September 1993

# ALS
# LIQUID HYDROGEN TURBOPUMP

Contract NAS8-37593

## SUMMARY FINAL REPORT

Prepared for:

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

Prepared By:

Deborah K. Rickman
Project Engineer

Approved By:

Colin Faulkner
Program Manager

Aerojet Propulsion Division
P.O. Box 13222
Sacramento, CA 95813-6000

The Requirement For Use Of International System Of Units Has Been Waived For This Document

TABLE OF CONTENTS

## FIGURES

## TABLES

## 1.0 INTRODUCTION

This is the Final Summary Report for the Advanced Launch System (ALS) Rocket Liquid Hydrogen Turbopump Program, Contract NAS8-37593. This program was conducted by Aerojet Propulsion Division (APD) for NASA's Marshall Space Flight Center (MSFC). Authority-to-proceed (ATP) was given on 1 May 1989. APD was directed to close out the program on 6 August 1993.

The objective of the program was to design and develop a highly reliable, low cost liquid hydrogen (LH2) turbopump for the ALS engine. The total effort planned is defined in the Technical Implementation Plan, DR-15. Due to funding constraints, particularly in later stages of the program, and due to premature closeout, the program was not completed as originally planned. However, significant data from design, and materials and process development were obtained.

Funding was limited for program closeout. APD was directed to minimize the final reporting effort. Therefore, this document does not have the depth normally associated with program final reports. With the limited effort permitted, it was structured to enable readers to understand program scope and content, and to lead them to reference material which gives more detailed program data. It gives a top level overview of the program, highlighting results and data pertinent to likely future NASA programs. Recommendations are made for follow-on work which could be performed using data and/or hardware available from this program.

The program as planned consisted of two distinct phases:

Phase 1 - Preliminary Design/Cost Model

Phase 2 - Component Test Article/Detailed Cost Model

Figure 1-1 shows the overall program logic and the interrelationships between major tasks. Phase 1 was completed in October 1990. A period of performance of forty six months was originally allocated for the total program.

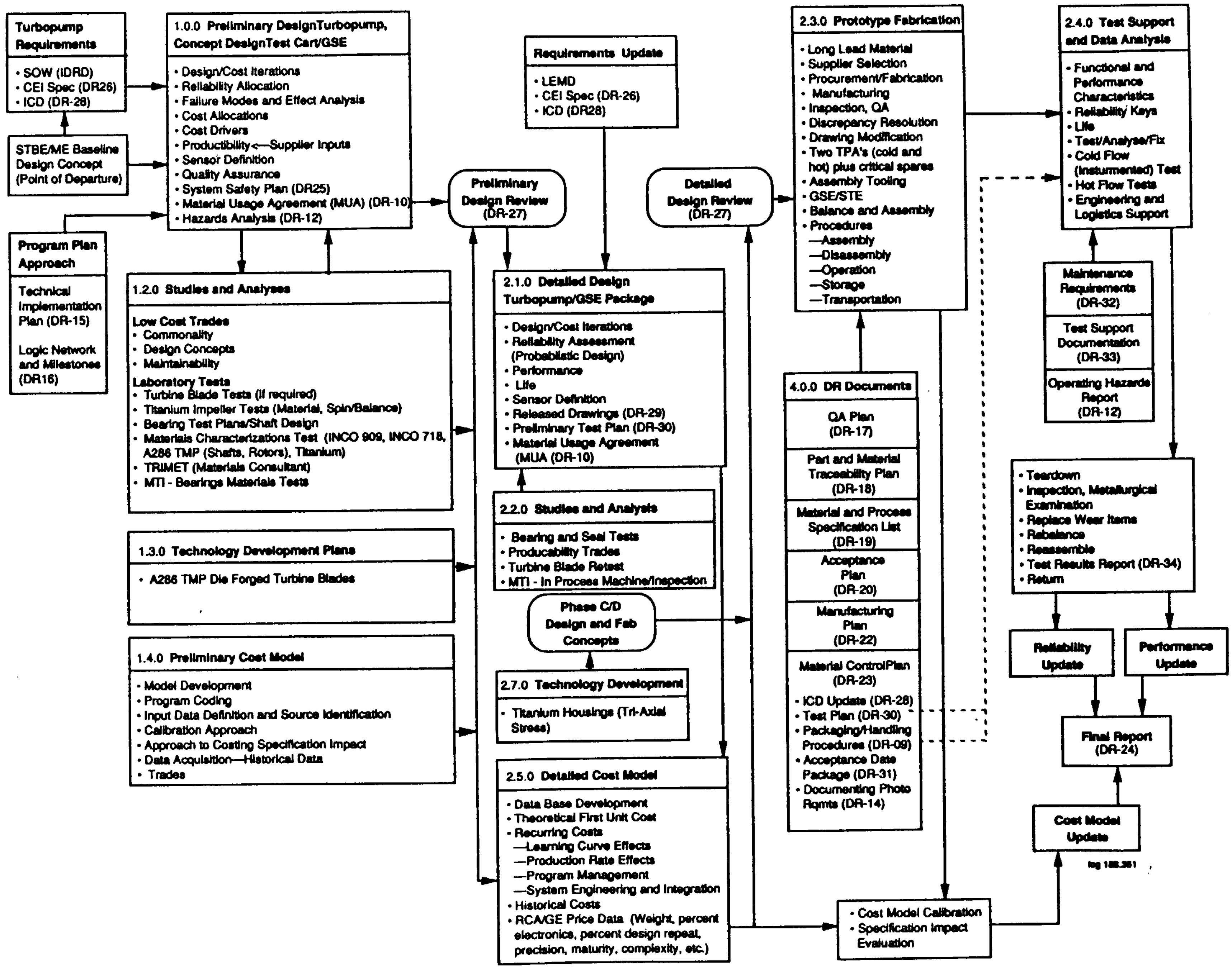


Figure 1-1. Proposed Logic Diagram

This report is structured around the program work breakdown structure (WBS) shown in Figure 1-2. (WBS numbers are also identified in the program logic diagram, Figure 1-1.). By reporting in this fashion, the reader is informed on the total program plan content as planned and on actual results achieved prior to program closeout in each specific WBS task.

# 2.0 KEY ACCOMPLISHMENTS

## 2.1 Overview

This program generated and/or utilized a number of innovative approaches to the design and manufacture of $LH_2$ turbopumps. Although some tasks were not completed, results from this program represent a significant contribution to the NASA data base. More detail on individual tasks performed is given in Section 3.

## 2.2 Cost Model

A cost model was developed which was to be used to track program progress in meeting design-to-cost goals. This is a comprehensive data base addressing recurring in-house manufactured ("make") and supplier-provided ("buy") parts and recurring operations and support (O&S) costs It is Microsoft Excel application-based and can be used on either Macintosh or PC desktop computers. The model has broad applicability to any component and will consolidate costs up to engine level. It gives the model user authority over input costs and manufacturing cost relationships. The model has not been validated but is a potentially useful tool for unit production cost projection and tracking.

## 2.3 Turbopump Design

Using the results of design trades and laboratory tests, and incorporating lessons learned from current generation turbopumps such as those of Space Shuttle Main Engine (SSME) and the Titan family of engines, a preliminary design of the LH2 turbopump was developed. This was presented to MSFC at a Preliminary Design Review, DR-27.

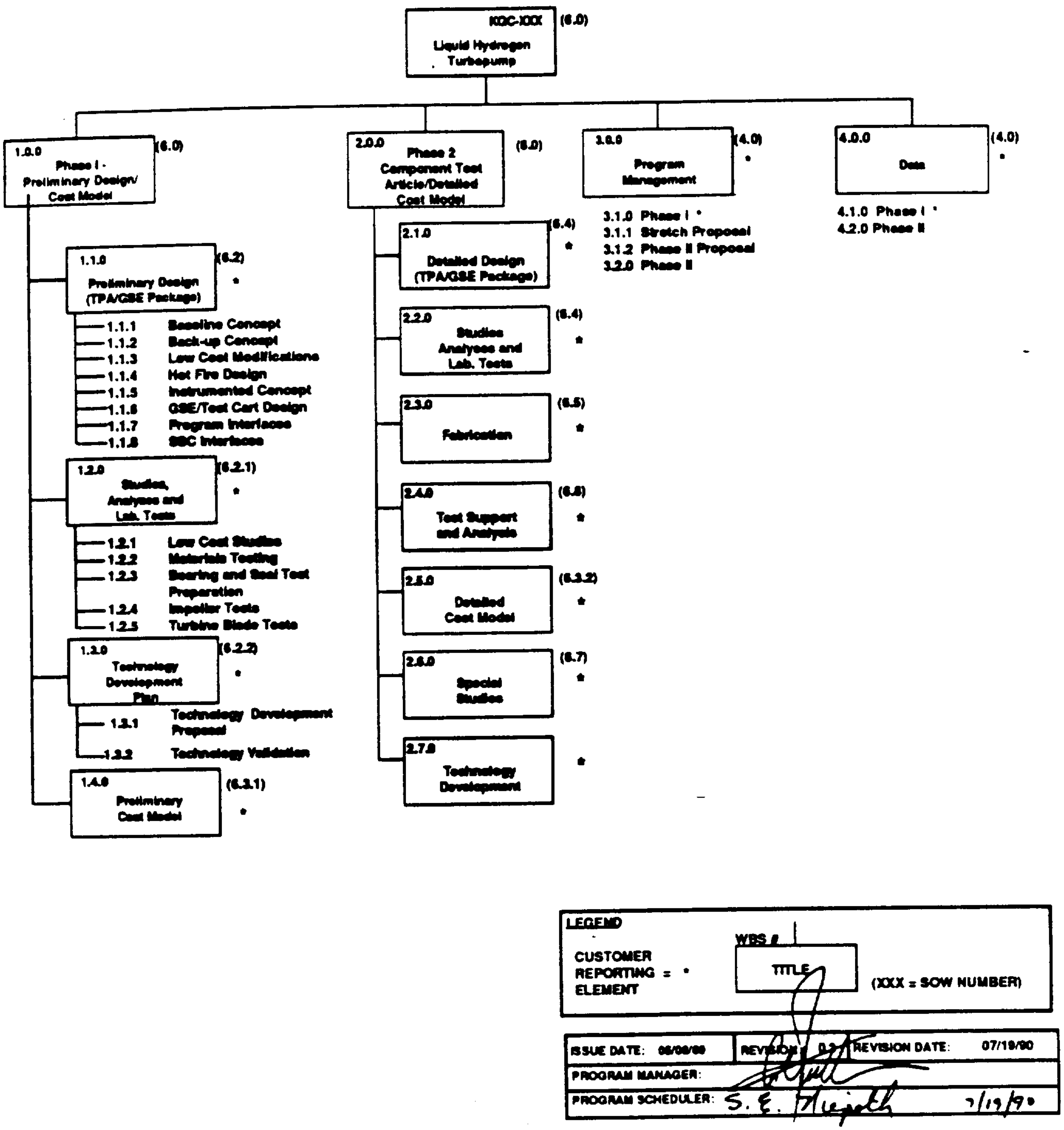


Figure 1-2. Program Work Breakdown Structure

The design was simplified by minimizing parts complexity and parts count. A key objective was to achieve a modular design with full parts interchangeability, rather than having individually matched subassemblies. Where possible, functions of parts were separated. This lead to better understanding of load paths with fewer "unknown unknowns," leading to a more robust design.

Using a Total Quality Management (TQM) teaming approach with qualified suppliers, design emphasis was on use of low cost processes. All major static parts were near-net cast. For rotating parts, numerically-controlled (NC) machining was eventually selected because of the hydraulic geometry and material properties consistency that this approach offers.

### 2.4 Impeller Development

Work focused heavily on identifying and verifying an approach to producing low cost, yet consistently reliable LH2 turbopump impellers. In current cryogenic turbopumps, eg. SSME, these are expensive items with long lead times.

Initial work concentrated on development of investment cast impellers in Ti 5Al/2.5Sn ELI alloy. Excellent ductility was obtained from test bars. Wax injection tooling was prepared and two full scale impeller castings poured. Dimensions were satisfactory with the exception of shroud thickness which was generally undersize and subject to large variations.

Because of concern over cast impeller shroud thickness variations, it was decided to reexamine the machined impeller approach. Modern machining offered the potential for identical parts but the question of cost remained an issue. Concurrent engineering work with NuCon Corporation resulted in reoptimizing impeller geometry to arrive at a machinable design while retaining acceptable hydraulic performance and structural integrity. Aerojet CAD data including digital blade coordinates were transmitted to the supplier who programmed his machine tools using these data. Following proof-of-concept machining of an aluminum block, the shrouded impeller was NC-machined from a titanium alloy forging. Finished product cost was found to be less than using the near-net casting process, and lead time was dramatically reduced. Part and material properties consistency are also more assured with the forging/NC-machining approach.

As an essential part of this impeller work, integrated material properties/structural evaluations of candidate Titanium 6Al/4V ELI and 5Al/2.5Sn alloys confirmed that the latter was strongly preferred. However, 5Al/2.5Sn alloy historically had a poor yield rate due to strain-induced porosity occurring during fabrication. (This contributes significantly to impeller costs). Investigations conducted with a qualified material supplier resulted in a decision to explore the potential of using Ti 5Al/2.5Sn in beta-worked billet form. Experiments confirmed that this approach may be feasible. If adopted, about six months in lead time and approximately $5,000 in forging cost per impeller could be saved.

## 2.5 Turbine Section Development

Initial work focused on selection of a suitable material for the turbine section of the turbopump. With data available at that time, Incoloy 909 was an attractive potential material due to its low coefficient of thermal expansion. This minimized engine start-induced cold-to-hot low cycle fatigue stresses, particularly on the thick-walled hot gas inlet manifold casting. A key supplier had also had good results forging turbine discs from Inco 909, and Aerojet-sponsored work on casting a Titan turbine inlet manifold in this material was also encouraging. Relatively unknown were its properties in cast form and its reaction to the hot hydrogen gas environment, although there were limited data suggesting that embrittlement might not be a problem.

Cast and wrought test bars were fabricated and conditioned with a variety of heat treatment and annealing routines. In addition, disc forgings were made and readied for turbine wheel machining. Tests of some of these bars conducted by MSFC showed that, contrary to predictions, the material was susceptible to hydrogen environment embrittlement (HEE). This called for materials reselection. For forged/machined rotating parts, Waspalloy was selected. For cast static parts, fine grain Inco 718 was favored (Pratt & Whitney had, by then, obtained good results on this process under their parallel liquid oxygen turbopump contract).

Based on excellent Titan flight experience and on modern jet engine practice, blisks were selected for the turbine wheel configurations. This is a lower cost approach than the more traditional separate blade/fir tree attachment configuration. An NC-machining process similar to that used for the pump section impeller was planned for blisk machining. Ring forgings were manufactured and CAD data exchanges between Aerojet and its machining supplier were initiated. Program shutdown occurred just before NC-machining was to start. However, pre-machining work clearly indicated that, as with the pump impeller, CAD-to-NC machining linkage would have resulted in a low cost blisk product with excellent dimensional and tolerance repeatability.

Prior to program shutdown, CAD exchanges were also occurring with Howmet Corporation Hampton Casting Division with the intent of producing turbine inlet manifold and turbine exit housing investment castings.

### 2.6 Turbopump Assembly

As stated in Section. 2.3, a key program objective was to achieve a modular design with full parts interchangeability, rather than having individually matched subassemblies. This permits a continuous flow production line, without interruptions for part-to-part and/or subassembly-to-subassembly matchings.

By using NC-machined forgings (see also Sections 2.4 and 2.5), all rotating parts would be nearly identical and capable of being easily balanced to a common standard.

Using Titan and jet engine experience, curvic couplings were used to connect rotating subassemblies. These joints are compact, have high torque capacity, and are tolerant of small misalignments.

Following trades with conventional rolling element bearings, hydrostatic bearings were selected. They offered high stiffness for improved rotordynamics, simplicity, and longer life. At issue was their sensitivity to shaft misalignment. Use of conventional hydrostatic bearings would have required matching of parts to ensure proper bearing clearances and would have defeated the full interchangeability approach. A "pivoted/tilt pad" hydrostatic bearing was therefore selected for the design. It is self-compensating and adjusts to changes in shaft tilt and position.

The unique combination use of NC-machined forgings for all rotating parts, curvic couplings to connect subassembly modules, and pivoted/tilt pad bearings results in an easily assembled, easily repaired turbopump which does not demand matched parts or overly elaborate balancing operations.

# 3.0 TASK SUMMARIES

## 3.1 Cost Model

### 3.1.1 Objective

The cost model activity objective was to lay the foundation for subsequent evaluation of cost reduction design and manufacturing approaches. Model inputs to be included were hardware definitions, identification of basic component-specific factors and processes, incorporation of general procedures for data collection, and incorporation of any new requirements. The modeling effort generated allocation data. All subcontractor cost information was stored in specific component data bases.

### 3.1.2 Activity Overview

During Phase I of the cost model development, Microsoft Excel was selected as the core application. This spreadsheet program permits data transfer between Macintosh and IBM PCs, has multiple windowing capability, and customized menus and dialog boxes. A Supplier Cost Information Form was developed to collect supplier cost data in a consistent manner, with the intent of using this same form in other Aerojet NLS Advanced Development Programs. The Phase I activity culminated in a detailed presentation of program objectives, logic, features and cost model work at the September 1989 Quarterly Review.

When cost model activities ceased in response to GFY 1990 and 1991 funding reductions, cost model logic had been updated and development of uncertainty algorithms was 90% complete. A data dictionary was also developed which included definitions used in model software, as well as all algorithms, and formed the basis for a Preliminary Users Manual. Preliminary software programming was completed but not checked out/validated. Record layouts (monitor screens) were formulated.

### 3.1.3 Results

Cost model development work defined and partially developed a tool for analyses and tracking of STME engine components costs.

The cost model was formulated to address all recurring production and operations and support (O&S) costs of the turbopump and to project the impact of such variables as total production quantity, production rate, lot size, specification impact, and engine thrust and chamber pressure change sensitivities. Model logic, algorithm formulation, and basis programming were completed. Model operation was demonstrated using preliminary cost data derived from existing Aerojet-produced flight hardware. Model development was discontinued after the eighth program month.

The basic cost model was constructed to be applicable to all Aerojet NLS Advanced Development Program hardware: thrust chamber assembly, fuel turbopump, controller, and effector. It utilized Microsoft Excel the application base and can be used with either Macintosh and/or PC hardware. The model logic is shown in Figure 3-1. Touch labor and supplier costs for all constituent parts were to be inputted and continually updated as actual costs became available. Using algorithms developed, the model accounts for the variables cited above.

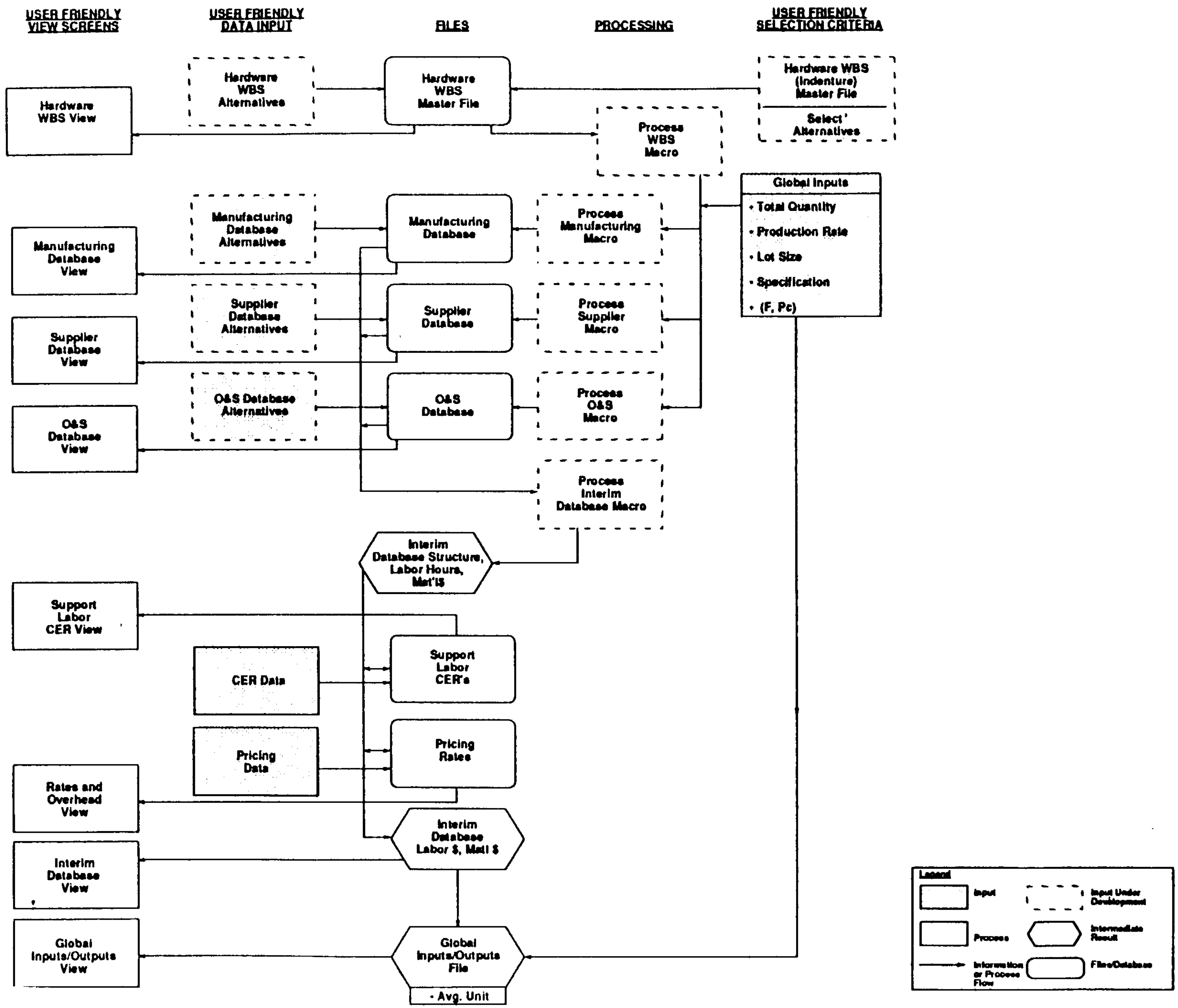


Figure 3-1. Cost Model Logic

The model, although not fully validated, remains as potentially useful tool for similar cost studies in future programs. Since it is based on actual or estimated costs for given manufacturing process flows and specification requirements, rather than on simple cost estimating relationships, it is suitable for studying new manufacturing approaches or more broadly, new ways of doing business.

## 3.2 Turbopump Design

### 3.2.1 Objective

The objective of the turbopump design task was to mature the point of departure design (POD) from the proposal to a detailed final design ready for fabrication. The final design was to have been fabricated and tested to validate the design approach, low cost technologies, reliability goals, and performance. The design underwent several modifications during the program, including the consolidation of the Aerojet and Rocketdyne designs. Figure 3-2 shows the evolution of the turobpump design.

A second objective of the design task was to develop a test cart for use during the demonstration phase of the program. This cart was designed to interface with the NASA-SSC Component Test Facility.

### 3.2.2 Activity Overview

Design activity was divided into a preliminary design phase and a detailed design phase. Included in Phase I of the program were studies, analyses, and laboratory tests planned to supply data to the preliminary design effort. Phase I was completed at PDR in October 1990 and included the design of the full hydrogen turbopump. Early in Phase II a team of propulsion contractors was formed, resulting in divided hydrogen turbopump responsibilities. Aerojet continued with detailed design of the hydrogen turbine, as illustrated in Figure 3-2, for the Consolidated Design.

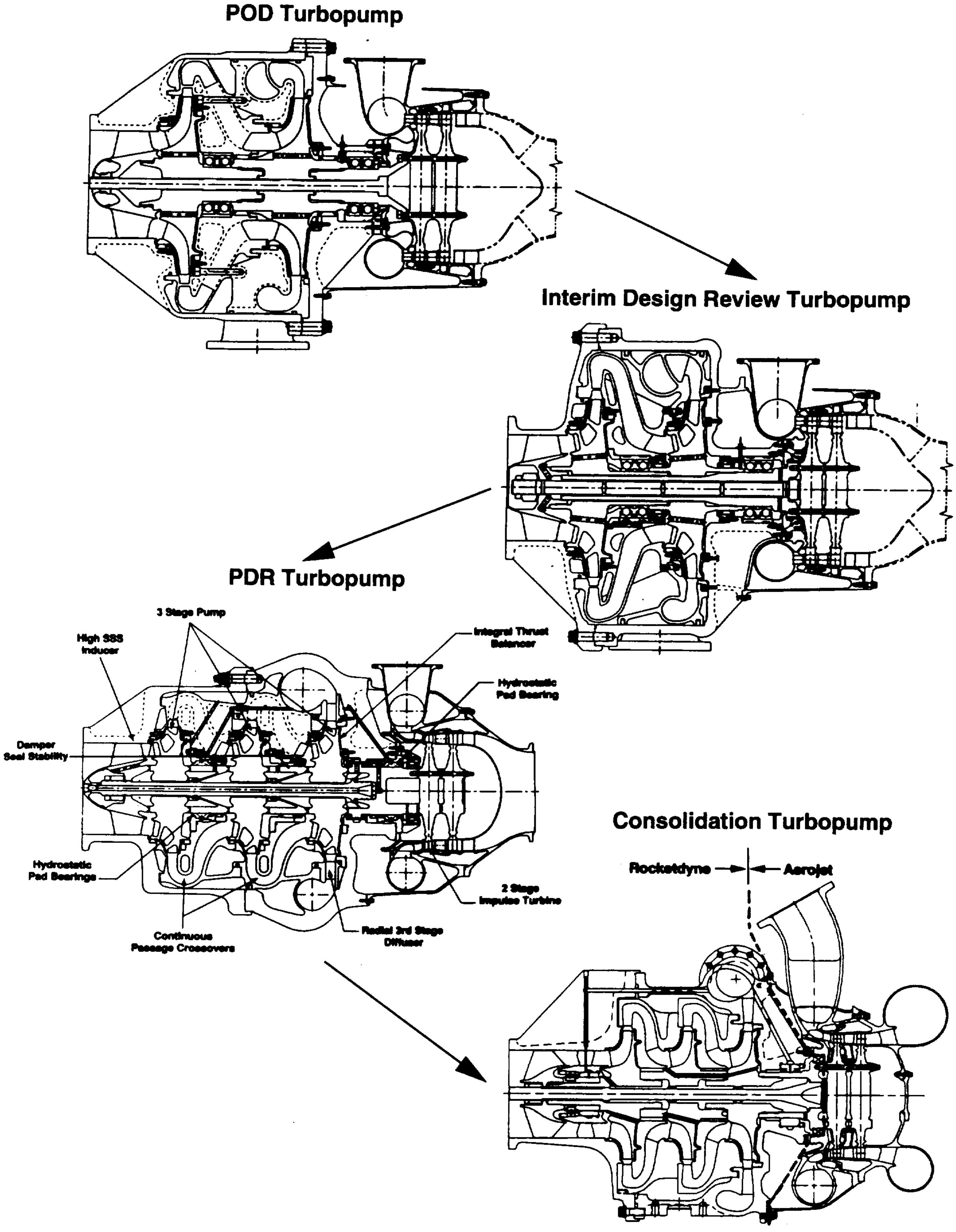


Figure 3-2. LH2 Turbopump Design Evolution

### 3.2.3 Results

At program start in June 1989 the POD turbopump concept was reviewed and modified as the first step in the preliminary design process. The initial modifications were as follows:

1. The dual pump discharge arrangement was changed to a single discharge. The complexity of extra ducting and flex joints was not justified in the STME system. Radial loads resulting from the unsymmetrical pressure gradients were felt to be manageable with the single discharge, double tongue configuration selected.
2. 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.
3. 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.
4. A 10% turbine power margin was imposed, to be obtained by increasing turbine inlet pressure if required. The impact was a 10% higher design pressure for the turbine inlet manifold and gas generator.
5. A backup concept, as an alternative to the use of cast impellers, was incorporated using forged/machined shrouded impellers.

Aerojet contracted with MTI during the preliminary design phase of the program to investigate rolling contact wear in ball bearing materials and material coatings in an ambient environment. Results of this activity have been submitted separately to MSFC. Other bearing activities included comparative trade studies on rolling element, foil, ring hydrostatic, and pivoted/tilt pad hydrostatic bearings.

The bearing trade studies resulted in the selection of the pivoted/tilt pad hydrostatic bearings for the PDR configuration on the basis of operability, cost, and performance considerations. Analysis showed that this bearing concept features high load capacity, high stiffness, and low cross-coupling for dynamic stability in liquid rocket engine turbomachinery. The pivoted/tilt pad bearing also has a low flow rate requirement, which improves engine system operability.

Its self-aligning, self-adjusting features simplify turbopump assembly and reduce required maintenance. In addition, the high radial preload inherent in the pivoted/tilt pad design increases stability and facilitates transportation of the turbopump or engine assembly since no special tooling is required to secure the shaft. The bearing concept is shown in Figure 3-3 and 3-4.

In November of 1989 an internal Interim Design Review was conducted at Aerojet to assure baseline design compliance to customer requirements, including reliability and design-to-cost goals. This review was structured to identify and eliminate any deficiencies prior to the Preliminary Design Review.

Several months into the program the Space Transportation Engine Program developed requirements for greater margins and growth capacity than a two-stage pump could provide. Results of trade studies and analyses led to baselining of a three-stage pump configuration. The three-stage design point characteristics are presented in Table 3-1.

The program Preliminary Design Review was conducted at MSFC in October 1990. The review highlighted the updated turbopump layout which featured a three-stage pump, pivot/tilt pad hydrostatic bearings, unshrouded two-blisk turbine rotor, and curvic coupling drive system. The NC-machined impeller concept had been demonstrated and the impeller was on display at the PDR. Details of the impeller task are discussed in Section 3.3.2 of this report. A package of technical analyses supporting the PDR was provided to MSFC.

Formation of the Space Transportation Propulsion Team resulted in a division of responsibilities for the hydrogen turbopump between Aerojet and Rocketdyne. Aerojet became responsible for the turbine section and Rocketdyne for the pump section. With MSFC's concurrence for this work split, Aerojet proceeded to further define the turbine design and to coordinate interfaces with Rocketdyne.

Consolidation of the Aerojet and Rocketdyne designs along with an engine thrust upgrade from 580,000 lbf to 650,000 lbf required a turbine speed increase from 23,500 rpm to 25,000 rpm. The increase in thrust and evolving engine requirements also resulted in the change to a subsonic turbine design.

Figure 3-3. Pivoted pad Bearing Concept


Figure 3-4. Pivoted Pad Bearing Unit

Table 3-1

3-Stage TP Design Point Characteristics

| | Step Composite | ADP Nominal | ADP MDC |
|---|---|---|---|
| Pump | | | |
| P inlet - psia | | 30 | 30 |
| T inlet - °R | | 37 | 37 |
| P Discharge - psia | 3,654 | 3,650 | 4,056 |
| $\dot{W}$ - lb/sec | 191.6 | 192 | 198 |
| Speed - rpm | | 28,300 | 30,000 |
| Turbine | | | |
| P inlet - psia | 2,236 | 2,375 | 2,636 |
| T inlet - °R | 1,600 | 1,600 | 1,700* |
| P Discharge - psia | 404 | 460 | 511 |
| $\dot{W}$ - lb/sec | 48.4 | 49.8 | 57.4 |
| | Limits | Actual | |
| Nss | 55,000 | 37,600 | 41,000 |
| $AN^2 \times 10^9$ | 34.0 | 30.2 | 34.0 |
| $U_{m\ turb}$ | 1,400 | 1,320 | 1,400 |
| $U_{t\ imp}$ | 1,950 | 1,570 | 1,664 |

*Perf. based on 1,600 °R

A transonic turbine was initially baselined due to the large pressure ratios in the early engine power balance. An update to the engine power balance resulted in lower pressure ratios and increased turbine temperatures. Additional analysis resulted in the selection of a subsonic turbine, which was more robust by virtue of the elimination of shocks.

The subsonic design eliminated shock interaction on the first rotor. These shocks are a large driver in the alternating stress field. Major transonic and subsonic design parameters are compared in Table 3-2. In the transonic design, the first-to-second rotor power split is 65%/35%. This changes to 55%/45% in the subsonic design. The increased work performed by the second rotor raises second stage blade stresses, but this is offset by increased blade camber. Increased blade camber has the benefit of stiffening the blades, thereby improving dynamic stability.

Exhaust configuration was influenced by this change to a subsonic design. The higher exit swirl of the subsonic design required a more efficient volute-type exhaust collector. The volute reduced the unsymmetrical pressure loading on the back side of the second rotor, thereby also increasing robustness. Another benefit of the volute was increased tolerance to off-design operation--an important aspect in an engine that was to operate over the 70-107 percent thrust range. The volute also offered benefits to integration and shipping.

An on-site engine and ADP review was held in July 1992 where the update of the turbine design was presented. Minor changes were made to the design after this review. Subsequently, the government directed that work be stopped.

A test cart was designed to meet NASA-SSC Component Test Facility requirements. Major features of the cart, shown in Figure 3-5, are the use of a commercially available dolly with ball bearing rollers for mobility, electrical and fluid interfaces in separate, dedicated panels, and the ability to mount the turbopump with the centerline vertical.

Table 3-2

NLS Fuel Turbine Blade Data

Nominal Conditions: Speed - 25,000 rpm
Blade Speed - 1336.3 ft/sec
Turbine Power - 56,500 hp

Second Rotor Blade Summary Data

| | Transonic | Subsonic |
|---|---|---|
| Second Stage Power (hp) | 18775 (35%) | 25425 (45%) |
| Second Stage Number of Blades | 62 | 56 |
| Second Blade Force Tang (lbs) | 131.3 | 186.9 |
| Second Blade Force Axial (lbs) | 50.7 | 105.6 |
| Second Blade Force Total (Result) (lbs) | 140.7 | 214.7 |
| Second Blade Height (in.) | 1.20 | 1.20 |
| Second Blade Mean Dia (in.) | 12.25 | 12.25 |
| Second Blade Axial Chord Hub (in.) | 0.90 | 0.90 |
| Second Blade Axial Chord Tip (in.) | 0.80 | 0.80 |
| Second Blade Section Area Hub ($in.^2$) | 0.1775 | 0.2395 |
| Second Blade Section Area Tip ($in.^2$) | 0.1417 | 0.1686 |
| Second Blade % Taper ~ | 20% | 30% |
| Second Blade Hub $I_{max}$ ($in.^4$) | 0.008880 | 0.01272 |
| Second Blade Hub $I_{min}$ ($in.^4$) | 0.001588 | 0.003295 |
| Second Blade Hub Principal Angle | 10.8° | 17.7° |
| Second Blade $d_{max}$ (in.) | 0.234 | 0.290 |
| Second Blade $I_{min}/d_{max}$ ($in.^3$) | 0.006788 | 0.01136 |
| Second Blade Moment M (in.-lb) | 84.4 | 128.8 |
| Second Blade Bending Stress $\frac{M \cdot d_{max}}{I_{min}}$ ksi | 12.44 | 11.34 |
| Centrifugal Stress (ksi) (includes approx. taper effect) | 34.9 | 32.9 |

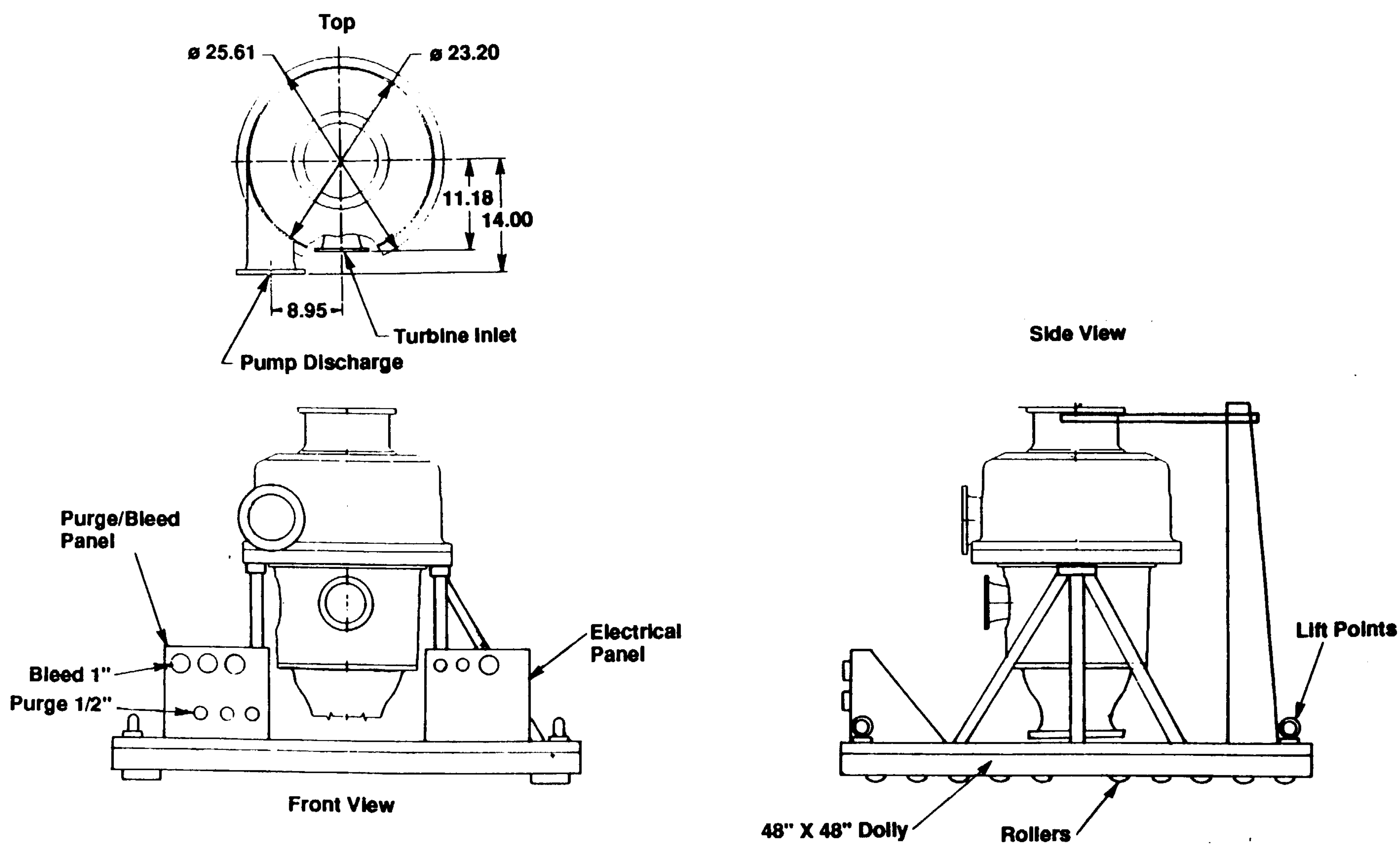


Figure 3-5. Test Cart Concept

### 3.3 Impeller Development

Two approaches were identified for the development of a low cost impeller for the hydrogen turbopump. These were a near-net casting and an NC-machined impeller.

#### 3.3.1 Cast Impeller Development

##### 3.3.1.1 Objective

The objective of the cast impeller development task was to determine if a cast impeller could meet the low cost goals of the program as well as provide sufficient design margin to meet robustness goals.

##### 3.3.1.2 Activity Overview

A near-net cast impeller was pursued as a low cost manufacturing approach for the fabrication of the pump impeller. The technology demonstration plan was to produce final deliverable castings at Howmet Corporation Hampton Casting Division. Howmet work on impeller castings was initiated using a dual path approach involving the use of an existing impeller design and tooling for gating development while tooling-up for the Aerojet proof-of-concept impeller. The impeller design is shown in Figure 3-6.

Existing impeller design castings were used to provide early cast hardware that could be sectioned and used for cryogenic materials testing. Use of impeller hardware for materials evaluation was selected over the use of cast test bars because this would show the effect of cast section thickness on material properties.

##### 3.3.1.3 Results

Two Ti 5Al/2.5Sn ELI impeller castings were sectioned and the material machined into test bars for evaluation of cryogenic material properties. Photographs of the wax mold used to produce the castings and the cast impeller are shown in Figures 3-7 and 3-8.

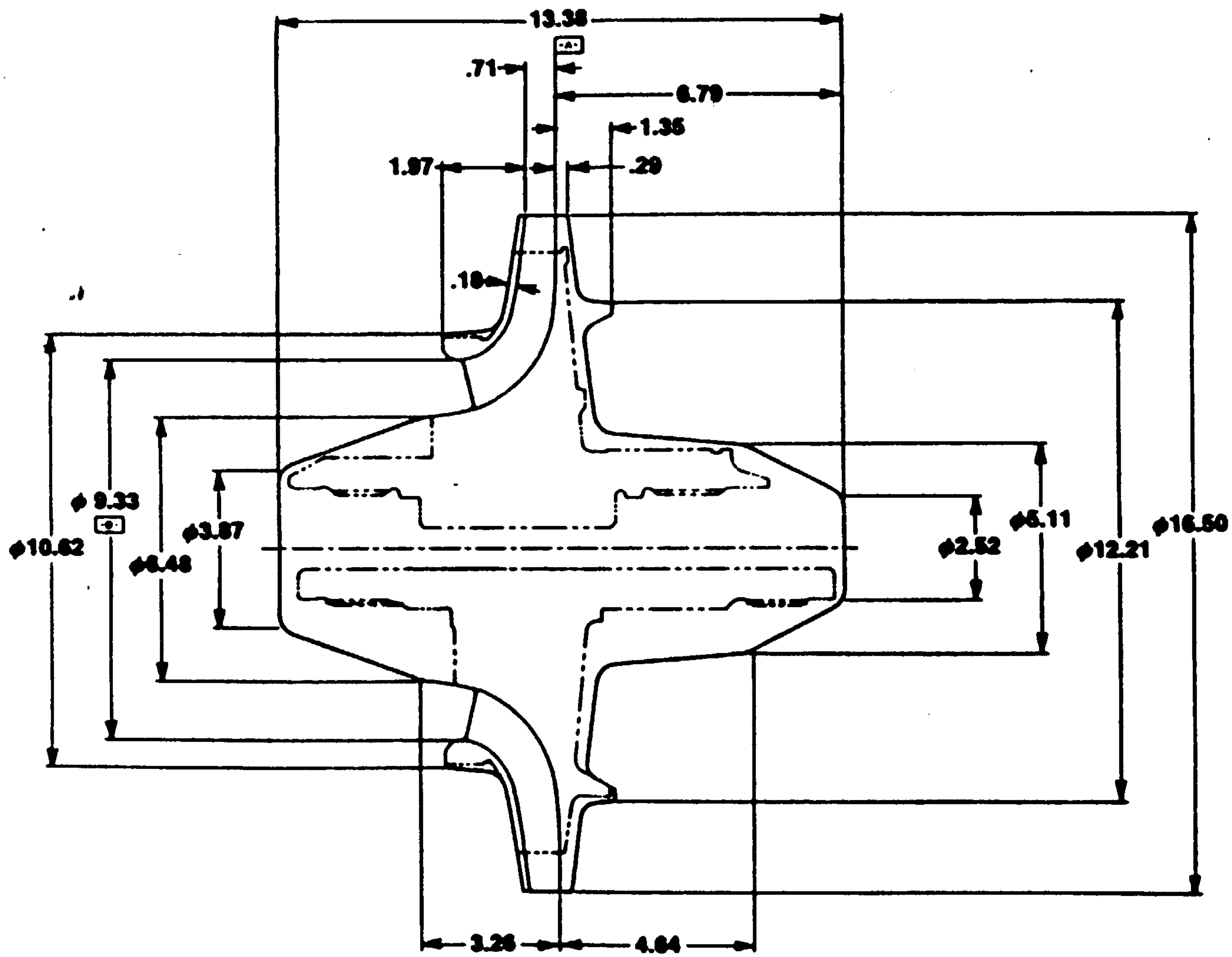


Figure 3-6. CAD Drawing For Cast Titanium Impeller

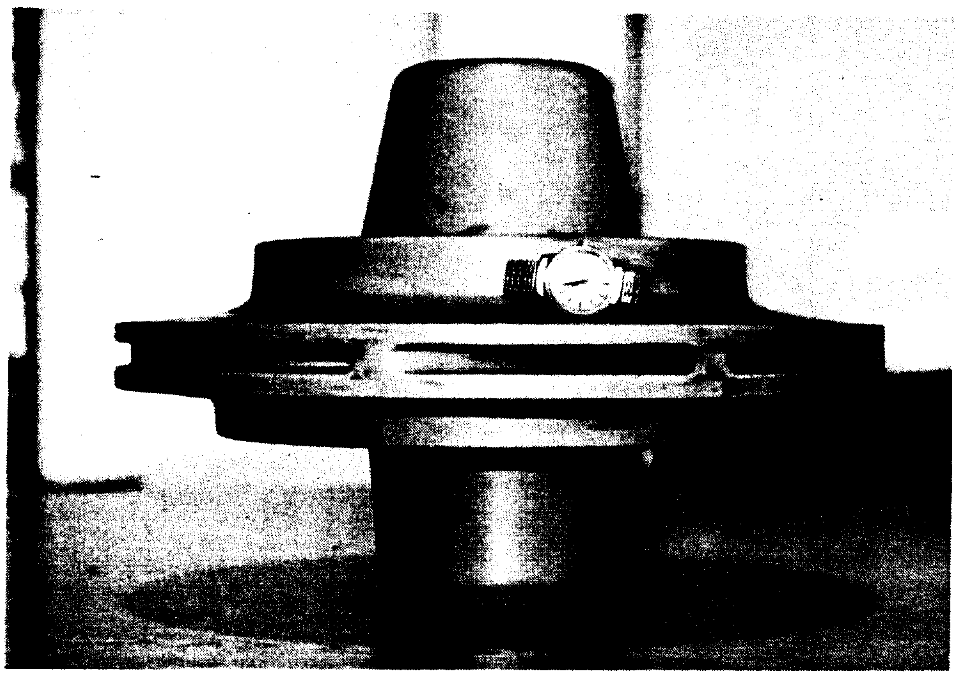

Figure 3-7. Wax Mold For Cast Impeller

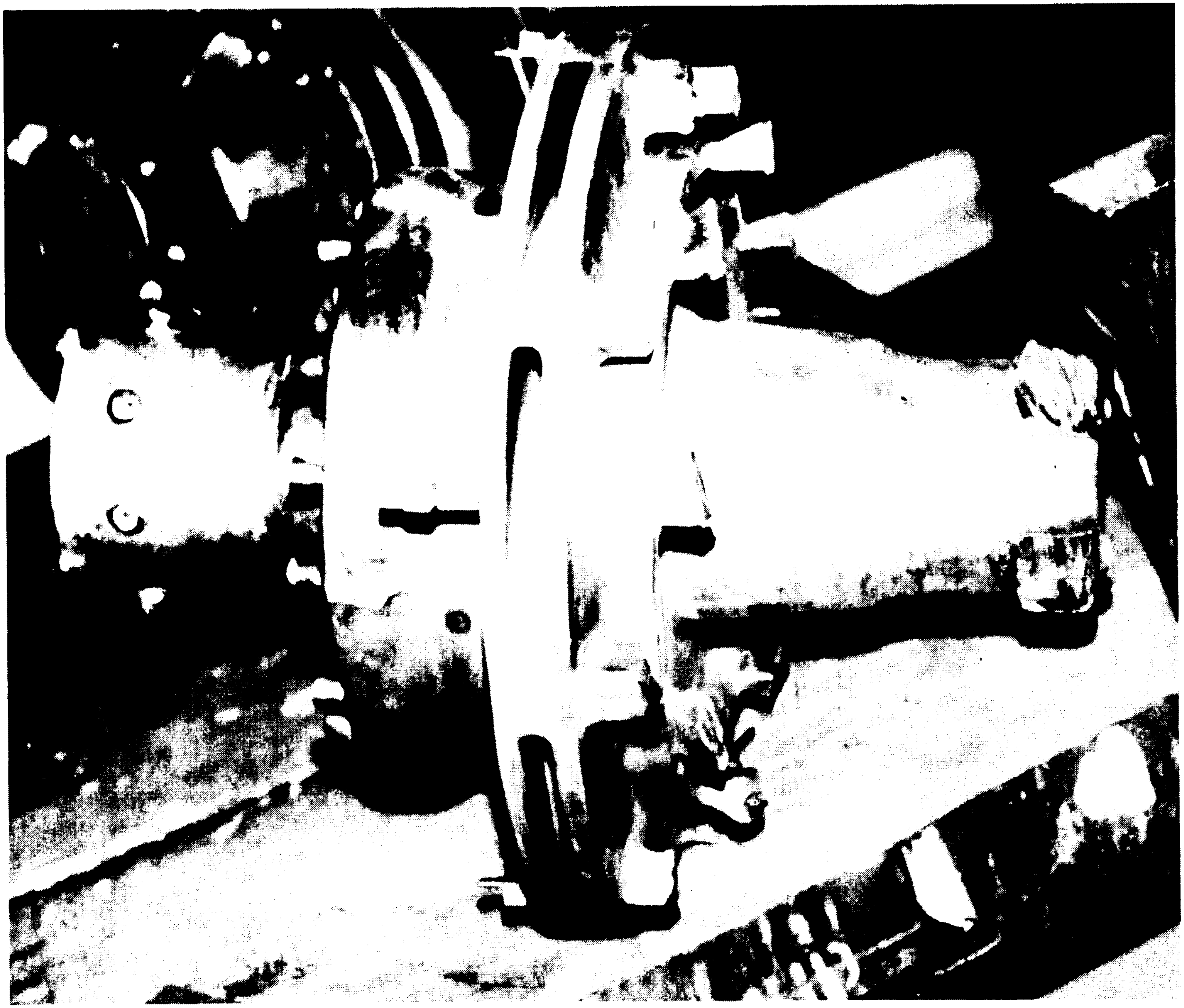

Figure 3-8. Cast Ti 5A1/2.5Sn ELI Impeller

Testing of the cut-up impellers yielded lower-than-expected material properties. This work showed that castings were a viable low cost candidate for impellers; however, the margin was lower than had been planned. There was also concern over the ability to achieve repeatable geometry and material properties with castings. The trade of robustness and repeatability against low cost led to the decision to evaluate the machined impeller approach.

### 3.3.2 NC-Machined Impeller Development

#### 3.3.2.1 Objective

The objective of the NC-Machined Impeller Development task was to demonstrate that NC-machining of a titanium forging was a viable approach to quantity production of pump impellers. This task would also provide data on costs and schedules associated with forged titanium and NC-machining.

#### 3.3.2.2 Activity Overview

The NC-machined impeller plan had two parts: the development of a low cost forging, and the evaluation of NC-machining processes for the production of pump impellers. The two major subcontractors for this task were Timet for forging development, and NuCon for the machining feasibility demonstration.

The Timet approach to impeller forging development was to produce titanium of microstructure and properties appropriate for pump impellers in the original billet. This approach would save the cost and lead time of secondary forging processing. Two billet conversion options were studied by Timet, one involving Beta conversion and the other Alpha-Beta conversion of the material. Timet results show that the Alpha-Beta worked version is preferable.

The Alpha-Beta worked material showed excellent results. There was no porosity observed in ultrasonic examination. Under higher magnification, some minor porosity (<.001 in.) was observed in metallographic sections. A final HIP process would eliminate this microporosity. Sufficient material was produced for material characterization. With the consolidation of the Aerojet and

Rocketdyne hydrogen turbopump activities, this part of the task was terminated. The titanium material was delivered to MSFC for evaluation.

The second part of this task was to evaluate machining processes appropriate for the production of impellers. Several specialized machine shops were contacted and all indicated that the Aerojet impeller configuration was economically machinable on NC multi-axis, multi-spindle equipment. They indicated that the key to low cost machining is design simplicity. The Aerojet design had eight full passages and no partial vanes or splitters. Cost estimates for the production of a machined impeller were within $2,000 of cost estimates for cast impellers. NuCon was selected as the subcontractor to perform this task. The approach was to machine the initial part from aluminum to check out the programming and then to machine a titanium impeller.

3.3.2.3 Results

Two machined impellers were produced in this task, one of aluminum and the other of titanium. The original approach was to fabricate the titanium impeller using the 5Al/2.5Sn ELI titanium billet from Timet. However, it was not available in time to meet the NuCon schedule and forged 6Al/4V titanium was used instead for the machining trial.

From the time NuCon received the purchase order for the aluminum impeller to delivery was 53 days. The scope of the activity included the digital data transfer of the blade coordinates from Aerojet to NuCon, material procurement, NC programming, rough turning, NC-machined finishing, and inspection. A photograph of the aluminum impeller is shown in Figure 3-9. An in-process photograph is shown in Figure 3-10.

Titanium impeller work was begun in July 1991. The design of the impeller was based on engine power balance 8A. The proof-of-concept impeller, shown in Figure 3-11, is a full size impeller. The Ti 6Al/4V material was delivered to NuCon in September. The machining was completed in November.


Figure 3-9. NC-Machined Aluminum Impeller

Figure 3-10. In-Process Machining Of Pump Impeller

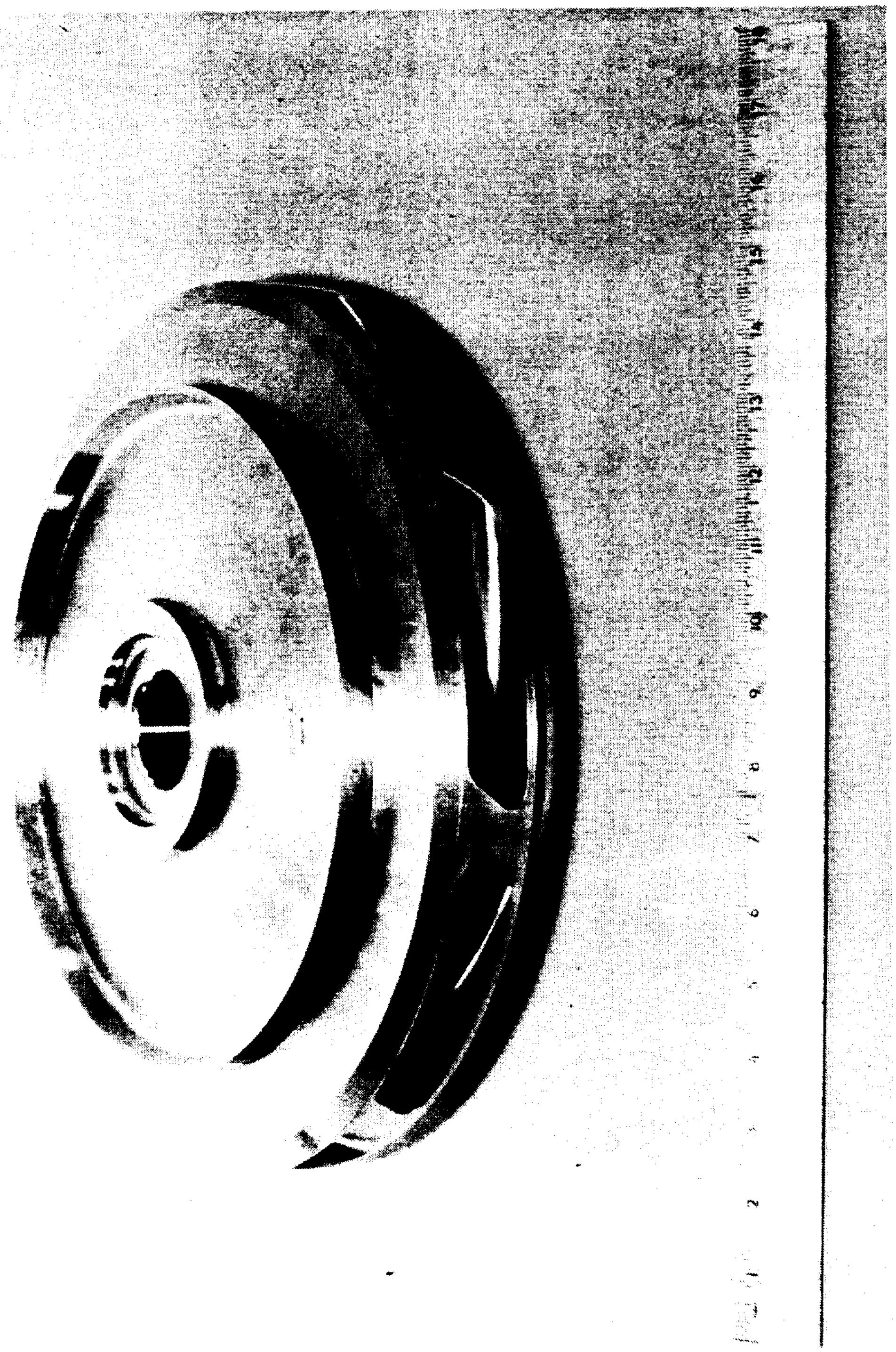

Figure 3-11. NC-Machined Titanium Impeller

Quotes from three machining suppliers were received for the Aerojet impeller configuration and compared to the cast impeller cost. The results are shown in Figure 3-12. Both NC machining and casting are viable approaches to the fabrication of impellers for turbopumps. Machining results in a more robust part for very little additional cost.

## 3.4 Turbine Section Development

After PDR, Aerojet concentrated on the development of the hydrogen turbopump hot section--the turbine. Included in this activity was the turbine blisk, the turbine nozzle, and the hot gas manifold.

### 3.4.1 Turbine Blisk and Nozzle

#### 3.4.1.1 Objective

The objective of the turbine blisk and nozzle task was to fabricate a blisk and nozzle using low cost approaches such as use of materials that would not require coatings for hydrogen embrittlement protection, and testing the blisk holographically and in a spin pit to demonstrate the feasibility of one-piece construction. The task included development of Incoloy 909 pancake and ring forgings, material characterization, and manufacturing producibility studies. Work stoppage occurred prior to the fabrication of a blisk or nozzle.

#### 3.4.1.2 Activity Overview

Proof-of-process fabrication of a representative turbine rotor and nozzle was planned to take place using the updated configuration resulting from the engine thrust change. The design reflected 650,000 lbf engine thrust and enhanced rotational speed capability to minimize turbopump/engine weight. Other design features that had the potential to offer system benefits were being studied when the stop work order was received. They were features such as blade taper, hollow blades, and elliptical fillets. Two CAD views of the turbine blisk design are shown in Figures 3-13 and 3-14. A view of the turbine nozzle is shown in figure 3-15.

| Quantity | Supplier "A" | Supplier "B" | Supplier "C" |
|---|---|---|---|
| 10 | 19,065 | | 25,550 |
| 100-200 | 16,175 | 16,854 | |
| 1000 | 13,970 | | |

- **Machined Impeller Cost Including Material $19-20K**
- **Cast Impeller Cost Including Material $16-18K**

**Machining Is Cost Competitive**

Figure 3-12. Fully Machined Impeller Competitive With Net Cast Configuration

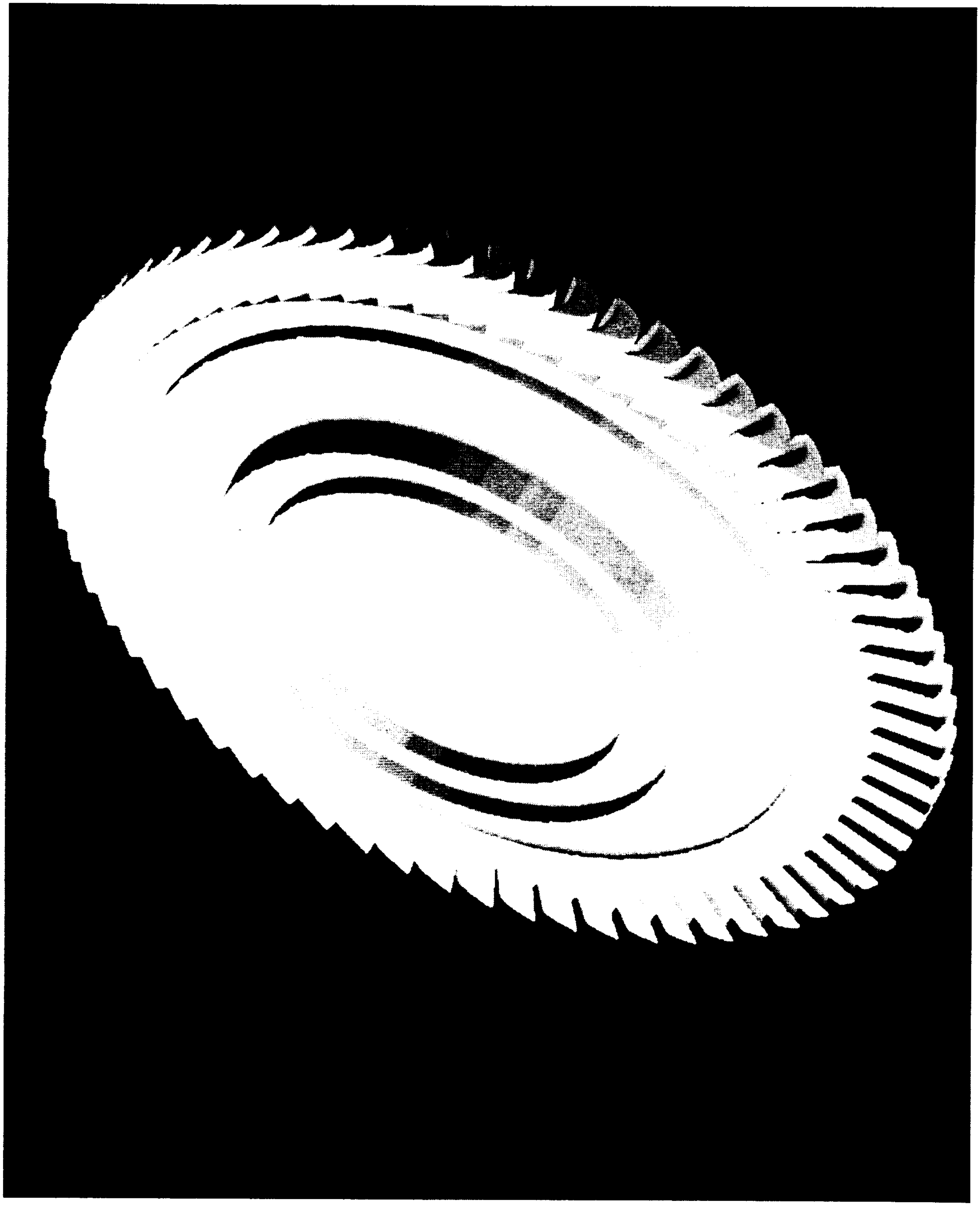

Figure 3-13. CAD View Of Turbine Blisk

Figure 3-14. CAD Cutaway View Of Turbine Blisk

Figure 3-15. CAD View Of Turbine Nozzle

Schlosser Forge Company was the subcontractor responsible for the development of the pancake forgings for the turbine blisk and the rolled ring. They prepared trial pancake forgings that yielded ASTM 7 grain size and approximately 5% block grain area. Tensile elongation was slightly under target (12 to 13%) in one test bar. For the rolled ring forgings the grain size was a uniform ASTM 6 and approximately 5% black grain area was observed. Notch sensitivity was noted at 145 ksi/1000°F. All other properties were acceptable. Schlosser felt that increased forging reduction at high temperature would result in improved properties. The stop-work order was received prior to initiating the second phase of forging development.

In parallel with Schlosser characterization of their forgings, Aerojet was characterizing Incoloy 909 in a hydrogen environment. Initial results early in the program indicated little degradation of properties in hydrogen; however, continued testing by both Aerojet and MSFC resulted in lower-than-acceptable elongation in hydrogen. An evaluation of other candidate materials was underway when the program was stopped.

Several subcontractors participated in the review of the blisk and nozzle designs and contributed producibility comments and cost estimates for the NC-machining of these components. Both designs were producible as configured. The plan was to fabricate both a turbine blisk and a nozzle once forgings became available .

#### 3.4.1.3 Results

This activity resulted in producible designs for both the turbine blisk and nozzle. Quotes from subcontractors for the NC-machining of these two components met cost goals allocated from the engine level. Development work accomplished in the forging area identified a process by which large 909 forgings can be produced in the future. Material test results have been submitted to MSFC.

### 3.4.2 Turbine Manifold

#### 3.4.2.1 Objective

The objective of this task was to develop low cost approaches to the fabrication of the hot gas turbine manifold for the hydrogen turbopump. Two approaches were pursued: a cast manifold and a machined/welded manifold. The casting approach was thought to be a lower cost method of fabrication for the downstream production program while the fabricated manifold offered schedule benefits.

#### 3.4.2.2 Activity Overview

The two subcontractors for the cast manifold task were Precision Castparts Corporation (PCC) Large Structural Business Operation and Howmet Corporation Hampton Casting Division. Both organizations supported this program with company-sponsored programs structured to provide early data to Aerojet and NASA.

Prior to detailed design, Aerojet and PCC conducted a joint company-sponsored program to evaluate the castability of Incoloy 909. A Titan turbine manifold was cast. PCC indicated that there would be no special problems associated with casting the STME turbine manifold. The Titan turbine manifold is shown in the as-poured condition with gates and risers in Figure 3-16; the finished casting is pictured in Figure 3-17.

Additional cast manifold producibility work was conducted with Howmet. Aerojet and Howmet formed a team for the development of the castings for the STME hydrogen turbopump housings. While waiting for additional funding, Howmet initiated an internally-funded program to cast candidate material test bars for Aerojet. Incoloy 909, 718, and Astroloy were the primary materials under consideration for this hardware. A structural analysis using the 3-D finite element model pictured in Figure 3-18 showed that a high strength alloy was required for the manifold.

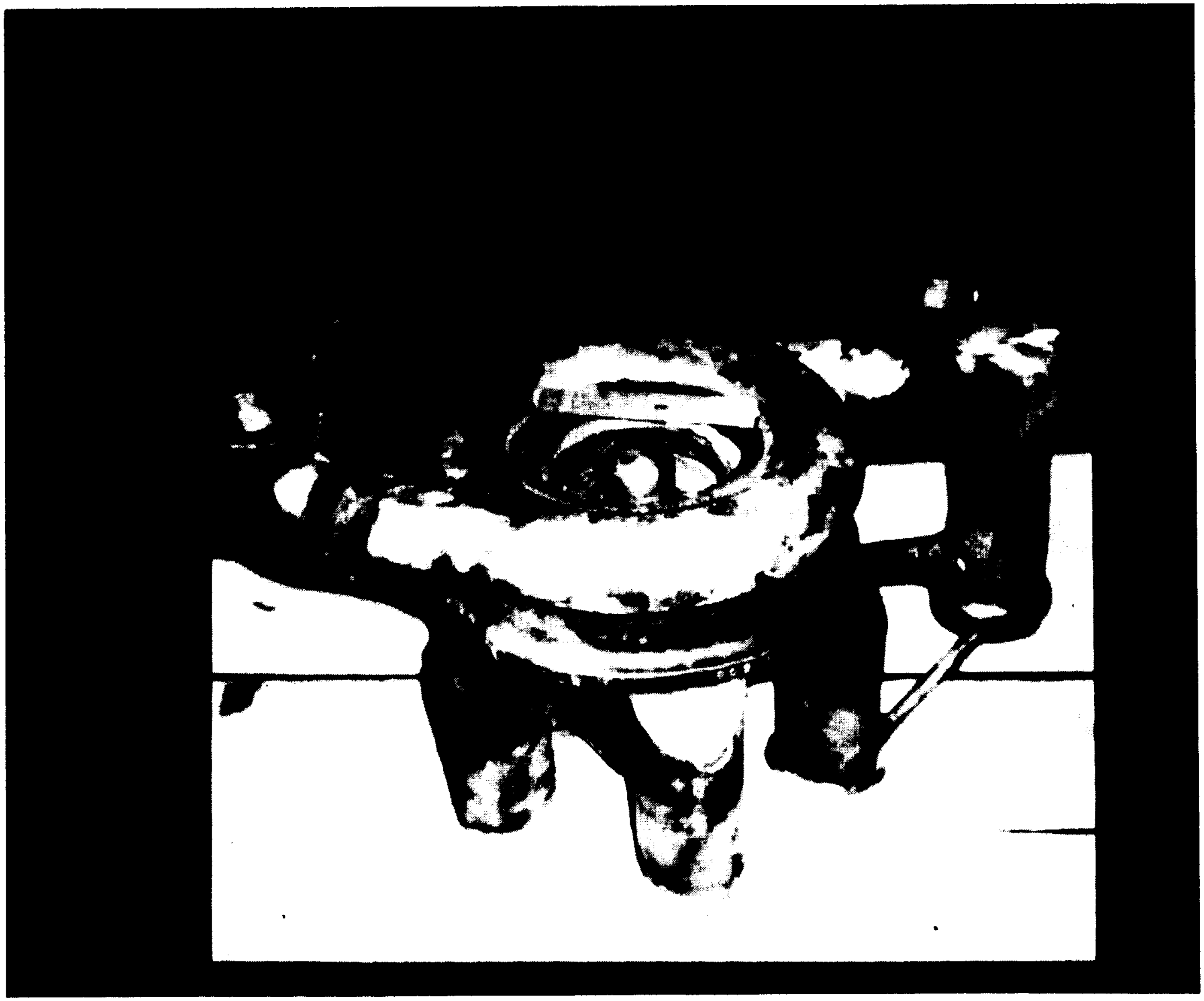

Figure 3-16. As-Poured Casting Of Titan Turbine

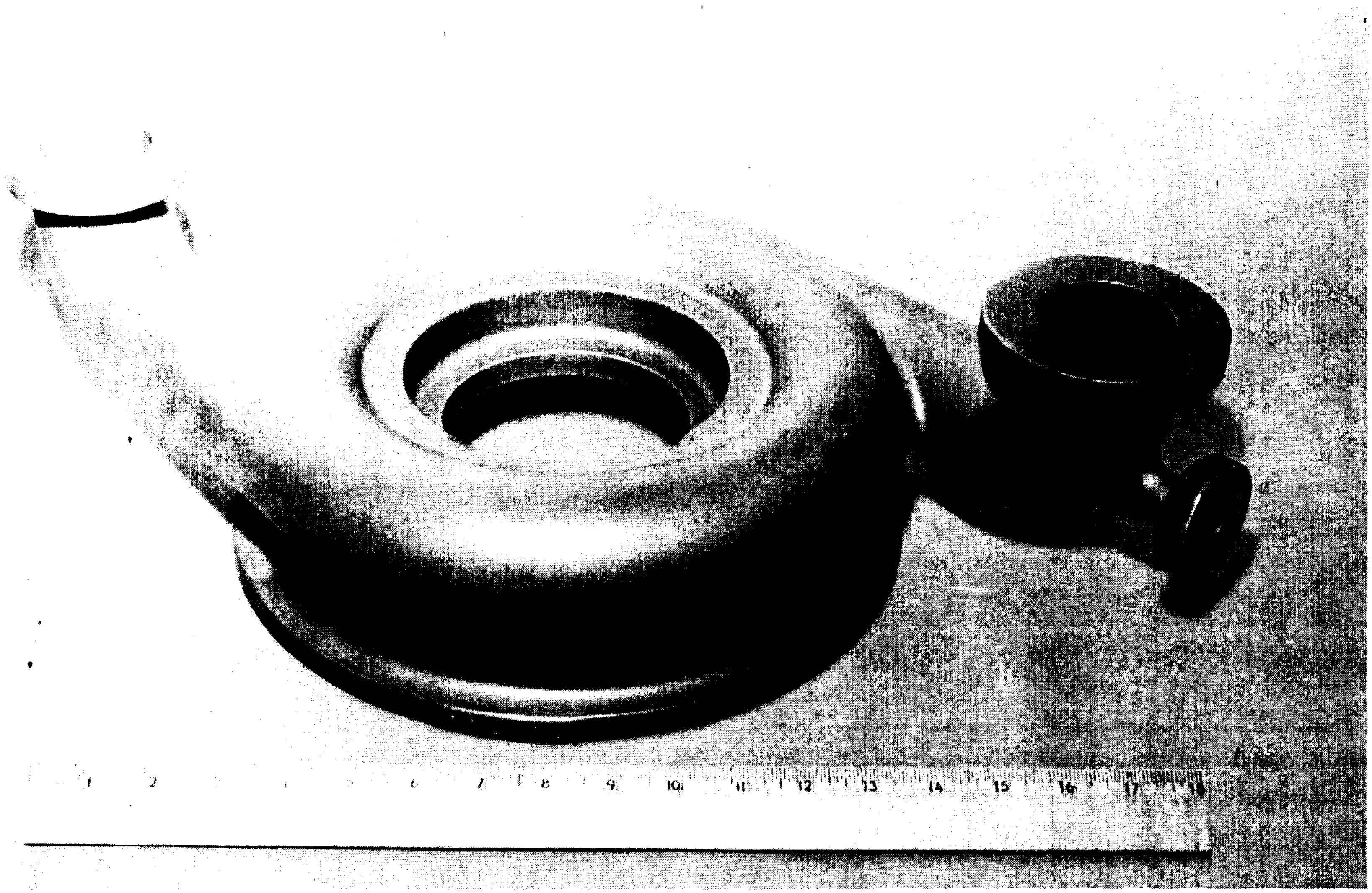

Figure 3-17. Finished Casting of Titan Turbine

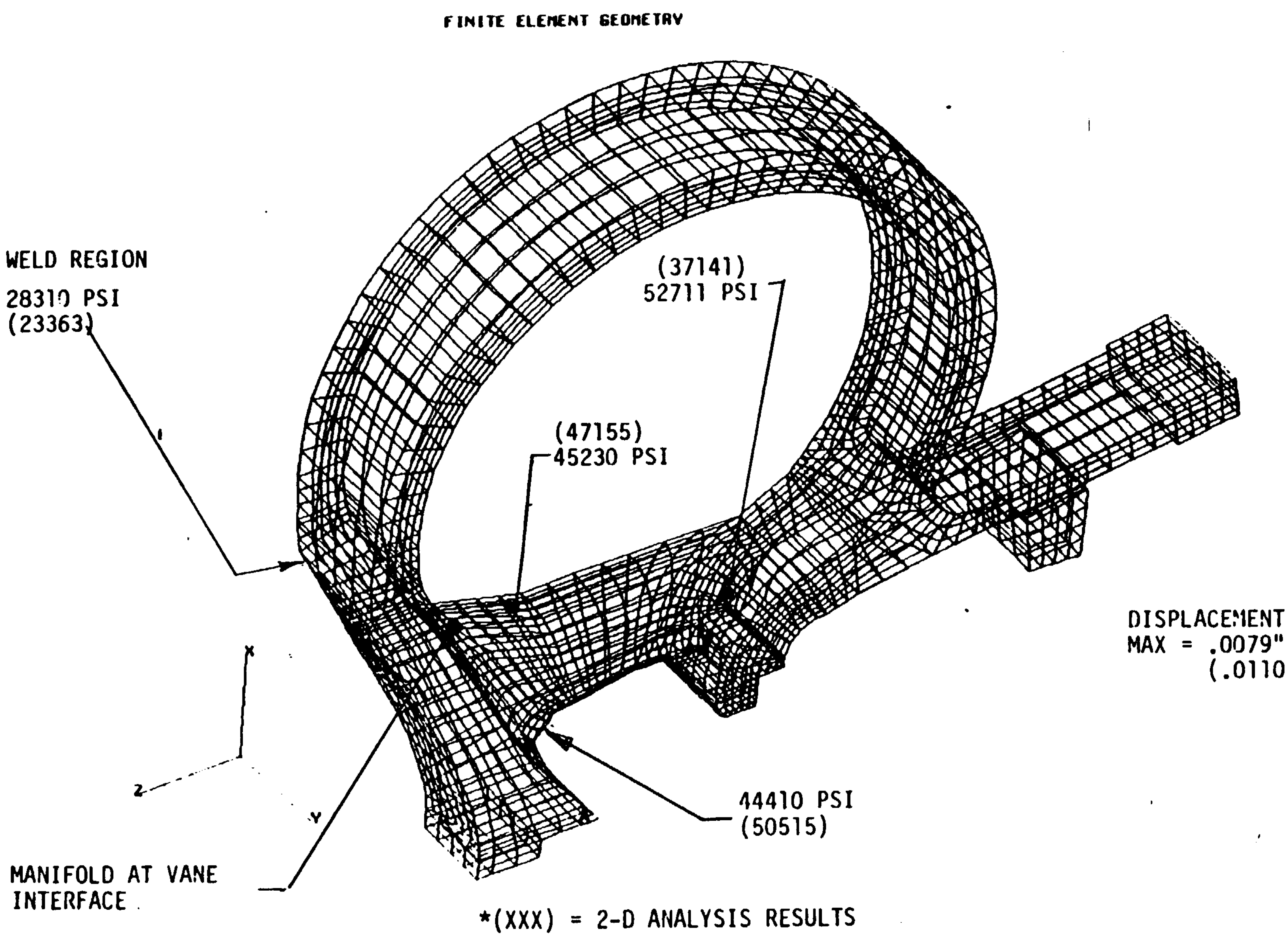


Figure 3-18. Manifold Finite Element Model

#### 3.4.2.3 Results

Producible designs were developed for the turbine manifold and applicable materials and processes were being identified and developed by the casting subcontractors. CAD solid and cut-away views of the manifold are shown in Figures 3-19 and 3-20 respectively. Schedules and costs were being quantified at the time of program stop-work. All available cast material data developed in this task have been provided to MSFC.

## 3.5 Technology Validation Tasks

### 3.5.1 Objective

The objective of this effort was to identify, prioritize, and plan validation tasks for technology that could be retrofitted into the STME turbopumps and/or other suitable turbopump test article(s). The program resulted in detailed plans for promising technology items. The plans included risk assessments, rough order-of magnitude cost estimates, concept layouts, and definition of facilities, equipment, and instrumentation required to demonstrate the technology.

### 3.5.2 Activity Overview

This activity was planned for six months and was structured into three phases:

Step 1 Technology Task Selection and Prioritization
Step 2 General Design and Engineering Plans
Step 3 Detailed Implementation Plans

The program logic network is presented in Figure 3-21.

### 3.5.3 Results

The conclusion of the first program step resulted in the identification of seventy-three technology items for further evaluation. These technologies were ranked using a rating system based on Quality Function Deployment (QFD) procedures addressing customer wants. Results of this prioritization were reviewed with MSFC, which approved the selection of twenty-two technology

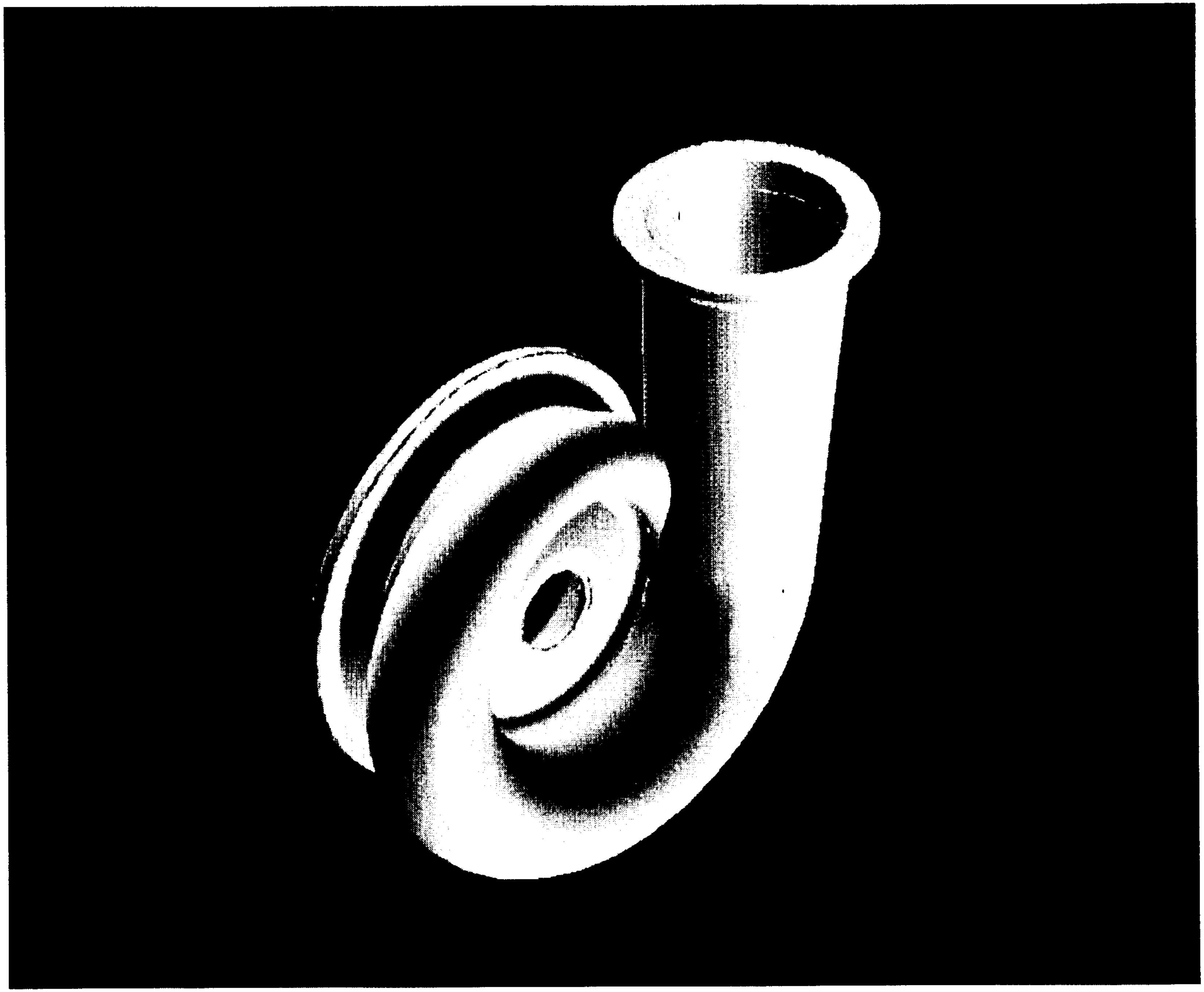

Figure 3-19. CAD View of Turbine Manifold

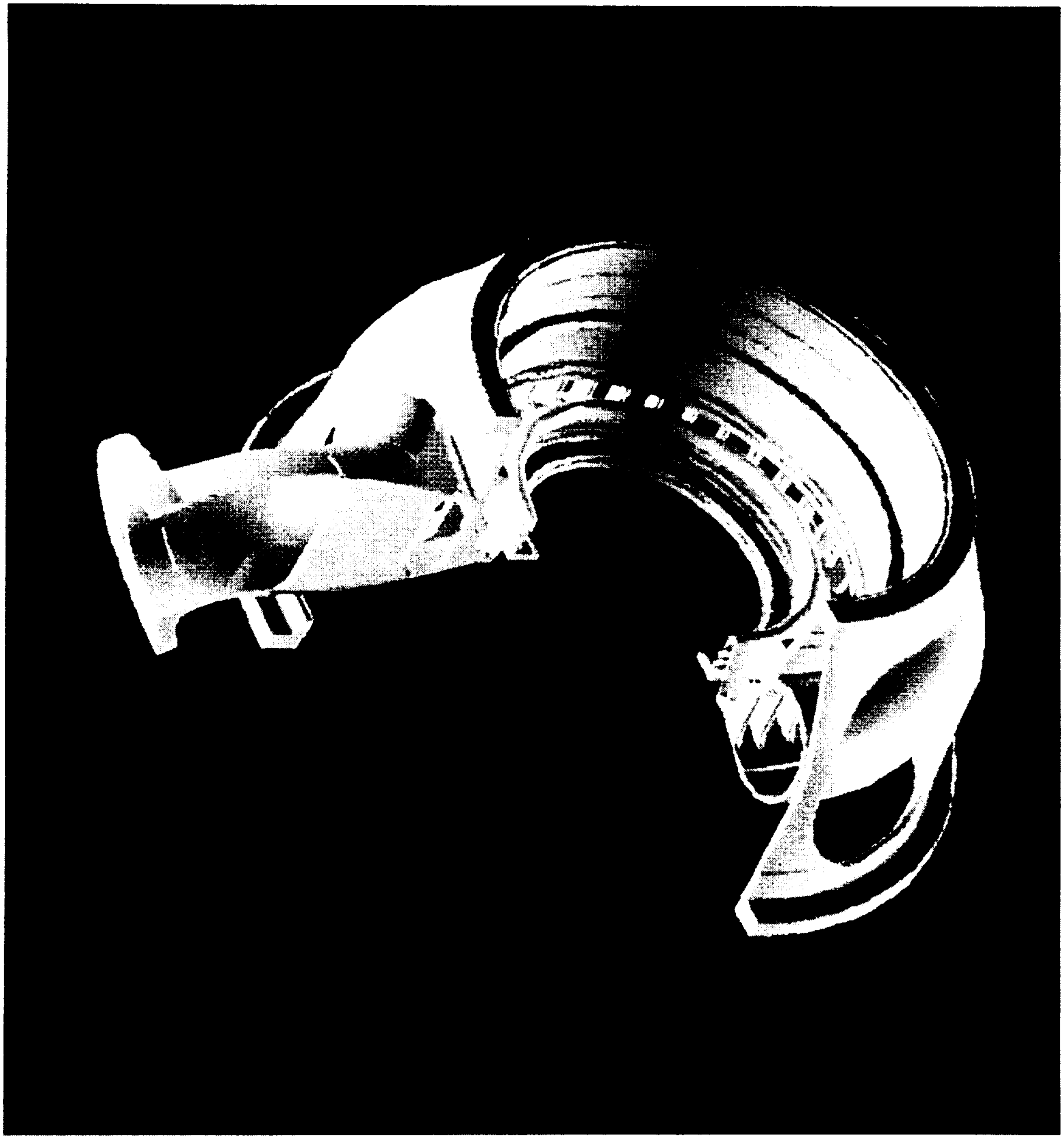

Figure 3-20. CAD Cutaway View Of Turbine Manifold

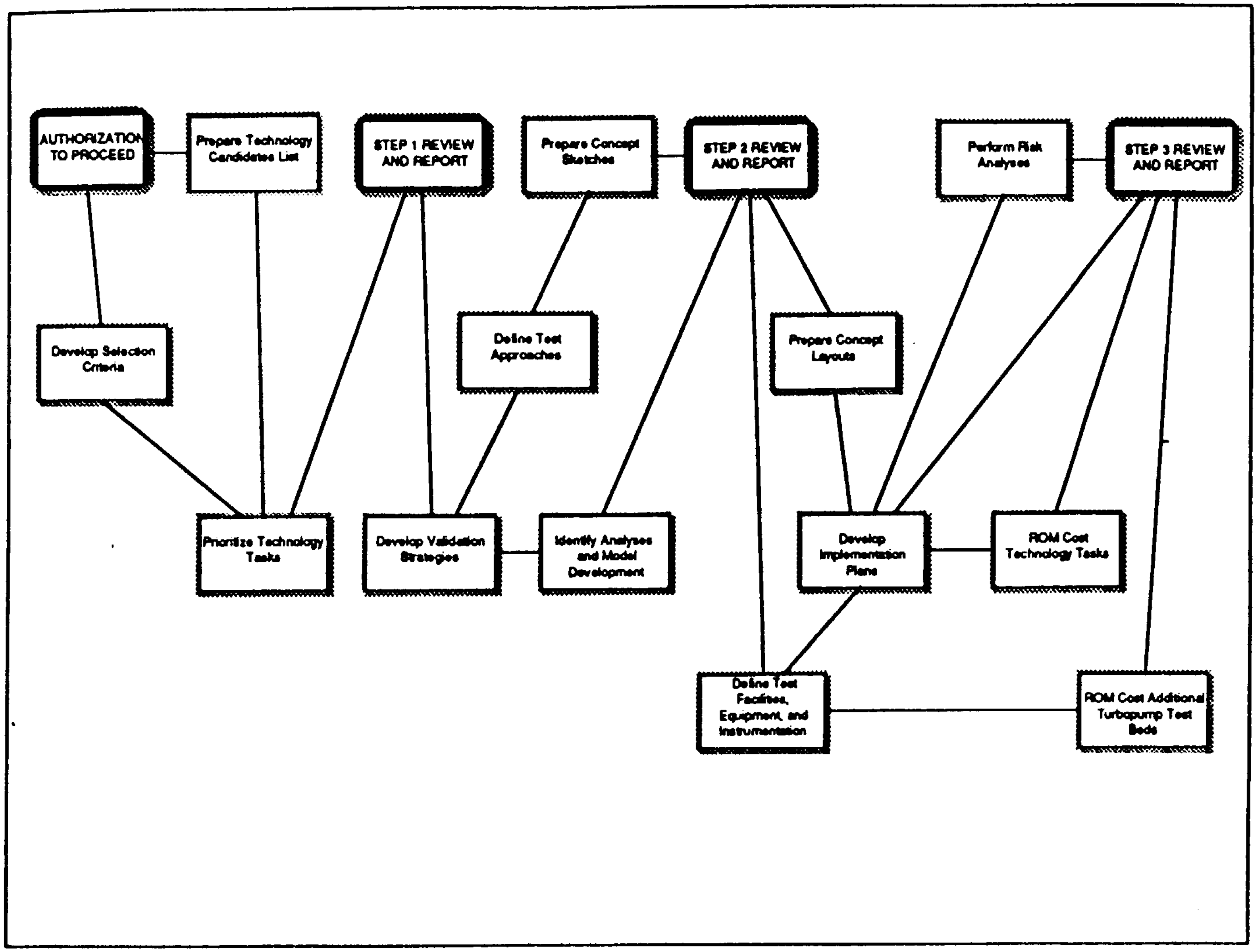


Figure 3-21. Technology Validation Task Logic Network

candidates to carry into the second step of this program. The technologies for further study included bearings and seals, dynamics, fluid flow analysis, structures and mechanical elements, and instrumentation.

A multi-disciplinary concurrent engineering team was assembled to identify test approaches, validation strategies, and required analysis for the 22 technology candidates. During the course of preparing the detailed descriptions, it was observed that the candidates could be grouped into four technology families. These families were primarily based on verification approaches, since the majority of candidates required suitable component rig testing prior to being installed in turbopumps. The four family groupings are:

Fluid Film Bearing Technology - Cryogenic bearing and seal technology to be validated in test rigs

Hydraulic Technology - Turbine component performance and load prediction technologies, validated in a component test rig

Turbine Technology - Turbine component performance and load prediction technologies, validated in a turbine test rig

Mechanical Technology - Various stand-alone mechanical technologies that require limited or unique validation.

The 22 technology candidates broken down to the four categories are shown in Figures 3-22 through 3-25. Detailed implementation plans for the selected technologies, step 3 of this program, were presented to NASA in the final Technology Validation Task report.

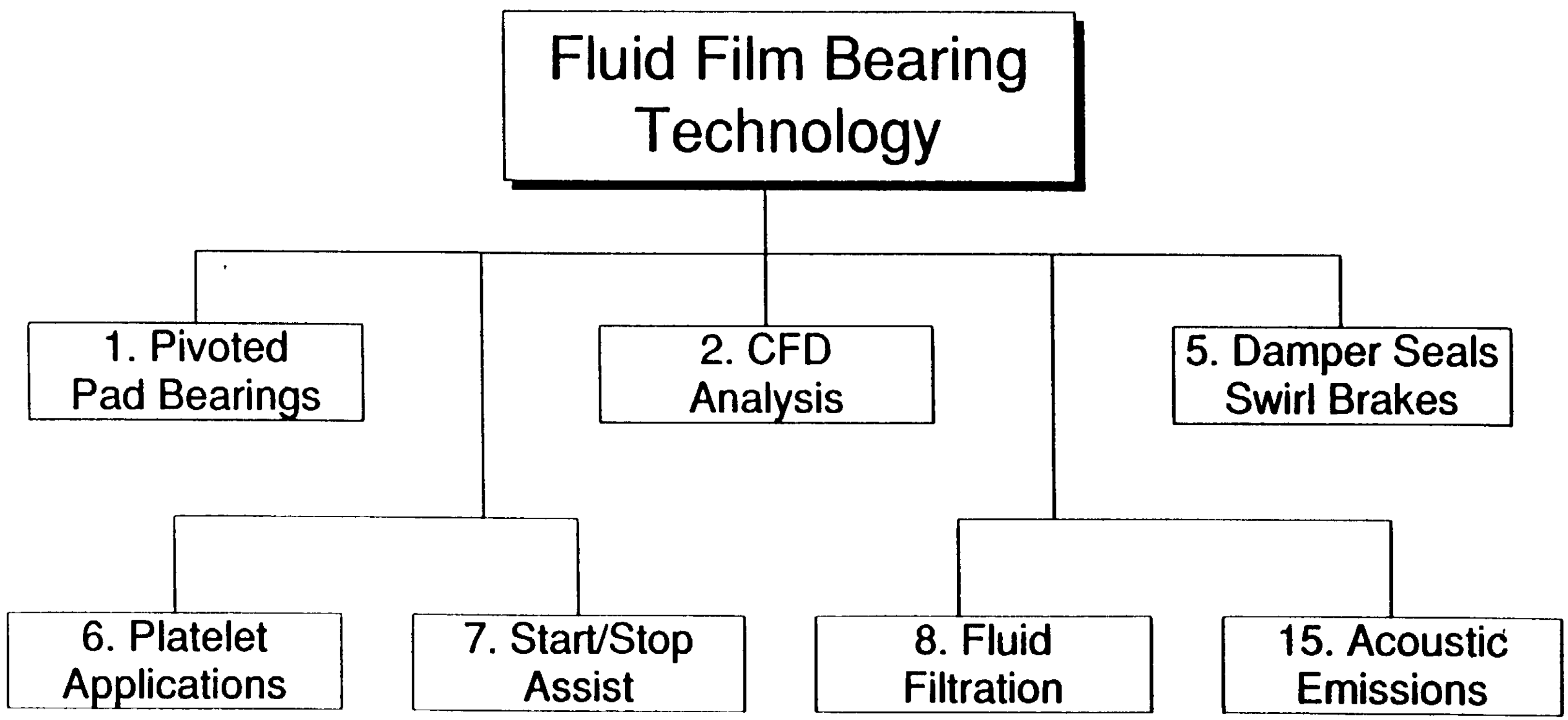


Figure 3-22. Candidate Fluid Film Bearing Technologies

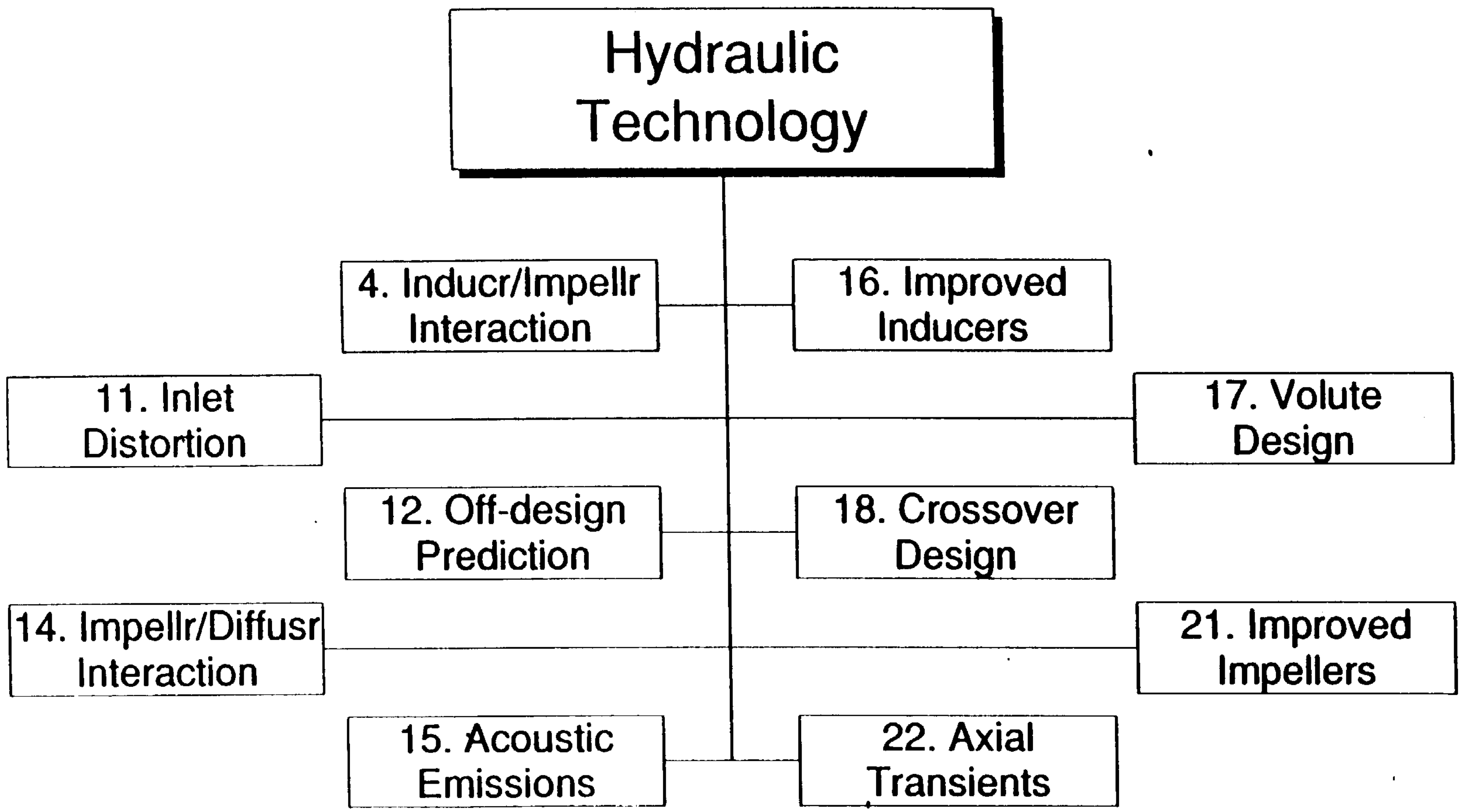


Figure 3-23. Candidate Hydraulic Technologies

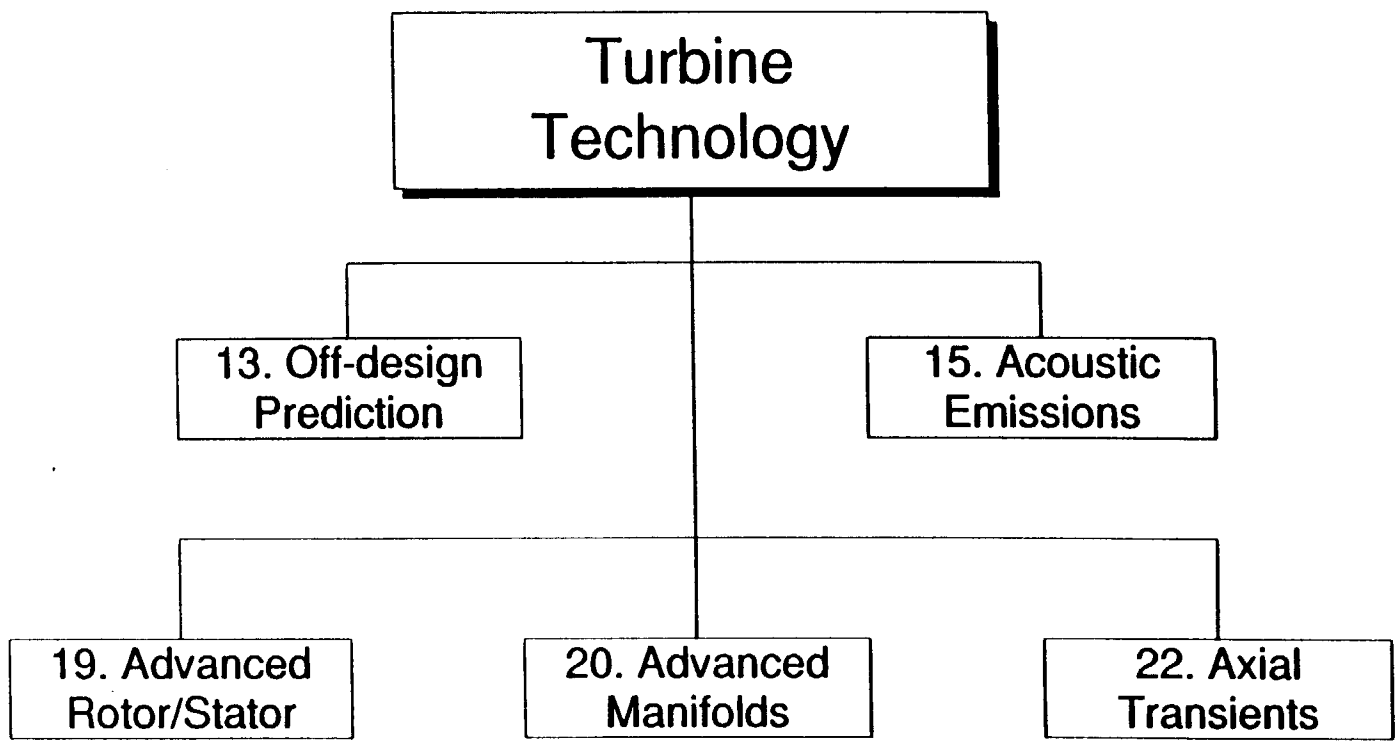


Figure 3-24. Candidate Turbine Technologies

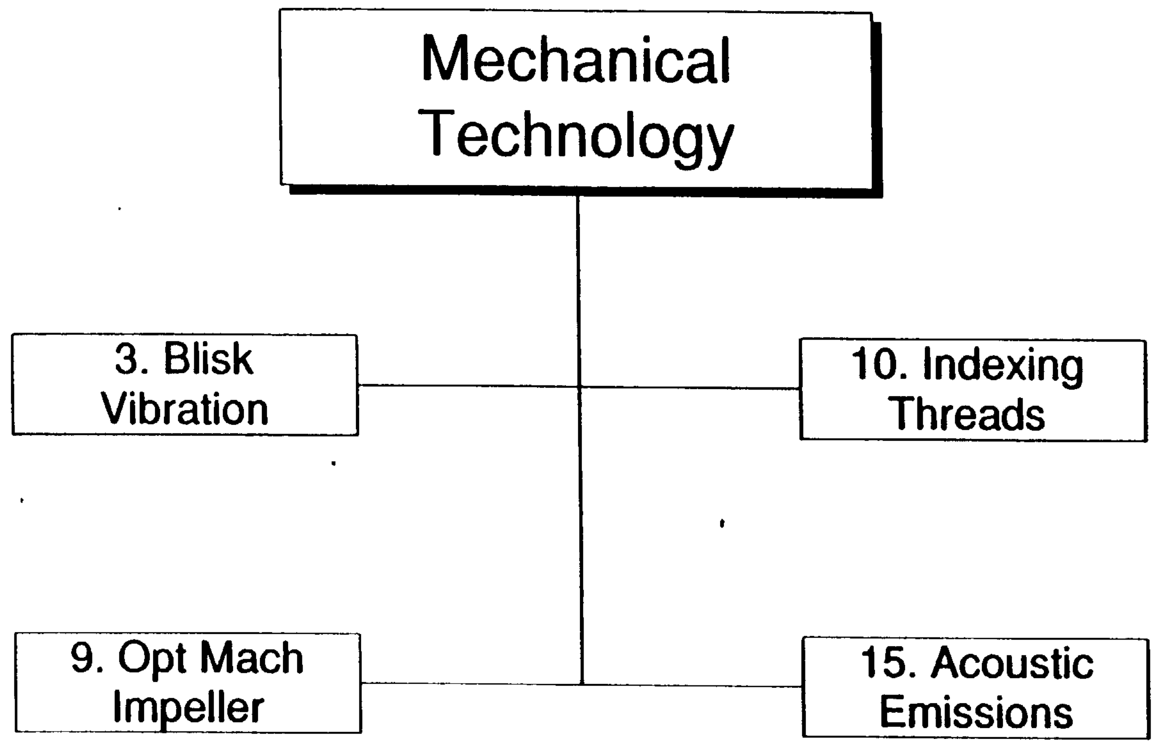


Figure 3-25.  Candidate Mechanical Technologies

## 4.0 FUTURE APPLICABILITY

### 4.1 Overview

This program has evolved and/or proven a number of innovative approaches to the design and manufacture of cryogenic turbopumps. Although the LH2 Turbopump was designed to apply specifically to the NLS Main Engine (STME), the products of this program should be applicable directly or indirectly to other future NASA engine programs, either for upgrading existing designs or for entirely new engine types.

### 4.2 Data

Cost Model: The cost model is the foundation of an excellent tool for estimation, tracking, and control of recurring costs. The model has broad applicability to any component assembly and allows the user authority over input costs and manufacturing cost relationships. Development of a standard tool to be used by NASA and its contractors should be beneficial to all programs.

### 4.3 Hardware

Impeller Integrated Design/Manufacture: By electronically iterating geometry changes, an optimum impeller shape which gave the required hydraulic performance together with NC-machining capability was obtained. The result was an impeller design which could be produced at very low cost and with repeatible form. This technique would be applicable to future NASA engine designs and/or to upgrades of existing turbopumps. NASA should also examine the potential of further automating this process, for example by melding current stand-alone computer programs so that an optimized impeller geometry can be electronically evolved.

Blisks: The blisk offers simplicity and low cost in comparison to conventional separate blade/fir tree attachment systems. It can be geometry-optimized and NC-machined in a manner similar to that used for the pump impeller on this program but, in this instance, blade vibration must be considered in the optimization process. Considerable vibration analysis work was performed on this contract and, as a spinoff, there is an ongoing effort exploring blisk blade damping technology as an STME Phase B technical directive. Blisks should certainly be considered for any future NASA-MSFC new turbopump and/or turbopump upgrade work.

Pivoted/Tilt Pad Bearings: The pivoted/tilt pad hydrostatic bearing proposed for the LH2 Turbopump has great potential. It is a very forgiving design which self-aligns to ensure proper bearing-to-shaft clearance. This avoids the very close tolerance, match-machining required for conventional hydrostatic bearings. As part of the bearing package, the turbopump design incorporated thrust take-out pads which are much simpler than the clutching bearing alternate. It is recommended that NASA-MSFC consider maturing these technologies through an integrated analysis/test program so that the pivoted/tilt pad bearing package is ready to be applied to next generation turbopumps.

Impeller Material: Work performed on the Ti 5Al/2.5Sn ELI beta-formed billet process indicated that poor yields due to strain-induced porosity could be avoided, resulting in significant impeller cost savings and a reduction in material lead time. It is recommended that this effort be continued to the level required to permit a firm decision on the benefits of this novel processing approach.

Turbine Section Static Parts: There is a clear cost saving case for using castings for static turbine (and pump) section parts. Many materials currently used in turbopumps and other engine components are not sufficiently characterized in their cast form, with the result that cast part designs are penalized by risk factors. It is recommended that, leveraging from the preliminary materials and process work performed on this and other ALS ADP contracts, MSFC conduct a systematic evaluation of the material properties of engine parts produced using the investment and centrifugal casting processes. Major engine cost savings without significant weight penalties can result.

## 5.0 RECOMMENDATIONS

It is recommended that the application potentials discussed in Section 4.0 be given consideration by NASA. Much valuable additional data could be gathered by completing the planned tests in this program. The pivoted/tilt pad hydrostatic bearing/thrust pad package offers real potential to improve turbopump assembly and balancing. In the area of process development, the work on performance/NC-machinability optimization for rotating parts was particularly promising. It is strongly recommended that, in particular, these efforts be completed, as the results should be broadly applicable to a range of future NASA programs.

## 6.0 REFERENCES

Data Requirements (DRs) submitted during the course of the contract are identified in Table 6-1. Other technical data generated in the contract have been provided to MSFC.

Table 6-1 List Of References

Data Requirement (DR) -

| | |
|---|---|
| 03 | Monthly Progress Report |
| 04 | Facilities Plan |
| 05 | Equipment List |
| 06 | Government-Furnished Property Plan |
| 12 | Hazard Analysis |
| 15 | Technical Implementation Plan |
| 16 | Logic Network |
| 17 | Quality Program Plan |
| 18 | Part & Material Plan |
| 21 | Safety Analysis Report |
| 23 | Materials Control Plan |
| 25 | System Safety Plan |
| 26 | Contract End Item Specification |
| 27 | Design Review Package |
| 28 | Interface Control Document |
| 29 | Drawings |

# REPORT DOCUMENTATION PAGE

NASA
National Aeronautics and Space Administration

| | | |
|---|---|---|
| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |

| | |
|---|---|
| 4. Title And Subtitle<br>ALS Liquid Hydrogen Turbopump<br>Summary Final Report | 5. Report Date<br>15 November 1993 |
| | 6. Performing Organization Code |
| 7. Author(s)<br>Colin Faulkner - Program Manager<br>Deborah Rickman - Project Engineer | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Aerojet Propulsion Division<br>P.O. Box 13222<br>Sacramento, CA 95813-6000 | 10. Work Unit No. |
| | 11. Contract or Grant No.<br>NAS8-37593 |
| | 13. Type of Report and Period Covered<br>Summary Final Report |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, DC 20546<br>NASA, MSFC, Huntsville, AL | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

This report summarized analysis, design and experimental work done on the Liquid Hydrogen turbopump for the ALS main engine.

| | |
|---|---|
| 17. Key Words (Suggested by Author(s))<br>Rocket Engine Turbopump | 18. Distribution Statement<br>Unclassified, Unlimited |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of pages<br>52 | 22. Price |

NASA FORM 1626 OCT 86