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MANAGEMENT SUMMARY
OF LOW COST TURBOPUMP STUDY

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA George C. Marshall Space Flight Center
Contract NAS 8-24859
Lee Jones, Project Manager

NOTICE

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FOREWORD

The study summarized herein, which was conducted by the Aerojet Liquid Rocket Company, Sacramento, California, was performed under Contract NAS 8-24859. It covers the period 30 June 1969 through 13 February 1970. The contract was sponsored by the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. It was administered under the technical direction of the Propulsion and Thermodynamics Division with Mr. Lee Jones as Project Manager.

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I. INTRODUCTION

The purpose of the Low Cost Turbopumps Study was to develop a methodology for synthesizing lowest over-all cost turbopumps, which means that turbopump resulting in the lowest cost for a particular mission. This effort is part of an increasingly sophisticated NASA approach as it proceeds into the post-Apollo era wherein costs are rapidly emerging as a dominant factor in selecting and promulgating alternative space goals. The technology planners now are oriented toward the evolvement of a body of knowledge as well as technical capability which will permit the attainment of meaningful goals at the lowest over-all costs.

Traditionally, the methodology has been to generate a number of systems, all of which satisfied the specific technical requirements, and to select the lowest cost system or component from those generated. In the subject study, the object was to develop a new or modified methodology which would permit synthesis of the lowest over-all cost system by including cost as a parameter at the outset. In this way, costs are considered as one of the elements of the system during the earliest apportionment of performance requirements. Additionally, any methodology developed for the turbopump portion of the system offers a high potential for applicability to the other elements of the engine/vehicle system.

The accomplishment of study objectives within contractual schedule and budgetary constraints necessitated that the scope of the effort be limited to a single representative application. Consequently, the following guidelines were established.

Characteristic	Constraint/Value
Propellant Combination	LOX/LH_2
Engine Type	Conventional: Bell Nozzle, Gas Generator, and Gimbal Mount
Chamber Pressure	1200 psia
Altitude Thrust	300,000 lb
Application	Half-Size AMLLV; 500,000 lb Payload
Fuel Turbopump Base Configuration	Single-Stage Centrifugal Pump, Two-Stage Axial Turbine, Central-Propellant-Cooled Bearings
Oxidizer Turbopump Base Configuration	Single-Stage Centrifugal Pump, Single-Stage Axial Turbine, Central-Propellant-Cooled Bearings

The Multipurpose Large Launch Vehicle (MLLV) is similar in design to the Advanced Multipurpose Large Launch Vehicle (AMLLV) as defined by NASA Contract NAS2-4079. The MLLV was sized to provide a single-stage-to-orbit (100 nautical mile circular earth orbit) payload of approximately 500,000 lb. Greater payload capability (approaching 2-million lb) could be achieved by using injection stage modules and/or strap-on solid propulsion stages.

Only the core vehicle is utilized in the mission selected for this study, which is to place approximately 20-million lb of payload into orbit.

Recurring costs are most realistically expressed in terms of cost-per-unit while the maintenance of capability costs are best denoted in terms of cost-per-unit-of-time. Consequently, a program life and procurement rate were needed to permit an adjustment between the two and provide a basis for consistency. Two combinations of rate and life had to be investigated, but the individual values were left to the discretion of the Project Engineer.

The study was divided into the following specific contractual tasks:

Task I - Relationship of Turbopump Design Requirements to Over-all Costs

Task II - Examinations of Cost-Contributing Operations

Task III - Conceptual Design

II. SUMMARY

Integral considerations for the Low Cost Turbopumps Study were the mission, vehicle, engine trade-offs, detailed subcomponent analyses, and subcomponent optimizations. The representative design case selected was a half-size version of an Advanced Multipurpose Large Launch Vehicle (AMLLV) with a 500,000 lb payload capability to low earth orbit. The contract imposed study constraints of a LOX/LH_2 propellant combination and a conventional packaging arrangement with a bell nozzle, gas generator, and gimbal mount. Chamber pressure and altitude thrust also were fixed at 1200 psia and 300,000 lb, respectively. This resulted in the following design characteristics being defined as those applicable to the base turbopump design:

		Turbopump Values	
Symbol	Characteristic	LH_2	LOX
ΔP	Pump Pressure Rise	1900 psi	1700 psi
$\dot{w}_P$	Pump Flow Rate	125 lb/sec	585 lb/sec
$P_{\tau i}$	Turbine Inlet Pressure	1190 psia	135 psia
PR	Turbine Pressure Ratio	7.5	3.4

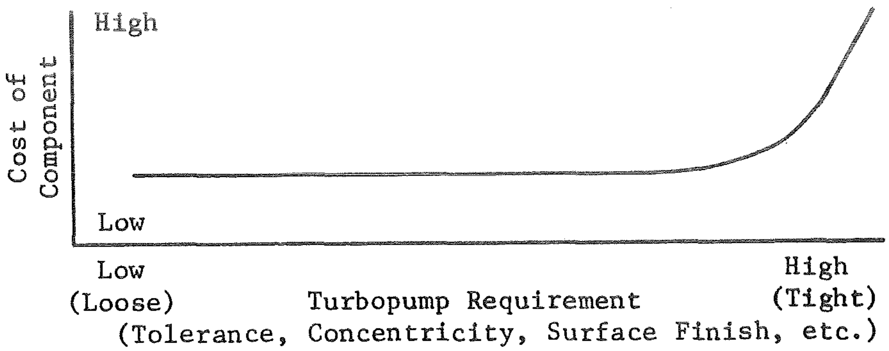
Symbol	Characteristic	Turbopump Values	
		LH_2	LOX
T_{TI}	Turbine Inlet Temperature	1660°R	1250°R
$\dot{w}_T$	Turbine Flow Rate	20 lb/sec	20 lb/sec
NPSH	Pump Net Positive Suction Head	130 ft	25 ft

These basic requirements were used to generate reference conceptual designs for fuel and oxidizer turbopumps. Then, the operational costs for producing these turbopumps were determined. Thus, the results of Task I (Relationship of Turbopump Design Requirements to Over-all Costs) provided the basic data for synthesizing the design offering the lowest over-all cost. These data included cost and performance information in terms of identical variable requirements as well as turbopump performance information in relationship to vehicle and mission costs.

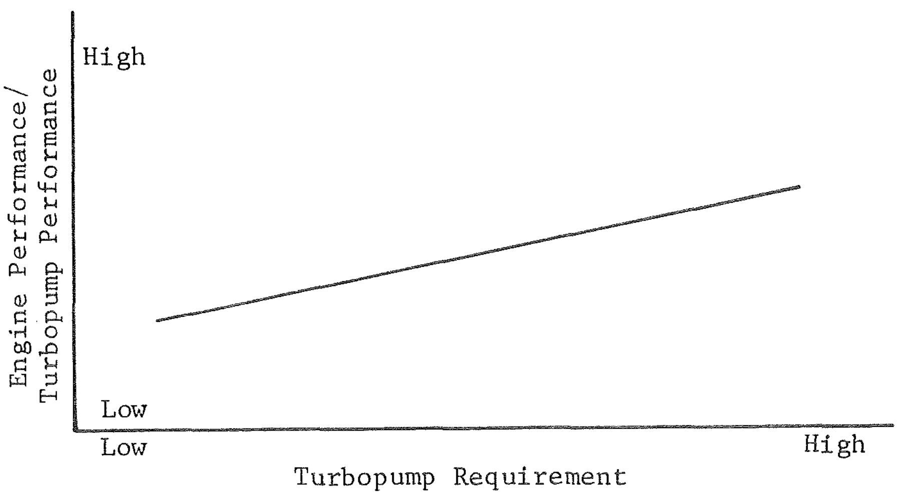
Next, the requirements were altered. Changes in the cost-contributing operations and performance were noted as part of Task II (Examinations of Changes in Cost-Contributing Operations). Cost data similar to that of Task I was provided but now it was in terms of variable requirements for different technological levels of performing the significant (high cost) operations. These data showed at what level of requirements substantial savings could be achieved by altering the method of designing, fabricating, or testing a component of the system. Following this, the changes in requirements and performance were related to the mission level costs.

The methodology developed was tested by utilizing the study results as a basis for final conceptual designs as well as the formulation of development, production, and acceptance plans for these designs. Task III (Conceptual Design) served to demonstrate that the design methodology formulated from Tasks I and II actually could be applied to a realistic program while resulting in a turbopump cost savings reaching as high as 3% or 10-million dollars for a 17-million pound-to-orbit program. However, when the sensitivity of over-all program costs to performance is considered, these savings are nullified and the potential for increased costs actually exists.

Consequently, the overwhelming conclusion from this study is that the relaxation of requirements to reduce turbopump costs is not a fruitful way to decrease program costs. In effect, the potential exists for reducing turbopump program costs by as much as 40% (or 200-million dollars) through the appropriate tightening of design requirements to a degree that would permit the elimination of acceptance test operations. Additionally, large over-all program cost reductions could be accrued through this approach because of the cost sensitivity to engine performance (I_{sp}). This can best be visualized from the following qualitative curves:

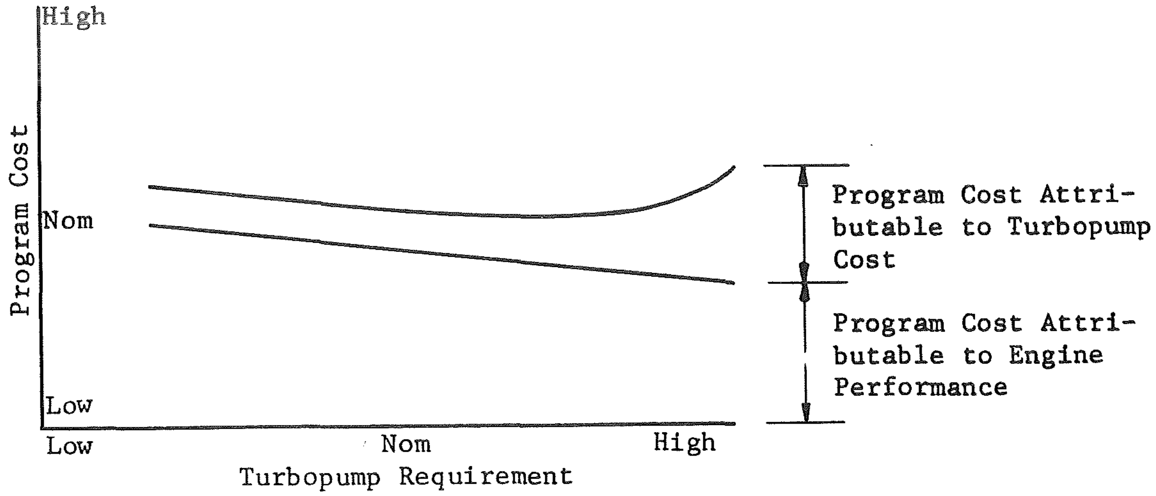


In the above curve, the general trend that the effect of turbopump requirements has upon the cost of the turbopump components is illustrated. Most experienced engineering personnel will select a requirement that falls near the "knee" of the curve even when data is unavailable.



It can be seen from this second curve that turbopump performance is rather gradually affected by requirements in the reasonably attainable range.

When the above two trends are combined and superimposed, the following curve is evolved:



Note that a broad optimum results in terms of turbopump requirements. In highly performance sensitive vehicles (i.e., existing Space Shuttle concepts), the total program curve could become steeper than that for the highly performance-sensitive, single-stage to orbit MLLV. This would tend to drive the cost optimum turbopump toward even more rigid requirements.

III. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

A. RESULTS

1. Categorized Cost-Contributing Operations

There are seven major categories of cost-contributing operations associated with a turbopump during its usable life. These categories, which maintain strict separation between the development and production phases, are as follows:

- Development Design Operations
- Development Fabrication Operations
- Development Test Operations
- Production Design Operations
- Production Fabrication Operations
- Production Test Operations
- Production Field Maintenance Operations

Each of these broad categories consists of many detailed operations and these finer breakdowns are accomplished to the level appropriate for calculating the costs of concern.

2. Categorized Design Requirements

All turbopump design requirements fall into the three categories of performance, operational, and mechanical. However, all requirements must ultimately be reduced to the turbopump part level before a quantitative assessment of their influence upon costs can be accomplished.

3. Relationship Between Variations in Requirements and Cost-Contributing Operations

Variations in the categorized requirements and cost-contributing operations were investigated in great detail. The relationships invariably showed that as the requirement became more stringent, a higher technological level of operations was needed to sustain it. This is not meant to imply that the highest over-all cost necessarily results from stringent requirements, rather it is only the cost of the affected operations which increases.

4. Description of Alternative Methods for Performing Cost-Contributing Operations and Recommendations for Additional Technology

Because of their relative importance (in terms of percentage of program costs), the most attractive area for utilizing alternative methods of performing cost-contributing operations is the production phase as well as the fabrication and test operations. In the referenced MLLV program, these contribute in excess of 82% of the turbopump program costs.

Many alternative methods for performing fabrication operations were investigated. Two such examples of alternatives are sandblasting instead of hand-polishing machined or cast impellers to obtain the necessary surface finish and the casting instead of fully-machining pump diffuser vanes to obtain the required vane profiles. Substantial cost savings in fabrication can be realized by using such alternatives where the appropriate technology is generally available. However, in each instance, it is necessary to evaluate the performance (hence, over-all cost) effect that will result from relaxing the pertinent requirements. Additionally, the optimum method among available alternatives must be selected.

No reasonable alternative methods for performing the turbopump test operations are apparent. However, if the engine balance requirement can be relaxed or if turbopump performance repeatability can be improved, there is a possibility that the production phase testing could be eliminated. Such an approach would require experimental verification to validate its feasibility. A program of this type is strongly recommended. It would be conducted in the following sequence:

Step 1: Select an active engine production program wherein the engine balance requirements are known.

Step 2: Utilizing the appropriate effects data (i.e., Effect of Impeller Discharge Blade Height upon Pump Performance) for the selected program, revise the turbomachinery mechanical design requirements to obtain the necessary performance repeatability.

Step 3: Adjust the turbomachinery fabrication drawing per Step 2.

Step 4: Fabricate a reasonable sample (i.e., 10) of parts in accordance with the revised drawing.

Step 5: Test the sample turbopumps in the usual manner to verify that the theoretical performance repeatability has been achieved.

Step 6: Utilize the sample turbopumps in the selected production program.

The costs involved in the above recommended program are those associated with engineering to accomplish Steps 2 and 3 as well as those involved with evaluating the results of Step 5 and the increase in fabrication costs to produce the sample machines against more stringent requirements.

5. Relationship Between Turbopump Requirements and Cost

The relationship between requirements and cost was defined in rigorous detail at the turbopump level in terms of man/machine hours and prime (supplier charged) dollars. A grosser definition was evolved for several composite turbopump level alternatives in terms of program dollars applying a sample overhead structure.

6. Optimal Turbopump Requirements and Design Criteria

Turbopump design requirements were made optimum for the reference MLLV case.

7. Low Over-All Cost Turbopump Conceptual Designs and Associated Development, Production, and Acceptance Plans

A brief optimization study was accomplished using the reference (contract specified) performance requirements. This resulted in the selection of the basic mechanical configurations and the accomplishment of limited conceptual design. Detailed optimizations and mechanical designs were not accomplished. The associated development, production, and acceptance plans also were generated.

B. CONCLUSIONS

The most significant conclusions and implications which became apparent during the course of the program as well as from the results of the study are summarized as follows.

1. Requirements Influence Level

Generally, the influence of design requirements upon the cost of operations is apparent at the part or feature level only.

2. Program Size Implications

In terms of over-all program cost, the relative importance of any category of operations performed in association with the turbopump is very strongly influenced by the size of the production program assumed. Any reasonably high production program (where delivered units exceed research units by at least one order of magnitude) costs are of a nature that individual costs (excluding production, phase fabrication, and test operation costs) probably are lower than the estimating tolerance for the production, fabrication, and test costs. Clearly, the elimination of all development phase costs from the reference program would result in less than a 5% reduction in the turbopump program costs and an almost indiscernible decrease in over-all program costs.

3. Individual Operations Cost Implications

A lack of visibility of costs for individual operations in any size program at the level where they are influenced by the requirements is apparent although as individual operations they might constitute a high proportion of the component costs.

4. Synthesis of Designs

Based upon the conclusions detailed, the synthesis of optimal turbopump requirements and design criteria from individual requirements versus cost of operations data is both imperative to low over-all cost and so unwieldy that it becomes virtually impossible because of the almost infinite number of microscopic effects to be considered.

C. RECOMMENDATIONS

The results of this study indicate that costs should not be attacked at the individual requirement and operation level in an effort to reduce the cost of operations. Instead, it is recommended that costs be attacked at the major operations category level with the objective of eliminating the entire category. In keeping with this philosophy and based upon the results of Tasks I and II, it is further recommended that methods be investigated to eliminate production phase turbopump acceptance testing.

The requirement to perform turbopump acceptance tests results from the desire to make a mechanical check of the turbopump functional capability as well as to obtain calibration or balance data for subsequent engine checkout and calibration testing. Actually, at the reliability levels of current rocket engine turbomachinery, the only function served by the turbopump acceptance test is to provide engine balance data. Therefore, if turbopump performance repeatability (from unit to unit) can be achieved within the engine balance requirements, the turbopump acceptance tests can be eliminated with the engine calibration test serving as the turbopump functional and performance calibration checkout.

It is recognized that to accomplish what is recommended requires some technological development so as to obtain the needed performance repeatability. However, much of the required technology is available from this Low Cost Turbopump Study. The cost of sustaining individual part level mechanical design requirements is known as well as their influence upon performance. Therefore, the only data required for performing the necessary trade-off is the relationship between part level mechanical design requirements and performance repeatability as such. This extension in the data provided herein, along with experimental verification of the results, would constitute a relatively straightforward technology development program which could provide major reductions (up to 40%) of turbopump costs in future programs.

IV. SUMMARY OF TECHNICAL DISCUSSION

A. TASK I - RELATIONSHIP OF TURBOPUMP DESIGN REQUIREMENTS TO OVER-ALL COSTS

Task I was divided into four subtasks. Firstly, the cost-contributing operations were identified and categorized. This was next accomplished for the design requirements. Then, the relationship of variations in design requirements to cost-contributing operations, turbopump/vehicle costs, and over-all costs was ascertained. Finally, a synthesis of design requirements was completed to yield minimum over-all costs.

1. Cost-Contributing Operations

It was essential that a realistic conceptual design be utilized as the basis for selecting the appropriate operations and requirements. However, budgetary and schedular limitations severely restricted the effort and base designs were generated at only one thrust level, 300,000 lb. Consequently, the configurations selected (see Figures No. 1 and No. 2) as the bases for the Task I effort are non-optimum and result from a morphological evaluation as well as the necessary preliminary calculations. The specific requirements for these base case turbopump designs are listed on Table I while the pertinent characteristic dimensions generated for both cases are listed on Table II.

The cost-contributing operations then were identified and categorized in a number of variations. These were largely based upon the commonality of the same requirements variations affecting the cost of both design operations, primarily at the functional assembly level (i.e., pump, turbine, or power transmission), and fabrication operations at the subcomponent level (i.e., impeller and pump volute).

The general categorized listing evolved revealed a significant weakness in the original program. Each of the operations costs could be explicitly described and quantified in terms of man and machine hours based upon the particular set of detailed requirements assumed for the base case designs, but this would result in single point data not useful by itself in performing optimizations or trade-off studies. Determination of the relationship between variations in requirements and cost-contributing operations required that the operations costs be quantified over a range of requirements. Identical techniques and manpower would be used for quantifying the base case operations costs and alternative requirements operations costs, but the original plan necessitated a redundant performance. This would have resulted in accomplishing the same effort twice as well as two separate tabulations of the data. Therefore, quantification of the base case operations costs was deferred until quantified ranges of design requirements became available.

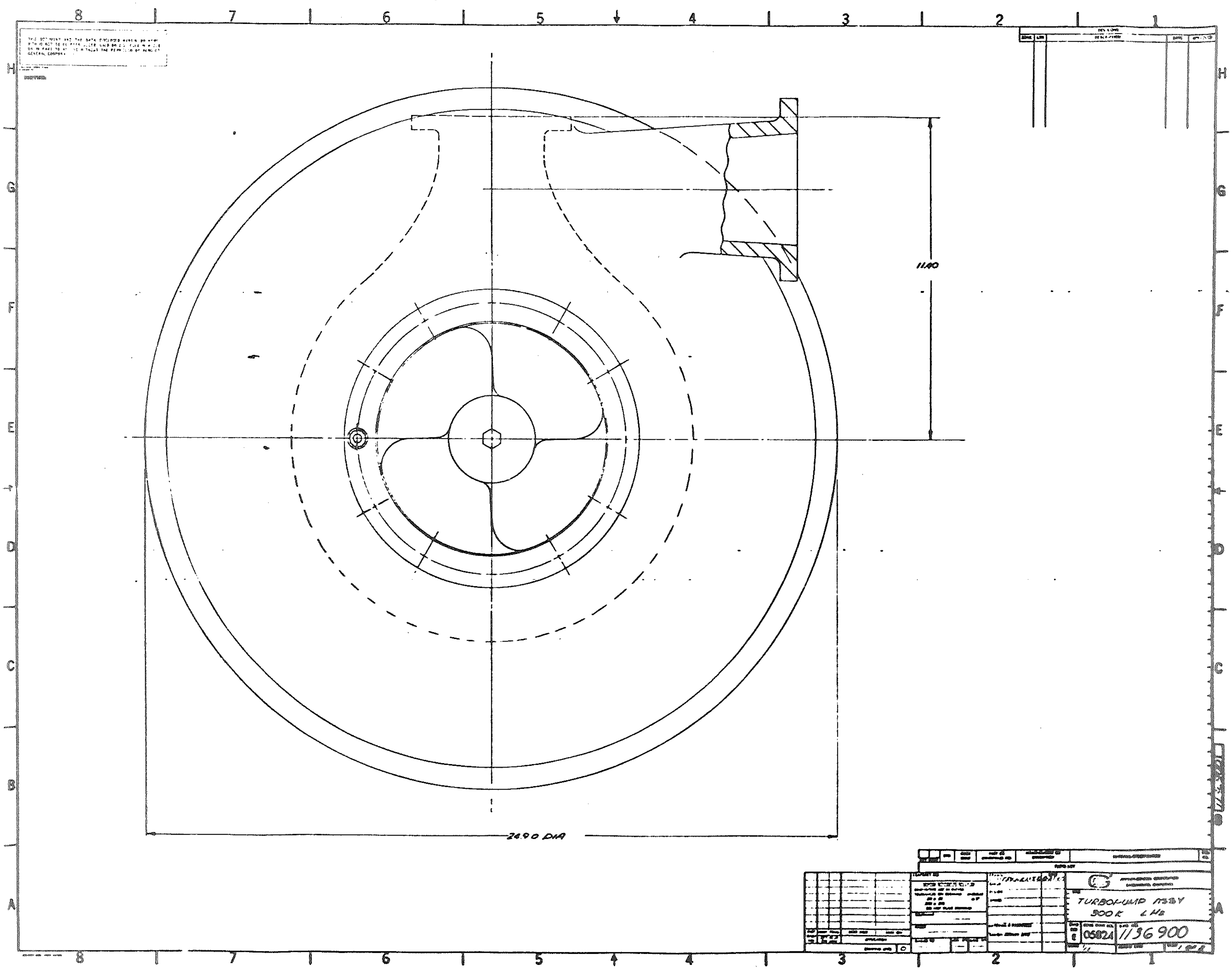


Figure 1. - LH_2 Turbopump Assembly (Sheet 1 of 2)

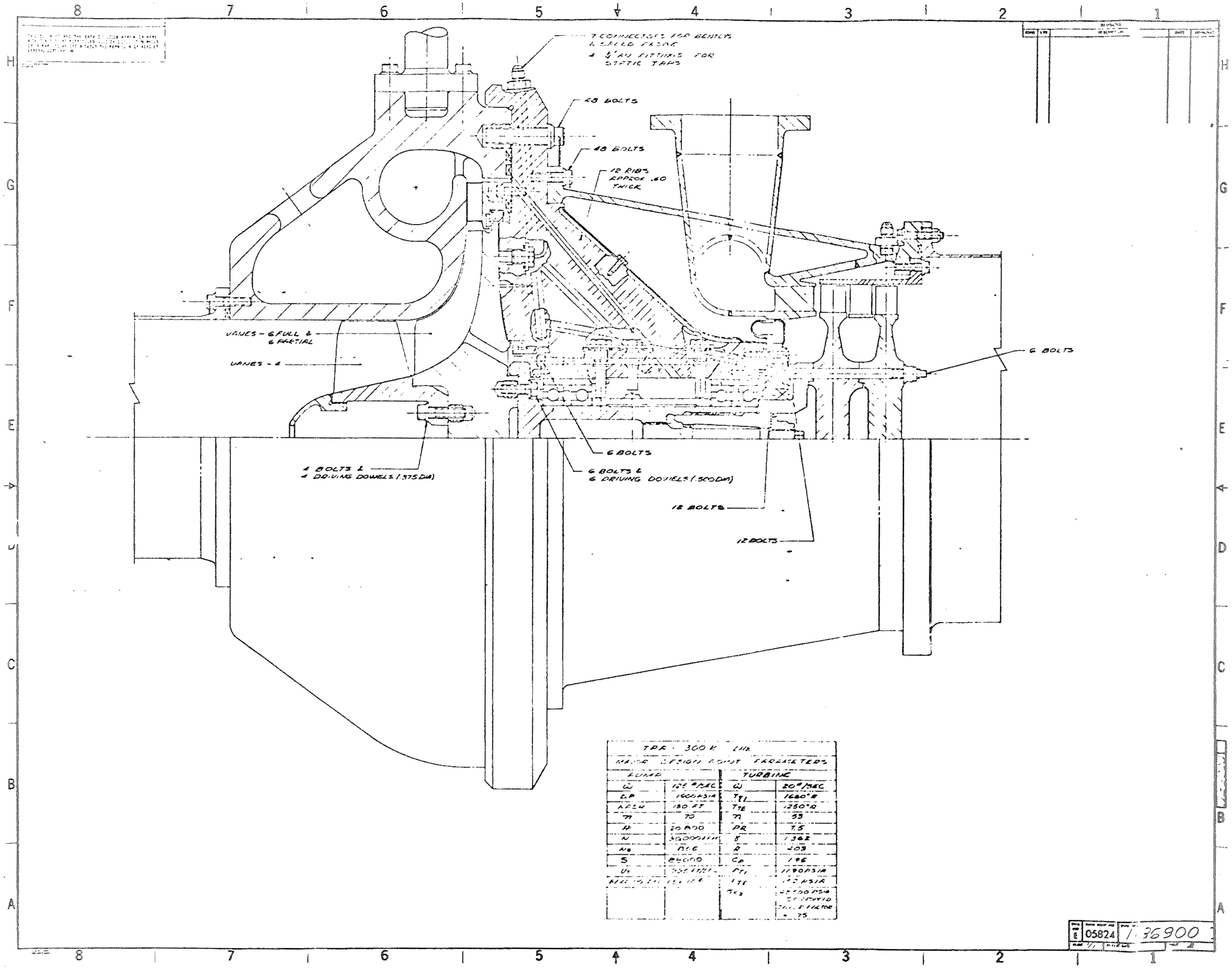


Figure 1. - LH_2 Turbopump Assembly (Sheet 2 of 2)

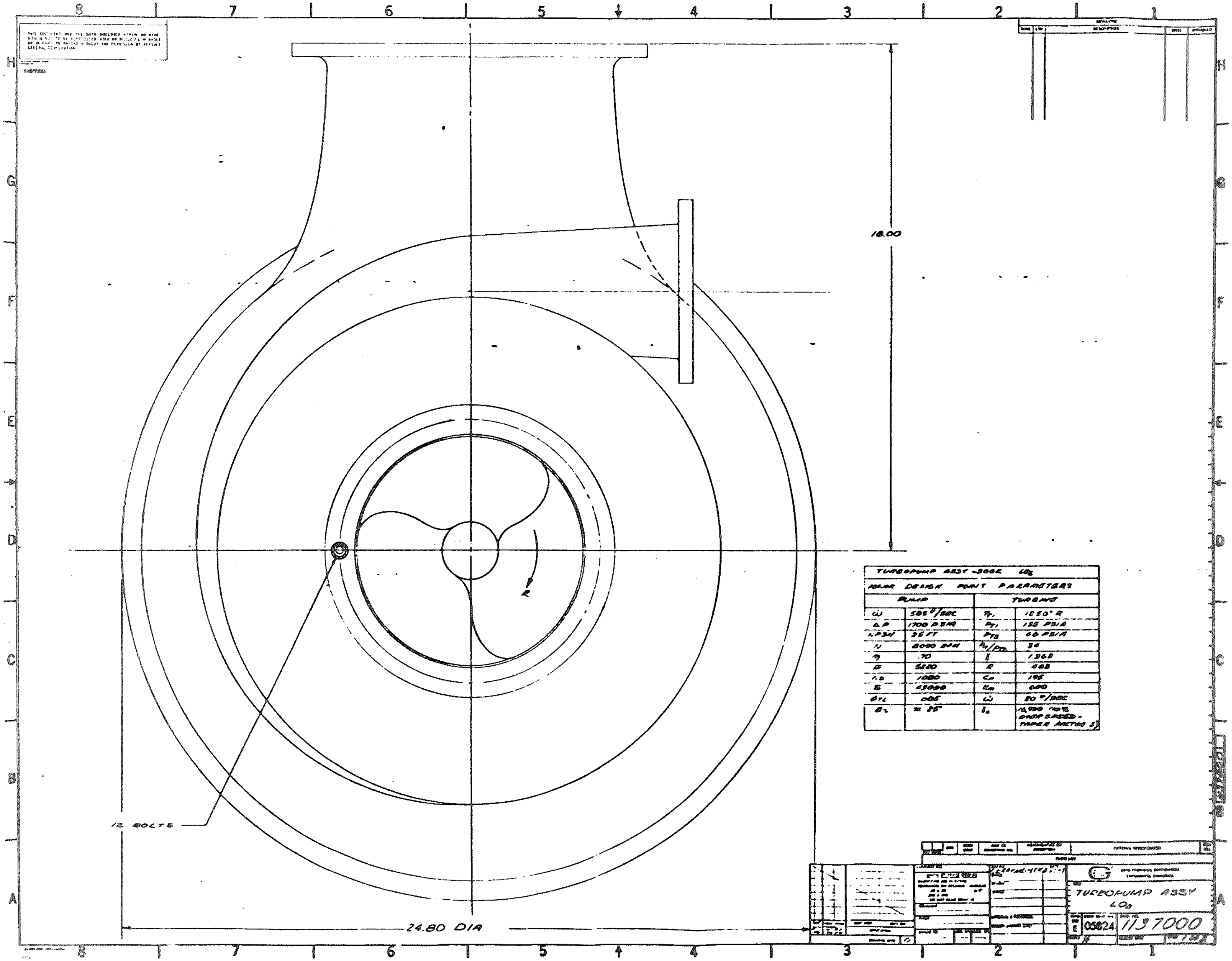


Figure 2. - LOX Turbopump Assembly (Sheet 1 of 2)

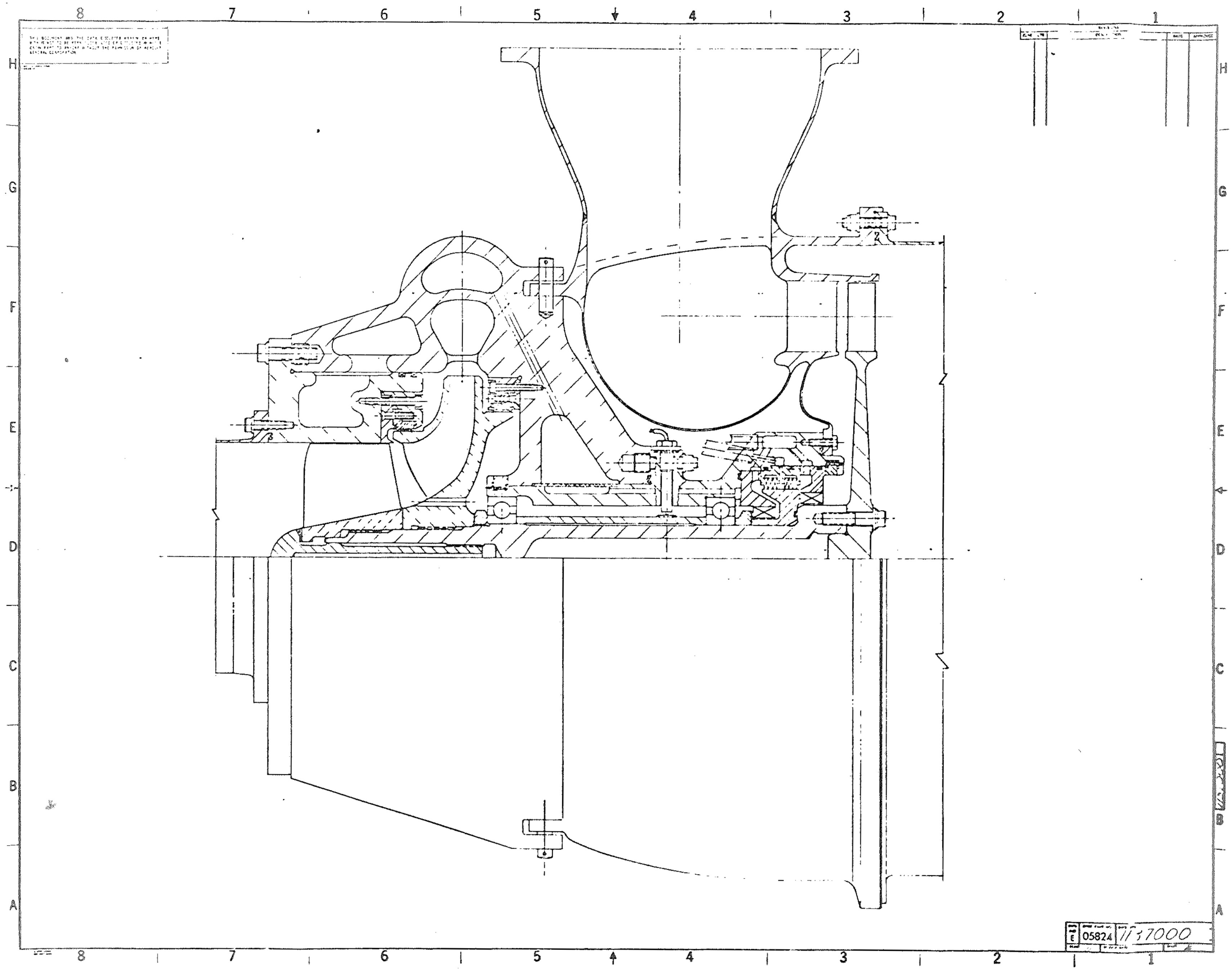


Figure 2. - LOX Turbopump Assembly (Sheet 2 of 2)

TABLE I. - BASE CASE REQUIREMENTS

Parameter	Requirement		
	Engine	Fuel Turbopump	Oxidizer Turbopump
Propellants	LOX/LH_2	LH_2	LOX
Application	MLLV (1/2 Size AMLLV)	-	-
Throttling	None	None	None
Startup	3 sec + Prechill	3 sec + Prechill	3 sec + Prechill
Duty Cycle	1 Start 300 sec	10 Starts/10 Hours	10 Starts/10 Hours
Reliability	0.97	0.998	0.998
Thrust	300,000 lb	-	-
Thrust Tolerance	$\pm$ 3%	-	-
Chamber Pressure	1200 psia	-	-
Chamber Pressure Tolerance	$\pm$ 1.5% (Control Value)	-	-
Specific Impulse	433 sec	-	-
Specific Impulse Tolerance	$\pm$ 3 sec	-	-
Mixture Ratio	5:1	-	-
Mixture Ratio Tolerance	$\pm$ 2.5%	-	-
Pump Pressure Rise	-	1900 psi	1700 psi
Pump Pressure Rise Tolerance	-	$\pm$ 3%	$\pm$ 3%
Pump Flow Rate	-	125 lb/sec	585 lb/sec
Pump Flow Rate Tolerance	-	Control Value	Control Value
NPSH	-	130 ft	25 ft
NPSH Tolerance	-	Minimum Value	Minimum Value
Turbine Inlet Pressure	-	1190 psia	135 psia
Turbine Pressure Ratio Tolerance	-	7.5	3.4
Turbine Pressure Ratio Tolerance	-	$\pm$ 2%	$\pm$ 2%
Turbine Flow Rate	-	20 lb/sec	20 lb/sec
Turbine Flow Rate Tolerance	-	$\pm$ 5%	$\pm$ 5%
Turbine Inlet Temperature	-	1660°R	1250°R
Turbine Inlet Temperature Tolerance	-	$\pm$ 250°	$\pm$ 180°
Static Seal Leakage	-	None	None
Dynamic Seal Leakage	-	0.05 lb/sec	0.05 lb/sec

TABLE II. - PRELIMINARY CHARACTERISTIC DIMENSIONS

Characteristic Dimension	Value	
	Fuel Turbopump	LOX Turbopump
Impeller Inlet Diameter (Tip)	8.40	8.14
Impeller Inlet Diameter (Hub)	3.20	2.03
Impeller Discharge Diameter	14.75	12.90
Impeller Port Height	0.58	0.81
Base Circle Diameter	15.50	14.00
Diffuser Height	0.62	-
Diffuser Width	1.40	-
Volute Size (max section equiv dia)	2.37	3.50
Turbine Inlet Size (max section equiv dia)	3.65	9.94
Rotor Mean Diameter	9.95	17.20
1st Rotor Blade Height	0.92	2.48
2nd Rotor Blade Height	1.05	-
1st Rotor Chord	0.86	0.96
2nd Rotor Chord	0.78	-

2. Identification/Categorization of Design Requirements

Design requirements at the vehicle, engine, and turbopump levels generally can be segregated into the two broad categories of performance requirements and operational/mechanical requirements. At the subcomponent or part level, where the design requirements can be manipulated to affect design, fabrication, and test operations costs, virtually all design requirements must ultimately be mechanical or dimensional even though they can stem from performance requirements. Early recognition of this led to the realization that vehicle, engine, and turbopump level variations in design requirements would result in an overwhelming number of subcomponent alternatives because of the many possible ways of meeting a given set of the higher order design requirements. Therefore, it was decided to select only a base case set of vehicle, engine, and turbopump requirements from which to generate base case turbopump subcomponent requirements. Variations in subcomponent design requirements then could be selected and their impact upon both performance and cost parameters assessed. Next, the effects of the subcomponent requirements changes could be iterated at that level to synthesize realistic designs and an optimum set of turbopump level design requirements.

3. Design Requirement Relationship to Cost Parameters, Turbopump/Vehicle Costs, and Over-All Costs

a. Cost Versus Design Requirements

This aspect of the study included consideration of all phases of development (design, fabrication, and testing) as well as production (design, fabrication, testing, and field maintenance).

Three major segments of information were needed to relate design requirement variations to over-all costs. These were to ascertain how design requirements influenced both component costs and component performance and thirdly, how component performance influenced over-all costs.

Information concerning how design requirements influence component costs and performance was generated as part of this study program. The influence of component performance upon over-all costs was extracted from existing data developed by the Boeing Company under Contract NAS 2-5056.

(1) Development Phase

The initial data developed was that for cost versus design requirements. In doing this, it was recognized that aside from reliability and schedule requirements the cost of design operations is relatively unaffected by design requirements. Additionally, no reasonable alternatives to the existing design methodology have presented themselves which will satisfy the mechanical reliability levels now needed to assure that essentially no flight or mission failure can occur during the life of the program. It is simply not possible to attain and demonstrate the required engine reliability by a test-fail-fix design/development philosophy within a reasonable (10 years or less) schedule. The implicit series flow of such a program, along with the known lead times for turbopump major subcomponents, makes it physically impossible to test even two alternative subcomponents to failure within the schedular restraint.

Failure mode analyses were performed for the base case fuel and oxidizer turbopumps to ascertain appropriate mean-time-to-failure for subcomponents. The results obtained were compared with historical Titan data using the necessary scale factors and good agreement was demonstrated.

Only schedular requirements variations were related to the cost of performing design operations because NASA interest does not extend to totally redundant and expendible weapons systems. Also, current space goals require that all design techniques be utilized in conjunction with one another rather than selecting one which appears to offer the lowest cost of executing the design at a possibly lower turbopump reliability. The schedular variations investigated included the currently used "semiparallel" design and development effort as well as a proposed "full series" approach. The overall schedular impact of these variations upon the base case and alternative program schedules was maintained.

Briefly, in the "full series" program, the following six subcategories make up the design task and each must be accomplished either during the proposal effort or in the contractual program.

<u>Subcategory 1</u>: Recognized existing technology design limits are established for pumps, seals, turbines, bearings, and structural materials.

<u>Subcategory 2</u>: Parametric analysis of individual subcomponent characteristics is made based upon the design limits established.

<u>Subcategory 3</u>: Design point is selected based upon a combination of the parametric analysis and the cost-contributing operations. This gives specifications for turbopump, engine, and vehicle performance levels and tolerances.

<u>Subcategory 4</u>: Conceptual and final design layouts along with supporting stress and performance calculations.

<u>Subcategory 5</u>: Detailed drafting (turbopump).

<u>Subcategory 6</u>: Subcomponent test article design and turbopump development fabrication release.

Although the above subcategories in themselves are similar to those of the "standard" design phase, they are accomplished sequentially and to a different degree of completion. Actually, the only schedule changes attributable to the "full series" approach occur in the development phase operations and result in an apparent delay of the turbopump qualification program of approximately three to six months. However, the design costs reveal that the "full series" approach offers a potential design cost saving of 8.7% or $340,000 for the reference program design phase costs. These savings are probably conservative for an actual program because of the greatly reduced likelihood of committing design errors, especially in the detail drafting operations.

Development fabrication operations costs are strongly dependent upon design requirements at the part or subcomponent level. The methodology followed in generating the data used in relating these costs to the requirements was to furnish conceptual sketches, similar sketches prepared for higher and lower NPSH requirements, the base case and alternative part level mechanical requirements listing, and actual part fabrication drawings of representative components selected from the Titan, NERVA, and M-1 programs to several typical aerospace and commercial subcomponent fabricators, including Aerojet-General's own shops. Cost estimates and manufacturing plans were requested at the cost-contributing operation level for virtually all turbopump subcomponents. All costs were requested in terms of both manhours and dollars for production quantities of one (pilot model), 10 (typical R&D order), 40 (initial production quantity), and more than 40 (production runs).

While the response to the requests for cost information was generally quite good, there were several notable exceptions. All of the commercial pump manufacturers contacted declined to quote anything other than over-all costs of producing the assembly, implying that their production methods are proprietary information. Also, several vendors declined to quote at any level below that of casting, machining, or welding.

A review of the raw (as received) data yielded one overwhelmingly significant fact. The commercial jobber's prices were significantly lower than the aerospace vendors as expected, but the apparent reason for the price differences was surprising. The hourly dollar rate charged for performing a given operation was for all practical purposes a constant for all vendors contacted, both aerospace and commercial, but the hours estimated to be required to complete an operation varied widely in direct contradiction to the expected result. It appears that commercial vendors do not fully understand the lost time implications of the quality control requirements usually imposed upon aerospace hardware. Also, these vendors largely are unfamilar with the difficulties associated with machining the higher strength materials typically used in rocket engine turbopumps.

The overwhelming conclusion is that a large body of the data collected during the course of this study was not useful in determining cost optimum requirements. Further, data interpretation was necessarily limited, for the most part, to that obtained from the typical aerospace vendors. Restricted use of the commercial vendor data was made where subcomponents could be fabricated from conventional strength materials and quality was easily controlled to the level required by reliability considerations. As a consequence, the requirements versus cost data were almost exclusively derived from estimates supplied by accredited aerospace vendors as well as Aerojet historical records. Significant fabrication operations were reduced to fuel and oxidizer subcomponent. Cost versus NPSH/size data were evolved for several representative fuel and oxidizer subcomponents. Turbopump unit cost versus NPSH/size data also were generated.

Development test operations costs are not strongly dependent upon any requirements other than schedule and reliability for the class of machinery investigated in this study where the technology to execute a successful design clearly exists. As in the case of the design operations, the reliability levels required to assure that essentially no flight or mission failures can occur dictates that only the most rigorous development philosophy be used. Again, it is not possible, within a reasonable schedular restraint of 10 years or less, to attain or demonstrate the required reliability without utilizing the full depth of every known turbopump development technique. Accordingly, only one development test plan was formulated and costed as an implement for determining over-all program cost.

(2) Production Phase

Design operations during the production phase of a high reliability rocket engine turbopump must be limited to those required for performance-oriented modifications (to satisfy changing engine requirements) and to mechanical feature modifications (to satisfy life/reliability requirements under unanticipated flight environments). Any redesign for ease of production would invalidate the results of the development/qualification program. Therefore, production phase design operations are not a definable function of design requirements and cost studies were limited to definition of the design manpower required to make the types of modifications indicated.

In keeping with the philosophy that the production turbopumps must be identical to those qualified, production phase fabrication operations were related to design requirements in exactly the same manner as development fabrication operations. All cost estimates were prepared under the assumption of high volume production and the tooling costs reflected that assumption. Production lot sizes larger than 40 to 50 were not specifically investigated but discussions with contributing suppliers indicated no significant change in cost would occur within the range from 50 to 100 units. Some significant additional reduction might occur in the range from 100 to 1000 units, but it did not appear that the reference application program would approach this number at the time the estimates were prepared.

Production phase test operations can be divided into five subcategories and operations. These are subcomponent level tests (rotor proof spin tests and housing proof pressure tests), component level tests (pump calibration and turbine calibration), turbopump level tests (acceptance tests post-test checkout, and post-test inspections), engine level tests (engine acceptance tests, post-test checkout, and post-test inspections), and stage level tests (flight readiness tests, post-test checkout, and post-test inspections).

The MLLV Program ground rule requirements of engine acceptance test and stage static test firing eliminated the last two subcategories from consideration. Therefore, the optimum method for performing the production phase test operations is that combination of the first three subcategories which will sustain the performance and reliability requirements at the lowest cost. Past programs generally have utilized elements of all three levels of tests to assure that the requirements were met. Consequently, little data exists to support the elimination of entire subcategories. However, the bulk of the test cost is incurred during the turbopump level acceptance tests and checkout. Therefore, programs including as well as omitting these tests were studied.

It was found that a program plan wherein the formal turbopump acceptance tests are eliminated actually defers the mechanical and performance checkout of the turbomachinery until the engine level acceptance tests. Titan and Gemini engine production test program results offer some evidence that such an approach is feasible. The negligibly low assembly error incidence achieved in those programs virtually eliminated the necessity to verify the turbopump mechanical integrity by a hot firing test of the turbopump alone. However, the hydraulic and aerodynamic performance data obtained during a turbopump acceptance test serves as prime input for the initial engine trim or calibration. Attempts to trim the engine based upon nominal turbopump performance levels often resulted in unacceptable thrust or mixture ratio conditions. The variations in turbopump hydraulic and aerodynamic performance which must be accounted for in the engine trim are related to the subcomponent design requirements. This dependency of acceptance test and engine trim requirements upon subcomponent design requirements was not recognized early enough in the study. Therefore, only minimal useful data were obtained at the more stringent requirements that are necessary to reduce component performance scatter to a level which would allow initial engine trim to be made accurately without first calibrating (acceptance test firing) the turbopump. The subcomponent cost data generated can be extrapolated to more stringent requirement levels but the performance analysis was not extended over a sufficient range to allow definition of requirements levels where calibration would not be needed. For the purposes of developing the study objective of cost optimization methodology, it was assumed that the most stringent requirement/performance levels studied corresponded to the level where calibration can be eliminated. This approach merely serves to illustrate the technique which would be used in an actual production program.

The cost of the production phase test operations for the program alternative described above would be reduced from the base case program by the entire turbopump acceptance test manpower costs as well as the propellant costs for the 60 unit-per-year production rate. The higher production rate alternatives would result in those same savings plus the additional facility activation cost savings.

The field maintenance operations related to turbopumps normally are limited to periodic seal checks, periodic rotor torque checks, interface static seal replacement, and turbopump removal as well as replacement in the engine. These operations are performed to assess and provide any necessary remedies for the mechanical integrity or the performance (in terms of lost propellant) of the system. In the subject study, no way was found by which the cost of the mechanical integrity (torque) checks or resulting replacement operations could be traded with design requirement variations. However, the seal checking costs can be weighed against leakage requirements variations at two technological levels; all seals can be checked or those which are actually controlled leakage devices (i.e., labyrinths) can be excluded from the check. Seals are subject to handling/shipping damage while labyrinths are not. There is an obvious cost difference for field servicing the two types of machines. Titan/Gemini records show that 93 manhours-per-seal-per-check were expended, upon apportioned historical field service costs, and only two hours-per-seal were required, based upon apportioned historical post-fire inspection costs at the engine contractor's facility. The large discrepancy between the two can be partially attributed to the increased complexity of performing the check in the engine and stage, but the major difference appears to result from the need to maintain the checking capability during periods of inactivity.

b. Design Requirements Versus Component Performance

The base case component arrangement of series flow turbines and the turbopump configurations of single-stage centrifugal pumps, two-stage axial flow turbine, and single-stage axial flow LOX turbine strongly influence the relative worth of fuel turbopump versus LOX turbopump subcomponent performance in terms of engine specific impulse degradation through their effect upon gas generator or turbine flow rate. Ideally, the minimum turbine flow rate would occur when fuel and LOX turbopump component performances are balanced in a way that the required fuel and LOX turbine flow rates are exactly equal at the optimum turbine pressure ratio division. In practice, component performance variations from the nominal require that one turbopump performance be biased such that the turbine pressure ratio split can be varied to adjust the input power balance. Usually, this is accomplished by either by-passing some of the turbine flow around the highest performance system or by adding a control pressure drop between the turbines. The base case designs are such that the fuel turbopump establishes the turbine flow rate requirement at a value 5% to 10% higher than that required by the LOX turbine to allow for the control pressure drop.

The relative engine performance (I_{sp}) degradation contribution of fuel and oxidizer turbopumps is, therefore, a complex function of turbine pressure ratio and flow rate. The problem can be simplified to a manageable level by using the following assumptions:

- Similar performance changes can be made simultaneously in both fuel and LOX turbopumps.

- Such changes will always be made in the same (either improving or degrading performance) direction.

- Performance improvements or degradations of fuel and LOX turbopump alternatives are equal in terms of the turbine flow rate effect upon specific impulse.

It is recognized that these assumptions are not necessarily valid, but a comprehensive systems analysis defining the actual relative weighting factors was beyond the scope of the study. Thus, these assumptions allowed definition of the cost optimization methodology to proceed. A more rigorous systems analysis would be required for any future program using the methodology developed here.

The above reasoning allowed determination of the effect of design requirements variations upon component performance to proceed almost independently for the fuel and LOX turbopump subcomponents. It was not necessary to select complete propellant feed system level alternatives for study.

In the case of the pumps, dimensional variations up to and in excess of commonly specified tolerance bands were investigated to determine the resulting effects upon over-all pump efficiency and head rise. The surface quality or surface finish of important flow passages was varied over a wide range to assess friction losses and resulting effects upon pump performance. These effects were investigated for both the oxidizer and fuel pump because of the characteristically different concept and method of fabrication between these pumps.

The LOX and fuel turbine designs were evaluated to determine the effects of mechanical design requirements upon the gas flow rate needed. Surface finish and dimensional control of the flow passages were varied over a wide range to obtain performance effects. The design speed of the turbines was varied by a ratio exceeding 2 to accommodate a constant pump suction specific speed. The resulting changes in tip diameter, blade height, and gas flow rate are noteworthy. Effects were investigated for both LOX and fuel turbines because they are characteristically different in concept.

The LOX and fuel turbopump designs then were evaluated to determine the effect of NPSH upon turbopump weight. Detailed weight estimates were prepared for three levels of required NPSH for both the LOX and fuel turbopumps.

c. Component Performance Versus Engine Performance

While all of the data discussed can readily be used to relate mechanical design requirements and cost variations to performance in terms of turbine flow rate or bleed ratio, it was still necessary to relate turbine flow rate to engine performance. The basic engine data used in the study were:

Engine Vacuum Thrust	-	300,000 lb
Thrust Chamber Pressure	-	1200 psia
Engine Mixture Ratio	-	5.0
Nozzle Area Ratio	-	50

For series flow turbines with the fuel turbine preceding the oxidizer turbine, the following nominal data were used:

Parameter	Fuel Turbine	Oxidizer Turbine
Inlet Pressure, psia	1190	135
Exit Pressure, psia	152	40
Inlet Temperature, °R	1660	1250
Efficiency, %	53	28
Flow Rate, lb/sec	20	20

In addition to the nominal point investigation, the turbine flow rate was varied arbitrarily to determine the effect upon engine performance. The results of this analysis show that the reduction in engine specific impulse with increasing turbine flow rate is caused by two major factors. Increasing the turbine flow rate causes increases in the thrust chamber mixture ratio which result in reduced theoretical specific impulse. This loss is in addition to the loss associated with dumping a higher percentage of the engine flow inefficiently overboard through a turbine exhaust nozzle.

Fuel turbine inlet temperatures of 1960°F and 2460°R also were investigated. Oxidizer turbine inlet temperatures were calculated assuming a constant fuel turbine pressure ratio. The nominal turbine flow requirement for the increased inlet temperatures was adjusted accordingly for the higher energy drive fluid. Also, the effect of variations in this turbine flow rate upon nominal engine performance was determined. For fixed pressure ratio turbines with constant efficiencies, increasing the turbine inlet temperature results in reduced turbine weight flow requirements and hence, higher engine specific impulse.

The data generated then were utilized in conjunction with turbopump performance calculations to formulate the engine specific impulse influence coefficients shown below. It should be noted that only the turbine flow rate and turbine inlet temperature coefficients are independent partial derivities. Also, the pump and turbine efficiency coefficients are derived from the flow rate coefficient and linearized base case turbopump performance curves.

Coefficient	Value
Turbine Flow Rate	0.296 sec/lb/sec
Turbine Inlet Temperature	0.003 sec/°F
Pump Efficiency	0.086 sec/point
Turbine Efficiency	0.114 sec/point

d. Component Performance Versus Over-All Cost

The third and final major segment required in developing the cost optimization methodology was the relationship between component performance and over-all costs. The Boeing Company had recently completed a major cost versus performance study (Contract NAS 2-5056) for the referenced MMLV missions and the published data were utilized in the Low Cost Turbopump Study because of the applicability of the MMLV mission requirements. However, in any future program wherein the optimization methodology developed herein is used for a different mission, it will be necessary to conduct mission level studies to define the cost versus performance relationships in a manner similar to that done for the mission considered in this study. While it is recognized that extensive over-all cost studies of this type represent significant expenditures in both time and money, no reasonable alternative to this procedure now exists.

e. Fixed Costs

All development and production phase design costs can be considered to be fixed for any particular schedule requirement because of their insensitivity to design requirements at the performance and reliability levels of interest. However, for the purposes of this study, they were considered a variable function of the turbopump qualification schedule.

All fabrication and assembly facilities costs (i.e., machine tools, assembly clean room, part storage, part cleaning, part balancing, and proof test) as well as facilities and maintenance costs are considered to be fixed. They are not included in the data shown for this study, except as they influence applicable overhead rates. Special fabrication tool costs are considered to be variable functions of the requirements, but generally, no variation in cost was noted over the range of requirements investigated.

Test facilities construction costs are considered to be fixed and were not included in the study. Facilities activation costs are variable functions of schedular requirements in that they are dependent upon the number of facilities requiring activation.

4. Synthesis of Design Requirements to Yield Minimum Over-All Costs

The technique used in Task I to quantify the relationship of requirements to turbopump cost parameters, vehicle cost parameters, turbopump cost, vehicle cost, and over-all nonrecurring cost is digested below:

Step 1: Establish vehicle/engine design requirements "base values."

Step 2: Select turbopump "base" configuration.

Step 3: Categorize turbopump design requirements.

Step 4: Establish turbopump "base" value design requirements.

Step 5: Establish the variation of turbopump design requirements.

Step 6: Determine turbopump cost parameters (i.e., manhours) as a function of design requirements including all turbopump cost-contributing operations (i.e., part fabrication, assembly, and inspection).

Step 7: Prepare graphical displays of each major turbopump cost parameter for each turbopump design requirement influencing the cost.

Step 8: Determine the linear cost function of cost versus hourly manhours and salary manhours for various turbopump operations activities.

Step 9: Determine turbopump operation cost for each turbopump design requirement by applying the linear cost function to cost parameters.

Step 10: Prepare graphical displays illustrating the influence of design requirements upon subcomponent and component performance.

Step 11: Determine the effect of component performance upon engine performance.

Step 12: Define the linear effect of engine weight and performance upon over-all program costs.

Step 13: Establish turbopump functional assembly level alternative requirements groups and tabulate cost as well as performance in terms of engine I_{sp} variation.

Step 14: Tabulate over-all cost versus requirements groups.

Step 15: Select cost optimum requirements group.

Step 16: Select cost optimum subcomponent requirements from functional assembly level grouping.

B. TASK II - EXAMINATION OF COST-CONTRIBUTING OPERATIONS

Task II also was divided into four subtasks. The technological level of cost-contributing operations was examined, followed by an examination of the types of operations. Next, the most significant operations in terms of program costs were selected and alternative operations were evaluated. Finally, the operations for technology development were selected. All but the last of these subtasks were conducted in conjunction with the identification and categorization of the cost-contributing operations and the ascertaining of the relationship of variations in design requirements to cost-contributing operations, turbopump/vehicle costs, and over-all costs in Task I. The results of these subtask efforts are summarized on Table III, which provides a clear picture of what cost-contributing operations categories are responsible for the major turbopump costs. As would be expected in any high production program, the production phase fabrication and turbopump level test operations costs completely overshadow all others. In research and development type programs with relatively few launches or vehicles with a minimal number of engine modules, increased importance is placed upon the development phase operations.

Consequently, the Task II effort was directed toward investigating alternative fabrication and test technological levels as well as types that would be applicable to either development or production phase operations. Little reduction in fabrication costs is available from changes in the technological level because "commercial" technology either is not able to sustain even the minimum requirements postulated or the "commercial" costs are identical to the "aerospace" costs. However, the types of operations offer significant potential for fabrication cost savings. The technology needed to obtain these savings currently is available and should be utilized in future programs.

The investigators were unable to define alternative test operations technologies which would permit turbopump calibration to satisfy engine balance requirements. This resulted largely because of the extensive facilities required merely to operate a large turbopump. If engine balance requirements can be relaxed sufficiently or if the turbopump performance variations from unit to unit can be minimized, the type of testing can be changed from hot firings to either air flow tests or even be completely eliminated.

Thus, the sole result of the Task II effort is the recommendation that the possibility of eliminating the turbopump calibration/acceptance tests be eliminated, especially for production phase operations.

TABLE III. - TECHNOLOGICAL LEVEL AND SIGNIFICANCE OF COST-CONTRIBUTING OPERATIONS

Operations	Technological Level		Type		Significance (% Turbopump Program Cost)	Requires Technology Development
	Base	Alternative	Base	Alternative		
DEVELOPMENT PHASE						
DESIGN OPERATIONS						
1. Analysis	Aerospace	None	Manual and Computerized	Manual Only	1.23	No
a. Hydraulic/Aerodynamic Performance						
b. Hydraulic/Aerodynamic Loads						
c. Thermal Conditions						
2. Mechanical Design						
a. Critical Speed Determination	Aerospace	None	Manual and Computerized	Manual Only		
b. Structural Analysis						
(1) Static Stress/Deflection Analysis						
(2) Inertia Stress/Deflection Analysis						
(3) Dynamic Stress/Deflection Analysis						
(4) Thermal Stress/Deflection Analysis						
c. Drafting						
(1) Layouts						
(2) Part Fabrication Drawings						
(3) Assembly Processing Drawings						
d. Checking						
3. Fabrication Follow-Up	Aerospace	None	Manual and Computerized	Manual Only		
4. Test Planning and Follow-Up	Aerospace	None	Manual	None		

TABLE III. - TECHNOLOGICAL LEVEL AND SIGNIFICANCE OF COST-CONTRIBUTING OPERATIONS (cont.)

Operations	Technological Level		Type		Significance (% Turbopump Program Cost)	Requires Technology Development
	Base	Alternative	Base	Alternative		
DEVELOPMENT FABRICATION OPERATIONS	Aerospace	Commercial			0.58	Yes Selected Part Operations
1. Advance Vendor Quotes/Consulting						
2. Procurement Processing/Planning						
3. Tooling Fabrication						
4. Rawstock Procurement						
5. Casting or Forging	See Detailed Part by Part Discussion in Section III,A, Appendices H and I, and Figures No. 11 through No. 62.					
6. Machining						
7. Welding						
8. Subassembly						
9. Assembly						
10. Inspection						
11. Shipping						
DEVELOPMENT TEST OPERATIONS						
1. Subcomponent Test (Part or Feature Level)					0.25	No
a. Subcomponent Proof Tests						
(1) Rotor Proof Tests	Aerospace	None	Spin Tests	Eliminate		
(2) Housing Proof Tests	Aerospace	Commercial	Pressure Tests	Eliminate		
b. Subcomponent Integrity Evaluation						
(1) Vibration Characteristics Definition	Aerospace	Commercial	Vibration Tests	Eliminate		No
(2) Housing Burst Pressure	Aerospace	Commercial	Pressure Tests	Eliminate		
(3) Rotor Burst Speed	Aerospace	Commercial	Spin Tests	Eliminate		
(4) Bearing Life Tests	Aerospace	Commercial	Rotating-Loaded	None		No

TABLE III. - TECHNOLOGICAL LEVEL AND SIGNIFICANCE OF COST-CONTRIBUTING OPERATIONS (cont.)

Operations	Technological Level		Type		Significance (% Turbopump Program Cost)	Requires Technology Development
	Base	Alternative	Base	Alternative		
DEVELOPMENT TEST OPERATIONS (cont.)						
2. Component Tests (Subassembly Level)					0.28	No
a. Pump Performance Evaluation	Aerospace	Commercial	Simulant Pumping Tests	Eliminate		
b. Power Transmission Performance Evaluation	Aerospace	Commercial	Rotating Propellant	Eliminate		
c. Turbine Performance Evaluation	Aerospace	Commercial	Dynamometer	Eliminate		
3. Turbopump Development Tests					1.95	No
a. Performance Evaluation	Aerospace	None	Hot Firings	None		
b. Life/Reliability Evaluation	Aerospace	None	Hot Firings	None		
c. Malfunction Survival Evaluation	Aerospace	None	Hot Firings	None		
4. Turbopump Acceptance Tests (For R&D Engines)	Aerospace	Commercial	Hot Firings	Eliminate	0.32	Yes
PRODUCTION PHASE						
DESIGN OPERATIONS					0.74	No
1. Performance Modifications	Aerospace	None	Not Applicable	Not Applicable		
2. Mechanical Modifications	Aerospace	None	Not Applicable	Not Applicable		
PRODUCTION FABRICATION OPERATIONS	Aerospace	Commercial			42.4	Yes Selected Part Operations
1. Procurement Processing/Planning						
2. Tooling Fabrication						
3. Rawstock Procurement						
4. Casting or Forging	See Detailed Part by Part Discussion in Section III,A, Appendices H and I, and Figures No. 11 through No. 62.					
5. Machining						
6. Welding						
7. Subassembly						
8. Assembly						
9. Final Assembly (Engine)						

TABLE III.- TECHNOLOGICAL LEVEL AND SIGNIFICANCE OF COST-CONTRIBUTING OPERATIONS (cont.)

Operations	Technological Level		Type		Significance (% Turbopump Program Cost)	Requires Technology Development
	Base	Alternative	Base	Alternative		
PRODUCTION FABRICATION OPERATIONS (cont.)						
10. Inspection						
11. Storage						
12. Shipping						
PRODUCTION TEST OPERATIONS					39.62	
1. Subcomponent Level Tests					0.12	
a. Rotor Proof Tests	Aerospace	None	Spin Tests	Eliminate		
b. Housing Proof Tests	Aerospace	Commercial	Pressure Tests	Eliminate		
2. Component Level Tests						
a. Pump Calibration	None	Aerospace	None	Analytical	0.0	Yes
b. Turbine Calibration	None	Aerospace	None	Analytical		
3. Turbopump Level Tests					39.50	Yes
a. Acceptance Tests	Aerospace	None	Hot Firing	Eliminate		
b. Post-Test Checkout and Inspections	Aerospace	None	Leak and Torque Checks	Eliminate		
4. Engine Level Tests					Excluded	-
a. Engine Acceptance Tests	Aerospace	None	Hot Firing	None		
b. Post-Test Checkout and Inspections	Aerospace	None	Leak and Torque Checks	None		
5. Stage Level Tests					Excluded	-
a. Flight Readiness Tests	Aerospace	None	Leak and Torque Checks	None		
b. Post-Test Checkout and Inspections	Aerospace	None	Leak and Torque Checks	None		

TABLE III. - TECHNOLOGICAL LEVEL AND SIGNIFICANCE OF COST-CONTRIBUTING OPERATIONS (cont.)

Operations	Technological Level		Type		Significance (% Turbopump Program Cost)	Requires Technology Development
	Base	Alternative	Base	Alternative		
FIELD MAINTENANCE AND REPAIR OPERATIONS					12.63	No
1. Seal Checks	Aerospace	None	Pressure Test	Eliminate		
2. Seal Replacement (Interfaces)	Aerospace	None	Manual	Eliminate		
3. Torque Checks	Aerospace	None	Manual	Eliminate		
4. Removal and Replacement	Aerospace	None	Manual	None		

C. TASK III - CONCEPTUAL DESIGN

1. Turbopump Pre-Design and Mission, Vehicle, and Engine Trade-Offs

The mission, vehicle, and engine trade-off studies, together with the detailed subcomponent analyses and optimizations form integral parts of the conceptual design. A half-size version of an Advanced Multipurpose Large Launch Vehicle (AMLLV) with a payload capability to low earth orbit of 500,000 lb was selected as a representative reference design case to serve as the basis for optimization. This resulted in the following definition of design characteristics:

Symbol	Characteristic	Value	
		Fuel Turbopump	LOX Turbopump
ΔP	Pump Pressure Rise	1900 psi	1700 psi
$\dot{w}_p$	Pump Flow Rate	125 lb/sec	585 lb/sec
P_{Ti}	Turbine Inlet Pressure	1190 psia	135 psia
T_{TT}	Turbine Inlet Temperature	1660°R	1250°R

Qualitative consideration of the mission/vehicle interactions revealed a strong dependency upon aerodynamic and hydraulic performance of both the turbine and pump. The weight and length of the turbopump became somewhat secondary effects. It was found that the basic, separate turbopump configurations which best served as a basis for generating performance characteristics and investigating mechanical design constraints while offering a reasonable compromise between performance and weight effects incorporated overhung centrifugal pumps. The fuel pump would be driven by a two-row, Curtis, staged, overhung turbine operating in series with a single-stage oxidizer impulse turbine.

The conceptual designs of machines of this type were completed in sufficient depth to demonstrate the cost optimization methodology. Additionally, supporting optimization studies were completed which served to either confirm the basic configuration tentatively selected or permitted modification of the initial configuration to evolve an optimum turbopump for the reference engine.

2. Turbopump Optimization and Mechanical Design

Contractually negotiated funding restraints precluded the accomplishment of detailed turbopump optimizations and mechanical design. However, plans detailing such optimization were completed.