONSUMED IN TIME STEP
 C IN3(6,I)= MASS CONSUMED IN TIME STEP
 C IN3(7,I)= TOTAL LENGTH OF CHARGE INVOLVED
 C IN3(8,I)= LOCAL BURN RATE
 C IN3(9,I)=
 C IN3(10,I)=

C INITIALIZE THE BASIC PROPELLANT BURN ARRAY

COMP3(1) = 0
 COMP3(2) = Pint
 COMP3(3) = T0
 COMP3(4) = BV/mair
 COMP3(5) = mdia
 COMP3(6) = 0
 COMP3(7) = 0
 COMP3(8) = 0
 COMP3(9) = 0
 COMP3(10) = 0
 COMP3(11) = 0
 COMP3(12) = 0
 COMP3(13) = 0
 COMP3(14) = 0
 COMP3(15) = 0

C OBTAIN GEOMETRY CONSIDERATIONS FOR THIS MODEL

CALL CSCREEN

WRITE(6,*)'WHAT IS CHARGE DIAMETER? '
 READ(6,*)CDIA

WRITE(6,*)'WHAT IS DIAMETER OF IGNITER CORD? '
 READ(6,*)IGDIA

WRITE(6,*)'WHAT IS ADVANCEMENT RATIO? '
 READ(6,*)ARATIO

WRITE(6,*)'WHAT IS THE THICKNESS OF THE IGNITED ZONE? '
 READ(6,*)IGZONE

$CAREA = (\pi * (((CDIA/2)**2) - ((IGDIA/2)**2)))$
 $LENGTH = (imass / (bden * CAREA))$

$IGVOL = (\pi * (((IGDIA/2) + IGZONE)**2) - ((IGDIA/2)**2)) * LENGTH$

```

C   INITIALIZE INCREMENT DATA ARRAY
DO 150 J=1,1500,1
    IN3(1,j)= mdia
    IN3(2,j)= IGZONE
    IN3(3,j)= (IGVOL)*spart
    IN3(4,j)= mdia
    IN3(5,j)= 0
    IN3(6,j)= 0
    IN3(7,j)= IGZONE+(IGDIA/2)
    IN3(8,j)= 0
    IN3(9,j)= 0
    IN3(10,j)= 0
150  CONTINUE

201  FORMAT(6E17.4)

    L = 1

    WRITE(21,201)COMP3(1),COMP3(2),COMP3(3),COMP3(4),IN3(7,L),
A   COMP3(11)

    DO 500 WHILE (((imass-COMP3(11)) .GT. 0.00)
A   .AND. (IN3(1,L) .GT. 0.0))

    DO 400 K=1,L

C   DETERMINE LOCAL BURN RATE FOR EACH INCREMENTAL ELEMENT

    RELPOS = (IN3(1,K)/mdia)

    if (DET .EQ. 1) THEN
        CALL EXPLAW(irate, nc, relpos, deterr)
    else if (DET .EQ. 3) THEN
        CALL POLYLAW(irate, li, relpos, deterr)
    else
        deterr = 1
    end if

    IN3(8,K) = (A*(COMP3(2)**n))*deterr

    IF (IN3(1,K) .GT. 0.0) THEN

    IN3(4,K) = (IN3(1,K)-(2*IN3(8,K)*dt))

    IF (IN3(4,K) .LE. 0.0) THEN
        IN3(4,K) = 0
    END IF

C   DETERMINE VOLUME OF PROPELLANT CONSUMED IN SEGMENT K
C   IN THIS TIME STEP.

```

```

IF (IN3(1,K) .GT. 0.0) THEN
  V1 = ((pi*(IN3(1,K)**3))/6)
  V2 = ((pi*(IN3(4,K)**3))/6)

  IN3(5,K) = (V1-V2)*IN3(3,K)

C   DETERMINE MASS OF PROPELLANT CONSUMED IN SEGMENT K FOR
C   THIS TIME STEP.

  IN3(6,K) = IN3(5,K)*den

ELSE
  IN3(5,K) = 0.0
  IN3(6,K) = 0.0

END IF

COMP3(11) = COMP3(11) + IN3(6,K)

C   SET INITIAL DIAMETER FOR THE NEXT TIME STEP TO CURRENT DIAMETER

IN3(1,K) = IN3(4,K)

ELSE

  IN3(5,K) = 0.0
  IN3(6,K) = 0.0

END IF

400  END DO

IF (IN3(7,L) .LT. (CDIA/2)) THEN

C   INCREMENT SEGMENTOR INDEX

  L = L + 1

C   DETERMINE RADIUS OF NEXT SEGMENT IN REACTION.

  RELPOS = 0

  IF (DET .EQ. 1) THEN
    CALL EXPLAW(IRATE, NC, RELPOS, DETERR)
  ELSE IF (DET .EQ. 3) THEN
    CALL POLYLAW(IRATE, LI, RELPOS, DETERR)
  ELSE
    DETER = 1
  END IF

  IN3(8,L) = (A*(COMP3(2)**N))*DETERR
  IN3(2,L) = IN3(8,L)*DT*ARATIO

```

```

C   DETERMINE DIAMETER OF CHARGE INVOLVED IN REACTION

IN3(7,L) = IN3(7,(L-1))+IN3(2,L)

IF (IN3(7,L) .GT. (CDIA/2)) THEN
    IN3(7,L) = (CDIA/2)
    IN3(2,L) = IN3(7,L) - IN3(7,(L-1))
ELSE
    CONTINUE
END IF

C   DETERMINE NUMBER OF PARTICLES IN THE NEW SEGMENT

SEGVOL = LENGTH*(pi*((IN3(7,L)**2)-(IN3(7,L-1)**2)))
IN3(3,L) = SEGVOL*spart

C   DETERMINE DIAMETER AT END OF TIME SEGMENT

IN3(4,L) = IN3(1,L) - (IN3(8,L)*dt)

IF (IN3(4,L) .LE. 0.0) THEN
    IN3(4,L) = 0
END IF

C   DETERMINE AMOUNT OF PROPELLANT BURNED IN THE NEXT SEGMENT
C   FIGURED AT 1/2 OF FULL RATE

V1 = ((pi*(IN3(1,L)**3))/6)
V2 = ((pi*(IN3(4,L)**3))/6)

IN3(5,L) = (V1-V2)*IN3(3,L)

C   COMPUTE MASS BURNED IN SEGMENT DURING THIS TIME INCREMENT

IN3(6,L) = IN3(5,L) * DEN

IN3(1,L) = IN3(4,L)

C   SUM UP MASS CONSUMED IN THIS TIME STEP

COMP3(11) = COMP3(11)+IN3(6,L)

END IF

COMP3(12) = COMP3(11) + MAIR

C   COMPUTE SPECIFIC VOLUME AT END OF TIME STEP

COMP3(13) = (BV/COMP3(12))

C   COMPUTE TEMPERATURE AT END OF TIME STEP

```

```

TVAR1 = mair*Cvair*T0
TVAR2 = COMP3(11)*Cv*TC
TVAR3 = mair*Cvair
TVAR4 = COMP3(11)*Cv

COMP3(14) = ((TVAR1 + TVAR2)/(TVAR3 + TVAR4))

C   COMPUTE THE PRESSURE AT THE END OF THE TIME STEP.

COMP3(15) = ((R * COMP3(14))/(COMP3(13)-covol))

C   ADVANCE INITIAL CONDITIONS FOR THE NEXT TIME STEP

COMP3(1) = COMP3(1) + dt
COMP3(2) = COMP3(15)
COMP3(3) = COMP3(14)
COMP3(4) = COMP3(13)

WRITE(21,201)COMP3(1),COMP3(2),COMP3(3),COMP3(4),IN3(7,I),
A  comp3(11)

500  END DO
      REWIND(21)
      CLOSE(21)

      RETURN
      END

C   *****

SUBROUTINE MODEL4

C   *****

C   COMPUTATIONAL SCHEME NUMBER 4
C   METHOD TO EVALUATE BURNING OF PROPELLANT RADially INWARD TO A
C   CYLINDRICAL CHARGE

C   *****

REAL V1,V2,COMP4(15),LENGTH,CAREA,ARATIO,IGZONE,CDIA,SEGVOL
REAL IGVOL
C   REAL IGDIA
REAL IN4(10,1500)

REAL imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,TC,R
REAL Pint,mdia,covol
REAL spart,bden
REAL lc, li, irate, nc

```

INTEGER DET

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A TC,R,Pint,mdia,covol

COMMON/MOD2/spart,bden

COMMON/DETER/DET,lc,li,irate,nc

C DEFINITION OF VARIABLES IN IN4(10,1500) ARRAY

C IN4(1,I)= PARTICLE DIAMETER
C IN4(2,I)= LENGTH OF SEGMENT
C IN4(3,I)= NUMBER OF PARTICLES IN SEGMENT
C IN4(4,I)= PARTICLE DIAMETER AT END OF TIME STEP
C IN4(5,I)= VOLUME CONSUMED IN TIME STEP
C IN4(6,I)= MASS CONSUMED IN TIME STEP
C IN4(7,I)= TOTAL LENGTH OF CHARGE INVOLVED
C IN4(8,I)= LOCAL BURN RATE
C IN4(9,I)=
C IN4(10,I)=

C INITIALIZE THE BASIC PROPELLANT BURN ARRAY

COMP4(1) = 0
COMP4(2) = Pint
COMP4(3) = T0
COMP4(4) = BV/mair
COMP4(5) = mdia
COMP4(6) = 0
COMP4(7) = 0
COMP4(8) = 0
COMP4(9) = 0
COMP4(10) = 0
COMP4(11) = 0
COMP4(12) = 0
COMP4(13) = 0
COMP4(14) = 0
COMP4(15) = 0

C OBTAIN GEOMETRY CONSIDERATIONS FOR THIS MODEL

CALL CSCREEN

WRITE(6,*)'WHAT IS CHARGE DIAMETER? '
READ(6,*)CDIA

C WRITE(6,*)'WHAT IS DIAMETER OF IGNITER CORD? '
C READ(6,*)IGDIA


```
WRITE(6,*)'WHAT IS ADVANCEMENT RATIO? '
READ(6,*)ARATIO
```

```
WRITE(6,*)'WHAT IS THE THICKNESS OF THE IGNITED ZONE? '
READ(6,*)IGZONE
```

```
CAREA = (pi*((CDIA/2)**2))
LENGTH = (imass/(bden*CAREA))
```

```
IGVOL = (pi*(((CDIA/2)**2)-(((CDIA/2)-IGZONE)**2)))*LENGTH
```

C INITIALIZE INCREMENT DATA ARRAY

```
DO 150 J=1,1500,1
  IN4(1,j)= mdia
  IN4(2,j)= IGZONE
  IN4(3,j)= (IGVOL)*spart
  IN4(4,j)= mdia
  IN4(5,j)= 0
  IN4(6,j)= 0
  IN4(7,j)= (CDIA/2) - IGZONE
  IN4(8,j)= 0
  IN4(9,j)= 0
  IN4(10,j)= 0
150 CONTINUE
```

```
201 FORMAT(6E17.4)
```

```
L = 1
```

```
WRITE(21,201)COMP4(1),COMP4(2),COMP4(3),COMP4(4),IN4(7,L),
A COMP4(11)
```

```
DO 500 WHILE (((IMASS-COMP4(11)) .GT. 0.00)
A .AND. (IN4(1,L) .GT. 0.0))
```

```
DO 400 K=1,L
```

C DETERMINE LOCAL BURN RATE FOR EACH INCREMENTAL ELEMENT

```
RELPOS = (IN4(1,K)/MDIA)
```

```
IF (DET .EQ. 1) THEN
  CALL EXPLAW(irate, nc, relpos, deterr)
ELSE IF (DET .EQ. 3) THEN
  CALL POLYLAW(irate, li, relpos, deterr)
ELSE
  deterr = 1
END IF
```

```
IN4(8,K) = (A*(COMP4(2)**n))*deterr
```

```
IF (IN4(1,K) .GT. 0.0) THEN
```

```

      IN4(4,K) = (IN4(1,K)-(2*IN4(8,K)*dt))

      IF (IN4(4,K) .LE. 0.0) THEN
        IN4(4,K) = 0
      END IF

C     DETERMINE VOLUME OF PROPELLANT CONSUMED IN SEGMENT K
C     IN THIS TIME STEP.

      IF(IN4(1,K) .GT. 0.0) THEN
        V1 = ((pi*(IN4(1,K)**3))/6)
        V2 = ((pi*(IN4(4,K)**3))/6)

        IN4(5,K) = ((V1-V2)*IN4(3,K))

C     DETERMINE MASS OF PROPELLANT CONSUMED IN SEGMENT K FOR
C     THIS TIME STEP.

        IN4(6,K) = IN4(5,K)*DEN

      ELSE
        IN4(5,K) = 0.0
        IN4(6,K) = 0.0

      END IF

      COMP4(11) = COMP4(11) + IN4(6,K)

C     SET INITIAL GRAIN DIAMETER FOR THE NEXT TIME STEP TO
C     CURRENT DIAMETER

      IN4(1,K) = IN4(4,K)

      ELSE

        IN4(5,K) = 0.0
        IN4(6,K) = 0.0

      END IF

400  END DO

      IF (IN4(7,L) .GT. 0.0) THEN

C     INCREMENT SEGMENTOR INDEX

      L = L + 1

C     DETERMINE RADIUS OF NEXT SEGMENT IN REACTION.

      RELPOS = 0

      IF (DET .EQ. 1) THEN

```

```

      CALL EXPLAW(IRATE, NC, RELPOS, DETERR)
    ELSE IF (DET .EQ. 3) THEN
      CALL POLYLAW(IRATE, LI, RELPOS, DETERR)
    ELSE
      DETER = 1
    END IF

    IN4(8,L) = (A*(COMP4(2)**n))*DETERR
    IN4(2,L) = IN4(8,L)*DT*ARATIO

C   DETERMINE DIAMETER OF CHARGE INVOLVED IN REACTION

    IN4(7,L) = IN4(7,(L-1)) - IN4(2,L)

    IF (IN4(7,L) .LE. 0.0) THEN
      IN4(7,L) = 0.0
      IN4(2,L) = IN4(7,(L-1)) - IN4(7,L)
    ELSE
      CONTINUE
    END IF

C   DETERMINE NUMBER OF PARTICLES IN TIME STEP

    SEGVOL = LENGTH*(PI*((IN4(7,L-1)**2)-(IN4(7,L)**2)))
    IN4(3,L) = SEGVOL * spart

C   DETERMINE GRAIN DIAMETER AT END OF TIME STEP

    IN4(4,L) = IN4(1,L) - (IN4(8,L)*dt)

    IF(IN4(4,L) .LE. 0.0) THEN
      IN4(4,L) = 0
    END IF

C   DETERMINE AMOUNT OF PROPELLANT BURNED IN THE NEXT SEGMENT
C   FIGURED AT 1/2 OF FULL RATE

    V1 = ((pi*(IN4(1,L)**3))/6)
    V2 = ((pi*(IN4(4,L)**3))/6)

    IN4(5,L) = (V1-V2)*IN4(3,L)

C   COMPUTE MASS BURNED IN SEGMENT DURING THIS TIME INCREMENT

    IN4(6,L) = IN4(5,L) * DEN

    IN4(1,L) = IN4(4,L)

C   SUM UP MASS CONSUMED IN THIS TIME STEP

    COMP4(11) = COMP4(11) + IN4(6,L)

    END IF

```

```

COMP4(12) = COMP4(11) + MAIR

C   COMPUTE SPECIFIC VOLUME AT END OF TIME STEP.

COMP4(13) = (BV/COMP4(12))

C   COMPUTE TEMPERATURE AT END OF TIME STEP.

TVAR1 = MAIR*CVAIR*T0
TVAR2 = COMP4(11)*CV*TC
TVAR3 = MAIR*CVAIR
TVAR4 = COMP4(11)*CV

COMP4(14) = ((TVAR1 + TVAR2)/(TVAR3 + TVAR4))

C   COMPUTE THE PRESSURE AT THE END OF THIS STEP

COMP4(15) = ((R * COMP4(14))/(COMP4(13) - covol))

C   ADVANCE INITIAL CONDITIONS FOR THE NEXT TIME STEP

COMP4(1) = COMP4(1) + DT
COMP4(2) = COMP4(15)
COMP4(3) = COMP4(14)
COMP4(4) = COMP4(13)

WRITE(21,201)COMP4(1),COMP4(2),COMP4(3),COMP4(4),IN4(7,L),
A COMP4(11)

500  END DO
      REWIND(21)
      CLOSE(21)

      RETURN
      END

C   *****
SUBROUTINE MODEL5
C   *****
C   COMPUTATIONAL SCHEME NUMBER 5
C   THIS SCHEME ASSUMES THAT ALL OF THE PROPELLANT IS
c   IGNITED SIMULTANEOUSLY
C   *****
REAL V1,V2,COMP1(15)
REAL imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,TC,R
REAL Pint,mdia,covol
REAL lc, li, irate, relpos, deterr,nc
REAL POI,MOD5(2),NUMG5(2),IRATE5(2),LI5(2)

INTEGER DET

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,

```

A TC,R,Pint,mdia,covol

COMMON/DETER/DET,lc,li,irate,nc

C OBTAIN GEOMETRY CONSIDERATIONS

CALL CSCREEN

WRITE(6,*)'WHAT IS THE PROPORTION OF INITIAL IGNITION?'

READ(6,*) POI

MOD5(1)=IMASS*POI

NUMG5(1)=numg*POI

MOD5(2)=IMASS

NUMG5(2)=numg*(1-POI)

C INITIALIZE COMPUTATIONAL ARRAY

COMP1(1) = 0

COMP1(2) = Pint

COMP1(3) = T0

COMP1(4) = BV/mair

COMP1(5) = mdia

COMP1(6) = 0

COMP1(7) = 0

COMP1(8) = 0

COMP1(9) = 0

COMP1(10) = 0

COMP1(11) = 0

COMP1(12) = 0

COMP1(13) = 0

COMP1(14) = 0

COMP1(15) = 0

C COMPUTATIONAL LOOP

102 FORMAT(5E17.4)

IF (DET .EQ. 1) THEN

105 WRITE(6,*)'WHAT IS FIRST STAGE DETERRENCE?'

READ(6,*)IRATE5(1)

IF((IRATE5(1).LT. 0.0).OR.(IRATE5(1).GT.1))THEN

CALL RETRY

PAUSE

CALL CSCREEN

GOTO 105

END IF

```

106      WRITE(6,*)'WHAT IS SECOND STAGE DETERRENCE?'

      READ(6,*)IRATE5(2)
      IF((IRATE5(2).LT. 0.0).OR.(IRATE5(2).GT.1))THEN
      CALL RETRY
      PAUSE
      CALL CSCREEN
      GOTO 106
      END IF

      ELSE IF (DET .EQ. 2) THEN
      CONTINUE

      ELSE IF (DET .EQ. 3) THEN
107      WRITE(6,*)'WHAT IS FIRST STAGE DETERRENCE?'

      READ(6,*)IRATE5(1)
      IF((IRATE5(1).LT. 0.0).OR.(IRATE5(1).GT.1))THEN
      CALL RETRY
      PAUSE
      CALL CSCREEN
      GOTO 107
      END IF

      WRITE(6,*)'WHAT IS FIRST STAGE INDEX? '
      READ(6,*) LI5(1)

109      WRITE(6,*)'WHAT IS SECOND STAGE DETERRENCE?'

      READ(6,*)IRATE5(2)
      IF((IRATE5(2).LT. 0.0).OR.(IRATE5(2).GT.1))THEN
      CALL RETRY
      PAUSE
      CALL CSCREEN
      GOTO 109
      END IF

      WRITE(6,*)'WHAT IS SECOND STAGE INDEX? '
      READ(6,*) LI5(2)

      END IF

      DO 300 J=1,2

      DO 200 WHILE ((MOD5(J) - COMP1(11)) .GE. 0.00)

      WRITE(21,102)COMP1(1),COMP1(2),COMP1(3),COMP1(4),COMP1(5)

C      determine burn velocity at time step

      relpos = 1 - (COMP1(5)/mdia)

```

```

if (DET .EQ. 1) then
  CALL EXPLAW(irate5(j), nc, relpos, deterr)

else if (DET .EQ. 2) then
  CONTINUE

else if (DET .EQ. 3) then
  CALL POLYLAW(irate5(j),li5(j),relpos,deterr)

else

  deterr = 1
end if

COMP1(6) = (A*(COMP1(2)**n))*deterr

c    determine diameter at end of time step

      COMP1(7) = COMP1(5) - (2*COMP1(6)*dt)

c    determine volume of propellant consumed in time step.

V1 = ((pi*(COMP1(5)**3))/6)
V2 = ((pi*(COMP1(7)**3))/6)

COMP1(8) = (V1 - V2)*numg5(j)

c    determine the total volume of propellant consumed

      COMP1(9) = COMP1(9)+COMP1(8)

C    determine mass of propellant consumed in time step

COMP1(10) = COMP1(8) * den

c    determine total mass of propellant consumed

      COMP1(11) = COMP1(11) + COMP1(10)

C    determine total gas phase mass in pressure vessel

COMP1(12) = COMP1(11) + mair

c    compute specific volume at end of time step

COMP1(13) = (BV/COMP1(12))

```

```

C      compute temperature at end of time step

      TVAR1 = mair * Cvair * T0
      TVAR2 = COMP1(11) * Cv * TC
      TVAR3 = mair * Cvair
      TVAR4 = COMP1(11) * Cv

      COMP1(14) = ((TVAR1 + TVAR2)/(TVAR3 + TVAR4))

C      compute pressure at end of time step

      COMP1(15) = ((R * COMP1(14))/(COMP1(13)-covol))

C      advance initial conditions in array for next time step.

      COMP1(1) = COMP1(1) + dt
      COMP1(2) = COMP1(15)
      COMP1(3) = COMP1(14)
      COMP1(4) = COMP1(13)
      COMP1(5) = COMP1(7)

200  CONTINUE

      COMP1(5)=MDIA

300  CONTINUE
      REWIND(21)
      CLOSE(21)

      RETURN
      END

C      *****

C      *****

SUBROUTINE MODEL6

C      *****
C      COMPUTATIONAL SCHEME NUMBER 6
C      THIS SCHEME ASSUMES THAT ALL OF THE PROPELLANT IS IGNITED
C      SIMULTANEOUSLY, AND THAT THERE IS A VENT TO RELEASE SOME OF THE
C      GENERATED GASES.
C      *****
C
      REAL V1, V2, COMP1(15)
      REAL imass,A,n,dt,pi,numg,mair,BV,Cvair,T0,Cv,Tc,R
      REAL Pint, mdia, covol

```



```

REAL lc,li,irate,relpos,deterr,nc
REAL ORFDIA,ORFNO,ORFEFF,ORFA
REAL DMASS,LOSTMASS,temp6(15),pcrit,cpress,p,rho,mdot

```

```

INTEGER DET
integer i

```

```

COMMON/MOD1/imass,A,n,dt,pi,numg,den,mair,BV,Cvair,T0,Cv,
A TC,R,Pint,mdia,covol

```

```

COMMON/DETER/DET,lc,li,irate,nc

```

C INITIALIZE COMPUTATIONAL ARRAY

```

COMP1(1) = 0
COMP1(2) = Pint
COMP1(3) = T0
COMP1(4) = BV/mair
COMP1(5) = mdia
COMP1(6) = 0
COMP1(7) = 0
COMP1(8) = 0
COMP1(9) = 0
COMP1(10) = 0
COMP1(11) = 0
COMP1(12) = 0
COMP1(13) = 0
COMP1(14) = 0
COMP1(15) = 0

```

C OBTAIN NECESSARY CONFIGURATIONAL DATA

```

CALL CSCREEN

```

```

WRITE(6,*)'THIS DATA IS NECESSARY TO CONFIGURE THE PROBLEM'
WRITE(6,*) '
WRITE(6,*)'WHAT IS THE DIAMETER OF THE ORIFICE?'
READ(6,*)ORFDIA
WRITE(6,*)'HOW MANY ORIFICES ARE IN THE PROBLEM?'
READ(6,*)ORFNO
WRITE(6,*)'WHAT IS THE EFFICIENCY OF THE ORIFICE?'
READ(6,*)ORFEFF

```

```

ORFA = ((ORFDIA/2.0)**2.0)*PI
pcrit = cpress(CV, R)
lostmass = 0.0

```

102 FORMAT(6E17.5)

C COMPUTATIONAL LOOP - COMBUSTION PHASE

```

CALL CSCREEN

```

```

DO 300 WHILE ((imass - COMP1(11)) .ge. 0.00)

```

```

a      WRITE(21,102)COMP1(1),COMP1(2),COMP1(3),COMP1(4),
      COMP1(5),LOSTMASS

C      DETERMINE BURN VELOCITY AT THIS TIME STEP

      relpos = 1 - (comp1(5)/mdia)

      if (DET .eq. 1) then
        call explaw(irate, nc, relpos, deterr)

      else if (det .eq. 3) then
        call polylaw(irate, li, relpos, deterr)

      else
        deterr = 1
      end if

c      computational loop for intermediate burning computations.

C      initialize temporary working array

      temp6(1) = 0
      temp6(2) = comp1(2)
      temp6(3) = comp1(3)
      temp6(4) = comp1(4)
      temp6(5) = comp1(5)
      temp6(6) = 0
      temp6(7) = 0
      temp6(8) = 0
      temp6(9) = 0
      temp6(10) = 0
      temp6(11) = 0
      temp6(12) = comp1(12)
      temp6(13) = 0
      temp6(14) = 0
      temp6(15) = 0

      do 200 i = 1,10

      temp6(6) = (A*temp6(2)**n)*deterr

C      determine diameter at the end of intermediate timestep.

      temp6(7) = temp6(5) - (2*temp6(6)*(dt/10))

C      determine volume of propellant consumed

      v1 = ((pi*(temp6(5)**3))/6.0)
      v2 = ((pi*(temp6(7)**3))/6.0)

      temp6(8) = (v1-v2)*numg

```

```

c    determine the total volume consumed in this time step

temp6(9) = temp6(9) + temp6(8)

C    determine mass consumed in intermediate time step

temp6(10) = temp6(8) * den

C    determine total mass consumed this time step

temp6(11) = temp6(11) + temp6(10)

C    determine total gas phase mass after intermediate time step.

temp6(12) = mair + comp1(11) + temp6(11) - lostmass

c    compute specific volume at end of intermediate time step.

temp6(13) = ((BV-((imass-(comp1(11)+temp6(11)))/den))/
a    (comp1(12)+temp6(12)))

C    compute temperature at end of intermediate time step.

TVAR1 = mair * Cvair * T0
TVAR2 = (comp1(11)+temp6(11))*cv*tc
TVAR3 = mair * cvair
TVAR4 = (comp1(11)+temp6(11))*cv

temp6(14) = ((TVAR1 + TVAR2)/(TVAR3 + TVAR4))

C    compute pressure at end of intermediate time step.

temp6(15) = ((R * temp6(14))/(temp6(13)-covol))

C    determine mass flow rate from orifice

    P = (temp6(2)+temp6(15))/2
    RHO = (temp6(4)+temp6(13))/2
    Tave = (temp6(3)+temp6(14))/2
    if (temp6(15) .ge. pcrit) then
        call subson(P,pint,rho,R,cv,mdot)
    else
        call sonic(p,Tave,R,cv,mdot)
    end if

    mdot = mdot * ORFA * ORFEFF
    dmass = mdot * (dt/10)
    lostmass = lostmass + dmass

temp6(12) = mair + comp1(11) + temp6(11) - lostmass

```

c compute specific volume at end of intermediate time step.

```
temp6(13) = ((BV-((imass-(comp1(11)+temp6(11)))/den))/
a      (comp1(12)+temp6(12)))
```

C compute pressure at end of intermediate time step.

```
temp6(15) = ((R * temp6(14))/(temp6(13)-covol))
```

```
temp6(2) = temp6(15)
temp6(3) = temp6(14)
temp6(4) = temp6(13)
temp6(5) = temp6(7)
```

200 continue

```
comp1(7) = temp6(7)
comp1(8) = temp6(8)
comp1(9) = comp1(9) + comp1(8)
comp1(10) = temp6(11)
comp1(11) = comp1(11) + comp1(10)
comp1(12) = temp6(12)
comp1(13) = temp6(13)
comp1(14) = temp6(14)
comp1(15) = temp6(15)
```

```
comp1(1) = comp1(1) + dt
comp1(2) = comp1(15)
comp1(3) = comp1(14)
comp1(4) = comp1(13)
comp1(5) = comp1(7)
```

300 continue

C do while (imass .ge. lostmass)

```
Rewind(21)
Close(21)
```

```
RETURN
END
```

C *****

```
SUBROUTINE EXPLAW (irate,nc,relpos,deterr)
REAL irate, nc, relpos, deterr
```

```
deterr = (irate+((1-irate)*log(1+(relpos*(nc-1)))))
```

```
RETURN
END
```

```

C *****
C
C SUBROUTINE POWLAW (irate,lc,relpos)
C REAL irate,lc,relpos
C
C POWLAW =
C
C END
C *****

SUBROUTINE POLYLAW (irate,li,relpos,deterr)
REAL irate,li,relpos,deterr

deterr = (irate+((1-irate)*(relpos**li)))

RETURN
END

C *****

REAL FUNCTION CPRESS(CV, R)
REAL CV, R, CPRESS

CPRESS = ((2/((R/CV)+2))**(((R/CV)+1)/(R/CV)))

RETURN
END

C *****

SUBROUTINE SUBSON(P,PEXT,RHO,R,CV,MDOT)
REAL P,PEXT,RHO,R,CV,MDOT,G
REAL TVAR1,TVAR2,TVAR3

G = (R/CV)+1

TVAR1 = ((2*G)/(G-1))
TVAR2 = ((PEXT/P)**(2/G))
TVAR3 = ((PEXT/P)**((G+1)/G))

MDOT = SQRT(TVAR1*P*RHO*(TVAR2-TVAR3))

RETURN
END

C *****

SUBROUTINE SONIC(P,T,R,CV,MDOT)
REAL P,T,R,CV,MDOT,G

G = (R/CV)+1

```

```
MDOT=((P/T)*SQRT((G/R)*((2/(G+1))**((G+1)/(G-1))))))
```

```
RETURN
END
```

```
C *****
SUBROUTINE CSCREEN
```

```
DO 100 J=1,24
    WRITE(6,*) ' '
100 CONTINUE
```

```
RETURN
END
```

```
C *****
SUBROUTINE RETRY
```

```
WRITE(6,*) ' '
WRITE(6,*) 'MUST BE BETWEEN 0 AND 1'
WRITE(6,*) ' '
```

```
RETURN
END
```

```
C *****
SUBROUTINE DATESTAMP
```

```
CHARACTER MONTH*3
```

```
CALL GETDAT(iyr,imon,iday)
CALL GETTIM(ihr,imin,iseq,i100th)
```

```
IF(IMON .EQ. 1) THEN
    MONTH = 'JAN'
ELSE IF(IMON .EQ. 2) THEN
    MONTH = 'FEB'
ELSE IF(IMON .EQ. 3) THEN
    MONTH = 'MAR'
ELSE IF(IMON .EQ. 4) THEN
    MONTH = 'APR'
ELSE IF(IMON .EQ. 5) THEN
    MONTH = 'MAY'
ELSE IF(IMON .EQ. 6) THEN
    MONTH = 'JUN'
ELSE IF(IMON .EQ. 7) THEN
    MONTH = 'JUL'
ELSE IF(IMON .EQ. 8) THEN
    MONTH = 'AUG'
ELSE IF(IMON .EQ. 9) THEN
    MONTH = 'SEP'
ELSE IF(IMON .EQ. 10) THEN
```

```

        MONTH = 'OCT'
    ELSE IF(IMON .EQ. 11) THEN
        MONTH = 'NOV'
    ELSE
        MONTH = 'DEC'
    END IF

    WRITE(21,100)iday,month,iyr
    WRITE(21,101)ih,imin,ise,100th

100  FORMAT(' DATE OF THIS RUN: ',I2.2,1X,A3,1X,I4.4)
101  FORMAT(' RUN START TIME: ',I2.2,1H:',I2.2,1H:',I2.2,1H.,I2.2)

    RETURN
    END

C *****
SUBROUTINE MENU1
C *****

    CALL CSCREEN
    WRITE(6,*)'+++++'
    WRITE(6,*)'WHICH DETERRENT SCHEME WOULD YOU LIKE TO USE?'
    WRITE(6,*)'+++++'
    WRITE(6,*)' '
    WRITE(6,*)'(1) - NATURAL LOG FORM:  $y = f(\ln(x))$ '
    WRITE(6,*)'(2) - POWER LAW:  $y = f(N^x)$ '
    WRITE(6,*)'(3) - POLYNOMIAL FORM:  $y = f(x^N)$ '
    WRITE(6,*)'(9) - NO DETERRENT '
    WRITE(6,*)'(0) - TO EXIT PROGRAM'
    WRITE(6,*)'+++++'
    WRITE(6,*)'DESIRED DETERRENT MODEL? '

    RETURN
    END

C *****
SUBROUTINE MENU2
C *****

    CALL CSCREEN

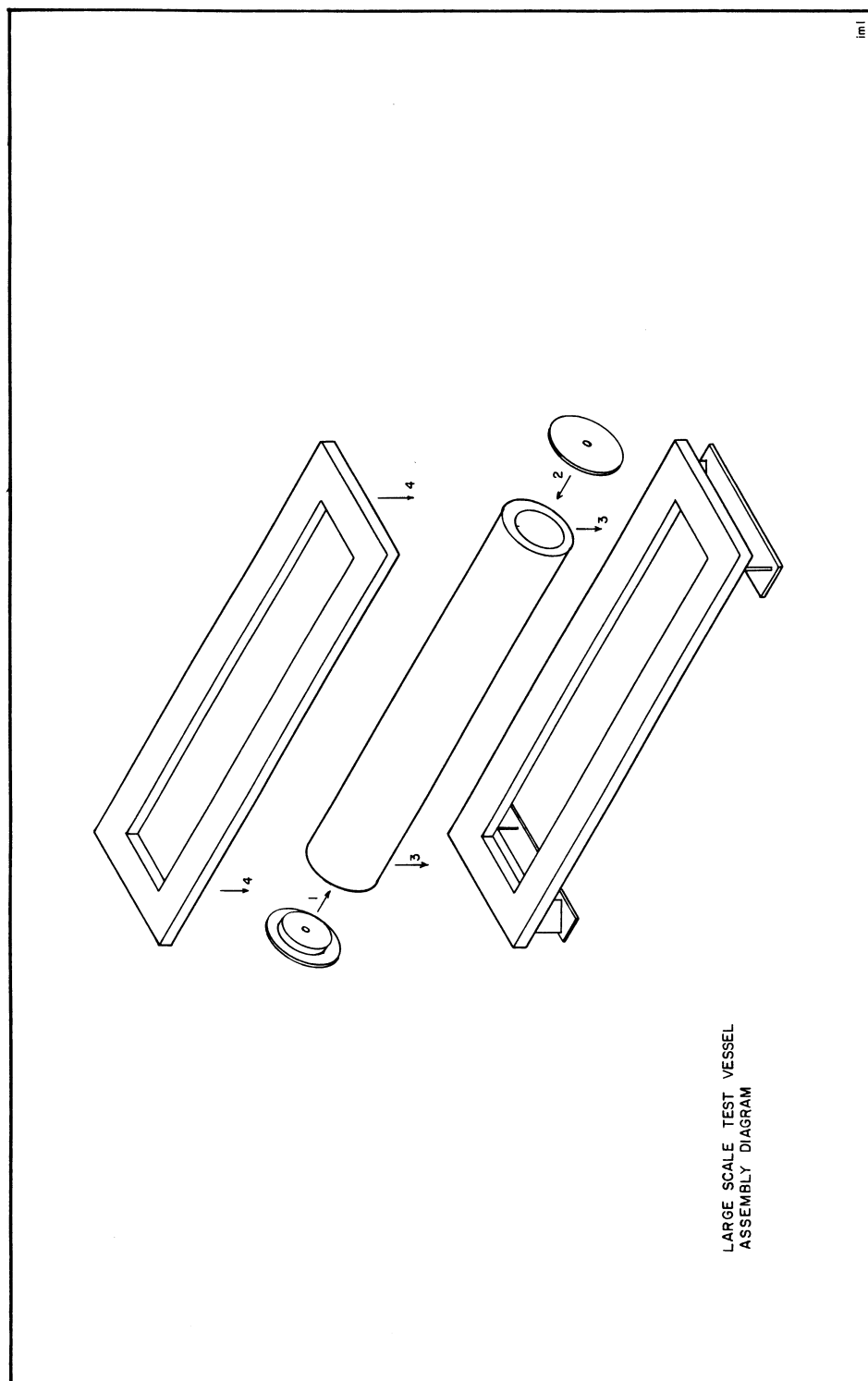
    WRITE(6,*)'*****'
    WRITE(6,*)'WHICH COMPUTATIONAL SCHEME WOULD YOU LIKE TO USE?'
    WRITE(6,*)'*****'
    WRITE(6,*)' '
    WRITE(6,*)'(1) - INSTANTANEOUS IGNITION OF ALL PROPELLANT'
    WRITE(6,*)'(2) - BURN DIRECTION ON CHARGE AXIS'
    WRITE(6,*)'(3) - BURN DIRECTION RADIAL FROM CENTER'
    WRITE(6,*)'(4) - BURN DIRECTION RADIAL FROM OUTSIDE'
    WRITE(6,*)'(5) - STAGED IGNITION OF PROPELLANT'
    WRITE(6,*)'(6) - VENTED INSTANTANEOUS IGNITION'
    WRITE(6,*)'(0) - TO EXIT PROGRAM'

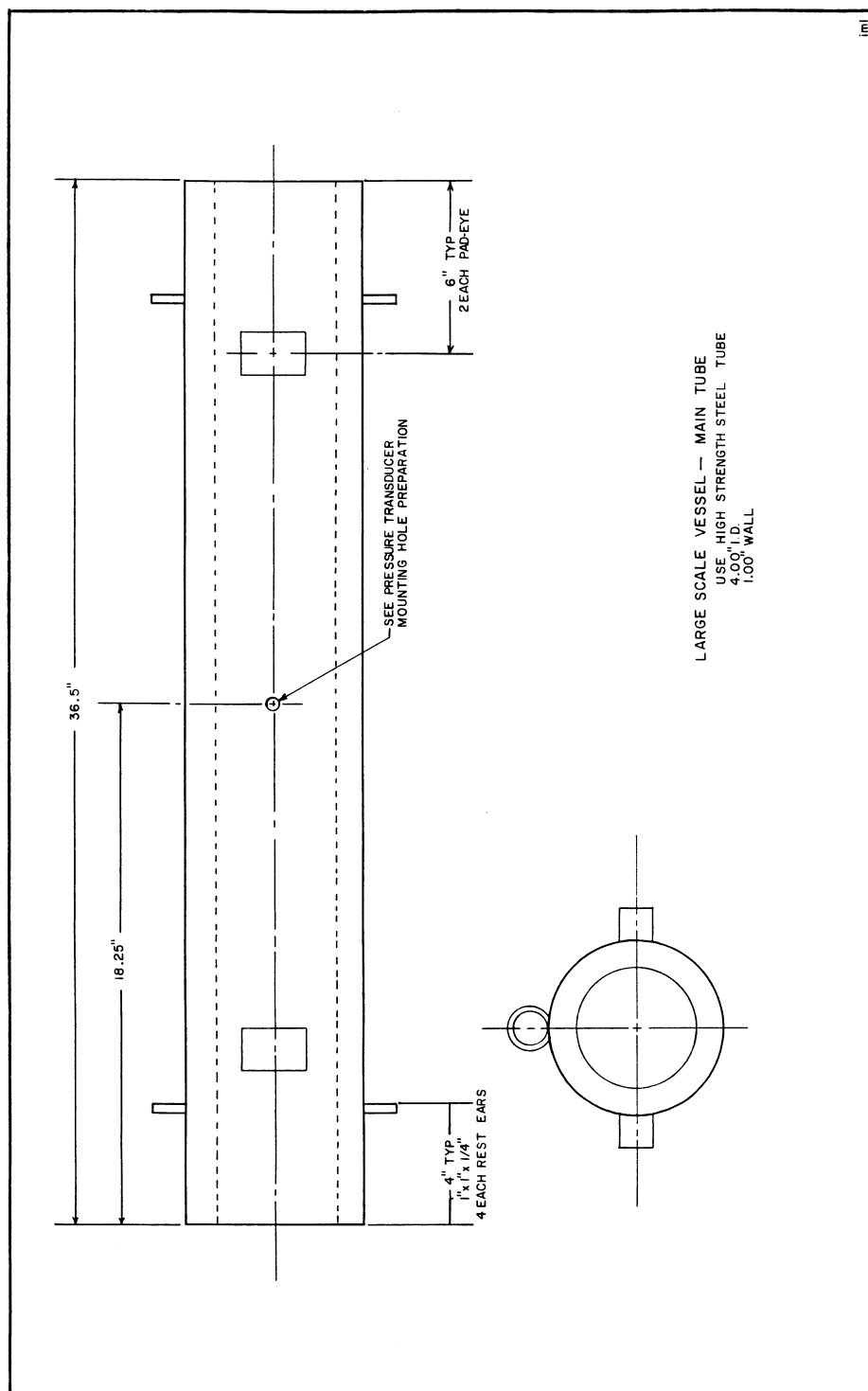
```

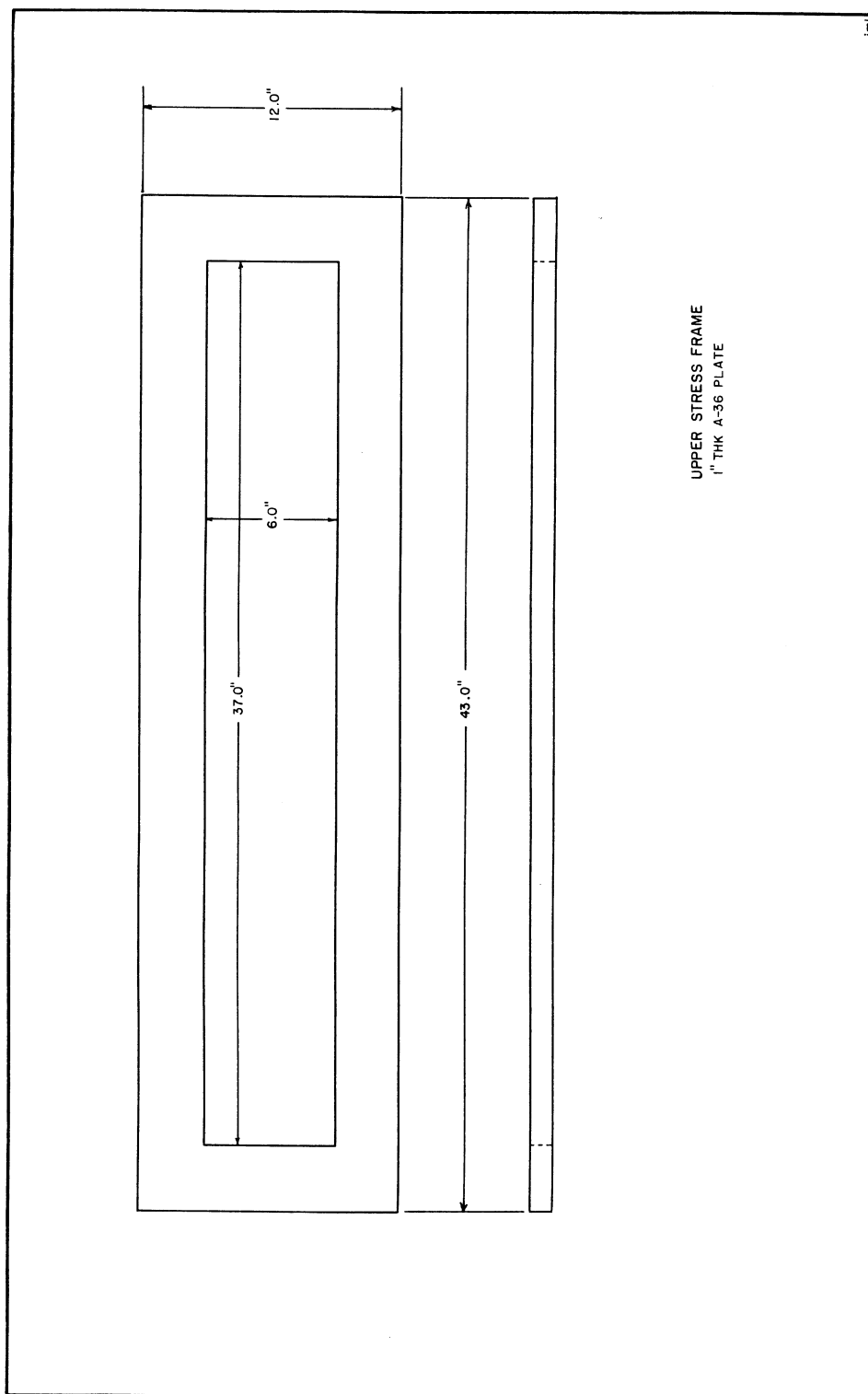
```
WRITE(6,*) '  
WRITE(6,*) '*****'  
WRITE(6,*) 'DESIRED MODEL: '  
  
RETURN  
END
```

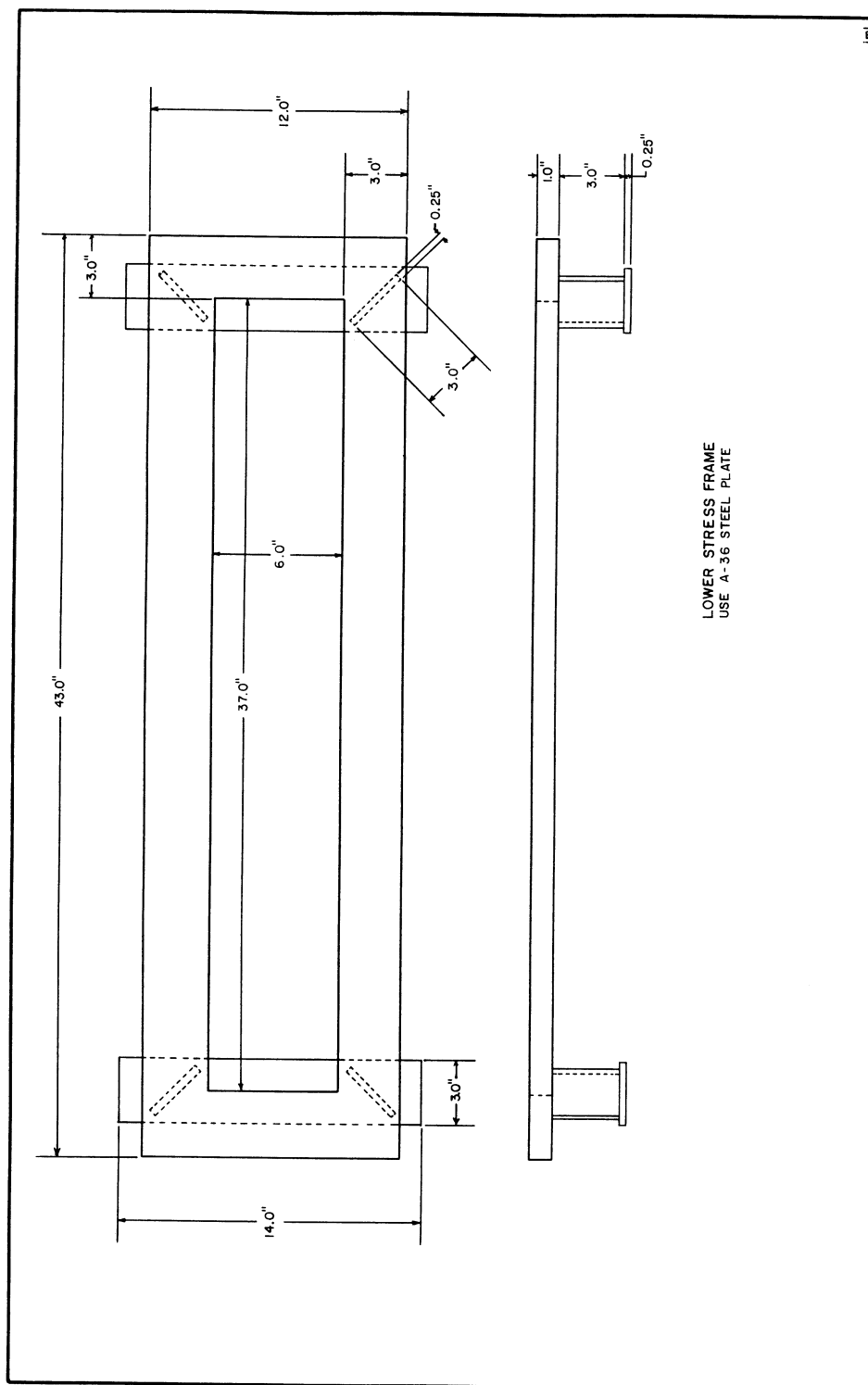

Appendix F

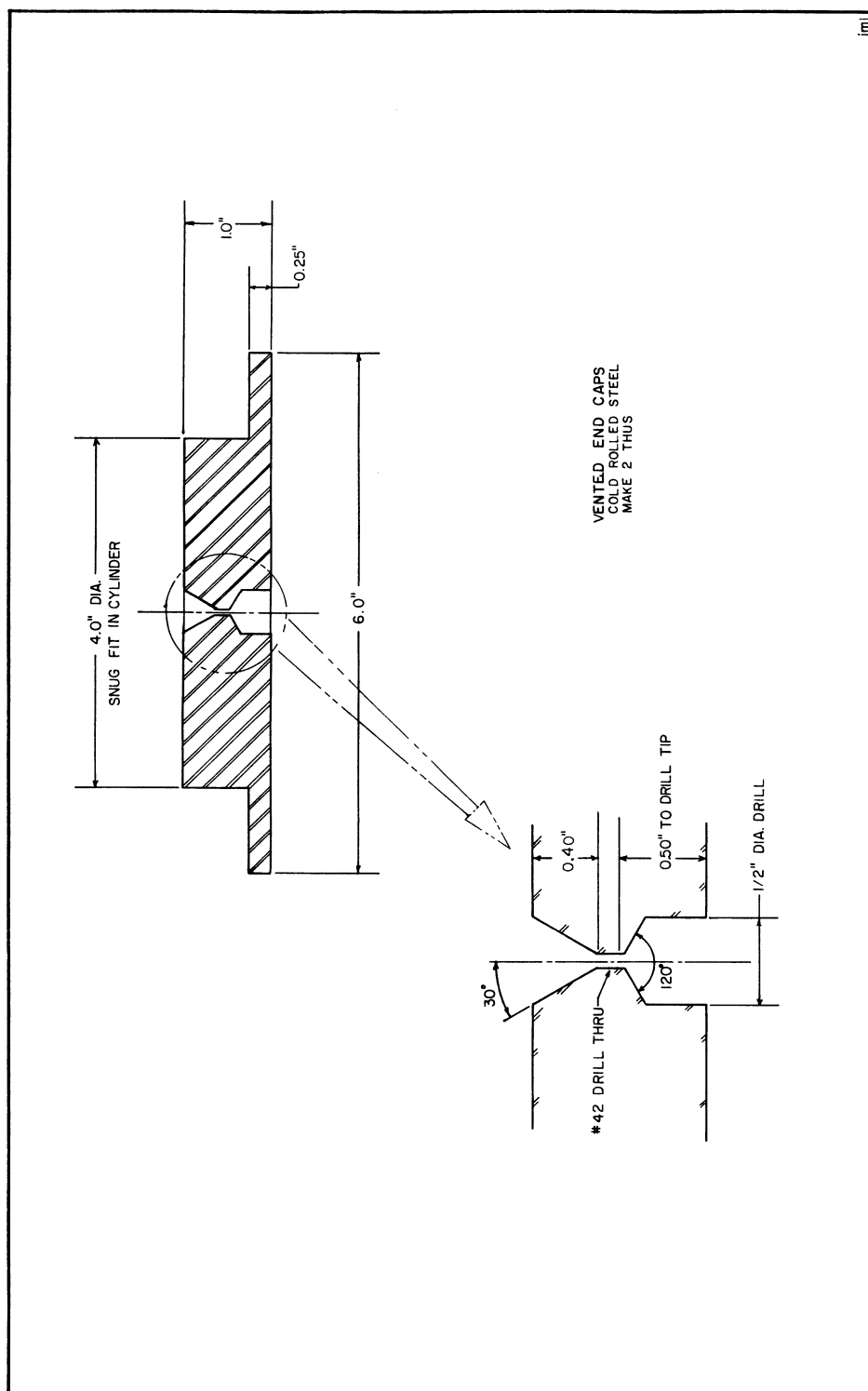
Large Scale Vessel Design









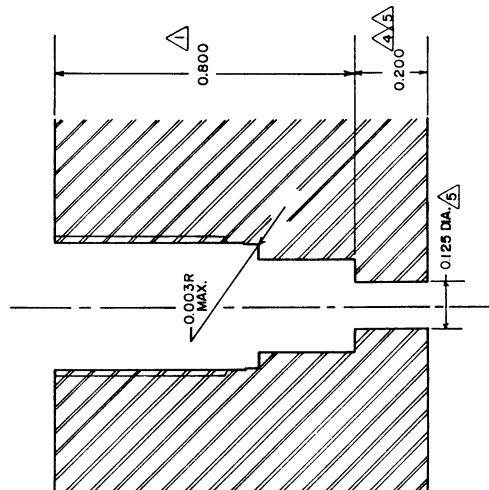


MOUNTING HOLE PREPARATION (PER MANUFACTURER)

1. DRILL THROUGH 0.125
2. DRILL AND FLAT BOTTOM REAM 0.2500 $\pm$ 0.0010-0.0000
DIAMETER X 0.800 DEEP $\triangle 3$
3. CBORE "P" (0.323 DIA) $\triangle 2$ $\triangle 3$ X 0.540 REF
4. CBORE "Q" (0.332 DIA) 3 X 0.510 DEEP
5. TAP 3/8 - 24 UNF-2B X 0.460 DEEP PERF THREAD $\triangle 6$

NOTES

- $\triangle 1$ DIMENSIONS ARE FOR 0.800 WALL THICKNESS COUNTERBORE, AS NEEDED, FOR THICKER WALLS
- $\triangle 2$ SEAL SURFACE MUST BE FLAT AND FREE OF TOOL MARKS WITH A MIN 63 $\sqrt{FIN}$
- $\triangle 3$ THESE DIAMETERS TO BE CONCENTRIC TO WITHIN 0.001 TIR
- $\triangle 4$ NOT APPLICABLE
- $\triangle 5$ - do -
- $\triangle 6$ CAUTION: DO NOT TOUCH SEAL SURFACE WITH TAP WHEN TAPPING HOLE



PROPELLANT TEST CELL

SCALE	4 X	APPROVED BY	DRAWN BY
DATE	21 Dec 95	REVISED	iml
TRANSDUCER MOUNTING DETAIL SECTION			
DRAWING NUMBER			6

STRESS CALCULATIONS

LARGE-SCALE VESSEL

CONSIDER - STRENGTH OF TUBE

- SHEAR OF STRESS FRAME
- TENSILE FAILURE OF STRESS FRAME

STRENGTH CHARACTERISTICSMATERIAL: CARBON STEEL

ALLOWABLE STRESS	
TENS/COMP	36000 psi
SHEAR	22000 psi

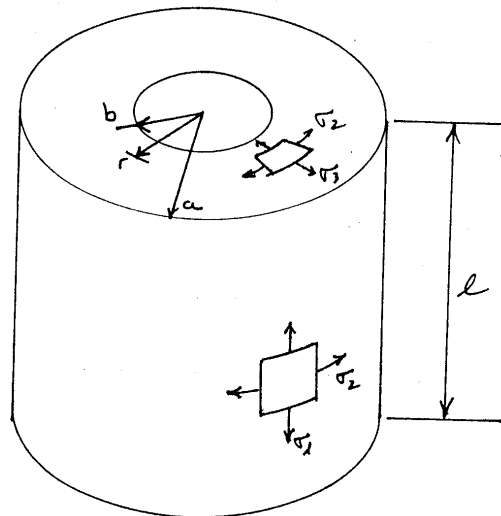
YOUNG'S MODULUS	
TENS/COMP	29×10^6 psi
SHEAR	12×10^6 psi

POISSON'S RATIO	0.30
-----------------	------

<u>MAX STATIC LOAD:</u>	7500 psi
-------------------------	----------

<u>EST DYNAMIC FACTOR:</u>	2
----------------------------	---

<u>DESIGN LOAD:</u>	15000 psi
---------------------	-----------

THICK-WALLED CYLINDER

From: (Warren 1989, pp. 636 - 640.

$$\tau_1 = \frac{\gamma b^2}{a^2 - b^2}$$

$$\sigma_2 = \frac{\gamma b^2 (a^2 + r^2)}{r^2 (a^2 - b^2)} \quad \max \sigma_2 = \gamma \frac{a^2 + b^2}{a^2 - b^2} \quad \text{at } r = b$$

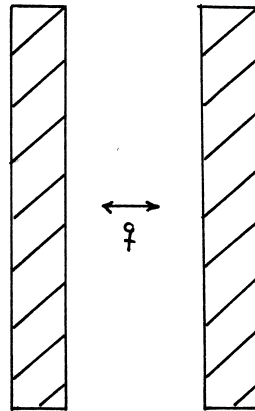
$$\sigma_3 = -\gamma \frac{b^2 (a^2 - r^2)}{r^2 (a^2 - b^2)} \quad \max \sigma_3 = -\gamma \quad \text{at } r = b$$

$$\text{Max SHEAR STRESS} = \frac{\sigma_2 - \sigma_3}{2} = \gamma \frac{a^2}{(a^2 - b^2)} \quad \text{at } r = b$$

$$\Delta a = \frac{\gamma a}{E} \frac{b^2 (2 - \nu)}{a^2 - b^2}$$

$$\Delta b = \frac{\gamma b}{E} \frac{a^2 (1 + \nu) + b^2 (1 - 2\nu)}{a^2 - b^2}$$

$$\Delta l = \frac{\gamma l}{E} \frac{b^2 (1 - 2\nu)}{a^2 - b^2}$$



CONSIDER

$$\begin{aligned} L &= 36.5'' \\ a &= 3.0'' \\ b &= 2.0'' \\ q &= 15000 \text{ psi} \end{aligned}$$

$$\sigma_1 = 0 \quad [\text{NO CONFINEMENT ON TUBE ENDS}]$$

$$\sigma_{2(\text{max})} = \frac{q(a^2 + b^2)}{(a^2 - b^2)}$$

$$= \frac{15000(3^2 + 2^2)}{3^2 - 2^2}$$

$$= \underline{\underline{39000 \text{ psi}}}^*$$

$$\sigma_{3(\text{max})} = -q = \underline{\underline{-15000 \text{ psi}}}$$

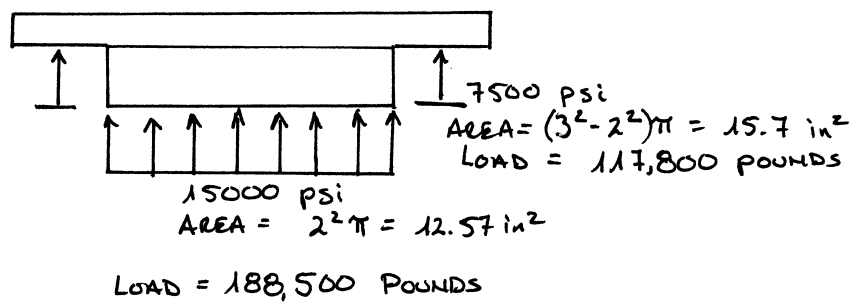
$$\text{Shear (Max)} \quad \tau_{23} = \frac{39000 + 15000}{2} = \underline{\underline{27000 \text{ psi}}}^*$$

* THESE CONDITIONS EXIST AT THE INSIDE SURFACE OF THE TUBE; AND EXCEED THE RESPECTIVE "ALLOWABLE" STRESSES FOR THIS PROBLEM. HOWEVER;

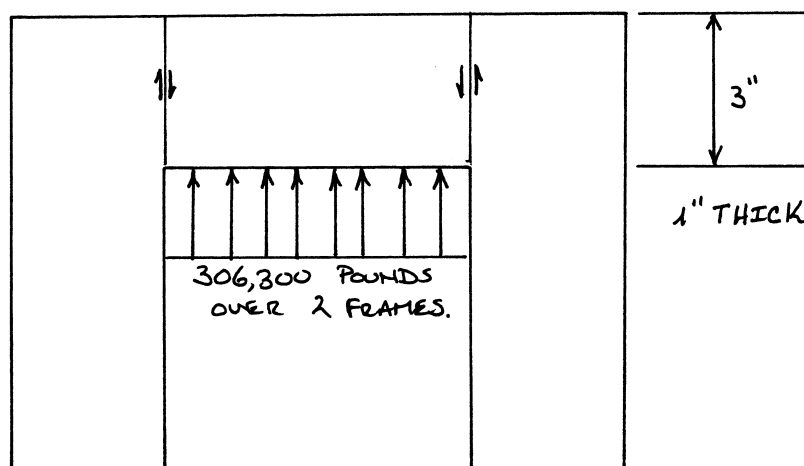
- VALUES > 30% LESS THAN YIELD
- CONDITIONS DO NOT EXIST ALL THROUGH VESSEL
- DYNAMIC STATE

ACCEPT STRESS CONDITIONS.

END LOAD ON END CAPS



$$\begin{array}{rcl} \text{TOTAL LOAD} & = & 117,800 \\ & + & 188,500 \\ \hline & = & 306,300 \text{ POUNDS} \end{array}$$

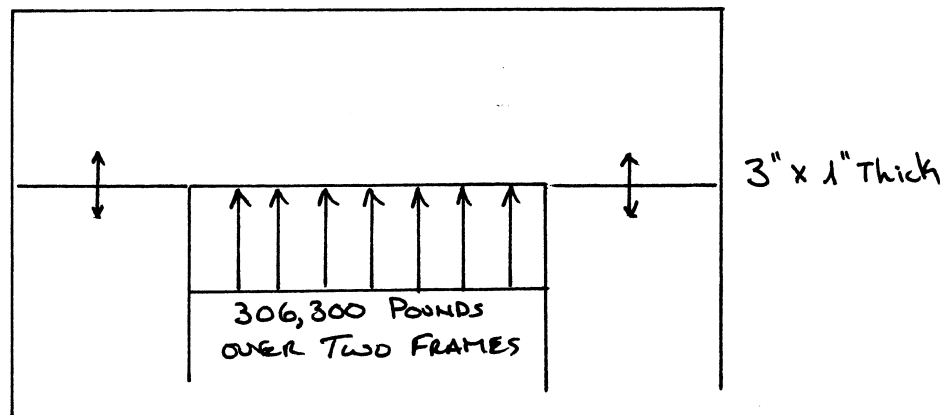
SHEAR ON STRESS FRAME

$$\text{SHEAR AREA OF RESISTANCE} = 3" \times 1" \times 2 = 6 \text{ in}^2$$

$$\text{SHEAR LOAD} = \frac{\left[\frac{306,300 \text{ POUNDS}}{2} \right]}{6 \text{ in}^2} = \underline{\underline{25,525 \text{ PSI}}}^*$$

* NOTE: THIS VALUE REMAINS ~70% OF YIELD;
ACCEPT CONDITION.

TENSILE STRESS ON FRAME



$$\text{TENSILE STRESS} = \frac{\left[\frac{306,300 \text{ lbs}}{2} \right]}{6 \text{ in}^2} = \underline{\underline{25,525 \text{ psi}}}$$

DIRECTLY ACCEPTABLE

Ian Morton Loomis

Ian attended Bartlett High School, in Anchorage Alaska, and graduated there in the spring of 1983. He attended the New Mexico Institute of Mining and Technology, in Socorro, New Mexico, where he graduated, with Honors, in the spring of 1987, with a bachelor of science degree in Mining Engineering. While there Ian was elected to the New Mexico Gamma chapter of the Tau Beta Pi association.

After completion of his bachelor's degree Ian began work with Dravo Engineering Companies, Inc., and later for Westinghouse Electric Corporation, at the Waste Isolation Pilot Plant, outside of Carlsbad, New Mexico. His first assignment was as a shift engineer in a materials handling shaft refit. Subsequent assignments included engineering responsibility for the underground ventilation facilities and structures, leading to cognizant responsibility for the entire underground ventilation system at this nuclear waste disposal site. While with Westinghouse, Ian received a George Westinghouse Signature Award for work involving the continuous monitoring of natural ventilation pressure in the underground facility.

Ian left Westinghouse to attend graduate school, completing his master of science degree in 1995, at the Virginia Polytechnic Institute and State University. The title of his master's thesis is "Application of Water Mist to Fuel-Rich Fires in Model Coal Mine Entries."

Ian is a registered Professional Engineer in the state of New Mexico, a member of the Society for Mining Metallurgy, and Exploration, Inc. and a Fellow of the Mine Ventilation Society of South Africa.