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ADVANCED LAUNCH SYSTEM ADVANCED DEVELOPMENT OXIDIZER TURBOPUMP PROGRAM

TECHNICAL IMPLEMENTATION PLAN

Prepared Under
NASA Contract NAS8-37595
DRL Sequence No. 15

Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

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PRATT&WHITNEY

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SECTION I
INTRODUCTION

The objective of the Advanced Launch Systems (ALS) Advanced Development Oxidizer Turbopump Program is to design, fabricate and demonstrate a low cost, highly reliable oxidizer turbopump for the Space Transportation Engine that minimizes the recurring cost for the ALS engines. This Technical Implementation Plan, submitted in response to Data Requirement DR-15 of Contract NAS8-37595, addresses Pratt & Whitney's (P&W's) plan for integrating the analyses, testing, fabrication, and other program efforts. This plan offers a comprehensive description of the total effort required to design, fabricate, and test the ALS oxidizer turbopump.

The proposed ALS oxidizer turbopump will reduce turbopump costs over current designs by taking advantage of design simplicity and state-of-the-art materials and producibility features without compromising system reliability. This will be accomplished by selecting turbopump operating conditions that are within known successful operating regions and by using proven manufacturing techniques.

The program is divided into two phases: Phase I (basic effort) is 12 months, and Phase II (priced option) is 28 months.

During the basic effort, P&W will perform trade and engineering studies, conduct cost trades, evaluate fabrication concepts, establish a configuration, complete the preliminary design, provide a Technology Implementation Plan for options that require further development, and provide a preliminary cost model.

During the option program, P&W will establish a detail oxidizer turbopump design, provide manufacturing drawings, procure material and hardware, assemble and deliver a prototype turbopump for evaluation testing at Stennis Space Center (SSC), support SSC testing, deliver a detail cost model, and provide a turbopump test report and a final report.

During the trade studies, engineering evaluation and design, tools that have been proven by substantiation in many Pratt & Whitney engine programs will be used to evaluate turbine aerodynamics, rotordynamics, structural dynamics, and pump hydrodynamics.

This plan describes P&W's design approach to developing low cost, highly reliable components, outlines the test and analysis plans, and identifies material and equipment requirements. Included are a baseline logic network and man-loading charts.

SECTION II
SUMMARY OF DESIGN METHODOLOGY

A. DESIGN APPROACH

Pratt & Whitney (P&W) will use an iterative design process involving several disciplines to establish a reliable, low cost, effective turbopump design. This approach will provide an Advanced Launch System (ALS) oxidizer turbopump design that meets or exceeds requirements for reliability, durability, safety, cost of production, cost of ownership, performance, and supportability.

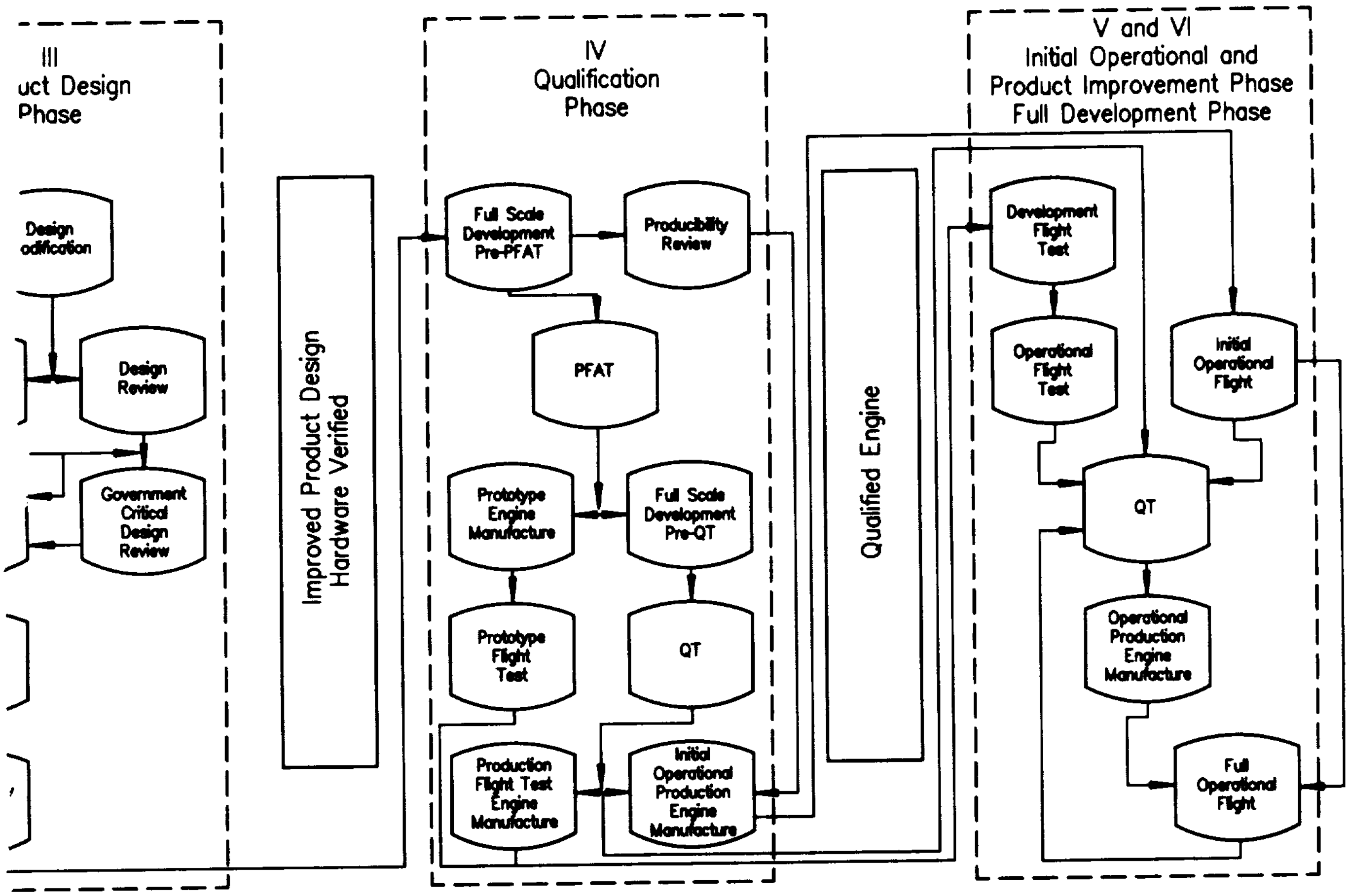
Pratt & Whitney's design process is summarized in Figure II-1. As shown, the process is divided into five phases:

- Concept Definition
- Initial Verification
- Product Design
- Qualification/Demonstration
- Operation.

Pratt & Whitney's mechanical design organization will design the hardware and will coordinate the activities of the specialized technology groups. This organization performs trade studies, develops the final configuration and specifies engineering requirements. The technology organizations develop and provide state-of-the-art technology in their areas of expertise, such as hydrodynamics, turbine aerodynamics, bearing technology, heat transfer and secondary flows, and materials. Cost and weight organizations also provide information to support trade studies; representatives from manufacturing operations provide technology for improving producibility and inspectability. During the trade studies, Product Integrity evaluates design concepts for reliability, safety, and maintainability to ensure all design goals will be met.

1. Design Approach to Low Cost and High Reliability

As the focus of this program is to develop a low cost, reliable ALS oxidizer turbopump, P&W will evaluate conceptual designs and select an optimized design based on reliability and cost goals. Pratt & Whitney will then demonstrate the technology needed to develop engines for the ALS program. The design process to be followed is shown in Figures II-2 and II-3.



and Verify
Design to
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Results
Producibility/
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- Develop Engine Through Qualification
- Assure Efficient Transition From Development to Full Rate Production

- Introduce Product Into Initial Operation
- Identify and Fix Early Problems
- Provide Customer With Full Complement of Operational Aircraft
- Provide Customer Support for Life of Product

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FOLDOUT FRAME

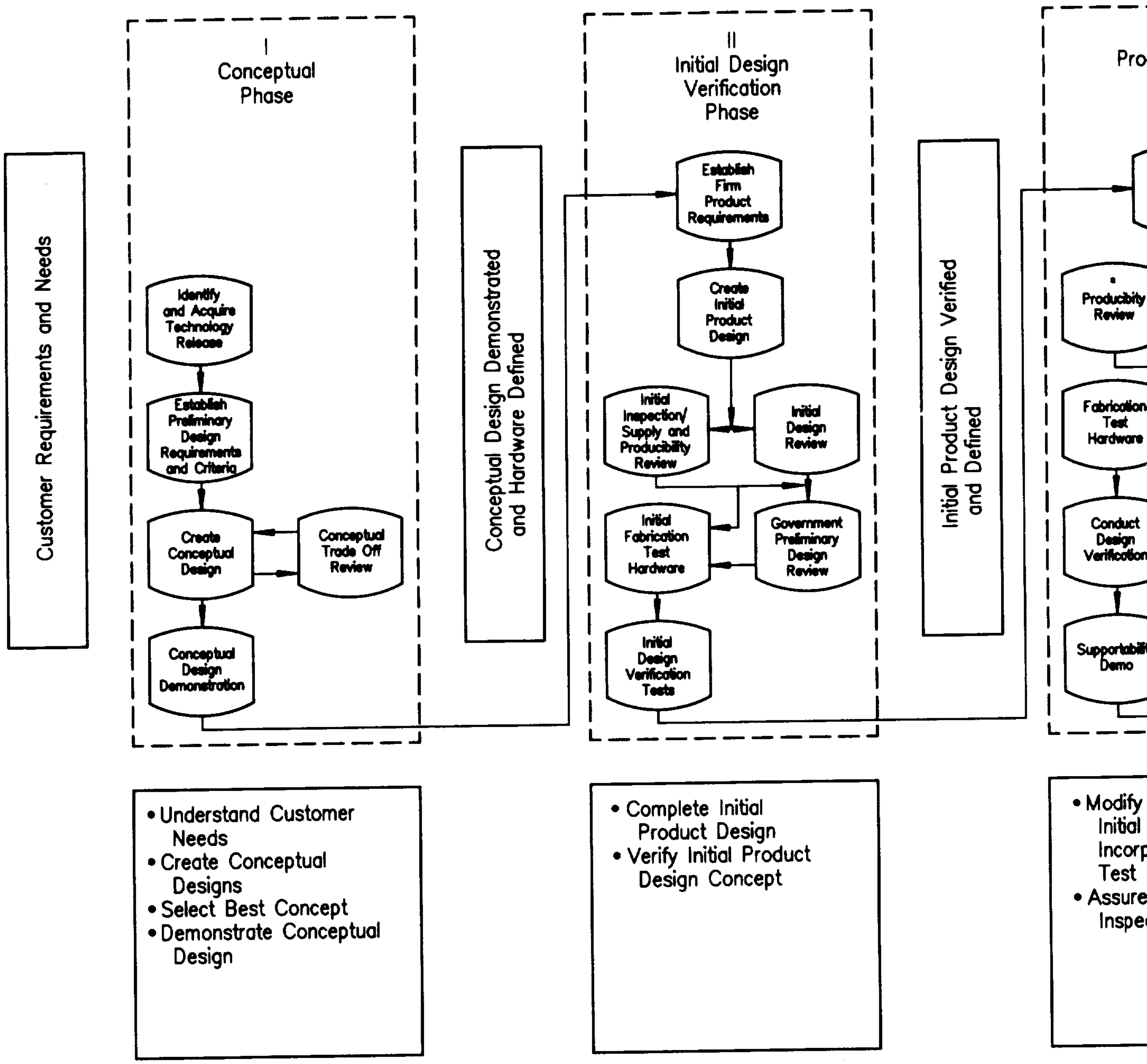

Figure II-1. Overview of the Pratt & Whitney Design Process

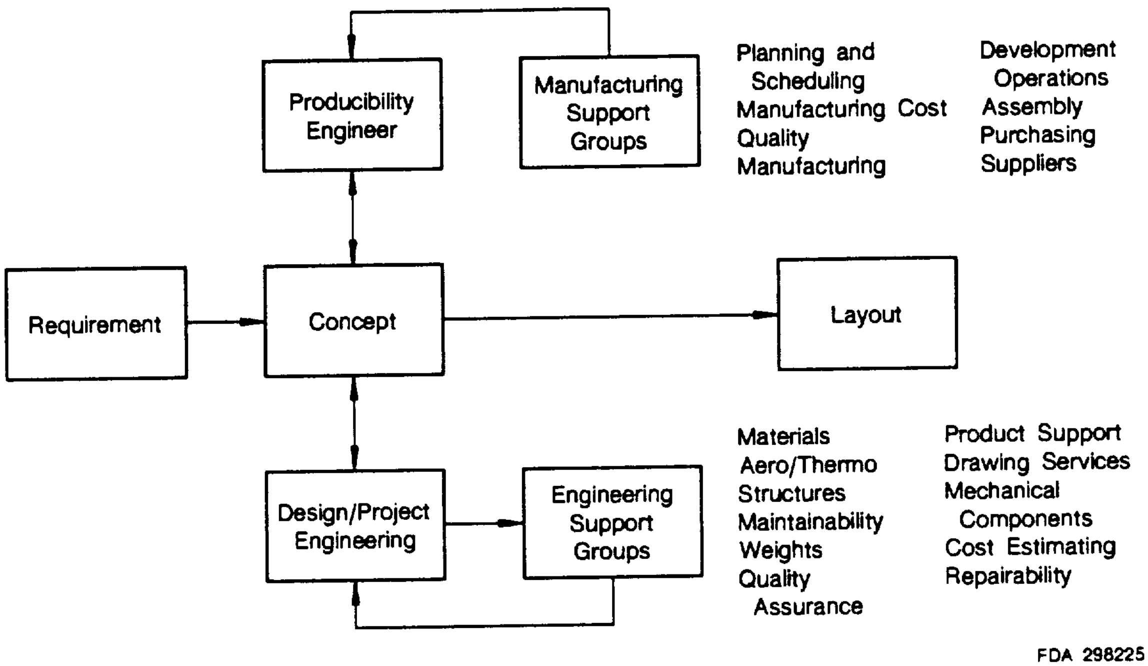

Figure II-2. Conceptual Design Review Procedure

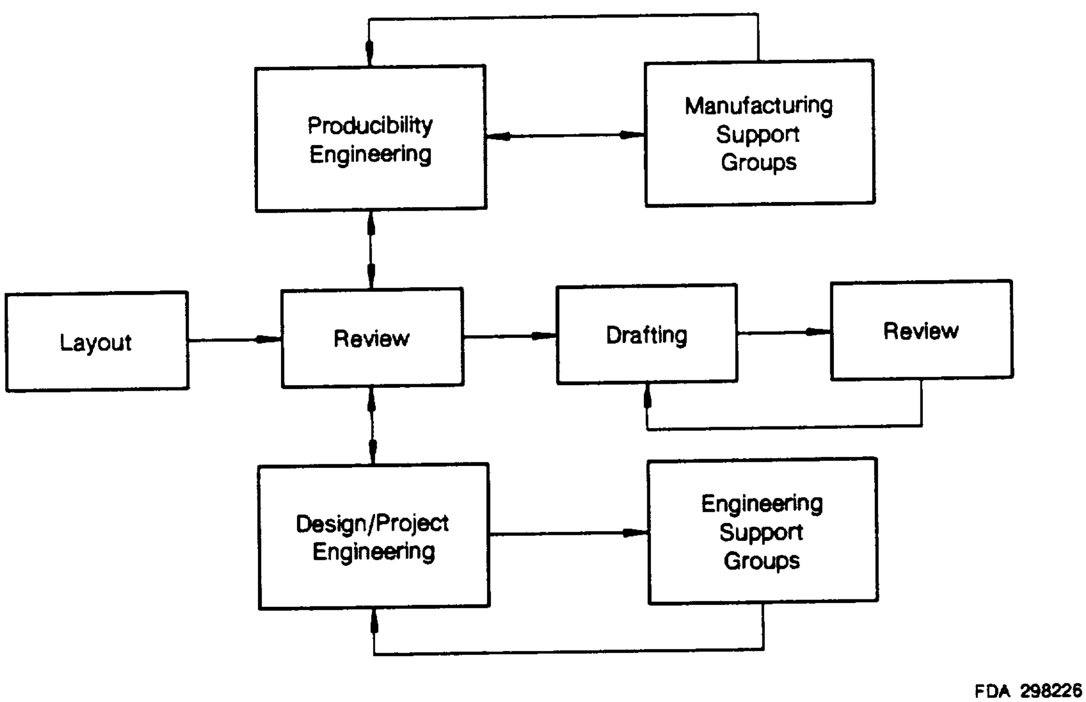

Figure II-3. Layout Review Procedure

Design concepts that P&W will consider include the following:

- Cast inducer and impellers to eliminate the machining process currently required to manufacture forged impellers

- Turbine shaft and disk made separately and inertia welded or near net forged to reduce forging and machining costs; an integrally bladed disk is also a consideration
- Axial flow inlets to provide better performance and durability by eliminating side loads associated with volute type inlets
- Fine-grain, cast housing materials that provide physical properties near those of forgings, thereby eliminating complex welded assemblies and reducing machining requirements
- Single disk with a common broach for both turbine stages for machining simplicity
- Turbine blade castings common to 1st- and 2nd-stage blades for reduced cost
- Stationary knife edge seals instead of rotating seals to increase durability
- Stiff rotor shaft and support for rotordynamic stability enhancement.

2. Basic Effort

Basic effort tasks, when completed, will result in a single preliminary turbopump design concept that has been optimized for low cost and high reliability. The turbopump configuration will be established 8 months after contract award. The preliminary design will be completed 4 months after the configuration is established. Work during this phase will include the following:

- Trade Studies
- Preliminary Design
- Fabrication and Process Analysis
- Laboratory Tests
- Reliability and Hazard Analysis
- Technology Development Program Plan
- Preliminary Design Review
- Preliminary Cost Model
- Specifications and Plans
- Program Management

a. *Trade Studies*

Trade studies, conducted by the various disciplines, will establish a preliminary design concept for approximately three separate turbopump configurations.

These trade studies will include the following activities:

- Systems performance groups will establish turbopump operating requirements and will revise them as needed to account for changes in pump characteristics.
- The compressor design group will provide pump design parameters and configurations for preliminary design evaluation.
- The mechanical components and system design group will provide bearing and seal concepts for evaluation.

- The mechanical design group will provide design concepts, incorporating low-cost configurations and manufacturing concepts for basic turbopump configurations.
- The structural design group will provide an evaluation of configurations for rotordynamic stability, turbine damping requirements and structural integrity.
- The cost group will provide cost trade information for evaluation of design concept and will review the concepts to determine the overall turbopump cost for the configurations.
- The weight group will provide preliminary weight information of the designs.
- The chief engineer's office will evaluate the concepts for the impact on reliability, inspectability, and maintainability.
- Materials engineering group will evaluate the potential application of low cost materials and manufacturing processes leading to low costs.
- Manufacturing will provide support and data to assist in the evaluation of the design and fabrication methods.
- Instrumentation engineering will provides concepts for instrumentation and data recording.

b. Preliminary Design

The preliminary design task includes the engineering studies and analyses required to establish the selected preliminary turbopump design, incorporating the low cost concepts identified in trade studies. As part of this task, P&W will prepare drawings and specifications.

Engineering analyses will evaluate low-cost concepts to determine the impact on reliability, maintainability, operability, and performance.

c. Fabrication and Process Analysis

Pratt & Whitney will perform fabrication analysis studies and sample fabrication demonstrations of low-cost manufacturing concepts. These analyses will determine whether manufacturing concepts such as integrally bladed rotors or cast impellers are sufficiently developed for consideration during the optional detailed design.

Specific concepts to be evaluated under this task include the following:

- Inconel 718 cast impellers with shrouds
- Inconel 718 powdered metal impellers with shrouds
- Cast-to-size turbine blades of PWA 1447, PWA 1480, and IN-100 materials
- Cast-to-size integrally bladed rotor of PWA 1447 and Waspaloy materials
- Electrode discharge machined (EDM) integrally bladed rotor of IN-100 and Waspaloy materials

- Cast housing of Haynes 242 and 230 materials
- Forged disk/shaft assembly
- Inertia welded shaft/disk assembly.

d. *Laboratory Tests*

Materials Engineering will perform materials characterization tests to determine material acceptability from a mission and fluid compatibility standpoint. These tests will include tensile, high cycle fatigue (HCF), low cycle fatigue (LCF), static and dynamic structural tests, and propellant compatibility tests.

e. *Reliability and Hazard Analysis*

Pratt & Whitney will perform a preliminary hazard analysis of the preliminary design to confirm the design meets the reliability requirement level of 0.99 with a 90 percent confidence level. This analysis will include the use of historical turbopump reliability data using statistical methods. This analysis will evaluate reducing failure modes and effects, applying materials characterized for the operating environment, simplifying the designs and minimizing stress concentrations, completing weld inspectability, verifying design criteria, and identifying high safety margins on critical parameters.

f. *Technology Development Program*

A technology development program plan of potential cost reduction ideas requiring additional development will be offered. These plans will include items that are in a preliminary stage but that could be available for the ALS engine C/D phase. Potential ideas include powder metal impellers, bearings with alternative material cages, directionally solidified (DS)/equiaxed cast bladed rings, hydrostatic bearings, and hybrid hydrostatic bearings that include hydrostatic and rolling/element bearing combinations.

g. *Preliminary Design Review*

A preliminary design review will be conducted at the conclusion of the basic effort. The options considered and selected will be reviewed in detail, and a summary of the analyses supporting the selected design will be provided.

h. *Preliminary Cost Model*

The effort to create the ALS engine turbopump component cost model will begin immediately after contract award (Figure II-4). The first three months will be spent defining the cost model concept so it can be presented at the first Quarterly Review. At this review, P&W will present its method for analyzing the impact of Government requirements on turbopump costs.

Detailed cost model planning and formulation will begin following the Quarterly Review. During this period, the model structure will be defined in detail along with the assumptions made for its construction and the sources and methods for obtaining input data. Pratt & Whitney will define the approach to be used in determining what impact the elimination of Government specification requirements has on costs. The method to be used to calibrate the model, using actual cost experience obtained during the fabrication phase of the program, will be identified. Coordination with the suppliers providing turbopump parts will be established early in the basic effort to set the format of the cost model input data they provide.

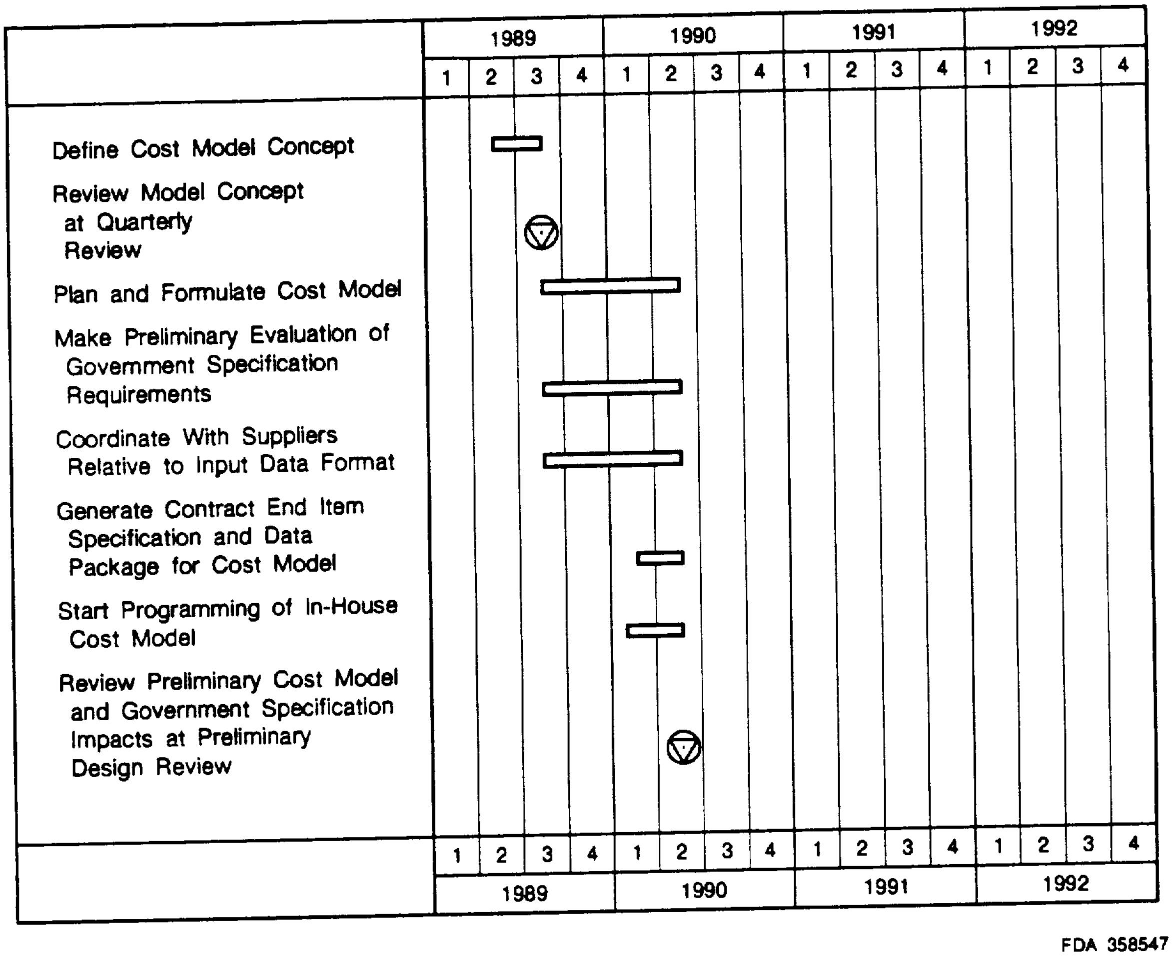

Figure II-4. Engine Turbopump Cost Model Schedule — Basic

The basic effort will also include a preliminary evaluation of Government specification requirements to determine which are applicable and to define the impact of each on component production and operating and support costs.

Actual programming of the in-house cost model will start under the basic effort in early 1990. This early start is needed to have a working model available before the turbopump Detail Design Review (DDR), where initial cost model results will be presented and discussed.

In the last two months of the basic effort, a baseline cost model Contract End Item (CEI) specification will be generated along with a data package for the cost model. At the Preliminary Design Review, the preliminary cost model will be presented, and the results of the preliminary evaluation of specification cost impacts will be reviewed.

This review will include a description of the general model structure, the assumptions used in its construction, the source of all impact data, the approach for including the impact of the Government specification requirements, the approach for using the actual cost experience acquired during the option program fabrication of the components to calibrate the model, and the estimated uncertainty of the model results.

i. Specifications, Plans and Reports

Plans and reports required for the basic effort will be provided and updated as required by Data Procurement Document 720.

j. Program Management

Program direction and coordination will be provided by the project manager and his staff, who will ensure that the disciplines and systems are available to support the tasks.

3. Priced Option

The priced option is a 28-month effort consisting of development of a detailed turbopump design, fabrication and assembly of development hardware, and test and evaluation of a turbopump at the Stennis Space Center. This option will consist of the following tasks:

- Turbopump Design
- Ground Support Equipment (GSE) Design
- Special Test Equipment (STE) Design
- Interface Control Document
- Test Plans
- Detailed Design Review
- Detailed Cost Model
- Turbopump Fabrication & Assembly
- GSE Fabrication
- STE Fabrication
- Procedures Development
- Laboratory Testing
- Hazard Analysis
- Final Test Plan
- Engineering and Support
- Final Inspection
- Test Report
- Specifications, Plans and Reports
- Program Management
- Special Studies
- Technology Development Plan

a. Detailed Design

A detailed design and analysis of the turbopump configuration selected in the basic program will be conducted.

During the detailed turbopump design, analyses will be conducted to ensure the integrity of the design. Included in this task are stress analyses on individual hardware details and assemblies; turbine and pump performance operating loads; thermal, dynamic, flow, rotor dynamics; and bearing and seal performance. (Section IV discusses P&W's Integrated Analysis Plan.) Four sets of preliminary drawings and data packages will be submitted before the design review.

A probabilistic failure analysis of life critical failure modes will be done to provide a quantitative estimate of turbopump reliability.

Any GSE and STE required to install, service, and operate the turbopump assembly at the Stennis Space Center will be analyzed and designed as defined in the Interface Control Document.

As part of the detail design, P&W will develop a turbopump test plan (DR-30) for verifying the design. This plan will describe the turbopump assembly, interface requirements, instrumentation needs, propellants requirements, test objectives, and operating conditions. An Acceptance Plan (DR-20) for other required tests (laboratory, subcomponent and components tests for design verification) will also be provided. Four weeks before delivery of the turbopump, a final test plan will be provided. (Pratt & Whitney's Integrated Test Plan is discussed in Section III.)

At completion of the detail design, a detail design review will be conducted at Marshall Space Flight Center (MSFC). The review will include, among other items, a summary of the analyses supporting the design. The proposed fabrication approach will also be reviewed.

b. Detailed Cost Model

The effort for constructing the detailed cost model (Option) will begin in May 1990 (Figure II-5). The first 3 months will be dedicated to completing the programming of the in-house version of the cost model. During this period, input data for the model will be gathered. A manufacturing plan will be generated for flight versions of the turbopump. Production cost and cost-related input data will be obtained for purchased parts from suppliers. The manufacturing cost and cost-related input data for P&W parts will be generated by P&W manufacturing engineers.

The Operating and Support (O&S) cost portion of the model will need failure mode Weibulls and scheduled and unscheduled maintenance event data for the O&S cost calculations. This data will also be generated.

The model will be capable of scaling components covering engine thrust sizes between 300K and 800K and chamber pressure levels between 1500 psia and 3200 psia. The dimensions and cost impacts for these scaled components will be defined.

In preparation for the DDR, the production and O&S cost impacts of eliminating Government specification requirements will be quantified. This information will be obtained from the suppliers for the purchased parts, and it will be generated for the P&W parts. These results, along with initial cost estimates generated by the cost model, will be presented at the DDR.

In the months following DDR, the in-house cost model will be exercised and perfected. Work will start in early 1992 on the deliverable cost model. A user's manual will be generated for the deliverable model.

After fabrication, updates will be made to all input data to reflect experience gained during the fabrication process. This updated data will include manufacturing cost and cost-related data for all P&W-manufactured and purchased parts, Weibulls and maintenance event data, Government specification impacts, and an updated Contract End Item specification.

In preparation for delivery of the model, the last 2 months will be spent generating substantiating data for the model. These data will include historical data, examples, and analogies. Component weight and design information needed for an independent cost assessment by the National Aeronautics and Space Administration (NASA) will also be generated. The cost model will be delivered to both NASA and the U.S. Air Force at the completion of the option program with the user's manual, a copy of the source code, and the independent cost assessment data.

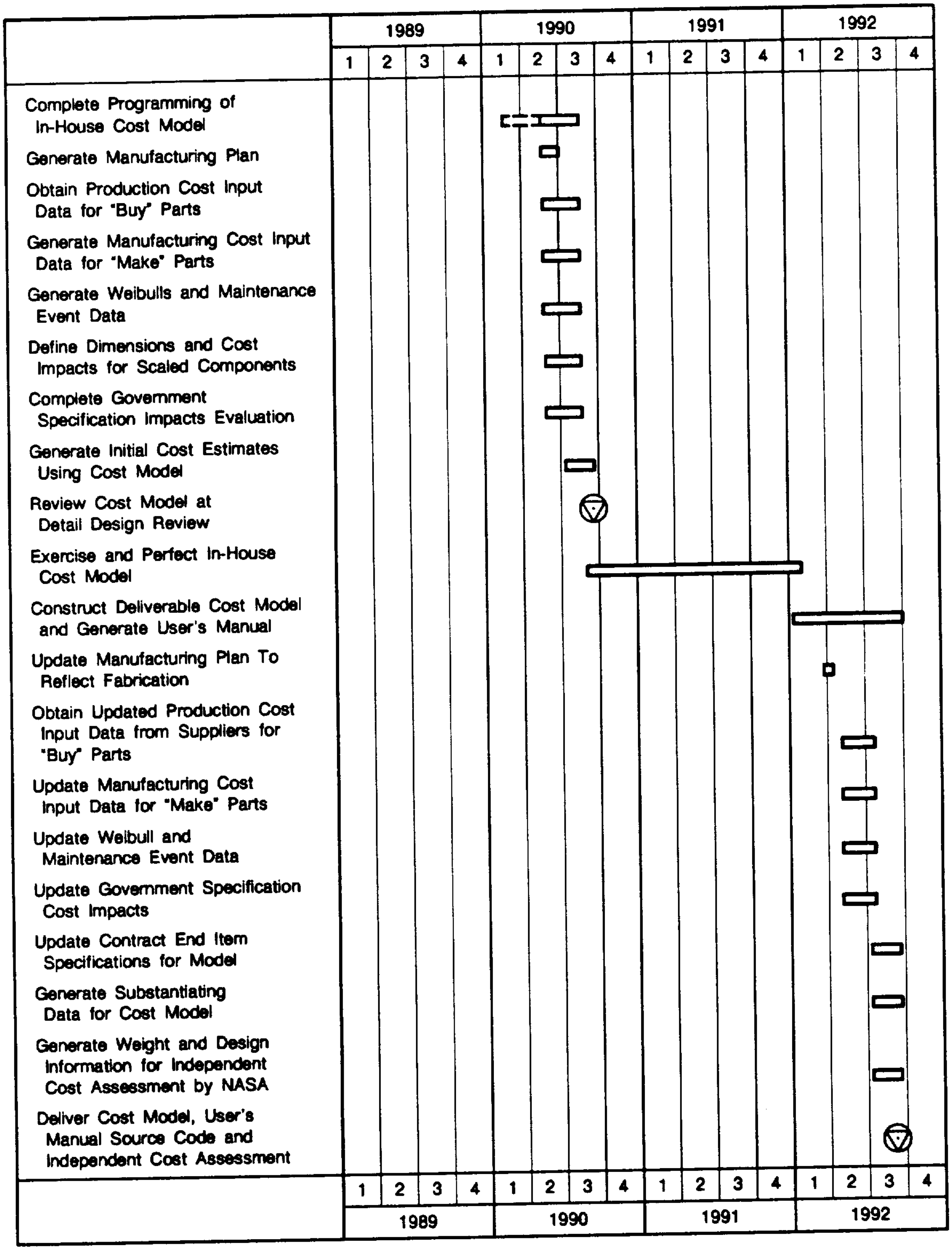

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Figure II-5. Engine Turbopump Cost Model Schedule — Option

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c. Prototype Fabrication

One complete set of turbopump hardware and one set of critical item spares (impellers, housings, bearings, etc.) will be procured based on the detailed design completed. GSE and STE required to support testing at SSC will also be fabricated. Assembly of the turbopump will be conducted at P&W using P&W's configuration control system. A comparison of the turbopump with the design previously reviewed will be conducted. Any discrepancies will be provided to MFSC per the Acceptance Data Package 14 days prior to delivery of the turbopump assembly. A hazard analysis will be conducted to determine potential for damage to the test facility, and the results will be delivered before turbopump testing. Laboratory testing to verify the design will be conducted. Included will be laboratory materials and property tests on fabricated hardware (weld sample material), evaluation of fabrication cycle (weld samples), spin tests on rotating hardware, vibration evaluations of hardware, and rig test evaluations of bearings (Table II-1).

Table II-1. *Turbopump Component Nondestructive Inspection and Design Verification Requirements*

Component	*Nondestructive Inspection*	*Design Verification Specification*
Impellers	X, F, S, D	M, SP, B
Inducer	X, F, S, D	M, SP, B
Disk/IBR	X, F, S, D	M, SP, B
Turbine Blades	X, F, D	M, D
Turbine Stators	X, F, D	M, D
Pump Housings	X, F, D	M, S, P
Turbine Housings	X, F, D	M, S, P
Tie Bolt/Shaft	X, F, D	M
EDM Cast Test Bars	X, F	M, F
Bladed Rotor		D
Rotor Assembly		D
Bearings		R

NDI Legend

X — X-ray
F — FPI
S — Sonic
D — Dimensional

DVS Legend

M — Materials Properties (Tensile, LCF, etc.)
SP — Spin Test
B — Burst Spin Test
S — Static Structural Test (Stress Coat, Strain Gage, etc.)
D — Dynamic Structural Test (Vibration, Holography, etc.)
P — Structural Proof Pressure
F — Surface Finish Evaluation
R — Rig Tests

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d. Procedures Development

A set of procedures will be generated for the assembly, disassembly, operation, inspection, storage and transportation of the turbopump and will be delivered to NASA.

e. Test Hardware Support and Analysis

Engineering and logistics support to maintain the test hardware will be provided. The full-scale turbopump assembly tests will provide functional evaluation of the pump, turbine, rotor support, and rotor thrust control systems.

Pratt & Whitney will provide an interface drawing defining fluid conditions and allowable interface loads as early as possible during the final design. Pratt & Whitney will work with the facility designers throughout the course of the program to ensure that installation and operational requirements are met. Data analysis will be performed as needed during the 3-month test period. When testing has been completed, a final inspection of the turbopump will be done, and the condition of the hardware will be documented. A test report will be provided as required by Data Requirement DR-34. The report will include the test results as well as findings from the final inspection.

f. Specifications, Plans and Reports

Plans and reports required for the option program will be provided and updated as required by Data Procurement Document 720. Included are monthly, quarterly and final reports and other various data procurement documents.

g. Program Management

Program direction and coordination will be provided by the Program Manager and his staff, who will ensure that the disciplines and systems are available to support the tasks required.

h. Special Studies

An level of effort equal to 1000 man-hours will be provided for conducting any special studies necessary during turbopump design and fabrication.

i. Technology Development Plan

The technology development program plan that was developed in the basic program will be updated during this phase. This plan addresses design and development concepts that are not mature enough to include in the present design. Technology that may be considered for the plan included, but are not limited to, cast powdered metal impellers, directionally solidified (DS)/equiaxed integrally bladed disk, bearings with alternative material cages, cast bladed rings, hydrostatic bearings, and hybrid bearings.

B. POTENTIAL PROBLEM AREA

Because of difficulties with the Space Shuttle Main Engine (SSME) inner race and the ATD roller bearing, the turbopump bearings are a potential problem area in the ALS oxidizer turbopump design.

C. INHERENT TECHNICAL RISK

1. Design

The SSME flight bearings have experienced flight inner race stress corrosion cracking. Pratt & Whitney is pursuing a program to optimize the properties of AISI 440C and, in parallel efforts, to develop a suitable replacement.

Sound design criteria for installation and controlled assembly procedures are essential to avoid stress corrosion cracking. Pratt & Whitney's bearing design system provides radial fits that are sufficient to prevent inner ring rotation but that avoid excessive race hoop stresses to minimize the potential for stress corrosion cracking.

For the ALS Program, the calculated maximum room temperature and operating stresses are provided in Table II-2.

Table II-2. ALS Program — Maximum Bearing Hoop Stresses

		Pump End Ball	Turbine End Roller
LOX Pump	R.T.	15,000 psi	16,900 psi
	Operating	7,800 psi	13,200 psi

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To further reduce the risk, specific assembly procedures are defined to prevent bearing damage during assembly. These procedures are designed to control moisture and to preclude the introduction of contaminants during assembly.

Because of the microcracks found in the ATD roller bearing inner race, microcracks are a serious concern for the ALS turbopump. Pratt & Whitney has identified the cause of the ATD roller bearing inner race fracture as microcracks or metallurgical damage produced by the manufacturing process. The ATD Program is now using a state-of-the-art eddy current inspection system that will detect such defects. With the increased sensitivity of this eddy current system, bearing manufacturers can refine and modify their manufacturing processes. Early eddy current screening using an equivalent system by FAG (German bearing supplier), provided the suppliers early feedback on their manufacturing techniques. This system is currently being refined before being fully implemented at the three ATD bearing manufacturers in April 1989. This refined eddy current inspection will be performed on all ALS bearings, preventing the occurrence of similar manufacturing-induced failures.

2. Material Development Plan

Pratt & Whitney is seeking alternative materials with improved fracture toughness and corrosion resistance under another contract. The results should be available in the 1991-92 time frame, and as a result, alternate bearing materials could be considered for this program.

In the ATD Program, stress corrosion cracking (SCC) evaluation testing of an AISI 9310 material inner race has accumulated 65 days in a 100 percent humidity environment mounted on an arbor at 50,000 psi hoop stress. The lack of general corrosion resistance of AISI 9310 material necessitates surface protection to ensure that corrosion itself does not induce/accelerate rolling fatigue.

Because of the SCC limitations of 440C material and the general corrosion limitations of AISI 9310 material, P&W is initiating a three-phase program approach to develop alternative materials.

One phase is to evaluate the use of powdered metal (PM) technology. Pratt & Whitney has an extensive background in developing and fabricating advanced PM alloys for blades, vanes, and disks. These resources were used under Air Force contract (AFWAL-TR-85-2097) to develop new corrosion resistant bearing alloys for gas turbine applications. One of the alloys in wrought condition will be evaluated by a bearing manufacturer. The PM technology capabilities demonstrated under this contract can be used to develop a new alloy. PM alloys with their finer and more homogenous carbide composition offer improved fracture toughness and ease of manufacturing.

Pratt & Whitney is also pursuing alternative materials development with bearings manufacturers who are developing advanced bearing materials and tough fracture resistant alloys, such as M50 NiL material and super M50 NiL material, for gas turbine applications.

A bearing manufacturer has successfully carburized high chrome steels (>12 percent) in experimental programs. Such an alloy could be available for experimental evaluation by early 1990.

The development of a new PM bearing alloy could also be coupled with the new Howmet VPSD™ (vacuum plasma structural deposition) process. This process offers the possibility of depositing a corrosion resistant alloy over a ductile core, producing improved fracture toughness and corrosion resistance.

In addition to the alternative material programs, the heat treatment and processing techniques for 440C material are being investigated. This phase of the program will concentrate on improving 440C material's resistance to SCC. This includes evaluating austenitizing temperature, quench media, tempering temperature, and in-process manufacturing procedures that can induce intergrannular attack or chemical contamination.

The most promising candidates from each phase will be evaluated in material characterization tests by P&W, with the best candidate materials selected for ATD bearing rig screening. Pratt & Whitney has developed unique rig testing capabilities, and these will be used to accelerate the screening process to minimize the total development time.

Since the ALS Program follows the ATD Program, the ALS Program will be able to take full advantage of ATD rig and bearing success. In the ATD Program, the bearing test program has already demonstrated a robust design. For the ALS Program, this means added margin because the ATD bearings operate at higher speeds and loads. The ATD high pressure oxidizer turbopump (HPOTP) ball bearing showed remarkable durability by accumulating 1.1 hours in LN_2 and 3.1 hours in LO_2, including 10 simulated SSME flight cycles. Post test inspection showed wear on the balls was less than 0.000050 in. In roller bearing testing, two bearings have totalled 7.1 hours each, again validating this unique bearing design. Also the capabilities of the fully matured rigs will be used to verify the ALS bearing designs. This one-two approach to design and test verification will ensure success for the ALS Program.

D. RISK REDUCTION

The following list summarizes the significant features of P&W's risk management plan for the ALS design and development program.

- Early detail screening and endurance demonstration in cryogenic rigs
  - Bearings
  - Damper Seals
  - Interpropellant Seals

- Supportive material characterization and thermal cycle test evaluations
  - Turbine blade and vane airfoils
  - Alternative alloy/casting process evaluation
- Alternative structural designs
  - Backup designs available upon determination of need
- Structural dynamic and proof tests at the detail/subcomponent levels
  - Pressure vessel proof tests
  - Spin test critical rotor details
  - Dynamic spin test of turbine rotors
  - Rotor assembly impedance tests
  - Bearing support spring rate evaluation
- Structural design margin
  - Structural design point of ALS components is 115 percent of RPL
- Design Verification System approach
  - Clear issues as early as possible
  - Clear issues at lowest test level possible

1. Alternative Plans

Each component has alternative low cost, high reliability concepts and technology programs to ensure that any potential impact to the design and schedule is prevented or minimized. Tables II-3 and II-4 list the major components with their material and fabrication alternatives.

2. Backup Approaches

A proven backup configuration is available to minimize schedule impact in the event that a primary design does not meet cost reliability or performance goals. Table II-4 illustrates the risk mitigation concept.

Table II-3. Oxidizer Turbopump Component Materials

Component	*Material*	*Rationale*	*Alternative Materials*
Bearing, Ball Race and Elements	440C	Corrosion Resistance	M-50 NIL, AISI 9310, 52100, BG-42
Cage	Bronze-Filled Teflon	Minimal Race and Ball Wear	Carbon Teflon, Carbon Polymide, Glass Cloth-Filled Teflon
Bearing, Roller Inner Race and Elements	440C	Corrosion Resistance	M-50 NIL, AISI 9310, 52100, BG-42
Outer Race	AISI 9310	Fracture Toughness	
Cage	Glass Cloth W/Teflon	Cost, Experience	Carbon Polymide, Carbon Teflon
Blade, 1st-Stage Turbine	MAR-M-247	Casting Experience, Cost, Withstand Thermal Shock	Stellite 31, IN-100, PWA 1480 SXL
Blade, 2st-Stage Turbine	MAR-M-247	Casting Experience, Cost, Withstand Thermal Shock	Stellite 31, IN-100, PWA 1480 SXL
Disk/Shaft, Turbine	Waspaloy	Yield and Fatigue Strength, Cost, Ductility	IN-100, Inco 718, Astroloy
Disk, Thrust	Inco 718	Machinability, Cost	Waspaloy, X-750
Housing, Pump Inlet	Inco 718	Supplier Casting Experience, Cost, Strength	Haynes 242, Mar-M-247, Haynes 230, A-286, Incoloy 909
Housing, Pump Discharge	Inco 718	Supplier Casting Experience, Cost, Strength	Haynes 242, Mar-M-247, Haynes 230, A-286, Incoloy 909
Housing, Turbine Discharge	Haynes Alloy 230	H_2 Resistance, Strength	Mar-M-247, A-286, Haynes 242, Incoloy 909
Housing, Turbine Inlet	Haynes Alloy 230	H_2 Resistance, Strength	Incoloy 909, A-286, Haynes 242, Mar-M-247
Impeller, Pump	Inco 718	Supplier Casting Experience, Cost, Strength	Waspaloy, 347 SST
Inducer, Pump	Inco 718	Supplier Casting Experience, Cost, Strength	Waspaloy, 347 SST
Seal, Labyrinth	Inco 718	Machinability, Cost	Waspaloy, X-750
Vane 1st-Stage Turbine	Haynes Alloy 230	Integrally Cast With Turbine Inlet Housing	Haynes 242, MAR-M-247
Vane, 2nd-Stage Turbine	MAR-M-247	Casting Experience, Cost, Withstand Thermal Shock	Inco 718, Inco 625, Stellite 31, IN-100

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Table II-4. Oxidizer Turbopump Component Fabrication Concepts

Component	*Fabrication Concept*	*Alternative Concepts*	*Risk Mitigation Concepts*
Bearing, Ball	Multi-Piece Cage	One-Piece Cage	
Bearing, Roller	One-Piece Cage		
Blade, 1st-Stage Turbine	Near-Net Equiaxed Casting with Hollow Airfoils	Near-Net Equiaxed Casting With Solid Airfoils	Cast Single Crystal with Hollow A/F
Blade, 2nd-Stage Turbine	Near-Net Equiaxed Casting with Hollow Airfoils	Near-Net Equiaxed Casting with Solid Airfoils	Cast Single Crystal with Hollow A/F
Disk/Shaft, Turbine	Forged Disk and Bonded Shaft	IBR (Integrally Bladed Rotor) with: •Solid-State Bonded Blades •ECM or EDM Blades •Milled Blades Bladed Ring (Cast Blade Ring) Bonded to Forged Hub Cast IBR	Forged Disk and Integral Extruded Shaft
Housing, Pump Inlet	One-Piece Casting (Fine Grain and HIP)	One-Piece Forging Combination Cast/Wrought Details Welded Together	Forged, Welded, and Machined Details
Housing, Pump Discharge	One-Piece Casting (Fine Grain and HIP)	One-Piece Forging Combination Cast/Wrought Details Welded Together	Forged, Welded, and Machined Details
Housing, Turbine Discharge	One-Piece Casting (Fine Grain and HIP)	One-Piece Forging Combination Cast/Wrought Details Welded Together	Forged, Welded, and Machined Details
Housing, Turbine Inlet	One-Piece Casting (Fine Grain and HIP)	One-Piece Forging Combination Cast/Wrought Details Welded Together	Forged, Welded, and Machined Details
Impeller, Pump	Cast Shrouded Impeller with Swept Vanes (Fine Grain and HIP)	Forged Hub and Vanes with Attached Shroud: •Solid-State Bonded •Brazed and Welded •Mechanical Shape Formed by Rapid Omnidirectional Compaction	Forged and Machined Shrouded Impeller with Radial Vanes
Inducer, Pump	Near-Net Casting (Fine Grain and HIP)	Shape Formed by Rapid Omnidirectional Compaction	Forged and Machined
Vane, 1st-Stage Turbine	One-Piece Cast Stator with Hollow Vanes	Bicast: Hollow Vanes Cast into Inner and Outer Shrouds	Cast Segments with Hollow Vanes
Vane, 2nd-Stage Turbine	One-Piece Cast Stator with Hollow Vanes	Bicast: Hollow Vanes Cast into Inner and Outer Shrouds	Cast Segments with Hollow Vanes

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SECTION III
INTEGRATED TEST PLAN

During the Advanced Launch System (ALS) oxidizer turbopump development program, Pratt & Whitney (P&W) will conduct testing to evaluate materials selected, to evaluate fabrication techniques, and to verify the design. Testing will be at the material/parts, component, and turbopump levels. Nondestructive Inspection (NDI), Design Verification Specification (DVS), and full-scale demonstration tests will cover the range of testing to be completed.

In the basic effort, laboratory tests of materials — such as high cycle fatigue (HCF), low cycle fatigue (LCF), structural tests and propellant capability tests — will determine materials/fabrication acceptability from a mission and fluid-compatibility standpoint.

In the priced option, laboratory material property tests will also be conducted. In addition, weld samples will be evaluated, spin tests will be performed on rotating hardware, and vibration evaluation will be performed on components and subassemblies. Bearings will be evaluated by rig testing and full-scale turbopump assembly tests will provide functional evaluation of the pump, turbine, rotor support, and rotor thrust control systems.

Facilities at the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center and Stennis Space Center and P&W facilities will be used to accomplish the turbopump program objectives. Special test equipment and tooling will be required for support of this program at P&W.

A. MATERIALS/PARTS

Initial testing will be performed at the material/part level. Qualification of part integrity and initial evaluation of the design will be accomplished by both NDI and DVS testing.

NDI techniques will include dimensional, x-ray, fluorescent penetrant inspection, and sonic inspection. DVS testing will include tensile, LCF, and HCF tests. The objectives of these tests is to verify that material properties are acceptable and that the design requirements have been met.

1. Design Requirements

The turbopump hardware will be designed to meet low acquisition and low operational costs as well as high reliability.

2. Objectives

The P&W goal is to verify the turbopump design at the lowest possible level by testing. NDI and DVS test objectives outline the testing that must be accomplished for qualifying a component. For the materials evaluation, fabricated samples will be tested to determine materials properties (tensile, LCF, HCF, etc.) of fine grain Inconel 718 and other selected materials.

3. Facilities and Equipment

Mechanical and physical properties tests for materials will be conducted on the existing test stands in P&W's Materials Engineering laboratory. These stands can test materials in either a helium or a hydrogen environment at pressures from ambient to 8000 psig. Test temperatures can be varied from ambient to 1800°F. Cryogenic testing can also be accomplished in the materials laboratory where a gaseous or liquid nitrogen environment is used at ambient pressure and temperatures down to −320°F.

4. Test Method

Material characterization will be performed through the P&W Materials Engineering laboratory. The characterization program will substantiate the material selections for the ALS hardware elements over the full range of environmental exposure encountered during the ALS operating cycle. A full description of the materials characterization program, as currently defined, is provided in the ALS turbopump "Materials Control Plan."

B. COMPONENTS

Both NDI and DVS testing will be used in the component test plan. Materials properties tests will concentrate on test bars produced with the individual component hardware rather than separate test bars. The DVS testing will further define and verify the design requirements by means of spin, structural pressure, and surface finish testing.

1. Design Requirements

The turbopump hardware will be designed to meet low acquisition and low operational cost as well as high reliability.

2. Objectives

The P&W objective is to verify the turbopump design at the lowest possible level by testing. NDI and DVS test objectives outline the testing that must be accomplished for qualifying a component. Materials will be evaluated to determine properties (tensile, LCF, HCF, etc.) of selected materials.

Spin and spin burst tests will be used to simulate operational rotating characteristics to verify component structural integrity. Spin burst testing will confirm the design margin and further define the operational safety margins for the structural characteristics involved.

A pressure proof test will ensure that the subject component can withstand design pressures and will define the structural design margins relative to these pressures. Surface finish testing will determine the quality of the finish as well as initialize a data base for further surface finish design.

Bearing rig tests and seal testing will be used to monitor bearing/seal performance, life, and wear characteristics. Testing at P&W's E20/21 test stands will simulate operational conditions and will verify design requirements before full-scale testing.

3. Facilities and Equipment

NDI and DVS material testing and proof pressure testing will be performed with existing P&W equipment. Existing facilities will be used for the spin tests; tooling modifications will be required to adapt the spin equipment to the ALS hardware. Existing Alternate Turbopump Development (ATD) Program bearing and seal rigs will be used for the bearing/seal tests. Some adaptive tooling may be required for the ALS application.

4. Test Method

Material testing will be accomplished by laboratory evaluation of fabricated test specimens. All turbopump pumping components (impellers, inducers) will be subjected to spin tests to verify analytical predictions of local cyclic strain range.

Turbine blades for the turbopump will be subjected to further dynamic stress analysis in a spin test that verifies the structural adequacy of the blade when dynamic (vibratory) stresses are imposed concurrent with rotating loads.

A full set of blades will be installed in the turbopump shaft/disk and fixtured for spin testing. Selected blades from each stage will have been instrumented with strain gages to measure both dynamic (vibratory) and steady strains. This instrumentation is routed through a slip ring device that is a part of the spin test facility. After the bladed disk assembly is rotated to the speed simulating the turbopump operating condition of interest, the blades will be excited with air jets or with piezoelectric crystals (also installed on the instrumented blades). The combined steady (rotating load) strains and vibratory strains will be monitored by the strain gage instrumentation and recorded by the data acquisition system. Post-test analysis will verify that superimposed vibratory and steady stresses representative of the operating environment are within the Goodman diagram criteria for infinite high cycle fatigue (HCF) part life. These tests will also quantify any change in resonant response resulting from the concurrent load application.

Spin stress evaluations for turbine components consist of static and vibratory strain-gage surveys of a component being spun in a spin rig at speeds ranging from zero to the maximum expected operating speed. Since the spin pit will be operated at room temperature, corrections will be made to account for material property differences. The static-strain survey will be performed at incremental speeds, with gages located at nominal and predicted high-stress areas. The vibratory survey will be conducted continuously through the entire speed range. Gages will be located at positions that allow identification of predicted mode shapes and determination of vibratory stress ratios. The vibratory modes will be excited by air jets impinging on the component while it is spinning, or by piezoelectric crystals attached directly to the test article.

Static strain data will be reduced and correlated with analysis of the components to verify that cyclic strain ranges are low enough to meet life goals. Vibratory data will be reduced to determine natural frequencies, mode shapes, and vibratory stress ratios. The vibratory data will also be compared to analytical predictions to ensure that potential high-energy vibratory modes are not present in the normal operating rotor speed ranges.

All turbopump major rotor components will be spin tested to verify burst margins and ultimate burst conditions. Each rotor part (impellers, inducers, and integral shafts/disks) will be individually mounted in an evacuated (vacuum) spin pit and rotated at incremental speeds up to a speed that simulates 122 percent of the design limit load speed, adjusted for room temperature material properties. Plastic growth measurements of the bore and pilot diameters, based on pre- and post-run dimensional inspections, will be used to verify structural burst margin and to calculate ultimate burst conditions.

All turbopump vessels will be pressure tested to verify structural integrity and to demonstrate that stresses at critical locations do not exceed the design criteria of 0.2 percent yield limit at 1.2 times the design point limit pressure condition (including tolerance additions). Pressure vessels will be assembled to tool fixtures or mating parts to provide interface restraints, load paths, etc. External loads will be applied through load frames and fixtures to complete the environmental load simulation. Strain gage instrumentation will be attached at the location of predicted high stress, or at locations of stress concentrations defined by analysis and laboratory test. Direct deflection measurements may also be recorded during testing. Each vessel will be pressurized using water or hydraulic oil at room temperature. The deflection and strain gage data will be reduced and correlated to the structural analysis to verify that all strains and strain ranges meet structural margin and life goals.

All critical turbopump parts having potential vibratory modes of excitation will be subjected to laser holographic analysis to determine resonant mode shapes and frequencies. These tests will concentrate on parts that have potential high-energy excitation sources, such as turbine blades, vanes, and struts and pump impellers and inducers. However, other critical hardware having possible mechanical or hydraulic excitation sources (such as housings, bellows, ducts, and structural supports) may also be evaluated using these techniques. Each part will be representatively mounted and excited over a range of frequencies covering all possible turbopump excitations using a vibratory force transducer. Laser holograms will be produced for all conditions of part resonance, identifying optically the deformation (mode shapes) of the structure. These data will be compared to the finite-element analysis predictions of resonant response to verify that the turbopump is free of resonant incidence at conditions of steady operation.

For detail part resonant responses that occur in the turbopump operating range, further testing to determine the dynamic stress associated with the resonant condition will be conducted. Further qualitative mapping of stress distributions will be performed on the shaker table using brittle lacquer coating or noncontacting infrared methods. Small, low mass strain gages will then be installed at maximum modal stress response locations, and a complete quantitative stress analysis conducted in all response modes of interest. These stress data will verify the low modal stress sensitivity (stress response/unit input) and associated suitability for turbopump operation over the full design speed range.

The turbopump rotor assembly will undergo impedance tests to provide modal data that will verify the analytically predicted rotordynamic characteristics. Rotordynamic characteristics at the impedance test conditions (zero rpm, room temperature) are predicted using the same design system that provides operational condition characteristics; therefore, these tests serve to provide maximum confidence in the accuracy of the on-condition dynamic rotor stability margins.

Experimental modal analysis is a state-of-the-art test procedure that uses a digital Fast Fourier Transform Analyzer to characterize the dynamic behavior of structures. The assembled rotor is supported by very soft, non-interacting mounts at the bearing support locations, simulating the rotor in the free-free, non-rotating state. Instrumentation consists of small piezoelectric accelerometers located along the length of the rotor.

Transient-impact techniques will be used to calculate frequency response functions (FRF) from measured input-force excitations and response accelerations generated at several locations along the axis of the rotor. Curve-fitting algorithms will be used to estimate a mathematical model of the structure response from which the resonant frequencies and corresponding mode will be extracted. Rotor modal response data will be correlated to the analytical rotordynamic predictions for the test conditions, providing verification of (or correction to) the assumptions and prediction system used for operational dynamic margins.

Cryogenic test rigs are available for turbopump ball and roller bearing evaluation. The objective of the bearing rig test program is to provide bearing performance and wear data, which supports turbopump bearing life goals, from cryogenic (design fluid) operation at actual speed and load conditions as defined by the duty cycle.

A GN2-powered turbine drive will be provided for each rig. Application of radial load to the test bearings is accomplished by a pneumatic actuator centered on the inboard bearing. The radial load reacted at the outboard tests bearing is lower than the load applied to the inboard bearing, providing the opportunity to evaluate a range of load values during each test.

In the ball bearing rig, axial loads can be simultaneously applied through an additional pneumatic actuator. This feature simulates the transient axial loads that occur during the short period before the thrust piston face pressure builds to an adequate level to react the net rotor axial loads. During steady-state operation, the axial loading required on the ball bearing to prevent excessive ball excursions is applied by the wave spring at the outboard test bearing.

Synchronization of applied loads with increasing speed, to simulate the actual load/speed ramp of the turbopump, can be accomplished by varying the pressurization rate of the pneumatic cylinders through fixed orifices. Redundant coolant flowpaths allow the test bearing flow rates to be set individually for test program flexibility. The rig will also accept a full complement of diagnostic instrumentation, including instrumentation to measure coolant temperatures and pressures at each bearing, speed, vibration, and outer race metal temperature.

C. FULL-SCALE TURBOPUMP

Turbopump testing will be conducted at the Stennis Space Center to provide functional evaluation of the pump, turbine, rotor support, and rotor thrust control system.

1. Design Requirement

The turbopump hardware will be designed to meet low acquisition and low operational cost as well as high reliability.

2. Objective

To demonstrate a highly reliable, low cost turbopump for the ALS program

3. Fabrication and Equipment

The turbopump test stand will be provided by NASA. Special test equipment, such as interface connections, and any ground test equipment will be provided by P&W.

4. Test Methods

A turbopump test plan outlining test objectives and operating conditions is provided in Table III-1.

A period of three months, including two weeks for mounting in the test stand, has been allotted for turbopump testing at Stennis Space Center. The assembled test article will be delivered in the middle of the 24th month, ready to be mounted in the Stennis test cell. The rig will be completely instrumented at P&W before shipment.

Table III-1. Preliminary Oxidizer Turbopump Test Program

Duration	*Pumping Fluid*	*Test No.*	*Objective*	*Test*	*Drive Fluid*
5 sec SS min	LN_2	1	A	Rotation	GH_2
5 sec SS min	LN_2	2	B,E,F	Run to 20%*	GH_2
5 sec SS min	LN_2	3	B,E,F	Run to 50%*	GH_2
10 sec SS min	LN_2	1	B,C,D,E,F	Run to 20%*	GG
10 sec SS min	LN_2	2	B,C,D,E,F	Run to 50%*	GG
TBD	LN_2	3,4,5	C,D,E,F	Run to 80, 90, and 100%*	GG
10 sec SS min	LO_2	1	B,C,D,E,F	Run to 50%*	GG
TBD	LO_2	2—6	C,D,E,F	Run to 80, 85, 90, 95 and 100%*	GG
TBD	LO_2	7,8,9,10	Optional		GG

*Percent of Turbopump Horsepower
A Demonstrate Breakaway Torque
B Verify Stability, Vibration, and General System Health
C Verify Transient Response
D Verify Bearing Cooling, Seal Performance, Thermal Conduction, and Perform Thermal Cycle
E Verify Pump Performance and Stability
F Verify Turbine Performance

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SECTION IV
INTEGRATED ANALYSIS PLAN

A key to the preliminary and detail design of the Advanced Launch System (ALS) oxidizer turbopump is the analytical work done during the design. This section outlines the analyses that will contribute to the design of the ALS oxidizer turbopump.

This integrated analysis plan covers the analytic resources to be used for design and design environment definition, requirements allocation, data evaluation, performance prediction, margin assessment, and compatibility assessment. The development process is iterative, resulting in multiple analyses by the same functional element as the product matures and is refined. The following elements are involved in designing a low cost, highly reliable oxidizer turbopump:

- System Design
- Pump Hydrodynamics
- Turbine Aerodynamics
- Turbine Airfoil Durability
- Structural Dynamics
- Rotor Dynamics
- Bearings
- Interpropellant Seal
- Heat Transfer
- Materials
- Structural Integrity
- Reliability/Maintainability/Safety
- Cost Model
- Process Selection
- Weights

Analyses for the oxidizer turbopump range from simple hand calculations supporting mechanical design to sophisticated computerized models simulating the complete system. The models of primary importance in the analysis effort are the Power Balance Model (PBM), used for steady-state requirement definition design trades and performance assessment, and the Digital Transient Model (DTM), used for establishing compatibility with other engine components. Output from these models provide the framework within which the detailed design and evaluation analyses are conducted.

Detail design and evaluation activity is supported by a variety of computer codes relating directly to the analysis item. These codes are validated through correlation with previous rocket system or gas turbine engine design and test data. The following sections provide a summary of the detailed analysis techniques, their input requirements, verification basis, output and products, and output empirical verification criteria.

A. SYSTEM DESIGN

Table IV-1 shows the system analyses to be used during the oxidizer turbopump system design. The analysis codes, based on various Space Transportation Engine models, will be used to define the system design environment, identify design requirements and margins, predict performance, and evaluate data.

Table IV-1. *System Design Analysis*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Conceptual Design	Steady state model	Preliminary design characteristics		Performance prediction and component design environment and compatibility	
Conceptual Design	Digital dynamic model	LOX turbopump performance • Hydrodynamic • Aerodynamic • Structural • Thermal • Rotor Dynamics	Turbopump requirements and design margins		
Conceptual Design	State variable stability and control model			Turbopump requirements and design margins	
Final Design			Turbopump component DVS test results	Pretest performance and component environment predictions	SSC DVS test results
Final Design				Post-test data evaluation	SSC, PFC, and FFC test results

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B. PUMP HYDRODYNAMIC ANALYSES

Table IV-2 identifies the analyses to be done on components to define and evaluate pump hydrodynamics.

Meanline calculations will be made for each subcomponent of the pump (inlet/discharge ducts, vanes, inducers, impellers), employing numerous empirical models and correlations to establish loss coefficients, fluid deviation angles, hydrodynamic loading limits, and basic sizing criteria.

Quasi 3-D Euler streamline analyses will be used for internal flow analysis of impellers and stationary vane cascades with solutions of radial equilibrium, continuity, intrablade, and energy equations to provide internal velocity-pressure distributions. Empirical correlations will be used to account for the influence of losses, fluid deviations, etc.

Two dimensional (2-D) Potential Flow Analyses will provide detailed evaluation of suction-pressure surface velocity distributions within blade and vane cascades. Boundary layer subroutines will account for viscous effects and predict flow separations.

A turbopump flow model will be constructed for the overall turbopump system, using subcomponent performance models, empirical seal leakage correlations, impeller disk friction/pumping analysis, and fluid property routines. The model provides overall pump performance map predictions and evaluation of turbopump axial thrust loads.

C. TURBINE AERODYNAMICS

The turbine design will have a mean diameter wheel speed that is compatible with allowable disk and airfoil root attachment stress criteria. The chosen wheel speed also provides a high design point wheel-to-gas velocity ratio, ensuring that efficiency will not fall off significantly at maximum power level (MPL) operation. The design point velocity ratios are conservative so the design aerodynamic risk is minimal. Table IV-3 outlines the turbine design analyses.

The size of the turbine annulus is defined by the last-stage blade root centrifugal stress limit for the chosen blade material, which is a function of annulus area $\times$ rpm^2. This annulus size is also selected to yield a favorable exit Mach number and low exit swirl. All these studies will be done by evaluating the turbine at the mean line velocity diagram aerodynamics.

Once basic parameters of annulus size, rpm, and wheel speed are determined, a detail study of the work splits between the stages, along with the stage reaction levels, will be performed to optimize the performance against known aerodynamic airfoil design risk parameters. Nearly equal work splits will be used, which is the natural high performance conclusion for turbines that have moderate overall pressure ratios. The choice of reaction level (ratio of static pressure drop across the blade to the pressure drop across the stage) will be the next study concluded.

Table IV-2. *Pump Hydrodynamics*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*
Conceptual Designs				
(a) Inducers	• One-dimensional meanline analysis • Empirical design correlations and criteria	• Engine cycle flowrate, pressure, and temperature • Inlet interface geometry	Empirical correlations from numerous past tests	One-dimensional velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(b) Impellers	• One-dimensional meanline analysis • Empirical design correlations and criteria	Output from (a), (c)	Empirical correlations from numerous past tests	One-dimensional velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(c) Crossover Ducts and Vanes	• One-dimensional meanline analysis • Empirical design correlations and criteria	Output from (b)	Empirical correlations from numerous past tests	One-dimensional velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(d) Discharge Vaned Diffusers	• One-dimensional meanline analysis • Empirical design correlations and criteria	Output from (b)	Empirical correlations from numerous past tests	One-dimensional velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses

Table IV-2. *Pump Hydrodynamics (Continued)*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*
(e) Discharge, Volutes and Diffusers	• One-dimensional meanline analysis • Empirical design correlations and criteria	Output from (d)	Empirical correlations from numerous past tests	One-dimensional velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
Preliminary/Final Designs				
(a) Inducers	• Quasi 3-D, inviscid potential flow, Euler analyses	• Engine cycle flowrate, pressure, and temperature • Inlet interface geometry	• Existing data base • Numerous past tests	Quasi 3-D velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(b) Impellers	• Quasi 3-D, inviscid potential flow, Euler analyses	Output from (a), (c)	• Existing data base • Numerous past tests	Quasi 3-D velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(c) Crossover Ducts and Vanes	• Quasi 3-D, inviscid potential flow, Euler analyses	Output from (b)	• Existing data base • Numerous past tests	Quasi 3-D velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses

Table IV-2. *Pump Hydrodynamics (Continued)*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*
(d) Discharge Vaned Diffusers	• Quasi 3-D, inviscid potential flow, Euler analyses	Output from (b)	• Existing data base • Numerous past tests	Quasi 3-D velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses
(e) Discharge, Volutes and Diffusers	• Quasi 3-D, inviscid potential flow, Euler analyses	Output from (d)	• Existing data base • Numerous past tests	Quasi 3-D velocities, velocity-diffusion gradients, flow angles, pressures, temperatures, and pressure losses

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Table IV-3. *Turbine Design*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Conceptual Design	1-D thermal, LCF, and creep analysis	Transient and steady operating environment	• Code verified by previous NASA thermal shock rig data (NASA contract NAS8-33821).	• Preliminary LCF and creep life estimates	Specific geometry thermal shock rig testing (if necessary)
		Materials creep data	• Hydrogen embrittlement creep data for the material. Also by comparison to codes M571 and F589	• Preliminary geometry and speed limits	
	Turbine meanline design (TMLD) system P774	Cycle performance and envelope	Code based on 30 past turbines test data	Size and performance	Component test
(a) Turbine Inlet Temperature Distribution	Average and peak temperatures, transient rise rates	Engine cycle-flows, temperatures, and pressures	Comparison with test data bases	Airfoil transient and steady-state temperatures	Gas path and metal temperature measurements
(b) Turbine Temperature Profile Attenuation	Empirical design correlations	Output from (a)	Correlations from past test	Airfoil and platform temperatures	Gas path and metal temperature measurements
(c) Turnaround Duct/Diffuser HGM Interface	• Empirical TAD, diffuser design curves	Turbine/exit HGM dimensions	Empirical data base from test	Internal flow patterns, pressure loss, and exit swirl	Water and air flow model tests in HGM flow models
	• 2-D axisymmetric teach code	• Turbine exit velocity, swirl angle, and velocity city profiles			
Preliminary Design	Same as above				
	Streamline flowpath analysis (SLD) Code W677	Output from TMLD Code P774	Cascade test data, past engine experience, and failure feedback	Detail airfoil design aerodynamic parameters	Component test
(a) Turbine Inlet Temperature Distribution	Rosner supercritical combustion calculation — inviscid mixing models	• Droplet size distribution, fluid properties	Comparison with test data bases	Hot-gas and airfoil transient and steady-state temperatures	Gas path and metal temperature measurements
		• Propellant injection flow rates, and velocities			

Table IV-3. *Turbine Design (Continued)*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
(b) Turbine Temperature					
Profile Attenuation	3-D inviscid Euler flow solver (N1 code)	• Turbine geometry • Output from (a) • Turbine inlet velocity profiles	Comparison with test data bases	• Airfoil and platform thermal environment • Temperatures • Heat-transfer coefficients	Gas path and metal temperature measurements
(c) Turnaround Duct/Diffuser/HGM Interface	3-D Navier/Stokes flow solver (INS3D, page, vast)	• TAD, HGM geometry • Turbine exit velocity, swirl angle, and flow profiles	Comparison with test data bases	• Streamline flow patterns • Pressure loss	Water and air flow model tests in HGM flow models
Final Design	Marc 2-D blade thermal shock analysis	Engine thermal data and centrifugal and gas bending loads	• Code verified by previous NASA thermal shock rig data. Also comparison to codes NASTRAN, M571 and F589 • Component test	Detailed airfoil geometry requirements and final LCF life	Component testing
	NASTRAN 3-D blade analysis	Engine thermal data, centrifugal loads, gas bending loads, and material properties	Test data from numerous successfully operating turbines designed by P&W	Maximum stress values and deflections	Component testing
	Airfoil design Code M905 pressure distribution Code T862 3-D Code U760	SLD output from Code W677	Cascade test feedback into evaluation system	Profile shape and airfoil pressure distribution	Component testing
	Airfoil curved line fairing and stress Code P824	Material properties and Code M905 output	Past jet engine stress and life feedback into P&W design system	Airfoil steady stresses and pulls	Component and engine test
TAD Diffuser/HGM Interface	3-D turbulent Navier-Stokes flow solver (preach, INS3D, page, vast — with modifications)	• TAD, HGM geometry • Turbine exit velocity, swirl angle, and flow profiles	Comparison with water flow test data	• Streamline flow patterns • Pressure loss	• Air flow test in HGM flow model • Measurements in simulator rig

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Low reaction levels yield low blade tip leakage losses but can also lead to airfoil aerodynamic flow separation because of the high degree of blade gas angle turning with little pressure drop across the airfoil. Airfoil convergence, the flow area entering the blade divided by the flow area leaving, is an important parameter for evaluating airfoil separation before the airfoil progresses to final design. Airfoil convergence will be an output of the meanline design program along with the predicted performance and exit conditions. Historically, turbines that have less than 25 percent mean reaction level or have blade convergence ratios of less than 1.20 tend to separate and perform poorly at off-design velocity ratios. Because this design must operate at off-design velocity ratios, considerable convergent ratio margin will be provided. Detail airfoil design, based on a three-dimensional flow analysis, will be performed to substantiate these conservative choices.

Airfoil chord selection will be a trade-off between the allowable airfoil bending stress versus the efficiency losses incurred from secondary flow losses in low blade height, large chord, widely spaced airfoils. Airfoil bending stress is inversely proportional to both the number of airfoils accepting the total turning load and also to their axial chord length squared.

Studies to optimize the number of blades and vanes will be finalized in the design process. The same number of blades will be used in each stage to allow the use of common broach slots for bladed disk configurations. If integrally bladed rotors (IBRs) are used, this requirement will be dropped.

To ensure that the preliminary sizing studies are correct, P&W will progress beyond the 2-D meanline design into the 3-D flowpath design in which 11 separate streamline velocity diagrams are modeled across the entire annular flowpath. This will fully define the airfoil inlet and exit angles and flow conditions across the entire blade height. Individual airfoil flowpaths will be designed at the critical root and tip sections to match the meanline sections. The channel flow between airfoils will also be evaluated.

The airfoil surface contours will be modified until smooth suction surface pressure distributions are obtained. The blade airfoil sections will then be hollowed to obtain a thin, tapered wall from root to tip to distribute the centrifugal stresses and to maintain the thin walls necessary for low thermal strains. The airfoil pull forces will then be calculated and the airfoil root attachment and disk configurations formed to meet life requirements. Similar design analysis is used to configure the vane airfoils.

The selected turbine efficiency goal is consistent with rocket turbines previously developed. Pratt & Whitney historically has shown good agreement between turbine efficiency predictions and test data.

D. TURBINE AIRFOIL DURABILITY

Table IV-3 shows the analyses to be done to evaluate turbine airfoil durability.

During the basic effort, limits on turbine blade pull stress will be generated based on the creep life requirements, predicted metal temperatures, and materials capabilities in the appropriate hot gas environment. Since blade pull stress is a function of turbine annulus area times rotor speed squared, setting limits on pull stress will help define an acceptable speed and turbine annulus size. Also, limits on vane gas bending stresses are generated based on stress rupture requirements.

A one-dimensional, thermal shock analysis will be performed on the turbine hot flowpath hardware to identify maximum wall thickness limits for the turbine blades, vanes, and endwalls. This analysis will require that the start and shutdown transient turbine parameters be defined. The results of this analysis, which sets maximum airfoil wall thicknesses when coupled with the turbine aerodynamic requirements for airfoil outside contour requirements, will identify whether the airfoil will be a hollow or a thin and solid design. This preliminary design will then be screened for vibrational characteristics to ensure high cycle fatigue (HCF) acceptability.

Selection of the turbine hot flowpath/airfoil materials will be governed by cost and manufacturing techniques, as well as its compatibility with the hot gas environment. For the turbine exposed to hydrogen, alloys previously characterized in high-pressure hydrogen will be considered. Use of equiaxed alloys will be preferred because of lower cost, and single-crystal alloys will only be considered if required for durability. In a methane environment, carbon will be included in such design considerations as foreign object damage and added pull due to carbon buildup on the blades.

During the priced option, the blade and vane geometry will be defined externally and internally if a core is used. Detailed heat transfer and structural analysis using the MARC computer code will be done on all the blades. This analysis will define the thermal shock capability of the blades. This analytical tool has been empirically correlated to results from the Marshall Space Flight Center (MSFC) and P&W thermal shock testing described in National Aeronautics and Space Administration (NASA) TM-86528 and AIAA-86-1443. The blades will also be analyzed using a probabilistic life model developed jointly between P&W and NASA's Jet Propulsion Laboratory (JPL). The model accounts for statistical variations in materials properties, airfoil geometry, engine parameters, and transient variations.

E. STRUCTURAL DYNAMICS

Table IV-4 outlines the structural dynamics analyses.

Pratt & Whitney's design system for the ALS oxidizer turbopump will use extensive finite element analysis to tune fundamental vibratory modes away from primary excitations. All components will be manufactured from alloys exhibiting high strength and satisfactory fatigue capability. Friction dampers will be used to lower the vibratory response of the turbine blades to increase HCF durability.

The P&W design criteria requires a minimum of 10 percent margin between the natural frequencies of all rotating and stationary hardware and the primary excitation frequencies in the turbopumps. Primary excitations include one, two, three and four times the rotor speed (1E, 2E, 3E and 4E) plus additional excitations caused by the pressure pulses produced as the rotating components pass a stationary vane, strut, or other flow disruption.

Table IV-4. *Structural Dynamics*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Conceptual Design	NASTRAN plate element finite-element analysis and hand calculations of critical airfoil components	Geometry, material characterization, and speed and temperature information	Measurements, material testing, and rig and component test measurements	Frequencies and mode shapes	Previous turbomachinery experience on similar designs
Preliminary Design	Detailed NASTRAN plate finite-element analysis of all rotating and critical nonrotating components	Same as above with more detail	Same as conceptual design	Frequencies, mode shapes, and stress ratios	Previous turbomachinery experience on similar designs
Turbine Rotor-Stator Interaction	3-D inviscid, unsteady Euler Flow slover (N1 code)	• Turbine geometry • Output from turbine inlet • Turbine inlet velocity profiles	Comparison with test data bases	• Airfoil surface pressure and temperature distributions • Streamline flow patterns	Time resolved rotor and stator pressure distributions from rig tests
Final Design	Detailed NASTRAN plate/solid element finite-element analysis of all major components	Same aas preliminary design with detail	Same as preliminary design	Same as preliminary design with more detail	• Lab holography • Stresscoat/Spate • Shaker table • Spin pit test • Engine strain gage testing
CFD Analysis of Rotor Stator Interaction	Quasi 3-D nonsteady Navier-Stokes flow solver (to be developed)	• Turbine geometry • Output from turbine inlet distribution • Turbine inlet velocity profiles	Comparison with test data bases	Airfoil surface time-dependent pressure temperature distributions	• Time-resolved rotor and stator pressure distributions from rig test • Time-resolved blade stress levels from simulator rig

Table IV-4. *Structural Dynamics (Continued)*

Design Phase	Analysis Codes	Input Required	Verification Basis	Output	Empirical Verification
Final Design Refinement	Quasi-3-D nonsteady Navier-Stokes flow solver (to be developed)	• Turbine geometry • Output from turbine inlet distribution • Turbine inlet velocity profiles	Comparison with simulator rig data	Airfoil surface time-dependent pressure temperature distributions	• Turbine life test data • TTB engine test data
DVS (Data Evaluation)	• Lab holography	• Actual hardware and fixturing	Dimensional checks	• Frequency and mode shapes	• Previous turbomachinery experience
	• Dynamic strain gage measurements lab and engine	• Actual hardware	• Similar techniques used on previous turbomachinery	• Vibratory stress and frequency	• Cross-checking of independent testing
	• High cycle fatigue (HCF) testing	• Hardware and specimen testing in environment	• Test environment measurement	• HCF capability	• Analytical predictions • Simplified model testing

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Blade platform-to-platform friction dampers are used to damp all blade excitations, and have proved to be effective at all power levels. These dampers control buffet and resonant vibratory stresses. Pratt & Whitney has developed an analysis code to size the damper and to predict the stress reduction. The program uses an energy method to evaluate the stress reduction for a range of loading forces. Frictional dampers will be used for both bladed disk and IBR configurations.

With IBR's, a method to damp blade resonances in the operation range must be provided. For dampers to be effective, relative motion between adjoining parts is required. One damping scheme eliminates the resonance energy through frictional heat with finger dampers. The dampers are placed between each airfoil in milled or cast channels. Another scheme is a tuned ring that eliminates the energy from the airfoils by being tuned to resonant frequencies different from those in the airfoil. Because of the extensive damper experience base available, the baseline configurations will be a stiff conventional damper to bridge the platform gap between blades to frictionally dissipate the vibrational energy through the relative motion of the adjacent platform.

Design criteria developed from operational hardware, in conjunction with proven analytical techniques, will help ensure the turbopumps exhibit dynamic structural integrity. Avoidance of resonance at all power levels will minimize vibratory excitation. Analytical predictions will be verified by a full laboratory and rig substantiation testing program as described in Section III.

F. ROTOR DYNAMICS

Table IV-5 outlines the rotor dynamics analyses.

The ALS turbopump design uses proven criteria and analytical methods to provide acceptable rotor dynamics. The high-pressure turbopump design provides stiff rotors, bearings, and rotor support structures with roughened stator damper seals. Each rotor is supported by strategically located, stiff, durable, bearings for optimum rotor dynamics. These features result in fundamental rotor bending modes, located a minimum of 20 percent above the maximum design operating speed. This, combined with an effective rotor balance procedure results in low synchronous response.

The ALS oxidizer turbopump design will be analyzed to ensure (1) operation below rotor bending modes, (2) sufficient stability margin, and (3) a high integrity rotor balance. Meeting these provisions will require optimization of the mechanical design of the rotor, bearings, rotor supports, damper seals, and housings for acceptable rotor dynamic characteristics.

Table IV-5. *Rotor Dynamics*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Conceptual Design	(1) Critical speeds analysis	(1) Geometry, material characterization, and temperature	(1) Measurements, material testing, and rig and component testing	(1) Undamped natural frequency and mode shape	N/A
	(2) Forced response analysis	(2) Geometry, material characterization, temperature, unbalance, and damping	(2) Measurements, material testing, and rig and component testing	(2) Synchronous dynamic bearing loads	N/A
	(3) Static deflection analysis	(3) Geometry, material characterization, temperature, and vehicle maneuver	(3) Measurements, material testing, rig and component testing, and mission requirements	(3) Static bearing loads, and bearing loads resulting from vehicle maneuvers and engine gimballing	N/A
	(4) Damper seal analysis (code provided by turbomachinery industrial consortium)	(4) Pressure drop, geometry, rotor speed, fluid characterization, and inlet conditions	(4) Measurements and rig and component testing	(4) Direct and indirect rotordynamic coefficients and leakage	N/A
Preliminary Design	(1) Same as (1) above	(1) Same as (1) above	(1) Same as (1) above	(1) Same as (1) above	N/A
	(2) Same as (2) above	(2) Same as (2) above	(2) Same as (2) above	(2) Same as (2) above	N/A
	(3) Same as (3) above	(3) Same as (3) above	(3) Same as (3) above	(3) Same as (3) above	N/A
	(4) Same as (4) above	(4) Same as (4) above	(4) Same as (4) above	(4) Same as (4) above	N/A
	(5) Nonlinear transient response analysis	(5) Geometry, material characterization, temperature, unbalance, and damping	(5) Measurements, material testing, and rig and component testing	(5) Synchronous response as a function of rotor speed during startup and shutdown	N/A
	(6) Stability analysis	(6) Geometry, material characterization, temperature, and destabilizing forces	(6) Measurements, material testing, and rig and component testing	(6) Nonsynchronous response as a function of rotor speed	N/A

Table IV-5. *Rotor Dynamics (Continued)*

Design Phase	Analysis Codes	Input Required	Verification Basis	Output	Empirical Verification
Final Design	Same as (1) through (6) above	Same as (1) through (6) above	Same as (1) through (6) above	Same as (1) through (6) above	(1) Rotor modal analysis and turbopump vibration monitoring during component testing (2) Turbopump vibration monitoring during component testing (3) Engine test monitoring (4) Damper seal rig (5) Turbopump vibration monitoring during component testing
	(7) Geometric rotor tiebolt balance	Geometric dimensions	Dimensional measurements	Balance correction requirements	(7) Rotor balance and turbopump vibration
DVS	(1) Modal Analysis	(1) Excitation and frequency response data	(1) Vendor testing and previous hardware experience	(1) Natural frequency and mode shape	(1) XLR-129 HPFTP and jet engine experience, critical speeds analysis, and simplified model test
	(2) Housing/bearing support static spring rate test	(2) Load and deflection	(2) Test calibration and measurements	(2) Housing/support springrate	(2) Previous turbomachinery experience on similar hardware
	(3) Engine component vibration analysis	(3) Turbopump response	(3) Test calibration and redundant measurements	(3) System response, displ, velocity, and acceleration	(3) Test calibration, redundant measurements, lab testing, and analytical predictions

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In high-pressure rocket turbopump designs, P&W provides combined rotor support system stiffness (bearing, carrier, and backup structure) that equals or exceeds the relative stiffness of the rotor structure to minimize rotor strain energy. Simplex bearing configurations are favored because of the stiffness uncertainties associated with duplex ball bearings.

Rotor dynamics synchronous response, seal characterization, and stability analysis codes will be used as needed to determine the damper seal configuration requirements for optimized system dynamics. Each of the seals is designed for high damping, moderate stiffness, and minimal leakage. The incorporation of damper seals in the pumps provides a reduction of synchronous response throughout the operating speed range, resulting in low dynamic bearing loads and rotor deflection, sufficient margin on the threshold speed of instability, and additional rotor load support.

G. BEARINGS

Table IV-6 gives the analyses to be done for the bearings.

Analytical work for the bearings will accomplish the following:

- Establish cooling requirements using Shaberth computer program for frictional heat generation and empirical equations for windage.
- Identify axial preload for ball bearings using Jones computer program. Optimize preload to minimize ball spin-to-roll ratio, minimize ball excursion, maximize stiffness, prevent ball skidding, provide acceptable contact stresses, and calculate rolling contaet fatigue life.
- Using P&W fit check codes, establish inner and outer ring fits to prevent ring spinning, minimize inner ring hoop stresses, and provide adequate outer race deadband clearance for ball bearing preload and roller bearing outer race flexibility.
- Select roller bearing negative inner race clearance (IRC) for proper roller guidance.
- Review cage clearances to determine if they are adequate for ALS operating conditions.

Table IV-6. *Bearing Design*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
System Requirements and Initial Engine Performance	Jones II High-Speed Bearing Analysis	Bearing geometry, speeds, assumed loads, and material	Rig test, inspection, and ATD experience	Life, stress, and radial stiffness	Experience and literature
Conceptual Design	Jones II High-Speed Bearing Program	Bearing geometry, speeds, loads, and material — system	Rig test inspection, and experience	Life, stress, and radial stiffness	Experience
	Jones IV Roller Bearing Program	Bearing geometry, speeds, loads, and material — roller bearing	Rig test inspection, and experience	Life, stress, and radial stiffness	Experience
Preliminary Design	Shaberth Bearing Heat Analysis	Bearing geometry, speeds, assumed loads, and material	ATD Rig test	Bearing Component temperatures	ALS rig test
	Fit Analysis	Bearing geometry, speeds, material, and fits	ATD rig test and inspection	Operating IRC and fit stresses	ALS rig test
	Skid Analysis	Bearing geometry and speeds	Experience and inspection	Load required	Rig test
	Jones II, High-Speed Bearing Analysis	Bearing geometry, speeds, loads, and material as system	Rig test and experience	Life, stresses, radial stiffness, and bearing dynamics	Rig test
	Jones IV, High-Speed Bearing Analysis	Bearing geometry, speeds, loads, and material — roller bearing	Rig test and experience	Life, stresses, and radial stiffness	Rig test
Detail Design	Heat Transfer Analysis (Finite-Element Program)	Bearing and compartment geometry, materials, coolants, temperatures, and loads	ATD rig test and inspection	Bearing compartment temperatures	ALS rig test
	Roller Load Analysis	Bearing geometry, thermals to prevent dynamic motion radial loads, and speeds	ATD rig test and inspection	Minimum roller load	ALS rig test

Table IV-6. Bearing Design (Continued)

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Detail Design (Continued)	ANVIL CAD/CAM Program	Bearing compartment and test rig dimensions	Inspection	Design geometry for finite-element analysis and manufacture	Inspection
	Jones II, Jones IV	Final bearing geometry, fits speeds, loads, materials, and temperatures	ATD rig test	Final analytical bearing life, stresses, and spring rates	ALS rig test and inspection
Verification Testing	Final Design Component Testing	Final lands, speeds, geometry, temperatures, coolant flow	Inspection	Final test life	Component test
	Final Subassembly Testing	Final loads, speeds, geometry, temperatures, coolant flow	Inspection	Final test life	Component test

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1. All-Ball-Bearing Configuration

During the design of the ALS oxidizer turbopump, P&W will conduct analyses aimed at developing all-ball-bearing configurations, with the goal of designing low-cost alternatives to roller bearings. All-ball-bearing configurations allow for increased bearing quantities, provide the capability to handle startup and shutdown axial loads in either direction, and allow for looser assembly tolerances. Additional analyses to be done to meet this objective include the following:

- A mechanical design study to ensure that the ball bearing will fit in roller compartment
- A rotor dynamics trade study to determine if ball bearing support provides adequate rotor dynamics.

During the priced option, P&W will conduct additional analyses during the final design to accomplish the following:

- Finalize fits and clearances taking into account shaft thrust loads and race clamping loads.
- Using Jones program, perform trade studies to determine effects of misalignments, ranges in preload, ranges in IRC from fit tolerances, and margin for increased sideloads.
- Through rig margin and endurance testing, verify heat generation, monitor bearing wear, and study effects of coolant depletion, and axial and radial overloads.

2. Alternate Cage Design

As an option, Pratt & Whitney will consider an alternate one-piece cage design for ball bearings under a technology development program. Analytical work would include the following:

- A Jones analysis to determine equivalent rig operating condition to simulate ball-to-race contact stress, ball spin velocities, and ball rotational velocity
- A literature search to identify candidate materials
- A rig test program and coverage to evaluate materials.

3. Hydrostatic Bearings

Pratt & Whitney will consider analyses under a technology development program to determine feasibility of using hydrostatic bearings in the ALS oxidizer turbopump.

H. INTERPROPELLANT SEAL

A transient thermal analysis will be performed for static and rotating components to determine thermal and structural stresses and resulting seal clearances during transient operating conditions. These clearances will be analyzed together with rotor deflections to avoid potential rubs. The final clearances will be used to determine seal performance, including flow rates and pressure profiles; the effects of the pressures on thrust balance and component loading; and the loss of cryogens overboard.

Test results obtained during testing of the various knife edge sealing systems in the interpropellant seal rig for the Space Shuttle Main Engine Alternate Turbopump Development (SSME ATD) Program will be used to calibrate analytical procedures for the design of labyrinth seals operating in cryogenic fluid environments. The same existing calibrated analytical tools will also be used for the ALS.

I. HEAT TRANSFER

A steady state thermal analysis will be performed to obtain steady state operating conditions for all turbopump components. The thermal output from these analyses will be used in all component stress and deflection analyses to ensure all design margins and requirements are met at steady state operation points. For critical parts which are identified as low cycle fatigue (LCF) or fracture critical, additional thermal analysis will be performed to fully define the start-up and shut-down transient thermal response of the identified hardware. This additional analysis will include the effects of tolerances, performance degradation with time, abnormal operation of surrounding hardware such as gas generator hot streaks, and the effects associated with engine cycle balances.

J. MATERIALS

During the fabrication evaluation, P&W will use its experience in developing material alloys and unique manufacturing techniques to evaluate viable low cost concepts. This experience has been gained in P&W's manufacturing facilities and by working with its large supplier base.

One consideration to reduce pump cost is the use of less expensive materials having either lower raw material costs or reduced fabrication costs. Some of these materials have not undergone full material characterization at cryogenic temperatures or in the proper operating environments. Materials will be selected based on a P&W and vendor data base and by comparing the demonstrated performance of alloys with similar chemical compositions, behavior, and thermal-mechanical processing influences. Early in the program, preliminary material characterization will be performed to confirm the material properties used in the early configuration analyses.

K. STRUCTURAL INTEGRITY

The analyses required to ensure structural integrity are shown in Table IV-7.

Technical support of the ALS turbopump designs will be based on the experience P&W gained from designing a high-pressure hydrogen turbopump and a high-pressure LOX turbopump for the SSME. Since the ALS turbopumps are similar to the SSME alternate turbopumps in design configuration, the extensive design experience gained with the SSME alternate turbopumps can be applied to the ALS program. By applying this experience, design iterations can be eliminated, known problems avoided, and a reliable and durable turbopump system can be produced.

Table IV-7. *Steady-Stress and Life Analysis*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Conceptual Design Phase I	NASTRAN 2-D finite element	Material properties, temperature, and pressure speed	Continous verification through instrumented engine and component test, and material quality control monitoring	Stress, deflections, and springrates	
	LCF life prediction	Surface stress, temperature, and time	Continous verification through instrumented engine and component test, and material quality control monitoring	LCF life	
	Fracture mechanics NDE requirements	Stress field, temperature, and time	Continous verification through instrumented engine and component test, and material quality control monitoring	NDE requirements	
Final Design Phase 2	NASTRAN 2-D finite element	Material properties, temperature, and pressure rotor speed	Continous verification through instrumented engine and component test, and material quality control monitoring	Stress, deflections, springrates, and stress concentration factors	Instrumented spin, pressure and load test
	Boundary integral equation stress 2-D and 3-D	Material properties, temperature, pressure, and rotor speed	Continous verification through instrumented engine and component test, and material quality control monitoring	Stress, deflections, springrates, and stress concentration factors	Instrumented spin, pressure and load test
	LCF life prediction	Surface stress, temperature, and time	Continous verification through instrumented engine and component test, and material quality control monitoring	LCF life	Specimen cyclic standards

Table IV-7. *Steady-Stress and Life Analysis (Continued)*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
	Fracture mechanics NDE requirements	Stress field, temperature, and time	Continous verification through instrumented engine and component test, and material quality control monitoring	NDE requirements	NASA NDE standards
DVS	Static strain analysis	Strain measurement, temperature, and calibrations	Calibrations traceable to NBS	Component stress	Repeatability and duplicate readings comparison to analysis

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Based on its SSME ATD experience, P&W will specify up front the flowpath factors, geometries, and materials that do not need additional characterization and that are known to be necessary to achieve structural life and durability. Pratt & Whitney will also use the SSME ATD experience to eliminate detail finite element computer analyses by using design curves and equations based upon known structural behavior and to predefine step-by-step proven analysis procedures for those critical areas that require detail structural verification. Pratt & Whitney will specify only those structural tests that have been proven to provide meaningful results. Although P&W will minimize the ALS structural analysis effort by using SSME ATD experience, the methods and procedures will be constructed to maintain the structural margins passed down from the SSME ATD Program.

1. Static Strength

The following analyses will be conducted to evaluate the static strength of the turbopump design.

- All structural loads and environments will be identified or derived as required.

- Static stress will be evaluated based upon methods of finite element analysis (NASTRAN, MARC, ANSYS), industry codes (ASME), or standardized handbook procedures.

- The burst speed of all rotating disks will be predicted based upon the average tangential stress in the rotor and a material use factor. Material use factors will be based upon spin tests of similar components. Containment energy/capability will be predicted. The permanent growth of rotors as a result of overspeed will be predicted.

- The burst pressure for all housings subjected to internal pressure will be predicted.

2. Life

The following analyses will be conducted to predict the durability of the oxidizer turbopump.

- LCF life will be predicted for all components that experience has shown to be critical. Finite element methods (2-D NASTRAN or similar), in conjunction with stress concentration factors derived from boundary integral methods (PESTIE) or standard tables (Peterson), will be used. A conservative approach will be followed to maintain a minimum life of 4.0 times the design life requirement.

- HCF life will be predicted for all components subjected to high vibratory stress. A conservative approach will be maintained by designing for a positive Goodman diagram margin based upon an infinite life endurance strength and calculated steady state stress. Airfoils and blades will be designed for a steady stress based upon a target allowable vibratory stress of 30.0 ksi peak-peak. Appropriate stress concentrations will be considered. Goodman diagrams will be drawn with margins indicated.

- Fracture control will be maintained by establishing allowable design stress levels for components designated as fracture critical. The determination of allowable design stress levels will be based upon previous similar designs

(SSME ATD). No formal Fracture Control Plan or detailed fracture analysis will be provided.

- Components operating in an environment where a potential for creep exists will be designed with allowable stress levels that will maintain a minimum life of 4.0 times the design life requirements.

3. Geometrical Specifications

Geometries relating to critical structural requirements will be identified and specified. These will include, but be not limited to, fillet radii, pilots and fits, minimum thickness, and airfoil tilts.

L. RELIABILITY, MAINTAINABILITY, AND SAFETY

1. Failure Modes and Effects Analysis/Critical Items List (FMEA/CIL)

The FMEA/CIL is initiated by the reliability engineer during the layout review phase. The FMEA provides a total assessment of the system to quantify the effects of a part failure on system operation. Using the FMEA in conjunction with the layout reviews, the reliability engineer ensures the design incorporates features to eliminate or reduce the probability of a catastrophic system malfunction by incorporating redundancy, increased safety margins, or eliminating parts through alternate design concepts.

The FMEA/CIL will integrate the turbopump failures to system level effects. It will establish the criticality of the failures and provide the emphasis to concentrate on the most critical failure modes. The FMEA/CIL will require a comprehensive analysis of the turbopump components to assess all potential failures to establish a high-to-low probability list, which will allow Design or Quality to prioritize their respective efforts for redesign or process control.

The failure modes addressed by the FMEA are derived from several methods. The preliminary FMEA is derived using historical failure mode data established on similar components. As the design progresses, the FMEA is updated to reflect the reliability design improvements built into the system. These modes are established through discussions with the designers, engineering concerns expressed during design reviews, and layout reviews by the reliability engineer. Further updates to the FMEA are made throughout the design and development cycles as the design reaches the production configuration.

2. Probabilistic Life Analyses

Probabilistic life analyses allows an understanding of the effects of varying parameter values on a design's life characteristics and operational capability to optimize the design verification testing, to quantify the effects of design and material variations, and to determine the safety margins for each component. The turbopump requirements will cause concerns of failure from low cycle fatigue, stress rupture, creep, and corrosion. These concerns are addressed through probabilistic design, an analytical process that allows selective statistical design and redesign of parts to eliminate or control those failure causes.

The Probabilistic Analysis is integrated with the reliability predictions through the design capability of the engine. The analysis will help quantify the design's capability to meet the system requirements. Depending on the outcome of the analysis, the reliability predictions will be changed to reflect the increase, decrease, or design change recommended by the analysis.

3. Reliability, Maintainability, and Safety (RMS) Design Evaluation and Reviews

The P&W reliability engineer is an integral part of the design process team. As a design's concept is established, Reliability Engineering initiates layout reviews to ensure that reliability features are properly incorporated in the design. These layout reviews further instill reliability concepts within the design by allowing the reliability engineer to assess the overall design, including critical dimensions and processes, and to evaluate how well the design will fit in with the component and engine systems.

The layout reviews also provide an opportunity to assess initial reliability allocations. These allocations are established by analytically quantifying a baseline system to the expected enhanced design. During the layout reviews, the allocations can be assessed with the conceptual design for better definition of the part count, material, etc. This permits the reliability engineer to increase the accuracy of the allocations and overall system reliability.

4. Support Cost Model Input

Reliability/Maintainability input to the support cost model includes failure rate predictions, mission schedules, maintenance plans, material and labor costs per maintenance event, turnaround requirements and specification, man-hour estimates per failure mode, and scaling requirements.

5. Reliability Predictions

The preliminary analyses to quantify and qualify the turbopump reliability will continue throughout the design effort. These reliability tools will be used to increase the effectiveness of the design verification process and to ascertain that the component reliability is not degraded when transitioned to production.

The methodology used to predict the reliability of the P&W ALS baseline engine will be a bottoms-up approach. The rocket and jet engine data bases will be queried to derive baseline component reliability. All pertinent component designs relating to similar ALS hardware will be studied and weighting factors established by the reliability engineer, in conjunction with the ALS design team, to account for various degrees of complexity, usage, and technology risks.

Each rocket engine (F-1, J-2, SSME, RL10, etc.) application in the data base has its own set of internal conditions, such as temperatures and pressures. Correlations will be established between these conditions and reliability to relate the ALS design and its usage to these correlations. Allowance will be made for different materials and design approaches in selecting the reliability estimate for each component.

As changes to the design are made through the design and development phases, the reliability engineer will work with Design using this same methodology to evaluate the reliability impact of each change. Extensive model runs to investigate material characteristics, design stress limits, flow characteristics, and other design parameters will be reviewed by the reliability engineer to evaluate any reliability impacts.

6. Maintainability Analysis and Demonstration

Pratt & Whitney will establish maintainability goals that minimize maintenance requirements and task times and eliminate labor-intensive preventive maintenance by maximizing the use of onboard system/component health monitoring devices. Initial actions will be the development of qualitative and quantitative design criteria that will be distributed to the ALS design team. The maintainability engineer's participation will begin at program start and continue throughout the program.

7. System Safety Program Plan

Pratt & Whitney will conduct the analyses required by the System Safety Program Plan, including the Preliminary Hazard Analysis, Operational Hazard Analysis, and Fault Tree Hazard Analysis. These are described in detail in the System Safety Plan.

M. COST MODEL

Detailed cost model planning and formulating will begin during the basic effort with the model structure being defined in detail along with all assumptions and the sources and methods that will be used for obtaining input data. The analytical formulation of the cost model will be completed and programming begun during the latter stages of the basic effort.

The first three months of the option phase will be dedicated to completing the programming of the cost model. During this period, a manufacturing plan will be generated for flight versions of the turbopump and empirical input data for the model gathered. Production cost and cost-related empirical input data will be obtained for purchased parts from suppliers. The manufacturing cost and cost-related empirical input data for P&W-manufactured parts will be generated by P&W manufacturing engineers.

Input data for the operation and support (O&S) cost portion of the model will be generated. Required failure mode Weibulls, and both scheduled and unscheduled maintenance event data, will be defined. Prelaunch and turnaround task requirements will be determined.

One of the tasks in the cost model effort is to determine the cost impacts of Government specification requirements and to recommend changes for high cost specifications that will meet the intent of the specifications while reducing cost. The cost impacts of the specification requirements will be quantified by assessing the impacts of the requirements on the turbopump design and fabrication processes and determining how cost is affected. P&W will perform these analyses for its manufactured parts, and the suppliers will support the analyses for the purchased parts.

The model will be capable of predicting costs for engines with a thrust range from 300 to 800K pounds and chamber pressure levels between 1500 to 3200 psia. Empirical dimension and cost scaling parameters will be developed for these routines and incorporated in the model.

A final step after completing fabrication of the full-scale turbopump will be to update all appropriate cost model input data to reflect experience gained during the fabrication and testing process. This data will involve manufacturing cost and cost-related data for all P&W-manufactured and purchased parts, Weibulls and maintenance event data, Government specification impacts and an updated Contract End Item (CEI) Specification.

N. PROCESS SELECTION

Table IV-8 summarizes the analyses planned for process selection.

During the basic effort, a variety of low cost design concepts and fabrication processes will be evaluated against the current baseline turbopump to determine whether these new concepts will provide an improved design. A number of parameters will be evaluated, with cost being one of the primary criteria considered. Among the cost impacts evaluated will be both low- and high-rate production costs, manufacturing investment costs, O&S, and design, development, test and evaluation (DDT&E) costs. The production cost assessments will be based on empirical analyses using data from existing P&W manufacturing data bases, adjusted where necessary for component and fabrication differences. Supplier experience for similar parts and processes will be used to assess costs for supplier parts. For new manufacturing processes where data does not exist, the production costs will be estimated from analytical assessments of the process steps involved.

Table IV-8. *Process Selection*

Design Phase	*Analysis Codes*	*Input Required*	*Verification Basis*	*Output*	*Empirical Verification*
Preliminary Screening of Alternative Concepts/ Configurations	Evaluation criteria "model" to screen and eliminate configurations	Relative comparison to baseline configuration • High volume production cost • Manuf. Investment Requirements • Meeting ALS Sched. • Operation & support cost • Reliability • Reusability • Performance • Weight • Development cost • Packaging • Transient operation • Fuel compatibility • Applicability over range of engine sizes and PC levels		Best concepts/ configurations based on weighted criteria score	Fabrication of hardware samples for demonstration program
Fabrication/Sample Demonstration of Best Alternative Concepts	Go/no-go tests to determine suitability of concepts			Concepts fit into the following categories: (a) Feasible and can be used in this program (b) Needs further development — may still fit into the program (c) Needs further development — may fit in phase C/D of STEP (d) Not feasible — no further investigation	
Final Evaluation of Alternative Concepts	Evaluation criteria incorporating demo program	Output from item (b) above		Selection of final turbopump configuration for Phase II	Fabrication and test of full scale turbopump in Phase II

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After the initial evaluation of the new concepts has been completed, those showing the most promise will be further evaluated in a fabrication demonstration program. Data from this activity will provide additional information which will permit a more definitive estimate of the production cost differences considering both high and low production volume rates. The availability of production facilities and equipment will be judged and a rough order of magnitude estimate made for manufacturing investment cost. The impact on DDT&E cost will be evaluated based on historical program data and this information considered in the selection process.

The final major cost category that will be evaluated is O&S cost. Reliability estimates will be used to define unscheduled maintenance requirements. Scheduled refurbishment, prelaunch and turnaround tasks will be defined to estimate scheduled maintenance requirements and costs.

O. WEIGHT

Table IV-9 summarizes the weight analyses.

During the basic effort, weights will be estimated for the baseline turbopump concept. The weights will be determined from preliminary drawings using calculations of part volumes and applying the appropriate density values. Alternative concepts and material changes will be evaluated by comparing the alternate designs to the baseline turbopump components and calculating volume and density differences.

In the priced option, weights of the selected turbopump design will be calculated from detailed prints.

Table IV-9. Weights

Design Phase	Analysis Codes	Input Required	Verification Basis	Output	Empirical Verification
I	Baseline weight estimate	Preliminary drawing of baseline turbopumps		Calculate part volumes from drawings and apply density factor for weights	
	Alternative designs and materials	Sketches or dimensions of pump changes req'd		Ratio part weights from baseline either dimension of density changes.	
II	Detail weights	Detail prints of turbopump parts		Calculate individual part weights from detail prints	
	Actual weights	Obtain pump actual parts and final pump assembly			Weight parts and final pump for verification

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SECTION V
OTHER EFFORTS

During the Advanced Launch System (ALS) Advanced Technology Oxidizer Turbopump Program, Pratt & Whitney will apply knowledge gained from other efforts to the oxidizer turbopump design. Other efforts likely to impact the turbopump design include the Space Shuttle Main Engine (SSME) Alternate Turbopump Development (ATD) Program and parallel technology programs.

Pratt & Whitney is developing an alternate turbopump for the SSME under National Aeronautics and Space Administration Contract NAS8-36801 and will apply the lessons learned from the ATD Program to the ALS oxidizer turbopump program. Details on the applicability of the SSME ATD program to the ALS turbopump design are discussed in Section II.

Since the ALS program follows the ATD program, the ALS program will be able to take full advantage of ATD successes. In addition, the capabilities of the fully matured ATD rigs will be used to verify the ALS bearing designs. This one-two approach to design and test verification will be used for the ALS program.

Pratt & Whitney may also conduct parallel programs to develop technology not yet mature enough to be incorporated into the ALS oxidizer turbopump design. Examples of such technology includes an alternate one-piece cage design for ball bearings and the development of hydrostatic bearings. Alternate materials may also be developed under related technology programs.

SECTION VI
HARDWARE NECESSARY TO ACCOMPLISH THE PROGRAM

One complete set of Advanced Launch System (ALS) oxidizer turbopump hardware and one set of critical item spares (impellers, housings, bearings, etc.) will be available to support turbopump testing at the National Aeronautics and Space Administration's (NASA's) Stennis Space Center (SSC). Assembly of the turbopump will be conducted at Pratt & Whitney (P&W), requiring assembly tooling. Ground support equipment and special test equipment required to support testing at SSC will be provided by P&W.

Additional turbopump hardware (rotating components, housings and bearings) will be required for verifying the design. Testing of this hardware will include materials property evaluation, weld specimen evaluation, rotating hardware evaluation using spin tests, proof pressure test of housings, vibration evaluation of individual components and rotor assemblies, and bearing evaluation by rig testing.

A more complete description of the facilities required for the ALS oxidizer turbopump program is contained in the Facilities Plan.

A. SPECIAL TEST EQUIPMENT (HARDWARE)

Special test equipment is required to test the turbopump at the SSC. Figure VI-1 shows the special test equipment. The following describes the special test equipment required for the oxidizer turbopump:

- *Turbine Inlet Adapter* — A pressure drop device at the gas generator to create the proper operating pressure (supplied by the gas generator contractor). A spoolpiece adapter to be provided with the turbopump.

- *Turbine Discharge Adapter* — A spoolpiece adapter and pressure drop device to be provided with the turbopump.

- *Pump Inlet Adapter* — A spoolpiece to be provided with the turbopump to adapt the inlet bolt circle to the test stand plumbing.

- *Pump Discharge Adapter* — A spoolpiece adapter to be provided with the turbopump.

- *Mount Skid* — A skid to be assembled that will serve as a transportation stand and as an SSC test facility mount.

During the turbopump design, P&W will design any special tooling required for the turbopump program that will be common to the development and delivery program. The degree of sophistication applied to these tools will be governed by labor versus tooling cost trade studies. Some detail part and components will require refined hard tooling, such as forming dies and impeller dies during initial manufacturing or assembly. This will be determined by the direct effect the parts or assemblies have on the overall quality and performance of the turbopumps. For these requirements, the special tools will be designed and built to guarantee the close dimensional control required on a repetitive basis. Tooling schedules will not impact the turbopump program and will be integrated into the manufacturing schedules.

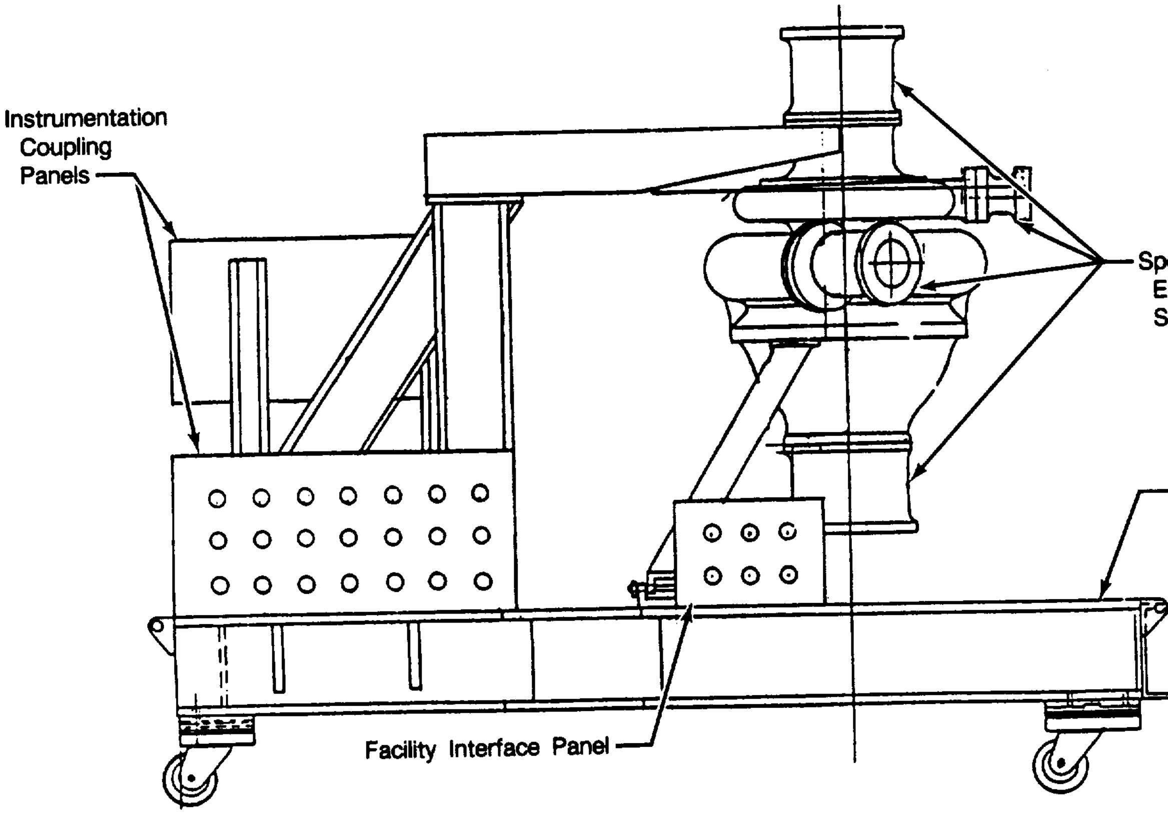

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Figure VI-1 Oxidizer Turbopump Shown With Special Test Equipment, Including Mounting Skid

B. SUPPORT EQUIPMENT

Support equipment required for ambient materials evaluation, cryogenic materials evaluation (tensile, low cycle fatigue, creep, etc.), and cryogenic bearing tests include existing P&W test stand and laboratory facilities.

SECTION VII
BASELINE LOGIC NETWORK

A. LOGIC NETWORK

The baseline logic network for the Advanced Launch System (ALS) oxidizer turbopump program is presented in Figure VII-1. This logic network represents the interrelationships among the program tasks and shows how information and data from each task will be used to accomplish the overall program goals. This initial submission is being made in accordance with the contract Data Requirement (DR-16) and will be updated as part of the monthly status report (DR-03).

B. PROGRAM MILESTONE SCHEDULE

Figures VII-2 and VII-3 present the major activities in the basic and option parts of the program respectively. These figures identify the tasks that were developed to achieve program objectives and against which progress can be measured.

C. SCHEDULE FLEXIBILITY

The program schedule has been established to be flexible to incorporate emerging technologies. The milestones for fabrication of low cost components will be closely monitored throughout the program. Alternatives will be incorporated into the schedule as required. New technologies can be added as well. During this program, P&W will identify technologies that may not be available for incorporation into the prototype turbopump. If some of these technologies are pursued in parallel to the primary component fabrication path, they could be incorporated into the prototype.

D. SCHEDULE REALISM

The schedule established for this program has been assessed for realism in accomplishing the program goals. The major lead times are those associated with the development of new technologies that will be incorporated into the turbopump. Through ongoing contacts and coordination with the suppliers of major hardware, the schedule has allowed for the lead times such as large castings. Due to these long lead times, procurement of the raw material must be started at the beginning of the option phase. For the large precision castings, coordination with the suppliers to define the final configuration will be started immediately upon selection of the turbopump configuration. Definition of tooling requirements will be based on information available from the layouts. During the detail design effort, drawings needed for final definition of tooling will be given priority to allow for early release.

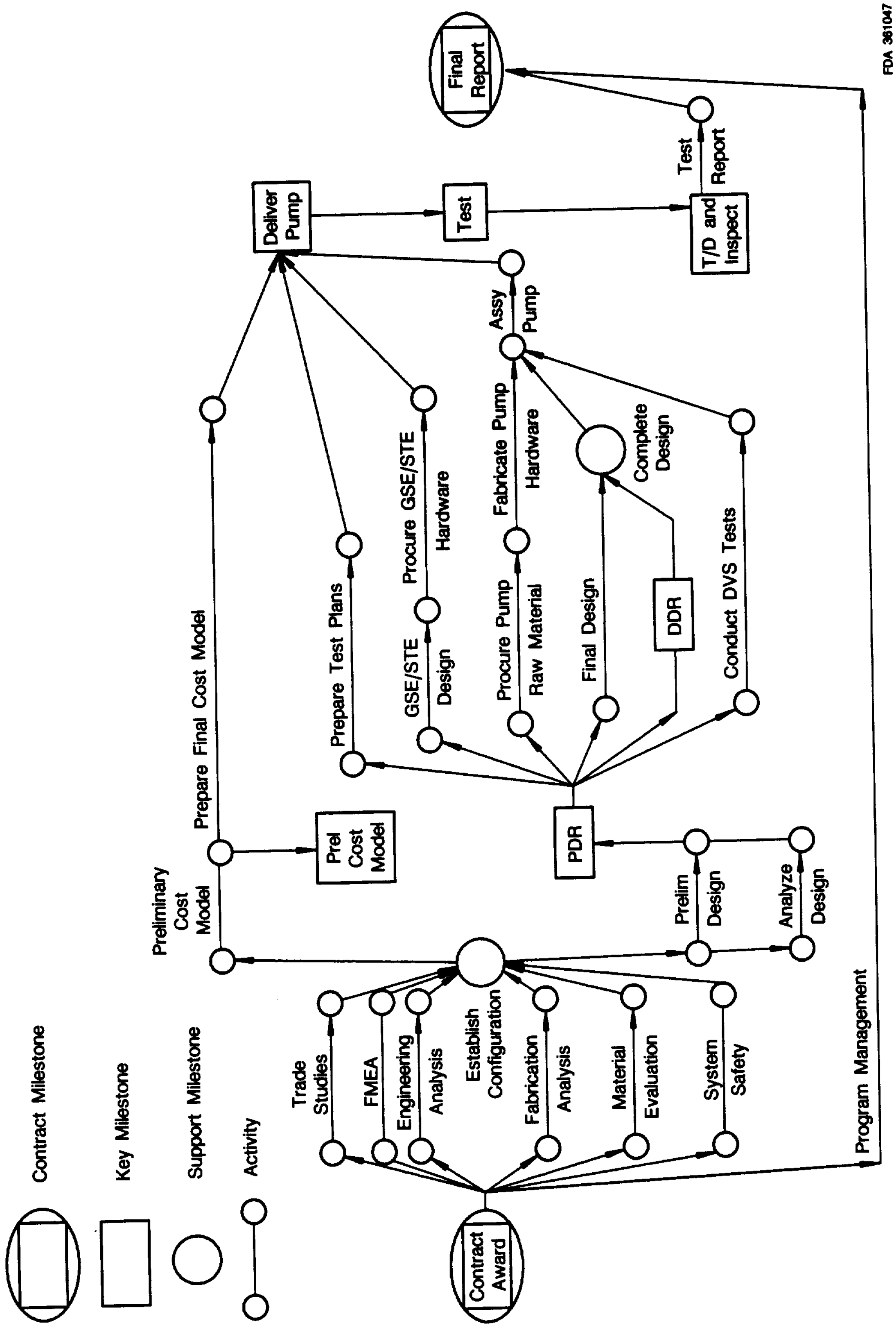

Figure VII-1. Logic Network

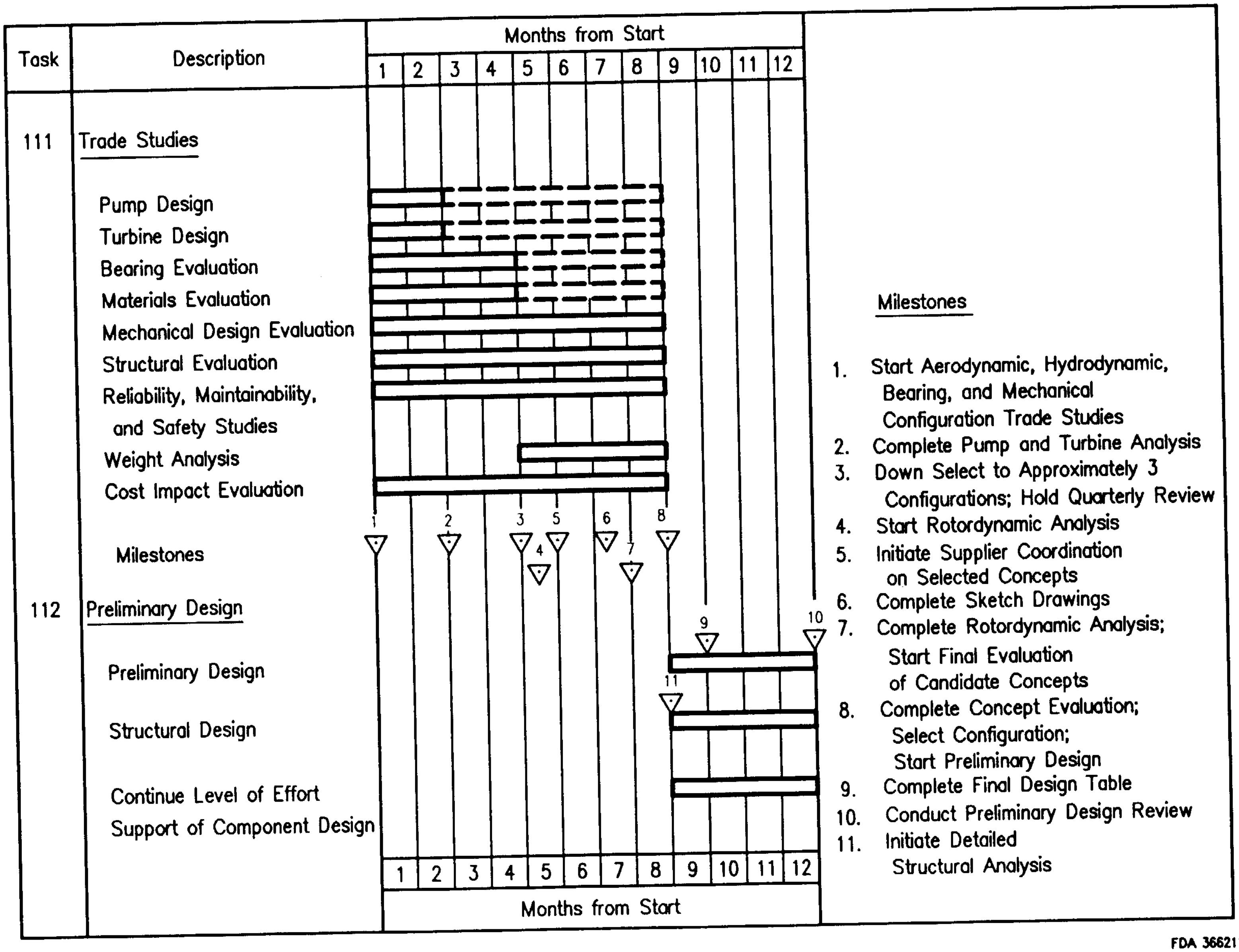

Figure VII-2. ALS Oxidizer Turbopump Basic Effort Schedule (Page 1 of 5)

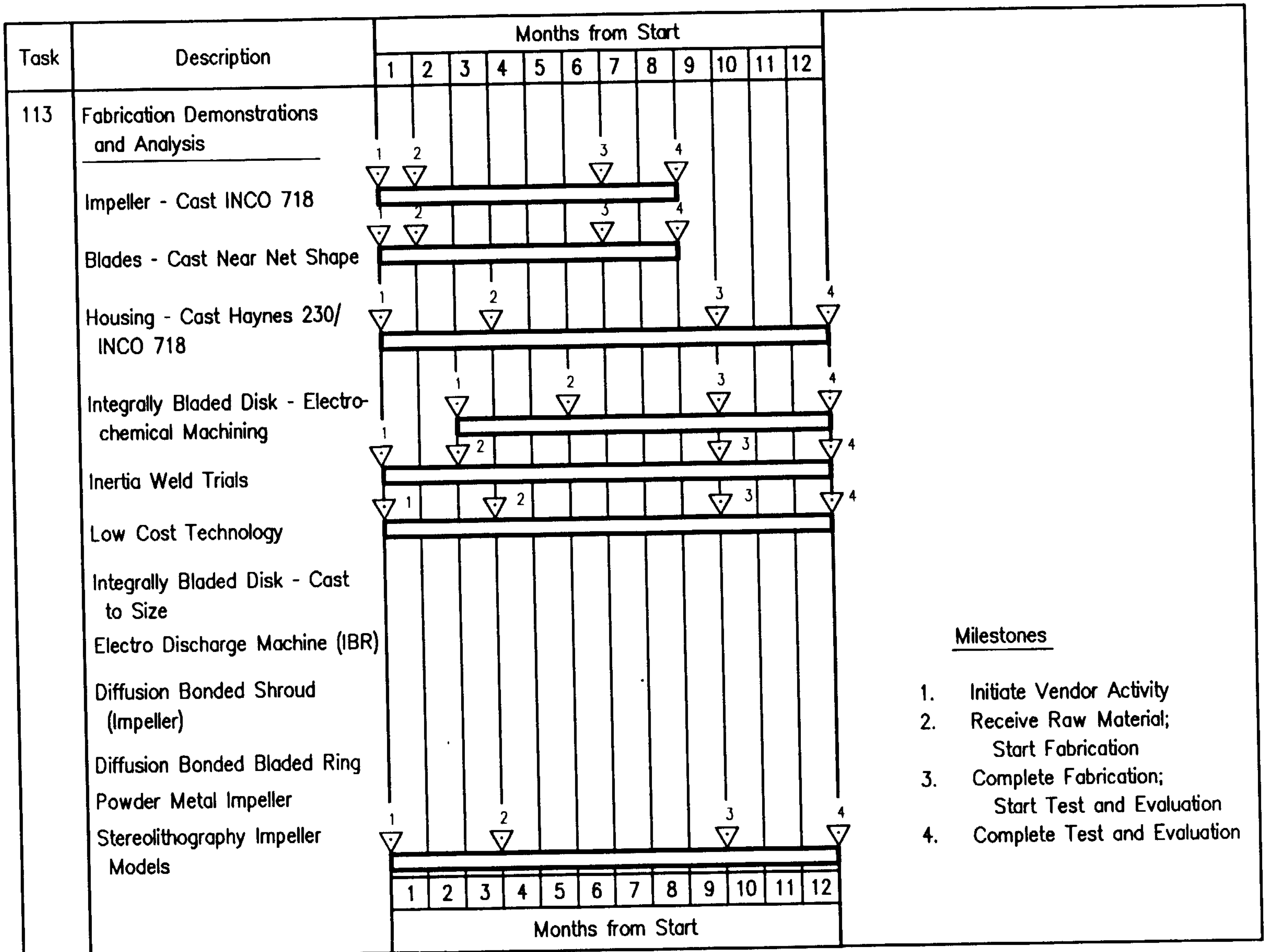

Figure VII-2. ALS Oxidizer Turbopump Basic Effort Schedule (Page 2 of 5)

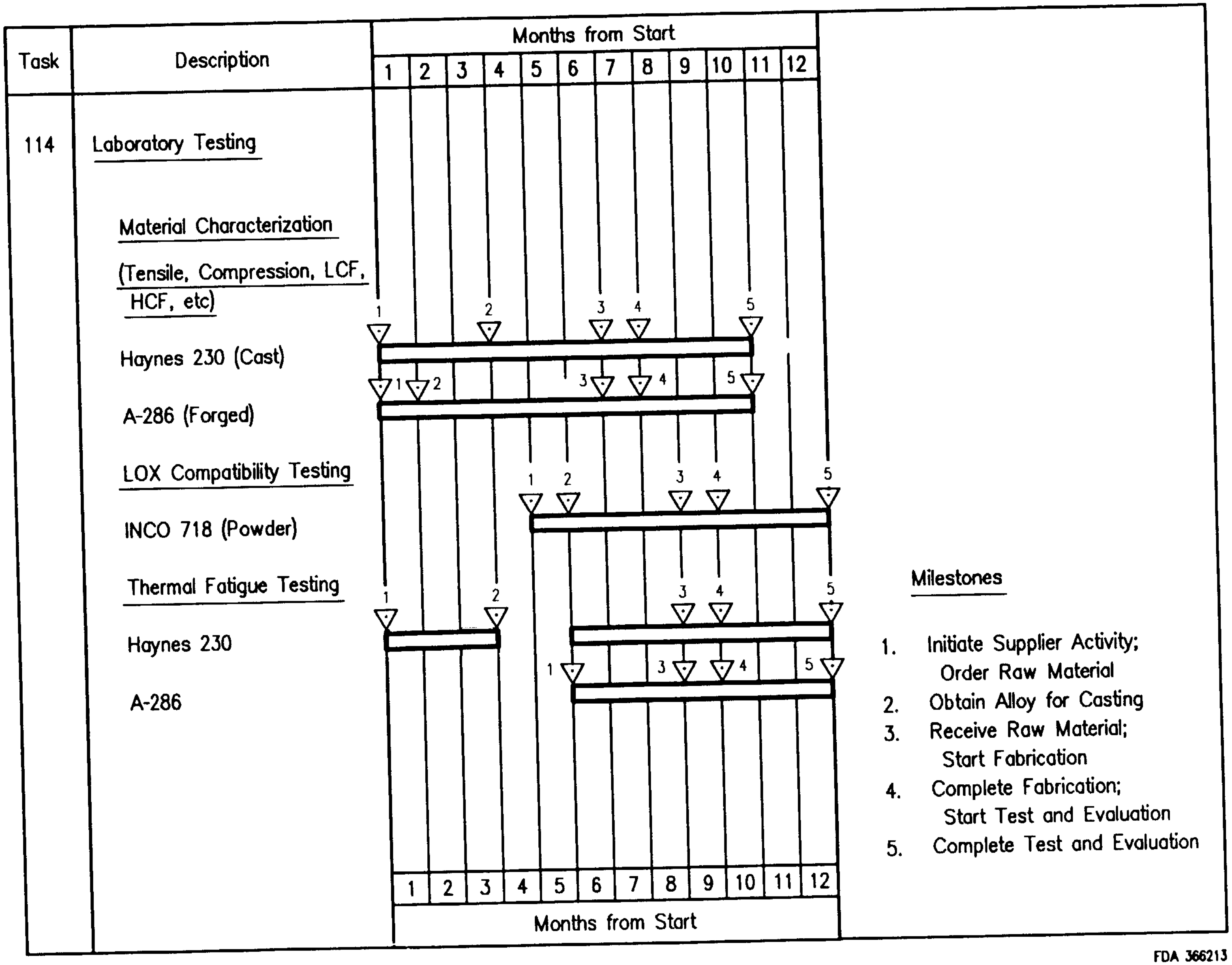

Figure VII-2. ALS Oxidizer Turbopump Basic Effort Schedule (Page 3 of 5)

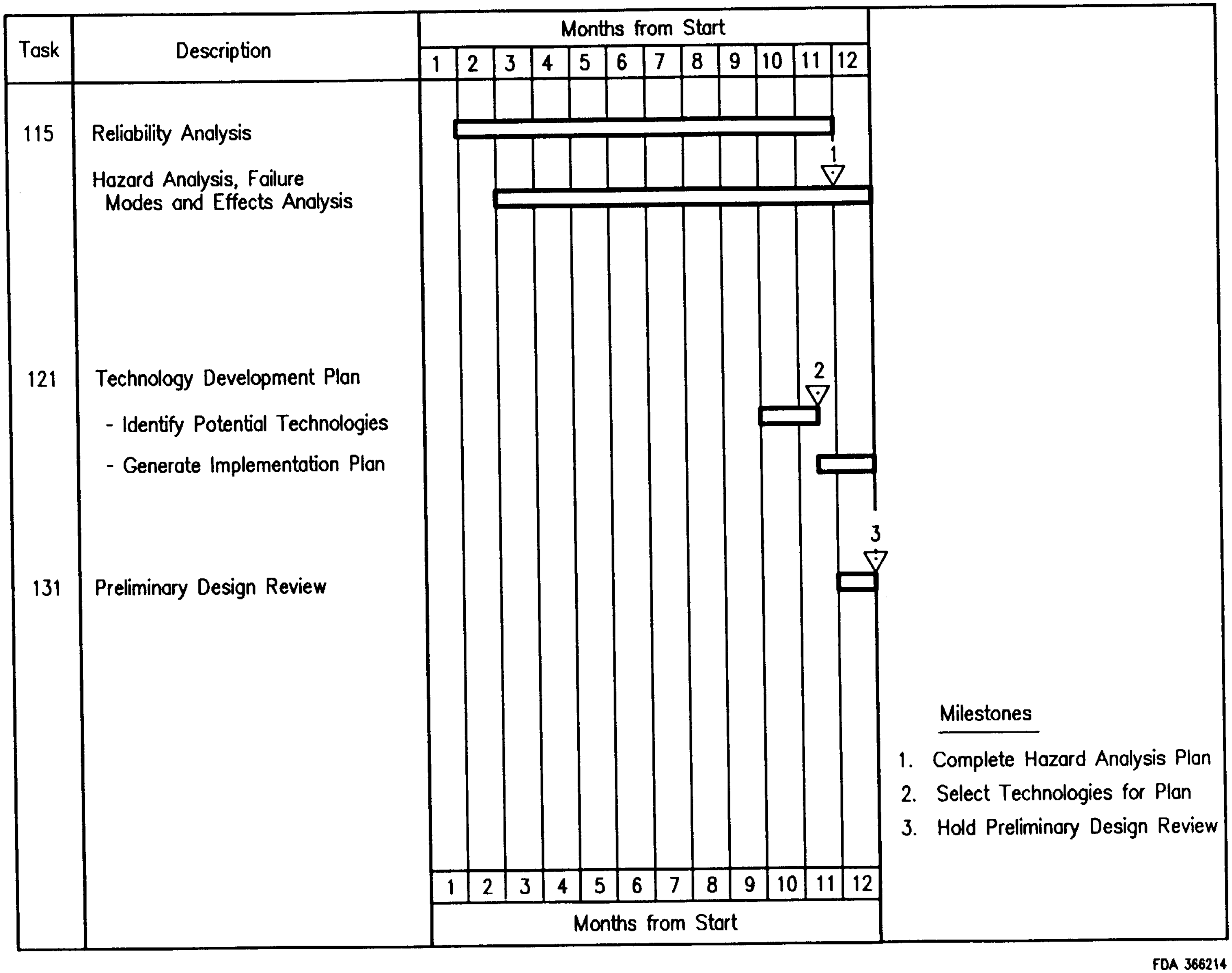

Figure VII-2. ALS Oxidizer Turbopump Basic Effort Schedule (Page 4 of 5)

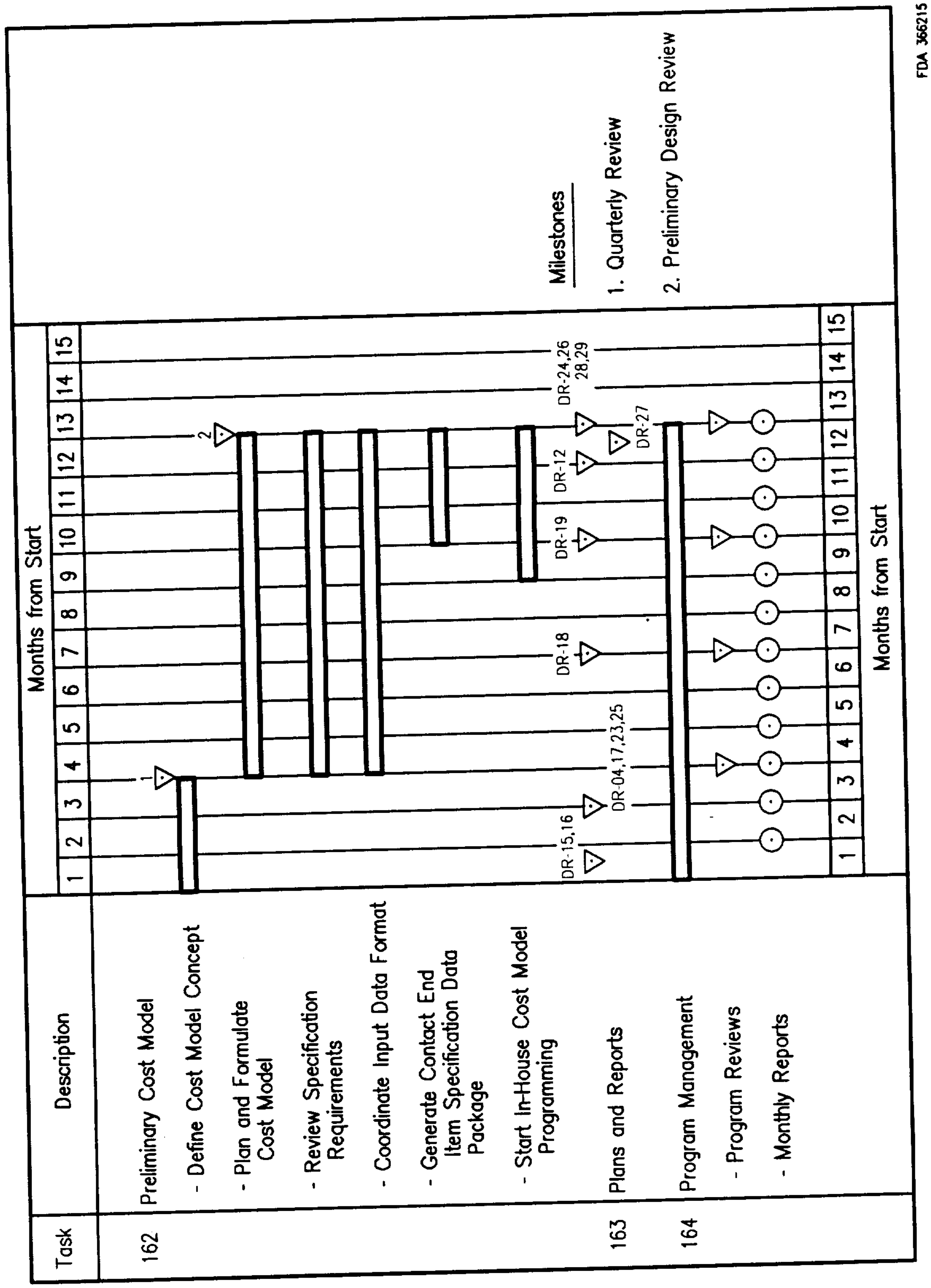

Figure VII-2. ALS Oxidizer Turbopump Basic Effort Schedule (Page 5 of 5)

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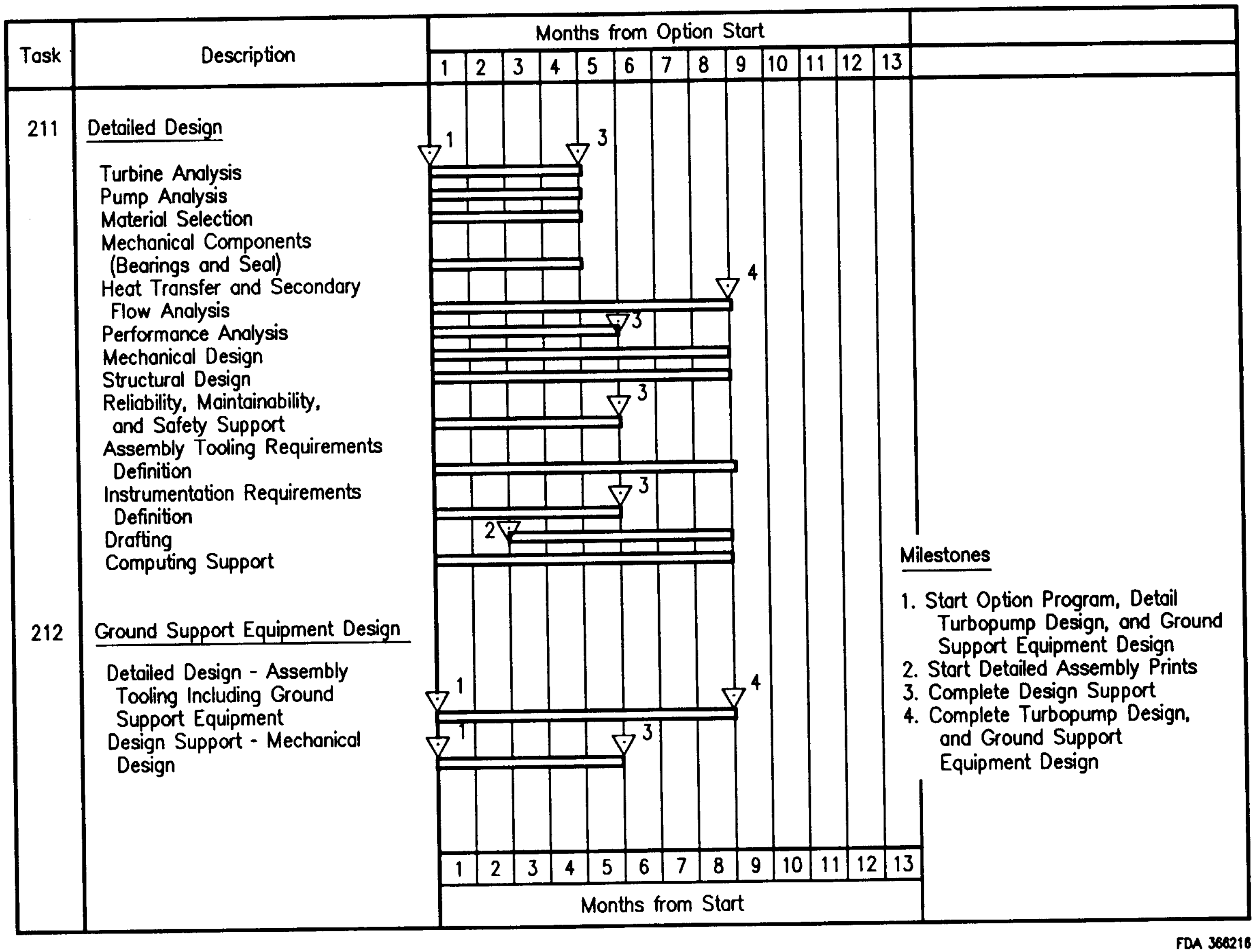

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 1 of 8)

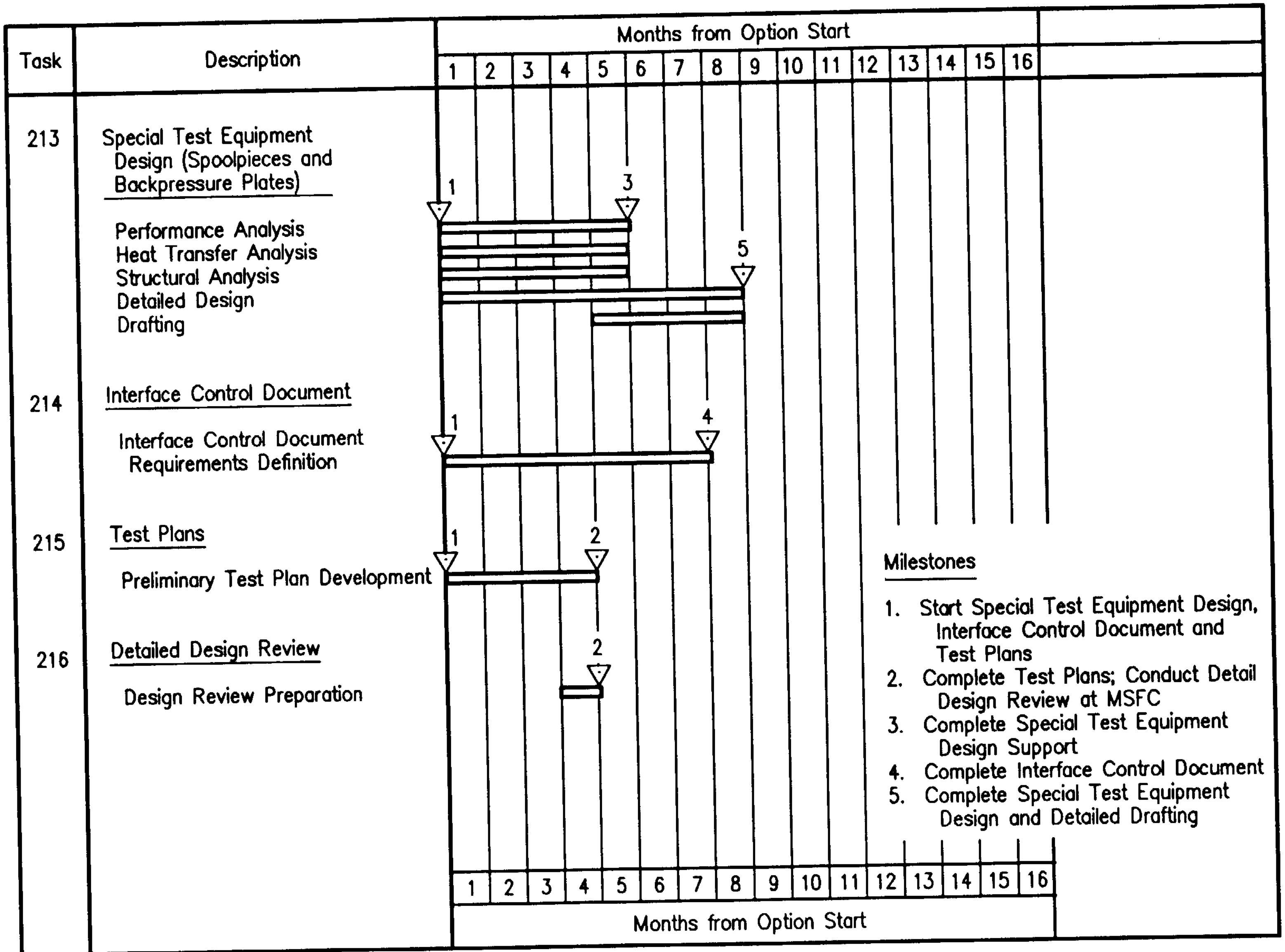

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Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 2 of 8)

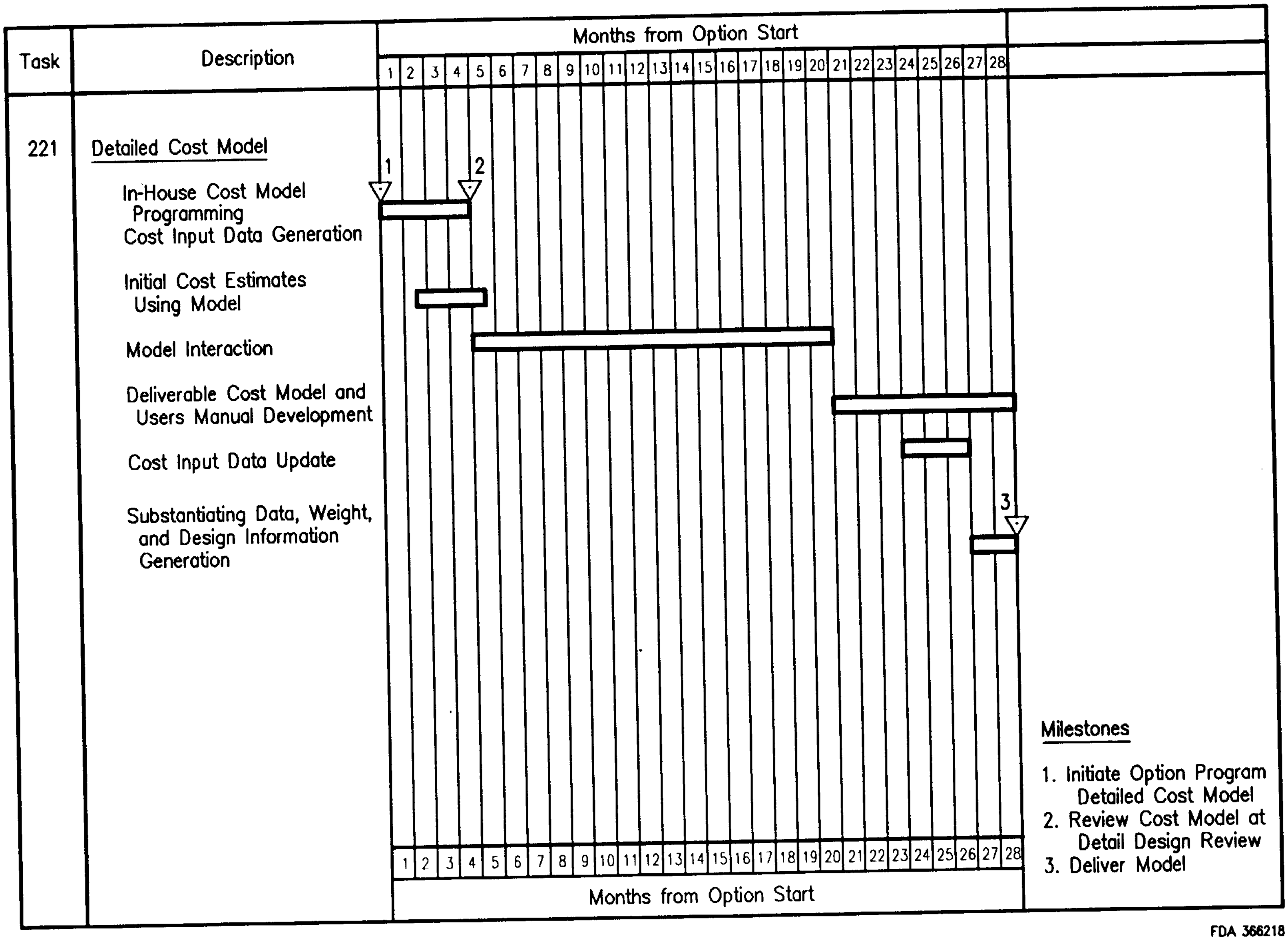

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 3 of 8)

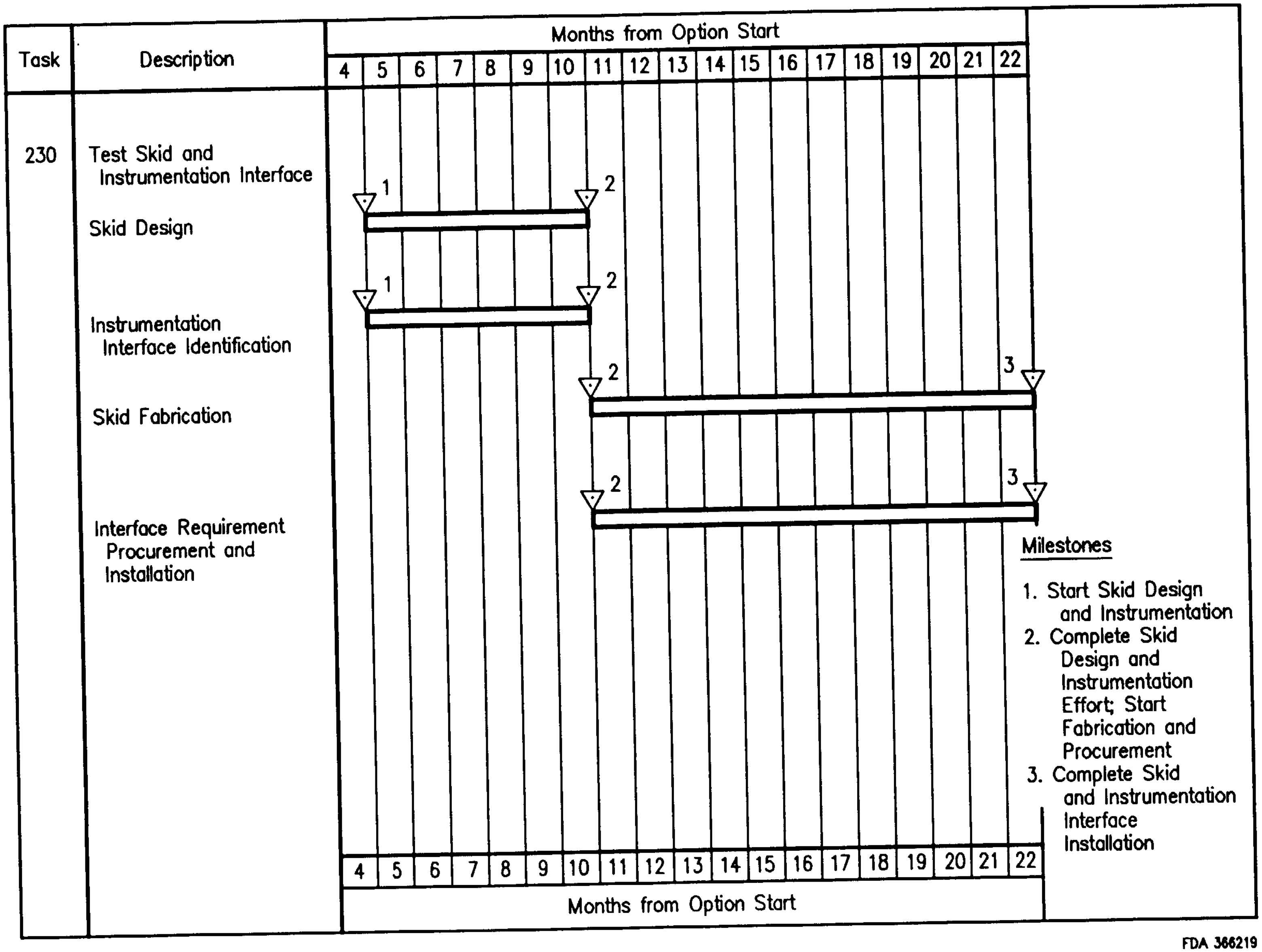

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 4 of 8)

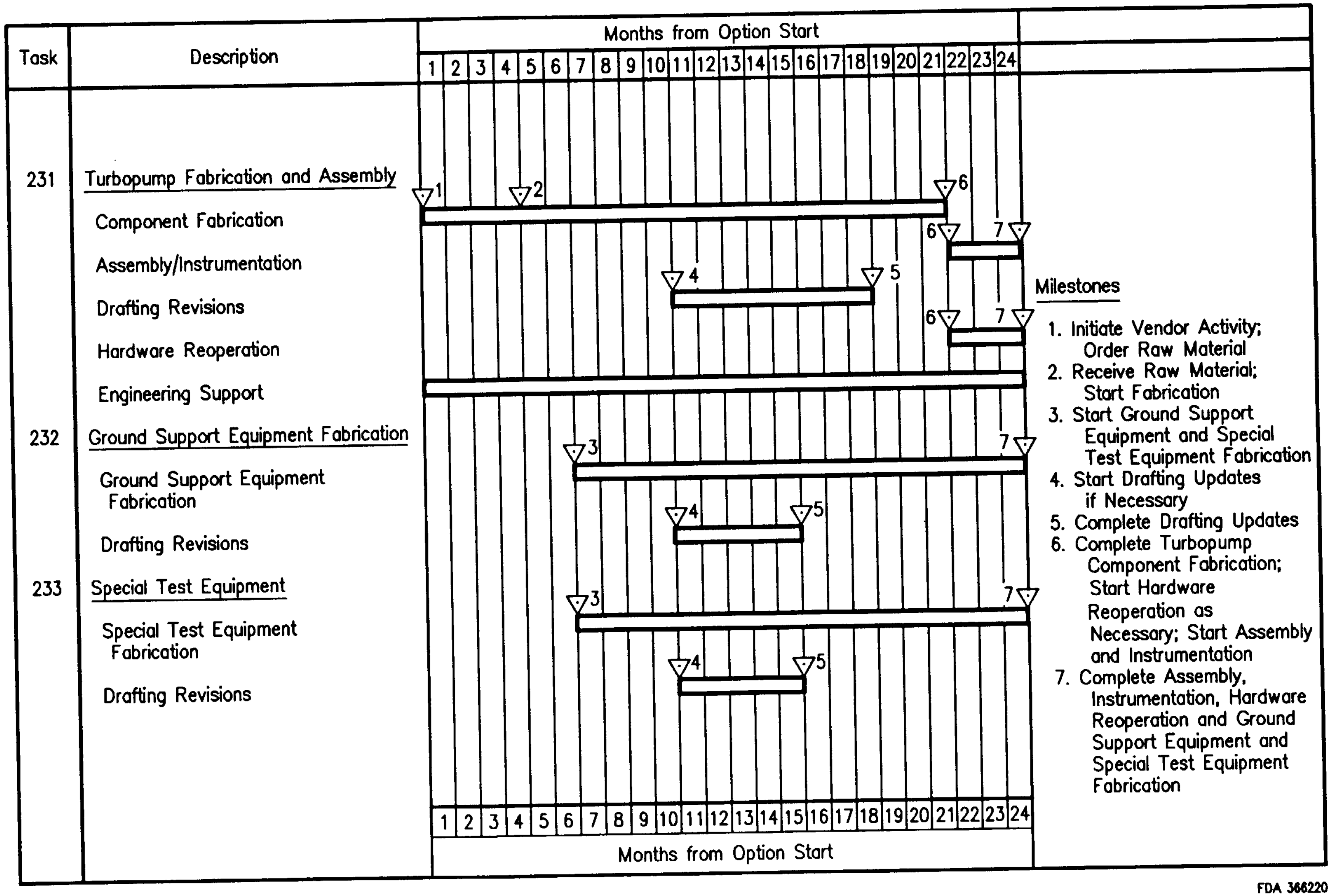

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 5 of 8)

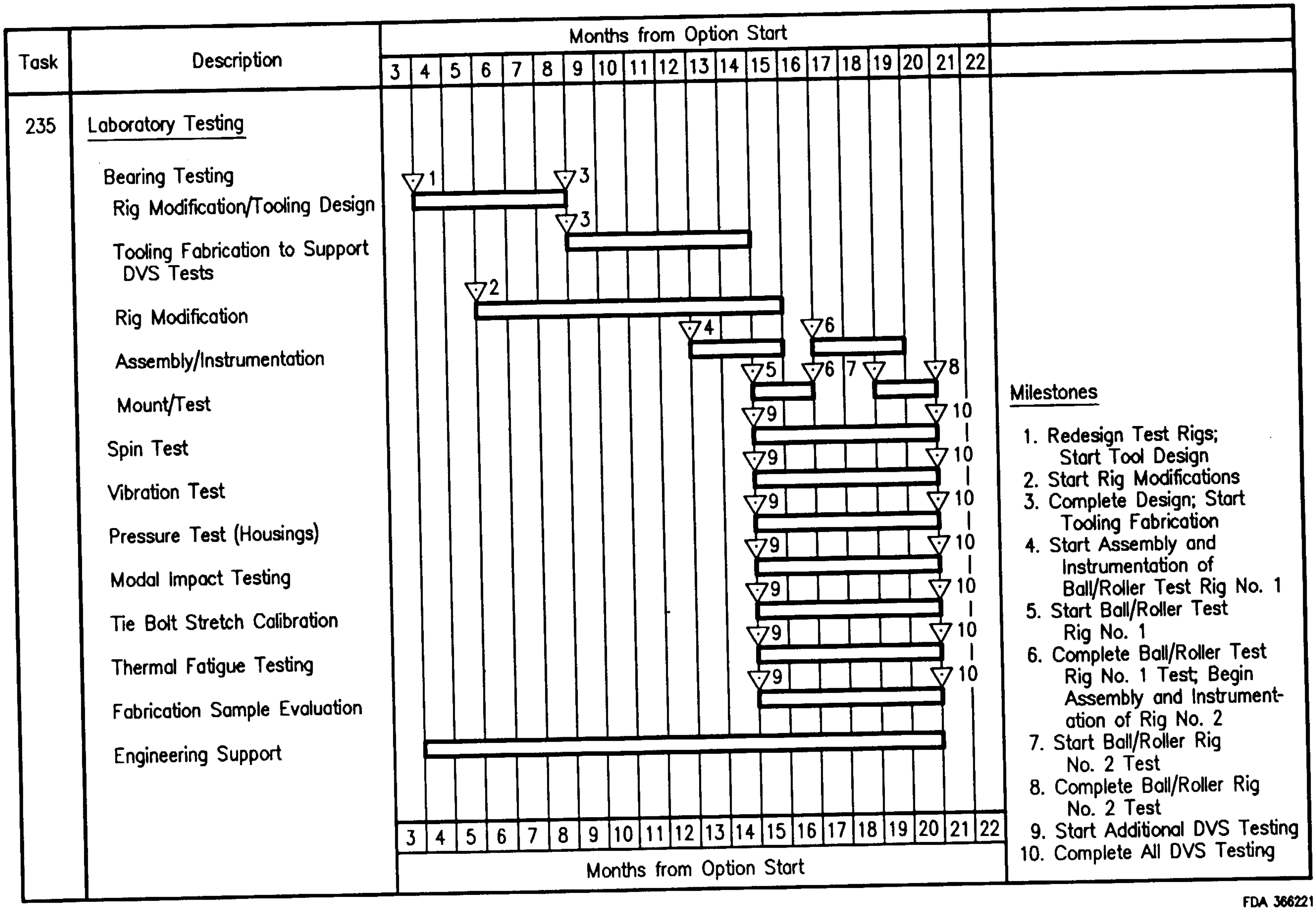

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 6 of 8)

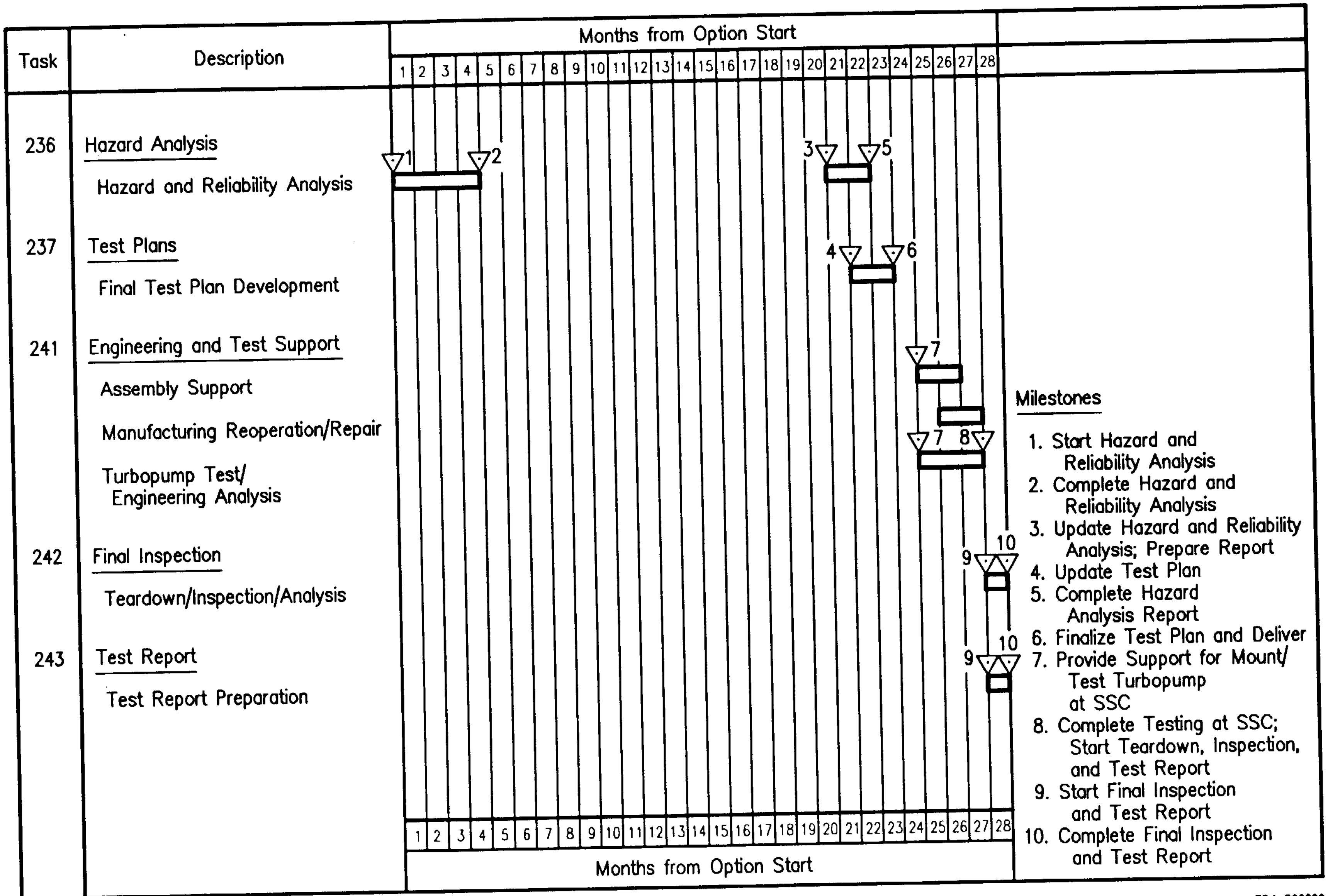

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 7 of 8)

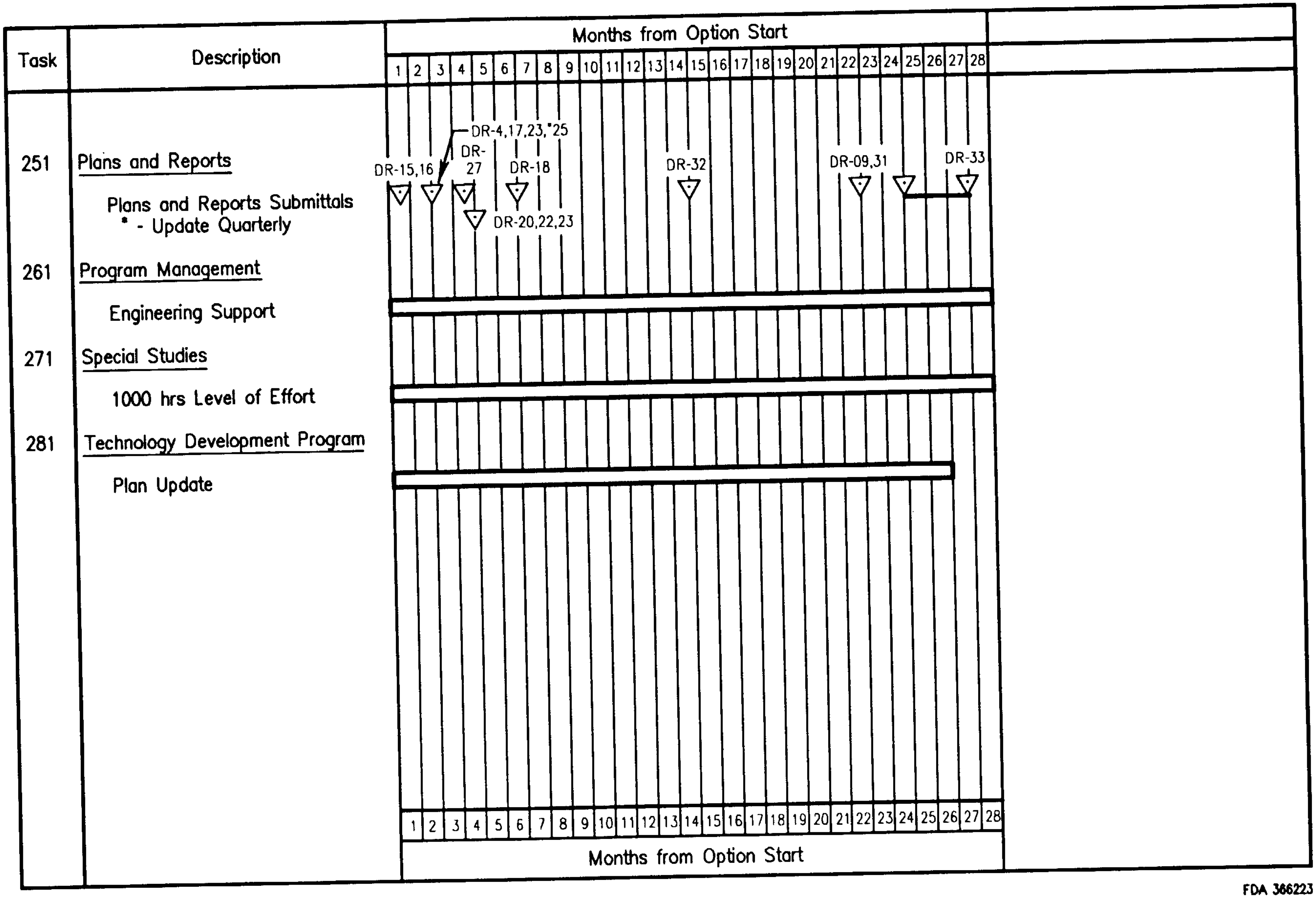

Figure VII-3. ALS Oxidizer Turbopump Option Program Schedule (Page 8 of 8)

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SECTION VIII
MAN-LOADING

Tables VIII-1 and VIII-2 show the man-loading for the basic and option programs.

Table VIII-1. *Liquid Oxygen Turbopump Program*
Time Phased Manhours

Basic Program
Total Program

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	3100	3490	4244	4167	4342	4326	4081	3865	4918	5170	5436	6485	53624
ASSEMBLY	—	—	—	—	—	—	—	—	37	37	37	37	148
TOTAL	3100	3490	4244	4167	4342	4326	4081	3865	4955	5207	5473	6522	53772

Table VIII-2. *Liquid Oxygen Turbopump Program Time Phased Manhours*

Basic Program
Task #111 Trade Studies

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	1398	1394	1597	1721	1776	1699	1467	1351	48	—	—	—	12451
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	1398	1394	1597	1721	1776	1699	1467	1351	48	—	—	—	12451

Basic Program
Task #112 Preliminary Design

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	19	19	19	19	19	19	19	19	2384	2540	2656	2706	10438
ASSEMBLY	—	—	—	—	—	—	—	—	37	37	37	37	148
TOTAL	19	19	19	19	19	19	19	19	2421	2577	2693	2743	10586

Table VIII-2. *Liquid Oxygen Turbopump Program*
Time Phased Manhours (Continued)

Basic Program
Task #113 Fabrication and Process Analyses

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	19	171	756	581	638	598	529	374	389	231	303	302	4891
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	19	171	756	581	638	598	529	374	389	231	303	302	4891

Basic Program
Task #114 Laboratory Tests

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	624	624	624	624	687	683	739	739	752	757	749	728	8330
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	624	624	624	624	687	683	739	739	752	757	749	728	8330

Table VIII-2. *Liquid Oxygen Turbopump Program*
Time Phased Manhours (Continued)

Basic Program
Task #115 Reliability and Hazard Analysis

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	—	129	144	144	144	249	249	249	105	105	105	—	1623
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	—	129	144	144	144	249	249	249	105	105	105	—	1623

Basic Program
Task #121 Technology Development Program Plan

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	—	—	—	—	—	—	—	—	29	176	203	203	611
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	—	—	—	—	—	—	—	—	29	176	203	203	611

Table VIII-2. *Liquid Oxygen Turbopump Program Time Phased Manhours (Continued)*

Basic Program
Task #131 Preliminary Design Review

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	—	—	—	—	—	—	—	—	—	—	63	1085	1148
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	—	—	—	—	—	—	—	—	—	—	63	1085	1148

Basic Program
Task #162 Preliminary Cost Model

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	78	176	257	231	231	231	231	268	346	341	337	336	3063
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	78	176	257	231	231	231	231	268	346	341	337	336	3063

Table VIII-2. *Liquid Oxygen Turbopump Program Time Phased Manhours (Continued)*

Basic Program
Task #163 Specifications, Plans, and Reports

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	149	164	34	34	34	34	34	52	52	52	52	157	848
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	149	164	34	34	34	34	34	52	52	52	52	157	848

Basic Program
Task #164 Program Management

FUNCTION	1989 M	J	J	A	S	O	N	D	1990 J	F	M	A	TOTAL
ENGINEERING	813	813	813	813	813	813	813	813	813	968	968	968	10221
ASSEMBLY	—	—	—	—	—	—	—	—	—	—	—	—	—
TOTAL	813	813	813	813	813	813	813	813	813	968	968	968	10221

SECTION IX
MAJOR SUBCONTRACTORS

While Pratt & Whitney does not expect to have any major subcontractors for this program, there will be several suppliers that are expected to provide materials or services exceeding $100,000. Table IX-1 identifies potential suppliers. Others will be added as necessary.

Table IX-1. *Potential Suppliers*

Supplier	*Location*	*Materials/Services*
Ace Industries Textron	Santa Fe Springs, CA	Machining
Cameron Forge	Houston, TX	Forgings
Caval Tool	Newington, CT	Machining
Howmet Corporation	LaPorte, IN	Castings
Howmet Corporation	Hampton, VA	Castings
Ladish	Cudahy, WI	Forgings
Lehr Precision, Inc.	Cincinnati, OH	Machining
Precision Castparts, Inc.	Portland, OR	Castings
Precision Castparts, Inc.	Cleveland, OH	Castings
Schlosser Forge	Los Angeles, CA	Forgings
Shultz Steel	South Gate, CA	Forgings

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