

ENGINEERING ANALYSIS INTO THE
REPLACEMENT OF THE CENTRALIZED HIGH PRESSURE
AIR SYSTEM FOR DDG 51 CLASS FLIGHT IIA

by

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Report submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

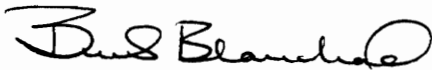
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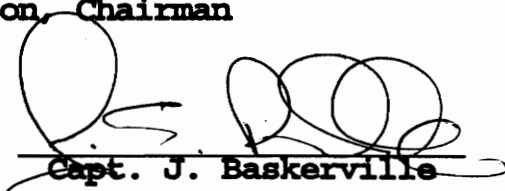
in

Systems Engineering

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DEDICATION:

To my wife (Sharon) and sons (Chad and Matt), thanks for the patience and support; your turns!

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LIST OF ABBREVIATIONS

ACC	Affordability Cost Candidate
ACOP	APU Control Operating Panel
Ai	Inherent Availability
Ao	Operational Availability
APU	Auxiliary Power Unit
BAS	Bleed Air System
BIW	Bath Iron Works Corporation
CD	Contract Definition
DART	Detection Action Reaction Technique
ECP	Engineering Change Proposal
EPCC	Electric Plant Control Console
FUM	Flight Upgrade Manager
FY	Fiscal Year
GPM	Gallons Per Minute
G&C	Gibbs and Cox, Inc.
HP	High Pressure
HPAC	High Pressure Air Compressor
HPAS	High Pressure Air System
ISD	Ingalls Shipbuilding Corporation
LBES	Land Based Engineering Site
LCEM	Life Cycle Engineering Manager
LOCOP	Local Operating Panel
LP	Low Pressure
MCCS	Machinery Central Control System
MCS	Machinery Control Station
MLDT	Mean Logistics Down Time
MPGT	Main Propulsion Gas Turbine
MTBF	Mean Time Between Failure
MTBO	Mean Time Between Overhaul
MITR	Mean Time to Repair
NAB	Naval Adjudication Board
NAVAIR	Naval Air Command
NAVSEA	Naval Sea Systems Command
NAWC	Naval Air Weapons Center
NSWC	Naval Surface Warfare Center
PPD	Project Peculiar Document
PSIG	Pounds Per Square Inch, Gage
RFP	Request for Proposal
RM&A	Reliability, Maintainability, and Availability
ROM	Rough Order of Magnitude
SCFM	Standard Cubic Feet per Minute
SDM	Ship Design Manager
SET	Shipbuilding Engineering Team
SSGTG	Ship Service Gas Turbine Generator
TGM	Task Group Manager
TL	Task Leader
UNI-JASU	Universal Jet Air Start Unit

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1.0 INTRODUCTION

1.1 Objectives

The objectives of this report are to demonstrate application of the systems engineering process utilized in the replacement of the Centralized High Pressure Air System (HPAS) aboard DDG 51 (Arleigh Burke) Class Flight IIA Destroyers, and the significant influences of Human Factors to the overall design of each new dedicated subsystem.

Replacement of DDG 51 Class Flight IIA HPAS is an ongoing effort at the Naval Sea Systems Command (NAVSEA) headquarters located in Crystal City, Virginia; this particular effort is being developed under the auspices of Engineering Change Proposal (ECP) ECP 51-1216 (Delete Centralized HPAS). As will be detailed in Section 1.2, this effort was undertaken primarily to support Flight IIA Program cost reduction initiatives, and secondly, to resolve longstanding technical concerns with available Ship Service Gas Turbine Generator (SSGTG) starting air capacity aboard Flights I and II. In addition, well established reliability, maintainability, and availability (RM&A) problems experienced Fleetwide with Centralized HPAS compressors were mitigating factors influencing the Flight IIA Program to seek alternatives. This particular initiative alone has been estimated by the lead DDG 51 Class shipbuilder to provide a recurring cost and weight savings of approximately \$1.2 million and 15 long-tons per hull, respectively.

This report will focus on requirements definition and tradeoff studies performed in the development of the ECP 51-1216 specifications. Figure 1 provides a graphical overview of the systems development process utilized for this rather "unique" design effort; this process was developed using reference (a) as guidance. The term unique is emphasized as unusual Flight IIA Program schedule requirements, coupled with Program Management decisions to utilize existing, proven, and supported hardware for ECP 51-1216 replacement subsystems resulted in deviation from the systems development process prescribed in reference (a). Section 1.3 details the Flight IIA Program schedule. Section 2 will describe the engineering process applied for ECP 51-1216, as well as overview deviations from reference (a).

Emphasis will be given to the primary operational performance requirements and physical configuration of each replacement subsystem, including underlying human factors considerations; it will be demonstrated that the later

NEED ASSESSMENT

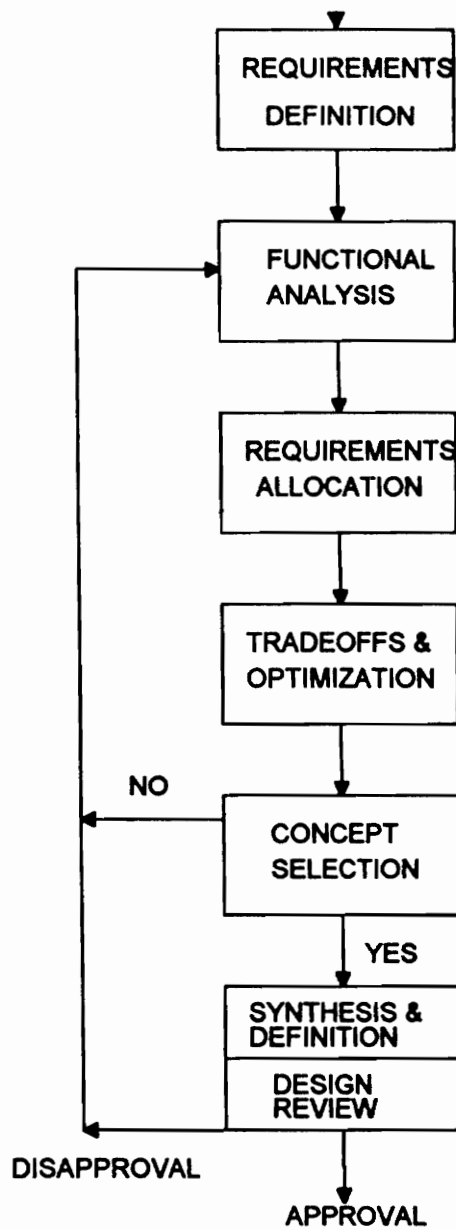


FIGURE 1: ECP 51-1216 DEVELOPMENT PROCESS

greatly influence the former. Figure 2 illustrates the human-machine interface model considered in the development of each new subsystem; this model was developed from reference (b). Section 3 of this report will detail the fundamental relationship of various human factors considerations to overall system design; a separate section is provided to emphasize the significance of human factors to proper system design.

As the most complex Centralized HPAS subsystem being replaced, the greater portion of this report will address development of the SSGTG starting air subsystem, featuring Auxiliary Power Units (APU's) as the pneumatic supply source. APU's are relatively small, lightweight, gas turbine engines capable of delivering large volumes of high temperature, low pressure compressed air. Starting SSGTG's from APU's, in lieu of high pressure (HP) air flasks, represents a significant departure from traditional U.S. Navy design practices.

This particular topic was selected as wholesale replacement of a vital auxiliary system, such as the Centralized HPAS, is considered a classic systems engineering problem. As the former Life Cycle Engineering Manager for U.S. Navy Compressed Air Systems and the former DDG 51 Class Fluid Systems Task Leader, NAVSEA 03YD, I was responsible to Flight IIA Program management for the initiation, design development and design integration of the subject Flight IIA effort. Section 1.3 describes the overall management hierarchy of the Flight IIA Program, as well as that for ECP 51-1216 development.

1.2 Problem Statement (Need Assessment)

As noted above, the decision to undergo replacement of the Centralized HPAS was primarily to support Flight IIA Program cost reduction initiatives; these initiatives resulted from the necessity to offset the costs associated with providing additional warfighting capability for Flight IIA ships. Secondary reasons for seeking replacement of the Centralized HPAS surrounded longstanding technical concerns with available SSGTG starting air capacity, particularly during dark-ship conditions, and chronic RM&A problems experienced Fleet-wide with HP air compressors serving Centralized HPAS's. Sections 1.2.1 and 1.2.2 below detail the programmatic and technical justification for undergoing development of ECP 51-1216; together they formulate the need assessment block illustrated in Figure 1.

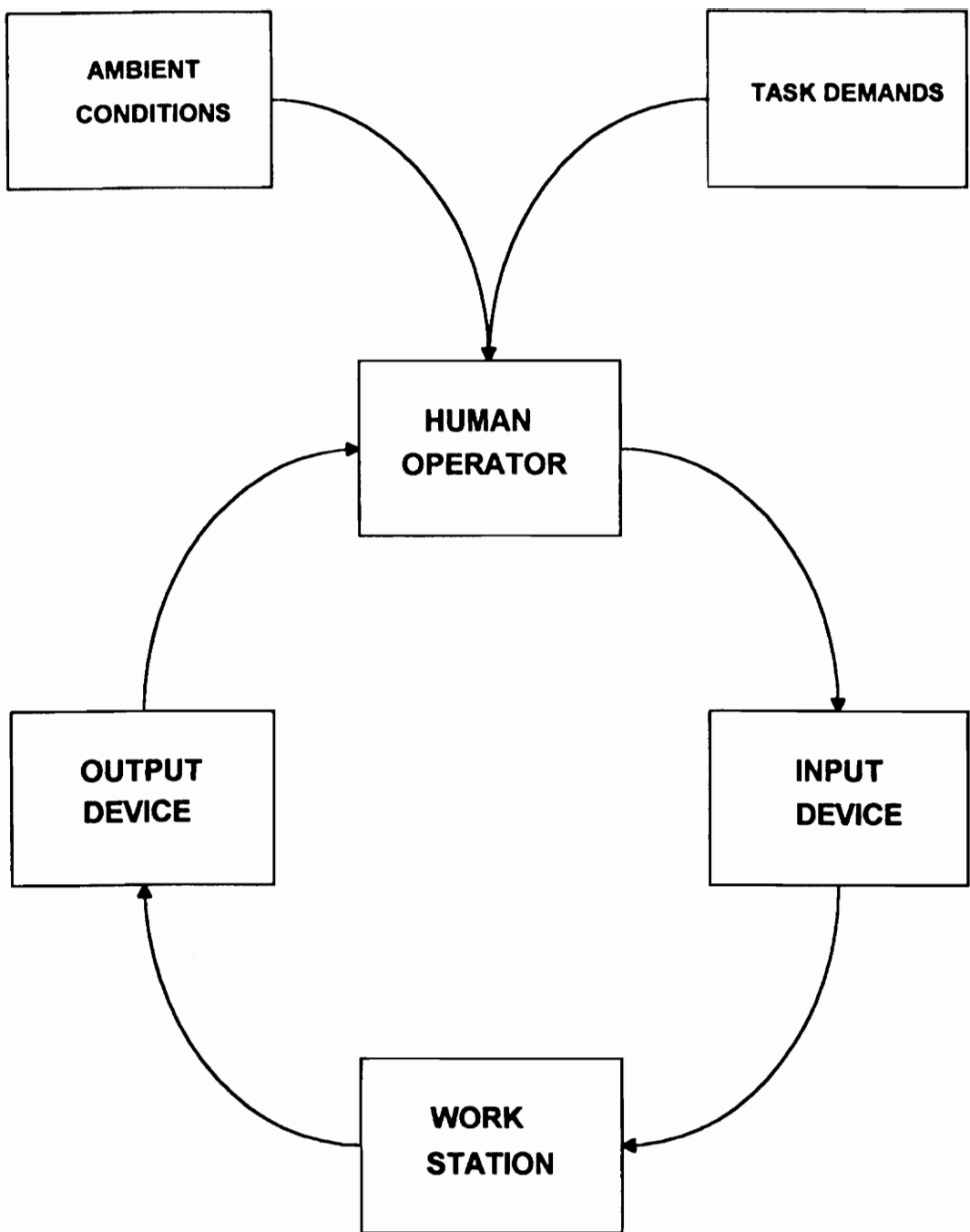


FIGURE 2: HUMAN-MACHINE INTERFACE MODEL

1.2.1 Programmatic Need Assessment

Feasibility and conceptual design phases for the DDG 51 Class began in the early 1980's with preliminary and contract design/award concluding in March 1985. Concurrent with this time span was detail design, construction, and delivery of CG 47 Class cruisers. Accordingly, and while the majority of primary weapons, propulsion, and auxiliary support systems are functionally similar, DDG 51 Class destroyers have incorporated numerous lessons learned, design enhancements, and technological improvements over CG 47 Class cruisers. Examples of such improvements include the advanced sea keeping bow design, an all steel (verses aluminum) superstructure with significantly reduced radar cross-section, modular missile vertical launch systems, enhanced damage control and fire-fighting systems, and more efficient SSGTG's for producing shipboard electrical power. Together, these and numerous other improvements formulate the initial baseline or "Flight I" DDG 51 Class configuration; Flight I hulls (DDG 51 through DDG 71) were awarded fiscal year (FY) 1985 through FY 1991. Subsequently, a second baseline, Flight II (DDG 72 through DDG 78) was developed to incorporate various combat and communications systems upgrades; Flight II hulls were awarded beginning with the last ship in FY 1991 through FY 1993.

Similarly, changes to perceived military threat since the fall of the Berlin Wall, lessons learned from the Persian Gulf conflict, and the disintegration of the Soviet Union, resulted in yet additional enhancements aimed principally at improving the U.S. Navy's capability to participate more effectively in regional conflicts abroad. Rather than canceling the DDG 51 Class shipbuilding Program and initiating a totally new ship design, which would create a significant void in the replenishment of Fleet capabilities, the challenge to the DDG 51 Program was to incorporate the necessary capability upgrades into the latest baseline without increasing overall acquisition cost, disrupting DDG 51 Class production schedules, or incurring unmanageable risks; ergo the establishment of the Flight IIA design initiative in March 92. References (c) and (d) detail the objectives and provide direction for the establishment of the Flight IIA Program. The principle Flight IIA upgrades include the following:

Additions

1. Organic LAMPS MK III helicopter facility.
2. General purpose armed helicopter.

3. Dual helicopter hanger facility with RAST.
4. Evolved Sea Sparrow Missile when available.
5. Kingfisher.
6. 6 VLS Cells.
7. 5 Blast Hardened Bulkheads.
8. Appropriate H,M,&E items such as non-CFC refrigeration and air conditioning plants

Deletions (Note those items with asterisk must be reconstitutable)

1. *CIWS (When Sea Sparrow becomes available).
2. *HARPOON
3. *TACTAS (AN/SQR-19)
4. *At-Sea Missile Handling Equipment
5. CPS Zone No. 4 (Aft of Frame 370)

Figures 3 and 4, gleaned from reference (e), are provided to illustrate the principle characteristics and major differences of Flight IIA hulls with baseline Flight II hulls. It has been estimated by the Flight IIA Program that incorporation of Flight IIA upgrades would add approximately 30 million dollars. As noted above, one of the principal objectives of the Flight IIA Program was/is to incorporate these upgrades without a net increase in overall acquisition cost. In order to offset such a cost increase, the Flight IIA Program team developed and approved 48 ECP's, of which ECP 51-1216 (Delete Centralized HPAS), reference (f), is among this group.

1.2.2 Technical Need Assessment

1.2.2.1 HP Air Compressor Concerns

The HP air compressors (HPAC's) serving Centralized HPAS's Fleet-wide are high capacity (60-100 scfm), high pressure (3000-5000 psig), oil-free units of various designs. Although highly specialized pieces of hardware (e.g. meet stringent USN standards for high shock, noise, and vibration), they suffer from high costs (both acquisition and maintenance), in addition to poor RM&A. Consequently, HPAC's have been on and off the Navy's Detection, Action, Reaction, Technique (DART) Program for much of the last 25 years; the DART Program was initiated to respond directly to the Fleet's most critical deficiencies. In addition to an initial acquisition cost of approximately \$250K - \$300K per unit, Table I reveals that average HPAC maintenance costs (per compressor) aboard four randomly selected CG 47 Class cruisers to be approximately \$80K. Note that CG 47 Class



LENGTH (LBP)	471 FT	DISPLACEMENT	9,195 LT
BEAM	59 FT	SPEED	30+ KTS
ACCOMMODATIONS	OFF / CPO / OEM	TOTAL	
	32 / 27 / 324	383	

FIGURE 3: FLIGHT IIA PRINCIPLE CHARACTERISTICS

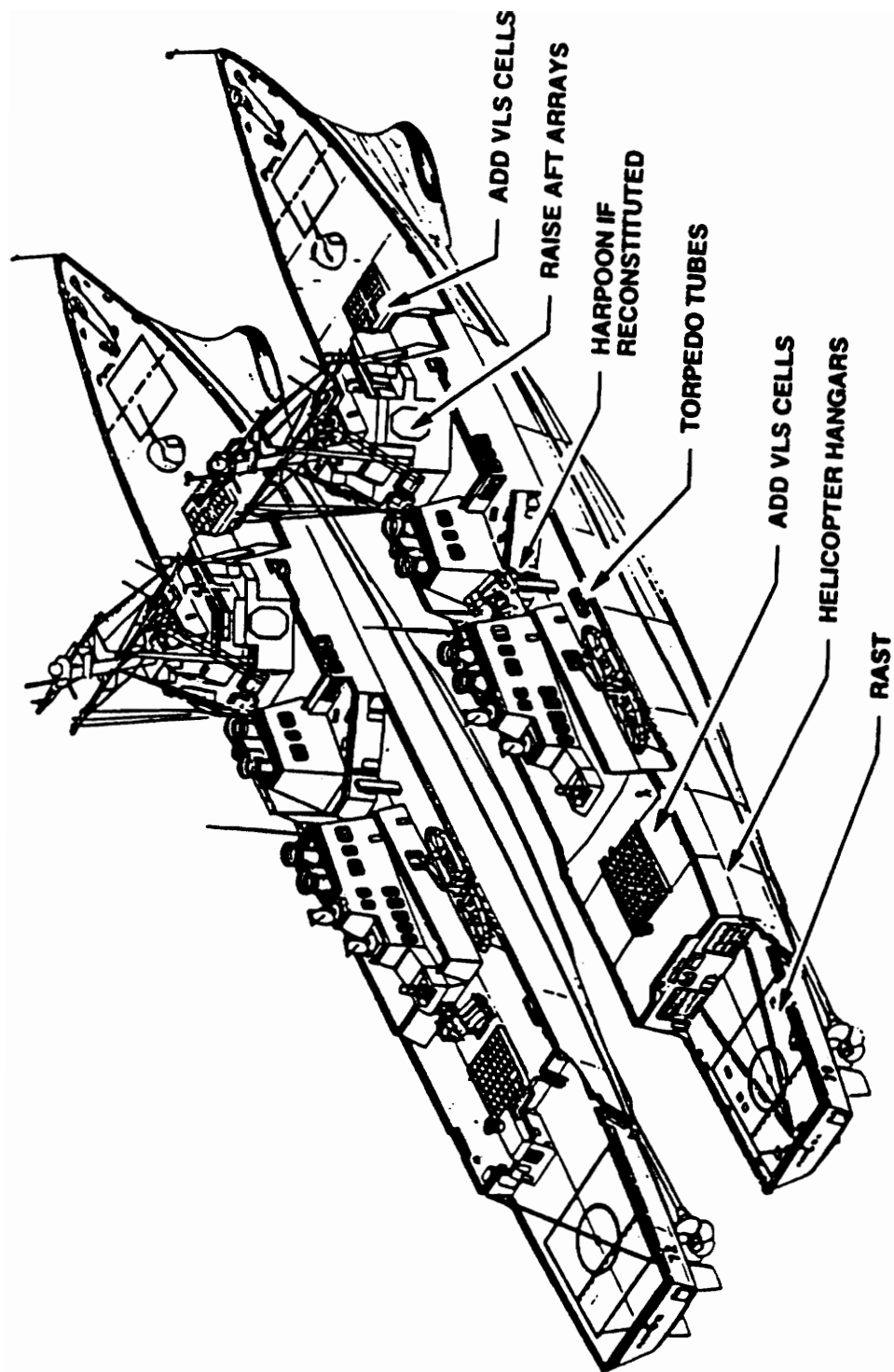


FIGURE 4: FLIGHT II/IIA MAJOR DIFFERENCES

Table I - MAINTENANCE/REPAIR COSTS FOR N20NL-11 HPAC
(Reporting Period 1/1/92 - 12/31/92)

SHIP	CG 47	CG 49	CG 51	CG 61
# Maint Actions	16	24	14	21
Cost for Maint Acts	\$8,726	\$2,915	\$187.00	\$21,115
# Ovrhls	2	2	2	2
Cost for Ovrhls	\$162,954	\$128,396	\$155,928	\$162,006
Total Cost	\$171,680	\$131,311	\$156,115	\$183,121
Avg Cost per HPAC	\$85,840	\$65,656	\$78,058	\$91,561

data was chosen as such information is not yet available for relatively new DDG 51 Class, and since DDG 51 HPAC's (Dresser-Rand Model NL20-12A) are a derivative of the Dresser-Rand Model NL20-11's installed aboard CG 47 Class.

Table II, developed from a recent NAVSEA Code 03Y4 DART briefing, provides quantitative information supporting the RM&A woes experienced Fleetwide with HPAC's contained in Centralized HPAS's. Note that the data provided in Tables I and II was not specifically used in the Flight IIA Program decision making process; it merely serves to quantify in general terms the USN's experience and inherent concerns with HPAC's installed in Centralized HPAS's.

1.2.2.2 SSGTG Starting Air Capacity Concerns

The existing SSGTG and main propulsion gas turbine (MPGT) starting air systems for Flights I and II are configured as shown in Figure 5. Starting SSGTG's and MPGT's is accomplished through one of two means; HP air from the ships' Centralized HPAS via HP starting air banks, or from low pressure (LP) bleed air which is extracted from the compressor section of an operating SSGTG or MPGT engine. As relatively high MPGT power levels (hence ship speeds) are required to develop sufficient LP bleed air pressure and flow, SSGTG's, which operate at relatively constant speed, are most often used for LP bleed air starting. Aboard DDG 51 Class destroyers and other gas turbine propelled ships such as CG 47, DD 963, and DDG 993 Classes, the general starting philosophy is to accomplish the first SSGTG start using HP air with subsequent SSGTG and MPGT starts using LP bleed air from one or more SSGTG's. This operating philosophy has evolved from poor reliability of the ships' HP air compressors, coupled with limited volume/capacity of the HP starting air banks; thereby making HP air a guarded commodity aboard gas turbine propelled ships.

Significant design features of the Centralized HPAS are the capability to provide **dark ship** starts (via HP storage banks), inherent survivability, and operational flexibility. The term dark ship is highlighted to emphasize that SSGTG's, as the principle source of electrical power for propulsion and weapons systems, must be capable of being restarted with the ship dead in the water for whatever reason (e.g. equipment malfunction, operator error, and/or battle damage) within a couple of minutes.

Regarding dark ship starting of SSGTG's from HP start banks, reference (g) details the difficulties experienced on

Table II - FLEETWIDE HPAC RM&A PROFILES

HPAC Model No.	Ship Type	MTBF 91 92	MTTR 91 92	MLDT 91 92	Ao 91 92
N20NL-7	FFG 7's	244 267	18 13	451 78	.34 .74
N20NL-10	DD 963's	452 489	18 29	235 271	.64 .62
N20NL-11	CG 47's	805 1129	14 14	152 236	.83 .82
13/20NL	LSD 41's	931 1364	25 18	317 171	.73 .88
20NL30	AD 41's	635 438	31 32	148 262	.78 .60
30NL30	CVN 70's	1022 5043	40 18	30 148	.94 .97
N30NL	CV & AS's	1758 1241	26 15	208 283	.88 .81
N13.5NL	LHA's	876 943	12 12	662 287	.57 .75

Note: SEA 03Y6 goals are MTBF (1000 hrs), MTTR (20 hrs),
MLDT (133 hrs), and Ao (.85).

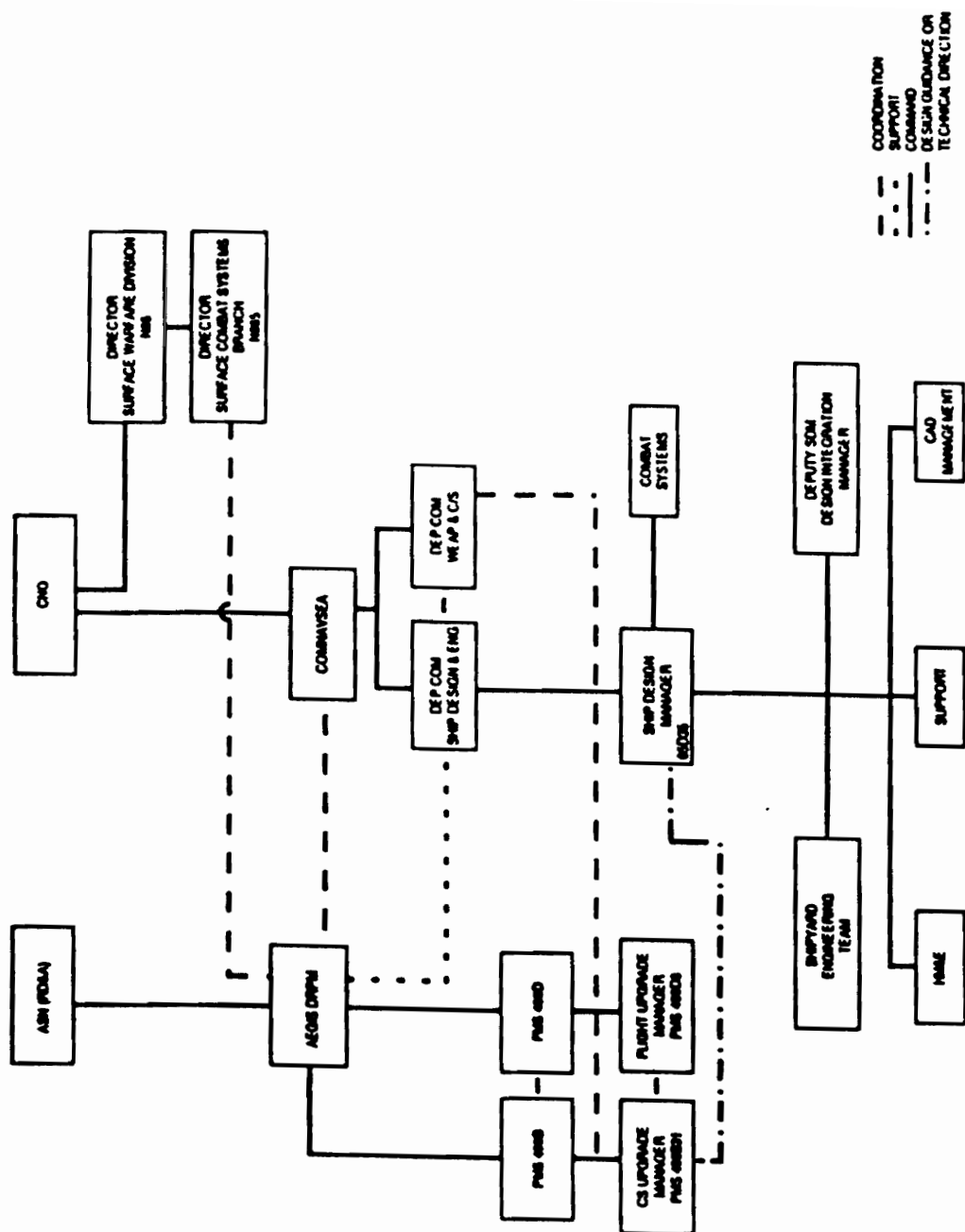
Flights I and II with meeting reference (h) requirements for three consecutive SSGTG start attempts per HP air starting bank without recharging from the ships' HP air compressors. Briefly, it was not known until well after contract award for the lead ship (USS Arleigh Burke) that the new Allison 501-K34 SSGTG's consume approximately 40 percent more start air than predecessor 501-K17 SSGTG's installed on CG 47, DD 963, and DDG 993 Classes. For Flight I hulls, this resulted in installed SSGTG HP starting air banks capable of supporting only a single complete SSGTG start attempt each. Despite the efforts of SEA 03YD and other technical representatives to minimize shipboard impacts for necessary SSGTG HP start system upgrades, DDG 51 Program cost constraints precluded "reasonable" compliance with reference (h) until Flight II, reference (i) applies. The term reasonable is highlighted since additional HP start bank capacity to support purging of unburned SSGTG combustion canister fuel between successive start attempts was not provided due to cost constraints. As for Flight I hulls, a reduced scope (two verse three SSGTG start capability) ship alteration package, reference (j) was developed. The net result to Flight IIA, at least from the viewpoint of the technical community, was strong concern over inadequate SSGTG HP starting air capacity for both Flights I and II; this concern weighed heavily in the decision to pursue and develop alternative SSGTG starting concepts for Flight IIA.

1.3 Management Approach

1.3.1 Organizational Structure

This section describes the organizational structure and hierarchy for the Flight IIA Program. Figure 6, extracted from reference (k), illustrates the top-level organization structure for the Flight IIA Program management, including identification of each group function and associated interrelationships. Of more direct significance to development of ECP 51-1216 is the organizational structure of the DDG 51 Class Flight IIA Upgrade Design Team; see Figure 7. Note that the hierarchy and functions shown in Figure 7 for the Shipbuilding Engineering Team (SET) differ slightly from those shown in Figure 6; the later Figure is more representative of actual SET roles and responsibilities exercised during development of ECP 51-1216.

The Flight IIA Upgrade Design Team was established to complete the design of Flight IIA and is a matrix-type organization directed by the Flight Upgrade Manager (FUM) and the Ship Design Manager (SDM); the former provides



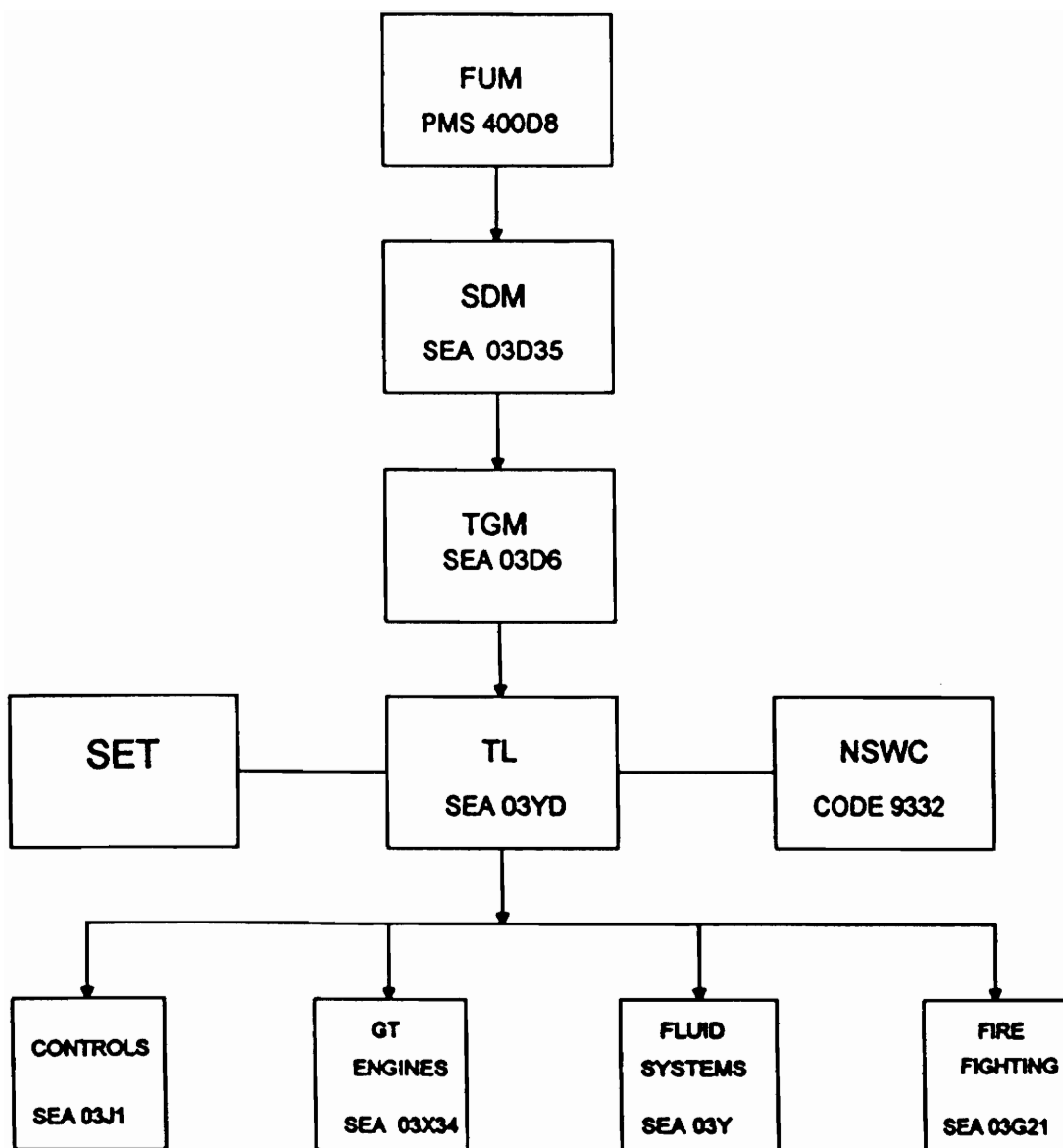


FIGURE 7: DDG 51 FLIGHT IIA DESIGN UPGRADE TEAM

funding and program-level technical guidance to the later who is responsible for daily technical program management of the Flight IIA Upgrade Design Team. In addition, the SDM serves as the principle liaison between the functional NAVSEA groups (e.g. hull, mechanical, electrical, and combat systems) and the FUM project groups. Serving immediately beneath the SDM are Task Group Managers (TGM's), who function to provide program direction and design coordination to Task Leader (TL's) within assigned functional groups. As the functional Life Cycle Engineering Manager (LCEM) for Compressed Air Systems and the DDG 51 Class Fluid Systems TL, my (SEA 03YD) responsibilities included initiation, development, management, and coordination of the technical design with other systems and equipment level LCEMS, as well as with the SET. Finally, the SET is comprised of the two DDG 51 Class shipbuilders, Bath Iron Works (BIW) and Ingalls Shipbuilding (ISD), and lead yard design agent Gibbs & Cox (G&C). The SET functions to provide primary engineering and producibility support to NAVSEA TL's, prepare the contract definition package for inclusion in the Flight IIA request for proposals (RFP's), and makes technical recommendations on design approaches to minimize cost and/or improve the design.

1.3.2 Design Schedule

This section describes the master program schedule for the rather unique Flight IIA Program; unique in the sense that shipbuilder detail design commenced well in advance of RFP and contract award of the lead ship. This schedule was developed by Flight IIA Program management to support Flight IIA Program objectives for incorporating additional warfighting design enhancements without disruption of shipbuilder production and delivery schedules. Funding for this design effort was made possible from Chief of Naval Operations, Director Surface Warfare Division (N86/OP-03), through a reprogramming of unspent funds resulting from the deletion of the HARPOON missile system for Flight II.

Figure 8 illustrates the Flight IIA Program's master schedule, as well as various highlights associated with development of ECP 51-1216. Briefly, the Flight IIA design schedule was/is comprised of three distinct phases; Feasibility Design, Contract Definition, and Detail Design. This schedule was established by the DDG 51 Flight IIA Design Upgrade Team to support the Program sponsor's requirement for continuous production of DDG 51 Class destroyers.

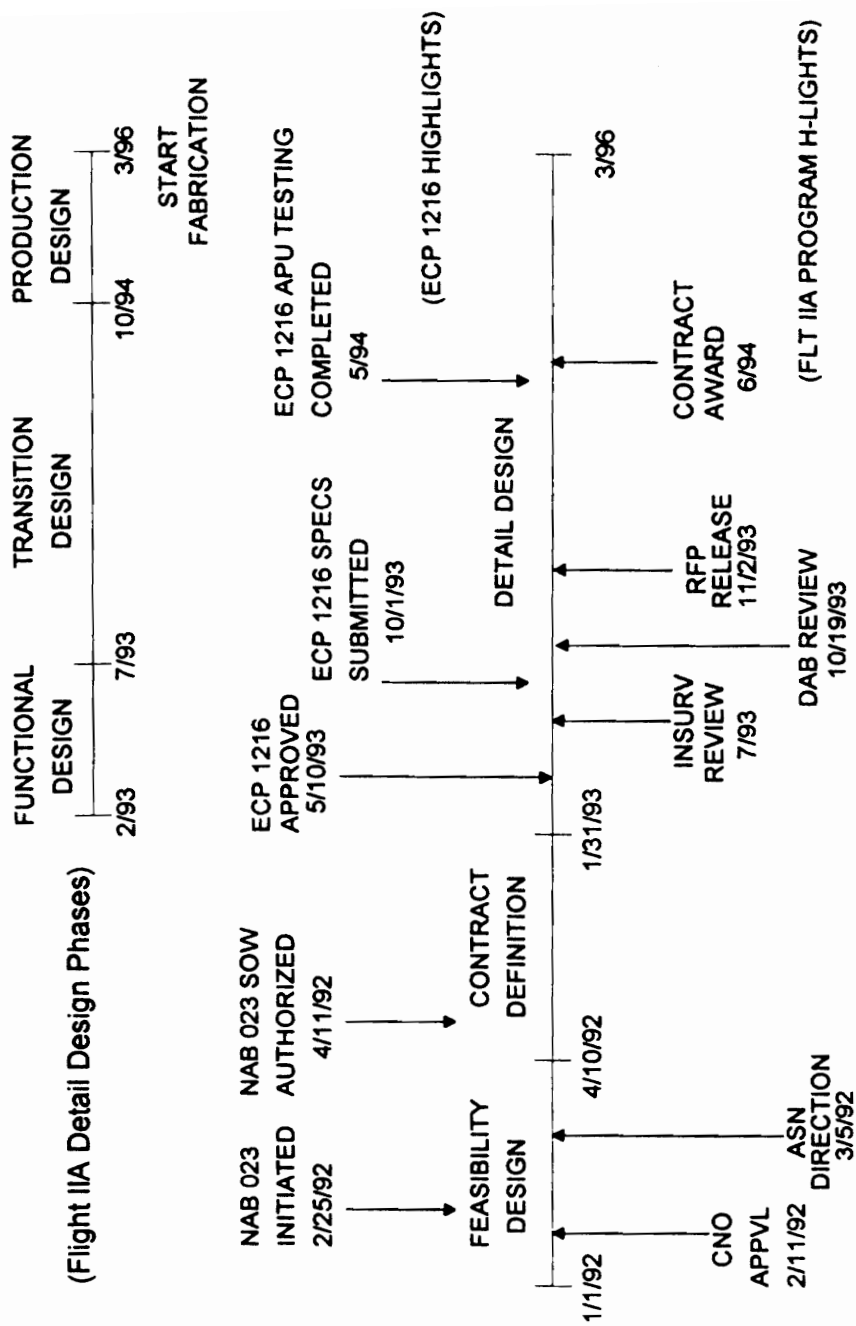


FIGURE 8 - FLIGHT IIA DESIGN SCHEDULE

Feasibility Design of the lead Flight IIA ship (DDG 79) began in January 1992 and ended approximately April 1992. During this short time period, the Flight IIA Design Upgrade Team and master program schedule was established; very little engineering, other than development of plans, policies, and procedures for meeting Program objectives, occurred during this initial design phase. Relative to the concept of deleting the Centralized HPAS, Flight II Affordability Cost Candidate (ACC) Item No. FLT-002, reference (1), was submitted by the Flight I/II SDM (SEA 5032) for Flight II. The ACC Program was developed as a forum for introducing and developing more cost effective alternatives for Flights I and II; the end result being a 50-50 split in any resultant savings between the Navy and the shipyards. ACC Item FLT-002 was initiated by SEA 5032 to reduce inherently high material and production (e.g. fabrication, installation, and testing) costs associated with Centralized HPAS's, as well as in consideration of known technical concerns overviewed in Section 1.2.2 with HPAC RM&A and SSGTG starting air capacity. It is worthy to note that this ACC Item actually contained no alternative proposals, it merely recommended that alternative means for satisfying HPAS service functions be developed.

Given the improbability of developing alternative solutions in time to support Flight II contract award/construction schedules, PMS 400D approved ACC FLT-002 for consideration during Flight IIA. This ACC proposal was redesignated as Flight IIA Naval Adjudication Board (NAB) proposal number 023; hereafter referred to as NAB 023. For information, NABs are simply proposals and are not contractual until approved by PMS 400D where they are then redesignated as ECPs. In any event, as it was recognized by the Flight IIA Program that a structured approach was required to properly develop NAB 023, the remainder of activity during the Feasibility Design phase dealt with development of a formal statement of work; this statement of work was developed through a series of meetings with the shipbuilders and NAVSEA personnel and supported the engineering process illustrated in Figure 1 and described in Section 2.

The Contract Definition phase marked the beginning of a very aggressive and rigorous time period for the Flight IIA Program. During this relatively short (8 month) time period, over 100 change proposals were initiated and developed (including supporting specification requirements) to sufficient levels for Program adjudication and/or the beginning of detail design. Of the 100 or so changes proposed, only 48, including ECP 51-1216 (Delete Centralized

HPAS), were actually approved for Flight IIA. Relative to ECP 51-1216, Figure 8 clearly illustrates that this particular ECP was a rather unique case; that is the ECP was neither officially approved or associated specification requirements developed until well into detail design. Consequently, as will be discussed in Section 2.0, the bulk of ECP 51-1216 design activity throughout the Flight IIA Contract Definition phase and into Detail Design centered on various tradeoff studies and development of alternative subsystem designs to a sufficient level of detail to facilitate PMS 400D review and approval. PMS 400D accepted the inherent risks of such delays as the baseline Centralized HPAS was considered an acceptable fallback position.

In order to prevent a "gap year", shipbuilder detail design schedules were adjusted to support production planning and the start of fabrication by October 1994 and March 1996, respectively. Consequently, as shown in Figure 8 detail design is comprised of three distinct sub-phases; Functional, Transition, and Production Design. Note again that the initial phase of detail design commenced approximately 18 months before contract award of the lead Flight IIA hull; only a 12 month advance start was originally planned, however, delays in reviewing the shipbuilder bid packages resulted in the 18 month delay. During this initial detail design phase, NAVSEA and SET solidified the configuration of each change, and the shipbuilders developed two-dimensional design drawings. The purpose the second phase (Transition Design) is to develop the ships' three-dimensional zone drawings for fabrication and installation of the various modular installation packages comprising the ship. Finally, the purpose of the third sub-phase (Production Design) is to transcend the three-dimensional software products developed during Transition Design into actual shipboard hardware.

As for ECP 51-1216, Figure 8 illustrates that associated design activity surrounded development of the necessary detail specifications as well as development and verification testing of the new prototype SSGTG start system. In short, detail design for ECP 51-1216 was delayed approximately 10 months relative to the rest of the ship. Again, Flight IIA Program Management considered the risks to be acceptable due to high anticipated payoffs and the existence of an acceptable fallback position.

2.0 ENGINEERING PROCESS

2.1 Requirements Definition

Having established and assessed the need to pursue less expensive more capable alternatives to the Centralized HPAS from both programmatic and technical viewpoints (see Section 1.2), the first step taken in development of ECP 51-1216 was an indepth review of existing Centralized HPAS operational requirements. It was through analysis of existing HPAS requirements that requirements were initially defined for alternative concept tradeoff studies. Prior to delving into a discussion of technical requirements, it is important to note that Program Management direction for all change proposals mandated a minimum payback within 3 ships, as well as utilization of existing/proven/supported hardware where possible to meet stringent Flight IIA schedule requirements.

Review of technical requirements and initial requirements definition was accomplished through liaison meetings held at the onset of the Flight IIA Program Contract Definition phase with shipbuilding and NAVSEA personnel. Through careful evaluation of existing HPAS operational requirements, subsequent decisions were made on allocation of Centralized HPAS functions into individual subsystems and establishment of mandatory core operational performance requirements for analyses into alternative subsystem design concepts. The following is a brief description of the Centralized HPAS and associated functions; operational performance requirements for each subsystem will be provided in succeeding subsections.

The Centralized HPAS for Flights I and II are comprised of two HP air compressor plants located one in each main machinery room, interconnected by a single piping main running the length of the ship on the second platform, with individual branch lines to subsystems and equipment. Each HP air compressor plant consists of a 3000 pounds per square inch gage (psig), 60 standard cubic feet per minute (scfm), oil-free, air compressor, a 0.5 cubic foot moisture separator flask, a dual tower, heat reactivated, desiccant dehydrator, and a 10 cubic plant storage flask. Operation of the HPAS is essentially automatic through on/off pressure switches located in the HP air main immediately downstream of each compressor plant. The 3000 psig compressed air delivered to the compressed air main is reduced by means of specialized pressure reducing manifolds to requisite subsystem pressure requirements.

Figure 9, extracted from references (m), provides a functional illustration of the Centralized HPAS for DDG 51 Class Flight II. Briefly, the Flight II HPAS serves to provide filtered, compressed, dry air from its two 3000 psig compressor plants for charging a myriad of 3000 psig HP air flasks for the following services:

- 1) SSGTG starting
- 2) MPGT emergency starting
- 3) A & B weapon zone deluge compression tank charging
- 4) 5"/54 cal gun gas ejection
- 5) MK 32 torpedo tube impulse flask charging
- 6) Ship Service LP Air System backup

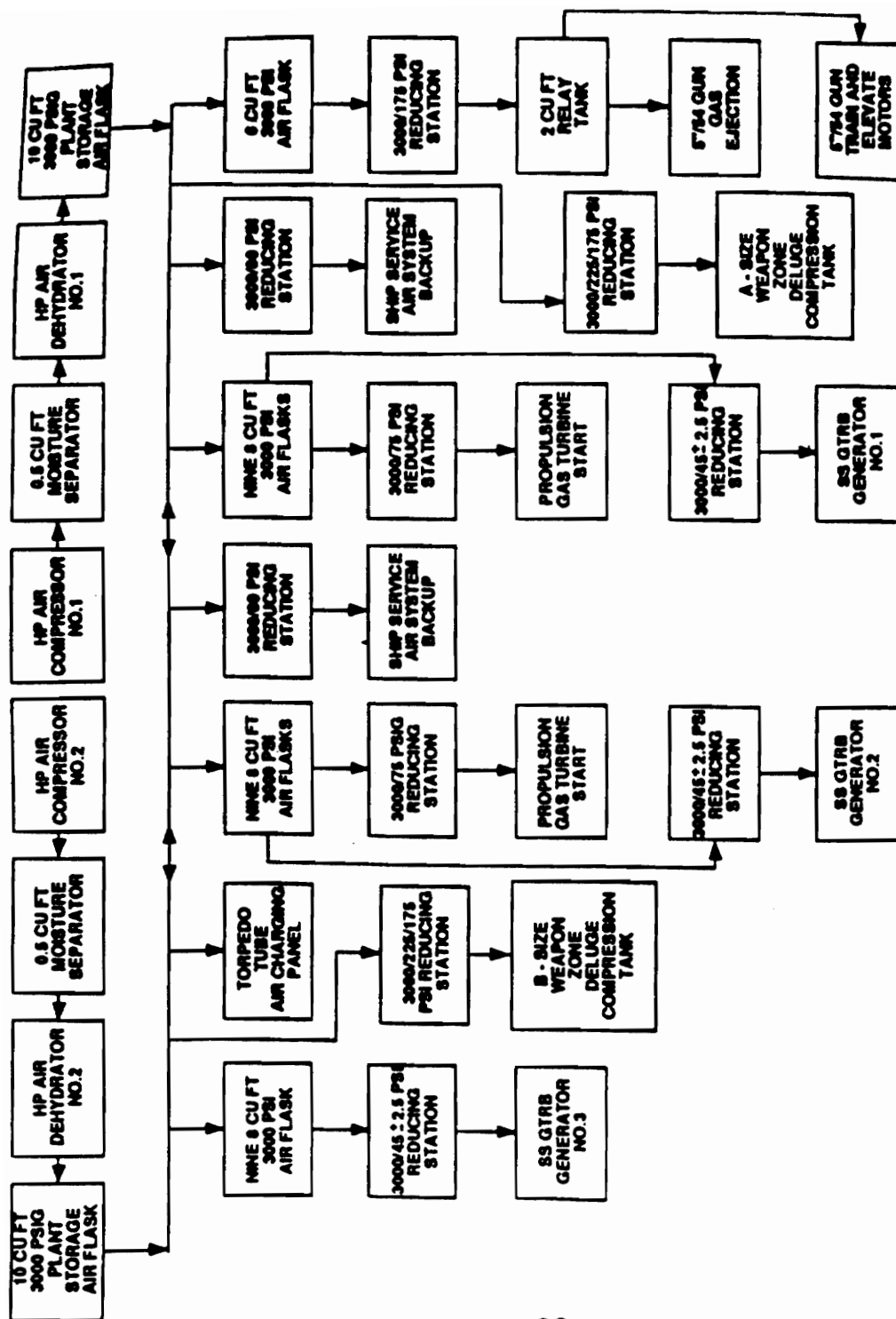
For clarity and consistency with stated objectives/emphasis, the SSGTG starting air system will be addressed separately from other HP air subsystems; the later will be hereafter discussed collectively as "Auxiliary" HP Air Subsystems.

2.1.1 Operational Requirements

2.1.1.1 SSGTG Starting System

The primary operational requirements based on information contained in the DDG 51 Class detail ship specifications, the DDG 51 Ship's Information Book, references n and m, as well as from discussions with SEA 03X personnel for the baseline HP air SSGTG starting air subsystem, are described as follows:

1. Mission Definition - The mission of the baseline SSGTG start air system is to store and deliver sufficient compressed air for three complete (60 second duration) SSGTG start attempts under all shipboard design operating conditions without recharging of HP starting banks from the ship's HP air compressors. In addition, the detail specifications require each SSGTG be capable of taking on electrical load within two minutes of start initiation. Given previously noted concerns inherent with a finite number of stored start attempts; most notably the restriction/inability to perform post shutdown fuel purges and support SSGTG motoring/waster-washing, it was agreed that alternative start concepts should strive to resolve this limitation. As for the two minute start time requirement, it was understood that alternative concepts might deviate, however, a goal of not more than five minutes was set.



2. Performance Requirements - For the baseline configuration (see Figure 9), execution of the above mission requires a minimum 3000 psig HP start air bank capacity of 72 cubic feet, a 3000/45 psig reducing station capable of delivering rated flow (approximately 4 lb/sec) and pressure (45 plus or minus 2.5 psig) with inlet air pressures as low as 500 psig for worst case machinery space design ambient conditions of 120 degrees F. It was understood that alternative start concepts might impose different and/or additional requirements; accordingly, it was agreed that all new starting concepts must meet minimum starting torque requirements specified by the SSGTG manufacturer for realistic worst case design conditions.

3. Use Requirements - Based on SEA 03X34 survey of SSGTG starting profiles for CG 47 Class cruisers, the average number of SSGTG start attempts from HP air per year was/is estimated at 150 starts each, or approximately 39 per month per unit. These values do not include additional air required for purging unspent fuel resulting from aborted start attempts or SSGTG maintenance and water-washing. As the compressed air contained in the HP start banks is a limited finite source, these functions are normally accomplished utilizing bleed air from an operating SSGTG. As noted in the mission definition discussion above, it was agreed that alternative start system concepts should be able to support starting and SSGTG motoring/water-washing requirements without necessitating switching to the ship's Bleed Air System.

4. Effectiveness Factors - Other than above noted performance requirements, there are no specific effectiveness factors such as Mean Time Between Failure (MTBF), Operational Availability (Ao), or Mean Time To Repair (MTTR) explicitly specified for the baseline SSGTG start system. However, the DDG 51 Class specifications require that each HP air compressor serving the Centralized HPAS have an MTBF of at least 760 hours and an MTTR of not greater than 25 hours. Based on SEA 03Y22 surveys of HP air compressor operating logs for DD 963 Class destroyers and CG 47 Class cruisers, which have virtually identical HPAS's to DDG 51 Class, each HP air compressor is assumed to log 2000 hours of operation per year. Consequently, the total number of failures per compressor, hence lost SSGTG start system replenishment capability, was

estimated at slightly less than 3 per year. For alternative concepts, no specific reliability or maintainability goals were set other than they should equal or better those of the baseline HP air compressors. As for Ao, it was agreed that a goal of 0.85 would be reasonable for commonality with current DART Program goals for HP air compressors (see Table II).

5. Mode of Operation - Operation of the baseline HP SSGTG start system is remote-manual from either the ship's Electric Plant Control Console (EPCC) located in the Machinery Central Control Space (MCCS), or the Local Operating Panel (LOCOP) located adjacent to each SSGTG. In addition, DDG 51 Class Specifications require automatic emergency starting of an SSGTG upon drop of switchboard voltage below approximately 220 volts. To facilitate SSGTG starting for all normal and emergency operating conditions, SSGTG and associated start system controls are supplied from individual No Break Power Supply (NBPS) systems which are comprised of 24-volt batteries, rectifiers and charging systems. For alternative starting concepts to be explored, it was agreed that a consistent mode of operation philosophy would be provided for the system selected.

6. Environment - As each SSGTG start system is located within the machinery spaces which are subject to wide temperature transients (40 to 120 degrees F), high humidity, and a potentially corrosive environment, DDG 51 specifications require suitable material compatibility. Additionally, as vital systems critical to execution of the ship's mission, requirements for Grade-A shock (MIL-S-901C), noise (structureborne and airborne per Section 073 of the ship specifications), and vibration (MIL-STD-167) apply. For alternative concepts, it was agreed that each should support aforementioned environmental requirements.

7. Survivability - With the exception of SSGTG #1, located in the Auxiliary Machinery Room (see Figure 5), each SSGTG HP start bank is located in the same space as its companion SSGTG; thus making the baseline HP starting scheme highly survivable. For alternative start concepts, it was agreed that no reduction in survivability would be permitted.

2.1.1.2 Auxiliary HP Air Subsystems

1. Mission Definition

a. MPGT Emergency Starting System - As noted previously in Section 1.2.2.2, the primary mode of starting ship's MPGT's is from LP bleed air extracted from one or more operating SSGTG's. Accordingly, the HP start banks, which serve as the primary starting source for SSGTG's, also serve as an emergency starting source for MPGT's. At the onset of the Flight IIA Contract Definition phase, it was originally agreed that this emergency MPGT start capability be retained, however, as will be discussed later in Section 2.4.2, this goal was eliminated due to cost constraints and significant improvements made to the SSGTG starting systems. As with SSGTG's, motoring/water-washing of MPGT's is accomplished from the ship's LP Bleed Air System.

b. A & B Weapon Zone Deluge Tank Charging - The mission of the baseline charging system is to provide an initial supply of reduced HP air to each deluge compression tank to support pneumatic actuation of the associate vertical launching system's magazine sprinkling control valve. Periodic recharging is required due to support system maintenance, testing, and/or potential compression tank leakage.

c. 5"/54 Caliber Gun Gas Ejection System - The mission of the gas ejection system is to supply reduced HP air sufficient to rid the 5"/54 caliber barrel and gun mount of toxic fumes resulting from firing all rounds (600) at maximum firing rate (40 rounds per minute) without recharging of the dedicated HP air flask from the ship's HP air compressors. For alternative concepts, no deviation from this mission requirement was permitted.

d. MK 32 Torpedo Tube Impulse Flask Charging - The mission of the baseline charging system is to supply reduced HP air for charging all six of the small (900 cubic inch) impulse flasks utilize to launch the MK 32 torpedo's from their respective launch racks. No reduction in capability was permitted for alternative concepts.

e. Ship Service LP Air System Backup - The mission of the baseline HP/LP air system cross-connect system is to provide reduced HP air to the LP vital air system in order to effect an orderly shutdown in the event of electric power loss to the ship's LP air compressors. It was recognized by both NAVSEA and BIW that if the HP air system were to be deleted, that this backup system would inherently be lost. Hence it was agreed that modifications to existing LP air services essential to regaining ship's electrical power would be required.

2. Performance Requirements

a. MPGT Emergency Starting System - As illustrated in Figure 9, emergency starting of the MPGT's is accomplished utilizing the SSGTG HP start banks and dedicated 3000/75 psig reducing valves. although there are no specific requirements for numbers of emergency HP MPGT starts, each start bank is capable of supporting three successive emergency MPGT start attempts. It was agreed that any/all new MPGT start concepts must satisfy MPGT manufacturer's requirements for minimum starting torque under realistic worst case design conditions; including 120 degrees F ambient temperature.

b. A & B Weapon Zone Deluge Tank Charging - Review of the existing/baseline charging system indicated the 3000/250 psig reducing station and associated piping is capable of recharging the small (1.9 cubic feet) deluge compression tanks in less than one minute; however, there exist no specification requirement or limit on recharge time. Accordingly, and in consideration of the fact that this particular service reflects a closed system requiring very infrequent recharging/makeup, it was agreed that recharge time could be increased to five minutes for alternative concepts.

c. 5"/54 Caliber Gun Gas Ejection System - For the baseline configuration (see Figure 9), satisfying above mission requirements for gas ejection feature a dedicated 3000 psig HP air flask with a volume of 6 cubic feet, a 3000/175 psig pressure reducing station capable of delivering rated flow (48.7 scfm) with inlet air pressures as low as 1000 psig, and a 2 cubic foot relay tank to dampen pressure oscillations to the gun mount supply

pipng. For alternative concept exploration, it was agreed that deviations from the above would be considered as long as they did not compromise the ability of the new system(s) to properly support firing of all 600 rounds in the magazine.

d. MK 32 Torpedo Tube Impulse Flask Charging - As shown in Figure 9, the baseline configuration supports impulse flask charging directly from the ship's HP air main via the torpedo air charging panel; the panel is comprised of a holding rack for the small (900 cubic inches) removable impulse flasks, a 3000/1800 psig pressure reducing station, and necessary flexible hoses and fittings. As the air charging panel and torpedo tube impulse flasks are located in the weather, the DDG 51 Class specifications also require that the compressed air supply have a dew point of not less than minus 40 degrees F; the baseline HP air compressor plant dehydrators exceed this requirement since they dry the air to minus 60 degrees F. As the impulse flasks are so small, hence can be charged in a manner of seconds with 1800 psig air, coupled with the lack of any specification requirement for recharge time, it was agreed that only the requirements for 1800 psig and minus 40 degrees F dew point air quality were pertinent for any alternative concepts.

e. Ship Service LP Air System Backup - The baseline system supports emergency LP vital air system backup via two 3000/80 psig reducing stations which provide approximately 10 minutes of reserve air from the 10 cubic foot HP compressor plant flasks in the event of an electric plant casualty. There exist no specification requirements on the duration of emergency HPAS backup support. As noted above, elimination of the HPAS inherently eliminate such a capability, hence it was agreed that any/all alternative concepts must ensure immediate restoration of ship's electrical power.

3. Use Requirements

a. MPGT Emergency Starting System - Based on discussions with SEA 03X32, there exist no data for numbers of actual emergency MPGT starts using the ship's HP start air banks, however, it was

thought to be an extremely rare situation given the poor reliability of Centralized HPAS's in general, and ships' force preference to utilize LP bleed air whenever possible. It was further noted/discussed that occasional Propulsion Examination Board testing aboard DD 963 and CG 47 Classes had revealed instances of complete MPGT 3000/75 psig pressure reducing station failure/inoperability; followup discussions with the valve vendor and waterfront personnel concluded valve failures were most likely attributed to lack of use and maintenance. These discussions were considered in the above noted decision to eventually omit this particular service capability from Flight IIA.

b. A & B Weapon Zone Deluge Tank Charging - Review of the baseline configuration supported by discussions with the cognizant NAVSEA technical code (PMS 422) concluded this manual system is used approximately once every two weeks.

c. 5"/54 Caliber Gun Gas Ejection System - Discussions with the cognizant NAVSEA technical code concluded no formal/set use requirements with the exception that the gas ejection system must support continuous firing of all 600 rounds at the maximum firing rate without use of auxiliary support from ship's air compressors. Normal use for periodic testing is much less stringent, however SEA 06Y12 maintained that any new concepts must support the worst case condition.

d. MK 32 Torpedo Tube Impulse Flask Charging - Similar to charging of the deluge tank discussed above, torpedo tube impulse flasks are small closed compressed air containers requiring only initial charging and very infrequent makeup for leakage. Additionally, discussions with SEA 06U312 concluded a random use profile dependent on ship's torpedo testing scenarios; accordingly, it was agreed that any new concepts must be capable of support simultaneous recharging of all 6 shipboard impulse flasks from atmospheric pressure to 1800 psig without the aid of ship's compressors or other auxiliary support.

e. Ship Service LP Air System Backup - Given the impending omission of this service and

aforementioned agreements that existing LP vital air services would be analyzed to ensure provisions would be added to ensure immediate restoration of shipboard electrical power.

4. Effectiveness Factors

a. MPGT Starting System - As with the baseline SSGTG start system, the DDG 51 Class specifications contain no specific requirements for MTBF, Ao or MTTR for the baseline MPGT start system with the exception of above note reliability and maintainability criteria specified for the ship's HP air compressors. Given that the baseline HPAS serves as an emergency backup source of starting air to the LP Bleed Air System, no specific MTBF/Ao/MTTR requirements or goals were set for alternative MPGT concepts; the apparent likelihood for complete elimination of this function weighed in this decision.

b. A & B Weapon Zone Deluge Tank Charging - Review of DDG 51 Class specifications concluded the existence of no specific RM&A requirements for this particular service either; accordingly, it was agreed that equivalent or better performance as ship's HP air compressors would be the goal for alternative concepts.

c. 5"/54 Caliber Gun Gas Ejection System - Same situation/goals as stated for above deluge tank charging.

d. MK 32 Torpedo Tube Impulse Flask Charging - Same situation/goals as stated above for deluge tank and gas ejection systems.

e. Ship Service LP Air System Backup - Consistent with Central HPAS as a whole and aforementioned subsystems, no RM&A requirements are provided in the specifications. As this particular service was to be deleted, no specific goals/requirements were set.

5. Mode of Operation

a. MPGT Emergency Starting System - Operation of the baseline emergency MPGT starting system is remote-manual from either the Machinery Central Control Space and from MPGT local operating panels

called Shaft Control Units. Accordingly, and prior to omission of this service early in Flight IIA Contract Definition, it was agreed that any new concepts would share a common mode of operation with the baseline system.

b. A & B Module Weapon Zone Deluge Tank Charging - Operation of the baseline deluge tank charging system is accomplished by manually connecting flexible hoses from the discharge of the associated 3000/250 psig pressure reducing station piping, and manipulating a manual throttling valve until full tank charging pressure (250 psig) is reached. For alternative concepts, it was agreed that a manual system was all that was required.

c. 5"/54 Caliber Gun Gas Ejection System - The baseline system is fully automatic in that firing of each round automatically initiates opening of an on/off solenoid control valve in the gas ejection pneumatic supply piping to the gun mount; it was agreed that no change in control philosophy would be permitted for any alternative concepts.

d. MK 32 Torpedo Tube Impulse Flask Charging - As previously discussed, charging of torpedo impulse flasks is a manual operation entailing manual removal of the impulse flasks from the torpedo launch/holding racks, and transporting the impulse flasks via handtruck to the torpedo air charging panel located in the weather on the 01 level. for alternative concept exploration, it was agreed that any new systems would be manual also.

e. Ship Service LP Air System Backup - The baseline system of two 3000/80 psig reducing stations is essentially automatic since the reducing stations are normally open and supply the LP vital main when the pressure decreases to 80 psig. As previously discussed, it was acknowledged agreed at the onset that this service would be omitted with the deletion of the Centralized HPAS, and that concentration would be applied towards ensuring any existing LP vital air services required to support restoration of shipboard electrical power would be provided ample backup provisions. Accordingly, it was also agreed that these backup provisions would also be automatic without necessitating human intervention.

6. Environment

a. MPGT Emergency Starting - The baseline emergency MPGT starting system has the same environmental requirements as previously described for the SSGTG starting system. Consequently, and until this particular service was deleted, it was agreed that no reduction in requirements would be permitted for alternative systems.

b. A & B Weapon Zone Deluge Tank Charging - As the baseline deluge tank charging systems are located fore and aft in the VLS Ready Service Rooms, which are ventilated non-machinery spaces, ambient temperatures extremes are limited to a range of 40 to 100 degrees F. In addition, as a mission critical service, the requirements for Grade A shock per MIL-S-901C and vibration resistance per MIL-STD-167 apply; it was agreed that new/alternative concepts would have similar requirements.

c. 5"/54 Caliber Gun Gas Ejection System - The environmental requirements of the baseline and alternative gas ejection systems are identical to those for the A & B Module deluge charging system.

d. MK 32 Torpedo Tube Impulse Flask Charging - In order to support impulse flask air charge dewpoint requirements, the baseline, as well as any new alternative charging systems were/are required to deliver air with a dewpoint of minus 40 degrees minimum. Similarly, the requirements for Grade A shock and vibration apply.

e. Ships LP Air System Backup - The baseline identical environmental requirements as the gas turbine start systems previously addressed, it was agreed that no reduction would be permitted for alternative concepts.

7. Survivability

a. MPGT Emergency Start System - As an emergency starting air system utilizing the existing SSGTG HP start banks, the baseline HP MPGT start system has no specific survivability requirements of its own. Further, as it was envisioned that potential alternatives would be located in the machinery

spaces, no formal requirements were made.

b. A & B Module Deluge Tank Charging - Baseline charging provisions are considered highly survivable since the existing charging equipment is collocated with the deluge tank. It was agreed that the same level of survivability should be provided for any alternative concepts to be developed.

c. 5"/54 Caliber Gun Gas Ejection System - Similar to the SSGTG starting system, the baseline gas ejection system is highly survivable since the dedicated 6 cubic foot HP air flask is collocated in the Loader Drum Room with the rest of the gas ejection system; it was agreed that any alternatives would have equivalent survivability features.

d. MK 32 Torpedo Tube Impulse Flask Charging - The baseline impulse flask charging system indicated rather poor survivability characteristics in that no dedicated HP air flask was provided; accordingly, it was agreed that alternative concepts should explore/incorporate improved survivability.

e. Ship Service LP Air System Backup - As there are two separate 3000/80 psig pressure reducing stations located on in each main machinery space serving the LP vital air main, the baseline system is considered quite survivable. Accordingly, it was agreed that new backup provisions for those LP vital air services supporting restoration of ships electrical power should be collocated with the service for survivability.

2.1.2 Maintenance Concept

2.1.2.1 SSGTG Starting System

The baseline HP air SSGTG starting system utilizes all three categories (i.e. organizational, intermediate, and depot levels) of maintenance. For the organizational level, various Maintenance Requirement Cards exist for regularly scheduled maintenance (e.g. periodic checks of performance, visual inspections, cleaning, adjustments) to the ship's HP air compressor plants, the 3000/45 psig pressure reducing valves, and start system components and controls located on

the SSGTG modules proper. Corrective maintenance performed by ship's force personnel is generally limited to execution of troubleshooting procedures contained in the aforementioned component technical manuals with limited actual unassisted equipment repair capability. Depending on the extent of the malfunction, either intermediate or depot level repair is required. For example, air-end overhauls of ship's HP air compressors are accomplished in place by either the Navy's Ships' Intermediate Maintenance Activity or representatives from the compressor manufacturer. Similarly, pneumatic starter motor failures generally require onboard replacement with depot-level repair of the damaged starter at the starter motor manufacturer's production facility.

Relative to development of alternative start concepts, it was discussed and agreed at the onset of the Contract Definition phase that a similar maintenance concept would be imposed; in addition, it was stipulated that the intermediate level repair capability must be in existence and/or be developed in parallel with ECP 51-1216, and that there be no increase in overall shipboard manning required. As will be discussed in Sections 2.4.1 and 2.5.1, these requirements are met with selection of APU's as the primary starting air source for starting SSGTG's. Briefly, the APU's determined to be technically acceptable are essentially off the shelf units having detailed technical manuals, repair parts lists, training curriculums, established logistics support systems, as well as established intermediate and depot level repair capabilities.

2.1.2.2 Auxiliary HP Air Subsystems

As noted for the baseline SSGTG HP air starting system, the baseline Centralized HPAS serving the remaining HP air subsystems, features organizational, intermediate, and depot level repair maintenance support requirements depending upon the severity of the corrective action taken. Similarly, for alternative concept studies, it was agreed that all maintenance requirements would be identified and associated support documentation status be ascertained. As also noted above, no increase in shipboard manning requirements was to be permitted as a result of ECP 51-1216. Given the previously noted Flight IIA Program Management direction to utilized existing/supported equipment, Sections 2.4.2 and 2.5.2 provide a more detailed overview of how the general maintenance requirements were fulfilled for auxiliary HP air subsystems.

2.2 Functional Analysis

As described in Chapter 4 of reference (a), functional analysis is a logical and systematic approach for translating system operational and support requirements into specific qualitative and quantitative design requirements; the primary objectives of functional analysis is to identify all system/subsystem functions, identify the method of accomplishing all functions (e.g. automatic or manual), and to identify the resources to accomplish each function. Reference (a) further details the methodology associated with preparation of functional flow and maintenance flow block diagrams to illustrate basic system organization (e.g. series and parallel relationships), the hierarchy of system functions, and to identify all system/subsystem functional interfaces; functional and maintenance block diagrams are typically prepared down to the level necessary to fully establish the needs (e.g. hardware, software, facilities, personnel, data) of the system under development.

Relative to NAB 023/ECP 51-1216 design development, formal preparation of functional and maintenance flow diagrams was not undertaken for a number of reasons. First and foremost, the Flight IIA Program schedule provided merely 10 months to perform tradeoff studies for numerous options explored and associated downselection, develop prototype testing plans (for SSGTG start system only), conduct prototype testing, and develop the necessary contract specification requirements to sufficient level of detail to gain PMS 400D approval and commence Detail Design phase development. Secondly, aforementioned Program direction to utilize existing, fully supported hardware also alleviated the risks of not preparing functional/maintenance flow diagrams. Lastly, monthly design reviews were held between NAVSEA and shipbuilding personnel to review the design of each alternative; these design reviews were supported by system diagrams of each new subsystem concept proposal along with detailed descriptions of system operation, support, and interface requirements as required by the NAB 023/ECP 51-1216 statement of work developed during the Feasibility Design phase (see Section 1.3.2). SEA 03YD efforts to document the results of these efforts are partially contained in references o, p, and q; complete historical documentation was not possible due to program priorities and the sheer magnitude of ECP 51-1216 design activity.

2.2.1 SSGTG Starting System

Figure 10 provides a notional functional flow diagram,

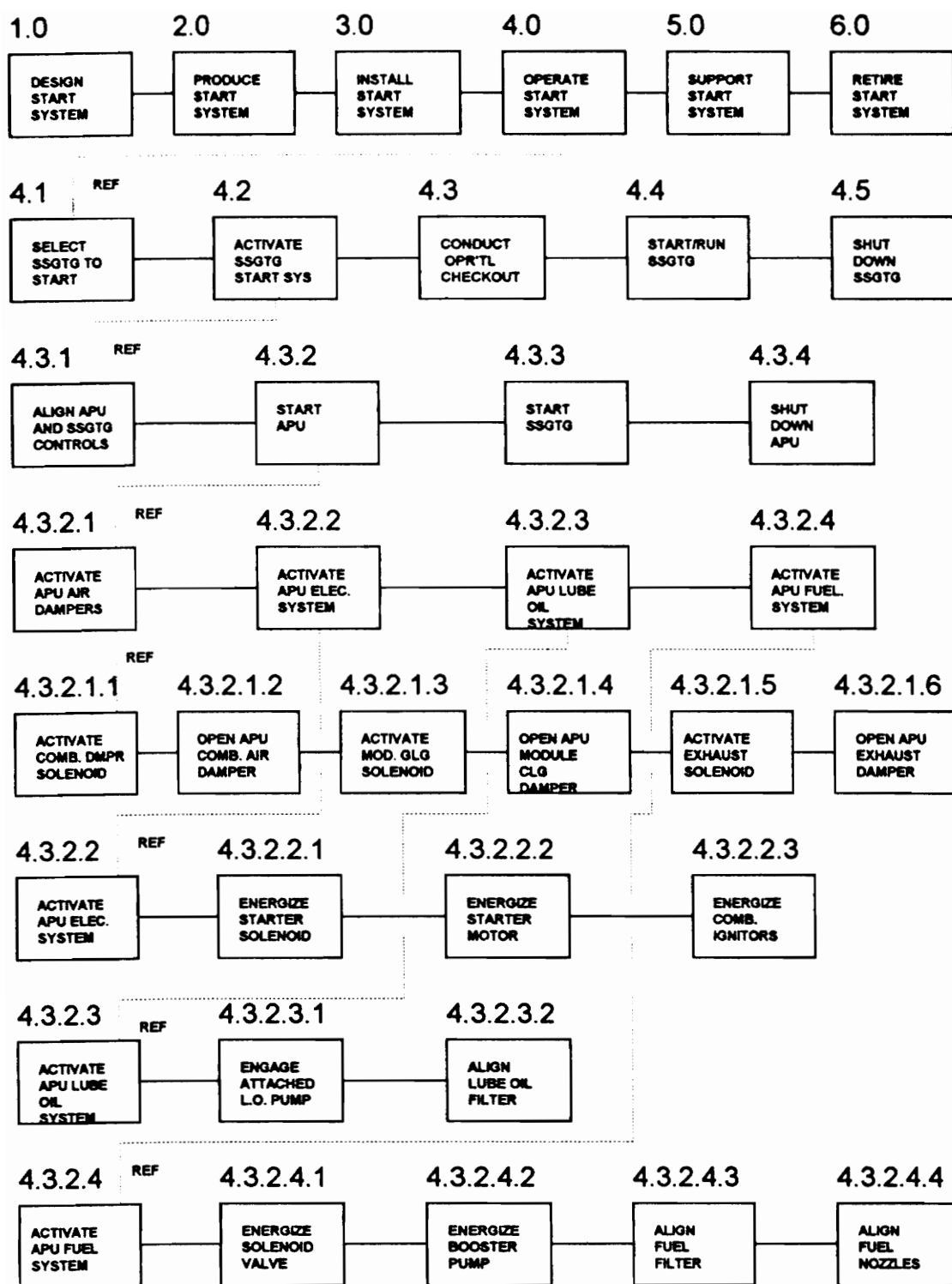


FIGURE 10: FUNCTIONAL FLOW DIAGRAM

prepared down to the fourth level, for the new SSGTG start system described in Section 2.5.1.

2.2.2 Auxiliary HP Air Subsystems

As noted above functional analysis visa-vi functional flow block diagrams was not conducted for NAB 023/ECP 51-1216 development; rather, subsystem functions and interfaces were determined through preparation of system diagrams and regularly scheduled design reviews.

2.3 Requirements Allocation

The preceding discussion pertaining to functional analysis described the process of translating operational and maintenance requirements into specific design criteria for the various elements of the new subsystems developed under NAB 023/ECP 51-1216; this process resulted in preliminary synthesis of each alternative concept into the overall ship design. The next step in the development process illustrated in Figure 1 is allocation of top-level requirements down to the various subsystems and lower level elements of each new subsystem. Reference (a) provides various algorithms and supporting examples for top-down allocation of such effectiveness factors as reliability (MTBF) and maintainability (MTTR) parameters. Such calculations were not prepared for the systems developed for ECP 51-1216 to date for many of the same reasons (e.g. time and manpower constraints, numerous versus single alternatives investigated in detail, and Program direction to utilize existing/supported hardware) discussed above for functional flow diagrams. Moreover, it should be reemphasized that the objective of ECP 51-1216 activity, from NAVSEA's perspective, was to establish the necessary overall system top-level systems' requirements for the shipbuilders to further develop during detail design. Further, it should also be understood that individual component vendor selections for each and every piece part typically do not occur until well into detail design by the shipbuilder, hence specific reliability and maintainability data was not available in all cases. Accordingly, only top-level requirements were established and included in the ECP 51-1216 specification package; refer to Sections 2.5 and 2.6.

In any event, proper consideration/allocation of primary operational requirements defined in Section 2.1 for ECP 51-1216 development was facilitated via system diagrams and monthly design reviews.

2.3.1 SSGTG Starting System

As noted above, requirements allocation for operational performance requirements was accomplished via regularly scheduled design reviews and indepth technical reviews of each new alternative SSGTG starting concept. Relative to reliability and maintainability, formal calculations were not prepared; rather top-level requirements were established to guide the shipbuilder during future detail design development and hardware selection. These top-level requirements are discussed in Section 2.1.

2.3.2 Auxiliary HP Air Subsystems

Similar to above for SSGTG Starting Systems, detailed reliability and maintainability calculations were not prepared; rather allocation of operational requirements was accomplished via regularly scheduled design reviews.

2.4 Tradeoff Studies and Optimization

The following section details the various alternative concepts explored for replacement of the baseline SSGTG starting and auxiliary HP air subsystems for Flight IIA. Note that due to Program schedule constraints, many alternatives were eliminated on the basis of subjective analysis of conformance to operational and maintenance requirements defined in Section 2.1 relative to other options being considered, and that more quantitative analyses were restricted to select few concepts demonstrating obvious technical and/or cost advantages.

2.4.1 SSGTG Starting System

Three entirely different methods of SSGTG starting were explored during the Flight IIA Contract Definition (CD) phase; hydraulic starting, electric motor starting, and pneumatic motor starting via APU's. For each different starting method, several alternatives were in turn reviewed.

Figure 11, illustrates one of two hydraulic starting concepts investigated relatively early in Contract Definition; hydraulic starting was proposed by BIW based on inputs/preferences from the SSGTG manufacturer (Allison), citing wide-spread use in the commercial power industry. The initial hydraulic starting concept featured three diesel-driven hydraulic pump skids, each dedicated and located adjacent to its companion SSGTG. Three dedicated hydraulic



FIGURE 11: HYDRAULIC STARTING, OPTION #1

pump skids were proposed in order to provide equivalent survivability with the baseline HP start banks. The diesel engine selected by BIW/Allison for analysis was a 200 horsepower (V6, 53 cubic inch displacement) turbo charged engine used in similar land-based commercial applications. Directly connected to the output shaft of each diesel engine was to be a variable displacement axial piston hydraulic pump located on a common sub-base; the pump in turn was to supply approximately 57 gallons per minute (gpm) hydraulic fluid at 2600 psig to a hydraulic starter motor mounted "somewhere" within the SSGTG module. The term somewhere is highlighted since discussions with the SSGTG manufacturer (Allison) indicated that substantial modifications to the SSGTG accessory gearbox would be required to fit both the existing pneumatic starter motor and the new hydraulic starter motor. This created significant concern as accessibility for maintenance within the SSGTG modules for Flights I and II is a known problem that has required costly ECP's to alleviate.

Once started, the diesel engine/hydraulic pump could provide nearly unlimited dark ship SSGTG start attempts with subsequent SSGTG starts from the LP bleed air system; the LP bleed air system and existing SSGTG pneumatic starter within each SSGTG module had to be retained in order to support SSGTG motoring/water washing requirements. It was envisioned that the diesel engines themselves could be started either hydraulically or from batteries.

The entire diesel engine/hydraulic pump skid was estimated to weigh 5000 pounds and measure 6'L x 3'W x 4'H'. Based on review of DDG 51 machinery arrangement drawings and shipcheck of DDG 53 by BIW, the engine/pump skids were to be mounted directly over the top of the associated SSGTG, and resiliently mounted on separate foundations welded to the overhead framing of the associated machinery space. Further, to minimize additional shipboard impacts, it was envisioned that the diesel engines could be supplied fuel from the existing SSGTG head tanks, and also share common intake/exhaust ducting with associated SSGTG's. Auxiliary support services for the diesels were negligible since the engine packages considered were "self-contained"; that is were provided with fresh water/glycol, fan cooled, engine cooling systems. As for controls, both local and remote starting from the MCCS located on the Main Deck, were considered; the later provisions for the diesel engines would replace existing logic provided for the HP Start Air System.

The second hydraulic starting configuration, illustrated in Figure 12, was similar to the first with the exception that a larger (400 verses 200 horsepower) diesel engine would drive a small 250 kilowatt generator mounted on a common skid with the diesel engine, and supply the necessary electrical power to an electric motor driven hydraulic pump skid located adjacent to the companion SSGTG. The hydraulic pump would then supply the same flow and pressure hydraulic fluid to an SSGTG mounted hydraulic starter motor. The weight of this, more inefficient configuration, was estimated to be 15,000 pounds per SSGTG starting package, and the diesel engine/generator skid measurements were only slightly larger than above. In any event, and though technically feasible, hydraulic starting concepts were eliminated from further consideration relatively early (22 June 92 Design Review) in CD due to poor U.S. Navy experience (principally high maintenance) with hydraulic start systems, technical concerns with adverse impacts to accessibility within the SSGTG modules, potential manning increases resulting from a mixture of gas turbine and diesel engines, high weight relative to APU and electric starting methods, and the fact that, like HPAS's, HP hydraulic systems are costly to fabricate, install, and test. Both require "P-1" Category welding in accordance with MIL-STD-278, which necessitates costly radiography testing and joint record cards, as well as stringent internal pipe cleaning of the entire system prior to placing in service.

Figures 13 and 14, extracted from references (o) and (p), represent the two electric starting configurations explored during CD for Flight IIA. The initial concept illustrated in Figure 13 was initiated by and aggressively pursued by the DDG 51 Class SDM for Flights I and II (SEA 503D2) in the hopes of deleting both the Centralized HPAS and the Gas Turbine Bleed Air System (BAS). Like the HPAS, the BAS requires costly P-1 quality welding and post fabrication cleaning and testing. In addition to gas turbine starting and motoring, the BAS provides compressed air from operating gas turbine engines for other services such as anti-icing of gas turbine air intakes, and Prairie and Masker air emission systems. It turns out that concurrent with NAB 023 efforts were separate developmental efforts for quieter propeller designs and special hull coatings which, if proven and approved, would have negated the need for Prairie and Masker air emission systems. For satisfying anti-icing requirements, it was suggested that electric strip heaters could be installed on the gas turbine air intake louvers to prevent the ingestion of damaging ice particles. Accordingly, this particular electric starting concept,

□ = New Components

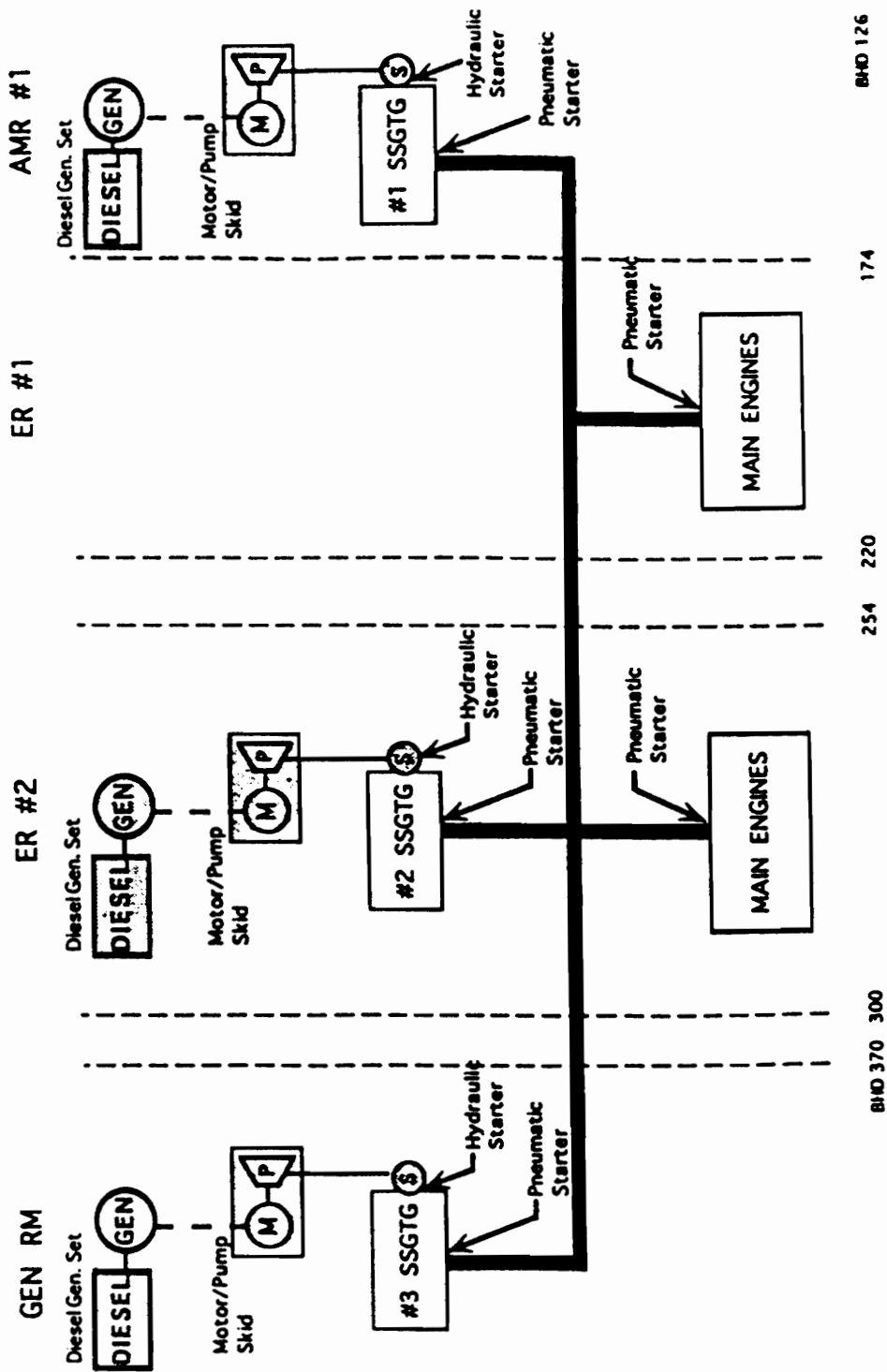


FIGURE 12 HYDRAULIC STARTING, OPTION #2

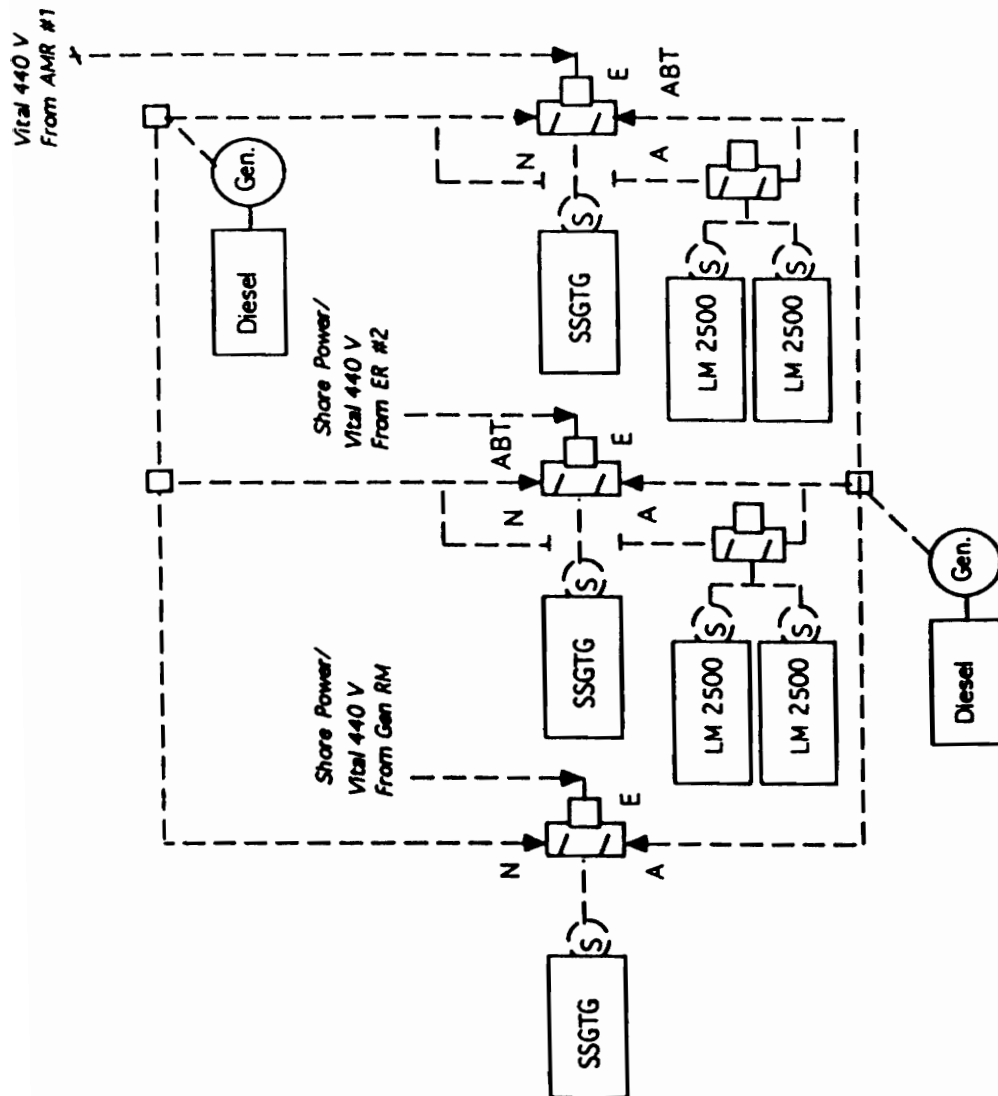


FIGURE 13: ELECTRIC STARTING, OPTION #1

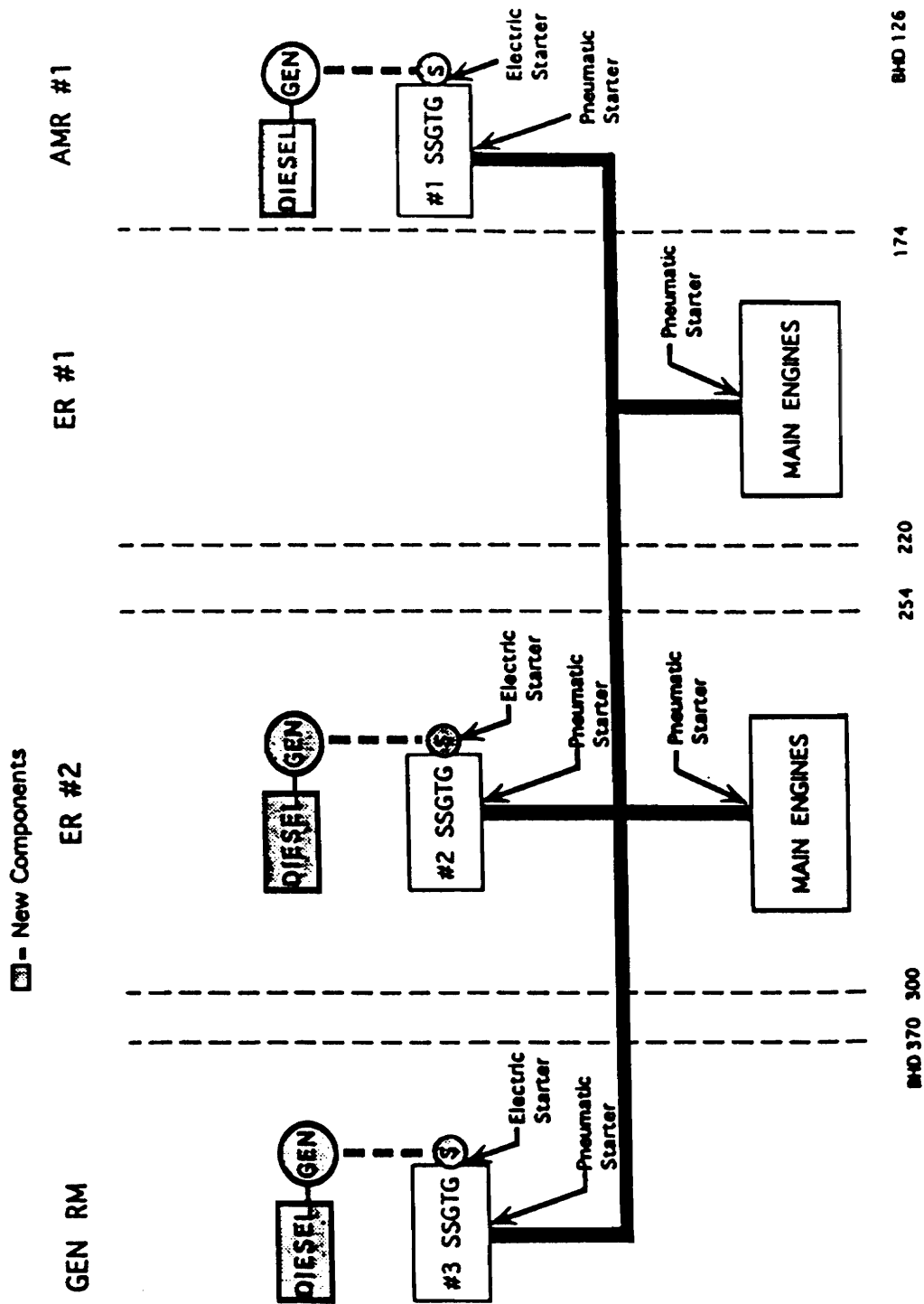


FIGURE 14: ELECTRIC STARTING, OPTION #2

which covered both SSGTG and MPGT starting, was initially pursued in conjunction with the electric start concept shown in Figure 14 in the event that replacements for Prairie, Masker, and Anti-Icing air systems were developed. Both concepts were invariably eliminated from further consideration at the 18 September 1992 Design Review, held at NAVSEA headquarters for a variety of reasons, including, technical concerns, high costs, and excessive Program risk; a very brief description of each configuration is provided below.

The initial electric starting configuration illustrated in Figure 13 featured two rather large (10'L x 3'W x 4'H, 12,000 lbs) diesel driven electric generators (425 kw, 60 hz, 440 volts), located one in Auxiliary Machinery Room No. 1 and one in Engine Room No. 2, for starting and motoring SSGTG's and MPGT's. It was envisioned that either of the diesel generators could provide ample electric power to similarly large (24" dia, 36" L, 1500 lbs) induction motors attached "somehow" to the accessory gearboxes of the SSGTG's and MPGT's. It was noted by both the SSGTG and MPGT manufacturers that development of such an electric motor and associated redesign of the associated modules would necessitate a 2-3 year development/testing effort. As previously noted for hydraulic starting schemes, space availability within and in the immediate vicinity of the gas turbine modules is virtually nonexistent and would necessitate complete redesign of both the modules and machinery spaces. In any event, like diesel-hydraulic starting systems, the diesel-electric starting scheme provided a virtually unlimited number of SSGTG and/or MPGT starts once the associated diesel engine was started; a hydraulic or battery start system was planned for the diesel engines.

In addition, it was originally assumed by BIW in reference (o) that 440 volt shore power could be supplied through automatic bus transfer switches for cold iron/pier-side gas turbine engine starts. Certain factions of the Flight IIA Program were intrigued by the possibility of utilizing the diesel generators for emergency shipboard electrical power and unsuccessfully argued that such an attribute offset the inherent reductions in survivability created by a two, verses three, diesel generator supply configuration.

In consideration of above noted technical concerns, coupled with lagging progress in development/testing of alternative Prairie, Masker, and Anti-Icing subsystem designs, BIW was directed in the 22 June 1992 NAB 023 Design Review to

discontinue further analysis of the Figure 13 electric starting scheme, to limit electric starting to SSGTG's only, and to investigate measures for minimizing SSGTG module and machinery space impacts.

Figure 14 reflects the second electric starting configuration examined during CD resulting from the 22 June 1992 NAB 023 Design Review direction. In order to reduce shipboard impacts, BIW proposed that a 425 kilowatt diesel generator, identical to the previously specified units, be provided in the overhead area of each SSGTG; thereby providing acceptable survivability and operational performance characteristics. With regard to minimizing SSGTG module impacts resulting from attachment of the electric starter motors, Allison proposed that consideration be given towards attaching the electric motors to the exciter end of the SSGTG's in lieu of the accessory gearboxes in conjunction with utilization of a smaller, radical, high frequency (330 hz), variable reluctance, electric motor design. Allison also noted that such a motor design and associated SSGTG module impacts would still necessitate a 2 to 3 year development and qualification effort.

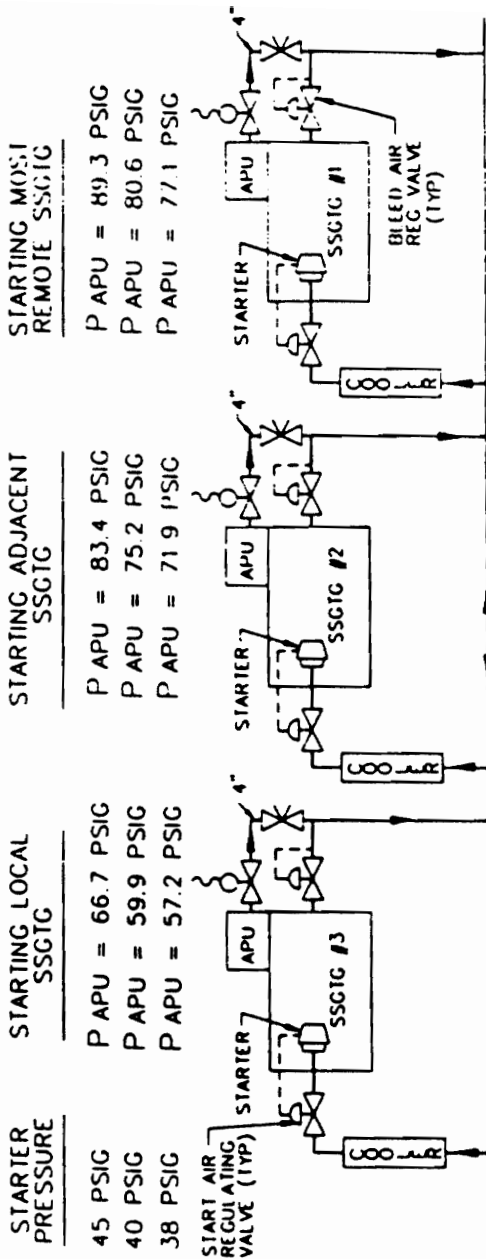
It was further noted during the 18 September 1992 Design Review that the high frequency electric motors proposed by Allison would also require 60/330 hz frequency inverters, thus adding more unknown cost and shipboard impacts. Accordingly, NAVSEA directed that the remaining electric starting scheme be discontinued in favor of more attractive APU starting options.

Figures 15 through 20 are provided to illustrate the various APU starting configurations initially considered at the onset of CD for Flight IIA; starting SSGTG's from APU's was proposed by SEA 03YD based on unsuccessful, yet encouraging, APU testing performed at LBES back in 1989 to resolve SSGTG starting capacity shortfalls for Flights I and II, in consideration of commercial/military aircraft starting practices, and an intuitive assessment of the relative impacts to Flight IIA machinery spaces and SSGTG modules. As previously noted, APU's are small gas turbine engines capable of supplying, either by compressor section bleed air or by attached load compressors, large volumes of high temperature LP air; once started, APU's can provide virtually unlimited numbers of SSGTG start attempts.

Figures 15 through 20 were developed by SEA 03YD for discussion during a 10 June 1992 technical liaison meeting with NAVSEA, NAVAIR, BIW, Allison, and APU vendors (Allied

CONFIGURATION 1: 3 APU'S, COOLING REQUIRED

APU DISCHARGE PRESSURE REQUIRED



CONDITIONS:

T AMBIENT	= 100° F
T APU	= 500° F
T STARTER	= 151° F
P STARTER	= 45 PSIG
W	= 220.8 LB/MIN
P STARTER	= 40 PSIG
W	= 202.3 LB/MIN
P STARTER	= 38 PSIG
W	= 194.9 LB/MIN

BENEFITS/ CONCERNS

- BETTER REDUNDANCY/SURVIVABILITY THAN EXISTING CONFIGURATION
- ADDED COST

FIGURE 15: APU STARTING, CONFIGURATION #1

CONFIGURATION 2: 3 APU'S, NO COOLING REQUIRED

APU DISCHARGE PRESSURE REQUIRED

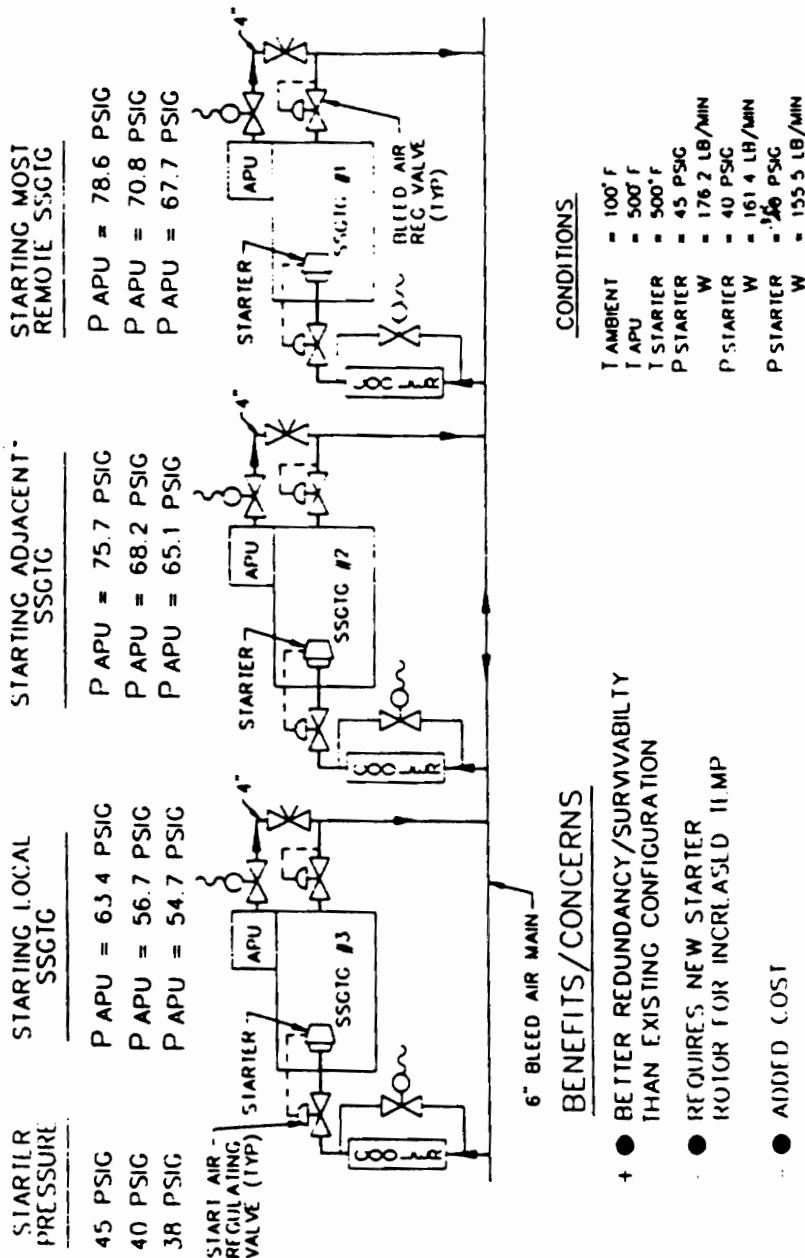
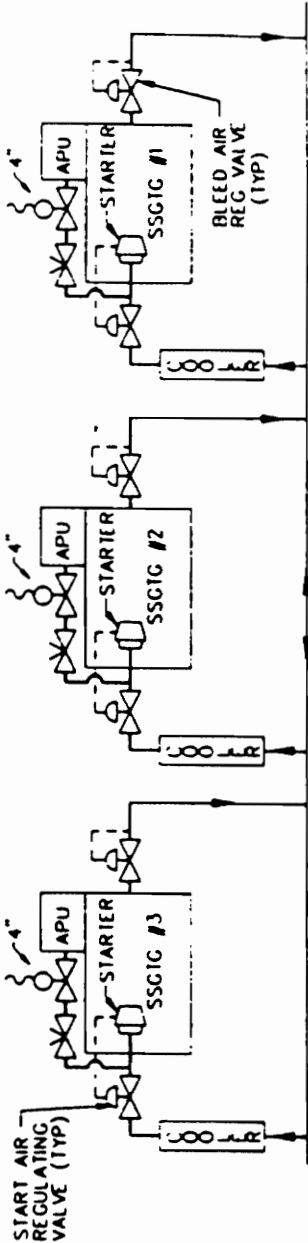


FIGURE 16: APU STARTING, CONFIGURATION #2

CONFIGURATION 5: 3 DEDICATED APUs, NO COOLING

APU DISCHARGE PRESSURE REQUIRED

STARTER PRESSURE	STARTING LOCAL SSGTG
45 PSIG	P APU = 51.4 PSIG
40 PSIG	P APU = 45.9 PSIG
38 PSIG	P APU = 43.7 PSIG



- 6" BLEED AIR MAIN
- BENEFITS/CONCERNS
- SAME REDUNDANCY/SURVIVABILITY AS EXISTING CONFIGURATION
 - REQUIRES NEW STARTER ROTOR FOR INCREASED TEMP
 - ADDED COST

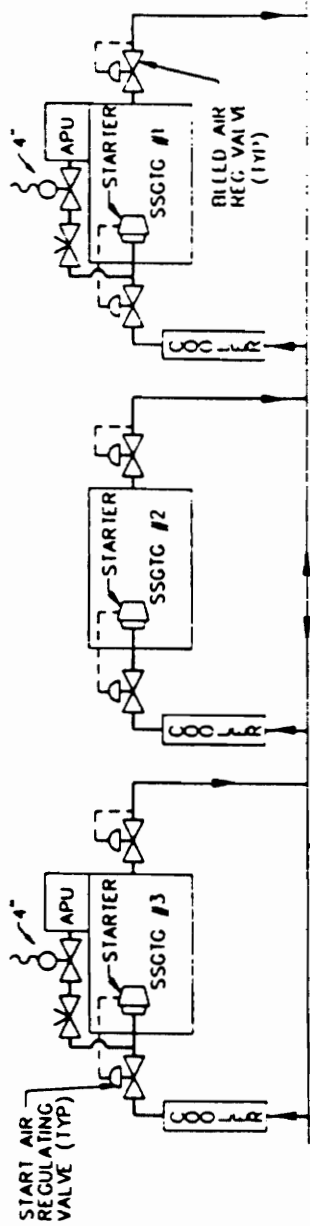
CONDITIONS	
T AMBIENT	= 100°F
T APU	= 500°F
T STARTER	= 500°F
P STARTER	= 45 PSIG
W	= 176.2 LB/MIN
P STARTER	= 40 PSIG
W	= 161.4 LB/MIN
P STARTER	= 38 PSIG
W	= 155.5 LB/MIN

FIGURE 17: APU STARTING, CONFIGURATION #3

CONFIGURATION 4: 2 DEDICATED APUS, NO COOLING

APU DISCHARGE PRESSURE REQUIRED

STARTER PRESSURE	STARTING LOCAL SSGTG
45 PSIG	P APU = 51.4 PSIG
40 PSIG	P APU = 45.9 PSIG
38 PSIG	P APU = 43.7 PSIG



6" BLEED AIR MAIN

BENEFITS/CONCERNS

- + ● LOWER COST
- ● REDUCED REDUNDANCY/SURVIVABILITY OVER EXISTING CONFIGURATION
- ● REQUIRE'S NEW STARTER ROTOR FOR INCREASED TEMP

CONDITIONS

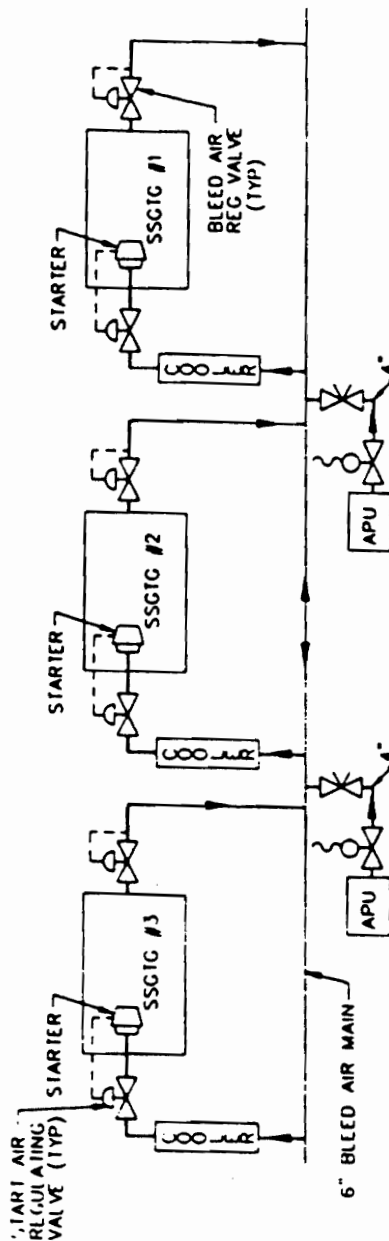
T AMBIENT	= 100° F
T APU	= 500° F
T STARTER	= 500° F
P STARTER	= 45 PSIG
W	= 176.2 LB/MIN
P STARTER	= 40 PSIG
W	= 161.4 LB/MIN
P STARTER	= 38 PSIG
W	= 155.5 LB/MIN

FIGURE 18: APU STARTING, CONFIGURATION #4

CONFIGURATION 5: 2 APU'S, COOLING REQUIRED

APU DISCHARGE PRESSURE REQUIRED

STARTER PRESSURE	STARTING ADJACENT SSGIG	STARTING MOST REMOTE SSGIG
45 PSIG	P APU = 72.7 PSIG	P APU = 76.3 PSIG
40 PSIG	P APU = 65.4 PSIG	P APU = 68.7 PSIG
38 PSIG	P APU = 62.5 PSIG	P APU = 65.6 PSIG



BENEFITS/CONCERNS

- LOWER COST THAN THREE APU'S
- REDUCED REDUNDANCY/SURVIVABILITY THAN EXISTING CONFIGURATION

CONDITIONS

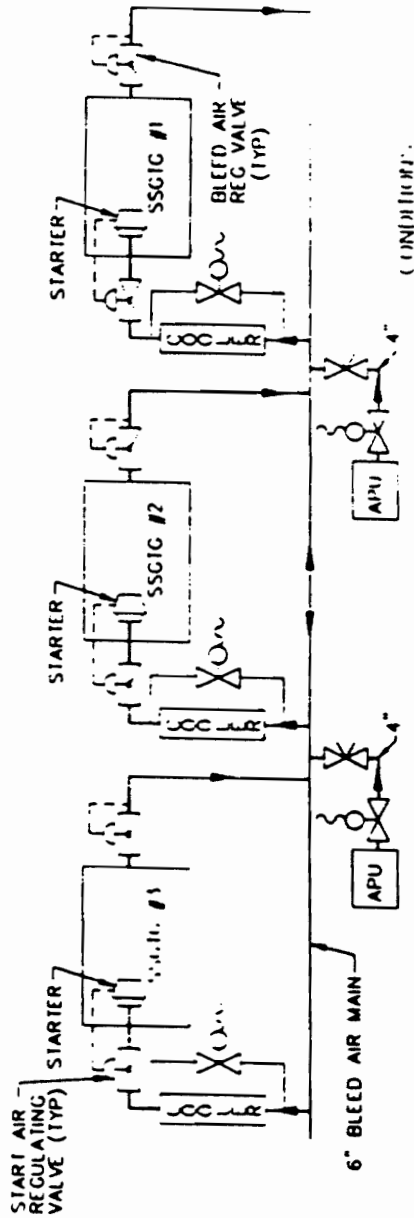
T AMBIENT	= 100° F
T APU	= 500° F
T STARTER	= 151° F
P STARTER	= 45 PSIG
W	= 220.8 LB/MIN
P STARTER	= 40 PSIG
W	= 202.3 LB/MIN
P STARTER	= 38 PSIG
W	= 194.9 LB/MIN

FIGURE 19: APU STARTING, CONFIGURATION #5

CONFIGURATION 6: 2 APU'S, NO COOLING REQUIRED

APU DISCHARGE PRESSURE REQUIRED

STARTER PRESSURE	STARTING ADJACENT SSGIG	STARTING MOST REMOTE SSGIG
45 PSIG	P APU = 68.5 PSIG	P APU = 71.6 PSIG
40 PSIG	P APU = 61.5 PSIG	P APU = 64.4 PSIG
38 PSIG	P APU = 58.7 PSIG	P APU = 61.5 PSIG



BENEFITS/CONCERNS

- LOWER COST THAN THREE APUS
- REDUCED REDUNDANCY/SURVIVABILITY THAN EXISTING CONFIGURATION
- REQUIRES NEW STARTER FOR INCREASED TEMPERATURE

CONDITIONS

T AMBIENT	- 100°F
T APU	- 500°F
T STARTER	- 500°F
P STARTER	- 45 PSIG
W	- 176.2 LB/MIN
P STARTER	- 40 PSIG
W	- 161.4 LB/MIN
P STARTER	- 38 PSIG
W	- 155.5 LB/MIN

FIGURE 20: APU STARTING, CONFIGURATION #6

Signal and Pratt & Whitney of Canada). The purpose of the meeting was to assess the pros and cons of the various APU start configurations, as well as to review capability of various candidate APU's for meeting SSGTG starter inlet pressure requirements under realistic design conditions specified in the DDG 51 Class specifications. At that particular time, there were three APU candidates, the Pratt & Whitney Model 901A, the Allied Signal (formerly Garrett) Model GTCF 100-82, and NAVAIR's new development unit, the Universal Jet Air Start Unit (UNI-JASU); see Tables III, IV, and V for comparison of APU compressed air delivery capabilities.

In addition to qualitative comparisons between the baseline HPAS and specific APU configurations surveyed, Figures 15 through 20 also provide quantitative information on the minimum APU discharge pressures required to satisfy a wide range of SSGTG starter inlet pressure conditions for estimated piping arrangements. An upper limit of 45 psig was selected for SSGTG starter inlet pressure for conformance to existing DDG 51 detail specification requirements, and a lower limit of 38 psig was chosen based on SEA 03YD experience in testing both HP and LP bleed air start systems aboard DDG 51. Values for required APU air discharge pressure were calculated by a "crude" pressure drop analysis of estimated piping configurations which assumed, vice calculated, the thermal losses in the SSGTG start air piping. At this point, a general discussion of the variables influencing SSGTG starting air requirements and their relationships to minimum requisite pneumatic starter motor torque will be provided to facilitate a better understanding of the factors, other than cost and weight, which influenced selection of the final APU start configuration during CD for Flight IIA. Section 3.1.1 overviews more detailed calculations that were later performed to demonstrate the functional effectiveness of the new SSGTG starting concept.

By reference (r), the pneumatic starter motor for the Allison K-34 SSGTG is the Garrett Model ATS 100-467B, and associated starter flow is governed by the following equation:

$$W = FF \times P_1 / 14.7 \times (519/T_1)^{1/2}$$

where:

W = Starter flow rate, lbm/min
FF = Starter flow factor, lbm/min
P₁ = Starter inlet pressure, psia
T₁ = Starter inlet temperature, degrees R

Table 3: UNI-JASU APU Performance

Ambient Temp (Degrees F)	Disch Pressure (Psig)	Disch Temp (Degrees F)	Disch Flow (Lb/Min)
-40	64.6	445	176
59	64.6	551	160
130	59.5	607	128

Table 4: GTCP 100-82 APU Performance

Ambient Temp (Degrees F)	Disch Pressure (Psig)	Disch Temp (Degrees F)	Disch Flow (lb/min)
-40	65.3	396	274
59	54.8	515	170
130	49.0	580	154

Table 5: P&W-901A APU Performance

Ambient Temp (Degrees F)	Disch Pressure (Psig)	Disch Temp (Degrees F)	Disch Flow (Lb/min)
59	43.3	500	363

Note: No data available for other than 59 degrees F.

From this short equation, it is clear that the primary variables affecting starter flow rate are starter flow factor and starter inlet pressure; starter inlet temperature has less direct impact on overall starter flow rate. The starter flow factor is dependent upon the geometrical configuration (effective flow area) of the starter itself and varies only within manufacturing tolerance allowances; for DDG 51 Class, the flow factor is permitted to vary between 55.2 and 59.0 by the detail specifications. As for starter inlet pressure, there are numerous variables which can have a pronounced affect; they include APU discharge flow and pressure outputs and piping system pressure losses. APU outlet flow and pressure, in turn, vary inversely with high ambient temperatures and increased intake/exhaust ducting losses, whereas piping system pressure losses vary directly with flow rate, overall piping length, and thermal losses. For given starter inlet conditions (pressure and temperature) starter flow factors, ambient conditions, and intake/exhaust ducting losses, reference (r) also contains resultant torque output curves for the SSGTG starter motor as well as the torque curve for minimum required SSGTG starting torque for all ambient conditions.

The net result of the 10 June 1992 meeting was elimination of all but configurations 3 and 6 (Figures 17 and 20) due to subjective analysis of relative cost, survivability, and/or incompatibility with APU air output capabilities; see Table VI for a summary of the meeting results. In addition, the necessity for more detailed calculations verifying feasibility of the remaining configurations to support SSGTG starting requirements for realistic design conditions was established. The Pratt & Whitney APU was also eliminated from further consideration due to inadequate discharge pressure characteristics and since acquisition costs were over three times greater (approximately \$900K verses \$250K) than the other candidate APU engines. It is also worthy to note that despite obvious survivability shortfalls, the dual APU concept illustrated in Figure 20 was permitted for further analysis by PMS 400D8/SEA 03D35 for cost considerations only; this decision was later overturned in the 22 December 1992 NAB 023 Design Review when it was finally agreed that the cost savings of an additional APU installation did not warrant such a survivability reduction. SEA 03YD/BIW technical concerns with the capability of remote, verses dedicated, APU's to satisfy minimum SSGTG starting torque requirements for realistic design conditions also weighed heavily in this decision.

Table VI: APU Comparison Matrix

Configuration	Relative Cost	Performance	Survivability
1			
2			
3		X	X
4			
5			
6	X		

Subsequent to the 10 June 92 liaison meeting and followup meetings with BIW and vendors for the APU's and SSGTG's, SEA 03YD issued reference (s) direction to BIW to prepare detailed piping arrangements for the APU configurations illustrated in Figures 17 and 20, to assess the capability of both the Allied Signal Model GTCP 100-82 and UNI-JASU APU engines for delivering sufficient compressed air to support minimum SSGTG starting torque requirements, and to provide RM&A data comparison of the two candidate APU's. It was further directed that the calculations demonstrate SSGTG starting performance for the complete range of ambient conditions (-40 to 130 degrees F), while considering the influences of maximum permissible SSGTG intake and exhaust ducting losses (10 inches water gage each) for both the APU and SSGTG; values for each of the above design conditions are specified in the DDG 51 Class detail specifications.

In response to reference (s) tasking, Allied Signal provided reference (t) starting analysis at the 2 April 93 NAB 023 Design Review; the analysis concluded that either the Allied Signal GTCP 100-82 or the UNI-JASU could support SSGTG starting requirements for Configuration 3 (Figure 17) only as long as the thermal losses between the APU air discharge and SSGTG starter inlet did not exceed 150 degrees F. The dual APU configuration of Figure 20 was included in the Allied Signal analysis for information only. Subsequently, SEA 03YD issued reference (u) calculations, which estimated actual piping system losses to be approximately 120 degrees F for the worst case design conditions of 130 degrees F ambient with maximum (10 inches WG APU ducting losses), and that either the UNI-JASU or Allied Signal GTCP 100-82 APU's would meet minimum SSGTG starting torque requirements. Starting at high ambient conditions is more difficult due to significant decreases in APU performance output, and due to higher thermal losses between the APU compressed air and the machinery spaces. For example, when operating a UNI-JASU with combustion inlet air at minus 40 degrees F and corresponding machinery space operating temperatures of 60 degrees F, the differential temperature between the UNI-JASU compressed air (445 degrees F) and the machinery space is 385 degrees F. Similarly, for a 130 degree F day and assuming machinery space operating temperatures of 120 degrees F, the differential temperature is 487 degrees F.

It is worthy to note that in the time period between the aforementioned December 1992 Design Review and receipt/preparation of more detailed calculations in April 1993, that there occurred considerable engineering and planning activity to develop the Figure 17 APU starting

concept to the necessary level of detail to gain PMS 400D approval for Flight IIA. These efforts included selection of an APU engine (UNI-JASU verses GTCP 100-82), identification and establishment of acceptable APU support/interface systems, and the development of a formal test plan to verify proper operation of a "ship-like" APU system at LBES prior to shipboard operation. The later was considered essential by the entire Flight IIA Design Upgrade Team due to the fundamental mission essentially of SSGTG starting to DDG 51 Class, not to mention the inherent benefits to the shipbuilders' detail design efforts. The remaining portions of this section will overview the net results of this CD activity.

Despite nearly identical performance characteristics, the new UNI-JASU APU was recommended by BIW and NAVSEA over the Allied Signal Model GTCP 100-82 APU unit for a variety of significant reasons; principally reliability, maintainability, supportability, cost, and future availability. The GTCP 100-82 APU is an aged (1960's vintage) design used by NAVAIR for starting military aircraft for nearly 30 years. Based on information provided by NAVAIR in a March 1993 liaison meeting with NAVSEA, which is supported by reference (v), the GTCP 100-82 APU has an MTBF of 50 hours, a MTTR of 2 hours, a MTBO of 270 hours, maintenance support only exists at the Depot level from a total of 3 sites, and production unit costs for the base engine alone are approximately \$150K. Additionally, NAVAIR highlighted significant logistics support difficulties with obtaining spares due to reduced production levels and, the existence of ongoing remedial efforts for the near term until the UNI-JASU becomes available.

Conversely, the new UNI-JASU APU, which is to replace NAVAIR's complete inventory of GTCP 100-82 APU's by the year 2007, is to have an MTBF of 150 hours, an MTTR of 2 hours, an MTBO of 1000 hours, and production unit costs are estimated to be \$144K per unit. Regarding maintenance and logistics support, reference (v) further outlines planning efforts for development of organizational, intermediate, and depot-level repair capabilities; there are to be 6 intermediate-level repair sites and 3 depot-level sites. Still further, NAVAIR has developed a comprehensive specification, reference (w), for the development, test, evaluation, production, and deployment of necessary Integrated Logistics Support (ILS) for the UNI-JASU APU; NAVAIR has structured the APU design schedule such that ILS

development is being accomplished in parallel with actual hardware development. The primary reference document for the various ILS tasks contained in reference (w) is MIL-STD-1388. Based on output data resulting from various ILS tasks, reference (w) also includes requirements for development of manpower training and training equipment, technical manuals, support equipment, spares and repair parts lists, and facilities for both intermediate and depot level maintenance. Such a complete ILS development scheme was instigated by lessons learned with support of the Garrett 100-82 APU.

In consideration of above RM&A attributes provided by NAVAIR and reference (s) SEA 03YD tasking, BIW provided a comparative analysis of the two candidate APU's during the April 93 Design Review; the results of this analysis, as well as a recently updated SEA 03YD RM&A analysis are provided in Tables VII and VIII. It should be noted that the number of APU starts per year (699) and the starting duty cycle (5 minutes) specified by BIW in Table VII are overly conservative. In fact, the number of starts specified supports the Figure 20 APU starting configuration wherein a single APU is capable of starting any of the three SSGTG's. Nonetheless, Table VII reveals extremely low APU failure rates (approximately 1 or less per year) and lengthy periods between APU overhauls. Utilizing more accurate values for numbers of APU starts and APU starting duty cycle, Table VIII indicates substantial improvements in APU failure rate and overhaul periodicity. The Table VIII values for numbers of APU starts (233) and starting duty cycle (3 minutes) are based on SEA 03X34 survey of SSGTG starts aboard CG 47 Class cruisers, and LBES APU test data, respectively. From Table VIII, it is also shown that the NAVSEA goal for operational availability (Ao) is 0.85, similar to that for the Centralized HPAS HP air compressors, and that the corresponding mean logistics down time (MLDT) is approximately 7 hours and 24 hours for the GTCP 100-82 and UNI-JASU APU's, respectively.

Figure 21, also provided by NAVAIR at the March 93 liaison visit, illustrates the procurement approach and schedule for the UNI-JASU acquisition program. Briefly, the initial phase of the program was funded in January 1992; Phase I consists mainly of development, evaluation, and downselection of APU's from two competing APU manufacturer's. The second phase, scheduled for funding approval prior to April 1995, features detailed hardware development, first article qualification testing, approval for full production, and

Table VII: BIW RM&A Analysis

Parameter	GTCP 100-82	UNI-JASU
Starts/year	699	699
Start duration	5 mins	5 mins
Hours/year	58.25	58.25
MTBF	50 hours	150 hours
Starts/failure	600	1800
Failures/year	1.17	0.39
MTBO	270 hours	1000 hours
Years/overhaul	4.6 years	17.2 years
MTTR	2 hours	2 hours
Ai	0.962	0.987

Table VIII: SEA 03YD RM&A Update

Parameter	GTCP 100-82	UNI-JASU
Starts/year	233	233
Start duration	3 mins	3 mins
Hours/year	11.65 hours	11.65 hours
MTBF	50	150
Starts/failure	1000	3000
Failures/year	0.23	0.08
MTBO	270 hours	1000 hours
Years/overhaul	23.2 years	85.8
MTTR	2 hours	2 hours
Ai	0.962	0.986
*Ao	0.85	0.85

*Note: To support NAVSEA Ao goals of 0.85, MLDT's must not exceed 6.8 hours for the GTCP 100-82 and 24.5 hours for the UNI-JASU.

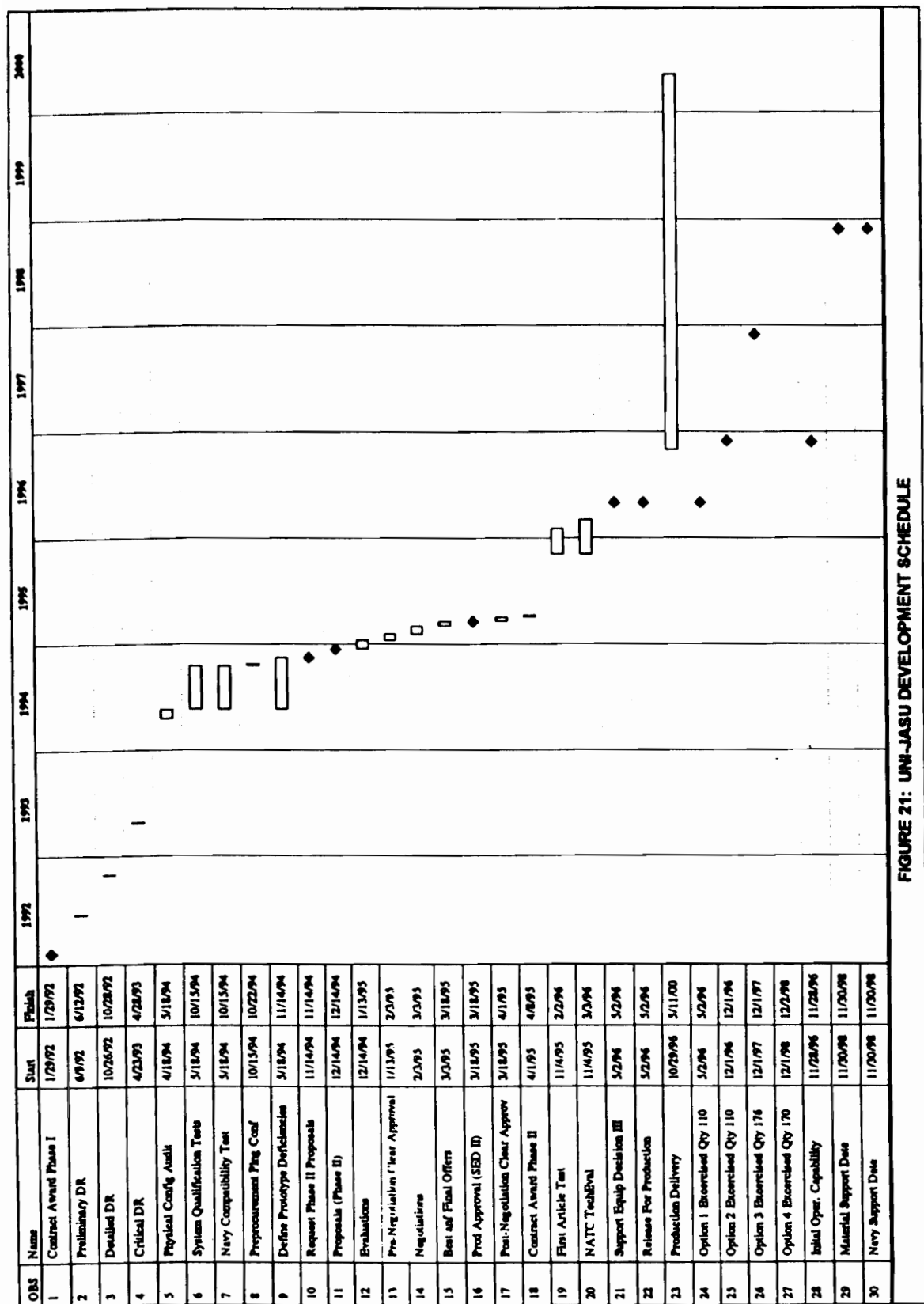


FIGURE 21: UNI-JASU DEVELOPMENT SCHEDULE

delivery of first production units to the Navy by November 1996. This schedule was reviewed closely by the Flight IIA shipbuilders and it was determined supportable with significant modifications to the shipbuilders' normal production schedule. More specifically, and in order to allow sufficient time for APU system first article testing (e.g. performance, EMI, shock, inclined operation, and vibration), the shipbuilders noted actual APU delivery could occur no later than 6 month prior to initial generator light-off scheduled for September 1998.

Such a late delivery would necessitate loading out of the APU system with the lead ship on the ways, verses in the pre-outfitting shops of the individual ship construction modules; loading out on the ways is substantially more expensive (approximately 3 times) than in pre-outfitting. Despite this rather ambitious, albeit risky, integration schedule the Flight IIA Program, NAVSEA decided in the April 92 NAB 023 Design Review that the UNI-JASU would be the APU of choice for Flight IIA, and the GTCP 100-82 would provide an acceptable short-term fallback position should any delays occur in NAVAIR's UNI-JASU acquisition program. Further, as NAVAIR procures large quantities of APU's and support (e.g. training, spares, and repair facilities) provisions either already exist or are in planning, it was decided that the APU's would be Government Furnished Equipment; this was/is clearly a cost effective procurement approach, and a win/win situation for both NAVSEA and NAVAIR. Supporting the DDG 51 Flight IIA lends further credibility and justification for the continued funding of the UNI-JASU Program.

Regarding identification of necessary APU support and interface system requirements supporting the Figure 17 APU configuration, numerous meetings were similarly held between NAVSEA and SET to establish an acceptable design approach to facilitate costing by the lead shipbuilder prior to seeking PMS 400D approval; the focus of these meetings was gaining the most cost effective approach while meeting reasonable design requirements. Inherently, this process required consideration of the systems engineering process; that is requirements were discussed and validated, alternative approaches were considered, shipboard synthesis/impacts were identified, and requirements were re-analyzed and modified as necessary to arrive at an acceptable solution. The following is a listing of the most significant, relative to cost and performance, decisions made during CD for the design of APU start system support and interfaces:

1. APU Enclosures - Human factors issues associated primarily with noise and safety dictated that each APU be mounted in an acoustical, fire-retardant enclosure capable of containing an APU blade failure. As will be detailed later in Section 3.2, the APU enclosures themselves raised interesting human factors challenges during detail design of Flight IIA, particularly in the areas of APU engine removal and accessibility for maintenance and repair. During CD, it was further agreed that dedicated fixed flooding carbon dioxide or halon fire extinguishing systems would be provided for each APU module enclosure. To resolve concerns with overheating of the APU engine within the module, special attention was also given towards the design of an exhaust eductor in the APU exhaust ducting; the eductor functions to provide a positive flow of module cooling air over the hot engine out through the APU exhaust ducting. In addition, it was further agreed that the cooling air supply would be from either or both the cool section (intake area) of the APU modules and the machinery space via separate dampers; ultimately, LBES test results would provide the necessary inputs for detail design.

2. APU Location - Satisfying minimum required SSGTG starting torque coupled with very limited space availability within relatively tight DDG 51 Class machinery space confines required locating the APU's in the vacant spaces directly above the companion SSGTG'; by coincidence, this particular agreement represented the least shipboard impact, thus costs could be minimized. For comparison with rather large diesel generators previously discussed, e.g. 10'L x 3'W x 4'H, 12,000 pounds each, each APU and associated enclosure was estimated during CD to be approximately 6.5'L x 4'W x 4'H, and weigh only 1100 pounds.

3. APU Intake/Exhaust Ducting Arrangement - There was considerable discussion concerning the arrangement of APU intake and exhaust ducting. To minimize shipboard impacts and Program costs, the decision was made to combine the APU ducting with that of its companion SSGTG. This decision was based on indepth ducting analyses performed by Gibbs & Cox which provided estimates for duct sizing and arrangement within the machinery spaces. Issues arising from these analyses and follow up meeting discussions involved the potential for recirculation of hot SSGTG combustion exhaust air back through an operating or idle APU to the SSGTG intake ducting and unknown impacts to the APU and/or SSGTG for prolonged operation at maximum ducting losses (intakes) and backpressures (exhaust ducting).

To alleviate these issues during CD, it was agreed that the APU enclosures would be fitted with an internal fire wall to separate the hot and cold sections (exhaust and intake), dampers would be provided in the APU intake and exhaust ducting, and testing would be conducted at LBES to validate performance of the resultant configuration and aid in detail design development of final ducting configurations. Figure 22 is a schematic depiction of the ducting air flow circuit arrangement developed during CD for the APU combustion air and module cooling.

4. APU Controls - As with APU/SSGTG ducting, development of an acceptable controls philosophy involved considerable discussion during CD; traditionally, modifications to existing shipboard controls systems are astronomically expensive. Accordingly, the first of two control philosophies featured local APU control only with no interface to the ships Machinery Central Control System (MCCS). The MCCS is the "brain" of the machinery plant and permits remote operation and monitoring of all critical functions from the Machinery Control Station (MCS), located outside the machinery spaces on the Damage Control deck. Relative to starting SSGTG's, this concept was immediately dismissed given the criticality of starting SSGTG's both locally and remotely. The second philosophy which was adopted for Flight IIA essentially required a one for one replacement of APU control and monitoring features with those MCCS features being deleted from the baseline SSGTG HP starting air system; the thought being that MCCS hardware was much more cost effective than removing it. As for software modifications, it was noted that it was more cost effective to group APU control and monitoring changes in with others being handled by an existing but separate ECP. Finally, it was agreed during CD that the specifics for the APU control operating panel (ACOP) and MCCS interfaces would be finalized prior to RFP.

5. APU Fuel Supply - Initially, it was proposed that the APU's be supplied fuel from the associated SSGTG's fuel head tanks, which contain diesel fuel marine, however it was later agreed that the APU's be provided with individual 30-gallon fuel service tanks, supplied from the ships' JP-5 Fuel Transfer System. This decision was based, largely in part, due to poor quality diesel fuel received on existing DDG 51 Class ships and associated SSGTG fuel system problems, and in consideration of APU manufacturer's recommendations that higher quality fuel be provided. A capacity of 30 gallons was selected to provide approximately

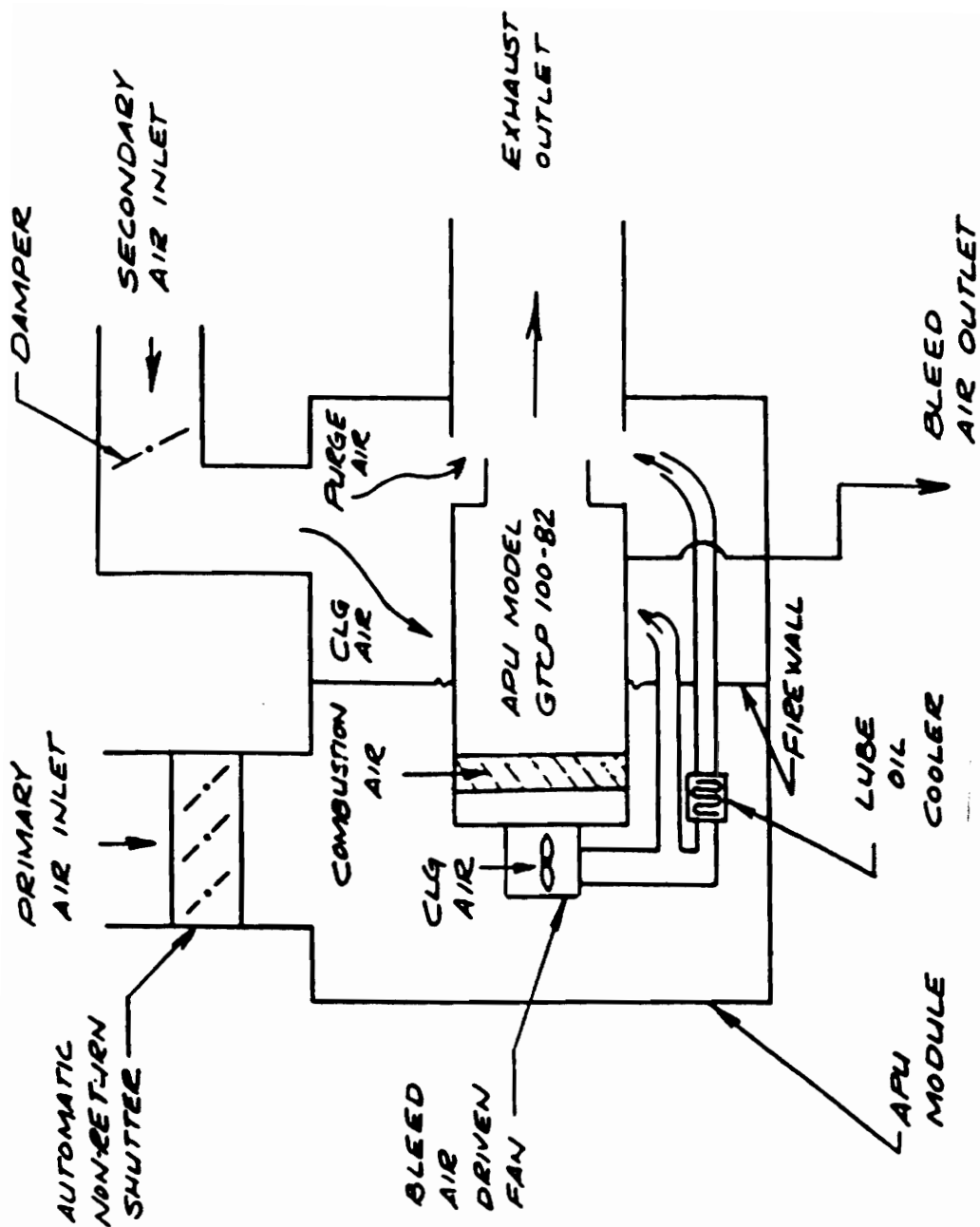


FIGURE 22: APU AIRFLOW CIRCUIT

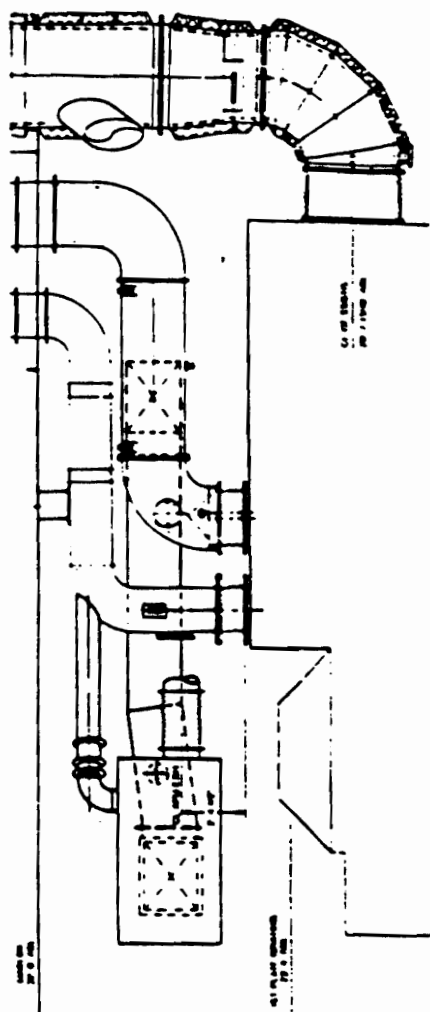
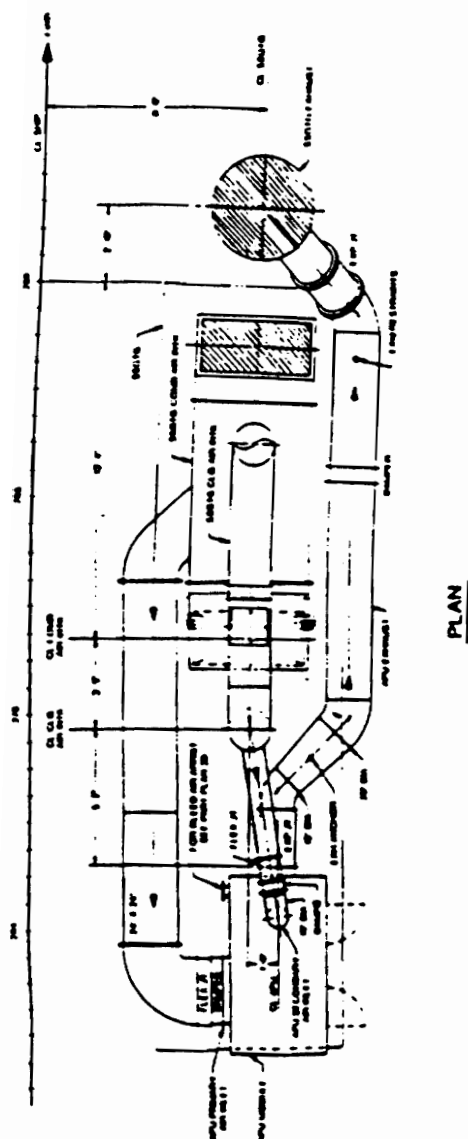
30 minutes of continuous APU operation.

6. APU Batteries - In order to support SSGTG starting during the dark ship condition, it decided that each APU would be provided with an individual, completely independent, power supply for starting and operation of all control functions. Coincidentally, both the UNI-JASU and GTCP 100-82 APU's are designed with 24 volt direct current starting and controls systems, hence it was decided during CD that each APU would be provided with rechargeable 24 volt batteries sized for a minimum of 4 successive APU starts, followed by 30 minutes of APU operation.

Given the significance of APU location and starting air piping arrangements to SSGTG starting torque requirements, human factors issues and technical concerns associated with APU enclosures, and further concerns with operation of combined APU/SSGTG intake and exhaust ducting, it was ultimately agreed that testing of a "ship-like" APU/SSGTG start system at LBES was mandatory for Flight IIA. Figures 23 and 24 are provided to illustrate the actual ducting arrangement and APU test configuration planned for testing at LBES, respectively.

Prior to arriving at this decision, there were numerous meeting discussions addressing other testing options; these options included a one time test of a simplified APU system aboard a DDG 51 Class ship under construction at BIW, and performing APU testing in a test cell with simulated piping and ducting losses. The later two were discounted based on relative cost to merit considerations; the one-shot test at BIW was estimated at \$750K largely due to adverse production impacts, and the test cell approach was estimated to be approximately half the \$600K cost as incorporating the APU into the DDG 51 Class ER 2 test site at LBES.

Reference (x) documents the cost estimate and testing agenda coordinated by SEA 03YD to support APU testing. Note development of the test agenda required considerable interaction with SET, SEA 03X34, NAWC Lakehurst, Allied Signal, and NSWC Code 9332. It is also worthy of noting that due to unavailability of the UNI-JASU, it was agreed that LBES testing would be performed with a GTCP 100-82 provided on consignment (no charge) from NAWC Lakehurst. Finally, testing was scheduled to be completed by August 1993, but as will be discussed later in Section 3.1, LBES testing was not completed until April 1994.



ENGINE ROOM NO. 2
APU MODEL GICP 100-82

FIGURE 23: APU DUCTING CONFIGURATION

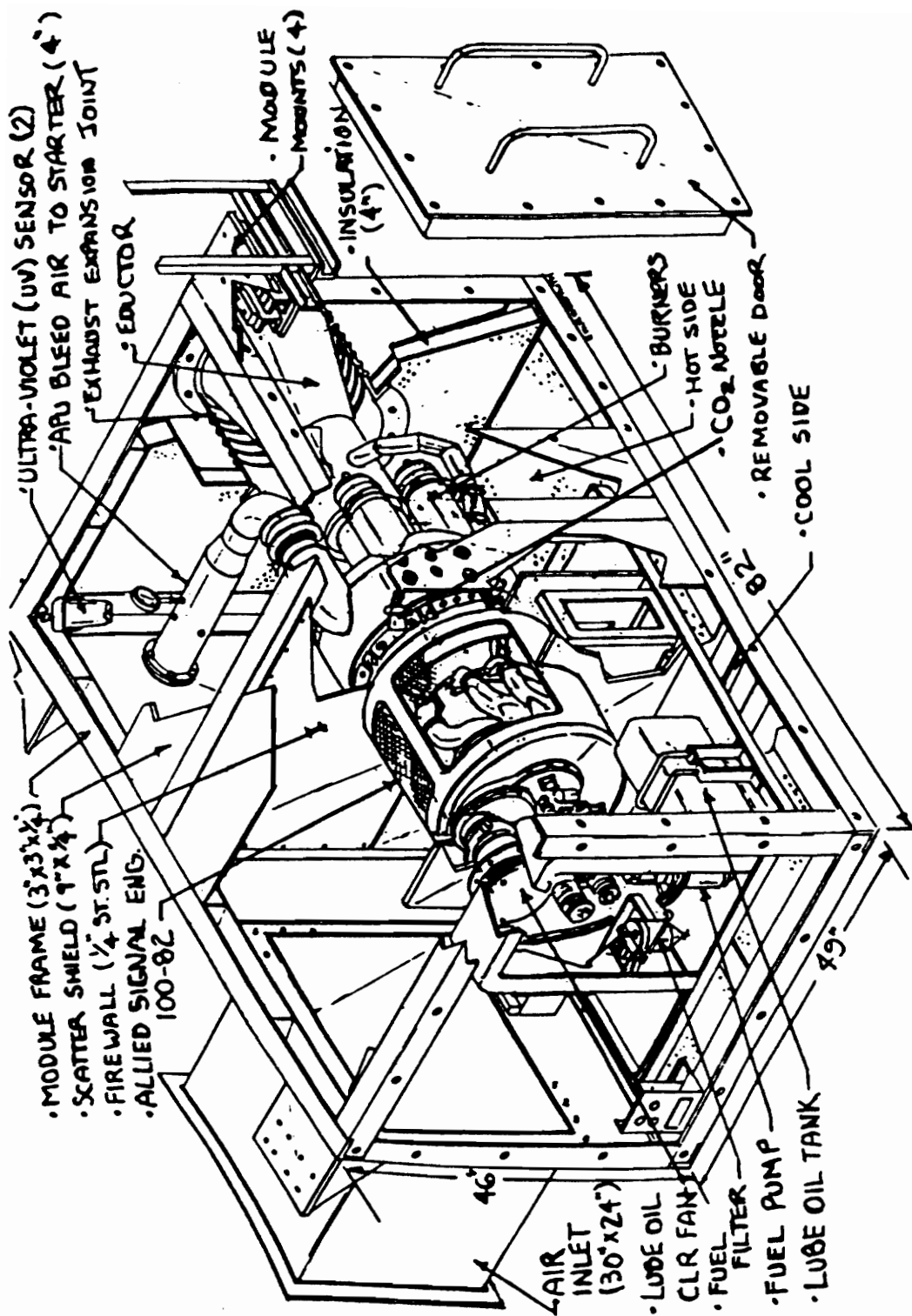


FIGURE 24: APU MODULE ARRANGEMENT

2.4.2 Auxiliary HP Air Subsystems

MPGT Emergency Starting - Other than the initial electric starting option (Figure 13), proposed by SEA 5032 for starting both SSGTG's and MPGT's, there were no alternatives considered as a result of ECP 51-1216. Replacement of the MPGT HP starting air systems was considered unnecessary since the primary mode of MPGT starting is from the LP Bleed Air System, which is pressurized by operating SSGTG's, and since any improvement in SSGTG starting capability would also translate to improved MPGT starting. MPGT starting from the SSGTG HP start flasks is only for emergency backup to the LP Bleed Air System. Neither NAVSEA nor BIW considered the loss of this emergency backup starting system to compromise the operational requirements cited Section 2.1.1.2 for starting and motoring of the MPGT's. It was/is anticipated that starting and motoring of MPGT's will continue to be from the ships' LP Bleed Air Systems, which feature a highly survivable piping main located along the ship centerlines relatively low (Second Platform) in DDG 51 Class ships.

A & B Module Deluge Tank Charging - Careful SEA 03YD review of the origin of the requirements driving the existing HP air piping arrangement to the A & B Weapon Zone compression tanks revealed that this elaborate/costly piping scheme was developed to support future replacement of the Vertical Launch Systems (VLS) with 5"/54 caliber guns; modularity of the VLS support services to accept alternatives such as 5"/54 caliber guns was a mandatory requirement set by PMS 422-31 in the original Flight I design. Periodic/infrequent charging of the 1.9 cubic foot deluge tank provided to support fresh water actuation of the associated VLS magazine seawater sprinkling system control valve using 3000 psig automatically reduced to 225 psig was considered not cost effective or practical for Flight IIA.

By reference (y), PMS 422-31 concurred with SEA 03YD reference (z) proposal to utilize a small LP air driven booster pump, of a similar design to that utilized successfully for 5"/54 gun nitrogen gas accumulators and counter recoil cylinders, for pressurizing the small (1.9 cubic feet) deluge compression tanks. SEA 03YD proposed utilizing a Haskel Model AAD-5 booster pump having a 15 to 1 compression ratio and 5-scfm output capacity capable of pressurizing the deluge compression tanks to 225 psig in approximately five minutes. Each booster pump weighs approximately 25 pounds and can be mounted on the bulkhead of each VLS Service Interface Room, along with the necessary

LP air hoses; see Figure 25 for an illustration of the simplified deluge air charging system.

5"/54 Caliber Gun Gas Ejection System - Two alternatives were investigated during CD for supplying gas ejection air for the 5"/54 caliber gun system. The first option initiated by BIW featured redesign of the gun's internal pneumatic piping to accept 125 psig compressed air from the ship's LP air system. On the surface, this concept appeared feasible, however was quickly abandoned in July 1992 due to excessive load (approximately 60-scfm) addition to the LP air system, anticipated high gun system redesign and qualification costs, and due to inability to meet Section 2.1.1.2 operational requirements in the event of damage to the LP air main or its compressors.

The second option, initiated by BIW at SEA 03YD's request, featured use of a small dedicated HP air compressor located in the same space (Loader Drum Room) as the existing 3000 psig, 6 cubic foot gas ejection flask and associated piping system; the idea being to minimize shipboard impacts while maintaining the integrity of the existing system for firing all 600 rounds without interruption. In addition, locating a small compressor in the same space would be a survivability enhancement over the Centralized HPAS. Alternatively, if space was not available in the Loader Drum Room, location in the machinery spaces was permitted.

The HP air compressor proposed by BIW at the August 1992 NAB 023 Design Review was/is a small (24"L x 14"W x 18"H, 100 pounds) 3000 psig, 5 scfm, unit currently used in the pneumatic drive system of the Phalanx guns aboard CG 47 Class cruisers and specified for DDG 54 and follow destroyers. This particular compressor unit includes a 5 horsepower, 440 vac, 60 hertz electric motor, a radial four cylinder air-cooled HP air compressor, a combination coalescing air filter and desiccant dehydrator capable of delivering minus 19 degrees F dewpoint at 3000 psig, and automatic on/off controls, all mounted on a resiliently mounted bedplate. The compressor package was developed and fully qualified (e.g. Grade A shock per MIL-S-901C, vibration per MIL-STD-167-1, 2000 hour reliability growth test) by PMS 413, it is fully supported (e.g. training, repair, and parts support) through NAVORD, Louisville, and the configuration is controlled by NAVSEA Drawing No. 630998.

Figure 26 illustrates the arrangement of the 5"/54 caliber gun gas ejection system developed during CD. Note that at

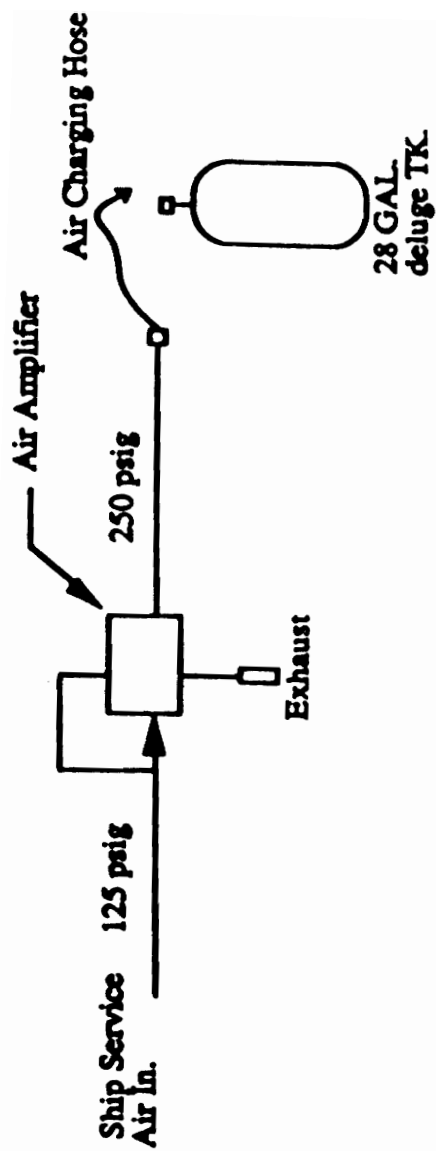


FIGURE 25: DELUGE TANK AIR CHARGING SYSTEM

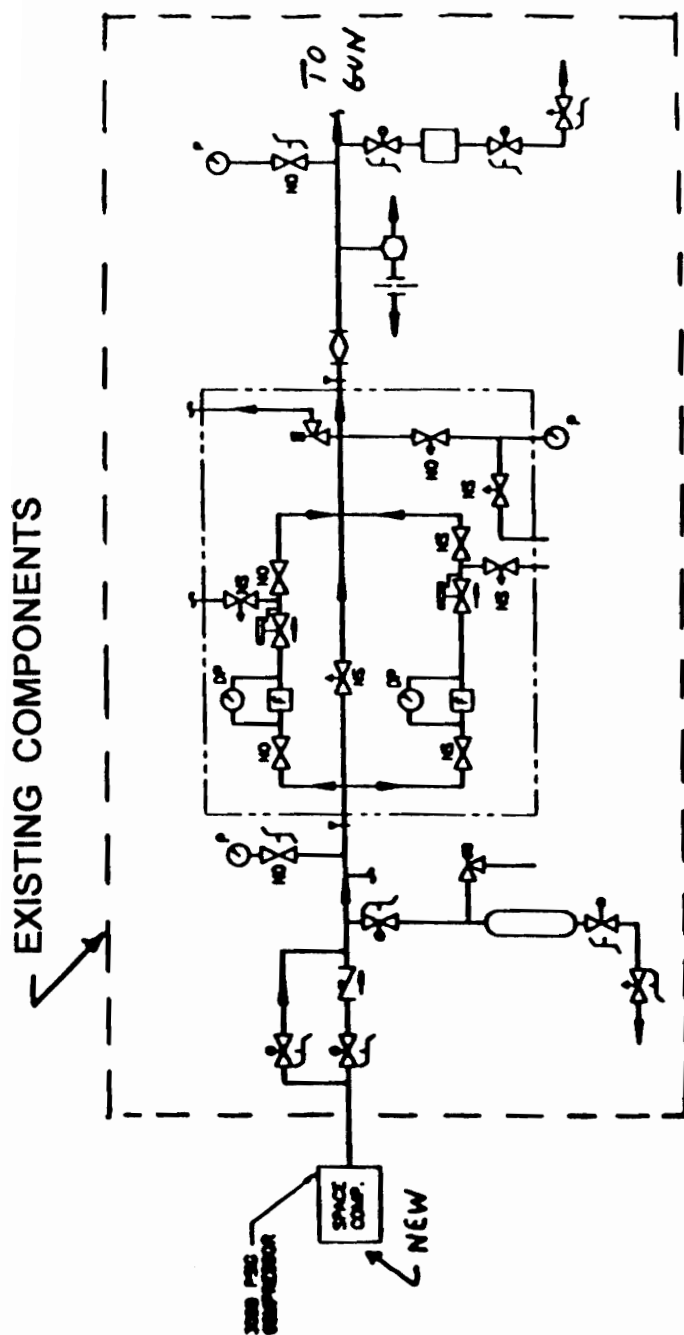


FIGURE 26: 5/54 CALIBER GUN GAS EJECTION SYSTEM

that time the location for the dedicated HPAC had not been firmed up, however, by reference (q), BIW confirmed space was available in either the Loader Drum Room or the Auxiliary Machinery Room Number 1. Ultimately, to save costs, it was decided that the dedicated compressor would be located in the Loader Drum Room.

MK 32 Torpedo Impulse Flask Charging - Two alternatives were reviewed during CD to satisfy charging of MK 32 torpedo tube impulse flasks from the NATO standard air charging panel located centerline on the 01 level at approximately frame 240. The air charging panel is comprised of a series of valves (isolation, pressure reducing, and safety relief), pressure gages, and flexible hose connections for charging each of the six, 900 cubic inch volume, impulse flasks with clean dry air to 1850 psig. As the torpedo impulse flasks are exposed to weather, the DDG 51 Class detail specifications (Section 070) inherently require the existing HP air supply have a dewpoint of not less than minus 40 degrees F at atmospheric pressure; the baseline HP compressor plant dehydrators exceed this requirement by supplying minus 60 degree F HP air at 3000 psig. The process for recharging the impulse flasks involves removing (unscrewing) the impulse flasks from the associated torpedoes and manually carrying via handtruck to the charging panel's impulse flask holding bracket where they are secured for manual recharging.

The first concept proposed by SEA 03YD featured charging of the impulse flasks by two standard portable nitrogen flasks, an LP air driven gas booster pump, and supporting flexible hoses all packaged together on a standard hand truck per NAVAIR Drawing H30003-1166A5100; this concept also proposed deletion of the NATO standard air charging panel for additional cost and weight savings. By reference (z), SEA 03YD estimated that two standard 1.5 cubic foot, 2265 psig nitrogen cylinders, in conjunction with use of the booster pump, could support charging of all six impulse flasks; it was proposed that four spare nitrogen cylinders be provided for charging remaining 3 spare torpedoes and to permit routine testing or recharging due to leaks. Reference (aa) relayed SEA 06U312 concerns with handling of the nitrogen handling truck in rough weather, availability of spare nitrogen cylinders, and the unknown impacts when launching from nitrogen in lieu of air; this concept was subsequently dropped in favor of a second more acceptable alternative.

The second alternative featured utilization a small dedicated 3000 psig HP air compressor, identical to that

proposed above for the 5"/54 caliber gun system, in conjunction with a dedicated 6 cubic foot HP air flask. To minimize costs and enhance survivability, space was found to be availability in the Pallet Truck Stowage/Battery Recharging Room on the 01 level (01-205-01-Q). This concept permits recharging of all 6 torpedo impulse flasks plus four spares from the new HP air flask without recharging from the HP air compressor. Figure 27 illustrates the revised torpedo air charging system configuration via dedicated HPAC.

Ship Service LP Air System Backup - Section 2.1.1.2 noted that the baseline Centralized HPAS provides emergency backup to the ships LP vital air system via two 3000/80 psig pressure reducing stations; this provides for approximately 10 minutes of backup supply to LP air services such as electronics dry air, BAS control valves, fuel and lube oil purifiers, MPGT and SSGTG module vent dampers, and SSGTG module controls in the event of an electric plant casualty. In consideration of Section 2.1.1.2 requirements, it was considered that loss of emergency backup capability to the ship's LP Air System was acceptable provided that electric power could be quickly restored by starting the SSGTG's. Based on review of existing LP air services, it was determined that only LP air to the SSGTG module controls themselves was required to support restoration of shipboard electrical power; SSGTG module controls include LP air actuation (opening) of the SSGTG compressor fifth, tenth, and fourteenth stage bleed valves and starter control valve, as well as post start fuel nozzle purging. Accordingly, it was agreed that a dedicated 5 cubic foot LP air receiver was necessary for each SSGTG. It turns out that a 5 cubic foot receiver was originally included within the DDG 51 SSGTG modules, however, was deleted by a Flight I ECP upgrade to improve module accessibility.

2.5 Concept Selection

The previous section detailed the various tradeoff studies performed for development and optimization of ECP 51-1216 during the Flight IIA Contract Definition phase; the focus of these efforts was to define each new subsystem concept to sufficient level of detail to ensure technical acceptability, and to facilitate cost and weight impact analyses prior to seeking PMS 400D approval and final concept selections.

Technical feasibility and acceptability of each new subsystem required comparative analyses for meeting core operational requirements previously defined in Section

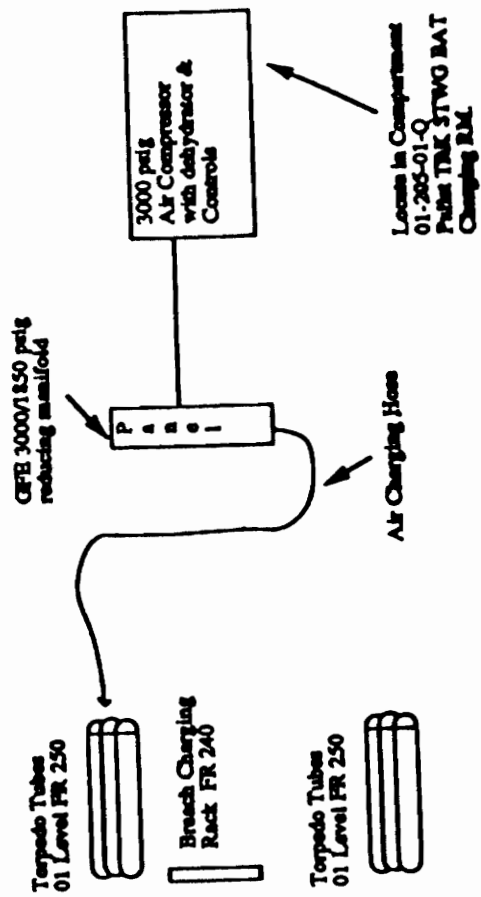


FIGURE 27: MK 32 TORPEDO AIR CHARGING SYSTEM

2.1.1; Table IX is provided to illustrate the net results of these efforts. Together with cost and weight assessments, PMS 400D was provided with the necessary information to ultimately approve the various new subsystem concepts developed for ECP 51-1216. Sections 2.5.1 and 2.5.2 overview the specifics of Table IX for the SSGTG starting system and auxiliary HP air subsystems.

Table X provides a summary of the Rough Order of Magnitude (ROM) cost and weight estimates developed by the lead shipbuilder for NAB 023/ECP 51-1216, and contained in reference (q). Note that for comparison purposes, the baseline Centralized HPAS and other technically acceptable starting options are included with the APU/SSGTG starting scheme developed during CD. Note also that cost and weight values for each starting option also include the impacts of the remaining auxiliary subsystem concepts developed during CD; it was established very early in the development of NAB 023 that there would be no reasonable payback associated with limiting HPAS redesign to the auxiliary services only due to the number of ship design zones impacted and the manner in which cost estimates are developed. Cost estimates for each individual subsystem are included in reference (q), but will not be discussed as part of this paper.

Briefly, ROM cost estimates are developed by the lead shipbuilder utilizing a proprietary costing model developed from detailed analyses of DDG 51 shipbuilding costing returns for the various disciplines associated with each ship design zone. Discussions with BIW indicate this costing model is continually updated (currently up through DDG 60), all charges are organized by technical discipline, the disciplines are listed by Ships Work Breakdown Structure, and charges include materials and manhours for design, fabrication, installation, and testing. The input to the costing model is an estimate of percentage impact to geographical area of each zone, and the output is a corresponding listing of estimated charging impacts for each affected discipline. Lastly, in order to ensure costing accuracy, the outputs from technical disciplines are scrutinized closely and the inputs modified until reasonable convergence is achieved; BIW advises that comparison with actual measured costs has proven the costing model to be quite effective for ROM cost estimates.

From Table X, starting SSGTG's from APU's, in conjunction with new auxiliary subsystems, provides for decisive recurring acquisition cost and weight savings over the baseline HPAS, as well as with hydraulic and electric

Table IX: Subsystem Operational Performance Comparison Matrix

SYSTEM	MISSION	PERFORM- ANCE	USE	EFFECT- IVENESS	OP. MODE	ENVIRON- MENT	SURVIV- ABILITY
SSGTG Starting	Exceeded	Met	Exceeded	Exceeded	Met	Met	Exceeded
MPGT Starting	Deleted	N/A	N/A	N/A	N/A	N/A	N/A
A&B Tank Charging	Met	Met	Met	Exceeded	Met	Met	Met
5/54 Gun	Met	Met	Met	Exceeded	Met	Met	Exceeded
MK 32 Charging	Exceeded	Exceeded	Exceeded	Exceeded	Met	Exceeded	Exceeded
LP Air Backup	Deleted	N/A	N/A	N/A	N/A	N/A	N/A

Table X: NAB 023 ROM Cost/Weight Summary

SYSTEM	NONRECURRING COST	RECURRING COST	RECURRING SAVINGS	WEIGHT	WEIGHT SAVINGS
HPAS	N/A	\$2.3M	N/A	20.4 LT	N/A
HYDRLIC, OPTN #1	\$3.7M	\$1.4M	\$900K	10.2 LT	10.2 LT
HYDRLIC, OPTN #2	\$4.5M	\$2.2M	\$100K	25.6 LT	-5.2 LT
ELECTRIC OPTN #2	\$6.4M	\$1.4M	\$900K	19.0 LT	1.4 LT
APU'S CNFIG #3	\$2.2M	\$1.1M	\$1.2M	5.4 LT	15.0 LT

starting concepts. In terms of Flight IIA Program Ship Construction funds, this translates to a payback within 2 ships, which exceeds the Program objectives for 3 ships payback minimum.

Appendices A, B, and C provide indepth life cycle cost analyses for the baseline Centralized HPAS, as well as for the new dedicated subsystems developed as part of NAB 023/ECP 51-1216. Note that life cycle cost information is provided for the new SSGTG starting system featuring APU's of both the UNI-JASU and Garrett 100-82 designs. As with the ROM cost estimates provided in Table XI, life cycle cost information was also included for auxiliary HP air subsystems. From Appendix A, life cycle costs for the Centralized HPAS, expressed in 1994 dollars, are estimated at approximately \$7.8M for the anticipated 30 year life of the ship. Similarly, life cycle costs for the dedicated subsystems, featuring UNI-JASU's and Garrett 100-82 APU's are estimated at \$4.5M and \$5.1M, respectively. Thus, replacement of the Centralized HPAS with dedicated subsystems, featuring APU's, will afford life cycle savings of \$2.7M to \$3.3M, depending on the type of APU's utilized. Refer to Appendices A, B, and C for assumptions and calculations utilized in deriving these figures.

Armed with detailed system descriptions, a detailed test plan, and above cost/weight impact assessments, PMS 400D approved NAB 023 for inclusion into the lead Flight IIA ship on 11 May 1993; approval was granted with the UNI-JASU as the primary APU choice, with the Allied Signal GTCP 100-82 as backup in the event of schedule or funding difficulties with NAVAIR's UNI-JASU acquisition plan. Upon PMS 400D approval, NAB 023 was redesignated as ECP 51-1216, and became the new baseline configuration for detail design of Flight IIA.

2.5.1 SSGTG Starting System

The new SSGTG starting system featuring a dedicated APU per SSGTG as described in Section 2.4.1 provides considerable improvements in operational performance over the baseline HP air SSGTG starting system. As illustrated in Table X, operational performance characteristics of the new starting concept meet or exceed those developed at the onset of CD and discussed in Section 2.1.1.1.

More specifically, it was originally stipulated that the mission of SSGTG start system should accommodate at least three consecutive SSGTG start attempts, that the SSGTG must

be started and ready to take on electrical load within 5 minutes, and that the new system be capable of supporting SSGTG purging/water-washing without switching to the ship's LP Bleed Air System. As discussed in Section 2.4.1, these mission requirements were exceeded since APU's provide virtually unlimited numbers of SSGTG start attempts, electrical load can be accommodated within 3 minutes, and APU's themselves can supply the necessary compressed air to support SSGTG purging/water-washing.

Relative to performance, detailed calculations were performed, and later validated through APU prototype testing to ensure compliance with SSGTG manufacturer's minimum starting torque requirements; see Section 3.1.1 for more detailed discussion of both the calculations and preliminary test results.

As for operational use and effectiveness (RM&A) requirements, Section 2.4.1 also highlights the new SSGTG start system is capable of supporting a substantial increase (233 verses 150) in APU start cycles with significantly less (less than 1, verses 3) failures per year. In terms of maintainability, the APU's provide an MTTR of 2 hours, verses 25 hours for HP air compressors. As for availability, Table VIII indicated inherent and operational availability for the UNI-JASU APU's to be excellent at 0.986 and 0.85 respectively; the later reflects a design goal and requires a maximum MLDT of 24.5 hours which should be easily accomplished since the UNI-JASU production effort features an extensive logistics support development program by NAVAIR. Relative to Garrett 100-82 APU's, Table VIII further notes that in order to meet an Ao goal of 0.85, that MLDT may not exceed approximately 7 hours; given the Program decision to utilize Garrett 100-82's in lieu of UNI-JASU's for the lead Flight IIA ship, operational availability is a technical concern. In order to alleviate these concerns, SEA 03X34 and BIW are working very closely with NAVAIR to ensure the necessary spares are provided onboard and at designated repair facilities.

Section 2.1.1 requirements/goals pertaining to operating mode (controls), environment, and survivability were also met or exceeded with the new SSGTG start system. As described in Section 2.4.1, the controls concept for the APU's features a one for one replacement with existing HP air starting controls; hence, remote-manual starting from EPCC, MCCS, as well as from SSGTG LOCOP's will be possible. In addition, the capability for automatic starting upon low electric switchboard voltage was retained. Section 3.4.1

details the APU/SSGTG start system controls concept from a human factors perspective. As for environmental requirements, Section 2.4.1 detailed the great lengths taken, via calculations and planned prototype testing, to ensure that APU's would be capable of starting SSGTG's under worse case machinery space environmental conditions. Relative to survivability, provision of a dedicated APU, collocated above each SSGTG, provides for an increase in overall survivability since the forward most SSGTG and APU are now located in the same space. As noted in Section 2.1.1, the HP air bank for starting SSGTG #1 with the baseline starting system was located in an adjacent space.

2.5.2 Auxiliary HP Air Subsystems

Table IX also highlights that substitute auxiliary HP air systems developed for NAB 023/ECP 51-1216 meet and/or exceed all operational requirements and goals first stipulated in Section 2.1.1 with the exception of the MPGT Emergency Starting System. For this unique case, the requirement to retain the secondary/emergency start source was subsequently deleted due to cost constraints and noted improvements to the primary starting source.

Relative to adherence to Section 2.1.2 maintenance concept, Program direction to utilize existing, proven, and supported hardware to ensure adherence to such requirements. Section 2.4.2 details the particular hardware selected.

For consistency with the stated scope and objectives of this paper, an indepth discussion of specifically how each of the operational and maintenance requirements were satisfied for each new auxiliary subsystem will not be presented; rather, a brief discussion of noteworthy highlights relative to Table IX will be provided.

MPGT Emergency Starting - As noted above, the original goal to retain this particular function was revised in view of cost constraints and noted improvements to the primary MPGT starting system; i.e. LP bleed air from operating SSGTG's. This decision was further influenced by poor Fleet experience with the baseline emergency start system and very low use/need of a secondary starting system for MPGT's.

A & B Module Deluge Tank Charging - Section 2.4.2 noted that the replacement pressurization source for charging of the deluge tanks is by dedicated LP air driven booster pumps of the same design as currently used throughout the Fleet for charging 5"/54 caliber gun counter recoil cylinders. While

no specific RM&A data was available for the booster pumps, discussions with users indicate that failures of these relatively simple devices are extremely rare; certainly much less than 3 failures per year and 25 hours MTTR experienced for HP air compressors. Accordingly, it was/is anticipated that there will be a marked improvement in overall RM&A for this particular replacement subsystem. Similarly, given the output capacity of these booster pumps (5 scfm), in conjunction with the small volume of compressed air required (1.9 cubic feet), the requirement to recharge a tank in approximately 5 minutes was met.

5"/54 Caliber Gun Gas Ejection System - In terms of actual modifications to the gas ejection piping system, Section 2.4.2 noted that the replacement concept developed for NAB 023/ECP 51-1216 features only a change to the source of compressed air pressurizing the existing 6 cubic foot air flask. The selection of a small dedicated HP air compressor having superior reliability, maintainability, and support characteristics far exceeds the effectiveness requirements originally stipulated for this system in Section 2.1. Further, that the new HP air compressors are to be collocated in the same space as the 6 cubic foot air flask provides a marked increase in overall subsystem survivability.

MK 32 Torpedo Impulse Flasks Charging - Table IX indicates that nearly all operational requirements were exceeded as a result of NAB 023/ECP 51-1216 replacement efforts. In comparison to the baseline configuration, which featured only a small (3/8") HP air pipe extending from Main Machinery Room #2 to the torpedo charging panel located on the 01 Level, the new system offers significant improvements in mission function support capability, performance, use, RM&A, environmental, and survivability requirements. Such improvements are made possible by virtue of the fact that both a dedicated HP air compressor (of same proven design as specified for 5"/54 gun system) and a dedicated 6 cubic foot HP air flask, are provided and are to be virtually collocated with the torpedo air charging panel.

LP Air System Backup - While it was agreed at the onset of requirements definition (Section 2.1) that this particular function would be deleted with the removal of the Centralized HPAS, subsequent technical investigations concluded that LP air services impacting restoration of shipboard electrical power were limited to the pneumatic controls supporting the SSGTG's themselves. Accordingly, Section 2.4.2 noted that a small (5 cubic foot) dedicated

air receiver is to be provided for this service. Thus, the original requirements were met.

2.6 Synthesis and Definition

Immediately upon approval of ECP 1216 began the arduous task of translating the concepts developed during CD into detail specification requirements for inclusion into the Flight IIA RFP contract package; this tasking was made more difficult due to the short time span available (approximately 4 months), the sheer magnitude of the changes required, and concurrent Program activity (e.g. briefings to INSURV and the FLEET, ongoing cost reduction initiatives, and LBES test site preparation). Review of SEA 03YD file records indicates there were no fewer than 75 significant events (design reviews, presentations, technical liaison visits and/or written pieces of correspondence) relating directly to development of the ECP 1216 contract package that occurred from 11 May 93 (ECP 1216 approval) to the final ECP 1216 reading session on 22 September 93. Further, SEA 03YD records indicate approximately 100 additional such entries for the time period between RFP release (2 November 1993) and the second Flight IIA lead ship contract award deadline of 25 March 1994. As noted in Section 1.3.2, the original contract award date was set for mid-January 1994; ultimately lead ship contract award did not occur until late June 1994. This 6 month delay resulted in difficulties experienced in reviewing and adjudicating the shipbuilders' bid packages.

Rather than "attempt" to trace each and every significant event and specification requirement, which would be not only be superfluous but a near impossible endeavor, Tables XI and XII have been prepared to both organize and illustrate the net results of ECP 1216 contract package design definition and synthesis effort; intrinsic with development and review of the contract package documentation listed in these tables was iterative application of the systems engineering process first described in Figure 1. For example, after initial ECP 51-1216 contract package approval in September 1993, ever present Flight IIA cost reduction initiatives and ongoing ECP 51-1216 design reviews surrounding such areas as sizing of CO2 flasks for APU module fixed flooding systems, refinement and simplification of APU controls, and simplification of the dedicated HP air compressor plant piping schemes, resulted in reanalysis/redefinition of associated requirements, tradeoff studies, concept reselection, and ultimately concept design definition and synthesis. References (ab) and (ac) document such efforts.

Table XI: List of Impacted Specifications

SECTION	TITLE
042	General Administrative Requirements
072	Passive Protection
073	Noise, Vibration, and Resilient Mounts
076	Reliability and Maintainability
085	Drawings
095	Testing Requirements
180	Foundations
200	General Requirements for Machinery Plant
202	Machinery Centralized Control System
234	Propulsion Gas Turbine Engines
256	Seawater Circulating and Cooling Systems
259	Combustion Intake and Exhaust Systems
313	Storage Batteries and Service Facilities
314	Electric Power Supply/Conversion Equipment
320	Electric Power Distribution Systems
430	Interior Communication Systems
436	Electrical Alarm, Safety, and Warning Sys.
502	Auxiliary Machinery (SSGTG's and APU's)
504	Instruments and Instrument Boards
506	Thermal Insulation for Machinery and Pipe
532	Fresh Water Service Systems
542	JP-5 Fuel Systems
551	Compressed Air Systems
555	Fire Extinguishing Systems
602	Hull Designating and Marking
671	Special Stowage Arrangements

Table XII: List of Drawings

DRAWING NO.	DRAWING TITLE
802-5774042(AA)	Machinery Arrangement
802-5774043(L)	Generator Room Arrangement
802-5774064(AK)	Alarm Indicating Systems
*802-6215480	Specification for HP Air Compressor
*802-6337224	Specification for APU
802-5774129(V)	Forward A-Size Weapon Zone Arrangement
802-5774130(W)	Aft B-Size Weapon Zone Arrangement
802-5959353(AA)	MIL-STD-777D Modified For DDG 51 Class
802-6215563(Y)	Testing Index and Numbering System
802-6337232	Specification for HP Air Compressor

Note: Drawings shown with an asterisk are new drawings developed by SEA 03YD and SEA 03X34

Referring to Tables XI and XII, approximately 26 different detail specification sections and 8 contract drawings were impacted as a result of ECP 51-1216; these contract requirements are contained in the consolidated Flight II Detail Ship Specification package (reference n as modified for Flight IIA). In addition, two complete sub-tier specifications (Project Peculiar Documents, PPD's) were developed for the APU's and new dedicated HPAC's, references (ad) and (ae), respectively. Altogether, the various modifications to baseline detail specifications and the addition of specifications for APU's and HPAC's resulted in over 350 pages of contract requirements for ECP 51-1216 alone.

It is important to highlight a rather significant Flight IIA programmatic decision which had considerable impact in the development and content of ECP 51-1216 specification requirements. Briefly, after careful reconsideration of the UNI-JASU's development schedule, unavailability of necessary technical data to initiate detail design development, and review of adverse impacts to shipbuilder production schedules previously discussed in Section 2.2.1, SEA 03D35 and PMS 400D8 directed (August 93 Design Review) that ECP 51-1216 proceed with the GTCP 100-82 APU in lieu of the UNI-JASU. So as to minimize costs associated with retrofitting the UNI-JASU, when/if it becomes available, it was further directed that the APU module design and interface systems be standardized in as much as possible.

At the risk of appearing boastful, development of the detail specifications and PPD's was a substantial effort, and is a tribute to the "focus" and technical capabilities of the ECP 1216 contract package preparation team comprised principally of SEA 03YD, SEA 03X34, M. Rosenblatt & Son, Inc., and BIW. These achievements are made more remarkable when one considers the short time available, the sheer scope of changes required, concurrent Program demands, and the fact that post-RFP modifications have been, for the most part, limited to yet further Program cost reduction initiatives. Without a doubt, the flexibility, appreciation, and confidence provided by Flight IIA management personnel, namely PMS 400D8, SEA 03D35, and SEA 03D6 contributed to the success of this effort. Clearly, involvement in ECP 1216 has been a unique professional opportunity of which I'm proud to have been a part of.

3.0 HUMAN FACTORS CONSIDERATIONS

Human factors considerations involving such areas as

operator safety, accessibility, and operability had a pronounced affect on the physical arrangement and configuration of each new subsystem. Moreover, a fundamentally important human factors attribute, functional effectiveness, was considered throughout the design process; functional effectiveness refers to the ability of a system to perform the function in which it was intended.

Figure 2, first introduced in Section 1.1, represents the basic human-machine interface model considered in the design of each new subsystem; this particular model formulates the essence of human factors in that the human operator must be considered an integral part of the overall design of each system. The significance of this statement is better understood when one considers, for example, the design development of the controls systems for the SSGTG Starting System, and the Auxiliary HP Air Systems as well. For each system, the human operator (ship's force) is required to activate the particular system (work station) via some type of input device (e.g. control panel or valve assembly) to achieve the desired output. For each subsystem, the human operator and associated control system are subjected to specific ambient conditions and/or limitations (e.g. lighting and temperature) and task demands (e.g. push button, read gage, or manipulate a valve assembly) which influence the design of the system. Similarly, for other human factors attributes such as operator safety and accessibility, the utility of the model can be easily visualized and understood for each particular application.

The remaining subsections will overview human factors considerations involving functional effectiveness, operator safety, accessibility, and operability. Consistent with the stated scope and emphasis of this paper, indepth discussions of each will be provided for the SSGTG Starting System only. For remaining Auxiliary HP Air Subsystems, very brief discussion/highlights will be provided.

3.1 Functional Effectiveness

3.1.1 SSGTG Start System

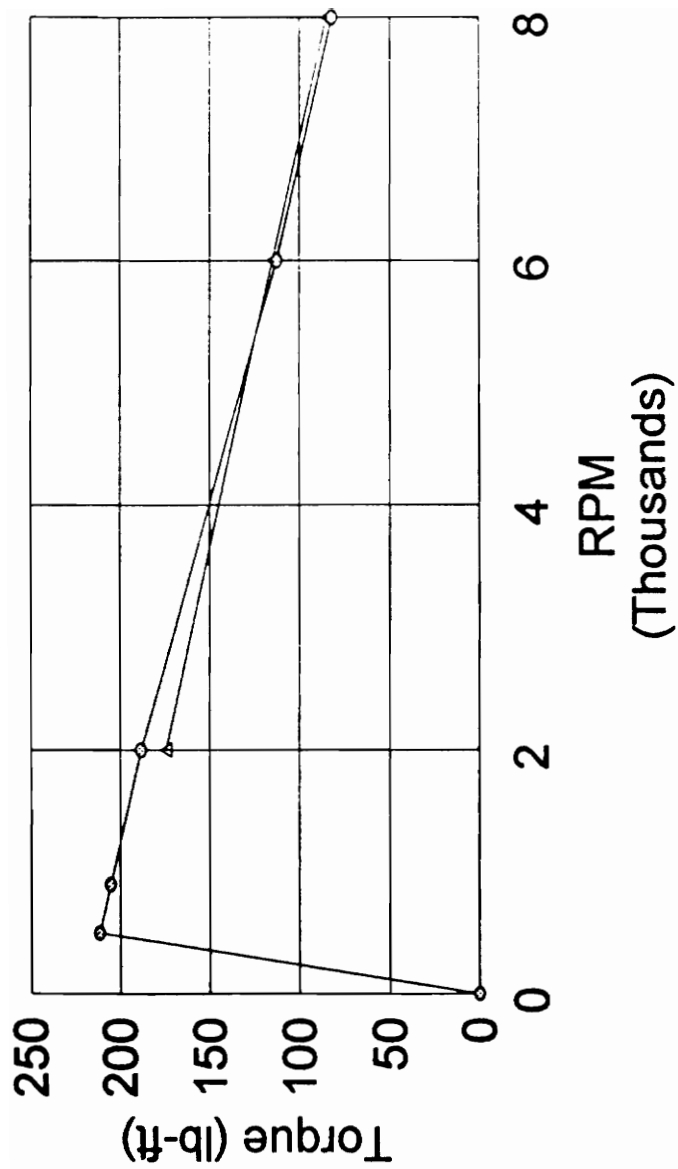
Functional effectiveness of the new SSGTG Starting System, featuring dedicated APU's, was first demonstrated through simplistic calculations described in Section 2.4.1, and later through preparation of very detailed calculations and prototype validation testing of a ship-like APU/SSGTG start system; the calculations and test results were forwarded to the Flight IIA Program by SEA 03YD during the 7 April 1994

ECP 51-1216 Design Review via reference (af).

The calculations feature an iterative calculation process employing Quatro Pro spreadsheets for determining piping system parameters (pressure, flow, and temperature) and various APU engine performance curves and SSGTG manufacturer's minimum starting torque curves, to ascertain overall start system performance. Primary inputs to the program are fluid flow and thermodynamic descriptions of the start piping system, as well as design values for ambient temperature and APU/SSGTG ducting losses. The calculation procedures were developed by SEA 03YD contractor (M. Rosenblatt & Son) under the direction of Allied Signal Corporation (SSGTG starter manufacturer) and SEA 03YD.

Figure 28, extracted from reference (af), illustrates the predicted performance of the new SSGTG start system for the worst case design conditions of 120 degrees F ambient temperature and 10 inches WG ducting losses for both the APU and SSGTG. From the figure, predicted performance for this conservative worse case condition is slightly below minimum requisite torque, however, it is anticipated that the planned (Flight II and follow) installation of orifices in the fourteenth stage bleed valves of the SSGTG compressor section will decrease the drag created by the SSGTG engine during startup; the net effect will be starting torques above the minimum required values. In any event, it should also be understood, that prototype start testing performed at NAVSSES Philadelphia has indicated the calculations to be somewhat conservative, and that SSGTG starts are well below the 60 second automatic start cutout feature associated with the SSGTG start logic.

Figure 29 and 30 are provided to illustrate partial results of the prototype testing performed at NAVSSES; the former clearly illustrates actual system performance exceeds minimum requisite starter torque requirements, and the later reveals SSGTG starts are achieved in approximately 30 seconds from start initiation. Reference (af) also forwarded a comprehensive test data package containing approximately 144 plots for the various test configurations tested. It is worthy of noting that the test configuration featured automated data collection of approximately 55 different APU, SSGTG, and piping system parameters. In addition to verification of meeting minimum torque, the testing provided invaluable data for the prevention of backflow of SSGTG exhaust air into an idling APU; this data led to the requirement for proper sequencing of the automatic APU intake and exhaust dampers.



△ procedure (120°F Day) ○ min required torque

FIGURE 28: SSGTG STARTING TORQUE COMPARISON

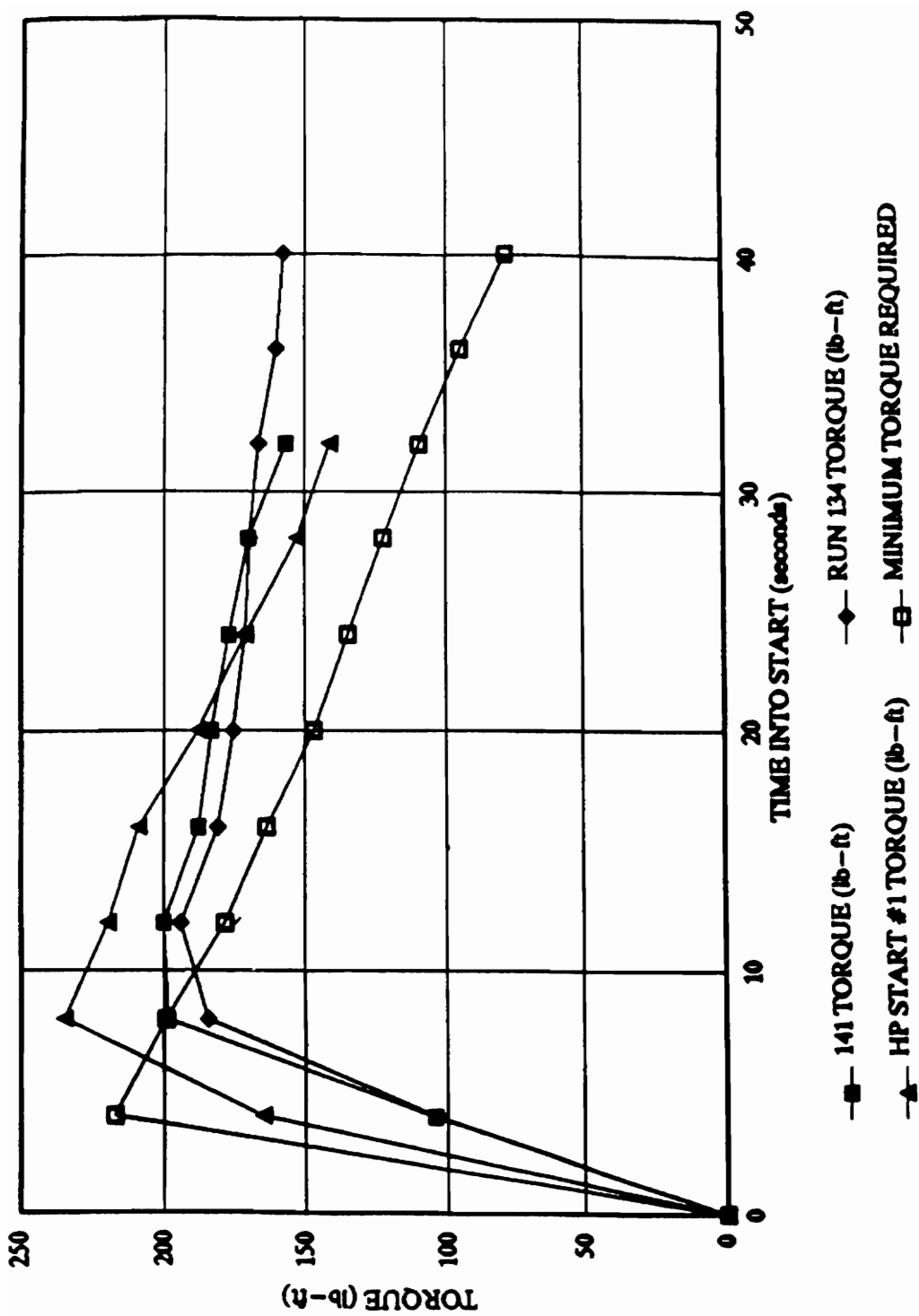


FIGURE 29: TIME VERSE SSGTG STARTING TORQUE

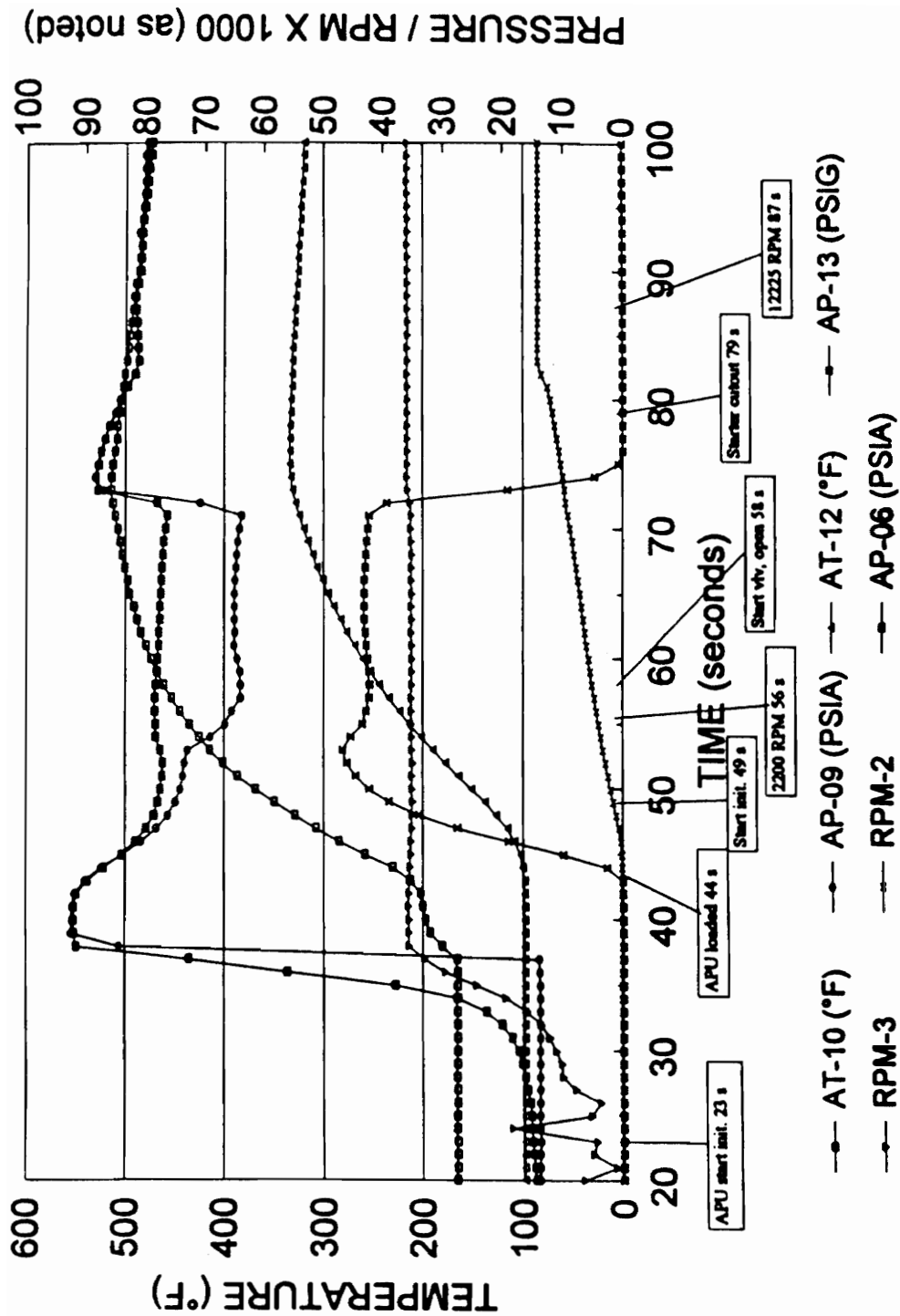


FIGURE 30: SAMPLE SSGTG START TEST DATA PLOT

3.1.2 Auxiliary HP Air Subsystems

MPGT Emergency Starting Air System - As previously noted in Section 2.4.2, this particular service was deleted from the Flight IIA design. Relative to functional effectiveness, INSURV expressed initial concern with this decision; it was contended that the emergency MPGT start source is mandatory for post shutdown MPGT fuel nozzle purging in a dark ship condition. Subsequent investigations by SEA 03YD and SEA 03X32 verified that nozzle fuel purging is only required if the MPGT's are not restarted within 10 minutes, and that the APU's are capable of restarting the SSGTG's and regaining ship's electrical power within 2 minutes. This response was validated through consultation with the MPGT manufacturer and forwarded to the Flight IIA Program via reference (ag).

Inherent survivability attributes of the ship's LP Bleed Air Starting System, improvements made to SSGTG starting, and consideration of low anticipated use/need for an emergency MPGT starting air source, influenced the Program's decision to eliminate this service from Flight IIA. Accordingly, no other human factors issues were considered for this service.

A & B Module Deluge Tank Charging - The functional effectiveness of the selected system to recharge each of the small 1.9 cubic foot deluge tanks via portable LP air driven booster pumps was satisfied since the 5 scfm booster pumps are capable of fully charging the tanks from atmospheric pressure in approximately 5 minutes. The time to recharge can be calculated utilizing the simplistic algorithm contained in reference (ah):

$$T = V \times (P1 - P2) / (14.7 \times Q)$$

where:

- T = recharge time, minutes (5.8)
- V = tank volume, cubic feet (1.9)
- P1 = initial tank pressure, psia (239.7)
- P2 = residual tank pressure, psia (14.7)
- Q = charging rate, scfm (5)

5"/54 Caliber Gun Gas Ejection System - The functional effectiveness of the replacement gas ejection system depicted in Figure 26 to support firing of all 600 rounds in the magazine without recharging from its dedicated HP air compressor was satisfied through retention of the dedicated six cubic foot HP air flask. By reference (ai) calculations, which are similar to above, only a 5.4 cubic foot HP air

flask is required for 600 rounds; thus the standard 6 cubic foot flask exceeds the requirement.

Further, inherent increases in survivability afforded by collocating the new HP air compressor with the 6 cubic foot HP air flask, coupled with increases in HP air compressor RM&A, served to increase the functional effectiveness of the replacement gas ejection system.

MK 32 Torpedo Tube Impulse Flask Charging - Section 2.5.2 detailed the merits of the replacement impulse flask charging system featuring the addition of a dedicated HP air compressor and 6 cubic foot HP air flask. Relative to functional effectiveness, calculations contained in reference (ag), indicate that the new charging system will be capable of charging the four spare torpedo impulse flasks in addition to the six located on the 01 level in the torpedo holding racks, as well as residual margin for periodic testing of torpedoes; this clearly exceeds the original requirements stipulated in Section 2.1.2. Further, as the baseline charging system was not provided with a dedicated HP air flask, the replacement system features increased survivability.

Ship Service LP Air System Backup - Section 2.5.2 noted that this particular service was deleted, and that functional effectiveness for ensuring restoration of shipboard electrical power was satisfied through the addition of a dedicated 5 cubic foot LP air receiver SSGTG pneumatic controls. Given that the flow required for SSGTG pneumatic controls is less than 1 scfm, the dedicated receiver provided for each SSGTG will support approximately 10 minutes of SSGTG control air. This exceeds the 2 minute maximum time specified for restoration of shipboard electrical power; hence functional effectiveness is satisfied. as the dedicated receivers do not require human operation, no further human factors issues were considered.

3.2 Operator Safety

3.2.1 SSGTG Starting System

Section 2.4.1 noted that the APU's are to be installed in protective enclosures. The primary rationale for the enclosure is operator safety; principally protection from catastrophic failure of the APU, excessive APU operating noise, and fire containment. Secondly, the enclosure and associated mounting system serves to reduce both the structureborne and airborne noise levels to values which

will not compromise either machinery space operational noise limits or the ship's acoustic signature. In addition, the enclosures serve to preclude damage to other vital equipment and controls located adjacent to the APU's within the machinery spaces.

APU's, as previously noted, are small gas turbine engines capable of providing relatively large volumes of LP compressed air. Inherently, gas turbine engines operate at very high rotational speeds and temperatures. The Garrett Model 100-82 APU engine, for example, is an isochronous engine which operates at approximately 37,000 rpm with exhaust gas temperatures in excess of 900 degrees F. With respect to the former, gas turbine blade containment is a serious safety concern, addressed in the APU specifications by specifically requiring each APU enclosure be provided with reinforced steel around the periphery of the gas turbine engine section. In addition, the requirement for safety markings on the exterior (top and sides) of the APU enclosures to denote the location of the gas turbine's planes of rotation, was also included in the specifications.

APU's, by virtue of large air flows processed through the gas turbine engine (approximately 8 lb/sec for GTCP 100-82) and high rotational speeds are extremely noisy in operation. Certainly, without an enclosure and appropriate mounting system, both airborne and structureborne noise levels would exceed maximum acceptable limits (OSHA and Flt IIA detail specification requirements) for personnel safety and ship's acoustic signature. Accordingly, Section 073 of the detail specifications requires that the APU enclosure and mounting assembly not exceed 100 dBA when measured in accordance with MIL-STD-740B. Note that LBES testing of the GTCP 100-82 has demonstrated that in excess of three inches of acoustic insulation will be required to meet these limits. Similarly, the Flight IIA ship specifications requires that the structureborne noise levels from the APU enclosure and mounting system not exceed those permitted for operating SSGTG's when measured in accordance with MIL-STD-740B. Figure 31 illustrates the mounting arrangement for the APU enclosure. Note that in order to meet both noise and Grade A shock requirements that a combination shock/noise mount will be required.

As shown in Figure 32 arrangement of the LBES test site, the APU's are to be located almost directly over the top of the companion SSGTG's. Fuel for the APU's is to be turbine fuel, Grade JP-5, in accordance with MIL-T-5624. Given the close

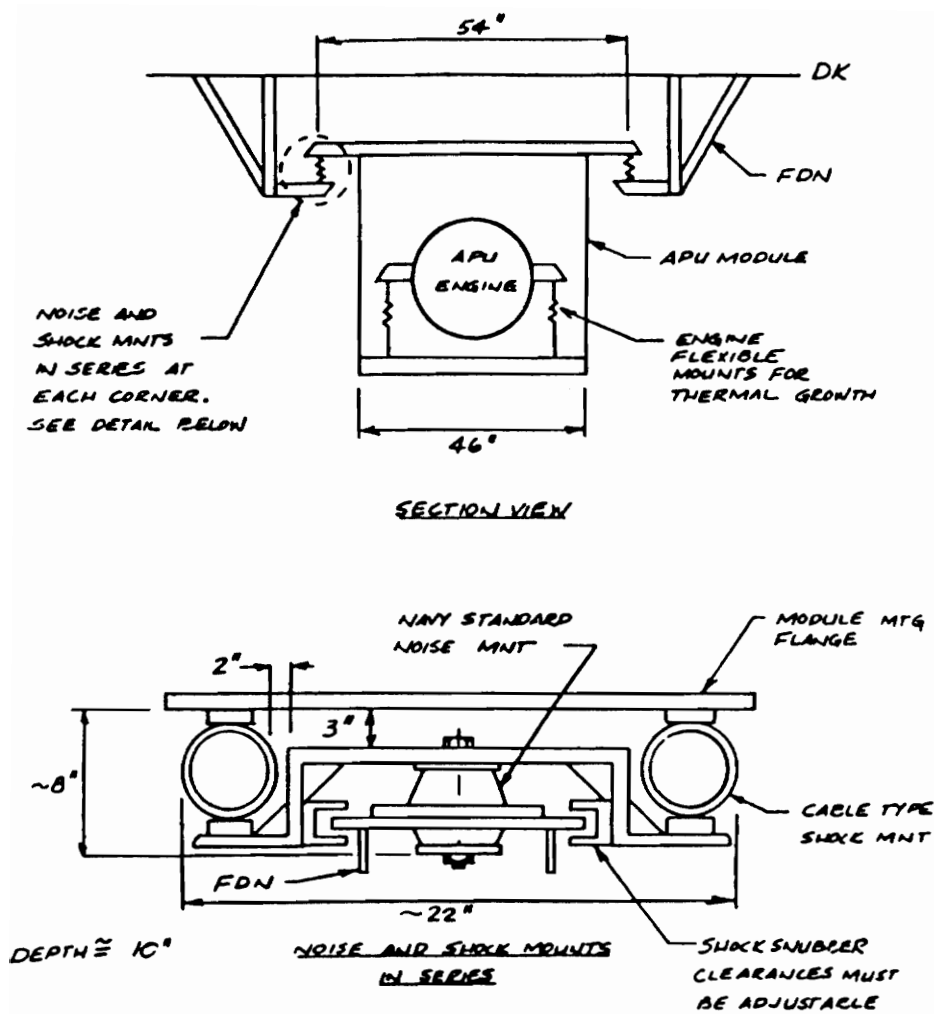


FIGURE 31: APU MOUNTING ARRANGEMENT

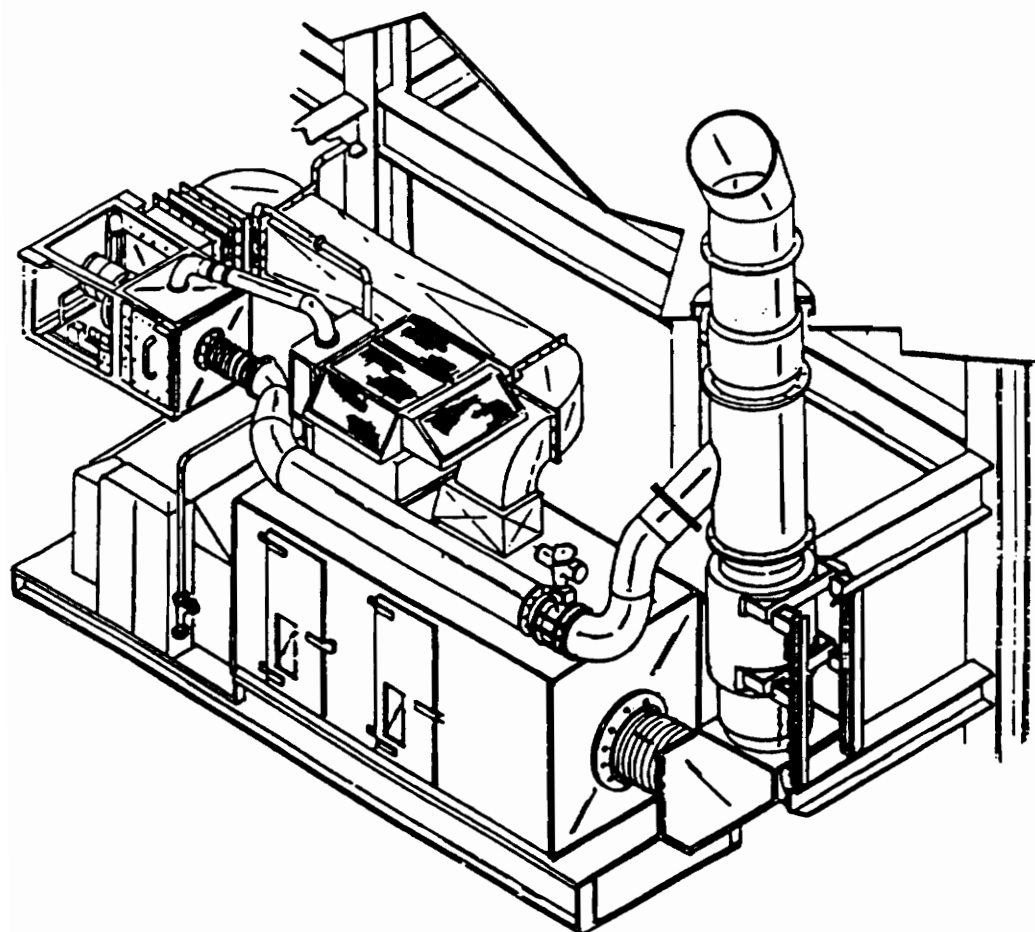


FIGURE 32: LBES APU/SSGTG ARRANGEMENT

proximity of the APU's to SSGTG's and other vital machinery and controls, coupled with the fact that APU turbine casing and exhaust ducting temperatures normally exceed the flash point (140 degrees F) of JP-5, the enclosure is an absolute must preventative measure for fire containment.

In addition to passive fire containment via the enclosure proper, protection for human operators, adjacent equipment, and the APU's themselves is provided by automatic CO2 fire detection and extinguishing systems. Briefly, the Flight IIA detail specifications require that each APU enclosure be provided with a dedicated CO2 fixed flooding system, complete with optical fire detectors, local/remote alarms and controls, and automatic APU shutdown features. Each enclosure is to be served by two 15-pound CO2 cylinders, one primary and the second a reserve supply. In general, operation of the APU enclosure fixed flooding systems is semi-automatic in that human actuation, either locally at the APU control operating panel (ACOP) or remotely at Machinery Control Station (MCS), is required upon receipt of a fire detection signal. Once manually activated, remote signals automatically shut off fuel to the APU and close associated APU combustion air intake, exhaust, and module cooling dampers. A thirty second time delay is provided to delay release of CO2 into the enclosure until the APU has spooled down and the module dampers are fully closed. Further, the APU specifications requires additional safety measures such as APU module door interlocks which prevent the release of CO2 when the door latches are not closed, such as during maintenance.

3.2.2 Auxiliary HP Air Subsystems

A & B Module Deluge Tank Charging - Operator safety was an important consideration in the decision to replace the HP air piping with safer, LP air piping. By reference (y), the cognizant NAVSEA LCEM for the VLS system relayed its approval for the new charging system depicted in Figure 25 on the basis of improvements in functional effectiveness, as well as operational safety associated with manually charging the deluge tanks with LP, vice HP, air.

5"/54 Caliber Gun Gas Ejection System - In view of the potential energy associated with HP air piping systems and inherent personnel hazards, considerable attention was given to operator safety in the design of the replacement gas ejection system. Examples of the safety provisions included in the detail specifications include requirements for pressure relief valves and overpressure protection switches

in the compressor discharge piping, and an acoustical enclosure surrounding the HP air compressor to reduce operating noise levels to below 115 dBA; this being the maximum exposure limit permitted by both OSHA and the Section 073 of the detail specifications. Inclusion of an acoustical enclosure will also alleviate concerns with hot compressor head surfaces and provide operator protection from the fan cooling drive assembly.

In addition, the HP air compressor specifications require that the compressor be designed to meet Grade A shock and withstand shipboard vibrations, as well as standard/general design guidance for such safety concerns as sharp edges, exposed moving parts, and insulation of surfaces above 125 degrees F.

MK 32 Torpedo Tube Impulse Flask Charging - Section 2.4.2 highlighted human factors safety concerns with the nitrogen charging cart scheme originally proposed by SEA 03YD; ultimately these concerns led to disapproval of utilizing portable nitrogen bottles for charging of the impulse flasks. Subsequently, the decision was made to utilize a dedicated HP air compressor and 6 cubic foot HP air flask, identical to the design specified for the new gas ejection system. Consequently, the Flight IIA detail specifications require the same safety provisions as noted above for the gas ejection system.

3.3 Accessibility

3.3.1 SSGTG Start System

Section 3.2.1 highlighted that concerns with operator safety and protection of adjacent machinery were the driving issues behind APU enclosures. While the requirement for enclosures is clearly evident, the existence of enclosures themselves raises other human factors concerns; principally, accessibility for maintenance and repair. To this end, special human factors considerations were included in the development of the APU specifications for the design of the APU enclosures.

Figure 32, prepared by NSWC (formerly NAVSSES) to support APU testing at LBES, provides a three-dimensional arrangement drawing of the APU/SSGTG configuration developed for Engine Room No. 2. Note that gas turbine combustion inlet air is taken from the space at LBES, vice the weather on a ship, hence the LBES test site is not a precise ship-like arrangement in all regards. Though not specifically

shown, access to the enclosure should be accomplished with relative ease since the bottom of the APU enclosure begins less than three feet off the First Platform level grating which surrounds the associated SSGTG; a similar situation exists for the other APUs in Auxiliary Machinery Room No. 1 and the Generator Room. To preclude burning hazards to personnel, the APU specifications further require the APU enclosures and ducting to be insulated to limit exterior surface temperatures to 125 degrees F.

Accessibility for maintenance and repair of the APU is to be provided via hinged (lockable in open and closed positions) doors and removable panels; their size and number in turn being driven by explicit MTR requirements. More specifically, the APU specifications requires that any preventative and corrective maintenance actions be performed, assuming capabilities of the 5th percentile female through 95th percentile male of the USN's maintenance population per MIL-STD-1472, within two continuous hours. These requirements apply to corrective and preventative repairs/replacements performed at both the organizational or intermediate levels of maintenance. Further, the APU specifications mandate these requirements to be demonstrated via a maintainability demonstration of the APU located within its enclosure. Specifically, the maintainability test is to be in accordance with task 301 of MIL-STD-470, test method 9 of MIL-STD-471. A minimum of 50 tasks are to be demonstrated.

As for complete APU engine removal, considerable attention was also given to development of ECP 1216 contract requirements for the APU and associated enclosure designs. For example, Section 095-502 of the Flight IIA detail specifications requires that the lead shipbuilder develop detailed removal route drawings and that an actual APU removal demonstration be conducted for APU #3. Section 095-502 requires that the APU be removed from its mounts within the module, transported through the ship, placed on the main weather deck, and then returned to its mounts within a total time not to exceed 32 continuous hours. Intrinsic in the total time measurement is the time required to make necessary disconnects, the installation of shipping/unshipping equipment, and reassembly and installation of the APU to full running condition. APU #3 was purposely selected as the Generator Room in which it is to be located is the tightest machinery space on the ship. It is worthy to also note that the most likely removal

routes for the APU's will be the same routes already developed for the SSGTG's.

3.3.2 Auxiliary HP Air Subsystems

A & B Module Deluge Tank Charging - Accessibility for manual operation of the LP air driven booster pump and flexible hose assemblies was a concern in the design of the replacement deluge tank charging system. To virtually guarantee acceptable accessibility, BIW was tasked by SEA 03YD to ensure sufficient space availability adjacent to each deluge tank; this was affirmed by the shipbuilder. Additionally, the detail specifications require that all components (e.g. booster pump, fittings, hoses, and valves) be located together and attached to the bulkhead adjacent to the associated deluge tanks.

5"/54 Caliber Gun Gas Ejection System - The Flight IIA specifications were specifically developed to ensure satisfactory accessibility for maintenance, repair, and replacement of the dedicated HP air compressors serving the replacement gas ejection system. For example, the specifications require that the compressors be designed and located such that compressor repairs, including complete replacement, can be accommodated within two hours; various tests are included for the shipbuilder to demonstrate compliance with such requirements.

MK 32 Torpedo Tube Impulse Flask Charging - As with the gas ejection compressor system, the torpedo tube impulse flask charging system is automatic in operation via pressure switch control (see Figure 27), hence accessibility for human operation is not a great concern. However, accessibility for compressor maintenance, repair, and replacement is, and identical requirements were stipulated for the impulse charging system as noted above for the new gas ejection system. It is also worthy of noting, that in conjunction with above noted portability requirements, SEA 03YD included the requirement for a complete spare HP compressor plant be provided for use in the event of failure to either HP air compressor.

3.4 Operability

3.4.1 SSGTG Start System

As previously noted in the Introduction/Problem Statement of this paper, the principle objective of the Flight IIA Program was/is to incorporate necessary warfighting

capability upgrades into the baseline ship without a net increase in overall acquisition cost. For any recent ship design, experience has taught that one of the largest cost drivers for any change is that associated with controls; in particular those modifications impacting software and documentation of the ships centralized electronic controls systems. Consequently, considerable care was taken in the development of the controls philosophy for the new APU start concept to ensure that it is both technically acceptable and affordable.

Figure 33 illustrates the general controls philosophy and MCCS interfaces for both the baseline HP starting air system and the new APU starting concept. From an operational perspective, the technical decision was made very early in the development of ECP 51-1216 not to accept a reduction in controls capability from the baseline system; as previously noted in Section 2.4.1 this decision actually enhanced the affordability of the APU concept relative to others analyzed since resultant Machinery Central Control System (MCCS) software modifications were minimized. Briefly, both the baseline and APU start systems feature the capability to start SSGTG's locally via SSGTG local control operating panels (LOCOPs) and remotely from either nearby SSGTG electrical switchboards or from the Electric Plant Control Console (EPCC) located on the damage control deck in the Machinery Control Station (MCS). For remote SSGTG starts, each starting air system provides for fully automatic SSGTG starts, which includes automatic sequencing of necessary control valves and APU starting/shutdown, whereas local SSGTG starts permit either semi-automatic or fully automatic SSGTG starts. For the switchboards, automatic SSGTG starts are provided as well as automatic dead bus starts, the later being activated automatically when the electrical voltage at the associated switchboard drops below approximately 220 volts.

Figure 34, modified from reference (m), illustrates the affected area of the EPCC for SSGTG starting. Note from a crew operator's perspective, that selection and execution of SSGTG starts from APUs will be virtually identical to the baseline HP air system; the only difference being that the relabeling of the lower left hand start air sources (HP air or Bleed Air) will be required (APU or Bleed Air). Otherwise, remote automatic SSGTG starts from EPCC will be accomplished the same as the baseline system, wherein the operator selects the appropriate starting air source (APU or Bleed air), ensures that the green light circuit indicating unavailability of the engine does not light, and then

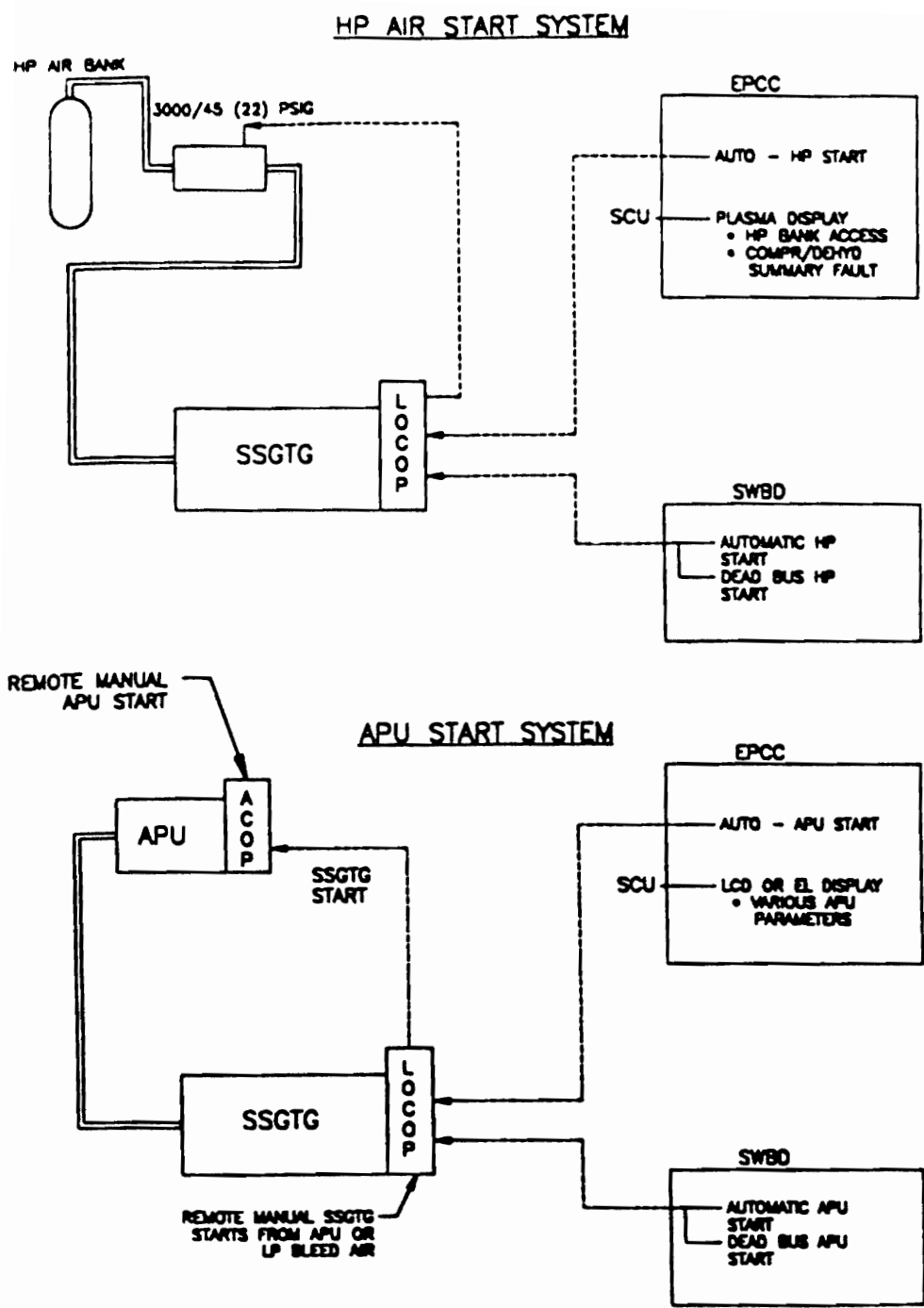


FIGURE 33: MCCS INTERFACES

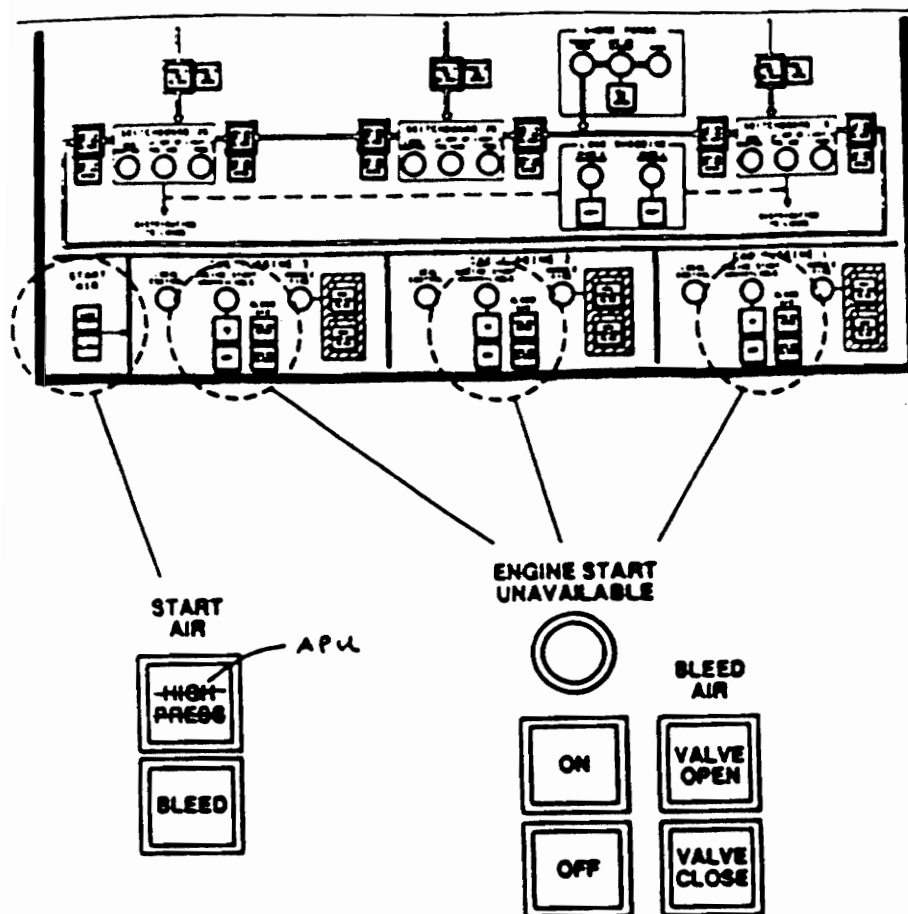


FIGURE 34: EPCC MODIFICATIONS

depresses the ON pushbutton to initiate the desired SSGTG start.

Relative to remote monitoring of the APU from EPCC, Section 202 of the Flight IIA detail specifications provides an extensive listing of the various control and monitoring signals required to interface between EPCC and the local APU control operating panels (ACOPs). At this particular stage of the Flight IIA design, display of these signals is anticipated to be directly on the EPCC via electroluminescent or liquid crystal display panel. Figure 35 is provided to shown the anticipated location of the APU display panel.

The preceding paragraphs have provided a very generalized description of the controls philosophy for both the baseline and new APU starting air concepts, as well as a glimpse of the many human factors issues involving operability and readability of APU controls from EPCC. The remainder of this section will briefly address development of the local controls concept at the ACOP's.

As previously noted, local control of SSGTG starts for the baseline system is accomplished locally at the SSGTG LOCOP's, these local panels are located adjacent to the associated SSGTG's. Given that starting of SSGTG's for Flight IIA will necessitate/involve preceding SSGTG starts with the starting of APU's, the logical location of the ACOP's is immediately adjacent to the LOCOP's; the APU specifications were developed accordingly. Though a Figure of the LOCOP's has not been specifically provided, the starting air portion is very similar to that illustrated for the EPCC by Figure 34, and relabeling of new starting air sources will be required for the LOCOP's as well. As also previously discussed, semi-automatic control/operation of the APU's will also be provided locally at the ACOP's to permit separate starting and operation of the APU's for such tasks as maintenance and water washing, as well as for manual remote SSGTG starts and fully automatic SSGTG starts. This "added operational dimension" raises additional, yet very interesting, human factors concerns involving the design and layout of the ACOP's.

Utilizing reference (b) and lessons learned from the APU test site at NAVSSES for guidance, Figure 36 was developed by SEA 03YD as a sample ACOP configuration; this drawing is currently under review by SET. Applying reference (b) logic regarding functional separation and arrangement of the various control parameters involved, Figure 36 was developed

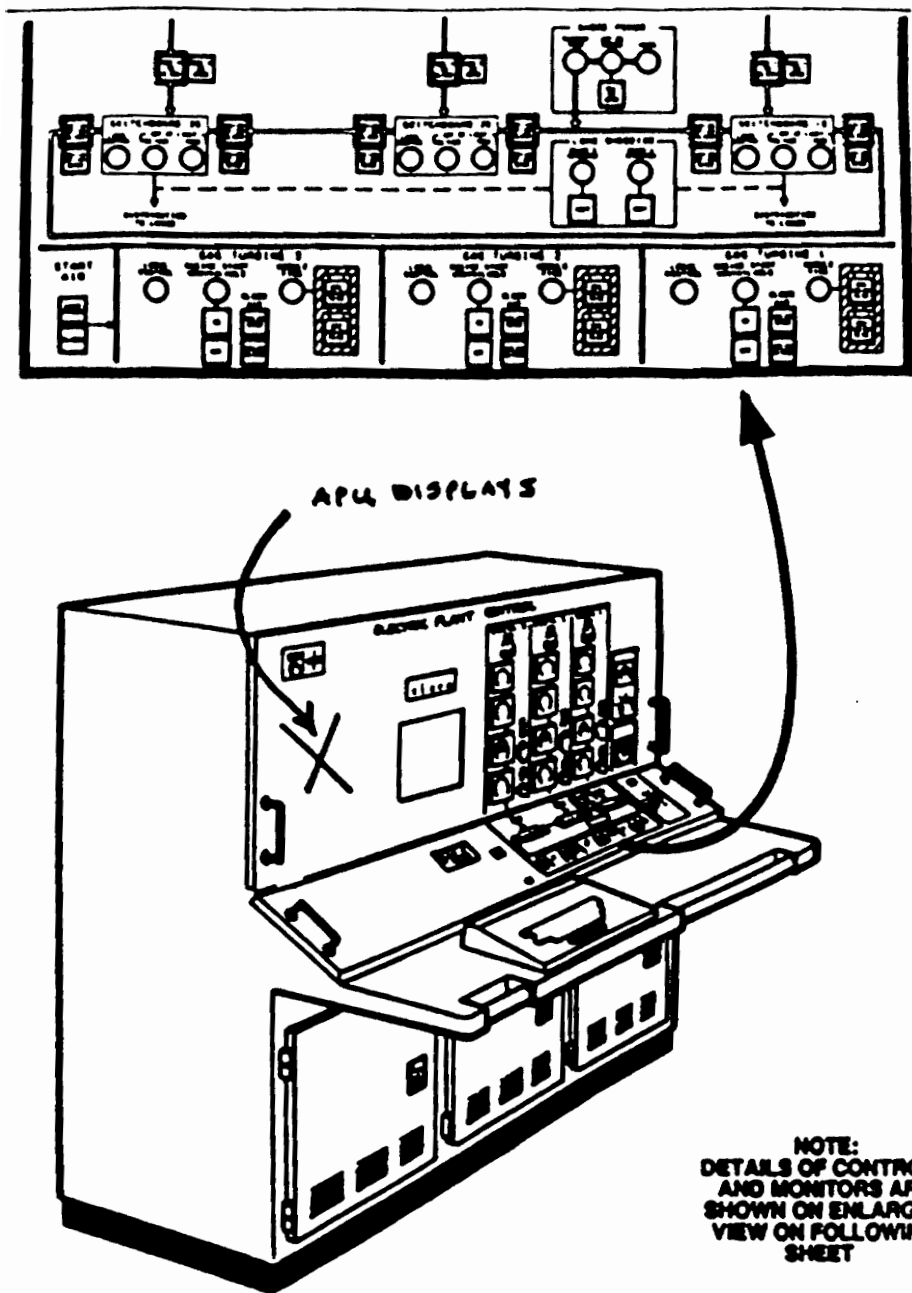
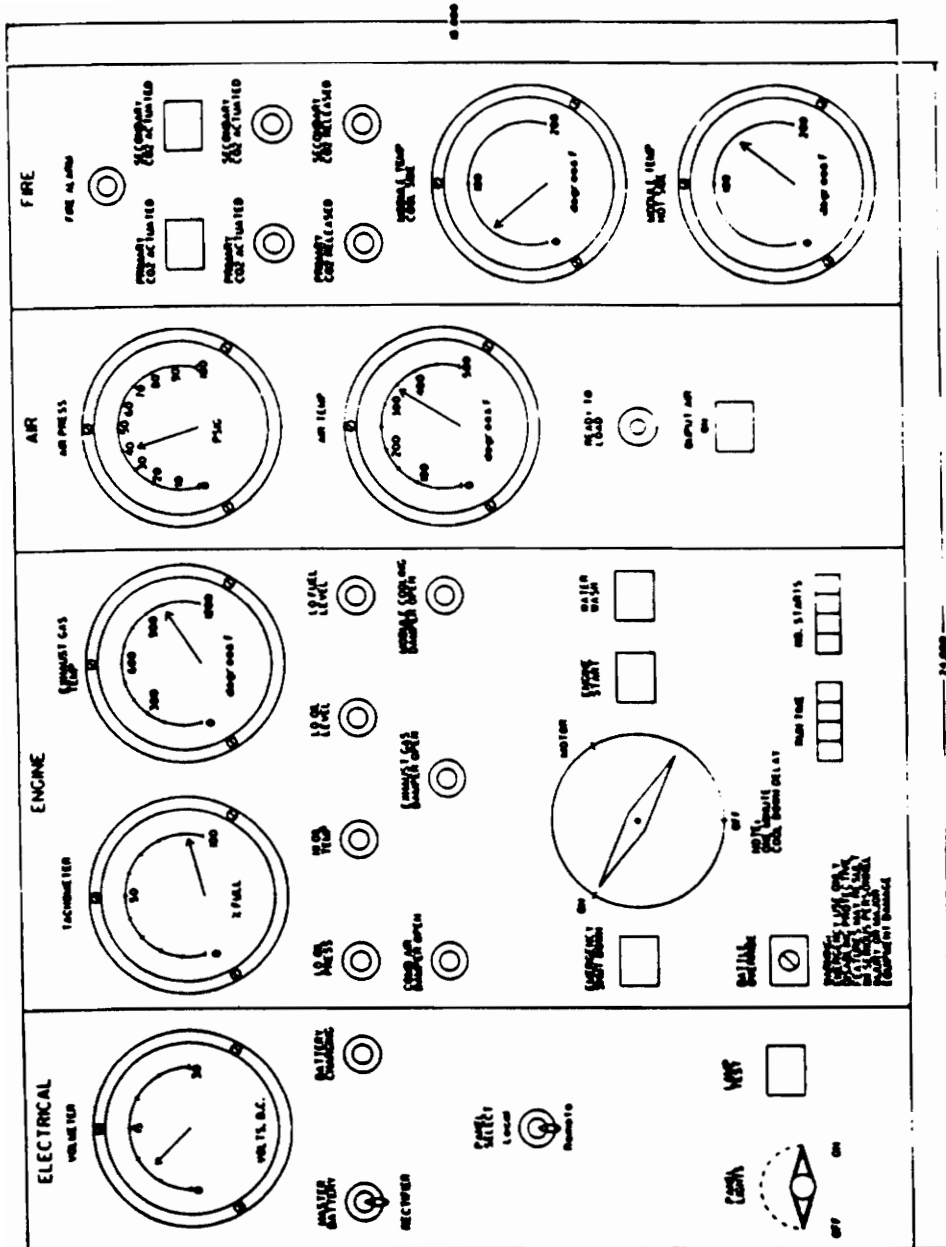


FIGURE 35: REMOTE APU DISPLAYS



SCALE: 3/8" = 1"

FIGURE 36: ACOP PANEL LAYOUT PROPOSAL

with a basic left to right, top to bottom, sequential arrangement philosophy. For example, assuming a remote manual SSGTG start is selected from the LOCOP, initiation of the APU start would begin on the top left hand section (Electrical) by operator selection of the electrical APU starting power source (batter or ship's power via rectifier), followed by switching APU controls to the local (vice) remote mode. Subsequently, the operator would be required to concentrate to the adjacent right hand section (Engine) of the ACOP and position the three-position selector switch to the ON position. Next the operator would energize/initiate the APU start by depressing the Engine Start pushbutton. Once the start was initiated, the operator could then observe normal or abnormal APU engine performance by observing the analog displays and watching for various alarm conditions also provided on the Engine section of the ACOP. Note that proper start sequencing would involve the sequencing open of the APU intake, exhaust, and module cooling duct dampers prior to actual APU starting; position indication lights are also provided on the Engine section, as well as emergency shutdown and battle override controls. Assuming that a successful APU start is achieved, the operator should see the Ready To Load lamp light on the adjacent Air section of the ACOP. Subsequently, the operator can then depress the Output Air On pushbutton to activate opening of the APU's bleed air flow control valve. Note that both pressure and temperature gages are also provided on the Air section to monitor proper APU bleed air discharge characteristics. The far right hand section (Fire) of the ACOP provides the necessary module fire alarms and controls for actuation of the fixed CO2 fire extinguishing systems, as well as analogue temperature gages for monitoring APU module temperatures. Finally, once the APU bleed air flow control valve has been opened, the operator can simply move to the adjacent LOCOP and depress the SSGTG ON pushbutton to initiate the SSGTG start sequence.

3.4.2 Auxiliary HP Air Subsystems

A & B Module Deluge Tank Charging - The new deluge charging system previously described in Section 2.4.2 and illustrated in Figure 25 is to be a manually operated system featuring a small portable LP air driven booster pump and a series of flexible hoses stored in a common rack adjacent to the associated deluge tank. To ensure ease of operation, special care was taken in the selection of the booster pump assembly; the Haskel Model AAD-5 selected weighs only 25 pounds, is approximately 18" x 12" x 12" (LxWxH), and utilizes standard hose connections.

5"/54 Caliber Gun Gas Ejection System - Operation of the new gas ejection system is to be fully automatic via on/off pressure switches located immediately downstream of the 6 cubic foot HP air flask; as flask air mass is consumed and internal pressure drops to 2500 psig, a pressure switch automatically activates the HP air compressor and subsequently a second pressure switch deactivates the compressor when air flask pressure reaches 3000 psig. Relative to local control and monitoring of the HP air compressor, the specifications provide explicit requirements pertaining to the type and number of indicators required on the associated compressor control panels. In addition, as the Loader Drum Room is normally unmanned, the specifications also require an HP air compressor summary fault alarm in the Machinery Control Space.

MK 32 Torpedo Tube Impulse Flask Charging - The HP air compressor system is identical to that described above for the gas ejection system with the exception that it is to be located in the Pallet Truck and Battery Stowage Room on the 01 Level. As this space is also not normally manned, a summary fault alarm in the Machinery Control Space was also specified.

4.0 CONCLUSIONS/RECOMMENDATIONS

The deletion of the Centralized HPAS from DDG 51 Class Flight IIA, and the development of improved, more cost effective, dedicated subsystems via ECP 51-1216 was a considerable effort which required a structured design approach. The approach taken and described in this paper closely resembled the systems development process prescribed by reference (a); deviations taken (i.e. formal preparation of functional flow diagrams and detailed R&M calculations/allocation), were carefully considered and balanced against Program schedule and cost constraints, as well as overall Program objectives for development of detailed specification requirements. Further, Program direction to utilized existing, proven, and supported hardware, coupled with limited prototype testing, reduced the risks associated with such deviations. Moreover, this paper demonstrated the significant influences of human factors in the design of each new replacement subsystem; it was shown that consideration of such human factors attributes as functional effectiveness, operator safety, accessibility, and operability are fundamental to proper system design throughout the system development process. To this end, the objectives cited in Section 1.1 of this paper were met. The remaining portions of this section will

synthesize the results the ECP 51-1216 developmental effort, and provide some recommendations for the future.

The primary reason for instigating replacement of the Centralized HPAS for Flight IIA was to support Program cost reduction initiatives in order to afford the addition of directed warfighting enhancements. Secondary reasons surrounded technical concerns with SSGTG starting capacity, particularly during dark ship conditions, and chronic Fleet-wide problems with HP air compressors. As a result of ECP 51-1216 efforts alone, Section 2.5 details that each Flight IIA ship will feature acquisition savings of \$1.2M and reduce the weight of the ship by approximately 15 long tons. Such recurring cost savings result in payback of the large nonrecurring design costs in approximately 2 ships, which exceeds the Flight IIA Program stipulation of 3 ships maximum. Life cycle cost savings for each ship were also calculated to range from \$2.7M to \$3.3M, depending on which APU (GTCP 100-82 or UNI-JASU) is installed. Similarly, Table IX, also detailed in Section 2.5, illustrated that each and every replacement dedicated subsystem selected either meets or exceeds all operational requirements set fourth in the requirements definition process (see Section 2.1). Provision of a dedicated APU for starting each SSGTG, will support virtually unlimited numbers of SSGTG start attempts for all shipboard conditions, including dark ship. Utilization of simpler, proven, and supported HP air compressors for the 5"/54 caliber gun's gas ejection system and for charging of the MK 32 torpedo tube impulse flasks should provide significant improvements in performance over existing HP air compressors serving Centralized HPAS's throughout the Fleet.

The decision to tailor or deviate from the systems development process prescribed in reference (a) was, as previously noted, made after careful consideration of Flight IIA Program design schedule and cost constraints, and overall Program objectives for the timeframe involved (i.e. develop Flight IIA detail specifications package to support RFP). Further, to reduce associated risks, it was directed that only existing, proven, supported hardware could be utilized for development of replacement subsystems. Figure 8, detailed in Section 1.3.2, and further elaborated on throughout Section 2 engineering process discussions, clearly illustrates the compressed timeframe allotted for such an ambitious undertaking as ECP 51-1216. In retrospect, much time was wasted performing detailed tradeoff studies of alternative design concepts proposed by and lobbied heavily for by various members of the Flight IIA design community; ultimately over 6 months was lost disproving alternative

concepts such as hydraulic and electric starting of SSGTG's. An additional 6 months applied toward development of the APU/SSGTG starting concept would have greatly reduced the stress and risks associated with prototype validation testing and development of the ECP 51-1216 specification requirements. Moreover, this additional 6 months could have been used to perform critical ILS tasks such as a Failure Modes, Effects, and Criticality Analysis (FMECA).

Relative to the specification of existing, proven, and fully supported hardware for the replacement SSGTG starting system, it is worthy of noting that original technical (SEA 03YD/03X34) and programmatic (PMS 400D) approval of ECP 51-1216 featured use of the UNI-JASU APU currently under development by NAVAIR; the UNI-JASU is superior to aged GTCP 100-82 APU's in performance and reliability, and is scheduled to replace the Navy's entire inventory of APU's by the year 2007. Further, in view of supportability difficulties experienced with the GTCP 100-82 APU's, the UNI-JASU development program features parallel development of a comprehensive support capability, including ILS, training, provisioning parts, technical manuals, and support facilities. The existence of such a comprehensive support development program weighed heavily in the decision to tailor the systems development process. Subsequently, and in view of growing concerns with the ability of the UNI-JASU to meet Flight IIA lead ship production schedules, a programmatic decision was made to specify the GTCP 100-82, in lieu of the UNI-JASU for at least the first two Flight IIA hulls. Much to the chagrin of SEA 03YD/03X34, this decision necessitated the development of a formal Memorandum of Agreement between NAVSEA and NAVAIR to ensure that the necessary training, provisioning parts lists, and repair support, etc, will be available for Flight IIA use. Ultimately, it is envisioned that a very costly ECP will be required to retrofit the UNI-JASU into the first two Flight IIA hulls; efforts are underway to control such costs through standardization of the APU modules and interfaces as much as practicable. It is worthy of noting that subsequent to my departure from the Flight IIA Program in May 1994, that the competitive nature of the UNI-JASU development program ceased as the two competing APU vendors merged. Accordingly, PMS 400D should investigate the resultant impacts to the UNI-JASU delivery schedule, and reconsider the decision to specify aged GTCP 100-82's for the lead ships. As a final note on ECP 51-1216 hardware selection, no such concerns exist for the new dedicated HPAC's as, like the UNI-JASU, parallel development of associated support

requirements and capabilities was accomplished by the Program Sponsor (PMS 413).

In consideration of my experiences with ECP 51-1216 and other design efforts, I strongly discourage deviation from the systems engineering process described in reference (a). Although there may appear to be viable reasons for streamlining the process, such as done for ECP 51-1216, there are significant risks which may, in all likelihood, increase costs and result in poorly functioning and/or insupportable systems; both the military and civilian sectors are full of such examples. Similarly, this paper revealed the fundamental significance of human factors considerations to proper system design. The criticality of gaining appreciation for and knowledge of the systems engineering process and human factors can not be over emphasized. In these times of ever increasing budgetary and manpower reductions, we simply can not afford the consequences of inattention to such detail. Accordingly, it is my recommendation that all NAVSEA personnel, both technical and program management, involved in the research, development, and acquisition of equipment and systems be required to undertake formal training in both Systems Engineering and Human Factors. From my 12 years of experience in the DOD sector, the existence of knowledgeable people in both areas is surprisingly sparse.

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SECTION 6.0

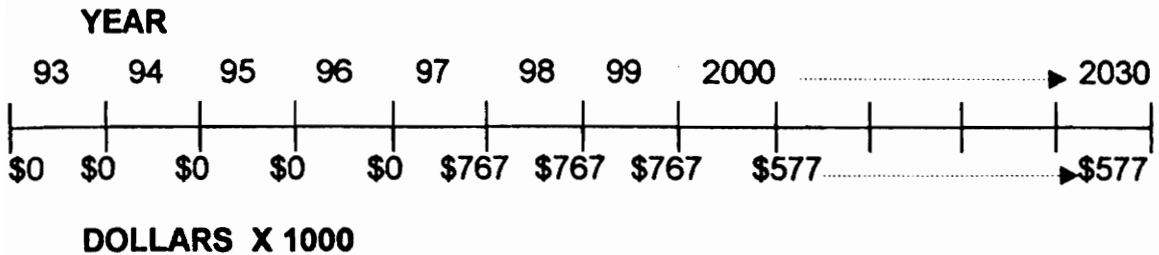
APPENDIX A

**Life Cycle Analysis for
Centralized HP Air System**

LIFE CYCLE COST ANALYSIS

(CENTRALIZED HIGH PRESSURE AIR SYSTEM)

ACQUISITION PHASE $\longleftrightarrow$ UTILIZATION PHASE



Where:

- 1993-1996 No additional testing or increase in nonrecurring design costs per BIW
- 1997-1999 Relects total BIW recurring production costs (\$2.3M) equally divided from start of fabrication (3/96) to lead ship delivery (5/99). For simplicity all costs assumed at year end.
- 2000-2030 Estimated maintenance and operation costs based on \$80K per HPAC (\$160K) plus \$400K for rest of HPAS (per 03Y4 DART analysis), plus annual fuel costs for running HPAC 2000 hrs (\$17K).

Discount rate estimated at 6% as conservative approximation for inflation.

Therefore, life cycle costs (LCC), expressed in 1994 dollars are calculated as follows:

$$\begin{aligned}
 \text{LCC} &= \$0 + [\$767\text{K} \times (\text{P/A}, 6\%, 3) \times (\text{P/F}, 6\%, 2)] + \\
 &\quad [\$577\text{K} \times (\text{P/A}, 6\%, 30) \times (\text{P/F}, 6\%, 5)] \\
 &= \$0 + [\$767\text{K} \times 2.6730 \times 0.8900] + [\$577\text{K} \times 13.7648 \times 0.7473]
 \end{aligned}$$

*Payment factors taken from ref (a)

$$\text{LCC} = \underline{\underline{\$7.76\text{M}}}$$

SECTION 6.0

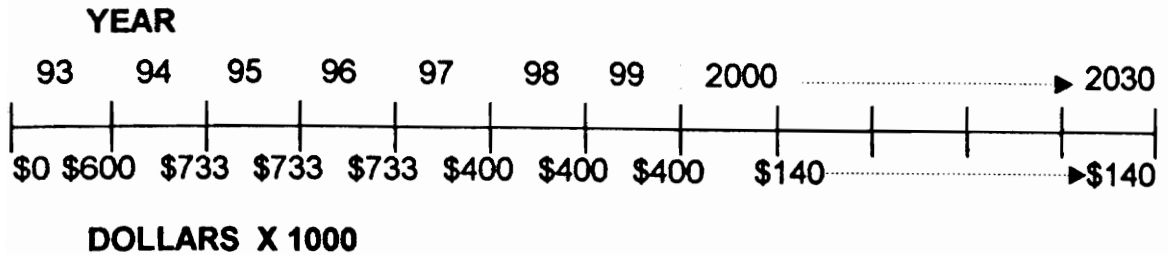
APPENDIX B

**Life Cycle Cost Analysis for
Dedicated Subsystems with GTCP 100-82's**

LIFE CYCLE COST ANALYSIS

(DEDICATED SUBSYSTEMS WITH GTCP 100-82's)

ACQUISITION PHASE $\longleftrightarrow$ UTILIZATION PHASE



Where:

- 1993 Relects \$600K APU testing at LBES
- 1994-1996 Total BIW non-recurring design costs (\$2.2M) equally divided from contract award (6/94) to start of fabrication (3/96).
- 1997-1999 Total BIW recurring production costs (\$1.2M) equally divided.
- 2000-2030 Total utilization costs (\$140K) per NAVAIR; maintenance (\$45K unit/yr) plus fuel (\$5K total).

Discount rate estimated at 6% as conservative approximation for inflation.

Therefore, LCC expressed in 1994 dollars are calculated as follows:

$$\begin{aligned}
 \text{LCC} &= [\$600\text{K} \times (\text{F/P}, 6\%, 1)] + \$733\text{K} + [\$733\text{K} \times (\text{P/A}, 6\%, 2)] + [\$400\text{K} \times (\text{P/A}, 6\%, 3) \times (\text{P/F}, 6\%, 2)] + [\$140\text{K} \times (\text{P/A}, 6\%, 30) \times (\text{P/F}, 6\%, 5)] \\
 &= [\$600\text{K} \times 1.060] + \$733\text{K} + [\$733\text{K} \times 1.8334] + [\$400\text{K} \times 2.6730 \times 0.8900] + [\$140\text{K} \times 13.7648 \times 0.7473] \\
 \text{LCC} &= \underline{\underline{\$5.10\text{M}}}
 \end{aligned}$$

SECTION 6.0

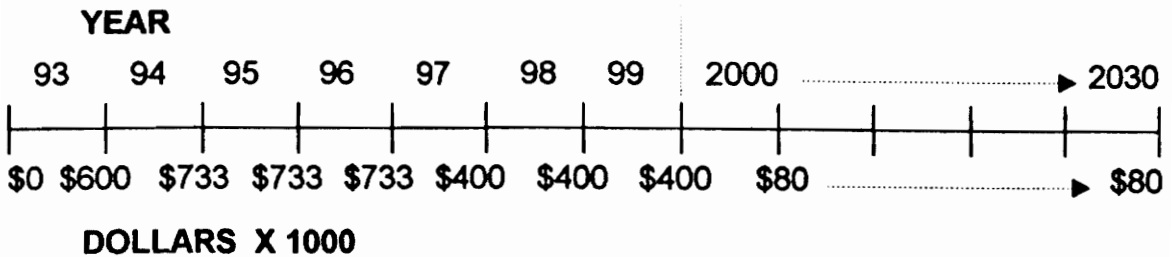
APPENDIX C

**Life Cycle Cost Analysis for
Dedicated Subsystems with UNI-JASU's**

LIFE CYCLE COST ANALYSIS

(DEDICATED SUBSYSTEMS WITH UNI-JASU'S)

ACQUISITION PHASE ← → UTILIZATION PHASE



Where:

- 1993 Relects \$600K APU testing at LBES
- 1994-1996 Total BIW non-recurring design costs (\$2.2M) equally divided for 3 years.
- 1997-1999 Total BIW recurring production costs (\$1.2M) equally divided.
- 2000-2030 Total utilization costs (\$80K) per NAVAIR; maintenance (\$25K unit/yr) plus fuel (\$5K total).

Discount rate estimated at 6% as conservative approximation for inflation.

Therefore, LCC expressed in 1994 dollars are calculated as follows:

$$\begin{aligned}
 \text{LCC} &= [\$600\text{K} \times (\text{F/P}, 6\%, 1)] + \$733\text{K} + [\$733\text{K} \times (\text{P/A}, 6\%, 2)] + [\$400\text{K} \times (\text{P/A}, 6\%, 3) \times (\text{P/F}, 6\%, 2)] + [\$80\text{K} \times (\text{P/A}, 6\%, 30) \times (\text{P/F}, 6\%, 5)] \\
 &= [\$600\text{K} \times 1.060] + \$733\text{K} + [\$733\text{K} \times 1.8334] + [\$400\text{K} \times 2.6730 \times 0.8900] + [\$80\text{K} \times 13.7648 \times 0.7473] \\
 \text{LCC} &= \underline{\underline{\$4.49\text{M}}}
 \end{aligned}$$