Turbopump ALS
Advanced Development Program

NASA-CR-1968-37593
Aerospace Progress Report No. KGC4-M-2

U.S. Department of Commerce, National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Marshall Space Flight Center, AL 35812

Date of general release 07-91
Report No. KGC4-M-2
21 July 1989

LIQUID HYDROGEN TURBOPUMP
ALS
ADVANCED DEVELOPMENT PROGRAM

Contract NAS 8-37593
Monthly Progress Report, DR-03
20 May - 23 June 1989

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

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1.0 INTRODUCTION

This is the second, June 1989, Monthly Progress Report submitted as Data Requirement (DR)-03 of the Advanced Launch System (ALS) Liquid Hydrogen Turbopump Advanced Development Program. This program is being conducted by Aerojet TechSystems (AT) for the Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA), under Contract No. NAS 8-37593.

This activity is defined in the Technical Implementation Plan, DR-15. It is designed to deliver and support two reliable, low cost, maintainable LH₂ turbopumps together with Ground Support Equipment (GSE) and Special Test Equipment (STE) packages to Stennis Space Center (SSC) for testing. One turbopump will be heavily instrumented and cold gas tested to measure the internal pump and turbine environments, the second turbopump will be flight type and hot fired. A key additional deliverable will be the LH₂ Turbopump Cost Model, which will be calibrated with actual hardware fabrication costs and with data from simulated launch support and production acceptance activities performed at SSC during the test period.

Cost and reliability studies, trades, and tests will be performed. Cost reduction and/or reliability enhancing technologies will be substantiated by the design, fabrication, and test of experimental and demonstration hardware.

The program covers a 40-month period of performance and is structured in two phases:

Phase I (12 mths) - Preliminary design and cost model development

Phase II (28 mths) - Detail design, fab., and full scale demonstration

The program is designed around the Work Breakdown Structure (WBS) shown in Figure 1.

This second month effort can be characterized as one of evolving activity from detail planning into the start of major long lead efforts involved with turbopump design and supporting experimental work.
ALS LIQUID HYDROGEN TURBOPUMP
Work Breakdown Structure (WBS)

KGC-XXX (6.0)
Liquid Hydrogen Turbopump

1.0.0 (6.0)
Phase 1 - Preliminary Design/Cost Model

1.1.0 (6.2)
Preliminary Design (TPA/GSE Package)
- 1.1.1 Baseline Concept
- 1.1.2 Back-up Concept
- 1.1.3 Low Cost Modifications
- 1.1.4 Hot Fire Design
- 1.1.5 Instrumented Concept
- 1.1.6 GSE/Test Cart Design

1.2.0 (6.2.1)
Studies, Analyses and Lab. Tests
- 1.2.1 Low Cost Studies
- 1.2.2 Materials Testing
- 1.2.3 Bearing and Seal Test Preparation
- 1.2.4 Impeller Tests
- 1.2.5 Turbine Blade Tests

1.3.0 (6.2.2)
Technology Development Plan

1.4.0 (6.3.1)
Preliminary Cost Model

2.0.0 (6.0)
Component Test Article/Detailed Cost Model

2.1.0 (6.4)
Detailed Design (TPA/GSE Package)

2.2.0 (6.4)
Studies Analyses and Lab. Tests

2.3.0 (6.5)
Fabrication

2.4.0 (6.6)
Test Support and Analysis

2.5.0 (6.3.2)
Detailed Cost Model

2.6.0 (6.7)
Special Studies

2.7.0 (6.7)
Technology Development

3.0.0 (4.0)
Program Management

3.1.0 (4.0)
Phase I

4.0.0 (4.0)
Data

4.1.0 (4.0)
Phase I

LEGEND

CUSTOMER REPORTING = ELEMENT
(TITLE = WBS #)

XXX = SOW NUMBER

ISSUE DATE: 03/08/89
REVISION #
REVISION DATE:
PROGRAM MANAGER:
PROGRAM SCHEDULER:

Figure 1. Work Breakdown Structure (WBS)
2.0 SUMMARY

2.1 SIGNIFICANT ACCOMPLISHMENTS

WBS 1.1.1 - The point of departure (POD) turbopump concept was reviewed and finalized during the report period (Figure 2). The basis for the POD was the configuration presented in the Aerojet proposal. After reviewing this proposal concept, several modifications were made. These modifications are outlined below with brief comments on the logic for incorporating them:

a. The dual pump discharge arrangement was changed to a single discharge. The complexity of extra ducting, and flex joints was not justifiable in the STME/STBE engine system. Radial loads resulting from the unsymmetrical pressure gradients are felt to be manageable with the single-discharge, double tongue configuration selected.

b. Commonality of the turbine inlet manifold with the ALS LOX TPA was dropped for this program. The reason was to avoid the inevitable delays which would be experienced in attempting to attain commonality with another contractor's configuration, which is also in a conceptual phase and subject to change. The turbine inlet will be sized specifically for the LH2 TPA, and will be reduced in size as a consequence.

c. The turbine housing flange arrangement was improved by relocating it away from the first stage nozzles. The large thermal mass, previously in close proximity to the thin nozzle trailing edges, posed a potential cracking problem due to differential thermal expansion.

d. A 10% head margin (5% diameter increase) was built into the impeller design to ensure meeting the required discharge pressure without the need for increasing speed.

e. A 10% turbine power margin was imposed, to be obtained by increasing turbine inlet pressure if required. The impact is a 10% higher design pressure for the turbine inlet manifold and the gas generator.
Figure 2. Turbopump POD Design Configuration
2.1, Significant Accomplishments (cont)

   f. The backup concept, as an alternative to the use of cast impellers, will now incorporate forged/machined shrouded impellers, rather than the unshrouded type originally planned.

   Extensive discussions were held with Mechanical Technology Inc. (MTI) on definitization of the scope and cost of their planned participation in the program. MTI will support the program in the areas of bearing/seal analysis and tradeoffs, bearing materials tests, lift-off seal design, instrumentation and test planning. It is anticipated that the MTI effort will commence during the July reporting period.

   A meeting was held at Aerojet during the report period with NASA-SSC personnel. A productive discussion of instrumentation and test requirements took place at this session.

   **WBS 1.1.6** - Conceptual design of the test cart for LH2 turbopump tests was initiated. Use of off-the-shelf hardware for this unit is being emphasized to minimize cost.

   **WBS 1.2.2** - Discussions were initiated with candidate test laboratories for performing materials tests on existing PCC-supplied cast Ti-5Al, 2.5Sn test bars.

   **WBS 1.2.4** - Procurement activity on the cast titanium impellers intensified during the report period. A CAD package (Figure 3) was completed defining a "typical" cast titanium impeller suitable for feasibility testing. The design is as close to the final LH2 ADP turbopump impeller design as is possible at this stage in the program. Responses were received from all solicited suppliers and viable candidates were identified. The responses indicated a potential schedule problem in this area. This is being worked at present, and is discussed further in Section 3.0 of this report.

   **WBS 3.1.0** - A program kick-off meeting was conducted at MSFC on 8 June 1989. A copy of the presentation package is included in this monthly progress report (Attachment 1) for record purposes.

   On 9 June 1989 a test facility interface meeting was held at MSFC with Stennis Space Center (SSC) personnel in attendance. Requirements for LH2 TPA
Figure 3. Casting CAD Drawing for Titanium Impeller
2.1, Significant Accomplishments (cont)

testing were discussed, a tentative schedule for future meetings was established, and action items were assigned.

Aerojet worked on two action items from the test facility interface meeting:

a. A listing of instrumentation for the LH2 turbopump tests showing types of sensors, quantities, ranges, and sampling rates.

b. After receipt of the SSC basic test facility definition, preparation of sketches showing the orientation of the turbopump in the test facility was initiated. This will be delivered in the July reporting period, along with the required fluid flows and conditions at the interface points.

Cost Account Plans (CAPs) were finalized and put in place during the report period. The required effort is now authorized and proceeding.

To enhance our simultaneous engineering approach (an essential TQM element) key personnel will be colocated within a dedicated ALS office area next month.

WBS 4.1.0 - Delivery of data items will henceforth be reported under Section 2.6 "Correspondence".

2.2 SCHEDULE

All tasks are on-schedule at close of this reporting period other than the cost model, which requires NASA input before major effort can commence.

The Master Schedule for the LH2 Turbopump Program is shown in Figure 4. Milestones are defined in the Milestone Dictionary, Figure 5. The DR delivery schedule is given in Figure 6. Figure 7 shows the percentage completion on the ALS Master Network. All schedules indicate program status as of close of the reporting period.
## ALS LIQUID HYDROGEN TURBOPUMP MASTER SCHEDULE

**Contract No. NAS8-37593**

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- **○** PROCUREMENT COMM.
- **★** MAJOR MILESTONE
- **⊙** MAJOR/S/COMM.
- **-upload** PERCENT COMP.
- **-** TIME NOW

**Initial Date:** 05/10/89  
**Rev:** 1  
**Status:** 1  
**Rev Date:** 7/12/89  
**Pgm Mgr:** [Signature]  
**Date:** 7/12/89  
**Scheduler:** [Signature]  
**Date:** 7/12/89

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**Figure 4. Master Schedule**
## ALS Liquid Hydrogen Turbopump Milestone Dictionary

**Contract No. NAS8-37593**

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*Figure 5. Milestone Dictionary*
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</table>

**Figure 6. DR Schedule**
2.0, Summary (cont)

2.3 MANPOWER

Figure 8 presents our manpower assessment of the program, showing cumulative manhours expended versus those planned. For this accounting month of June 1989 (20 May program start through 23 June), we were 16% under budget.

2.4 PLANNED WORK FOR NEXT REPORTING PERIOD

2.4.1 Place MTI under subcontract and initiate effort.

2.4.2 Select supplier for cast titanium impellers and place under subcontract.

2.4.3 Initiate procurement process on test bars for materials testing program.

2.4.4 Continue baseline turbopump preliminary design effort.

2.4.5 Continue conceptual design of test cart.

2.4.6 Start low cost trade studies effort using POD design as the reference point.

2.4.7 Submit test instrumentation data for SSC.

2.4.8 Initiate cost model work.

2.5 CORRESPONDENCE

The following lists correspondence and data received from and transmitted to NASA during the reporting period:
LIQUID HYDROGEN TURBOPUMP

TOTAL HOUR BUDGET VS ACTUAL 5/19/89

BAC 38758 HOURS (LESS MANAGEMENT RESERVE)

BUDGET-4483 HOURS
ACTUAL-3768 HOURS

Figure 8. Total Hour Budget vs. Actual
2.5, Correspondence (cont)

### Incoming Corres.

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<tr>
<th>Date</th>
<th>Subject</th>
<th>Originator</th>
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<td>5/22</td>
<td>Contract NAS8-37593, copies for signature</td>
<td>CC Mitchell/NASA-MSFC</td>
</tr>
<tr>
<td>5/25</td>
<td>NAS 8-37593, Appointment of Contracting Officer's Technical Representative</td>
<td>CC Mitchell/NASA-MSFC</td>
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<td>Contract NAS8-37593</td>
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<tr>
<td>6/9</td>
<td>New Technology Reporting Requirement of Contracts NAS8-37593, NAS8-38073, and NAS8-38074</td>
<td>I Akbay/NASA-MSFC</td>
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<tr>
<td>6/16</td>
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### Outgoing Corres.

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<td>9001:0001</td>
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<td>Contract NAS8-37593, Acknowledgement</td>
<td>CS Montgomery</td>
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<td>9001:DM2372</td>
<td>6/16</td>
<td>Contract NAS8-37593, Monthly Progress Report, DR-03</td>
<td>CS Montgomery</td>
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</table>
3.0  TECHNICAL PROBLEMS AND PROPOSED SOLUTIONS

3.1 Responses from casting suppliers indicate that receipt of production-standard deliverable cast impellers may occur after the planned end date for Phase I. Development castings will be available during Phase I, which will support determination of material properties using test bars extracted from actual castings. The schedule may not, however, support planned spin testing of cast impellers in Phase I.

Aerojet will attempt to improve the schedule in meetings with suppliers during the July report period. One possibility would be to produce the deliverable castings in the supplier's development facility, rather than the production facility as now planned, avoiding the changeover delay.

4.0  SPECIAL NASA CONCERNS

4.1 During the conceptual design effort on the test cart, it became apparent that a cart for each turbopump, cold gas and hot gas, would greatly expedite transportation, handling, and testing of the test articles during Phase II. The present scope calls for fabrication of one test cart only. Aerojet recommends inclusion of a second test cart to improve test operations productivity.

4.2 NASA needs to provide Aerojet with the Contract End Item Specification to facilitate construction of the Cost Model architecture.
Attachment 1

Kickoff Meeting Charts
ADVANCED LAUNCH SYSTEM
ADVANCED DEVELOPMENT PROGRAM
LIQUID HYDROGEN TURBOPUMP
KICK-OFF MEETING

(Contract No. NAS 8-37593)

NASA—George C. Marshall Space Flight Center

8 June 1989
Kick-Off Meeting Objectives

- Implementation Plan Familiarization

- Identify NASA-Aerojet Links on Program

- Identification of Relevant NASA Resources:
  - Data
  - Tools
"When cost is a performance variable in engine design, the challenge is different."

- Col. Jack Wormington, USAF, ALS Program Director

"To achieve our goals for cost reduction, we've got to find new ways of doing business."

- Jerry Thomson, NASA-MSFC
Agenda—AM

Program Organization & Overview  C. Faulkner

PHASE I:

Preliminary Design  N. Shimp

Studies, Analyses, and Lab. Tests  N. Shimp/G. Claffy

Technology Development  G. Claffy

Preliminary Cost Model  C. Faulkner
Phased II:

- Detailed Design
  - N. Shimp

- Studies, Analyses and Lab. Tests
  - N. Shimp

- Component Test Article Fabrication
  - G. Claffy

- Test Planning, Support & Analysis
  - G. Claffy

- Detailed Cost Model
  - C. Faulkner

Concluding Remarks
  - C. Faulkner
Program Organization
And Overview

- Program Goals
- Basic Approach
- The Aerojet Team
- Coordinated Total Plan
Program Objectives

- Provide Proven Low Cost Technologies for Successful LH₂ Turbopump:
  - Lowest Cost With Required Reliability
  - Acceptable Performance and Weight
  - NO Compromises With Safety
Technologies Derived From STME/STBE Studies

- Conservative Design Criteria and Margins
- Extensive Use of Castings
- Bolted Assembly/No Assembly Welds
- Standardization Within Turbopump
  - Impeller Castings
  - Rotor Discs
- Blade Attachments
- Bearings
- Proven Materials and Fabrication Processes
- Minimum Weld Joints
- Minimize Plating and/or Coatings
- Participative Supplier Base
- Organization/Specification/Procedure Changes
- Advanced Machining
- Commonality Between Turbopumps
  - Blade Attachment/Dampers
  - Rotor Discs
  - Bearing Sets
Reliability Assessments Throughout The Program

- Materials Testing
  - As Processed
  - In Environment
  - Sacrificed Subcomponents

- Early Impeller Development

- Probabilistic Design

- Bearing Development Program

- Proof and Spin Tests During Fab

- Calibration of Analytical Models

- Validation of Internal Environment

- Hot Fire Tests at Full Loads
Cost Is Assessed
Throughout The Program

- Quantify Cost Reduction With Trade Studies
- Feasibility Proven Experimentally
  - Fab Experiments
  - Design Iterations
  - Process Development/Supplier Interaction
  - Specification Development
  - Parts Manufactured
  - Inspection Techniques Evaluation
  - Testing at Full Loads
- Cost Model Development
  - 1st Unit Cost Validation
Performance Is Assessed Throughout The Program

- Conventional Analysis
- Advanced Analysis
- Tolerance Analysis
- Cold Gas, Heavily Instrumented Turbopump
  - Calibration of Analytical Model
- Full-Scale Testing (Hot Gas)
  - Unit-to-Unit Variations
## Program Is Structured Around WBS

### GENCORP
### AEROJET
### Tech Systems

#### KGC-XXX (6.0)
- Liquid Hydrogen Turbopump

#### 1.0.0 (6.0)
**Phase I - Preliminary Design/Cost Model**

- **1.1.0 (6.2)**
  - Preliminary Design *(TPA/GSE Package)*
    - 1.1.1 Baseline Concept
    - 1.1.2 Back-up Concept
    - 1.1.3 Low Cost Modifications
    - 1.1.4 Hot Fire Design
    - 1.1.5 Instrumented Concept
    - 1.1.6 GSE/Test Cart Design

- **1.2.0 (6.2.1)**
  - Studies, Analyses and Lab. Tests
    - 1.2.1 Low Cost Studies
    - 1.2.2 Materials Testing
    - 1.2.3 Bearing and Seal Test Preparation
    - 1.2.4 Impeller Tests
    - 1.2.5 Turbine Blade Tests

- **1.3.0 (6.2.2)**
  - Technology Development Plan

- **1.4.0 (6.3.1)**
  - Preliminary Cost Model

#### 2.0.0 (6.0)
**Phase 2 - Component Test Article/Detailed Cost Model**

- **2.1.0 (6.4)**
  - Detailed Design *(TPA/GSE Package)*
    - 2.1.1 Studies Analyses and Lab. Tests

- **2.2.0 (6.4)**
  - Studies Analyses and Lab. Tests

- **2.3.0 (6.5)**
  - Fabrication

- **2.4.0 (6.6)**
  - Test Support and Analysis

- **2.5.0 (6.3.2)**
  - Detailed Cost Model

- **2.6.0 (6.7)**
  - Special Studies

- **2.7.0 (6.3.1)**
  - Technology Development

#### 3.0.0 (4.0)
**Program Management**

- **3.1.0 (6.3.1)**
  - Phase I

#### 4.0.0 (4.0)
**Data**

- **4.1.0 (6.3.1)**
  - Phase I

---

**Legend**

- **CUSTOMER REPORTING**: "*
- **ELEMENT**: **TITLE**
- **WBS #**: **(XXX = SOW NUMBER)**

**ISSUE DATE**: 05/08/85  
**REVISION #**: 0  
**REVISION DATE**: 
**PROGRAM MANAGER**:  
**PROGRAM SCHEDULER**: 
Coordinated Total Plan

Preliminary Design Of TP And GSE w/Instrumentation
- Pump dia. Turb Area Margin

Reliability Analysis
- Historical Study
- FMEA
- Identify & Substantiate Life Drivers
- Variability Identification

Prelim. Cost Model
- Historical Anal.
- Assumptions Defined
- Spec Approach
- Validate Approach
- Assess Accurancy

Studies And Analysis & Lab Tests
- Low-Cost Trades
- LH2 Impeller -
  Materials Test, TI, Unbalance Test
- Materials Testing
  - Inco 909
  - Inco 718
  - A286 TMP
- Bearing And Seal Test Plan
  - 2 Lift-Off Seal Designs
  - 2 Bearing and Designs
  - Bearing Materials Tests (MTI)
  - Damper (TIP) Testing
- Design Iteration and Test

Detail Design of TP And GSE, Instrumentation
- Spans Ident.

Reliability Analysis
- Prob. Anal. Of Life Drivers

Detail Cost Model
- Model Structure
- First Unit & Prod. Cost Prediction
  (Prelim) Materials Characterization Plan

Test Plans
- Cold Gas
- Large Scale
- Low Cost Trades
  - Production Options
- In-Process Inspection
- Factory Optimization
- High Speed Balance
- Bearing And Seal Tests
  - Lift-Off Seal Tests (2)
  - Bearings (2)

Analysis & Lab Tests
- Cold Gas
- Hot Gas
- Launch Support Simulation

Reliability Analysis
- Discrepancy And Review/Research Process
  Proof Test And Analyses

Cost Model Calibration
- Manuals/Procedures Handbooks
- Fab STE

Turbine-GG Interface
- Final Test Plan(s)

CER
- Perf. & Reliability Subsistance

Final Report
- Update Rel. Perf.
- Final Deliver
- Final Report

Acceptance
- Marshall
- Update 1st Unit & Prod. Costs
- Perf. & Reliability Subsistance

Install Complete
- "Cold"
- GSE
- LH2 Damper Seats
- Loads Measurements
- Performance Measurement
- Anchor Cables

Deliver
- Update Rel. Perf.
- Inspect
- Deliver

Final Test
- "Cold"
- GSE
- LH2 Damper Seats
- Loads Measurements
- Performance Measurement
- Anchor Cables

Alternate Specifications and Procedures
- Tom Peters

Special Studies
- Titanium Housings
- Hydrostatic Bearings
- A286 TMP Turbine Blades
- alternate specifications and procedures
Aerojet's Industrial Team

- Aerojet TechSystems
- Mechanical Technology Inc.
- Ingersoll Engineers
- Trimet
- Tom Peters Group
- Participative Supplier Base
- Contractor
- Balancing, Advanced Mfg., Bearings and Seals Support
- Production Planning
- Materials Support
- Organization & Procedures
- Castings, Forgings, etc.
Subcontractors Have Well-Defined Tasks

- INGERSOLL ENGINEERS
  - Cost Substantiation
  - Production Manufacturing Strategy
  - Facility and Equipment Optimization
  - Manufacturing Organization Streamlining
  - Aerospace/Defense and Commercial Cost Data
  - Quality Function Integration

- MECHANICAL TECHNOLOGY INC. (MTI)
  - Bearing and Seal Technologies
  - Instrumentation and Test Planning
  - Advanced Manufacturing Technology
    - In-Process Machine Control
    - On-Machine Inspection
    - Automated Balancing
Emphasis On TQM

- Simultaneous Engineering
- Probabilistic Design
- Colocated Core Team
- Participative Subcontractors and Suppliers
- Organization-Wide Education and "Ideas Gathering"
Key Program Deliverables

- Test Articles Package:
  - Turbopumps Incorporating Results of Studies, Trades, Analyses, and Experiments
  - Test Cart With "Clean" Test Facility Interfacing for Improved Test Productivity
  - Ground Support Equipment, STE

- Results and Analysis of Tests at NASA-SSC

- Materials and Processes Data

- Material Characterization Plan

- Technology Development Plans

- Cost Model Anchored With Program Data:
  - Projected Recurring Production and Operations Costs
  - Recommended Specification and Procedure Savings
Our Program Includes Two Test Articles

- Unit No. 1 - Cold Gas Tests (Heavily Instrumented)
  - Understanding the Internal Turbopump Environment
  - Major Element of Integrated Analysis/Test Effort

- Unit No. 2 - Hot Gas Tests
  - Simulate Actual Engine Operating Environment

Fuel Turbopump Commonality Offers Option to Operate One Test Article in STME (LH₂) and STBE (LCH₄) Modes
## The Program

### Phase I
**12 Months**
- Preliminary Design
- Analyses and Trades
- Lab. Tests
- Preliminary Cost Model

### Phase II - Option
**28 Months**
- Detail Design
- Analyses & Lab. Tests
- Fabricate Two Turbopumps
  - Cold Gas/Instrumented
  - Hot Fire/Flight Type
- Fabricate Test Cart and GS
- Test Support to SSC
- Detailed Cost Model
Preliminary Design
(WBS 1.1.0)

Nancy Shimp

Objective: To Develop a Master Dimensional Layout
Based on the Results of the Analyses and Lab Tests
Phase I Program Focuses On Feasibility Of Concept

- Experiments
  - Materials Characterization
  - Impeller Fab
  - Turbine Blade Fab
  - Bearing and Seals

- Trades
  - Design Options
  - Maintainability
  - Commonality

- Preliminary Design
  - Create Master Dimensional Layout
  - Analyses to Determine Feasibility
  - Initial Load Assessment

- Cost Model Development
  - Preliminary Data Base
Program Achieves Phase I Objectives
POD Design Includes Proven Low Cost Features
Update POD Design To Include Latest Results Of Phase A Studies

- Update POD Design
  - Include Results of Phase A Studies
  - Relax Commonality Requirements With LOX Pump

- Pump Collector
  - Single Discharge
  - Volute Type

- Turbine Manifold Redesign
  - Baseline-Integral Cast Nozzles
  - Thermal Growth Allowances
  - Castability
  - Torus Area Reduction

- Turbine Disc Optimization
  - Blade Chord Reduction

- Bearing Load Path
Baseline Design Will Include Developments of Phase A Studies
Reliability And Cost Trades Begin

- Historical Reliability Analyses
- Reliability Allocations
- Develop a Baseline Start Transient
- Finalize the Design Trades List
- Incorporate Appropriate Performance Margins
Update POD Design Serves As Anchor For Low Cost Studies

- Updated POD Will Be Used to:
  - Casting Development Experiments
  - FMEA/CIL
  - LEMD
  - Perform Preliminary Analyses
    - Structural
    - Dynamic
    - Thermal
    - Bearing Life
  - Initial Piece Parts Cost
  - Instrumentation
  - Bearing and Lift-Off Seal Design
  - Low Cost Studies
    - Design Options
    - Maintainability
    - Commonality
  - GSE/Test Cart Concept
A LEMD Document Will Provide A Basis For Analysis

LEMD $\rightarrow$ Loads, Environmental, Materials Document

- Contains Data Required to Support Design Requirements, Including:
  - Loads on Pump Components
  - Vibratory and Acoustic Environment
  - Uniform Set of Material Properties

- Data for Document Initially Compiled From Several Sources
  - Interface Specifications
  - Pump Design Requirements
  - Previous ATC Experience (Titan)
  - Similar Prior Analyses

- Final Document Intended to Be Revised as New Data Becomes Available
  - Revised Analyses
  - Early Test Data (Hot Fire, Cold Gas)
While The Low Cost Trades Are Performed, Maturity Of The POD Design Improves With Analyses

Baseline Analyses

- Pump Hydraulics
- Turbine Aerodynamics
- Dynamics
- Power Transmission
- Thermal
- Structural
- Reliability
## Proven Pump Analysis Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
<th>ANALYSIS CODE VERIFICATION BASIS</th>
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<tr>
<td>1</td>
<td>1D Meanline</td>
<td>1D Meanline Pressures, Velocities and Pressure Losses</td>
<td>ATC Experience Base</td>
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<td>Inviscid 2D Pressures, Velocities and Flow Angles</td>
<td>ATC Experience Base Industry/NASA Standard</td>
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<td>2D Viscous (Navier Stokes) - &quot;AEROVISCE&quot;, &quot;PHOENICS&quot;, &quot;FIDAP&quot;</td>
<td>Viscous 2D Pressures, Velocities, Flow Angles and Pressure Losses</td>
<td>IR&amp;D Validation Plan for &quot;AEROVISCE&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
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<td>IR&amp;D Validation Plan for &quot;AEROVISCE&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
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<td>CDF Analysis, Pre and Post Processor Codes - &quot;PATRAN&quot;/ &quot;TRANSLATE&quot;, &quot;OTHER ROUTINES&quot;</td>
<td>Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis</td>
<td>ATC Experience Base</td>
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</tbody>
</table>

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**Note:** The table above outlines the codes and their respective outputs and verification bases for pump analysis. Each code is designed to handle different aspects of fluid dynamics, from 1D meanline analysis to 3D viscous flow simulations, ensuring comprehensive analysis of pump performance.
Pump Design Elements Are Integrated Into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Element</th>
<th>Input Source</th>
<th>Analysis Codes</th>
<th>Test Verification</th>
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<td>SOW, ICD, LEMD</td>
<td>EDC, 1</td>
<td>CGT, HGT</td>
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<td>2. Inducer</td>
<td>CDC, LEMD, PE</td>
<td>EDC, 6</td>
<td>CGT, HGT</td>
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<td>3. Impeller</td>
<td>CDC, LEMD, PE</td>
<td>EDC, 2, 4, 6</td>
<td>CGT, HGT</td>
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<tr>
<td>4. Vaneless Space</td>
<td>LEMD, PE</td>
<td>EDC, 1</td>
<td>CGT, HGT</td>
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<td>5. Diffuser/Crossover</td>
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<td>EDC, 2, 4, 6</td>
<td>CGT, HGT</td>
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<tr>
<td>6. Discharge Collector</td>
<td>LEMD, PE</td>
<td>EDC, 6</td>
<td>CGT, HGT</td>
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<tr>
<td>7. Discharge Ducts</td>
<td>SOW, ICD, LEMD, PE</td>
<td>EDC, 1</td>
<td>CGT, HGT</td>
</tr>
</tbody>
</table>

SOW = Statement of Work  
ICD = Interface Control Document  
LEMD = Loads, Environment, and Material Documentation  
PE = Previous Element Analyzed  
CDC = Conservative Design Criteria  
EDC = Empirical Design Correlation  
CGT = Cold Gas Tests at Stennis Space Center  
HGT = Hot Gas Tests at Stennis Space Center
## Proven Turbine Analysis Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
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<td>Inviscid 2D Pressures, Temperature, Velocities and Flow Angles</td>
<td>ATC Experience Base Industry/NASA Standard</td>
</tr>
<tr>
<td>3</td>
<td>2D Viscous (Navier Strokes) - &quot;AEROVISC&quot;, &quot;PHOENICS&quot;, &quot;FIDAP&quot;</td>
<td>Viscous 2D Pressures, Temperature, Velocities, Flow Angles and Pressure Losses</td>
<td>IR&amp;D Validation Plan for &quot;AEROVISC&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
</tr>
<tr>
<td>5</td>
<td>3D Viscous (Navier Strokes) - &quot;AEROVISC&quot;, &quot;PHOENICS&quot;, &quot;FIDAP&quot;</td>
<td>Viscous 3D Pressures, Velocities, Flow Angles and Pressure Losses</td>
<td>IR&amp;D Validation Plan for &quot;AEROVISC&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
</tr>
<tr>
<td>6</td>
<td>Design Codes - &quot;MULTISTG&quot;, &quot;OFFTURB&quot;</td>
<td>Geometry - Basic Sizing, Off-Design Performance</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>7</td>
<td>CDF Analysis, Pre and Post Processor Codes - &quot;PATRAN&quot;/ &quot;TRANSLATE&quot;, &quot;OTHER ROUTINES&quot;</td>
<td>Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis</td>
<td>ATC Experience Base</td>
</tr>
</tbody>
</table>
# Turbine Design Elements Are Integrated Into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Element</th>
<th>Input Source</th>
<th>Analysis Codes</th>
<th>Test Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Turbine Inlet Flange</td>
<td>SOW, ICD, LEMD</td>
<td>EDC, 1</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>2. Turbine Inlet Manifold</td>
<td>SOW, ICD, LEMD, PE</td>
<td>EDC, 1, 5, 7</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>3. Nozzle Vanes (1st and 2nd Stage)</td>
<td>LEMD, PE</td>
<td>EDC, 2, 6, 3, 5, 7, 8</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>4. Rotor Blade (1st and 2nd Stage)</td>
<td>LEMD, PE</td>
<td>EDC, 2, 6, 3, 5, 7, 8</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>5. Turbine Exhaust w/ Guide Vanes</td>
<td>SOW, ICD, LEMD, PE</td>
<td>EDC, 1, 2, 5, 7</td>
<td>CGT, HGT</td>
</tr>
</tbody>
</table>

SOW = Statement of Work  
ICD = Interface Control Document  
LEMD = Loads, Environment, and Material Documentation  
PE = Previous Element Analyzed  
EDC = Empirical Design Correlation  

CGT = Cold Gas Tests at Stennis Space Center  
HGT = Hot Gas Tests at Stennis Space Center
## Proven Dynamic Analysis Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
<th>ANALYSIS CODE VERIFICATION BASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&quot;RODYNE&quot; Dynamic Simulation Code</td>
<td>Campbell Diagrams, Root Loci to Show Critical Speed Margin and Stability</td>
<td>ATC Experience Base SSME HPFTP Benchmark with NASA MSFC</td>
</tr>
<tr>
<td>3</td>
<td>&quot;ANSYS&quot; Finite Element Code</td>
<td>Detailed Stress Response to Dynamic Loading from Hub Motion and Fluid Pressure</td>
<td>Commercial Code Industry/NASA Standard</td>
</tr>
<tr>
<td>4</td>
<td>&quot;RODYNE&quot; Dynamic Simulation Code</td>
<td>Response of Vane/Hub or Bladed Disc/Rotor/Housing to Imbalance, Hydraulic/Aerodynamic Forces, Rubbing, Transient Operation</td>
<td>ATC Experience Base SSME HPFTP Benchmark with NASA MSFC</td>
</tr>
</tbody>
</table>
Dynamic Analysis Elements Are Integrated Into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Element</th>
<th>Input Source</th>
<th>Analysis Codes</th>
<th>Test Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rotating Assembly Critical Resonances &amp; Mode Shapes, Lateral</td>
<td>CDC, LEMD</td>
<td>1, 2</td>
<td>1, 2</td>
</tr>
<tr>
<td>2. Rotating Assembly Critical Resonances &amp; Mode Shapes, Torsional</td>
<td>CDC, LEMD</td>
<td>1, 2</td>
<td>1, 2</td>
</tr>
<tr>
<td>3. Impeller Blade and Shroud</td>
<td>LEMD, PD</td>
<td>3</td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>4. Diffuser/Crossover</td>
<td>LEMD, TD</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5. Pump Volute</td>
<td>LEMD, TD</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>6. Nozzle Vanes (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>3</td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>7. Rotor Disc (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>3</td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>8. Rotor Blades (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>3</td>
<td>1, 3, 4</td>
</tr>
</tbody>
</table>

CDC = Conservative Design Criteria  
LEMD = Loads, Environment, and Material Documentation  
PD = Pump Design  
TD = Turbine Design  
CGT = Cold Gas Tests at Stennis Space Center  
HGT = Hot Gas Tests at Stennis Space Center  
LT = Laboratory Tests
### Proven Power Transmission Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
<th>ANALYSIS CODE VERIFICATION BASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ATC Code</td>
<td>Flowrates, Pressure Drops, Velocities</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>2</td>
<td>ATC Code</td>
<td>Axial Thrust Load on Bearings and Balancer</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>3</td>
<td>1D Bearing Cooling Flow</td>
<td>1D Pressures Mass Flows and Temperature</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>4</td>
<td>2D Viscous (Navier Strokes) - &quot;AEROVISIC&quot;, &quot;PHOENICS&quot;, &quot;FIDAP&quot;</td>
<td>Viscous 2D Pressures, Velocities, and Mass Flows</td>
<td>IR&amp;D Validation Plan for &quot;AEROVISIC&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
</tr>
<tr>
<td>5</td>
<td>3D Viscous (Navier Strokes) - &quot;AEROVISIC&quot;, &quot;PHOENICS&quot;, &quot;FIDAP&quot;</td>
<td>Viscous 3D Pressures, Velocities, and Mass Flows</td>
<td>IR&amp;D Validation Plan for &quot;AEROVISIC&quot; Existing Empirical Data Base for &quot;PHOENICS&quot; and &quot;FIDAP&quot;</td>
</tr>
<tr>
<td>6</td>
<td>CFD Analysis, Pre and Post Processor Codes - &quot;PATRAN&quot;/&quot;TRANSLATE&quot;, &quot;OTHER ROUTINES&quot;</td>
<td>Advanced Mesh Generation and Color Graphics to Aid in Rapid CFD Design and Analysis</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>7</td>
<td>A. B. Jones</td>
<td>Life, Capacity, Stiffness, Cooling Pressure/Flow Characteristics</td>
<td>ATC Experience Base</td>
</tr>
<tr>
<td>8</td>
<td>Shabbreth</td>
<td>Bearing Life and Wear Rates Leakage and Rotordynamic Coefficients for Turbulent Annular Seals</td>
<td>NASA/SSME Published Technical Literature, Test Data</td>
</tr>
<tr>
<td>9</td>
<td>&quot;Groove&quot; Damper Seal and Grooved Seal Design</td>
<td></td>
<td></td>
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</tbody>
</table>
## Power Transmission Elements Are Integrated Into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Element</th>
<th>Input Source</th>
<th>Analysis Codes</th>
<th>Test Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Axial Thrust Loads</td>
<td>LEMD, TPD</td>
<td>1, 2</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>2. Balance Piston Loads and Performance</td>
<td>LEMD, TPD, PA</td>
<td>2</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>3. Radial Loads</td>
<td>LEMD, TPD, PA</td>
<td>4, 6</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>4. Pump End Bearing Design</td>
<td>LEMD, CDC, PA</td>
<td>3, 7, 8</td>
<td>LT, CGT, HGT</td>
</tr>
<tr>
<td>5. Turbine End Bearing Design</td>
<td>LEMD, CDC, PA</td>
<td>3, 7, 8</td>
<td>LT, CGT, HGT</td>
</tr>
<tr>
<td>6. Damper Seal Design</td>
<td>LEMD, CDC, PA, MTI</td>
<td>9</td>
<td>LT, CGT, HGT</td>
</tr>
<tr>
<td>7. Labyrinth/Damper Seal Design</td>
<td>LEMD, CDC, PA</td>
<td>3</td>
<td>CGT, HGT</td>
</tr>
</tbody>
</table>

**LEMD** = Loads, Environment, and Material Documentation  
**TPD** = Tubopump Design Definition (Preliminary or Detail)  
**PA** = Previous Analyses (Pump/Turbine Performance, Stress, Thermal, Dynamics)  
**CDC** = Conservative Design Criteria  
**MTI** = Mechanical Technology, Incorporated  

CGT = Cold Gas Tests at Stennis Space Center  
HGT = Hot Gas Tests at Stennis Space Center  
LT = Laboratory Tests
Proven Thermal Analysis Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
<th>ANALYSIS CODE VERIFICATION BASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&quot;SINDA&quot;</td>
<td>Detailed 2D/3D Temperature Distribution</td>
<td>Industry/NASA Standard</td>
</tr>
<tr>
<td>2</td>
<td>&quot;ONE - D - COND&quot;</td>
<td>1D Transient Temperature Distribution</td>
<td>ATC Experience Base/ATC In-House Code</td>
</tr>
<tr>
<td>3</td>
<td>&quot;PATRAN&quot;</td>
<td>Model Geometry and Input for &quot;P/ THERMAL&quot;</td>
<td>Industry/NASA Standard</td>
</tr>
<tr>
<td>4</td>
<td>&quot;P/ THERMAL&quot;</td>
<td>2D/3D Temperature Distribution and Stress Analysis</td>
<td>ATC Experience Base Titan Engine Margin Study</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compatible Results</td>
<td></td>
</tr>
</tbody>
</table>
### Thermal Analysis Elements Are Integrated into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Test Verification</th>
<th>Input Source</th>
<th>Preliminary Design</th>
<th>Analysis Code</th>
<th>Test Design</th>
<th>Test Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrayed, Ternary State Temperature Profiles</td>
<td>LEMD, TPD</td>
<td>2</td>
<td>2</td>
<td>3, 4</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>Turbine Inlet Manifold Transient and Steady State Temperature Profiles</td>
<td>LEMD, TPD</td>
<td>2</td>
<td>3, 4</td>
<td>3, 4</td>
<td>HGT</td>
</tr>
<tr>
<td>Nozzle Vanes (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>2</td>
<td>2</td>
<td>3, 4</td>
<td>HGT</td>
</tr>
<tr>
<td>Rotor Disc (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>2</td>
<td>3, 4</td>
<td>3, 4</td>
<td>HGT</td>
</tr>
<tr>
<td>Turbine Blades (1st and 2nd Stage)</td>
<td>LEMD, TD</td>
<td>3, 4</td>
<td>2</td>
<td>3, 4</td>
<td>HGT</td>
</tr>
<tr>
<td>Exhaust Housing w/ Guide Vanes</td>
<td>LEMD, TD</td>
<td>2</td>
<td>3, 4</td>
<td>3, 4</td>
<td>HGT</td>
</tr>
</tbody>
</table>

**Legend:**
- **CGT** = Cold Gas Tests at Stennis Space Center
- **HGT** = Hot Gas Tests at Stennis Space Center
- **LEMD** = Loads, Environment, and Material Documentation
- **TPD** = Turbopump Design Definition (Preliminary or Detail)
- **TD** = Turbine Design
Proven Stress Analysis Codes Will Be Used

<table>
<thead>
<tr>
<th>ANALYSIS CODE NO.</th>
<th>ANALYSIS CODE DESCRIPTION</th>
<th>ANALYSIS CODE OUTPUT</th>
<th>ANALYSIS CODE VERIFICATION BASIS</th>
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<tbody>
<tr>
<td>1</td>
<td>Emperical Correlations</td>
<td>Preliminary Stress Levels</td>
<td>ATC Experience</td>
</tr>
<tr>
<td>2</td>
<td>2D Finite Element Models - &quot;ANSYS&quot;, &quot;PATRAN&quot;</td>
<td>2D Matrix and Modal Models - Stress Levels</td>
<td>Commercial Code Industry/NASA Standard</td>
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<tr>
<td>4</td>
<td>&quot;FLAGRO&quot;</td>
<td>Fatigue Life of Cyclically Loaded Structures with Initial Cracklike Defects</td>
<td>NASA</td>
</tr>
</tbody>
</table>
# Stress Analysis Elements Are Integrated Into A Concerted Analysis Effort

<table>
<thead>
<tr>
<th>Element</th>
<th>Input Source</th>
<th>Analysis Codes</th>
<th>Test Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inducer</td>
<td>LEMD, PD</td>
<td>1, 2, 3, 4</td>
<td>FT, CGT</td>
</tr>
<tr>
<td>2. Impeller</td>
<td>LEMD, PD</td>
<td>1, 2, 3, 4</td>
<td>FT, CGT</td>
</tr>
<tr>
<td>3. Diffuser/Crossover</td>
<td>LEMD, PD</td>
<td>1, 2, 3, 4</td>
<td>FT, CGT</td>
</tr>
<tr>
<td>4. Pump Housing</td>
<td>LEMD, PD</td>
<td>1, 2, 3, 4</td>
<td>FT, CGT</td>
</tr>
<tr>
<td>5. Bearing Housing</td>
<td>LEMD, PTD</td>
<td>1, 2, 3, 4</td>
<td>HGT</td>
</tr>
<tr>
<td>6. Turbine Inlet Manifold</td>
<td>LEMD, TD</td>
<td>2, 3, 4</td>
<td>FT, HGT</td>
</tr>
<tr>
<td>7. Turbine Nozzle/Stator</td>
<td>LEMD, TD</td>
<td>2, 3, 4</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>8. Turbine Disc</td>
<td>LEMD, TD</td>
<td>2, 3, 4</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>9. Turbine Blades</td>
<td>LEMD, TD</td>
<td>2, 3, 4</td>
<td>LT, CGT, HGT</td>
</tr>
<tr>
<td>10. Turbine Exhaust Housing</td>
<td>LEMD, TD</td>
<td>2, 3, 4</td>
<td>FT, HGT</td>
</tr>
<tr>
<td>11. Shaft</td>
<td>LEMD, PTD</td>
<td>1, 2, 3, 4</td>
<td>CGT, HGT</td>
</tr>
<tr>
<td>12. Flange/Fasteners</td>
<td>LEMD</td>
<td>1, 2, 3, 4</td>
<td>FT, CGT, HGT</td>
</tr>
<tr>
<td>13. Turbopump Mount</td>
<td>LEMD</td>
<td>1, 2, 3</td>
<td>HGT</td>
</tr>
</tbody>
</table>

LEMD = Loads, Environment, and Material Documentation
PD = Pump Design
PTD = Power Transmission Design
TD = Turbine Design
CGT = Cold Gas Tests at Stennis Space Center
HGT = Hot Gas Tests at Stennis Space Center
FT = Fabrication Tests (Proof, Burst, Spin)
LT = Laboratory Tests
MTI Provides Analysis Support For Bearings And Seals

- Bearing Design - Cage Stability
  - CREB or RAPIDRED Computer Codes
- Lift-Off Seals
  - GFACE/SPIRALP Computer Codes
- Damper Seals
  - DSEAL Computer Code
  - Radial Loads
- Bearing Instrumentation
- Bearing Type Trade Study
  - Rolling Element
  - Hybrids
  - Hydrostatic
MTI Will Conduct Tests To Evaluate Candidate Bearing Materials

- Bearing Materials Tests
  - Material Candidate Selection
  - Rolling Contact Performance Tests
  - Cryogenic Sliding Wear Tests
  - Cryogenic Rolling Wear Tests
  - Stress Corrosion Cracking Tests
Bearing Materials Will Be Systematically Evaluated
## Preliminary Materials Have Been Selected For Evaluation

<table>
<thead>
<tr>
<th>Race Rolling Element Materials</th>
<th>Hard Coats</th>
<th>Soft Coats</th>
<th>Cage Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>440C (Baseline)</td>
<td>Ion Implantation Chrome</td>
<td>Ag</td>
<td>Armalon (Baseline)</td>
</tr>
<tr>
<td>CRB-7</td>
<td>Ion Implantation Titanium/Carbon</td>
<td>MoS₂</td>
<td>Salox-M</td>
</tr>
<tr>
<td>MRC-2001</td>
<td>PVD Cr 203</td>
<td></td>
<td>Silver-Plated Steel or Bronze</td>
</tr>
</tbody>
</table>
Multi-Pronged Approach to Stress Corrosion Cracking Issue

- Minimize Hoop Stress
  - Fit Analysis
  - Ball Bearings
    - Single Interferences
    - Fit Per Bearing
    - Preload Control

- Control Environment
  - Surface Treatment (Test Program)

- Optimize Materials
  - Forged Races (Test Program)
  - Alternates (Test Program)
  - Surface Treatment (Test Program)
Casting Feasibility

- Phase I Impeller Development Program
  - Contact Industry Casting Leaders for Input on Facility Availability and Experience Base
  - Perform Mechanical Properties Tests on Vendor Supplied Coupons
  - Iteration of Casting Practice to Develop Best Mechanical Properties and Component Geometry
  - Destructive Tests of Castings for Metallurgical and Mechanical Properties Evaluation
  - Balance Tests to Verify Symmetry
  - Spin and Burst Tests to Determine Design Margins
- Phase II Casting Development and Refinement
  - Development and Refinement of Cast Impellers, Manifolds, and Housings
# Mechanical Properties Evaluation

For Cast Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller</td>
<td>Ti-5Al-2.5 Sn ELI</td>
<td>T*, F*, CG*, Prolongation, Spin, Burst</td>
<td>Prolongation, Spin</td>
</tr>
<tr>
<td>Housing</td>
<td>Inconel 718</td>
<td>T, F, CG</td>
<td>Prolongation, Burst, Proof</td>
</tr>
<tr>
<td>Manifold</td>
<td>Incoloy 909</td>
<td>T, F, CG, SR*</td>
<td>Prolongation, Burst, Proof</td>
</tr>
</tbody>
</table>

*Preliminary Material Properties Evaluation, T - Tensile, F - Fatigue (LCF, HCF), CG - Crack Growth, SR - Stress Rupture
Design Approach To Ensure Producibility

- Producibility Engineering Input to Design
- Casting Vendors Review Preliminary Drawings
- Tooling Options to Produce Casting are Considered
- Iterations to Refine Casting Procedures Have Been Included in Casting Program
- Modifications Made to Final Design to Ensure Reliability, Producibility, and Low Cost With Compromise to Performance if Necessary
Parametric Analyses Will Be Used To Select Minimum Cost Design Configurations
Trade Studies Will Be Used To Refine Our Low Cost Concepts

- Inputs
  - Part Costs
  - Part Weight
  - Relative Reliability
  - Turbine Weight Flow

- Constraints
  - Turbopump Reliability
  - Turbine Weight Flow Maximum $\approx$ TBD
  - Turbopump Weight Maximum $\approx$ TBD

- Optimize Configuration
  - ADS Code
We Will Perform Design Trade Studies to Ensure a Reliable, Low Cost, Maintainable Design

<table>
<thead>
<tr>
<th>Options</th>
<th>Design Concepts</th>
<th>Evaluation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Point Selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suction Specific Speed Limit</td>
<td>Higher Limits Decrease Tolerance to Variations</td>
<td>Higher Limits Increase Turbine Blade Stress</td>
</tr>
<tr>
<td>Turbine Blade Stress Limit</td>
<td>Higher Limits Increase Turbine Blade Stress</td>
<td></td>
</tr>
<tr>
<td>* AN² = 25 x 10⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing Speed, DN</td>
<td>Higher Limits Decrease Bearing Load Capacity and Life</td>
<td>Lower Limits Increase Cost by Adding Weight but Reduce Costs by Increasing Life Expectancy</td>
</tr>
<tr>
<td>* DN = 2 x 10⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impeller Tip Speed Limit</td>
<td>Higher Limits Increase Impeller Blade Stress</td>
<td></td>
</tr>
<tr>
<td>U = 1800 fps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine Tip Speed Limit</td>
<td>Higher Limits Increase Turbine Disc Stress</td>
<td></td>
</tr>
<tr>
<td>* U = 1400 fps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine Inlet Temperature</td>
<td>Higher Limits Reduce Reliability by Reducing Material Strength</td>
<td>Higher Limits Increase Cost by Limiting Material Choices</td>
</tr>
<tr>
<td>* TTI = 1140 degrees F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine Manifold Casting</td>
<td>Potential Leak Path Removed with Single Piece Casting or Welded Two Piece Casting</td>
<td>Commonality Reduced With One Piece Casting Since Nozzle Ring Not Removable, Assembly and Machining Cost Increase With Two Piece Casting</td>
</tr>
<tr>
<td>* One Piece Casting</td>
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<td>Two Piece Casting with Bolted or Welded Nozzle Ring</td>
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<td>Turbine Manifold Flange</td>
<td>Welding Increases Variability in Material Properties; Bolted Design Increases Thermal Stresses</td>
<td>Welded Manifold Increases Assembly Costs</td>
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<td>No Pressure Containment</td>
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<td>* Welded - Inseparable Bolted - Separable</td>
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<td>Turbine Rotor Shaft Attachment</td>
<td>Evaluate Internal Friction Effect on Dynamic Stability; Critical Speed Windows</td>
<td>Evaluate Assembly/Disassembly Costs</td>
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<td>* Curvic Couplings</td>
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<td>Splices Integral</td>
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<td>Impeller Shroud</td>
<td>Performance Variations Associated with Varying Tip Clearance on Stationary Shroud Design</td>
<td>Costs Penalties Associated With Machining</td>
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<td>* Attached (Cast) Stationary (Back-up Only) (Machined)</td>
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<td>Bearing Type</td>
<td>Ball Bearings - Life Limited Hybrids - Load Sharing Hydrostatic - Rubbing Start</td>
<td>Evaluate Assembly and Parts Costs for Each Concept</td>
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<td>Pump Housing Material</td>
<td>Titanium Has a History of Cracking</td>
<td>Part Costs Increase Material Cost</td>
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<tr>
<td>* Inconel 718 Stainless 304L Titanium</td>
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* Selection for Point of Departure Design
## Maintainability Options Listing

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<th>Options</th>
<th>Evaluation Parameters</th>
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<tr>
<td>Breakaway Torque Movement</td>
<td>Reliability: With Mechanical, Leakage Potential in Access Port</td>
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<td>• Turbine Driven - Cold Gas</td>
<td>Performance: No Effect</td>
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<tr>
<td>• Mechanical - Wrench</td>
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<td>Turbine Blade Inspection</td>
<td>Damage to Turbine Blades</td>
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<td>• Best Method</td>
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<td>Leak Check of External Connections</td>
<td>No Effect</td>
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<td>• Pressure Between Dual Seals</td>
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<td>• Gas Chromatography</td>
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<td>• Bubble Check</td>
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<td>External Seals</td>
<td>Increased Reliability With Dual Seals</td>
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<td>• Dual Seals</td>
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<td>• Single Seals</td>
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<td>Health Monitoring</td>
<td>Increase in Bearing Life</td>
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<td>• Bently Probe for Bearing Distress</td>
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<tr>
<td>Vehicle Integration</td>
<td>Likelihood of Undetected Damage</td>
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<td>• Damage Rate Shipped, Installed, or Pulled from Engine</td>
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<td>Method of Packing/Shipping</td>
<td>Likelihood of Undetected Damage</td>
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<td>Number and Types of Ground Support Equipment</td>
<td>Complexity and Interfaces</td>
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<td>Number and Location of Pre-Flight Checkout</td>
<td>Increase Reliability Due to Additional Checkout; Reduce Breaking into System</td>
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* Selection for Point of Departure Design
## Commonality Provides Substantial Development and Life Cycle Cost Benefits

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<tr>
<th>Level</th>
<th>Options</th>
<th>Reliability</th>
<th>Cost - Development/LCO</th>
<th>Performance</th>
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<td>Common LCH&lt;sub&gt;2&lt;/sub&gt;/L&lt;sub&gt;H&lt;/sub&gt;&lt;sub&gt;2&lt;/sub&gt; TP 100%</td>
<td>LCH&lt;sub&gt;4&lt;/sub&gt; TP Reliability Increases Because TP Operating Derated</td>
<td>Substantial Cost Savings</td>
<td>Significant Adverse TP Weight Impact on LCH&lt;sub&gt;4&lt;/sub&gt; Pump</td>
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<td>V</td>
<td>Common Turbine Manifold</td>
<td>Reliability Increase on LOX Pumps; Operating Derated</td>
<td>Identical on All 4 Turbopumps</td>
<td>Small Increase in Manifold Pressure Loss in LOX Pumps</td>
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<td>V</td>
<td>Common Turbine Rotor Discos</td>
<td>Margin Decrease on LOX Turbine Blades; Short Chord</td>
<td>Identical on All 4 Turbopumps and Stages Within Turbopumps</td>
<td>Performance Decrease On Fuel Turbines; Chord Length</td>
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<td>Common Impellers</td>
<td>No Effect</td>
<td>Identical Within Common Fuel Turbopumps</td>
<td>Lower Performance on 2nd Stage Due to Increased Incidence</td>
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<td>Common Bearings</td>
<td>LOX TP DN Higher Than for Optimized LOX TP but Greatly Derated from Fuel Conditions</td>
<td>Identical Within Turbopumps and Between Turbopumps</td>
<td>Increased Weight on LOX Pumps</td>
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<td>Common Lift-Off Seals</td>
<td>Increased Reliability - Improvement/ Experience Curve</td>
<td>Between Turbopumps</td>
<td>No Effect</td>
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<td>V</td>
<td>Common Fir Tree Attachment for Turbine Blades</td>
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<td>No Effect</td>
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<td>V</td>
<td>Turbine Blade Dampers</td>
<td>Increased Reliability - Improvement/ Experience Curve</td>
<td>Identical Within Turbopumps and Between Turbopumps</td>
<td>No Effect</td>
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### Legend
- **V**: Within Vehicle
- **E**: Within Engine
- **P**: Within Turbopump
Results Of Low Cost Studies Will Be Incorporated In Baseline Design

- Update Preliminary Design Analyses
- Initial Reliability Estimates
  — Probabilistic Design
- Update Component Costs
- Tooling Concepts - Assembly/Disassembly
- Update GSE/Test Cart Concepts
- Begin Instrumented Design
- PDR
Laboratory Tests
(W.B.S. 1.2.0)

George Claffy

Objective: Determine Feasibility of Selected Technologies
Lab Tests Will Be Performed To Support Preliminary Designs

- Casting Feasibility
  - Material Characterization Tests
  - Impeller Spin Tests
- Turbine Blade Tests
- Bearing and Seal Tests
  - MTI Materials Tests
  - Stress Corrosion Cracking Test
Key Issues Addressed In Test Programs

Materials Testing

- Cast Materials Have Insufficient Data Base for Our Applications
  - Incoloy 909 - HEE, High Temp. Fatigue
  - Ti - 5, 2.5 - HEE, Cryo Fatigue and Ductility
  - Inconel 718 - HEE, Cryo Fatigue and Ductility

- Additional Data Required on Turbine Blade Material
Key Issues Addressed
In Test Programs (Cont)

Impeller Fab and Test

- Feasibility of Casting Impeller Geometry to Net Shape
- Feasibility of Using Titanium Castings for High-Speed Rotating Component
  - Dimensional Uniformity
  - Distortion at Speed
  - Variability of Physical Properties Within Casting
  - Effect of Non-Uniform Cooling Rates on Microstructure
  - Cryogenic Ductility
Key Issues Addressed In Test Programs (Cont)

Turbine Blade Fab and Test

- Feasibility of Forging Blade Geometry to Net Shape
- Sample-to-Sample Variability in A-286 TMP Material
  - Dimensions
  - Physical Properties
  - Natural Frequencies
Key Issues Addressed
In Test Programs (Cont)

Bearing/Seal Testing

- Selection of High-Reliability Bearing Materials
  - MTI Sliding/Rolling Tests Will Identify Candidates
  - Candidates Will Be Evaluated in ATC Test Unit Under Simulated Service Conditions
    - Speed
    - Loads
    - Cryogenic Fluid

- Demonstration of Lift-Off Seal Reliability
  - Operate in ATC Test Unit
Tests Will Confirm Properties Of Critical Materials (WBS 1.2.2)

Objectives

- Evaluate Four Materials
  - Incoloy 909 Cast - Verify HEE and High Temperature Properties
  - Stellite 31 (Backup for Incoloy 909)
  - Inconel 718 Cast - Verify HEE and Cryo Temperature Properties
  - Ti 5, 2.5 Cast - Verify HEE, Ductility at Cryo Temp, Uniformity of Properties
  - TMP A-286 - Verify HEE and High Temperature Properties

Approach

- Perform Tests in Simulated Environments
  - HEE - Aerojet Hydrogen Materials Test Facility
  - Turbine Materials - 1200°F Simulated Combustion Gas
  - Pump Materials - LH₂
<table>
<thead>
<tr>
<th>Material</th>
<th>Principal Component(s)</th>
<th>Tests: Tensile</th>
<th>Fatigue</th>
<th>Crack Growth</th>
<th>Stress Rupture</th>
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<td>R, G, H, E</td>
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<td>Turbine Disk</td>
<td>R, C, H</td>
<td>R, C, H</td>
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<td>E, G</td>
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<td>Pump Impellers</td>
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<td>Pump Hsg.</td>
<td>R, C, H</td>
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</table>

R = Room Temperature
E = Elevated Temperature
C = Cryogenic
G = 1200°F Gas
H = HEE (R.T.)
## Preliminary Design

### Materials Testing Schedule Supports

<table>
<thead>
<tr>
<th>Program Months</th>
<th>Incoloy 909 Test</th>
<th>A-286 TMP Specimens Test</th>
<th>Ti5Al, 2.5 Sn Specimens Test</th>
<th>Procure New Specimens</th>
<th>Procure Specimens</th>
<th>Finalize Prelim Design</th>
<th>Design Milestones (Ref.)</th>
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</table>

- **POD Update**
- **POD Analysis**
- **Low Cost Studies**
- **Changes**
- **PDR**
Feasibility Of Casting Pump Impellers Will Be Evaluated (WBS 1.2.4)

Objectives

- Develop Tooling and Process for Casting Ti Pump Impellers for ALS
- Produce Several Castings to Demonstrate Repeatability
- Evaluate Structural Integrity by Testing

Approach

- Prepare Preliminary Casting Drawing for Representative Pump Impeller of Ti 5, 2.5
- Prepare Tooling and Pour Trial Pieces. Iterate Tooling and Drawing Based on Results
- Pour Additional Cast Impellers for Testing
- Machine Interfaces for Spin Testing
- Evaluate Structural Integrity by Metallurgical Testing and Spin Tests - Spin One Impeller to Burst
Casting CAD Drawing For Titanium
Impeller Is In Progress
Impeller Testing Will Provide Confidence In Cast-Titanium Structural Integrity

- Metallurgical Tests
  - Machine Specimens From Critical Areas of Sectioned Casting to Provide Data on Microstructure and Properties

- Spin Tests
  - Take One Impeller to Burst Speed for Comparison With Value Predicted for Assumed Properties and Dimensional Uniformity
  - Spin Remaining Impellers to Maximum Operating Speed With Strain Gages Incorporated, as a Check on Unit-to-Unit Variations
  - Spin Tests at Cryogenic Temperature Are Desirable. Now Investigating Means of Accomplishing This
<table>
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<tr>
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</table>
Turbine Blade Test Approach Keyed To Analytical Results

- Blade Design Goal Is for All Natural Frequencies to be Above Blade Passing Frequency

- If There Is Insufficient Analytical Margin, a Vibration Survey Will Be Performed on Development Blades to Confirm Predicted Natural Frequency

- In Keeping With Good Design Practice, Dampers Will Be Incorporated During Detail Design—Assuming the Added Tip Mass Does Not Compromise Structural Integrity
# Turbine Blade Program Schedule

Supports PDR

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<th>Program Months</th>
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PDR (REF) △
Bearing/Seal Test Preparations Will Assure Readiness For Phase II Testing (WBS 1.2.3)

Objectives

- Evaluate Baseline and Alternative Ball Bearing Materials/Configuration

Approach

- Utilize Existing Tester Design and Generic Parts
- Fab All Tester Hardware in Phase I
- Prepare Bearing/Seal Test Plan
- Select Test Facility
Bearing/Seal Test Configuration Has Been Defined
## Brg/Seal Test Preparation Schedule

Leads to Early Phase II Test

<table>
<thead>
<tr>
<th>Program Months</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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</thead>
<tbody>
<tr>
<td>Prepare Bearing Dwgs (Ref.)</td>
<td>▲</td>
<td>▲</td>
<td></td>
<td>▲</td>
<td></td>
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<tr>
<td>Bearing Procurement</td>
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<tr>
<td>Test Unit Design</td>
<td>▲</td>
<td>▲</td>
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<td>▲</td>
<td>▲</td>
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<td>▲</td>
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<tr>
<td>Hardware Fab.</td>
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<td>▲</td>
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<td>▲</td>
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<td>▲</td>
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<td>▲</td>
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<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>

Build Up Test Unit in Phase II
Technology Development Plan
(WBS 1.3.0)

- Provides Vehicle for Identifying Technology Areas in Need of Further Pursuit

- Anticipate Awareness of Technology Development Needs

- Sufficient Documentation Will be Provided to Support ALS Phase C/D Planning
  - Problem Statement
  - Data Required
  - Recommended Approach
  - Suggested Facilities/Equipment

- One Program Already Identified for Inclusion
  - Extended A-286 TMP Turbine Blade Life
Preliminary Cost Model

Colin Faulkner

Objective: Develop and Anchor Cost Model
Phase I Cost Model Deliverables

- Model Architecture (Preliminary Version)
  - Assumptions Used
- Input Data Sources
- Approach for Evaluating NASA Requirements Impacts
- Approach for Application of Phase II Fabrication Data
- Model Results Uncertainties Identified
Cost Model Basis

- Piece-Part Based
  - Process Flows Developed for Each Part and Assembly
  - Production and Operations Activities
  - Specifications and Procedures Identified for Each Flow Activity

- Spreadsheet Based
  - Records and Manipulates Data (Learning Curves, etc.)

- Titan Data Base
  - Titan Production and Operations Costs Anchor Initial Model and "Test for Reasonableness"

Program Goal: Reduce Magnitude of Cost Uncertainties
Today: 20-30% (STME/STBE Studies)
Phase II End: 5-10%
O&S Costs Will Be Addressed

- O&S Costs Will Be Estimated Using:
  - Historical Data Base
    - Titan 1st and 2nd Stage
    - SSME
  - Defense Logistics Agency Reports
  - Analysis
    - Detailed Evaluation of Activities

- Estimates at Maintenance Significant Item (MSI) Level

- Estimates Will Include Mission Model, Launch Rate, Service-Free Life, Useful Life, Turnaround Time

- Apportion Propulsion System Level Costs to Component Assembly Level
Specifications And Procedures Impacts Analysis

- Concurrently Optimize Design, Fabrication, O&S and Specification Requirements
  
  — Specifications Analyzed as Up-Front Activity
  — Zero-Base Budget Approach
  — Verify Need for Each Specification Item
  — No Specification Duplication
  — Design to Avoid Sensitive Production Processes
  — Develop Simplified Specification Where Possible
  — Tailor Government Specifications or Substitute Contractor Specifications
Phase I Cost Model Network/Schedule
Phase II

Detail Design, Fabrication, And Test
Phase IIFocused On
Turbopump Fabrication And Test

- Detail Design
  - Productibility Trades
  - Drawings
  - Supporting Detailed Analyses

- Experiments
  - Bearing Life Testing
  - Seal Development

- Fabrication
  - Fabrication of Two Turbopumps
  - Proof Testing
  - Inspection Technique Development

- Testing
  - Cold Gas - Internal Environment
  - Hot Fire - Full Load

- Cost Model
  - Data Base Development
Objective: To Produce All Drawings With Supporting Analyses Required to Make the Two Turbopumps
Detail Design Will Re-Emphasize Producibility

- Producibility Refinements

  - Casting Options
  - Inspection Techniques
  - Production Enhancers for Cast Parts

  - In-Process Controls
    - MTI
    - Ingersoll

  - In-Process Inspection
    - MTI

  - Factory Floor Optimization and Organization
    - Ingersoll Engineering

  - High Speed Balance
    - MTI
We Will Perform Trade Studies to Enhance Design Productability

<table>
<thead>
<tr>
<th>Options</th>
<th>Evaluation Parameters</th>
<th>Cost</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Technique Pump Housing and Turbine Manifold • Investment * • Sand</td>
<td>Investment Results in Less Variability</td>
<td>Quantity Savings With Sand Castings</td>
<td>Efficiency Penalties From Surface Roughness With Sand Castings</td>
</tr>
<tr>
<td>Slurry Polishing • Pump Diffuser Vanes • Turbine Nozzles • Crossovers</td>
<td>No Effect</td>
<td>Quantity Cost Increases, Combine with Sand Castings</td>
<td>Efficiency Benefits From Improved Surface Roughness</td>
</tr>
<tr>
<td>Inducer • Machined from Billet * • Cast With Machined Leading Edges</td>
<td>No Effect</td>
<td>Quantity Cost Differences</td>
<td>No Significant Impact</td>
</tr>
<tr>
<td>Production Enhancers Study for Cast Parts • Hydro/Leak Check With Clamps Before Machining • Casting Targeting * • CAD/CAM/CAE • X-Ray or Spin Verification of Part Integrity • In-Process Controls * • NDE/Dye Pen</td>
<td>No Effect</td>
<td>No Effect</td>
<td>Quantity Cost Benefits</td>
</tr>
<tr>
<td>• In-Process Inspection for Machined Parts Including Electro-Optical Sensors (MTI) *</td>
<td>Less Part-to-Part Variations</td>
<td>Part Rejection Rate, Inspection Costs, Capital Expenditures</td>
<td>No Effect</td>
</tr>
<tr>
<td>Factory Floor Optimization * • Work Cells • Material Handling • Lead Time • Inventory, Just-in-Time • Assembly • Interface with Suppliers (Ingersoll Engineering)</td>
<td>No Effect</td>
<td>Determine Optimum Combination for All Parts; Capital Expenditures</td>
<td>No Effect</td>
</tr>
<tr>
<td>High Speed Balance (MTI)</td>
<td>Rub Risk Reduced Bearing Loads Reduced</td>
<td>Quantify Balancing Costs</td>
<td>No Effect</td>
</tr>
</tbody>
</table>

*: Selection for Point of Departure Design
Detail Design Provides Drawings For All Equipment Required For Testing At SSC

- Hot Fire Turbopump
  - Supporting Analyses
  - Long Lead Release
  - Probabilistic Design of Life Drivers
  - Assembly Manuals/Tooling Drawings
  - Test Plans

- Cold Gas Turbopump
  - Long Lead Release
  - Assembly Manuals/Tooling
  - Test Plans

- Reliability Predictions

- Test Cart

- GSE
Phase II Detail Design and Analysis Methodology

Cost Modelling

Thermal Analysis
- Thermal Analyses
  - Heat Transfer
  - Metal Temperature Distribution
  - Metal Temperature Gradients

Reliability Analysis
- Probabilistic - Oil Only
- Standard Assessment for Other Parts

Structural Analysis
- Stress Levels
- Life Prediction
- Variability
- Models

Dynamics Analysis
- Critical Resonances
- Housing Vibrations
- Shaft Dynamics

Productivity
- Fab Process
- Vendor Qualification

Quality Assurance Inspectability

Safety

Studies and Analyses
- Bearing Tests
- Tip Damper Tests
- LCF/HCF Tests

ILS
- GE
- Maintainability

Final Program Review
- Final CEI, ICD, LEMD
- Final Models/ Analyses
- Cost
- Reliability
- Performance

Technovations
- Model Validations
- Fab Costs
- Stress

Technovations Test and Evaluation
- Model Validations
- Reliability
- Performance
- Stress, Thermal, Dynamics
- Operations Costs

Action Items
- Resolution

Performance Assessment
- Model Validations
- Reliability
- Performance
- Stress, Thermal, Dynamics
- Operations Costs

Updated ICD, CEI, LEMD
- Probabilistic Reliability for Oil
- Reliability Assessment
- Others
- Cost Model
- Analyses Summary

Detail Drawing Package

POQ

OF POOR QUALITY
During Detail Design, Additional Technology Development Will Be Identified

— Materials Characterization Plan

— Analytical Model Development Plans

— Technology Development Plans
   — Titanium Housings

— Instrumentation Requirements
Phase II Laboratory Testing Supports Detail Design (WBS 2.2.0)

- Bearing and Lift-Off Seal Test
  - Substantiates Designs of These Elements
  - Provides Ranking of Bearing Material Combinations
    - Baseline: 440C/Armalon
    - Alternative: TBD
- Operate in Cryogenic Fluid at Rated DN
- Applied Bearing Loads 100% - 150% of Predicted Values
- Will Run Duty Cycle Simulating Mission Operation
- All Hardware Fab and Test Planning Accomplished in Phase I
Bearings and Lift-Off Seal Will Be Rig-Tested

<table>
<thead>
<tr>
<th>Test Series</th>
<th>No. of Tests</th>
<th>Duration (Sec)</th>
<th>Bearing Fluid</th>
<th>Bearing Pressure and Flow Rate</th>
<th>RPM</th>
<th>Test Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checkout</td>
<td>4</td>
<td>15-30</td>
<td>LN₂</td>
<td>300 psi/100 gpm</td>
<td>10,000</td>
<td>Ensure Proper Operating Conditions, Including Instrumentation and System Integrity</td>
</tr>
<tr>
<td>Start/Stop and Endurance Test</td>
<td>15</td>
<td>540</td>
<td>LH₂</td>
<td>300 psi/100 gpm</td>
<td>26,700</td>
<td>Evaluate Life Versus Wear of Ball Bearings and Cage Designs</td>
</tr>
<tr>
<td>Bearing Inspection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Measure Ball Diameters and Races for Wear; Inspect for Cracks</td>
</tr>
</tbody>
</table>

Notes:  
- Flow Past Lift-Off Seal Will be Monitored; Also Lift-Off Seal Axial Position Will be Measured.  
- Approximately 100-150% Design Radial and Axial Loads Apply to Bearings.  
- Existing Facility Drive Turbine Will be Used.  
- GN₂ (50-150°F @ 50 psia) Will be Used as Drive Gas.
Brg/Seal Test Schedule Supports
Detail Design

<table>
<thead>
<tr>
<th>Program Months</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
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<tbody>
<tr>
<td>Assemble Test Unit</td>
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<tr>
<td>Facility Prep and Installation</td>
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<td>Detail Design (Ref.)</td>
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<td></td>
<td>△</td>
<td>△</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Turbopump Fabrication
And Testing

G. Claffy

Objective: Fab, Assemble, and Test Two Turbopumps
Prototype Turbopump Fabrication Will Support Test Program And Calibrate Models (WBS 2.3.0)

- Long Lead-Approval Needed by Month 16
- Supplier Screening and Selection
- GSE/STE Detail Design and Fab
- Procure/Fab Hardware for Two Turbopumps Plus Critical Spares Plus Assembly Tooling
Prototype Turbopump Fabrication Will Support Test Program And Calibrate Models (WBS 2.3.0) (Cont)

- Inspection/QA
  - Acceptance Plan (DR-20) - Month 19
  - Acceptance Data Package (DR-31) - Month 32
  - Acceptance Review - Month 34

- Assemble and Deliver Two Turbopumps

- Collect Cost Data/Calibrate Cost Model

- Develop Key Procedures
  - Assy/Teardown
  - Balancing
  - Casting Inspection
  - Transportation/Storage
# Summary of Deliverable Hardware

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 01-Cold Gas/Instrumented Turbopump</td>
<td>1</td>
</tr>
<tr>
<td>Unit 02-Hot Gas/Instrumented Turbopump</td>
<td>1</td>
</tr>
<tr>
<td><strong>Critical Item Spares:</strong></td>
<td></td>
</tr>
<tr>
<td>Impeller</td>
<td>2</td>
</tr>
<tr>
<td>Pump Housing</td>
<td>1</td>
</tr>
<tr>
<td>Turbine Manifold</td>
<td>1</td>
</tr>
<tr>
<td>Turbine Exhaust Housing</td>
<td>1</td>
</tr>
<tr>
<td>Turbine Rotor Assembly</td>
<td>2</td>
</tr>
<tr>
<td>Bearings</td>
<td>8 misc</td>
</tr>
<tr>
<td>Seals</td>
<td></td>
</tr>
<tr>
<td><strong>GSE:</strong></td>
<td></td>
</tr>
<tr>
<td>(Subject to Change, Based on Test Cart Design):</td>
<td></td>
</tr>
<tr>
<td>Handling Fixture</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance Stand</td>
<td>1</td>
</tr>
<tr>
<td>Closure Kit</td>
<td>1</td>
</tr>
<tr>
<td>Shipping Container</td>
<td>1</td>
</tr>
<tr>
<td>Portable Crane</td>
<td>1</td>
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<tr>
<td>Work Table</td>
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<tr>
<td>Pallet Mover</td>
<td></td>
</tr>
<tr>
<td><strong>STE:</strong></td>
<td></td>
</tr>
<tr>
<td>Pump Discharge Line</td>
<td>1</td>
</tr>
<tr>
<td>Turbine Inlet Line</td>
<td>1</td>
</tr>
<tr>
<td>Test Cart</td>
<td>1</td>
</tr>
</tbody>
</table>
Major Fabrication Milestones Are Established

- Long Lead Item Detail Design and Fab Release - Month 16
- All Detail Drawings Complete, Released for Fab - Month 21
- Hardware Fab and Proof Testing Complete - Month 32
- Test Units Assembled, Delivered, and Installed at SSC - Month 34
- GSE/STE Fab Complete - Month 32
Phase II Turbopump Test Effort Includes Planning, Support, and Analysis (WBS 2.4.0)

- Test Plan Draft (DR-30) Prepared Concurrent With Detail Design

- Critical Experiment Review Will Include Finalized Test Plan

- ATC Personnel Will Support Turbopump Installation and Test, and Perform Data Analysis/Evaluation
  
  --- Installation, Maintenance, and Removal Data Will Be Closely Monitored and Documented (DR-33) for Cost Modeling Inputs

- Test Results Report Will Be Prepared After Conclusion of Testing (DR-34) Including Reliability Update

- Turbopump Will Be Disassembled and Inspected After Testing
## Key Test Objectives Defined for Cold-Gas Test

<table>
<thead>
<tr>
<th>Key Parameter Measured</th>
<th>Type Instrumentation Required</th>
<th>Overall Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor &amp; Stator Study &amp; Dynamic Blade Stresses</td>
<td>• Strain Gages</td>
<td>• Stress Models • Update Probabalistic Analysis and Loads/Environment Document</td>
</tr>
<tr>
<td>Bearing Radial Load</td>
<td>• High Freq. Pressure Transducers</td>
<td>• Calibrate CFD Models of Pump Volute and Turbine Inlet • Update Probabalistic Analysis and Loads/Environment Document</td>
</tr>
<tr>
<td>Shaft Axial Thrust</td>
<td>• Pressure Transducers • Proximity Gages</td>
<td>• Calibrate CFD Models of Impeller Front &amp; Rear Shroud Cavities Balance Piston Cavities, and Turbine Disk Cavities • Update Probabalistic Analysis and Loads/Environment Document</td>
</tr>
<tr>
<td>Bearing/Seal Operating Environment</td>
<td>• Pressure Transducers • Flow Meters • Temp. Sensors</td>
<td>• Calibrate Local CFD Models and Overall Bearing Cooling Scheme Model • Update Probabalistic Analysis and Loads/Environment Document</td>
</tr>
<tr>
<td>Turbopump Performance</td>
<td>• Pressure Transducers • Flow Meters • Temp. Probes • Speed • Torque Measurement</td>
<td>• Verify Pump and Turbine Performance Predictions</td>
</tr>
</tbody>
</table>
### Cold-Gas Turbopump Preliminary Test Matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Pump (Q/N)</th>
<th>N/N des**</th>
<th>Turbine (U/C)</th>
<th>Turbine PR/PR des</th>
<th>Turbine Inlet Pressure (psl)</th>
<th>Turbine Discharge Pressure (psl)</th>
<th>Pump Discharge Pressure (psl)</th>
<th>Turbine Mass Flow (lbm/s)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0.5</td>
<td>2.38*</td>
<td>1.0</td>
<td>889</td>
<td>207</td>
<td>803</td>
<td>117</td>
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<tr>
<td>2</td>
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<td>0.72</td>
<td>3.43*</td>
<td>1.0</td>
<td>3200</td>
<td>744</td>
<td>1665</td>
<td>421</td>
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<tr>
<td>3</td>
<td>1.1</td>
<td>0.72</td>
<td>3.43*</td>
<td>1.0</td>
<td>3200</td>
<td>744</td>
<td>1582</td>
<td>421</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>0.72</td>
<td>3.43*</td>
<td>1.0</td>
<td>2880</td>
<td>670</td>
<td>1830</td>
<td>379</td>
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<tr>
<td>5</td>
<td>0.8</td>
<td>0.5</td>
<td>2.38*</td>
<td>1.0</td>
<td>800</td>
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<td>883</td>
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<td>1.0</td>
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<td>18</td>
<td>142</td>
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</tbody>
</table>

*2nd Stage Removed for Improved Performance at High U/Lo
**Planned test speed may be adjusted after critical speed analysis
### Key Test Objective Defined For Hot-Gas Test

<table>
<thead>
<tr>
<th>Overall Objective</th>
<th>Type Instrumentation Required</th>
<th>Key Parameter(s) Measured</th>
<th>Value of Parameter Measured</th>
</tr>
</thead>
</table>
| Functional Validation in Real Engine Environment | Pressure Transducers
Flow Meters | Operating Environment | Performance |
| Verification of Probabilistic Design Analysis and Reliability Predictions | Speed
Temp. Probes | | |
| Verification of Performance Scaling | Pressure Transducers
Temp. Probes | | |
| Verify Dynamic Response Characteristics | Proximity Probes
Accelerometers | Rotodynamic Behavior | |
### Hot-Gas Turbopump Preliminary Test Matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Pump (Q/N)/Q(N) des</th>
<th>N/N des*</th>
<th>Turbine (U/C)/U(C) des</th>
<th>Turbine PR/PR des</th>
<th>Turbine Inlet Pressure (psf)</th>
<th>Turbine Discharge Pressure (psf)</th>
<th>Pump Discharge Pressure (psf)</th>
<th>Turbine Mass Flow (lbm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>0.7</td>
<td>0.7</td>
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<td>780</td>
<td>186</td>
<td>1589</td>
<td>21.7</td>
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<td>2</td>
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<td>1.0</td>
<td>1755</td>
<td>418</td>
<td>3211</td>
<td>48.8</td>
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<tr>
<td>3</td>
<td>0.8</td>
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<td>1580</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1755</td>
<td>418</td>
<td>3211</td>
<td>48.8</td>
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<tr>
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</tr>
<tr>
<td>7</td>
<td>TBD</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Planned test speed may be adjusted after critical speed analysis
Detailed Cost Model

Colin Faulkner

Objective: Develop a Verified Data Base for the Cost Model
Phase II—Cost Model Deliverables

- Completed Detailed Cost Model
  - Structure Description
  - Construction Assumptions
  - Input Data Sources
  - NASA Requirements Impacts
- Flight Hardware Cost Estimates
  - Theoretical First Unit Cost
  - Recurring Production Costs (Learning Curve and Rate Effects)
  - Recurring Operations Costs
- Cost Estimate Substantiation
  - Historical
  - "Similar TOS"
  - Phase I and II Fabrication
- Independent Assessment Weights
  - Parts and Assembly Weights
  - Complexity
  - Precision
  - Materials
# Multiple Approaches To Reduce The Magnitude Of Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Approach</th>
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</thead>
<tbody>
<tr>
<td>Piece Part Costs</td>
<td>• Prototype Build</td>
</tr>
<tr>
<td></td>
<td>• Quotes From Multiple Vendors</td>
</tr>
<tr>
<td></td>
<td>• Touch Labor and Touch Inspection</td>
</tr>
<tr>
<td>Learning Curve Effects</td>
<td>• Vendor Quotes on Lot Size and Quantities</td>
</tr>
<tr>
<td>Lot Size Effect</td>
<td>• Historic Data</td>
</tr>
<tr>
<td></td>
<td>• Scrap, Rework and Repair</td>
</tr>
<tr>
<td></td>
<td>• Tooling, and Tool Maintenance</td>
</tr>
<tr>
<td>Productivity</td>
<td>• Documented Productivity Improvements</td>
</tr>
<tr>
<td></td>
<td>• Historic Data</td>
</tr>
<tr>
<td></td>
<td>• Consultants - Ingersoll Engineering</td>
</tr>
<tr>
<td></td>
<td>• MTI</td>
</tr>
</tbody>
</table>

- Uncertainty Values Are Allocated to Each Piece Part
Emphasis On Production And Operations Costs

- Audit Manufacture of Test Articles at Piece Part Level:
  - Two Turbopumps
  - Test Cart
  - GSE

- Analyze Applications of Advanced Factory Organization, Layout, and Equipment
  - Ingersoll Engineering
  - MTI

- Audit Test Operations at SSC:
  - Test Cart (Projected Acceptance Test Costs)
  - Operation and Maintenance of Turbopumps (Simulated Launch Pad Conditions)

- Audit Specifications and Procedures Impacts
  - Manufacture
  - Operations
  - Tom Peters Group Contributes Unbiased Perspective
Launch Rates and O&S Costs Are Covered

- Bookkeeping
  - Straightforward Within Cost Model
  - Can Adjust for Launch (Production) Rate, Cost Year, Learning Curve Effects

- All O&S Costs Will be Included in Cost Evaluation:
  - Technical Data Revisions
  - GSE Maintenance
  - Base Maintenance
  - Depot Maintenance
  - Spare and Repair Parts
  - Inventory Storage
  - Personnel Training
  - Logistics Down-time
  - Packaging and Preservation
  - Administration
Phase II Cost Model Activities

Prototype Production Cost Strategy
- Engineering, Manufacturing Review
- Collection Review

Reporting Analysis
- ECS Specifications

Cost Specification Impact
- Document Specifications
- Existing Data
- Department Inputs
- Matrix Database

Ranking of Specification Cost Impact

Upgrade Model Capability and Data
- Prototype Data
- User Input/Output Screens
- Incorporate Uncertainty

Incorporate Uncertainty of Results
- Manufacture Build
- Cost Improvement Curves
- O & S
- Economic Indicators

Cost Model Testing
- Analytical Software
- Input/Output

Component Cost Model

Actual Production Process
- Collect Actuals

Costing Alternate 1
- Similar Parts Process

Costing Alternate 2
- Detailed Standards

Prototype Database
- Collect
- Data Entry
Concluding Remarks

Colin Faulkner
# We Have Back-ups for Identified Risks

<table>
<thead>
<tr>
<th>Component</th>
<th>Risk</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impellers</td>
<td>Cast Titanium Ductility and Uniformity</td>
<td>Cast or Forged/Machined Shroud Attachment Technique</td>
</tr>
<tr>
<td>Turbine Housing</td>
<td>Adequate HEE Resistance in Cast Form</td>
<td>INCOLOY 909 Baseline and Stellite Back-up</td>
</tr>
<tr>
<td>Pump Housing</td>
<td>Cast Properties Inadequate at Cryogenic Temperatures</td>
<td>INCONEL 718 Baseline and Stainless Steel Back-up</td>
</tr>
<tr>
<td>Turbine Blade</td>
<td>Insufficient Damping</td>
<td>Tip Dampers Design Iterations and/or Tests</td>
</tr>
<tr>
<td>Balancing</td>
<td>Unbalance at Operating Speed Causes Reduced Bearing Life or Dynamic Instability</td>
<td>Early Analyses and Testing to Define Balancing Requirements</td>
</tr>
<tr>
<td>Performance Margin</td>
<td>Not Meeting Required Performance</td>
<td>Design Margin Against &quot;Exhibit B&quot; Requirements with Turbine Horsepower and Pump Discharge Pressure Margin.</td>
</tr>
<tr>
<td>Lift-Off Seals</td>
<td>Short Axial Length; Cocking</td>
<td>Two Interchangeable Concepts</td>
</tr>
<tr>
<td>Test Article</td>
<td>Damage in Transport and/or Test</td>
<td>Two Test Articles</td>
</tr>
</tbody>
</table>
Program Status

- Critical "Long Leads" Started:
  - Impeller Castings (CAD Complete, Procurement Initiated)
  - Titanium Samples in Test Preparation
  - Procurement Initiated for Other Cast Test Bars
  - POD Concept Update Underway (Freeze in 3 Weeks)

- Planning Finalized for Rest of Phase I
Communications

- Interfaces Require Particular Consideration

- We Want to Benefit From SSME and ATP Experience

- We Want to Communicate as Closely as Possible With NASA
  — Disciplined System for Effective Follow-Ups
<table>
<thead>
<tr>
<th>4 Title and Subtitle</th>
<th>ALS Liquid Hydrogen Turbopump Monthly Progress Report</th>
</tr>
</thead>
</table>
| 6 Author(s)         | Colin Faulkner, Program Manager  
|                     | Nancy Shimp, Project Engineer  
|                     | George Claffy, Project Engineer |
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Washington, DC 20546  
NASA MSFC, Huntsville |

16. Abstract:

The monthly progress report provides visibility of significant technical and administrative activity occurring during the reporting period and work planned for next period.