Internal Flow Investigation of an Aft Finocyl Grain Configuration in a Solid Rocket Motor

by

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(ABSTRACT)

Cold-flow tests were conducted in mediums of air and water to investigate the internal flow field about the nozzle region of a proposed solid rocket motor (SRM) configuration that would potentially replace the current external boosters on NASA's Space Shuttle. One-eighth-scale clear acrylic models of the proposed submerged aft-dome and aft finned grain elements were constructed to simulate the aft segment of the SRM at ignition and 35 seconds into the firing sequence. Pressure, velocity, and turbulence profiles were obtained during cold air testing, while air bubbles and dye were used for flow visualization during water tunnel testing.

The flow visualization experiments indicated the presence of strong inlet vortices, alternating vortex shedding from both grain models' fins, circumferential flow in the aft-dome and around the nozzle, and recirculatory flow in the aft-dome and near an upstream portion of the 35-second grain model. Data acquired during cold air testing showed a turbulent low-velocity flow field in the aft-dome for both grain models. With respect to pressure and mean velocity,
virtually the entire nozzle/aft-dome region exhibited a minimal sensitivity to nozzle vectoring.
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Table of Contents

1.0 Introduction .................................................................. 1

2.0 Model Specifications ......................................................... 4
  2.1 Nozzle/Aft-dome Model .............................................. 4
  2.2 Grain Models ........................................................... 5
    2.2.1 Zero-second Burn-Time ........................................ 5
    2.2.2 Thirty-five-second Burn-Time ................................. 5

3.0 Test Facilities ............................................................... 7
  3.1 Water Tunnel Facility .................................................. 7
  3.2 Cold Air Test Facility .................................................. 8

4.0 Mass Flow Balancing ..................................................... 10
List of Illustrations

Figure 1. Loaded solid rocket chamber with aft finocyl grain. ............ 39
Figure 2. Proposed finned aft segment grain. ............................ 40
Figure 3. Internal solid propellant designs with corresponding thrust-time
curves. (Shafer.) ........................................ 41
Figure 4. Axisymmetric solid propellant configurations. (Zeller.) ....... 42
Figure 5. A typical movable nozzle. (Truchot.) ........................ 43
Figure 6. Primary internal flow field in submerged and external nozzle
configurations (Truchot.) .................................... 44
Figure 7. Aft-dome model with nozzle. ................................ 45
Figure 8. Ignition-time aft finocyl grain model. ........................ 46
Figure 9. Thirty-five-second burn-time aft grain model. ................ 47
Figure 10. Virginia Tech water tunnel test facility. ...................... 48
Figure 11. Cold air test facility. ................................ 49
Figure 12. Hot-wire path for mean velocity/turbulence measurements in
0-second model. ............................................. 50
Figure 13. Hot-wire path for mean velocity/turbulence measurements in
35-second model. ............................................. 51
Figure 14. Hot-wire positions for mean velocity/turbulence measurements in
aft-dome, 30 degrees from bottom. ................................ 52
Figure 15. Hot-wire probe alignments for vertical traverse ahead of nozzle. 53
Figure 16. Aft-dome static pressure tap locations: back view. .......... 54
Figure 17. Aft-dome static pressure tap locations: side view. .......... 55
Figure 18. Aft-dome static pressure tap locations: top view. .......... 56
Figure 19. Data acquisition flow chart. .................................. 57
Figure 20. Air bubble and dye injection observations in 0-second model: 
nozzle at 0 degrees. ........................................ 58
Figure 21. Air bubble and dye injection observations in 0-second model: 
nozzle at -8 degrees. .......................................... 59
Figure 22. Air bubble and dye injection observations in 0-second model: 
nozzle at +8 degrees. .......................................... 60
Figure 23. Air bubble and dye injection observations in 35-second model: 
nozzle at 0 degrees. ........................................ 61
Figure 24. Air bubble and dye injection observations in 35-second model: 
nozzle at -8 degrees. .......................................... 62
Figure 25. Air bubble and dye injection observations in 35-second model: 
nozzle at +8 degrees. .......................................... 63
Figure 26. Core axial mean velocity and RMS profiles in 0-second model: 
nozzle at 0 degrees. ........................................ 64
Figure 27. Core axial mean velocity and RMS profiles in 0-second model: 
nozzle at -4 degrees. .......................................... 65
Figure 28. Core axial mean velocity and RMS profiles in 0-second model: 
nozzle at -8 degrees. .......................................... 66
Figure 29. Core transverse mean velocity and RMS profiles in 0-second 
model: nozzle at 0 degrees. ................................ 67
Figure 30. Core transverse mean velocity and RMS profiles in 0-second 
model: nozzle at -4 degrees. ................................ 68
Figure 31. Core transverse mean velocity and RMS profiles in 0-second 
model: nozzle at -8 degrees. ................................ 69
Figure 32. Mean velocity in aft-dome with 0-second model, 30 degrees from 
bottom. ......................................................... 70
Figure 33. RMS velocity in aft-dome with 0-second model, 30 degrees from bottom. .......................................................... 71

Figure 34. Cp distribution on aft-dome surface, with 0-second model: nozzle at -8 degrees. ........................................ 72

Figure 35. Cp distribution on aft-dome surface, with 0-second model: nozzle at -4 degrees. .......................................... 73

Figure 36. Cp distribution on aft-dome surface, with 0-second model: nozzle at 0 degrees. ........................................... 74

Figure 37. Cp distribution on aft-dome surface, with 0-second model: nozzle at 0 degrees. ........................................... 75

Figure 38. Cp distribution on aft-dome surface, with 0-second model: nozzle at +4 degrees. .......................................... 76

Figure 39. Cp distribution on aft-dome surface, with 0-second model: nozzle at +8 degrees. .......................................... 77

Figure 40. Cp distribution on inside top dome surface, with 0-second model: nozzle at -8 degrees. ................................. 78

Figure 41. Cp distribution on inside top dome surface, with 0-second model: nozzle at -4 degrees. ................................. 79

Figure 42. Cp distribution on inside top dome surface, with 0-second model: nozzle at 0 degrees. .................................. 80

Figure 43. Cp distribution on inside top dome surface, with 0-second model: nozzle at +4 degrees. ................................ 81

Figure 44. Cp distribution on inside top dome surface, with 0-second model: nozzle at +8 degrees. ................................ 82

Figure 45. Core axial mean velocity and RMS profiles in 35-second model: nozzle at 0 degrees. ................................. 83

Figure 46. Core axial mean velocity and RMS profiles in 35-second model: nozzle at -4 degrees. ................................. 84

Figure 47. Core axial mean velocity and RMS profiles in 35-second model: nozzle at -8 degrees. ................................. 85
Figure 48. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at 0 degrees. .............................................. 86

Figure 49. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at -4 degrees. .............................................. 87

Figure 50. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at -8 degrees. .............................................. 88

Figure 51. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at -8 degrees. .............................................. 89

Figure 52. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at -4 degrees. .............................................. 90

Figure 53. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at 0 degrees. .............................................. 91

Figure 54. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at +4 degrees. .............................................. 92

Figure 55. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at +8 degrees. .............................................. 93

Figure 56. Cp distribution on aft-dome surface, with 35-second model: nozzle at -8 degrees. .............................................. 94

Figure 57. Cp distribution on aft-dome surface, with 35-second model: nozzle at -4 degrees. .............................................. 95

Figure 58. Cp distribution on aft-dome surface, with 35-second model: nozzle at 0 degrees. .............................................. 96

Figure 59. Cp distribution on aft-dome surface, with 35-second model: nozzle at +4 degrees. .............................................. 97

Figure 60. Cp distribution on aft-dome surface, with 35-second model: nozzle at +8 degrees. .............................................. 98

Figure 61. Cp distribution on inside top dome surface, with 35-second model: nozzle at -8 degrees. .............................................. 99

Figure 62. Cp distribution on inside top dome surface, with 35-second model: nozzle at -4 degrees. .............................................. 100
Figure 63. Cp distribution on inside top dome surface, with 35-second model: nozzle at 0 degrees. ........................... 101

Figure 64. Cp distribution on inside top dome surface, with 35-second model: nozzle at +4 degrees. ........................... 102

Figure 65. Cp distribution on inside top dome surface, with 35-second model: nozzle at +8 degrees. ........................... 103
1.0 Introduction

In an effort to increase the performance, reliability, and thrust characteristics of the Space Shuttle during the launch sequence, NASA desired to redesign the existing reusable external rocket boosters. Atlantic Research Corporation and Hercules, Inc. together proposed a movable submerged nozzle solid propellant rocket motor with an aft finocyl grain configuration. A typical segmented chamber (minus nozzle) is shown in figure 1, and figure 2 shows the proposed finocyl grain element within the aft segment of the rocket.

Although liquid propelled engines offer tailored thrust and easy shut-down advantages, they employ costly turbopumps and propellant feed systems that increase the booster's complexity; furthermore, susceptibility to salt water corrosion and structural damage due to water impact after expenditure from the shuttle's external fuel tank is also a major concern. Hence, only solid propellant configurations, which offer mechanical simplicity and ease of storage advantages, were seriously considered. Various grain configurations are shown in figures 3-4.
Such configurations have specific burning surface areas which allow for thrust tailoring throughout the burn sequence.

Because thrust vectoring is required with the Space Shuttle's booster rockets, it is necessary to gimbal the nozzle; hence, a submerged nozzle configuration similar to that shown in figure 5 was considered. In comparison of the primary flow field about the nozzle region for external vs. submerged nozzle configurations as depicted in figure 6, one might initially consider the aft-dome region of a submerged nozzle to be unimportant. However, prior water tunnel testing showed that secondary flow existed in a model of the current aft segment Space Shuttle solid rocket motor in the form of recirculatory, circumferential, and vortical motion (Marchman, et al., 1987; Squire, 1988). Such flow patterns increase convective heating in the aft-dome region, leading to the erosion of the internal insulation and possibly to the destruction of the nozzle-to-case joint of the SRM. In addition, the actual combustion process may be adversely affected by instabilities specific to the internal geometry of the SRM, such as pressure pulses due to the unsteady nature of the turbulent combustion process, longitudinal shock wave propagation, and fluid dynamic instabilities like vortex formation which may create pressure oscillations that propagate throughout the chamber.

The objective of this study was to investigate the internal flow field and possible existence of secondary flow phenomena about the nozzle region of Atlantic-Hercules' proposed nozzle/aft-dome and solid propellant configuration. Specific attention was to be paid to vortical, recirculatory, and circumferential
flow, and their behavior with respect to nozzle vectoring. Tests were conducted in mediums of water and air using one-eighth-scale models of the proposed nozzle/aft-dome, ignition-time aft finocyl (slotted tube) grain, and "scallop" grain which simulated the remaining aft finocyl grain at thirty-five seconds into the motor's firing sequence. In Virginia Tech's water tunnel test facility, flow pattern observations were made possible by the use of liquid dye and air bubbles, while velocity, turbulence, and pressure data were acquired in the cold air test facility described in Chapter 3.

In modeling the combustion chamber of an actual solid rocket motor, it would be desirable to match the Reynolds number in order to achieve good flow similarity. However, Reynolds number matching to simulate the extreme conditions of the actual SRM flow was not feasible. Dunlap, et al. (1974), Schetz, et al. (1983), and Winter (1958) concluded, though, that adequate flow similarity is achieved during tests with Reynolds numbers above 10^4, which guarantees the desired turbulent core flow found in combustion chambers. Another concern is the flow field behavior with extreme Reynolds number changes. Marchman, et al. (1988) found that even by increasing the Reynolds number by up to ten times, observed characteristics of the flow field in a modeled combustion chamber remained unchanged, although the relative flow rates increased accordingly. During this particular study, water tunnel testing was conducted with a Reynolds number, based on conditions within the main tunnel section, of at least 7.5×10^4, while the test Reynolds numbers in the cold air facility, based on model inlet conditions, were approximately 10^5.
2.0 Model Specifications

2.1 Nozzle/Aft-dome Model

The one-eighth-scale nozzle and aft-dome models are shown in figure 7. In an attempt to minimize visual distortion associated with previous nozzle/aft-dome manufacturing techniques (Squire, 1988), the aft-dome and nozzle models were machined from a single clear acrylic block to their proper dimensions. A circular rubber sheet was used to simulate the full-scale aft-dome-to-nozzle seal, allowing for full nozzle vectoring, while preventing the passage of water and air between the aft-dome and nozzle. Both the nozzle pivot rod and rubber seal simulated the flexible bearing commonly found in movable nozzle configurations.
2.2 Grain Models

2.2.1 Zero-second Burn-Time

A one-eighth-scale model of the ignition-time aft finocyl grain, shown in figure 8, was constructed of 1/4-inch and 3/16-inch sheets of clear acrylic. Not shown in figure 8 are over 6000 1/4-inch, 3/16-inch, and 1/8-inch holes drilled in the model to allow for the passage of secondary flow, which simulated propellant mass flow. This grain model was mated with the nozzle/aft-dome model and placed in either the water tunnel test section or the cold air test facility in order to examine internal flow phenomena in the nozzle/aft-dome region.

2.2.2 Thirty-five-second Burn-Time

In order to examine the internal flow characteristics associated with the solid propellant configuration at thirty-five seconds into the motor's firing, another one-eighth-scale clear acrylic model was constructed of circular sections of 1/8-inch-thick clear acrylic and mated to the nozzle/aft-dome model. This aft "scallop" model is shown in figure 9. Approximately 1000 1/4-inch holes were drilled into the model to allow for secondary flow. This scallop model simulated the solid propellant at a time when the base of the slots in the zero-second grain...
configuration had burned to the internal insulation on the solid rocket motor casing.
3.0 Test Facilities

3.1 Water Tunnel Facility

In order to visually record the internal flow phenomena associated with the solid propellant, a clear acrylic grain model and the nozzle/aft-dome model were mounted within an eighteen-inch-diameter clear acrylic tube in the test section of the Virginia Tech Water Tunnel. The water tunnel facility is shown in figure 10.

The water tunnel, which rests atop a wood and aluminum frame, is constructed of mated sections of eighteen-inch-diameter PVC pipe. The test section consists of clear glass side and bottom panels which are supported by a steel frame. A high-efficiency ten-horsepower Toshiba motor drives an Ingersol Rand size 18APL main pump which is capable of circulating up to 10,000 gallons of water per minute. A honeycomb flow-straightener, placed approximately five
feet upstream of the test section, served to reduce flow turbulence as well as to eliminate swirl caused by the 90-degree tunnel turn that preceeded the test section by five feet. Secondary flow is drawn from the main flow by a 6-1/2-inch-diameter Peerless model 830AM pump, driven by a three-horsepower Baldor industrial motor.

To minimize visual distortion during testing, it was necessary to fill the entire test section with water, in addition to filling the water tunnel. When the tunnel was fully operational, water was pumped axially through the grain model to simulate core flow upstream of the aft propellant element. In addition, a certain percentage of water was diverted from the main tunnel opposite the test section, through the secondary flow tube and pumped through four 2-1/4-inch-diameter holes in the clear acrylic tube surrounding the grain model. This secondary flow was then forced through the thousands of holes in the grain model to simulate local propellant mass flow. The amount of diverted secondary flow was set according to the required mass flow balance.

3.2 *Cold Air Test Facility*

In order to conduct gas testing of the solid rocket motor models, a cold air test facility was constructed using a high capacity Dayton model 2C988 industrial centrifugal blower with a 12-5/8-inch-diameter wheel. This blower, which was driven by a Dayton 1-1/2-horsepower motor, was attached to the rear of the
nozzle model, as shown in figure 11, and served to pull air through the one-eighth-scale acrylic models of the aft end solid rocket motor. To prevent possible upstream propagation of vortices emanating from the centrifugal blower, a honeycomb flow-straightener was placed between the blower and the nozzle. Surrounding the nozzle/aft-dome and the grain models was an eighteen-inch-diameter clear acrylic tube, similar to the surrounding tube used in the water tunnel test section. To assist in proper core-flow/secondary-flow balancing, bell-shaped nozzles were fastened to the mouth of the grain model and surrounding tube respectively.

When the cold air facility was fully operational, core flow upstream of the aft solid propellant element was simulated by air passing through the inner nozzle and proceeding axially through the grain model. The air that was pulled through the thousands of holes in the grain model, via either the outer nozzle or the twelve 2-1/2-inch-diameter holes drilled in the surrounding acrylic tube, simulated propellant mass flow. As in the water tunnel, the core flow and propellant flow were balanced to match the full-scale ratio in the proposed SRM.
4.0 Mass Flow Balancing

Mass flow balancing is the process of adjusting the rate of fluid motion of the primary axial flow, which simulates the core propellant mass flow upstream of the aft grain element, and the secondary flow through the holes of the model, which simulates the local normal propellant flow. In order to model the internal flow in the aft end of the solid rocket motor as accurately as possible in both the water and cold air tunnels, mass flow ratios were set to the levels determined by internal ballistics analyses conducted by Atlantic Research Corporation.

Proper balancing in the cold air test facility was made possible by the use of the twelve 2-1/2-inch-diameter holes in the eighteen-inch-diameter tube surrounding the grain model and by the use of the inlet nozzles attached to the mouth of the model and surrounding tube. Maximum secondary flow was achieved by leaving the outer nozzle and the twelve holes on the surrounding tube unobstructed, while minimal secondary flow was made possible by covering both the outer nozzle and some of the holes on the surrounding tube.
To determine the core mass flow rate, velocity profiles were measured at the mouth of the model using a pitot static tube. Similarly, velocity profiles were measured just downstream of the nozzle ahead of the blower, to determine the overall mass flow rate. The difference between the overall and core mass flow rate was considered to be the total secondary flow rate. By solely adjusting the amount of secondary flow with the outer inlet nozzle and holes on the surrounding tube, the proper core-flow/secondary-flow ratio was set. This flow ratio for the ignition-time aft fin model was set to 59/41 percent, while the ratio was set to 78/22 percent for the thirty-five-second burn-time scallop model.

In the water tunnel, secondary flow was drawn in only by the secondary flow tube, which was connected to the four holes in the tube surrounding the model. The main tunnel flow entered only the mouth of the grain model, since passage of this flow into the surrounding tube and through the holes on the model was prevented by an acrylic restrictor plate. Hence, secondary flow rates were set solely by adjusting the power of the motor driving the secondary flow pump.

Water manometers and pitot tubes were used in the flow rate determination in the secondary flow tube, while a March-McBirney electromagnetic current meter, mounted slightly upstream of the tunnel test section, was used to determine the main tunnel flow rate. Unlike the method of determining mass flow rates in the cold air facility, measurements solely in the center of the main tunnel and secondary flow tube were found to be sufficient in calculating the respective mass flow rates. The core-flow/secondary-flow ratios were set to the same values used in the cold air facility.
As previously mentioned, the Reynolds numbers based on model inlet conditions for both the air and water tests were above the critical value of $10^4$; therefore, Reynolds number matching was not required for flow similarity. Mass flow balancing by itself was sufficient for accurate internal flow simulation.
5.0 Instrumentation and Experimental Techniques

During the water tunnel testing, two methods were used for flow visualization. First, fluorescein dye, a water soluble dye that fluoresces at a specific light frequency, was injected at various points in the bottom of the nozzle/aft-dome region. Such regions include those within and near the slots (zero-second model) and scallops (thirty-five-second model), in the core flow, and near the nozzle entrance plane. High-intensity photofloodlights were used with incandescent room lights to illuminate the injected dye. Air bubbles also served as a good tool for flow visualization. The air trapped inside the grain model and aft-dome, either prior to tunnel start-up or by injection, was sometimes swirled into highly visible vortices originating from the forward portion of the aft dome and proceeding through the nozzle. Each of the water tunnel tests was recorded from various angles about the test section by a Panasonic professional model cam-corder on standard VHS videotape.
Three intruments were used in the acquisition of data in the cold air test facility. A standard pitot static tube was used in conjunction with a Validyne model PS309 electric manometer with a useful range of ±14 inches of water, to obtain velocity profiles aft of the nozzle exit plane and within the mouth of the model, as previously mentioned, to calculate mass flow rates. By employing a trial and error method of covering a number of secondary flow holes on the tube surrounding the model and calculating the resulting mass flow rates, the proper core-flow/secondary-flow ratio was set.

Hot-wire anemometry in the constant temperature mode was used to measure velocities in the nozzle/aft-dome region and in a plane slightly upstream of the nozzle face. The hot-wire probe was connected to a Dantec model 56C17 anemometer bridge and model 56C01 circuit controller, which were linked to a 56B10/56B12 mainframe. Data acquisition was made possible via an IBM personal computer containing a Metrabyte DASH-16/16F A/D board with sixteen A/D channels and two D/A channels. Prior to each experiment, the hot-wire probe was calibrated between a range of zero and two inches of water. At each of the measurement points along the hot-wire traverse, shown in figures 12-14, the sampling rate was 100 per second for twenty seconds, and from these readings, mean and RMS values were calculated using a computer program and stored on a computer diskette. The primary source for velocity uncertainty results from the hot-wire calibration. A least squares voltage-velocity curve fit was employed during calibration, which yielded uncertainties of approximately ±2.5% in the high-velocity core flow region. Velocity uncertainty in the
low-velocity regions (less than 15 ft/sec) was much greater. Uncertainty in voltage measurements was minimal compared to the velocity uncertainty.

There were two probe alignments during the vertical traverses, slightly ahead of the nozzle as depicted in figure 15. Radial and axial fluid motion contributed to the "axial" measurement when the probe was aligned perpendicular to the model's centerline axis, while tangential and radial components accounted for the "transverse" measured velocity. Similarly, there were two probe alignments when the probe was placed within the aft-dome region, 30 degrees circumferentially from the lower wall. The probe aligned along a radial line from the center of the circular dome sensed "tangential" velocity containing tangential and axial constituents, while the "axial" velocity measurements contained radial and axial components. The probe locations during these horizontal traverses in the aft-dome, 30 degrees from the bottom wall, are shown in figures 12-13. Figure 14 shows the hot-wire positions downstream of a slot and a fin.

Finally, 48 static pressure taps, whose locations are shown in figures 16-18, were connected to a single Setra-System pressure transducer by a Scanivalve selector and digital interface unit. After 100 pressure samples per second were obtained in 10 seconds for each static pressure tap, the mean pressure differences (between static and atmospheric, or total) were stored on a computer diskette. From these values, pressure coefficients were calculated using the following relation: 

$$C_p = \frac{[(p_{\infty} - p_{\infty}) - (p_{\infty} - p_{\infty})]}{(1/2 \rho V^2)}$$

where \(\infty\) refers to the value at the centerline axis of the grain model, four inches upstream of the nozzle entrance.
plane. Figure 19 shows a rough schematic diagram of the data acquisition system.
6.0 Experimental Results

6.1 Water Tunnel Results

6.1.1 Zero-second Burn-time Model

In an effort to properly adjust the mass flow ratio, it was necessary to set the main tunnel velocity to 1 ft/sec. Dye injected into the core of the model quickly proceeded down the centerline axis in a random, wavy fashion, indicating a well-developed turbulent core flow. With the nozzle in the unvectored position, dye injected within the aft-dome remained in this region for an extended period of time, slowly swirling at about 1/2 in/sec within the dome to approximately 90 degrees before being pulled upstream and into the nozzle. Virtually all of the dye injected within a slot about five inches upstream of the nozzle entrance plane proceeded into the core flow. Sometimes, however, a small portion of the dye
was entrained into the shed vortices from the edge of the fins, mixing with fluid flowing from the adjacent slot. Regardless of the initial direction taken, though, all of the dye injected within the slot quickly entered the nozzle. An illustration of these flow patterns is shown in figure 20.

When the nozzle was vectored to -8 degrees dye injected at the bottom base of the aft-dome remained in the aft-dome, as in the unvectored case, but only swirled circumferentially to approximately 45 degrees at approximately 1/4 in/sec. All of the dye injected within the slots was forced into the core flow and through the nozzle. Figure 21 shows these flow phenomena.

Dye injected in the aft-dome when the nozzle was vectored to +8 degrees also remained in this region, and slow circumferential flow was observed with dye travelling up to 120 degrees at a rate of approximately 1 in/sec. Dye that was injected into the slots behaved as in the unvectored case. Most of the dye was pushed into the core flow and through the nozzle, while the dye that was entrained into the shed vortices from the fin corners showed a tendency to proceed under the nozzle until it was pulled into a spin sufficient to move the dye 5-10 degrees circumferentially, then upstream and through the nozzle, as shown in figure 22.

For all vectoring cases, when dye was injected into the aft-dome region it was random as to which side the observed circumferential motion existed in the base of the dome. Sometimes, however, the circumferential flow proceed to both the left and right from the point of dye injection. When this splitting pattern was observed, the angle to which the dye swirled circumferentially before ingestion
into the nozzle was typically one-half of that observed during one-sided circumferential flow. For instance, when the nozzle was vectored to +8 degrees, dye proceeded circumferentially 120 degrees as previously mentioned; however, dye flowed only to about 60 degrees when circumferential flow splitting was observed at the dye injection point.

6.1.2 Thirty-five-second Burn-time Model

To properly adjust the mass flow rates for the thirty-five-second case, it was necessary to set the main tunnel speed to 3 ft/sec. During testing using this model, strong vortices were seen originating on the forward portion of the aft-dome and proceeding into the nozzle. This phenomenon, visualized with the presence of air bubbles, occurred for all nozzle vector angles tested. The vortex labelled "A" in figure 23 was observed when the nozzle was in the 0-degree and +8-degree positions, appearing to be stronger in the +8-degree position, while vortex "B" of figure 24 was observed primarily when the nozzle was vectored to -8 degrees. Air bubbles travelling axially down the inside surface of the model made visible the vortices, labelled "C", being shed from the scallop edges, or fin remnants, for all vector angles tested. Flow from adjacent scallops mixed together within these particular shed vortices.

Dye injected into the center of the model indicated, as in the ignition-time case, a well-developed turbulent core flow. When dye was injected into the scallop region approximately twenty inches upstream of the nozzle entrance
plane, most of the dye immediately moved into the core flow and proceeded down through the nozzle. A small portion of this dye, however, was entrained in weak reverse flow at approximately one foot downstream of the model's mouth/scallop pattern break-point.

For the unvectored case, when dye was injected into the bottom base of the aft-dome, there was little apparent circumferential flow, with the dye moving only up to 30 degrees from the lower dome before flowing upstream and into the nozzle. Most of the dye injected in this lower dome region moved immediately upstream to the core flow and into the nozzle. When dye was injected at the downstream edge of the scallop model, as shown in figure 23, about one-half of this dye was drawn into the nozzle, while the other half moved under the nozzle and proceeded circumferentially to approximately 90 degrees before moving upstream to the core flow.

When dye was injected in the base of the aft-dome, while the nozzle was vectored to -8 degrees, the movement of dye was both upstream to a point under the nozzle and circumferential in the dome to about 60 degrees, as depicted in figure 24. The dye that moved forward under the nozzle was then drawn circumferentially 90 degrees before being ingested into the nozzle. After injection at the aft end of the scallop model, dye was entrained into shed vortices from the scallop edges, then moved into vortex "B", which quickly swirled the dye into the nozzle. Sometimes, however, the dye moved from the probe, directly into a region directly below the nozzle face, then proceeded circumferentially 90 degrees before being drawn into the nozzle.
The quickest circumferential flow was observed in the base of the aft-dome when the nozzle was positioned at +8 degrees, as depicted in figure 25. The dye injected into this area flowed up approximately 120 degrees at about five in/sec then into the core flow. Dye injected at the aft edge of the scallop model immediately moved under the nozzle and into the aft-dome region, where it also swirled circumferentially 120 degrees prior to clearing the dome area.

6.2 Cold Air Tunnel Results

6.2.1 Zero-second Burn-time Model

A hot-wire traverse at 1.05 inches upstream of the nozzle face, as depicted in figure 12, yielded mean and RMS velocities whose profiles are shown in figures 26-31. With the hot-wire probe aligned perpendicular to the centerline axis of the model, the profiles and magnitudes of the mean and RMS velocity remain unchanged through all vectoring angles. A well-developed symmetric core flow is evident, with the greatest axial velocity fluctuations occurring, as expected, just outside of the slanted slot regions of the grain model. Profiles obtained with the hot-wire probe aligned parallel to the model's centerline axis also indicate that the highest velocity fluctuations occur just outside of the slanted slot regions, or break-point of the grain element. The transverse velocity, which consists of radial and tangential components, has magnitudes that are typically about one-tenth...
as large as those of the axial velocity in the core region, or about 6 ft/sec. The transverse (with tangential and radial components) RMS curve mimicks its corresponding mean velocity profile and displays similar characteristics as the RMS curve of the axial velocity, which also contains a radial component. Therefore, the radial portion of the transverse velocity appears to be much greater than the tangential component in the region slightly upstream of the nozzle entrance plane. As observed in these figures for the ignition-time case, the flow patterns in this region are insensitive to nozzle gimbling.

Figures 32-33 present results of the tests conducted during the horizontal hot-wire traverse within the aft-dome, at an angular position of 30 degrees from the lower base of the dome. Data was acquired for cases behind both a slot and a fin, as depicted in figure 14. The first observation is that the fluid's velocity in this region is usually just over one-tenth of the mean core velocity, or about 6 ft/sec. Both axial and tangential mean velocities behind a fin, or between slots, appear negligible compared to the mean velocities behind a slot for most nozzle vector angles. "Axial" velocity was greater behind the slots due to minor jetting, and it increased in magnitude as this region was enlarged by vectoring the nozzle away, from -8 degrees to +8 degrees. For these test cases, the "axial" velocity measurement consisted of both an axial and radial component, while the "tangential" measurements contained axial and tangential contributions. Hence, the radial velocity component of the fluid from the slots seemed to be greater than the true tangential component, indicating minimal circumferential velocity under and behind the nozzle region.

Experimental Results
Pressures obtained from the static pressure taps located circumferentially about the aft dome are plotted in coefficient form in figures 34-39. Figure 37 is provided merely to assist the reader in profile/pressure tap superposition. The $C_p$ profile is generally the same throughout all vectoring angles, with increasing magnitudes of up to 15% as the nozzle angle increases to +8 degrees. Changes in $C_p$ of less than 5% between static pressure taps are evident for a given nozzle vector angle, indicating the lack of any severe pressure gradients in the aft dome region. Pressure distributions from taps located slightly upstream of the base in the aft dome are plotted in figures 40-44. As in the base of the dome, pressure variations between taps are minimal, and the pressure coefficients increase by less than 15% as the nozzle is rotated towards the top of the dome wall containing the static pressure taps. The pressure results indicate, as do the hot-wire results, that the flow in the aft dome region behind the 0-second grain model is relatively stagnant, with velocities typically about 10% of the core velocity, which is consistent with water tunnel findings.

6.2.2 Thirty-five-second Burn-time Model

Figure 13 shows the hot-wire path, 1.05 inches upstream of the nozzle entrance plane, for the 35-second burn-time scallop model. The results of the axial and transverse traverses are shown in figures 45-50. A symmetric core flow is present, and strong axial velocity fluctuations become apparent as the scallops are approached, when the nozzle is unvectored. As the nozzle is gimbaled away
from the centerline position, the centerline mean axial velocity decreases, and the mean axial velocity profile shifts with the motion of the nozzle inlet. There exist slightly higher transverse turbulence intensities (transverse velocity fluctuations relative to the mean centerline velocity) in this case, compared to the ignition-time case. The magnitude of the transverse velocity, however, does not follow the decreasing trend of the axial velocity's magnitude as the nozzle angle increases, and it reaches a maximum at the most extreme vector angle of -8 degrees. Note that the transverse velocity plots show magnitudes and not a particular direction. Again, since the axial traverse detects both an axial and radial component, and the transverse hot-wire traverse detects both radial and tangential components, the majority of the transverse velocity in the unvectored case is thought to be radial, due to the similar RMS curves and assumed symmetry within the traverse region.

Velocities obtained from a horizontal hot-wire traverse at a radial position 30 degrees from the bottom of the dome are depicted in figures 51-55. Each of the RMS velocity curves exhibit virtually the same behavior as the profile of its corresponding mean velocity, and their magnitudes increase as the nozzle face is approached. As in the hot-wire data in the aft dome region in the ignition-time model, the measured "axial" velocity is composed of both an axial and radial component, and the "tangential" velocity contains axial and tangential components. For each nozzle vector angle the mean velocities are slightly higher, as expected, behind the slot or open scallop of the model than behind the fin or fin remnant of the grain model. With the exception of the +8-degree case, all
velocities increase as the hot-wire probe is inserted further upstream away from the base of the dome, indicating the increasing presence of axial/radial and especially circumferential flow under the nozzle. As the nozzle face is approached, the "axial" velocity dominated, indicating that the fluid that was proceeding circumferentially under the nozzle was being pulled upstream and into the nozzle, verified in the water tunnel test results. With the nozzle in the +8-degree position, the velocity profiles indicate that there exists tangential or circumferential motion near the base of the aft-dome. This tangential motion decreases as the nozzle entrance plane is approached, due to the increasing presence of axial/radial motion. In the unvectored case, there appears to be little circumferential motion in the base of the aft dome at a radial position of 30 degrees from the bottom; however, it seems to exist in this region during positive vectoring, with magnitudes typically about 20% of the core velocity, which is also consistent with water tunnel results.

Pressure coefficients calculated from pressure differences obtained at the base of the aft-dome are presented in figures 56-60. As with the ignition-time model, Cp variations between pressure taps for a specific nozzle vector angle are small, usually approximately 5%, while overall variations are typically under 10% during vectoring. Hence, this region which experiences no severe pressure gradients seems relatively insensitive to nozzle gimbaling. Pressure distributions on the inside top of the dome wall, upstream of the base, are plotted in figures 61-65. Again, Cp variations are minimal between adjacent static pressure taps for a given nozzle angle. As the nozzle was moved toward the pressure taps on
the inside dome surface, the average magnitudes of the pressure coefficients decreased, indicating higher local velocities as the region becomes constricted by the nozzle.
Circumferential flow was always present, either in the base of the aft-dome or around the nozzle, with both aft-segment model configurations of the solid rocket motor, regardless of the nozzle's angular position. When circumferential flow existed in the base region of the aft-dome, the degree to which fluid in this area proceeded around the aft-dome before being ingested into the nozzle seemed to depend primarily upon the horizontal distance between the aft-dome and nozzle entrance plane. Vertical clearance between the nozzle and grain model produced a secondary influence. For instance, dye that recirculated circumferentially in both +8-degree cases travelled 120 degrees to a position where there was minimal distance between the nozzle face and aft-dome, before it proceeded into the nozzle. Conversely, dye only flowed circumferentially 45 degrees in the -8-degree ignition-time case before clearing the aft-dome region. Circulatory motion about the underside of the nozzle, upstream of the aft-dome, was only observed during non-positive nozzle vectoring. Velocity fluctuations in
this region were greater than in the aft-dome, due primarily to the unsteady mixing of fluid from both the aft-dome and scallop regions.

The relative rates of circumferential motion appear to be affected by the clearance between the nozzle and grain model. The fastest circumferential flow in the aft-dome occurred in both models when the nozzle was vectored +8 degrees, which essentially allowed more fluid from the fin and scallop slots to enter the aft-dome region. (Note that the point of reference, where hot-wire measurements and visual observations via dye were made, is in the lower half of the dome model.) The slowest circumferential flow rate in the aft-dome of the ignition-time case occurred with a nozzle angle of -8 degrees, when the smallest portion of fluid from the rear of the slots was able to pump the recirculating fluid circumferentially within the aft-dome.

During the thirty-five-second case, strong inlet vortices that originated on the forward portion of the dome wall were similar to the inlet vortices witnessed during prior experiments that employed different nozzle/aft-dome and non-zero burn-time grain models (Squire, 1988; Marchman, et al., 1988 & 1989). This particular phenomenon did not occur with grain configuration models that filled the immediate region about the nozzle inlet, as did the ignition-time models. Therefore, the existence of these inlet vortices appears to be associated primarily with grain models that simulate propellant well-into the solid rocket motor’s firing sequence. At this particular burn-time, the fluid in the nozzle region behaves similarly to the air around a gas-turbine aircraft engine operating at static and near-static conditions. De Siervi et al. (1982) found that the formation
of inlet vortices between the ground and engine inlet depends upon the presence of circulation in the air that is to be drawn into the inlet. The vorticity of vortex lines in the rotational flow ahead of an engine inlet, or nozzle inlet in this case, is amplified by stretching as these lines are pulled through the inlet; and as a strong vortex line passes over a stagnation point on the ground (or wall) near the inlet, a visible inlet vortex may form. Also, Colehour and Farquhar (1971) found that the stability of an inlet vortex increases as the distance between the inlet and ground decreases. Because of the non-uniform core velocity field, circulation did indeed exist in the fluid upstream of the nozzle/aft-dome. Hence, inlet vortices were observed at the top of the aft-dome immediately behind the scallop termination point, as expected, when the nozzle was vectored +8 degrees toward this area.

Velocity profile shifting was another pattern that existed during nozzle vectoring when the region immediately ahead of the nozzle face was unobstructed, as in the thirty-five-second model. This velocity profile movement did not occur during nozzle vectoring in the ignition-time case, however, since the presence of the grain model in this region essentially prevented such shifting. Axial and transverse velocity fluctuations were greater near the edges than at the center of both models due to both physical boundary effects and secondary flow mixing. This behavior is similar, as the walls are approached, to both that of the increasing axial and normal turbulence intensities in flow over porous surfaces (Kong and Schetz, 1982) and to that of the increasing axial turbulence intensity in turbulent flow through porous tubes (Dunlap, et al., 1974; Yamada, et al.,
This increased turbulence near the wall, or grain, will increase heat transfer, and thus increase erosive burning. It also acts to enhance the mixing rate of the decomposition gases.

Since the hot-wire sensor detects all cooling velocities as a positive quantity (negative or backflow velocities are rectified), it is a directionally insensitive instrument. Simpson (1976) showed that when the RMS-mean velocity ratio becomes greater than 1/3, the amount of backflow is significant, and it becomes increasingly more difficult to determine flow directions. When this ratio reaches 1/2, as it did in the aft-dome and slots of both grain models, it becomes impossible to interpret velocity components with the mean and RMS data acquired in this study. Because of the rectification of negative velocities about the zero velocity line in a Gaussian velocity probability distribution, the measured mean velocity is higher than the actual mean, while the measured RMS velocity is lower than the real RMS velocity. Therefore, the comparison in mean velocity magnitudes in these regions, where the RMS-mean velocity ratio is above 1/3, should be primarily qualitative, and precise quantitative behavior should not be inferred. Even though the velocity uncertainty is high in these slot and aft-dome regions, the flow field is characterized by high turbulence, near-stagnant velocities, and directional uncertainty with respect to the velocity component resolution.

For both grain cases, regardless of the nozzle angle, the majority of fluid within the aft portion of the slots proceeded into the core flow directly, or via either the alternating shed vortices from the fins or the radial inlet vortices.
Approximately twenty inches upstream of the nozzle face, secondary flow proceeded into the core flow immediately, except for a small portion of secondary flow in the thirty-five-second model, as mentioned in Chapter 6. This portion of fluid was entrained in weak recirculatory flow caused by separation of the upstream core flow at the scallop break-point near the mouth of the model.

The minor pressure gradients that existed in the aft-dome for both burn cases with an unvectored nozzle indicate slight asymmetries in the nozzle/aft-dome model and/or the grain models. As opposed to prior tests with different nozzle/aft-dome configurations that exhibited varying pressure gradients during nozzle vectoring (Marchman, et al., 1988), tests with this particular nozzle/aft-dome indicated a circumferential pressure gradient insensitivity toward nozzle gimbaling. The pressure field on the inside top of the dome surface is, however, affected by nozzle rotation. The pressure coefficients did decrease as the nozzle approached the taps on the upper dome surface, indicating a slightly higher velocity in the region possibly caused by the swirling near the inlet vortices that existed at such nozzle angles.
8.0 Conclusions

Since circumferential flow in the aft-dome also existed during prior experiments that employed various combinations of nozzle/aft-dome and grain configurations, it seems that at least some degree of circumferential motion will always be present within the dome region of practical solid rocket motors employing a submerged nozzle. This phenomena results from a complex interaction between primary and secondary flow patterns in the region around the rotating nozzle, and its strength and speed exhibit a significant dependence upon nozzle/aft-dome geometry, propellant geometry, nozzle vectoring, and the upstream flow field.

On the one hand, strong circumferential motion about the nozzle and within the aft-dome is undesirable, since increased convective heating would occur and potentially erode parts of the nozzle and aft-dome casing insulation. On the other hand, though, at least some aft-dome axial and/or circumferential "flushing" seems advantageous, since propellant debris that may collect and lodge
within the region and continue burning on the wall may also damage the internal insulation. Although slowly recirculating fluid in the aft-dome had a high residence time with the ignition-time case, where the propellant cast in this region prevented quicker clearance, it was eventually drawn out either axially or circumferentially. In addition, the circumferential motion that occurred for both burn-time cases around the nozzle and/or in the aft-dome was still slow enough, even during maximum nozzle vectoring, to be considered relatively harmless to the nozzle/aft-dome insulation, versus much faster circumferential flow associated with previously tested nozzle/aft-dome configurations at similar conditions. Circumferential motion in both burn-time cases almost always proceeded in a direction toward the region of minimal distance between the surface of the aft-dome and the nozzle lip. Within this particular aft-dome, the pressure gradient pattern was insensitive to nozzle vectoring, and the overall relative pressures and velocities only changed slightly.

Inlet vortex formation at a stagnation point on the dome wall immediately aft of the fin remnants appears to be an unavoidable characteristic that may always exist with submerged nozzle solid rocket motors. Within SRM core flow, circulation will always exist and a stagnation point will usually be present, either due to separation in the regions of vortex shedding from the fin remnants or due to secondary flow phenomena associated with submerged nozzle SRM designs. Methods to eliminate or control inlet vortices associated with aircraft engines cannot easily be applied in a solid rocket motor. One such method requires blowing fluid at the stagnation point in an attempt to move the point aft of the
engine inlet, thereby making inlet vortex formation more difficult. Such a method applied in a SRM, if the jet tubes could withstand the intense heat, would only act to increase undesirable erosive burning in the aft-dome.
9.0 Recommendations

Since circumferential flow within the nozzle/aft-dome region is a major concern with its tendency to erode insulation, testing to understand the effects of flow restrictors placed within the aft-dome is recommended. Also, as the use of finned and near-finned grain configurations becomes more popular in an effort to maximize propellant loading, further studies to understand the effects of vortex shedding from fins and fin remnants upon circumferential flow is suggested. Finally, similar testing using various generic grain configurations is recommended, unless advances in insulation, casing, and nozzle materials render such circumferential flow concerns negligible.
References


References
Figures
Figure 1. Loaded solid rocket chamber with aft finocyl grain.
Figure 2. Proposed finned aft segment grain.
Figure 3. Internal solid propellant designs with corresponding thrust-time curves. (Shafer.)
Figure 4. Axisymmetric solid propellant configurations. (Zeller.)
Figure 5. A typical movable nozzle. (Truchot.)
Figure 6. Primary internal flow field in submerged and external nozzle configurations (Truchot.)
Figure 7. Aft-dome model with nozzle.
Figure 8. Ignition-time aft finocyl grain model.
Figure 9. Thirty-five-second burn-time aft grain model.
Figure II. Cold air test facility.
Figure 12. Hot-wire path for mean velocity/turbulence measurements in 0-second model.
Figure 13. Hot-wire path for mean velocity/turbulence measurements in 35-second model.
Figure 14. Hot-wire positions for mean velocity/turbulence measurements in aft-dome, 30 degrees from bottom.
Figure 15. Hot-wire probe alignments for vertical traverse ahead of nozzle.
Figure 16. Aft-dome static pressure tap locations: back view.
Figure 17. Aft-dome static pressure tap locations: side view.
Figure 18. Aft-dome static pressure tap locations: top view.
Figure 19. Data acquisition flow chart.
Figure 20. Air bubble and dye injection observations in 0-second model: nozzle at 0 degrees.
Figure 21. Air bubble and dye injection observations in 0-second model: nozzle at -8 degrees.
Figure 22. Air bubble and dye injection observations in 0-second model: nozzle at +8 degrees.
Figure 23. Air bubble and dye injection observations in 35-second model: nozzle at 0 degrees.
Figure 24. Air bubble and dye injection observations in 35-second model: nozzle at -8 degrees.
Figure 25. Air bubble and dye injection observations in 35-second model: nozzle at +8 degrees.
Figure 26. Core axial mean velocity and RMS profiles in 0-second model: nozzle at 0 degrees.
Figure 27. Core axial mean velocity and RMS profiles in 0-second model: nozzle at -4 degrees.
Figure 28. Core axial mean velocity and RMS profiles in 0-second model: nozzle at -8 degrees.
Figure 29. Core transverse mean velocity and RMS profiles in 0-second model: nozzle at 0 degrees.
Figure 30. Core transverse mean velocity and RMS profiles in 0-second model: nozzle at -4 degrees.
Figure 31. Core transverse mean velocity and RMS profiles in 0-second model: nozzle at -8 degrees.
Figure 32. Mean velocity in aft-dome with 0-second model, 30 degrees from bottom.
Figure 33. RMS velocity in aft-dome with 0-second model, 30 degrees from bottom.
Figure 34. Cp distribution on aft-dome surface, with 0-second model: nozzle at -8 degrees.
Figure 35. Cp distribution on aft-dome surface, with 0-second model: nozzle at -4 degrees.
Figure 36. Cp distribution on aft-dome surface, with 0-second model: nozzle at 0 degrees.
Figure 37. Cp distribution on aft-dome surface, with 0-second model: nozzle at 0 degrees.
Figure 38. Cp distribution on aft-dome surface, with 0-second model: nozzle at +4 degrees.
Figure 39. Cp distribution on aft-dome surface, with 0-second model: nozzle at +8 degrees.
Figure 40. Cp distribution on inside top dome surface, with 0-second model: nozzle at -8 degrees.
Figure 41. Cp distribution on inside top dome surface, with 0-second model: nozzle at -4 degrees.
Figure 42. Cp distribution on inside top dome surface, with 0-second model: nozzle at 0 degrees.
Figure 43. $C_p$ distribution on inside top dome surface, with 0-second model: nozzle at +4 degrees.
Figure 44. Cp distribution on inside top dome surface, with 0-second model: nozzle at +8 degrees.
Figure 45. Core axial mean velocity and RMS profiles in 35-second model: nozzle at 0 degrees.
Figure 46. Core axial mean velocity and RMS profiles in 35-second model: nozzle at -4 degrees.
Figure 47. Core axial mean velocity and RMS profiles in 35-second model: nozzle at -8 degrees.
Figure 48. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at 0 degrees.
Figure 49. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at -4 degrees.
Figure 50. Core transverse mean velocity and RMS profiles in 35-second model: nozzle at -8 degrees.
Figure 51. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at -8 degrees.
Figure 52. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at -4 degrees.
Figure 53. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at 0 degrees.
Figure 54. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at +4 degrees.
Figure 55. Mean and RMS velocity between nozzle and aft-dome, with 35-second model: nozzle at +8 degrees.
Figure 56. Cp distribution on aft-dome surface, with 35-second model: nozzle at -8 degrees.
Figure 57. Cp distribution on aft-dome surface, with 35-second model: nozzle at -4 degrees.
Figure 58. Cp distribution on aft-dome surface, with 35-second model: nozzle at 0 degrees.
Figure 59. Cp distribution on aft-dome surface, with 35-second model: nozzle at +4 degrees.
Figure 60. Cp distribution on aft-dome surface, with 35-second model: nozzle at +8 degrees.
Figure 61. Cp distribution on inside top dome surface, with 35-second model: nozzle at -8 degrees.
Figure 62. Cp distribution on inside top dome surface, with 35-second model: nozzle at -4 degrees.
Figure 63. Cp distribution on inside top dome surface, with 35-second model: nozzle at 0 degrees.
Figure 64. C_p distribution on inside top dome surface, with 35-second model: nozzle at +4 degrees.
Figure 65. Cp distribution on inside top dome surface, with 35-second model: nozzle at +8 degrees.
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