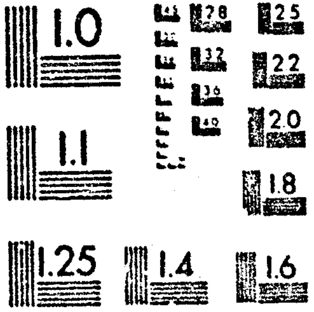
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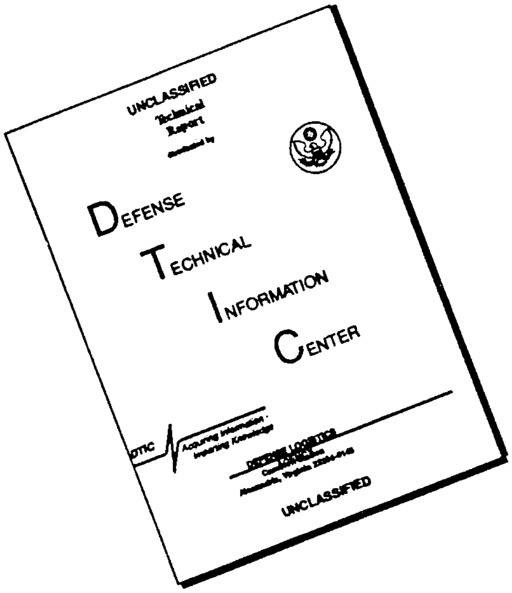

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Final Report

by

D. C. Judd
Aerojet Liquid Rocket Company

Prepared For

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

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16. Abstract

The major objectives of this study were to (1) determine the extent to which composite materials can be beneficially used in liquid rocket engines, (2) identify additional technology requirements, and (3) determine those areas which have the greatest potential for return. The assessment was based primarily on weight savings but also considered material and fabrication costs, performance, life, and maintainability factors. Two baseline designs, representative of earth-to-orbit and orbit-to-orbit engine systems, were selected for analysis. All components of these baseline designs were evaluated to determine which could benefit most from fabrication with composites. Weight savings from 50 to 80% were predicted for selected components with the substitution of reinforced plastic composite (RPC) materials for metal, and overall engine weight savings from 25 to 30% were found possible. Various technology needs were identified before RPC material could be used in rocket engine applications, and follow-on activities addressing these needs were proposed. Metallic or ceramic composites offered advantages in high-temperature or performance-driven applications but otherwise were not competitive to RPC on the basis of weight or cost.

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FOREWORD

The work described herein was performed at the Aerojet Liquid Rocket Company under NASA Contract NAS 8-34623, with Mr. Dennis Gosdin, NASA-Marshall Spaceflight Center, as project manager. The ALRC program manager was Mr. Roy Michel, and the project engineer was Mr. Craig Judd. ALRC material engineering specialists for the study were Mr. George Janser and Mr. Ed Carter.

The technical period of performance for the study was from 24 February 1982 to 30 November 1982.

The following individuals contributed significantly to this report:

Fred Fischietto (Structural Analysis)
Ralph Shultz (Drafting)
Craig Judd (Project Engineering)
George Janser (Materials Analysis)
Ed Carter (Materials Analysis)
Chuck O'Brien (Engine Systems)

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TABLE OF CONTENTS

		Page
I.	Summary	1
	A. Study Objectives and Scope	1
	B. Results and Conclusions	3
II.	Introduction	12
	A. Background	12
	B. Purpose and Scope	13
	C. Approach	13
	D. Program Schedule and Major Mileposts	15
III.	Task I - Baseline Engine Configurations	17
	A. Objectives	17
	B. Engine Selections	17
	C. Component Requirements Data Sheets	42
IV.	Task II - Component Assessment and Identification	48
	A. Objectives	48
	B. Composite Properties and Fabrication Processes	48
	C. Methodology and Evaluation Form	54
	D. Component Selection	54
V.	Task III - Conceptual Design Assessment	65
	A. Objectives	65
	B. Stress Analysis	65
	C. Final Drawings and Weight Estimates	65
	D. Outside Vendor Design Input Concerning Reinforced Plastic Composites	78
	E. Outside Vendor Design Input Concerning Metal Matrix Composites	81
VI.	Task IV - Criticality Ranking of Technology Needs	84
	A. Objectives	84
	B. Technology Needs	84
	C. Criticality Ranking of Technology Needs	92

TABLE OF CONTENTS (cont.)

Page

VII. Task V - Recommended Tasks 93
A. Objective 93
B. Recommendations 93
C. Program Plans for the Selected Components 94
VIII. Conclusions and Recommendations 119
A. Conclusions 119
B. Recommendations 120
References 121
Appendices
A. Component Requirement Forms A-1
B. Reinforced Plastic Composite Properties B-1
C. Metal Matrix Composite Properties C-1
D. Task II Evaluation Forms D-1
E. Vendor Trip Memos E-1
F. Technology Needs Definition Forms F-1

LIST OF TABLES

Table No.		Page
I	Technology Needs Cross-Reference Chart	5
II	Advanced Expander Cycle Engine Weight Data	29
III	LOX/LCH$_4$ Cycle C Engine Weight Data	43
IV	Task II Evaluation Form	55
V	Task II Selected Components	63
VI	Component Metallic Weight Versus Composite Weight	79
VII	Outside Vendors Consulted	80
VIII	Plastic Matrix Versus Metal Matrix Comparison Chart	83
IX	Technology Needs Listing	85
X	Design and Analysis Steps for Recommended Parts	94

LIST OF FIGURES

Figure No.		Page
1	Overall Study Program Summary	2
2	OTV Valve Housing	7
3	LCH_4 TPA Impeller Housing	8
4	OTV Nozzle Extension Shaft	9
5	OTV Skirt Support Ring	11
6	Major Milestone Schedule	16
7	OTV Engine Layout	18
8	Igniter/Injector Assembly (ALRC Drawing No. 1191990)	21
9	Chamber and Tube Bundle Nozzle (ALRC Drawing No. 1191991)	22
10	LO_2 Boost Pump (ALRC Drawing No. 1191994)	23
11	LO_2 Boost Pump (ALRC Drawing No. 1191996)	24
12	LH_2 TPA (ALRC Drawing No. 1191997)	25
13	LO_2 TPA (ALRC Drawing No. 1191999)	26
14	Shutoff Valve (ALRC Drawing No. 1193176)	27
14A	OTV Flow Schematic	28
15	LOX/LCH_4 Engine Layout	33
16	High-Speed LCH_4 TPA	35
17	High-Speed LOX TPA	36
18	Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed RP-1 TPA	37
19	Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed LOX TPA	38
20	Alternate Mode 1 Gas Generator Cycle Engine Thrust Chamber Injector	39
21	Alternate Mode 1 Coaxial Gas Generator	40
21A	LOX/LCH_4 Engine Flow Schematic	41
22	Sample "Component Requirements" Form	47
23	Task II Schematic	49
24	Fabrication Processes	50
25	Reinforcement Characteristics	51

LIST OF FIGURES (cont.)

Figure No.		Page
26	Matrix Characteristics	52
27	Properties of Various Composites	53
28	Detailed Description of Task II Evaluation Form	57
29	LCH_4 High-Speed TPA (ALRC Drawing No. 1196001)	66
30	High-Speed LOX TPA (ALRC Drawing No. 1196002)	67
31	LOX Low-Speed TPA (ALRC Drawing No. 1196003)	68
32	Support Structure - Throat, Combustion Chamber (ALRC Drawing No. 1196004)	69
33	Seat - Gimbal Bearing (ALRC Drawing No. 1196005)	70
34	Shaft - Nozzle Extension (ALRC Drawing No. 1196006)	71
35	Injector Housing (ALRC Drawing No. 1196007)	72
36	Support Ring - Skirt Extension (ALRC Drawing No. 1196008)	73
37	Jacket - Tube Bundle, Nozzle (ALRC Drawing No. 1196009)	74
38	Manifold - Coolant, Thrust Chamber (ALRC Drawing No. 1196010)	75
39	Housing - Valve, Propellant (ALRC Drawing No. 1196011)	76
40	Gear - Actuator, Valve (ALRC Drawing No. 1196012)	77
41	Technology Risk Assessment Procedure	86
42	Technology Need Definition, Barrier Coating Process	88
43	OTV Valve Housing	100
44	OTV Valve Housing Fabrication Process Flowchart	101
45	1196011 Valve Housing Technology Program and Component Testing	102
46	Schedule and Budget for the OTV Valve Housing	103
47	LCH_4 Impeller Housing	105
48	LCH_4 TPA Impeller Housing Fabrication Process Flowchart	106
49	1196001 LCH_4 TPA Discharge Housing Technology Program and Component Testing	107
50	Schedule and Budget for the LCH_4 TPA Impeller Housing	109
51	OTV Nozzle Extension Shaft Fabrication Process Flowchart	110
52	1196006 Shaft, Nozzle Extension Technology Program and Component Testing	111

LIST OF FIGURES (cont.)

Figure No.		Page
53	Schedule and Budget for the OTV Nozzle Extension	112
54	OTV Skirt Support Ring Fabrication Process Flowchart	114
55	1196008 Skirt Extension Support Ring Technology Program and Component Testing	115
56	Schedule and Budget for the OTV Skirt Support Ring	116
57	Schedule and Budget for Combining the Support Ring and Extension Shaft	118

I. SUMMARY

A. STUDY OBJECTIVES AND SCOPE

The major objectives of this study were to (1) determine the extent to which composite materials can be beneficially used in liquid rocket engines, (2) identify additional technology requirements, and (3) determine those areas which have the greatest potential for return. The assessment is based primarily on weight savings, but also considers materials and fabrication costs, performance, life, and maintainability factors as applicable.

The five-task study program summarized in Figure 1 was conducted to accomplish the stated objectives. Two engine systems were selected to be baseline configurations for both orbit-to-orbit and earth-to-orbit engines. All components from these baseline engines were assessed to identify those which could potentially benefit most from fabrication with composites.

Twelve components were ultimately selected for further study as a result of this assessment. Preliminary drawings of the twelve selected components were reviewed by structural analysts to establish wall thickness requirements and to validate the design integrity. Subsequent to the structural analysis, final cross-sectional drawings were prepared for the selected components, and accurate weights were determined by measuring the cross sections and determining the volumes.

Thought was then given to defining the technological barriers that would need to be overcome in order to successfully build production rocket components out of composite materials. A list of these technology needs was formulated, and a "Technology Needs Definition" form was filled out for each of the individual technology needs. This form was used to define each technology need, assess its risk, suggest an approach to the problem, and propose a solution.

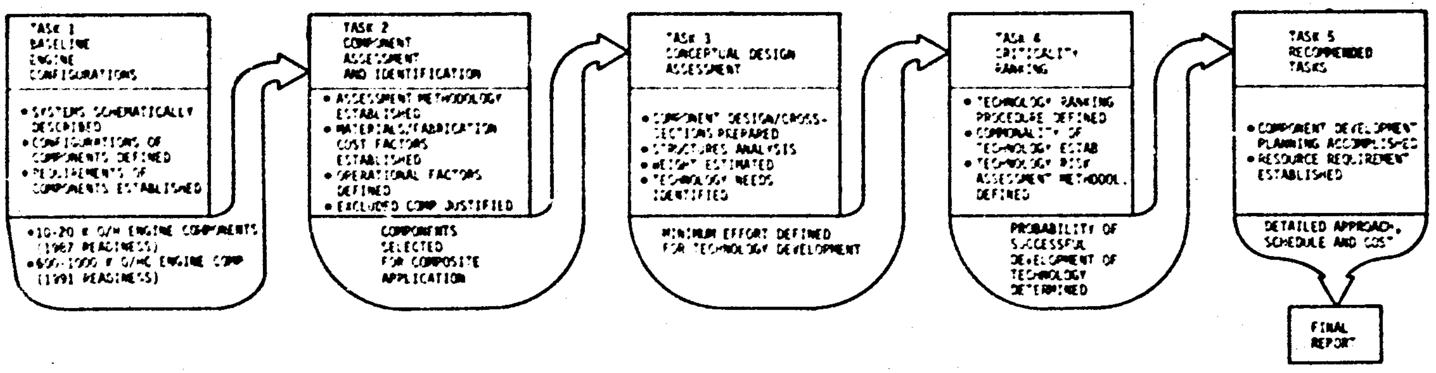

Figure 1. Overall Study Program Summary

I. A. Study Objectives and Scope (cont.)

Using the previously generated weight data and the information from the "Technology Needs Definition" forms, a "Technology Needs Cross-Reference Chart" was formulated. This chart displayed the number of components common to each technology and showed the percentage of weight reduction associated with the application of each technology need. This allowed the ranking of technology needs as well as specific components in terms of weight reduction payoffs. It also displayed an assessment of the risk associated with overcoming each technology barrier.

The "Technology Needs Cross-Reference Chart" was used in selecting four follow-on tasks recommended for further study and fabrication. The selected components not only showed promising weight savings through composite substitution, but their construction also encompassed the solution of a wide variety of technology needs.

Finally, a plan, schedule, and budget were formulated for the design, fabrication, and testing of the four selected components.

B. RESULTS AND CONCLUSIONS

This study determined that weight savings between 50 to 80% are possible on selected components when substituting reinforced plastic composite (RPC) materials for metal. This translates to an engine weight savings of 31.4% for the OTV engine and 25.5% for the LCH_4 600K engine when composites are used wherever possible. The lower weight savings percentage for the LCH_4 600K engine results from its greater number of hot-gas components (>350°F) which cannot use RPC substitution. Metal or ceramic matrix composites (MMC or CMC) could be used if high temperatures or performance became bigger "drivers" than weight savings. For the purposes of this study, however, RPC's were selected over MMC's and CMC's because of their lower cost, greater ease of fabricability, and higher specific strength.

It was also determined that a wide variety of technology needs (thirteen major categories) remain to be explored in substituting RPC's for metallic parts. Many of these technology needs lend themselves to easy solutions and were only included out of a desire for thoroughness (i.e., solar radiation effects, bearing surface lubricant, etc.). It is believed that the remainder of the more difficult technology needs can be solved through straightforward laboratory and fabrication test programs, as discussed in Section VI,B of this report.

Table I is an abridgement of the results obtained in Tasks I through IV and was used to select the follow-on tasks recommended for fabrication in Task V. The vertical columns show which technology needs are applicable to a given component and also give the percentage of engine weight savings possible if the component used composite substitution. The horizontal rows show the number of components common to each technology need, as well as the potential for weight reduction associated with the application of each technology need. Consequently, Table I allows the ranking of technology needs as well as specific components in terms of weight savings. It also displays our assessment of the risk associated with overcoming each technology barrier. A rating of "high risk" in no way signifies "next to impossible" in this chart; it merely indicates that the technology has only been proposed or theorized and that a reasonable amount of technology testing remains to be done to completely solve anticipated problems. A rating of "medium risk" indicates that less research and testing will be required to implement a given technology. A "low risk" technology need is one that is just short of being operational.

The recommended follow-on tasks were selected, using Table I as a guide. This ensured that a combination of promising weight savings and technology advancement features were incorporated into a minimum-cost, low-risk program. The components selected for fabrication in a follow-on program are as follows:

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TABLE I

TECHNOLOGY NEEDS CROSS-REFERENCE CHART

- ALLOWS RANKING OF TECHNOLOGY NEEDS AS WELL AS SPECIFIC COMPONENTS IN TERMS OF WEIGHT SAVINGS
- ALSO DISPLAYS ASSESSMENT OF RISK

TECHNOLOGY NEED	CH_4 High Speed TPA 1190B01	LOX High Speed TPA 1190B02	LOX Low Speed TPA 1190B03	OTV Thrust Support Structure 1190B04	Gimbal Seat 1190B05	OTV Nozzle Extension Shafts 1190B06	Injector Housing 1190B07	OTV Skirt Support Ring 1190B08	Nozzle Jacket 1190B09	Combustion Chamber Manifolds 1190C10	OTV Valve Housing 1190C11	Valve Gear 1190F12	Risk	Sum % Engine Wt Saved	Rank
1.0 O_2 Compatibility											✓		H	1.3	22
2.0 H_2 Compatibility		✓	✓				✓				✓	✓	H	8.4	15
3.0 CH_4 Compatibility	✓						✓			✓	✓	✓	H	4.5	18
4.0 Low Temperature Toughness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	L	26.3	2
5.0 Fabrication													***	***	***
5.1 Mechanical Fastening	✓	✓	✓		✓								L	6.9	19
5.2 Sealing Surface Finish	✓	✓	✓				✓				✓		L	9.2	16
5.3 Dome Manufacturing Method	✓	✓	✓										L	6.7	17
5.4 Dome Attachment Method	✓	✓	✓										L	6.7	17
5.5 Fabrication Sequence	✓	✓	✓		✓		✓			✓			M	7.8	10
5.6 Barrier Coating Process	✓	✓	✓				✓			✓	✓	✓	M	11.7	6
5.7 Plumbing Connections	✓	✓	✓				✓			✓	✓		L	8.8	13
5.8 Detail Joining Methods	✓	✓	✓		✓		✓			✓	✓		M	9.1	11
5.9 Detail Fabrication Methods	✓	✓	✓		✓		✓			✓	✓		L	6.5	13
5.10 Weld Design	✓	✓	✓		✓		✓			✓		✓	M	10.7	9
6.0 Cryogenic Properties	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	L	26.3	1
7.0 Interface Properties	✓	✓	✓		✓		✓		✓	✓	✓	✓	M	12.9	5
8.0 Metal Coating Interface Properties	✓	✓	✓				✓			✓	✓	✓	M	11.7	6
9.0 Differential Exp-Alloy Properties	✓	✓	✓		✓		✓		✓	✓	✓	✓	L	17.5	4
10.0 Solar Radiation Effects				✓		✓			✓				L	9.3	12
11.0 Low Cycle (Thermal) Fatigue	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	L	20.3	3
12.0 High Cycle Fatigue (HCF)				✓	✓	✓		✓					L	10.9	8
13.0 Bearing Surface Lubricant					✓	✓						✓	L	8.8	14
% Engine Wt	3.2	2.0	3.0	3.0	0.6	4.7	1.0	0.7	1.1	1.5	1.7	3.7			
% Engine Wt Saved	2.6	1.8	1.9	2.8	0.2	1.1	0.5	2.2	0.9	5.6	1.3	2.9			
Rank	④	⑦	⑥	③	⑫	①	⑨	⑤	⑪	⑩	⑧	②			

Risk

H = Only Proposed or Theorized. Technology Testing Necessary to Solve Anticipated Problems

M = Less Research and Testing Necessary

L = Just Short of Being Operational

PN	Component	% Weight Savings Rank	Number of Technology Needs Addressed
1196011	OTV Valve Housing	8	14
1196001	LCH_4 High-Speed TPA Impeller Housing	4	17
1196006	OTV Nozzle Extension Shafts	1	6
1196008	OTV Skirt Support Ring	5	4

The graphite-epoxy OTV valve housing shown in Figure 2 was selected both for its significant engine weight savings (1.3%) and because of the fact that its fabrication would address a total of fourteen technology needs. It is also a component which could be immediately useful on several engines. This program could be completed in thirteen months for a cost of $380K. It should be noted that this program could just as easily be split into distinct segments (i.e., technology, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding (approximately $150K/year).

The graphite-epoxy impeller housing shown in Figure 3 is the biggest engine weight saver on the 600K booster (2.5% engine weight savings) and is also the most complicated in terms of advancing the state of the art. Its complex shape and propellant exposure would result in the need to address seventeen technology needs before a housing could be successfully fabricated and tested. Its successful fabrication, however, would greatly facilitate the construction of any of the other engine subcomponents. This program is the most ambitious of the recommended tasks and could be completed in sixteen months for a cost of $448K.

The graphite/fiberglass epoxy OTV nozzle extension shaft shown in Figure 4 shows the greatest percentage of engine weight savings of any of the components selected in this study (3.3%) and is also fairly simple to

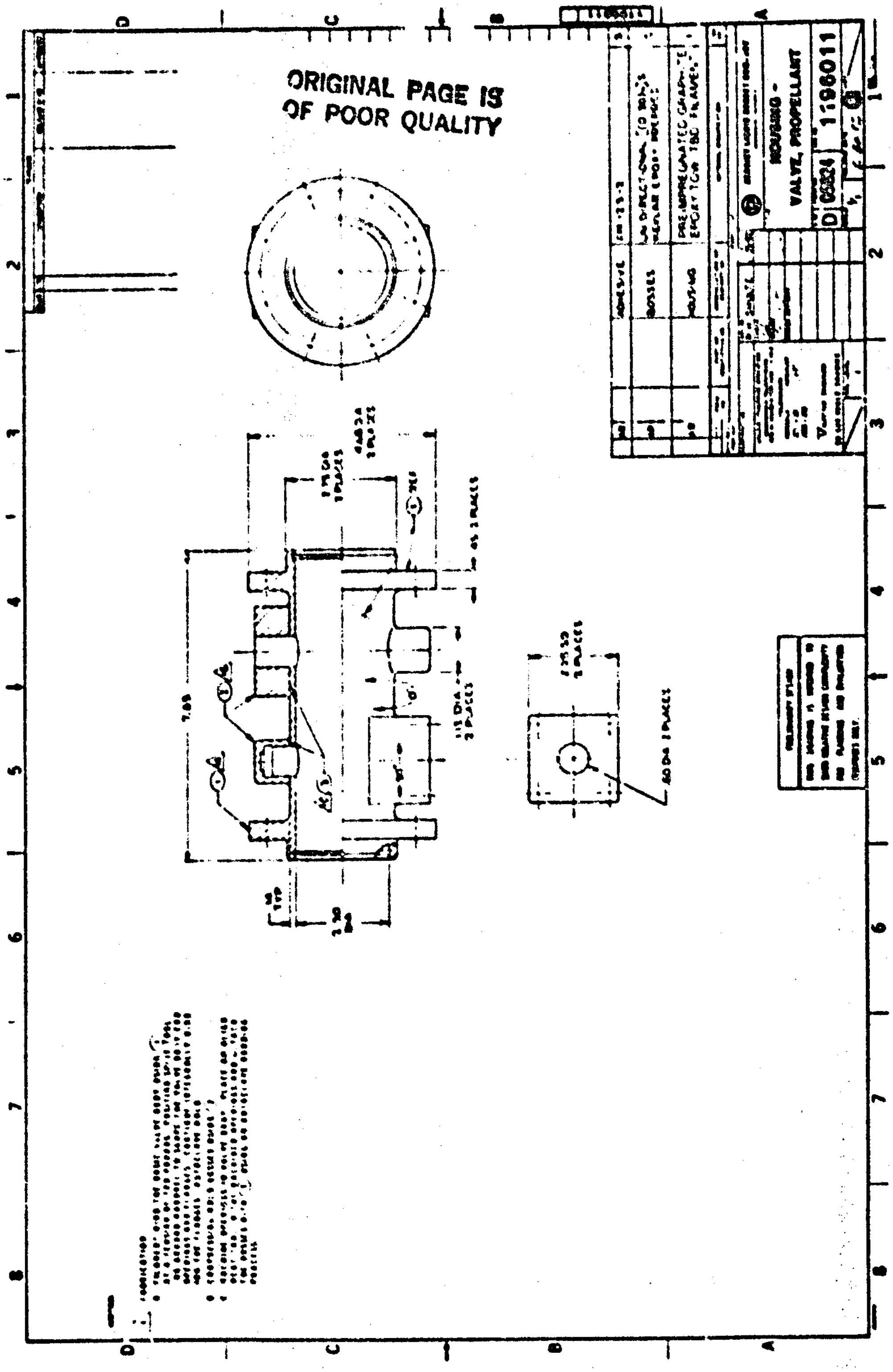

Figure 2. OTV Valve Housing

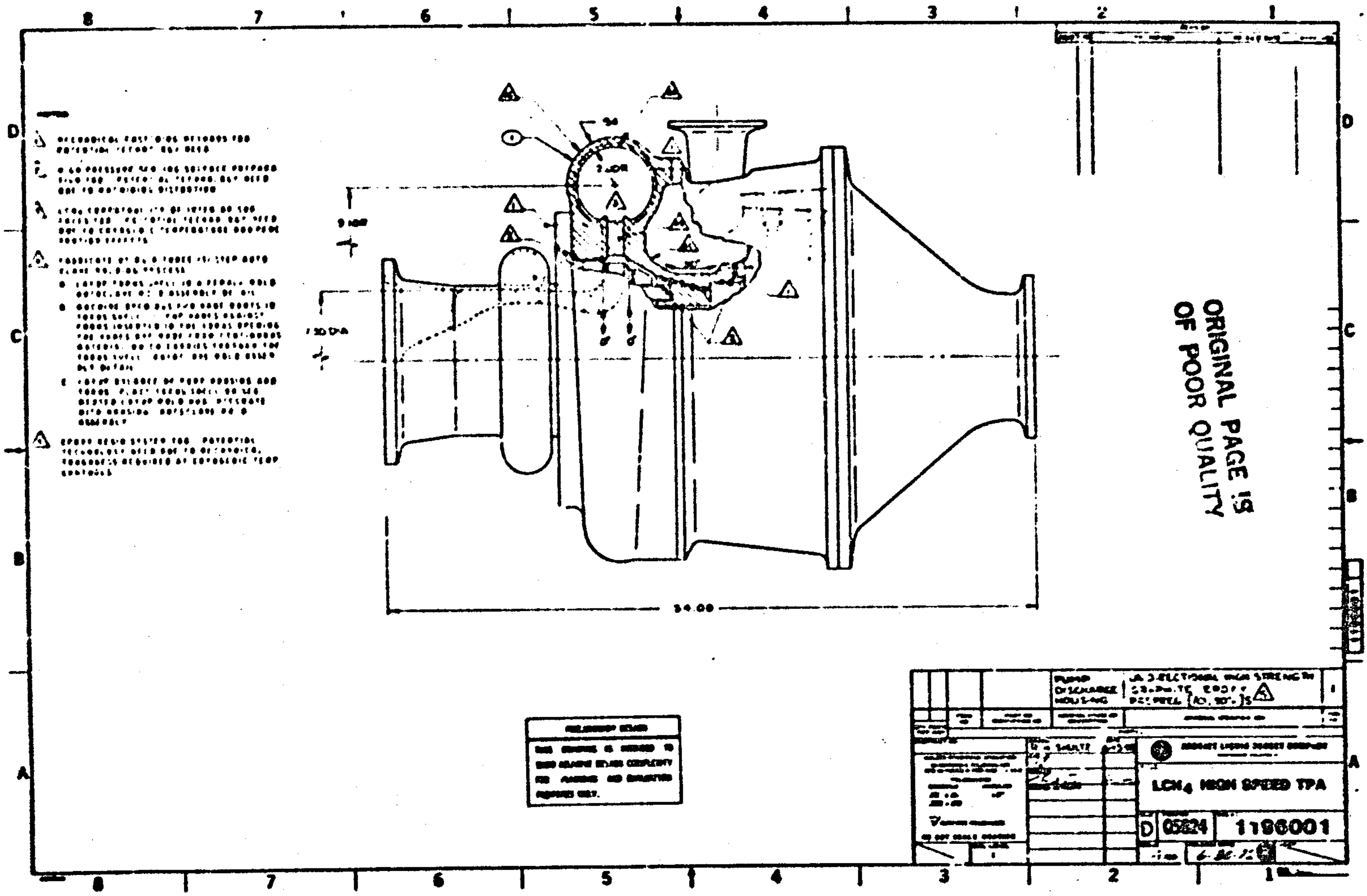

Figure 3. LCH$_4$ TPA Impeller Housing

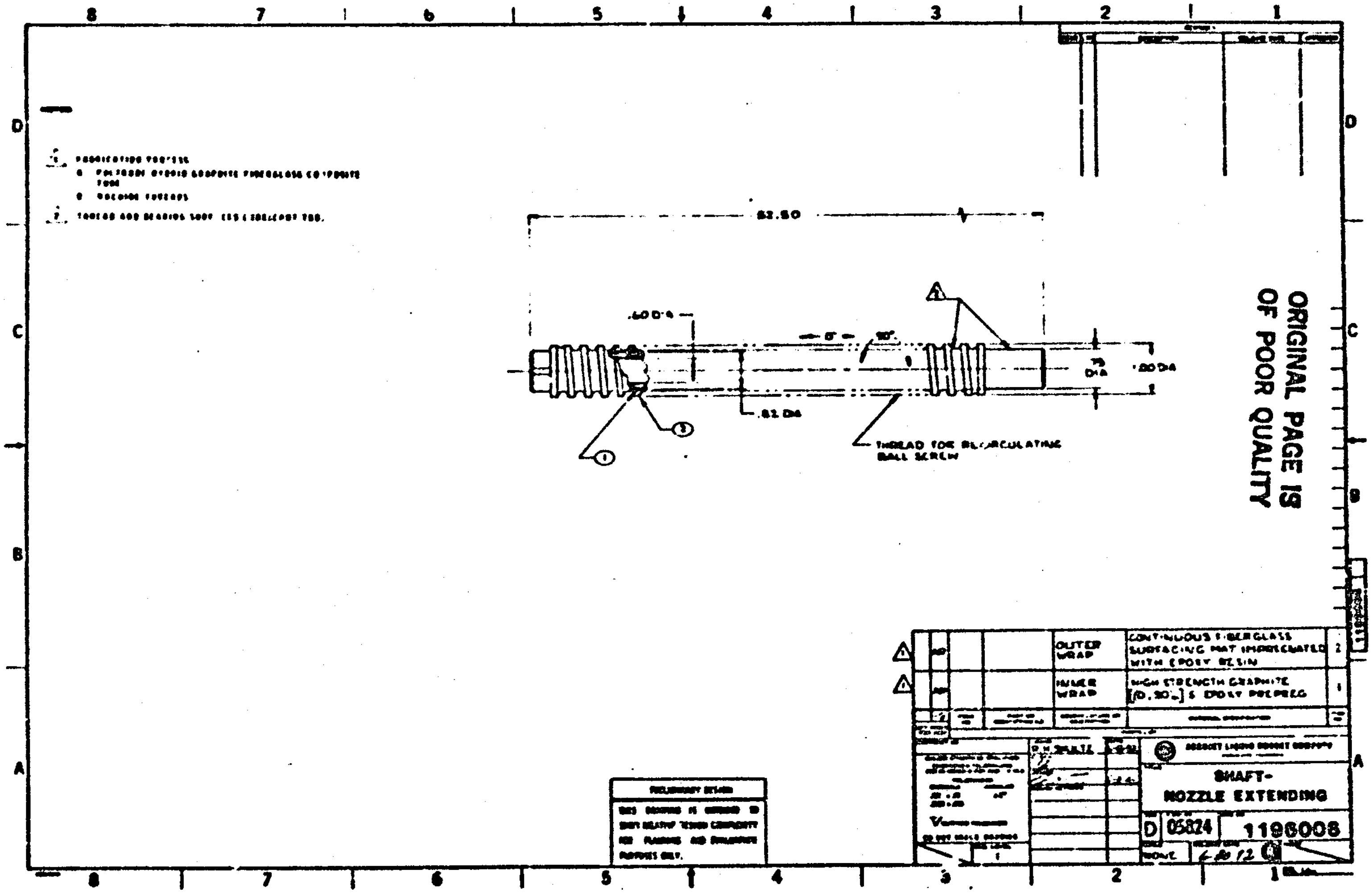

Figure 4. CTV Nozzle Extension Shaft

I, B, Results and Conclusions (cont.)

fabricate. This program could be completed in thirteen months for a cost of $231K. This is one of the simplest and least costly programs which could be performed and still result in significant weight savings.

The honeycomb/graphite-epoxy OTV skirt support ring shown in Figure 5 shows an engine weight savings of 2.2% and is also simple to fabricate. Additionally, it could be mated with the aforementioned extension shaft to form a subassembly. The support ring could be developed and tested in thirteen months for a cost of $231K. Developing both the extension shaft and support ring together would result in certain economies because of the commonality in the technology testing and subcomponent tests. They could both be developed in the same 13-month time frame for a cost of $281K.

It is recommended that a follow-on program be funded to 1) resolve technology needs, 2) design and fabricate a RPC subcomponent, and 3) test and evaluate the subcomponent. At the very least, a fabrication and materials technology program should be initiated to find solutions for the identified technology needs.

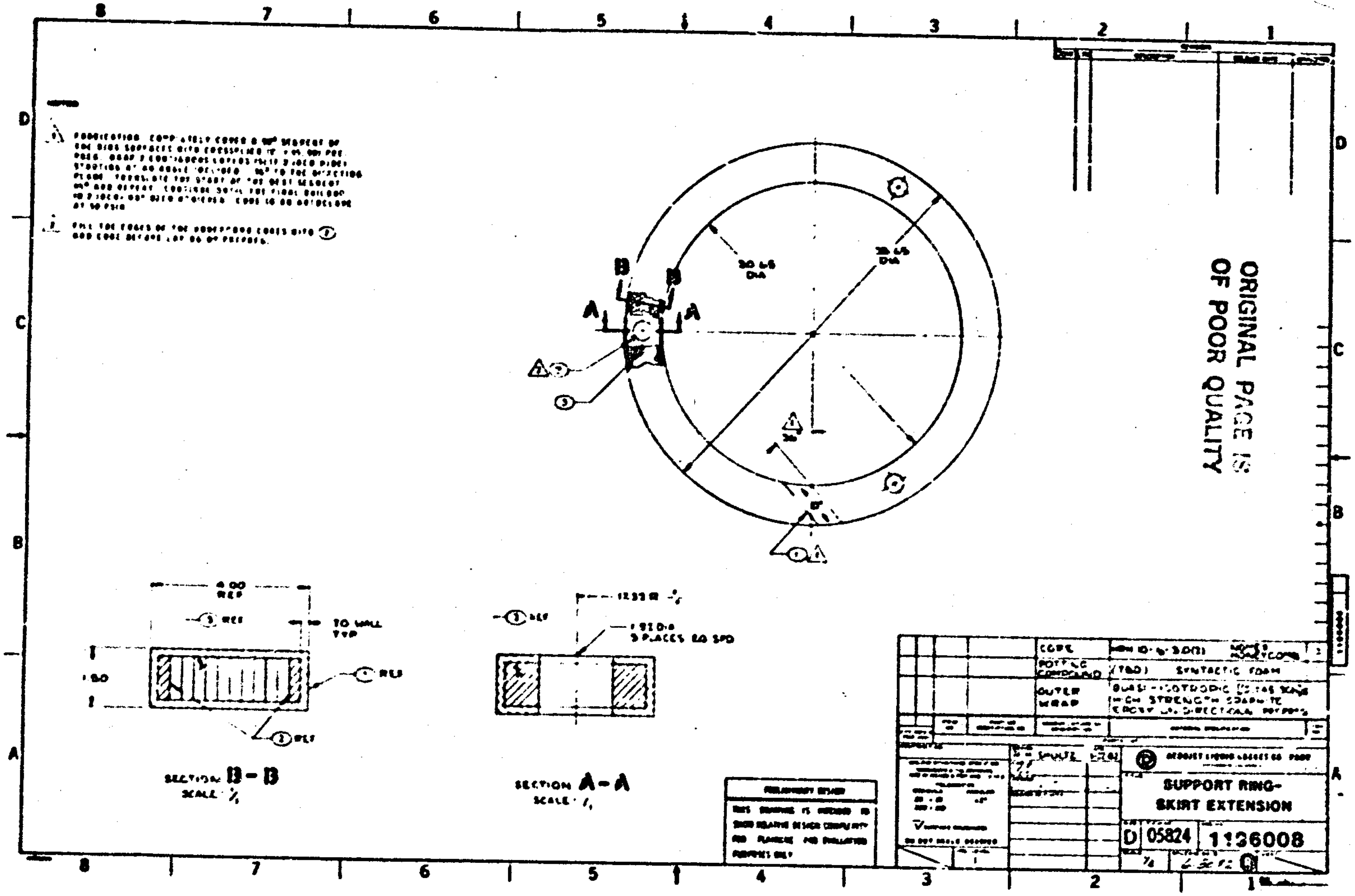

Figure 5. OTV Skirt Support Ring

II. INTRODUCTION

A. BACKGROUND

Many improvements in liquid rocket propulsion are being evaluated in an effort to define an economical space transportation system. One such improvement involves the use of composite materials in rocket engine design.

Composites are a family of high-performance materials consisting of a matrix reinforced with a fiber. The matrix is usually a thermosetting resin such as epoxy, a ceramic, or a metal such as aluminum. The reinforcement can be Kevlar, fiberglass, graphite, or boron in the form of either continuous fibers, chopped fibers, or whiskers. The combination of a matrix and a fiber results in a new composite material which is lighter, stiffer, and stronger than either of its constituents.

Recent studies indicate that weight reductions of 30 to 45% can be achieved for specific components of existing engines by using current and near-term composite technology. The Advanced Oxygen-Hydrocarbon Rocket Engine Study (NAS 8-33452), conducted by ALRC for NASA-MSFC, suggested that weight savings of 30 to 40% are possible for an entire LOX/hydrocarbon booster engine employing near-term and future composite technology.

Previous applications of composites in military, NASA, and commercial projects provide a broad base of experience. Rocket engine application, however, will impose additional material, design, and fabrication requirements due to such factors as hot gas and cryogenic temperature extremes, maintainability requirements, and a dynamic environment. Further, past experience has shown that the application of composites requires much hands-on development of design procedures and fabrication techniques which are unique to specific components.

B. PURPOSE AND SCOPE

The major objectives of this program were to 1) determine the extent to which composite materials can beneficially be used in liquid rocket engines, 2) identify additional technology requirements, and 3) determine those areas which have the greatest potential for return.

The scope included examining all major components from both earth-to-orbit and orbit-to-orbit engines to determine which could benefit most from composite substitution. The study guidelines dictated that the major consideration be weight savings, although cost, life performance, and maintainability were also considered. Drawings were made, technology needs were assessed, and a program plan was presented for designing, fabricating and testing four selected components.

C. APPROACH

To accomplish the program objectives, an effort involving five technical tasks was conducted. The tasks conducted were as follows:

1. Task I - Baseline Engine Configurations

Establish baseline representative engine configurations for both orbit-to-orbit and earth-to-orbit engines. This task was limited to schematic descriptions of the two selected engine systems and to documenting the general configurations and requirements of the engine components.

2. Task II - Component Assessment and Identification

Establish a methodology for assessment of the component concepts. Apply this methodology to all baseline components from Task I and identify the components which can potentially benefit from fabrication with composites. A brief justification was also provided for each component where composite materials do not show a benefit.

3. Task III - Conceptual Design Assessment

Prepare conceptual design drawings (cross sections) of each component with potential composite application. Perform appropriate structural analyses as required to obtain realistic weight estimates. Define the minimum effort needed to illustrate the feasibility of technology development for each component.

4. Task IV - Criticality Ranking of Technology Needs

Establish a criticality ranking of identified technology needs. The degree of risk for successfully developing the technology was categorized between low (for components that are just short of being operational) to high (for components that have only been proposed or theorized). The degree of risk assessment included such factors as commonality, cost, schedule, and performance. Life-cycle cost data, where available or readily approximated, were also utilized.

5. Recommended Tasks

Recommend a minimum of two follow-on tasks involving component fabrication and testing. The recommendations encompass the integration of multiple technology needs and include a detailed approach, schedule, and estimate of the resources required.

D. PROGRAM SCHEDULE AND MAJOR MILEPOSTS

Figure 6 presents a detailed program schedule of the events in Tasks I through V. The mileposts shown include submittal of data for NASA approval, reviews, and task completions.

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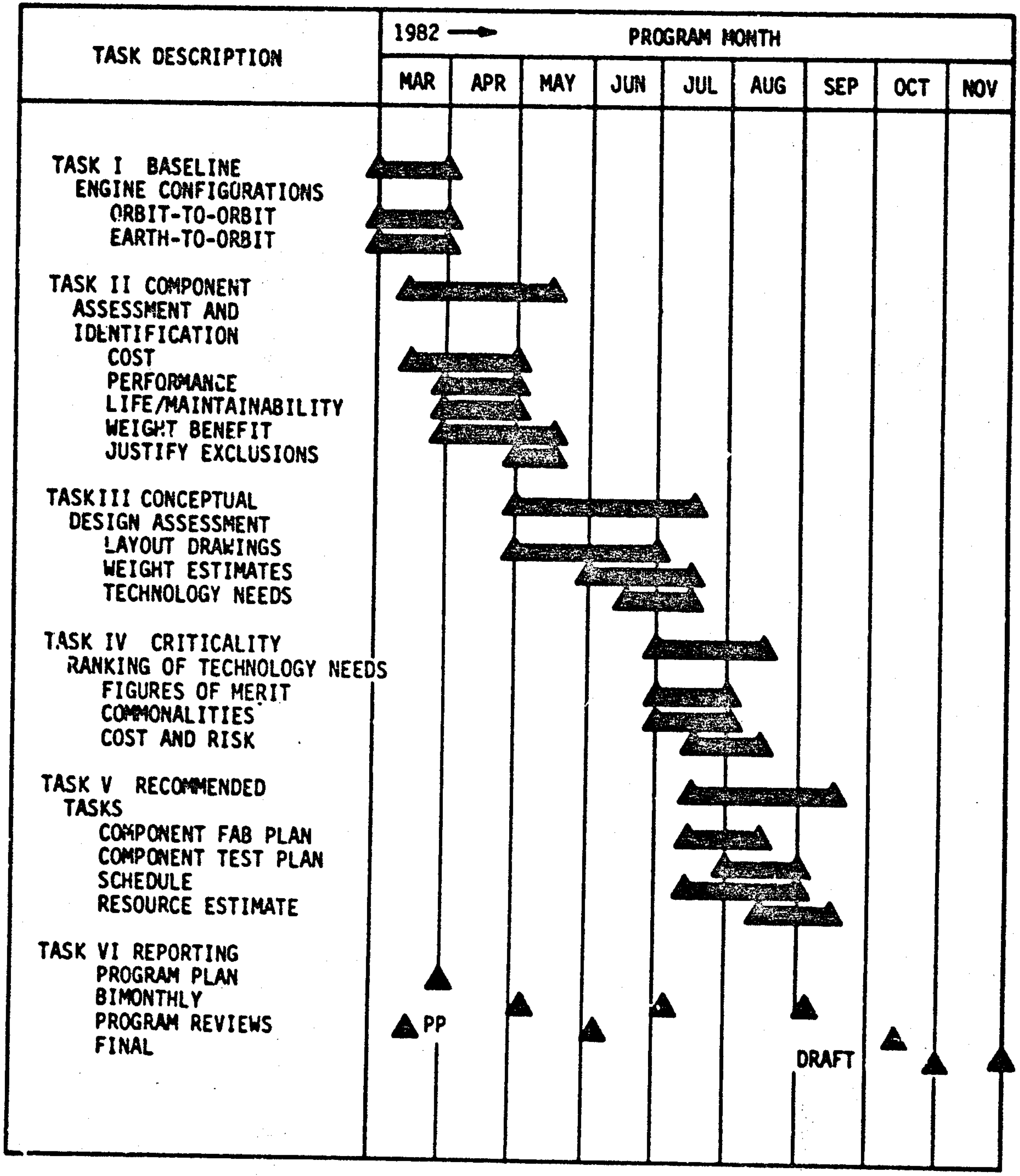

Figure 6. Major Milestone Schedule

III. TASK I - BASELINE ENGINE CONFIGURATIONS

A. OBJECTIVES

The objective of Task I was to establish baseline representative engine configurations for both orbit-to-orbit and earth-to-orbit engines. The task was limited to schematic descriptions of the selected engine systems and to general configurations and engine component requirements.

B. ENGINE SELECTIONS

After consideration of the three orbit-to-orbit point design studies (Ref. 1, 2, and 3), the 15,000-lbF Advanced Expander Cycle Engine (OTV) was selected to represent the orbit-to-orbit configuration. A layout of this engine is shown in Figure 7. Component layouts for the injector, chamber and nozzle, boost pump, main pump, and valves are given in Figures 8 through 14. These layouts, plus the corresponding component dimensions that were utilized in preparing the layout, provide the means for estimating the composites' impact on weight and structural integrity. A flow schematic for the OTV engine is shown in Figure 14A. A detailed component weight breakdown for the metallic OTV baseline engine is shown in Table II. This table also shows a preliminary estimate of what the engine would weigh if RPC's were substituted wherever possible.

A study of the earth-to-orbit engines described in Contracts NAS 8-33452 and NAS 8-32967 (Ref. 4 and 5, respectively) led to the selection of the 600,000-lbF LOX/LCH_4 (Cycle C - Gas Generator Cycle) engine to represent the earth-to-orbit configuration. A layout of this engine is shown in Figure 15. Layouts of the major components (turbopumps, injector, and gas generator, etc.) are available from Contract NAS 3-19727 and are shown in Figures 16 through 21. A flow schematic for the 600-K booster is shown in Figure 21A. A detailed component weight breakdown for the LOX/LCH_4 base-

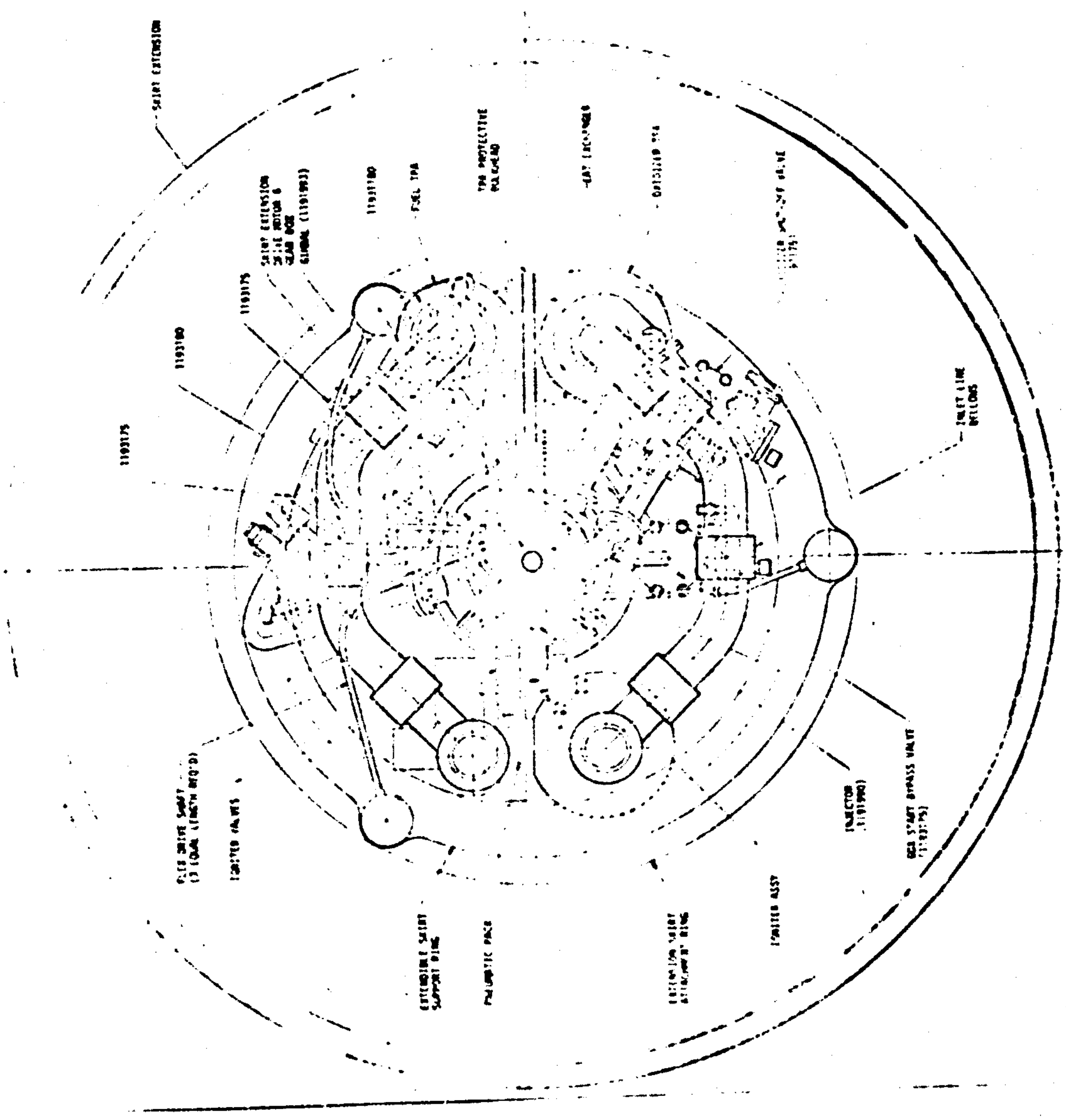

Figure 7. OTV Engine Layout (ALRC Dwg. No. 1193100) (Sheet 1 of 3)

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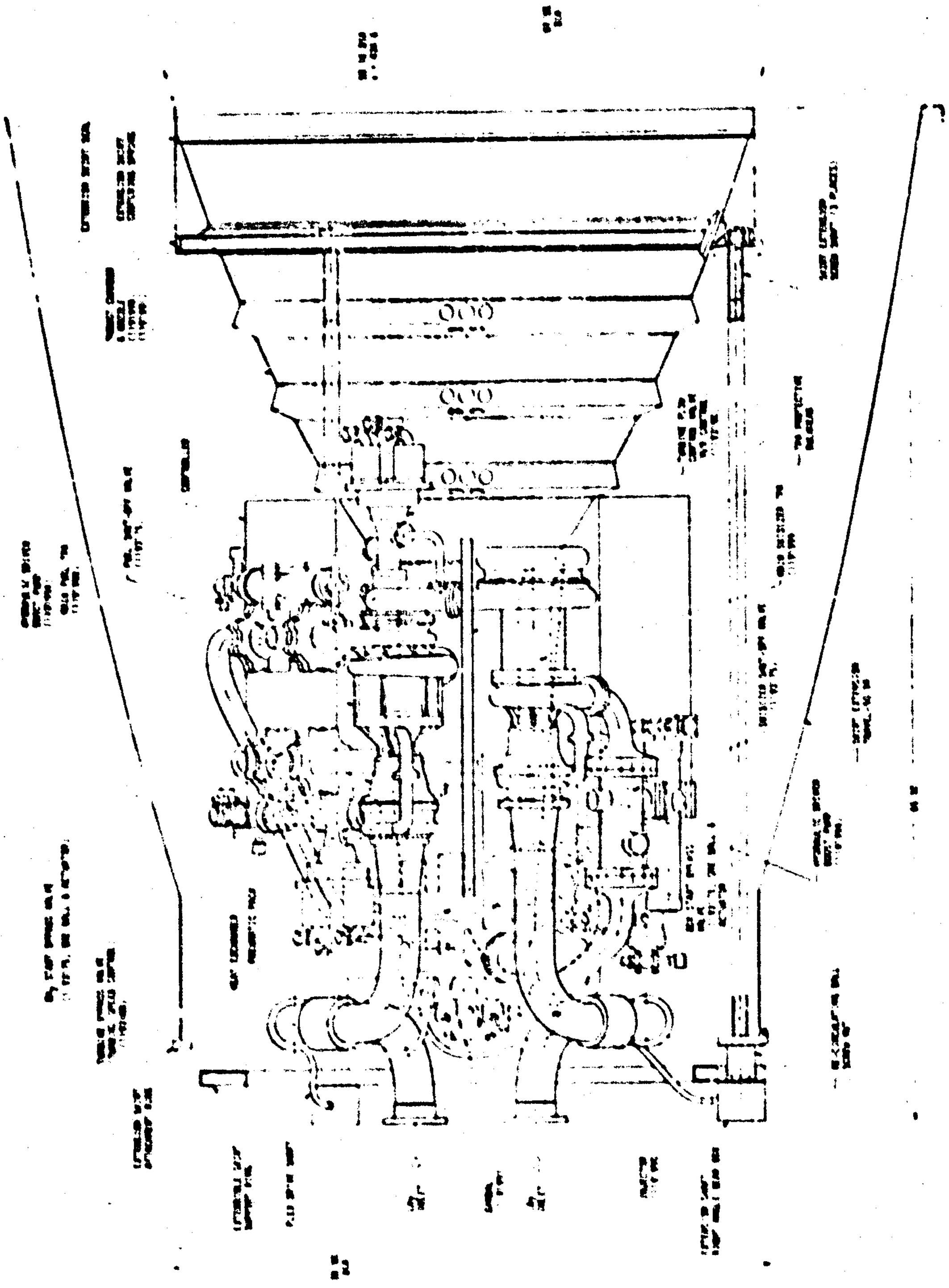

Figure 7. OTV Engine Layout (Sheet 2 of 3)

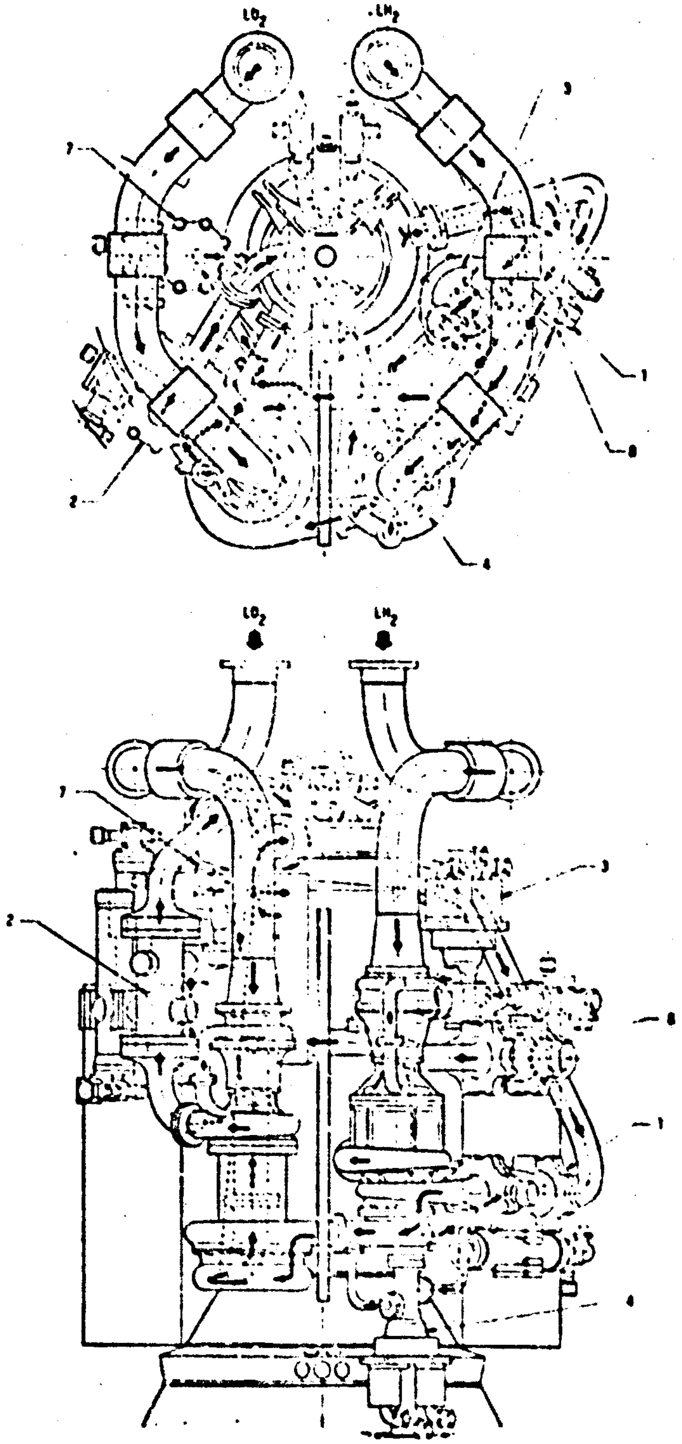

Figure 7. OTV Engine Layout (ALRC Dwg. No. 1193100) (Sheet 3 of 3)

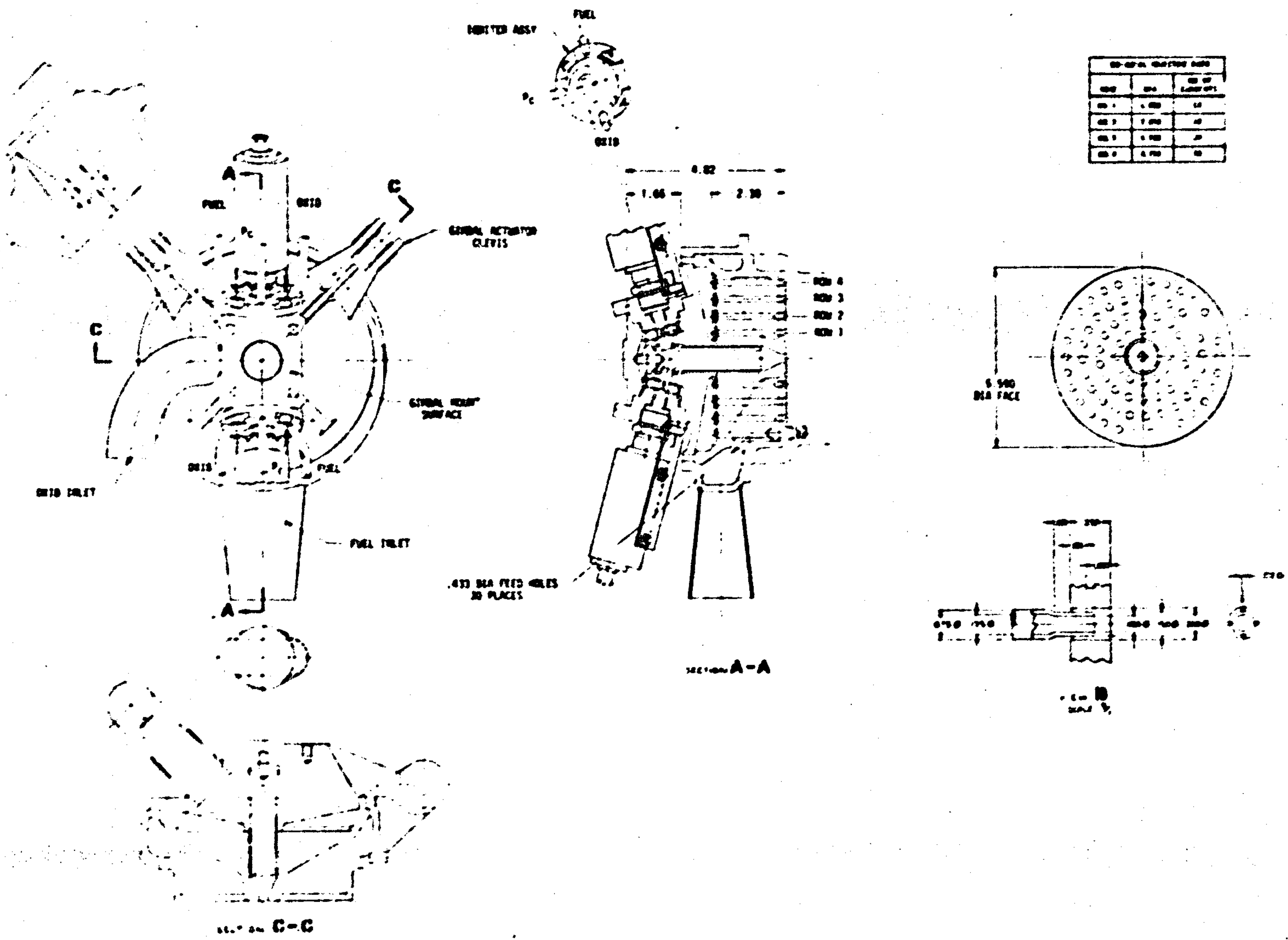

Figure 8. Igniter/Injector Assembly (ALRC Dwg No. 1191990)

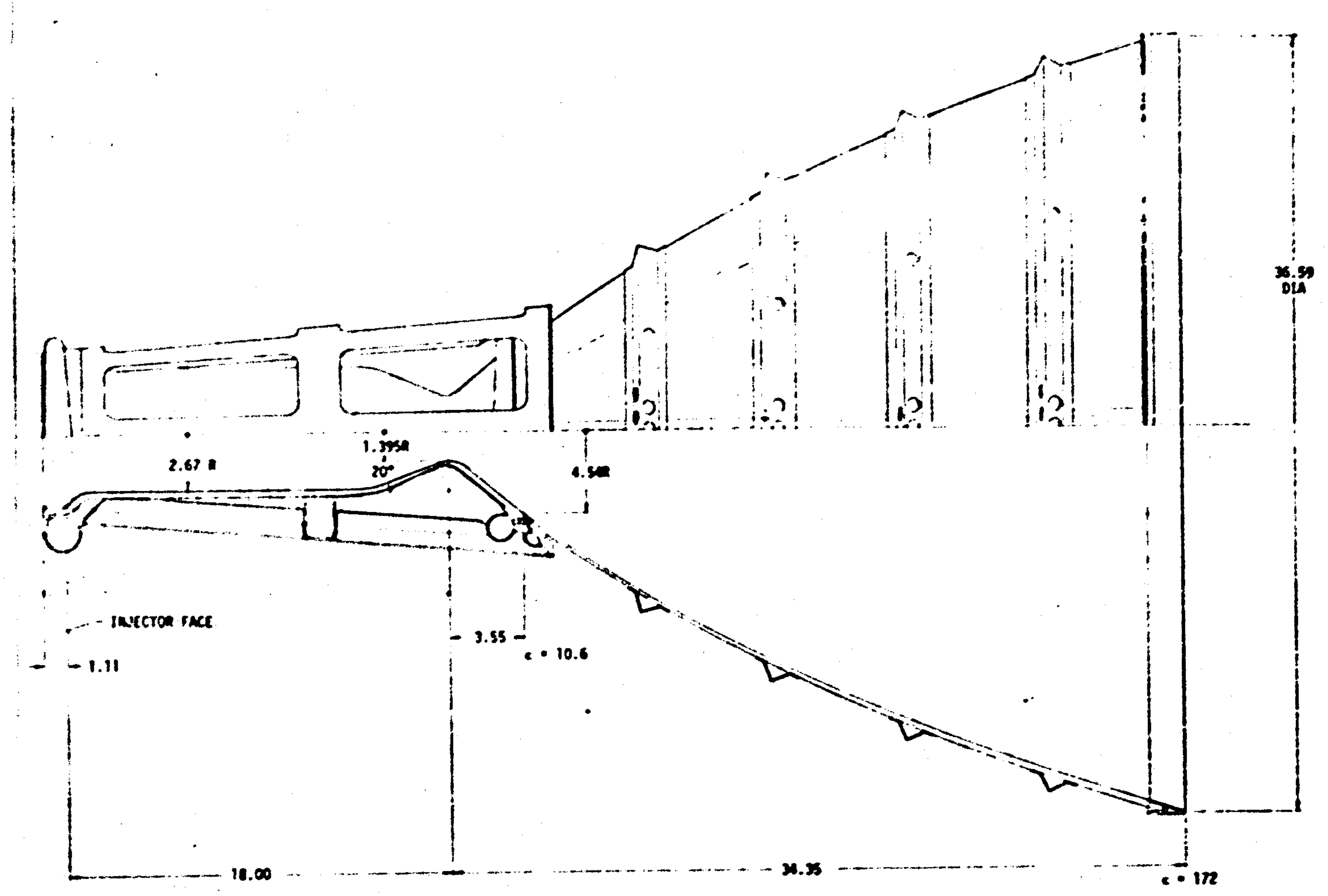

Figure 9. Chamber and Tube Bundle Nozzle (ALRC Dwg No. 1191991)

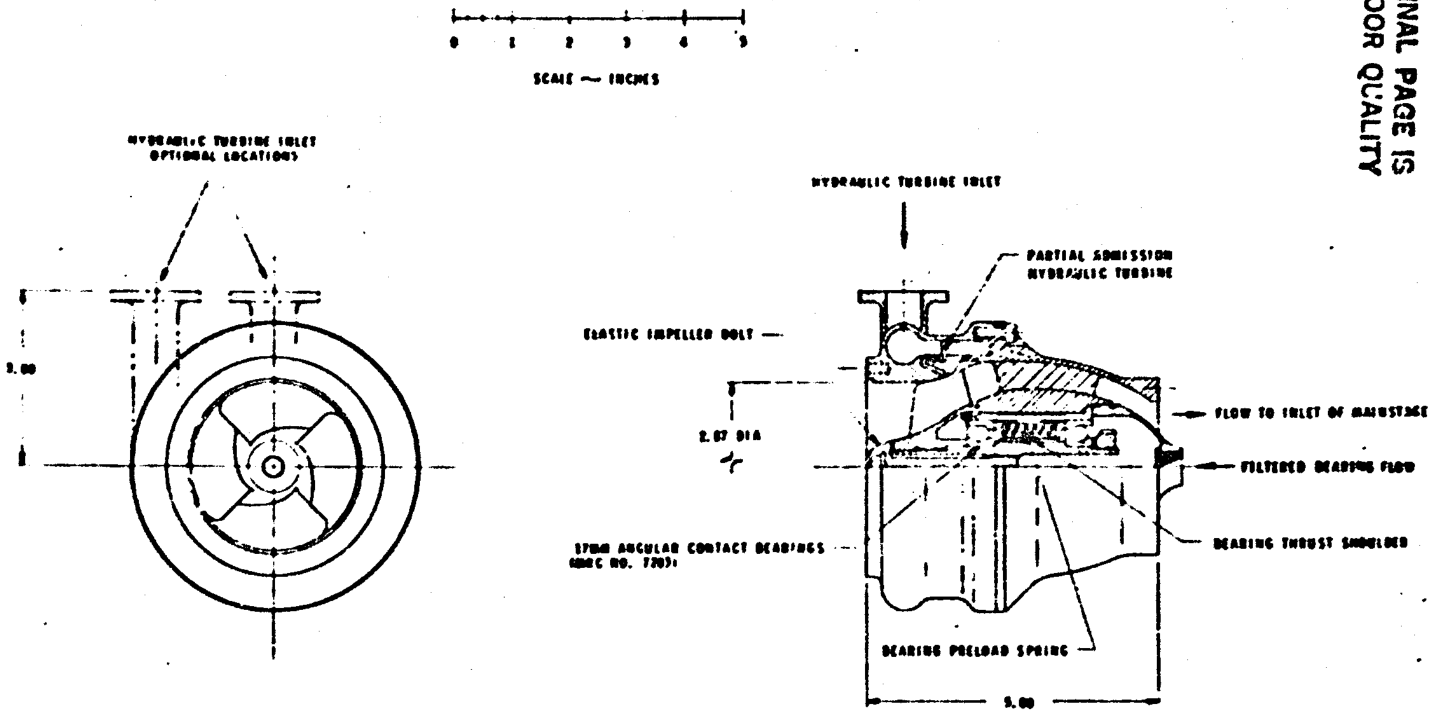

Figure 10. LO_2 Boost Pump (ALRC Dwg No. 1191994)

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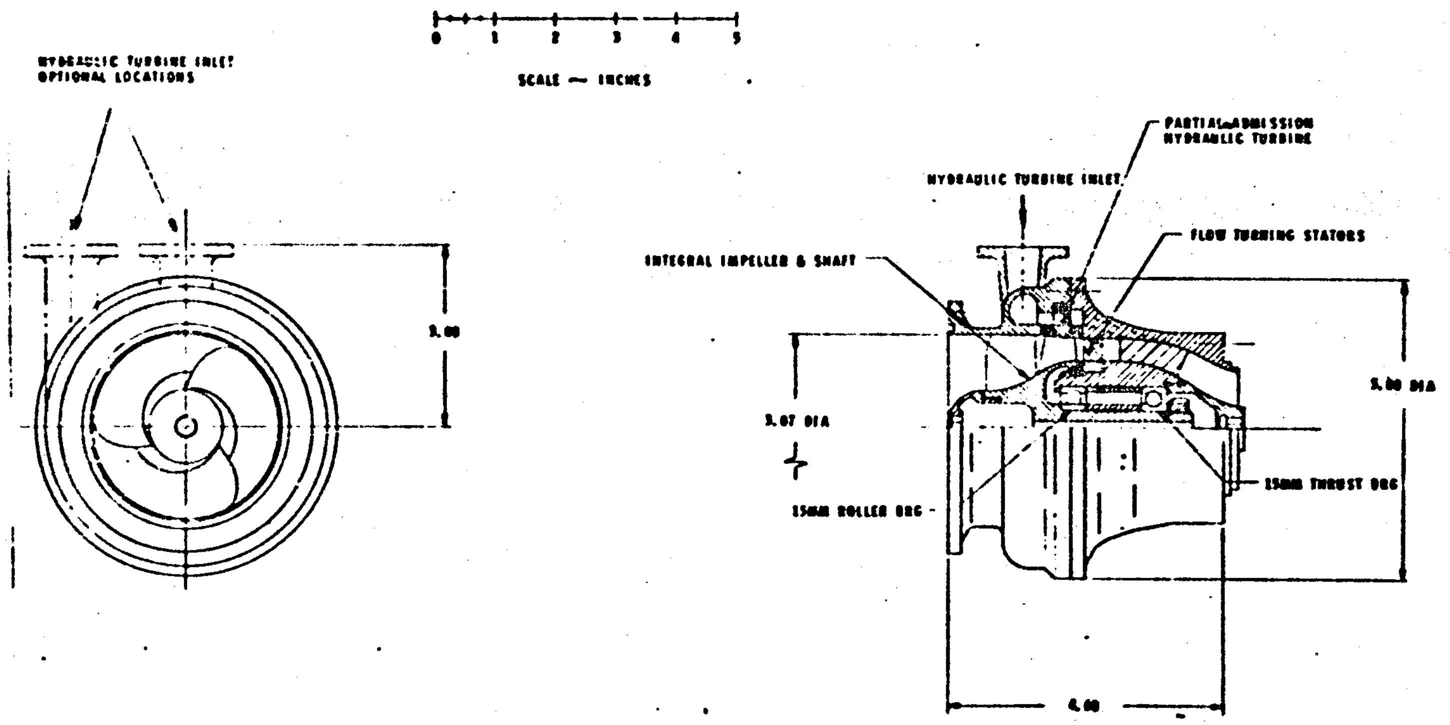

Figure 11. LO_2 Boost Pump (ALRC Dwg No. 1191996)

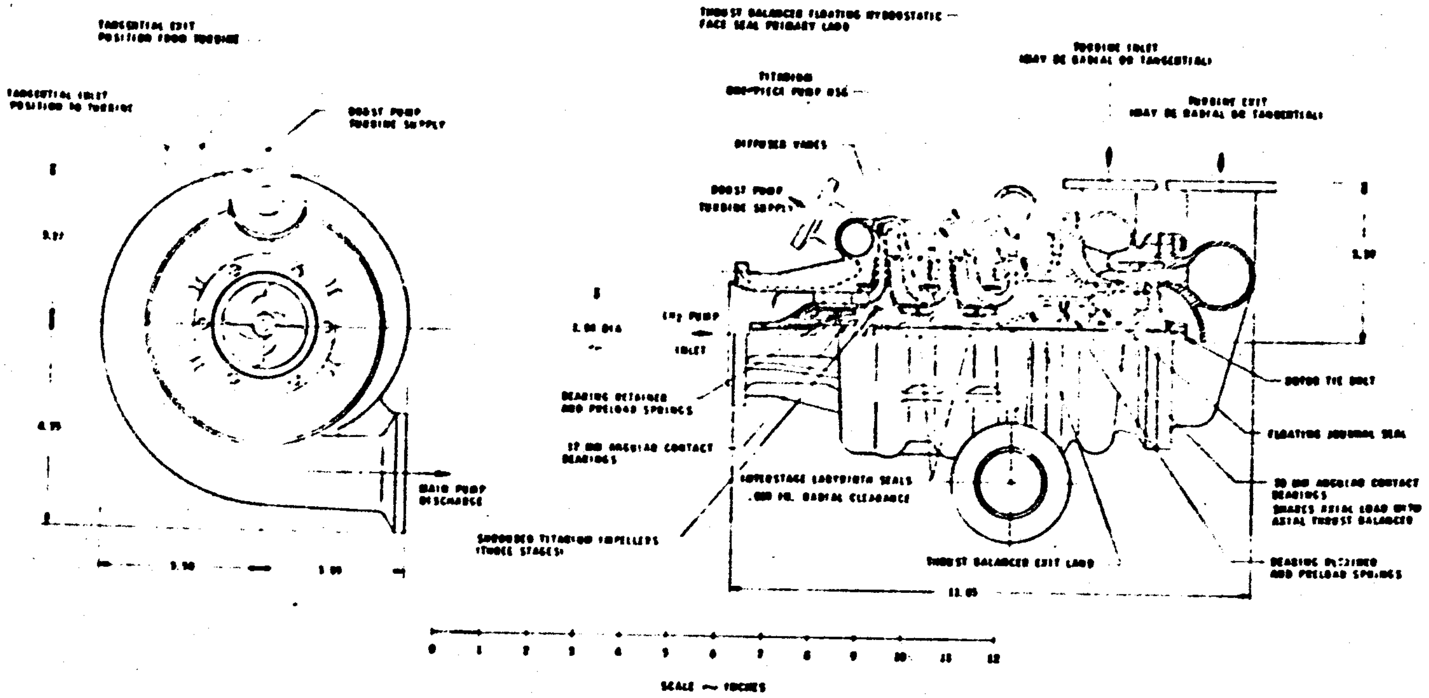

Figure 12. LH_2 TPA (ALRC Dwg No. 1191997)

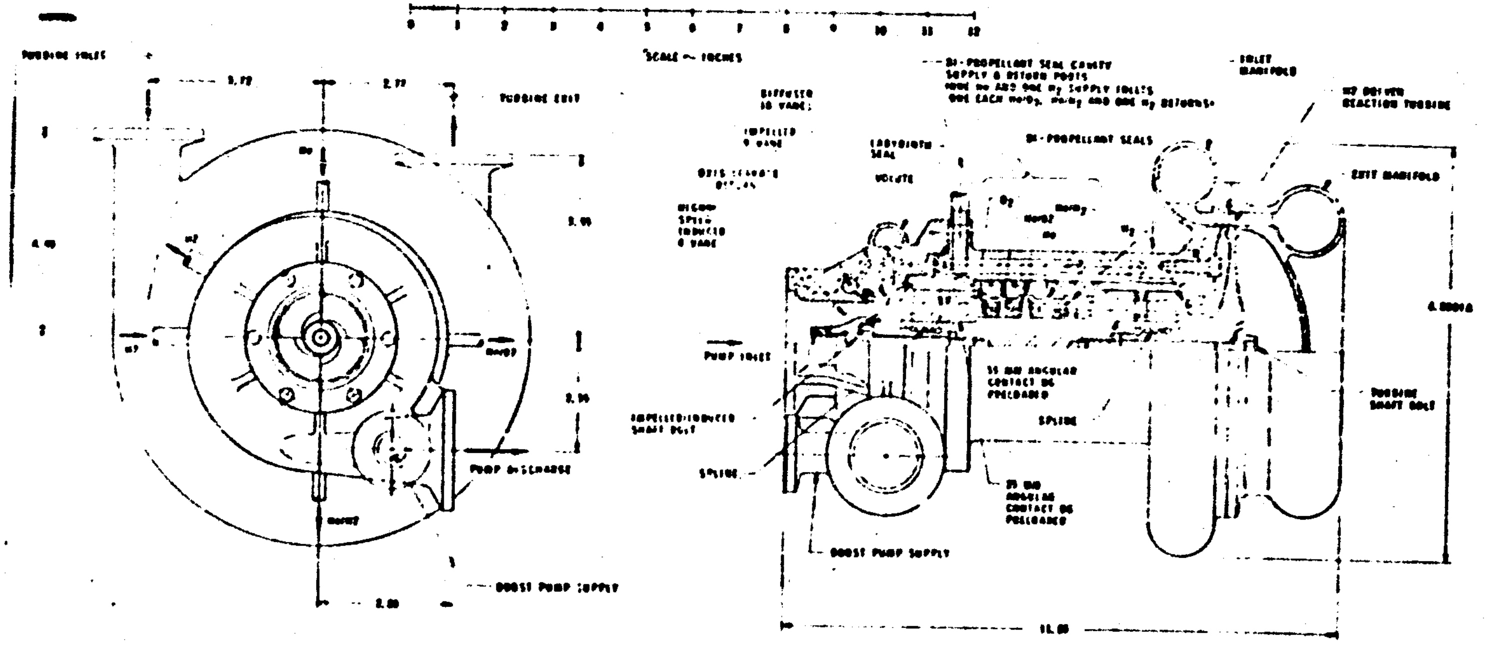

Figure 13. LO_2 TPA (ALRC Dwg No. 1191999)

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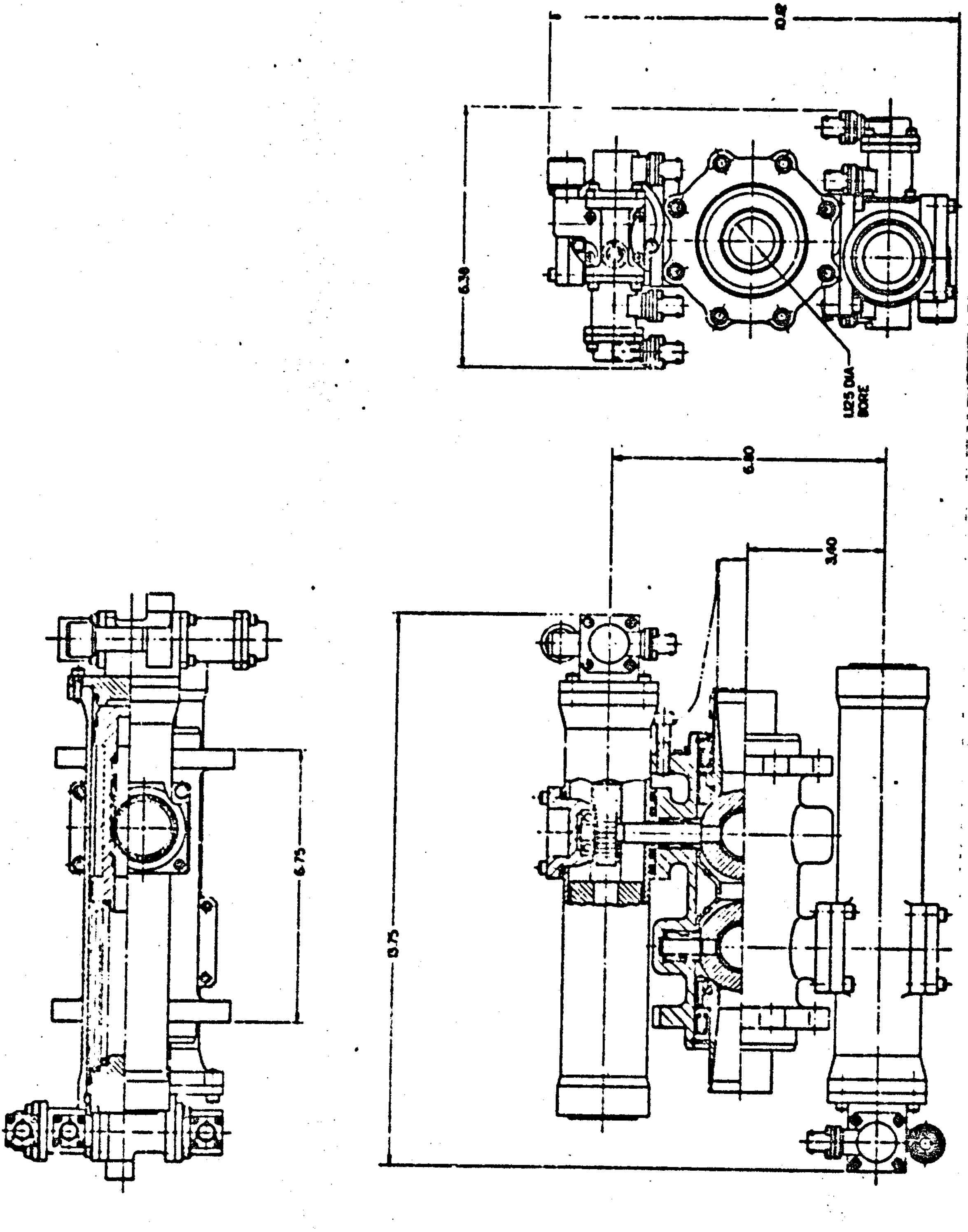

Figure 14. Shutoff Valve (ALRC Dwg No. 1193176)

F = 15000 lbF
Pc - 1200 psia
Isp_{VAC} = 475.4 sec
O/F = 6.0
Expansion Ratio = 435:1
Oxidizer Main Pump Horsepower = 252.5 HP
Oxidizer Main Pump Discharge Pressure = 1470 psia
Fuel Main Pump Horsepower = 1022 HP
Fuel Main Pump Discharge Pressure = 2473 psia

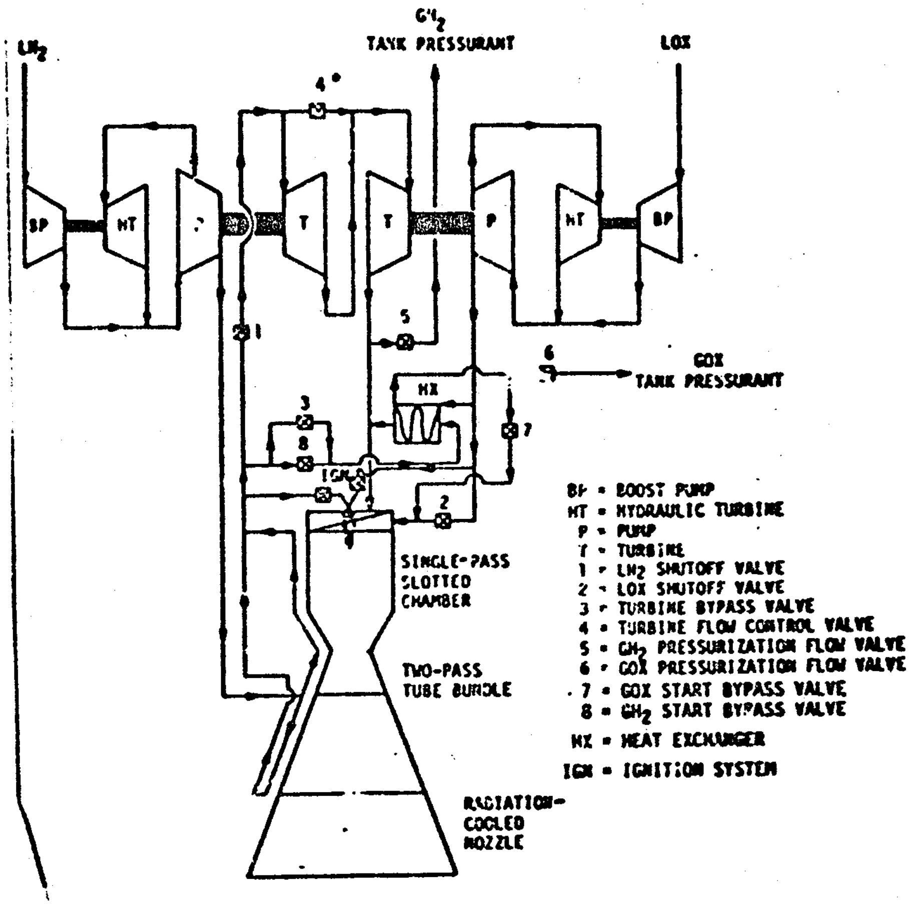

Figure 14A. OTV Flow Schematic

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TABLE II

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA

Engine Components	Current Weight	New Weight	Weight* Reduction
Radiation-Cooled Nozzle	(80)	(80)	-
Valves and Actuators	(72.8)	(23.5)	(49.3)
Two Valve Bodies	10	2.6	7.4
Four Actuator Bodies	29	8.7	20.3
Actuator End Closures	7.8	2.2	5.6
Four Gates	5.0	1.8	3.2
Shafts	10	3.6	6.4
Gears	10	3.6	6.4
Springs	1	1	-
Nozzle Deployment System	(72)	(39.9)	32.1
Three Extension Shafts	24	4.9	19.1
Support Ring	27	14	13.0
Gear Box	-	-	-
Ball Screws	21	21	-
Flex Shafts	-	-	-
Combustion Chamber	(74.3)	(43.7)	30.6
Liner	20.4	20.4	-
Closeout	9.4	3.7	5.7
Manifolds	22.5	14	8.5
Support Structure	22.0	5.6	16.4
Nozzle-Tube Bundle	(38.4)	(34.4)	(4.0)
Tube Assembly	29.4	29.4	-
Four Reinforcing Rings	3	1.2	1.8
Manifold	6	3.8	2.2

NOTES:

* Potential weight reduction with use of composite materials

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA (Cont'd)

Engine Components	Current Weight	New Weight	Weight Reduction
Propellant Lines	(37)	(17.4)	(19.6)
Tubes	9	3.8	5.2
Flanges	10	6	4
Flex Joints	18	7.6	10.4
Controller	(35)	(32.4)	(2.6)
Case	11	8.4	2.6
Add Other	24	24	-
Injector	(30.6)	(23.1)	(7.5)
Body	21	16	5
Face	1.0	1.0	-
Coaxial Elements	1.2	.5	.7
Manifold	5	3.8	1.2
Two Clevises	2.4	1.8	.6
LOX TPA	(25.1)	(15.0)	(10.1)
Pump Housing	5.4	2.4	3
Seal Housing	7.0	5.3	1.7
Turbine Housing	4.0	1.8	2.2
Impeller	.2	.1	.1
Shaft	2.0	.9	1.1
Turbine	4.0	2	2
Bearing	2.5	2.5	-
LH_2 TPA	(21.5)	(9.8)	(11.7)
LH_2 Inlet Housing	4.0	1.8	2.2
Pump Housing	8.5	3.8	4.7
Inducer	.1	.05	.05
Impellers	3.0	1.5	1.5
Turbine Exit Housing	3.7	1.4	2.3

Engine Components	Current Weight	New Weight	Weight Reduction
LH_2 TPA (Cont'd)			
Shaft	1.4	.7	.7
Turbines	.6	.3	.3
Bearings	.2	.2	-
Misc. Valves and Pneumatic Package	[12.6]	[12.6]	-
Ignition System	[9.2]	[9.2]	-
LH_2 Boost Pump	(8.6)	(3.9)	(4.7)
Turbine-Impeller Housing	3.6	1.6	2.0
Exit Housing	4.1	1.8	2.3
Turbine Impeller	.3	.15	.15
Impeller Bolt	.1	.1	-
Shaft	.4	.18	.22
Bearings	.08	.08	-
LOX Boost Pump	(5.5)	(2.5)	(3.0)
Turbine-Impeller Housing	2.4	1.05	1.35
Exit Housing	2.7	1.2	1.5
Impeller Shaft	.3	.15	.15
Bearings	.08	.08	-
Heat Exchanger	(5)	(2.5)	(2.5)
Outer Shell	3.5	1.75	1.75
Inner Shell	1.5	.75	.75
Gimbal	(3.3)	(2.1)	(1.2)
Thrust Pad	1.2	.54	.66
Thrust Mount	.7	.49	.21
Cap	.2	.15	.05
Shaft	.8	.58	.22
Monoball	.2	.15	.05
Fasteners	.2	.2	-

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA (Cont'd) Page 4 of 4

Engine Components	Current Weight	New Weight	Weight Reduction
Miscellaneous	[37]	[37]	-
Electrical Harness	12.5	12.5	-
Service Lines	6.5	6.5	-
TPA Protective Bulkhead	.4	.4	-
Attachment Hardware	15.0	15.0	-
Instrumentation	2.6	2.6	-
TOTAL WEIGHT	567.9	389	178.9

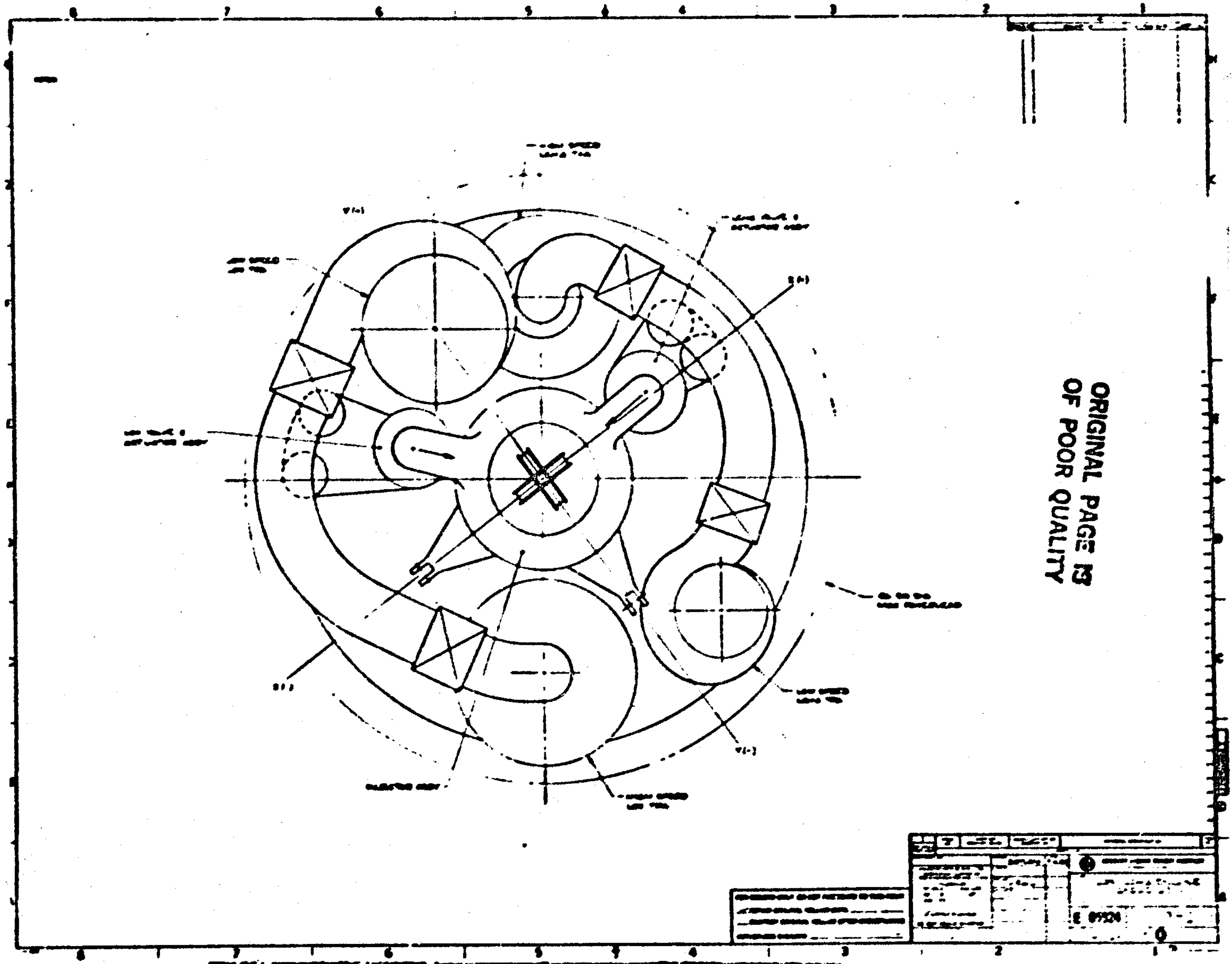

Figure 15. LOX/LCH$_4$ Engine Layout (Sheet 1 of 2)

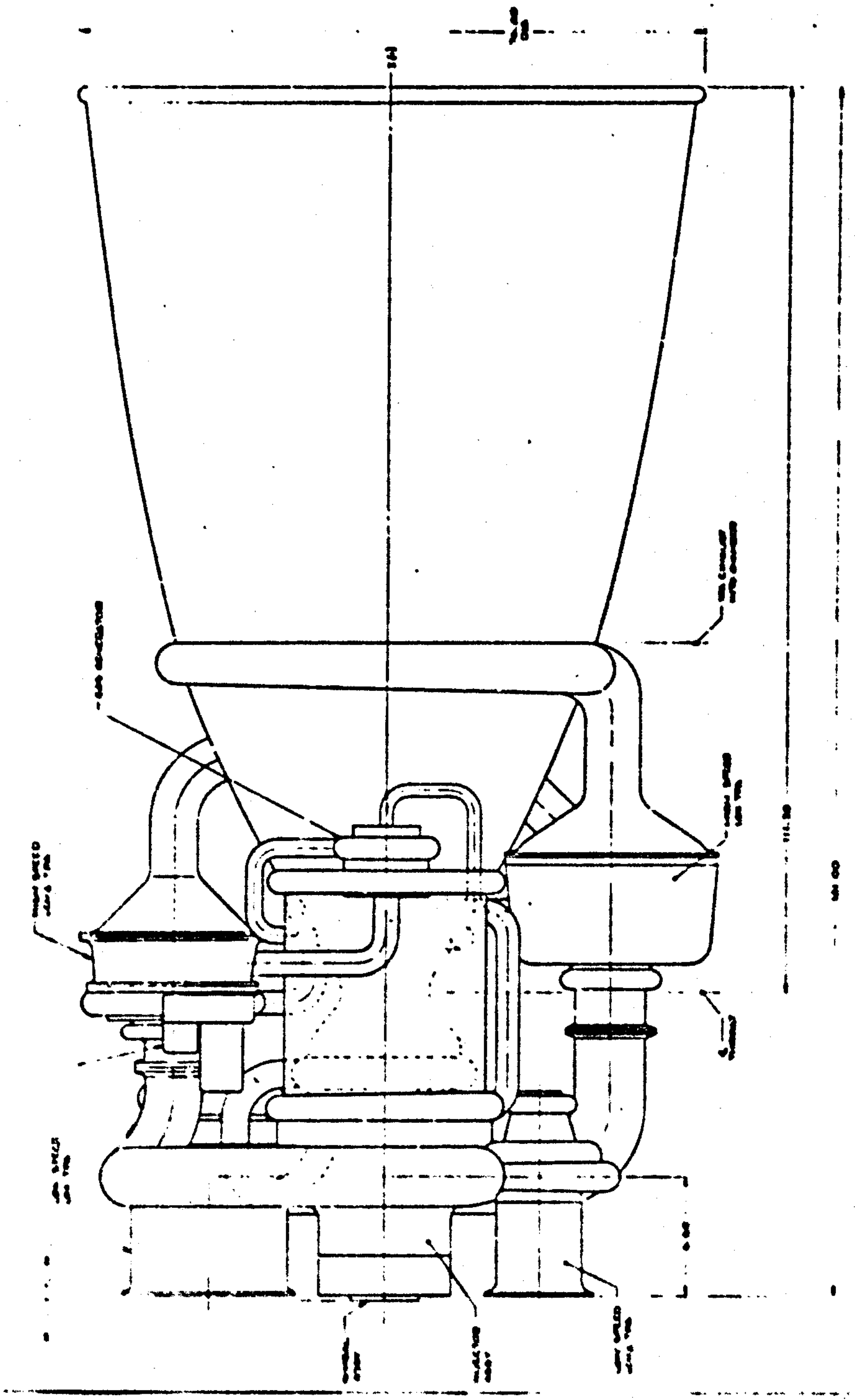

Figure 15. LOX/LCH$_4$ Engine Layout (Sheet 2 of 2)

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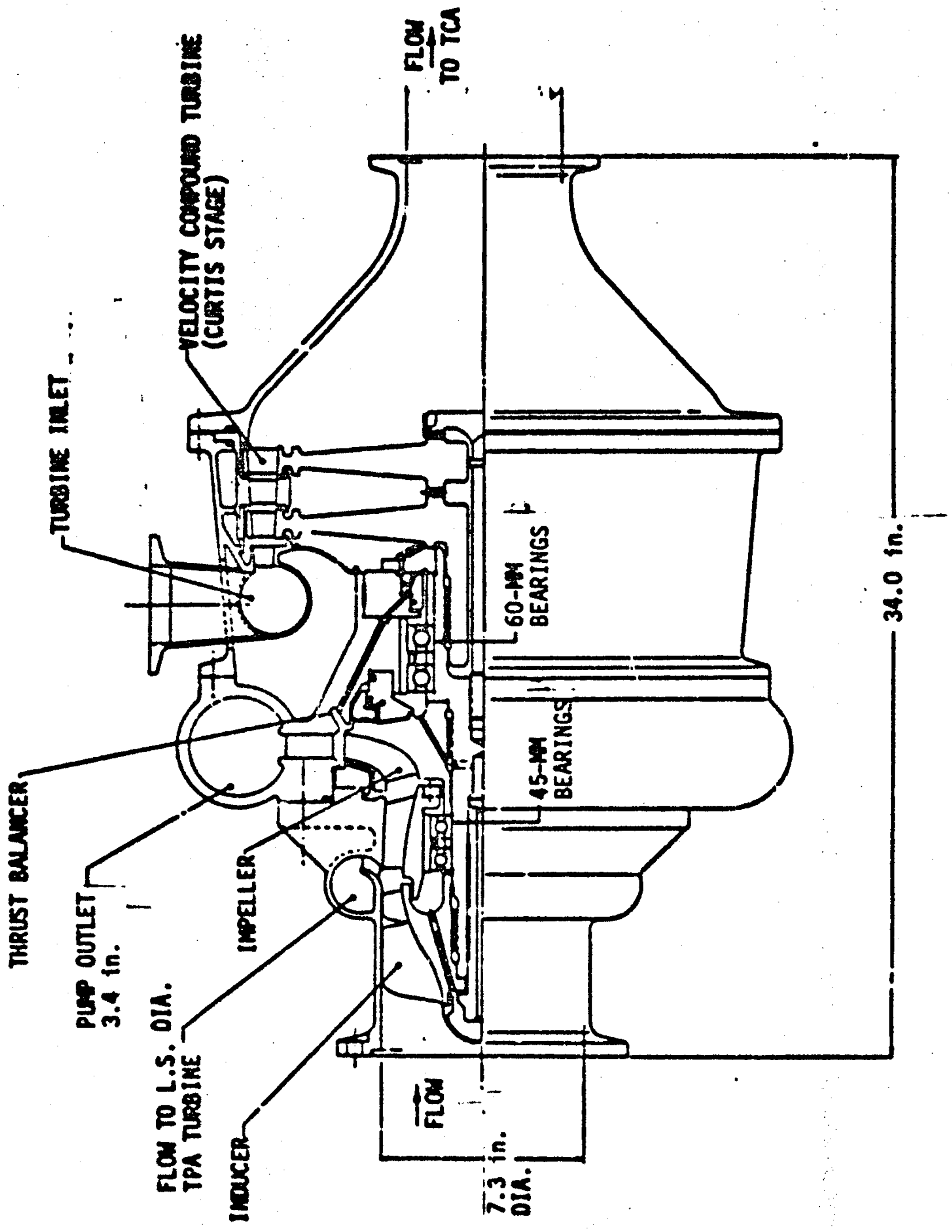

Figure 16. High-Speed LCH_4 TPA

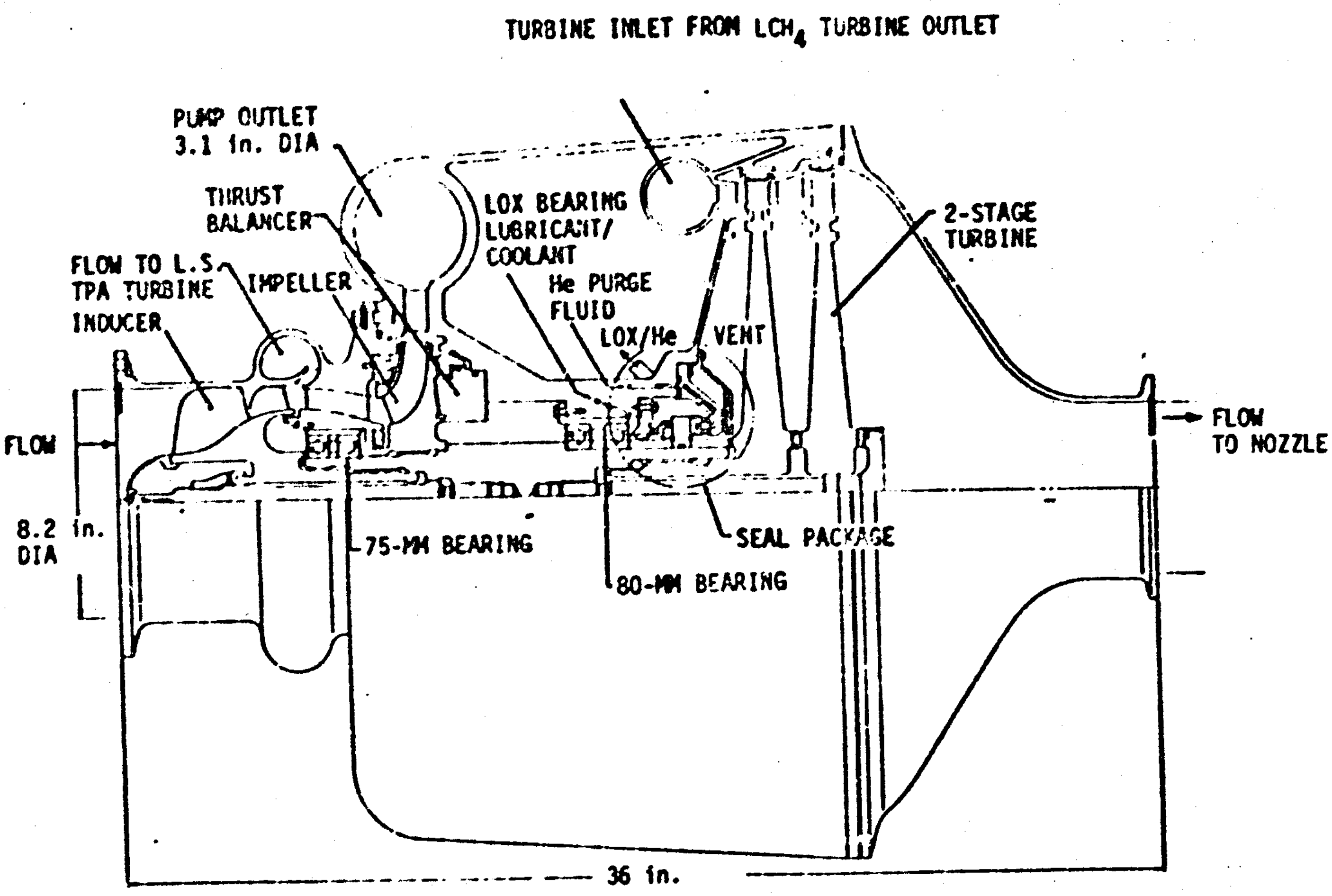

Figure 17. High-Speed LOX TPA

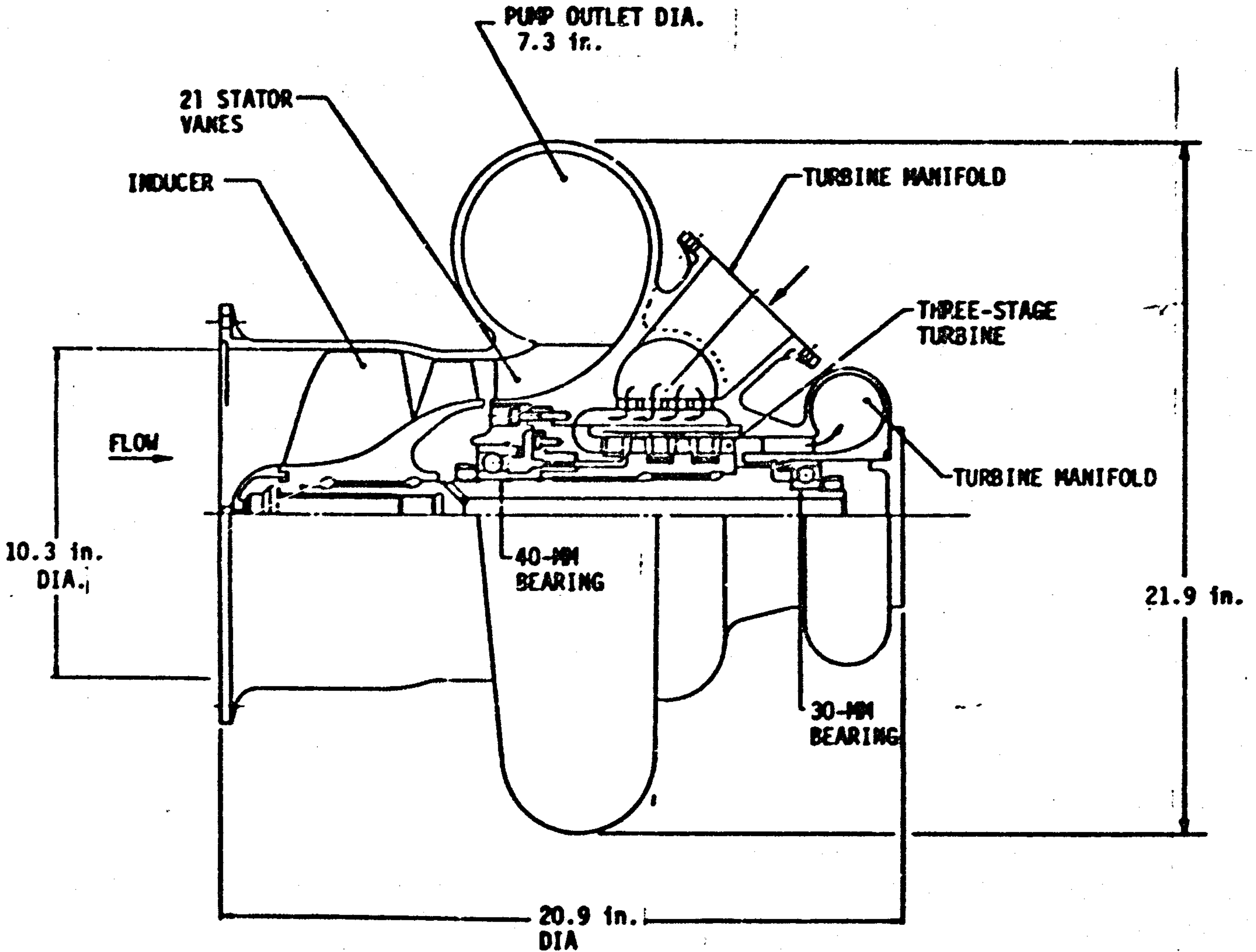

Figure 18. Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed RP-1 TPA

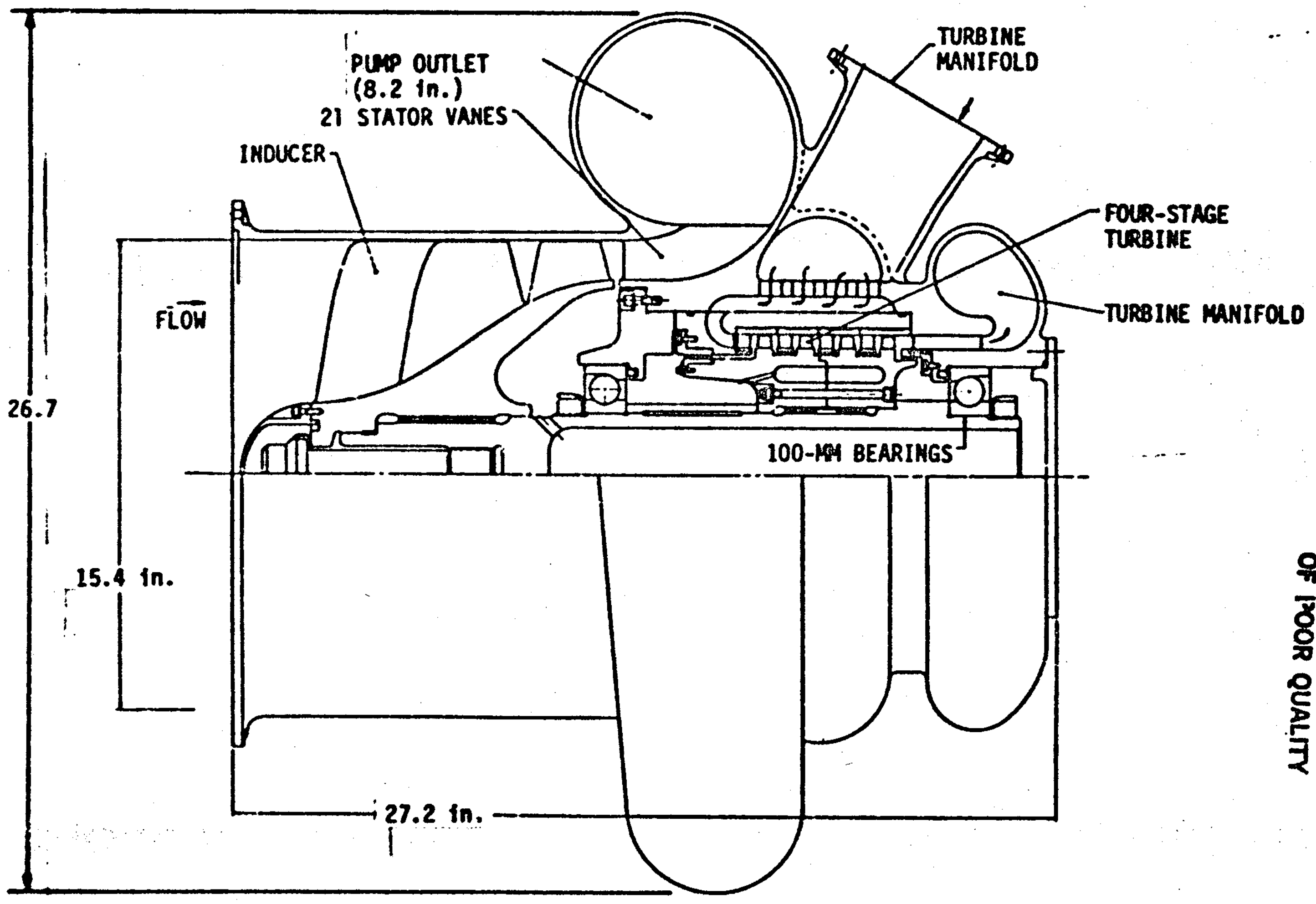

Figure 19. Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed LOX TPA

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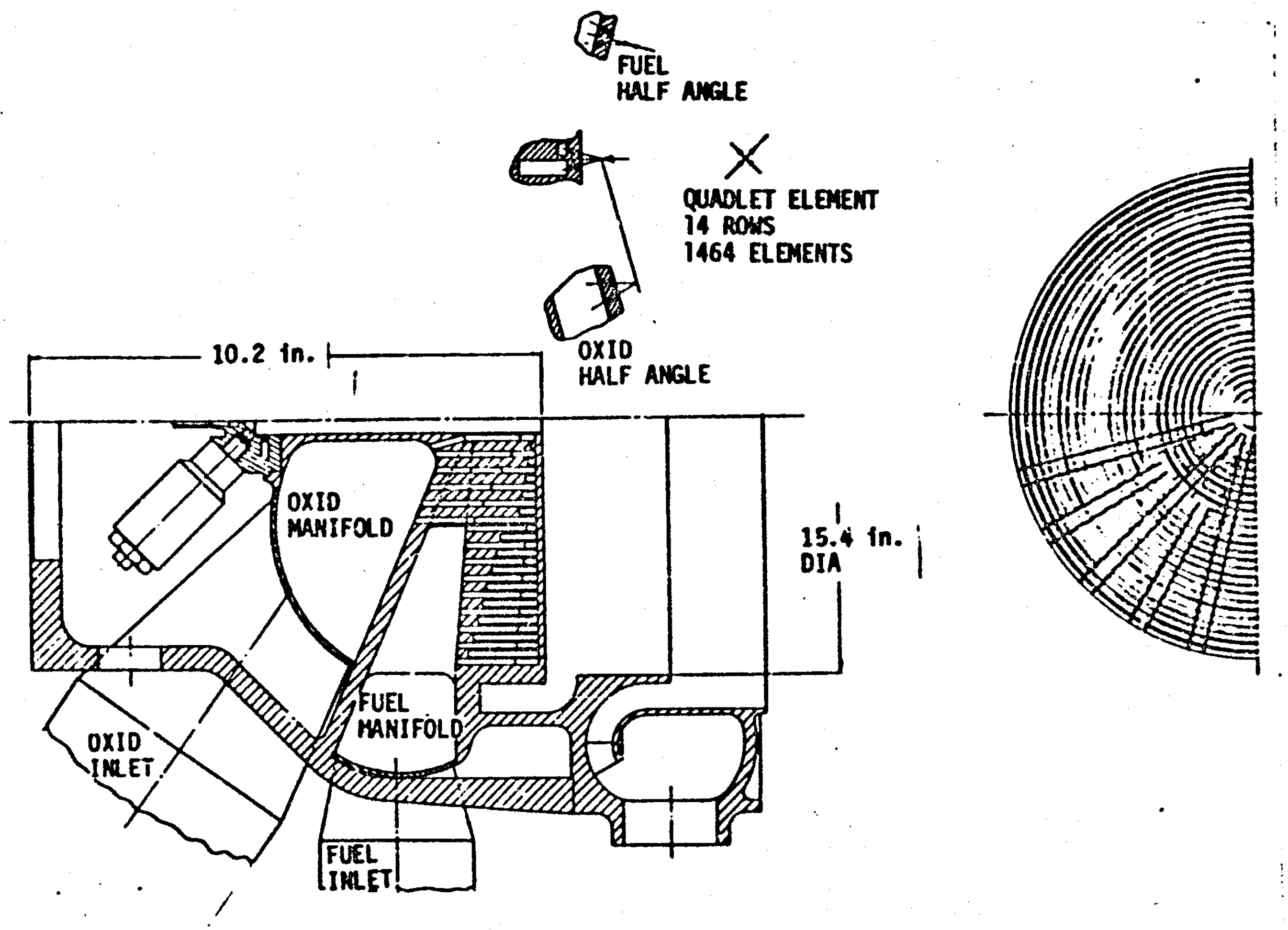

Figure 20. Alternate Mode 1 Gas Generator Cycle Engine Thrust Chamber Injector

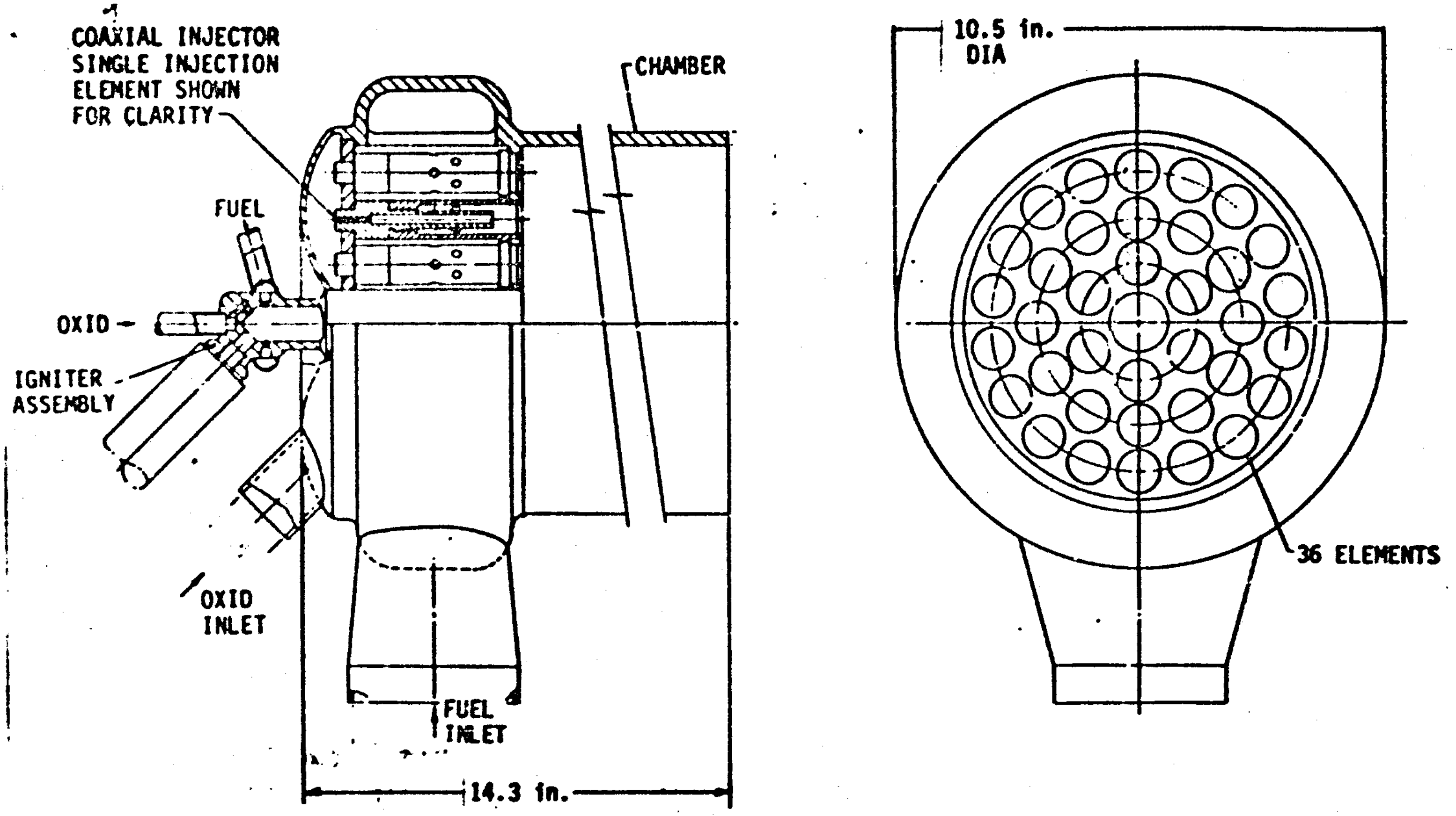

Figure 21. Alternate Mode 1 Coaxial Gas Generator

F = 600K lbF
Pc = 4300 psia
Isp_{SL} = 309 sec
Isp_{VAC} = 345.8 sec
O/F_{TCA} = 3.5
O/F_{GG} = 0.40
Expansion Ratio = 56.5
Oxidizer Main Pump Discharge Pressure = 5262 psia
Fuel Main Pump Discharge Pressure = 7953 psia

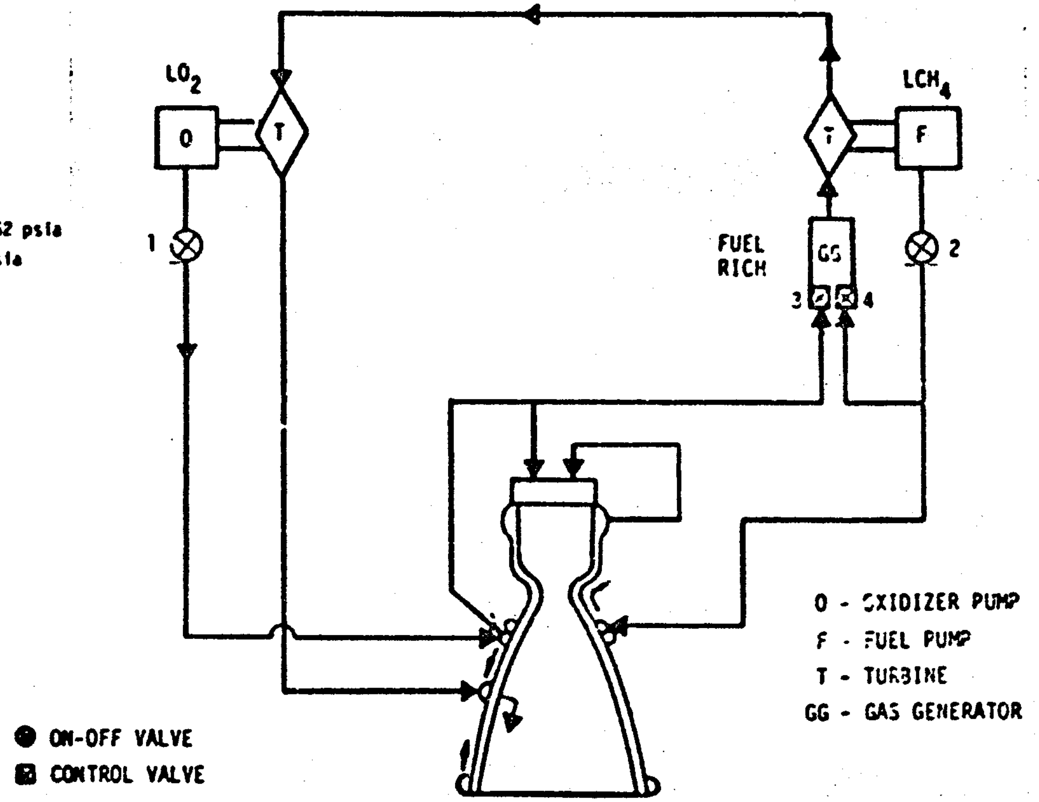

Figure 21A. LOX/LCH_4 Engine Flow Schematic line engine is shown in Table III. (The table includes estimates for engine weight using composites wherever possible.) The majority of the component weights shown in Tables II and III were based only on scaling equations or preliminary drawing volumes. The ten components selected for further study during Task III (Section V of this report) were stress-analyzed and drawn in detail to obtain more precise weights. (See Table VI.)

C. COMPONENT REQUIREMENTS DATA SHEETS

After selecting the two baseline engine configurations, physical requirements for the major engine components were documented on "Component Requirement Sheets." An example of a "Component Requirements Sheet" for the oxidizer TPA on the LOX/LCH_4 engine is shown in Figure 22. The remainder of these data sheets is contained in Appendix A. This evaluation of each component's physical characteristics (i.e., thrust, Isp, temperature, pressure, weight, etc.) laid the groundwork for beginning Task II.

TABLE III

Page 1 of 4

LOX/LCH_4 CYCLE C ENGINE WEIGHT DATA

Engine Components	Current Weight	New Weight	Weight Reduction
LO_2 TPA	(895)	(624.2)	(270.8)
Inducer Housing	122	90.7	31.3
Inducer	84	41.7	42.3
Impeller	51	25.4	25.6
Impeller Housing	144	49	95
Turbine Inlet Housing	66	66	-
Turbine Vanes	62	62	-
Turbine Rotors	217	217	-
Shaft	145	68.4	76.6
Bearings	4	4	-
CH_4 TPA	(661)	(396.8)	(264.2)
Inducer Housing	79	52.4	26.6
Inducer	63	19.9	43.1
Impeller	40	19.9	20.1
Impeller Housing	163	34	129
Turbine Inlet Housing	46	46	-
Turbine Vanes	42	42	-
Turbine Rotors	138	138	-
Shafts	86	40.6	45.4
Bearings	2.2	2.2	-
Add Miscellaneous	1.8	1.8	-
Injector	(611)	(477)	(134)
Body	373	282	91
Face	17	17	-
LOX Manifold Cover	33	25	8
Fuel Manifold Cover	33	25	8
Housing	51	24	27
Add Misc	4	4	-
Acoustic Cavity	100	100	-

LOX/LCH_4 CYCLE C ENGINE WEIGHT DATA (Cont'd)

Page 2 of 4

Engine Components	Current Weight	New Weight	Weight Reduction
High-Pressure Lines	(384)	(334.4)	(49.6)
Tubes (1)	30	12.8	17.2
Tubes (2)	178	178	-
Tubes (3)	40	40	-
Flanges (1)	80	47.6	32.4
Flanges (2)	16	16	-
Flex Joints	40	40	-
Combustion Chamber	(364)	(228.6)	(135.4)
Liner	154	154	-
Closeout	61	24	37
Manifolds	50	11	39
Support Structure	99	39.6	59.4
Nozzle	(328)	(220)	(108)
Tube Assembly	109	109	-
Manifold	93	58.5	34.5
Manifold	49	31	18
Reinforcing Rings	22	10.5	11.5
Jacket	55	11	44
LO_2 Boost Pump	(311)	(176)	(135)
Housing Hybrid	193	97	96
Inducer Bolt	7	7	-
Turbine	12	6	6
Shaft	60	27	33
Bearings	1	1	-
Add Miscellaneous	38	38	-

LOX/LCH_4 CYCLE C ENGINE WEIGHT DATA (Cont'd)

Engine Components	Current Weight	New Weight	Weight Reduction
Low-Pressure Lines	(253)	(113)	(140)
Tubes (1)	12	72	113
Tubes (2)	19		
Tubes (3)	54		
Tubes (4)	100		
Flanges	68	41	27
Gimbal	(204)	(133.6)	(70.4)
Seat	29	13	16
Body	166	114	52
Block	7	5	2
Shaft	2	1.6	.4
Miscellaneous	[174]	[174]	-
LOX Valves	(156)	(117.1)	(38.9)
Bodies	80	60.9	19.1
Balls	38	25	13
Shafts	13	6.2	6.8
Miscellaneous	25	25	-
Pressurization System	[138]	[138]	-
CH_4 Valves	(134)	(110.9)	(23.1)
Bodies	70	64	6
Balls	33	21.7	11.3
Shafts	11	5.2	5.8
Miscellaneous	20	20	-
Controller	(130)	(120)	(10)
Housing	42	32	10
Add Other	88	88	-

LOX/LCH$_4$ CYCLE C ENGINE WEIGHT DATA (Cont'd)

Engine Components	Current Weight	New Weight	Weight Reduction
Fuel Boost Pump	(103)	(62.5)	(40.5)
Housing	62	42	20
Inducer	15	7.5	7.5
Turbine	4	2	2
Inducer Bolt	.5	.5	-
Shaft	21	10	11
Bearings	.3	.3	-
Add Miscellaneous	.2	.2	-
Interpropellant Seal	[90]	[90]	-
Gas Generator	(76)	(52.8)	(23.2)
Injector Body	8	6	2
Manifold	13	9	4
Dome	5	3.3	1.7
Chamber	25	25	-
Elements	25	9.5	15.5
Ignition System	[40]	[40]	-
Hot-Gas Manifold	[23]	[23]	-
TOTAL WEIGHT	5075	3632	1443

BASELINE ENGINE: LOX/LCH$_4$ ENGINE (CYCLE C)

COMPONENT: OXIDIZER MAIN TPA

PUMP PRESSURE = 5262 PSIA
TURBINE PRESSURE = 4200 PSIA
$T_{PUMP} = 166^{o}R$
$T_{TURB} = 1860^{o}R$
W_{PUMP} = 1396.5 lbm/SEC
W_{TURB} = 156.61 lbm/SEC
ENVELOPE = 26.9 IN. (DIAM) x 36 IN. (LENGTH)
D_{IN} = 8.2 IN.
D_{OUT} = 3.1 IN.
WEIGHT = 895 lbm

MATERIALS:

a) SHAFT	A-286
b) IMPELLER	INCONEL 718
c) PUMP AND TURBINE HOUSING	ARMCO NITRONIC 50
d) INDUCER HOUSING	INCONEL 718
e) TURBINE	INCONEL 718
f) BOLTS (PUMP)	A-286
g) BOLTS (TURBINE)	WASPALOY
h) BEARINGS	CRES 440C

Figure 22. Sample "Component Requirements" Form

IV. TASK II - COMPONENT ASSESSMENT AND IDENTIFICATION

A. OBJECTIVES

Task II involved the assessment of all baseline engine components from Task I and the identification of those components which could potentially benefit the most from composite material substitution. Figure 23 displays a schematic which outlines the steps taken in performing this ta

The basic contractual ground rules from NASA-MSFC mandated that the selections for composite substitution be based primarily on weight savings, and secondarily on cost, life, and maintainability. It was also desired that the selections address a variety of new technology needs and not merely represent a direct application of existing airframe composite technology to simple components such as frames and gimbal rings.

B. COMPOSITE PROPERTIES AND FABRICATION PROCESSES

The initial effort in Task II was to gather and organize information pertinent to the uses and limitations of composite materials.

Material properties for the most commonly used reinforced plastic composites (RPC's) are contained in Appendix B. The material properties data were obtained from one of the following sources: 1) vendor data, 2) Air Force Composite Design Guide (Ref. 6), 3) technical seminars, 4) textbooks (Ref. 7), and 5) literature search of technical papers. Appendix C contains similar material properties data for the most commonly used metal matrix composites (MMC).

A short summary of composite fabrication processes, reinforcement characteristics, matrix characteristics, and material properties is shown in Figure 24 through 27, respectively. These figures are included for the

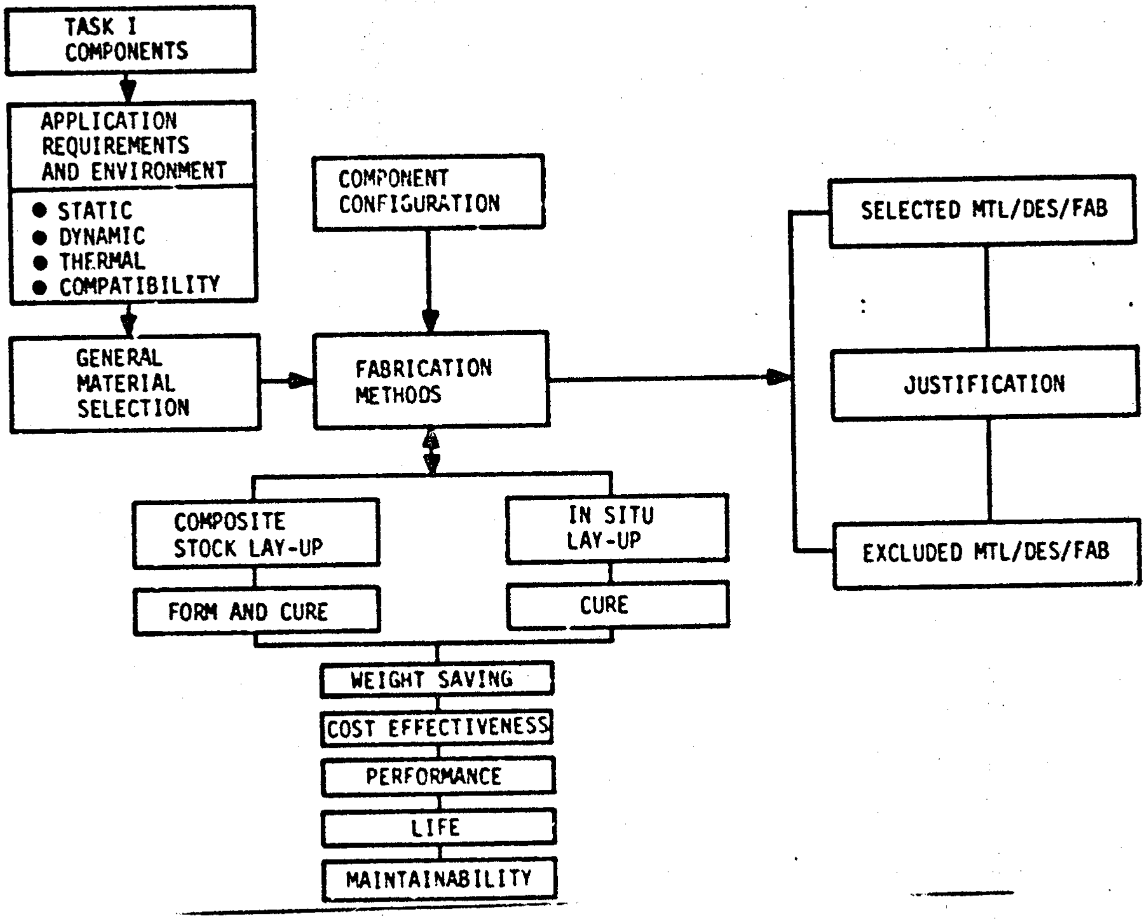

Figure 23. Task II Schematic

- COMPRESSION MOLDING - RESIN IMPREGNATED FIBER MATERIAL (CALLED PREPREG OR MOLDING COMPOUND) IS PLACED IN A MATCHED DIE MOLD AND HEAT AND PRESSURE ARE USED TO FORM AND CURE THE PART. FINISHED DETAIL IS GOOD AND INSERTS AND LINERS CAN BE INTEGRALLY ATTACHED
  (AUTOMOTIVE AND ELECTRONIC STRUCTURAL PARTS)
- AUTOCLAVE MOLDING - PREPREG IS PLACED ON A FORMING TOOL ALONG WITH A BLEEDER SYSTEM. THE LAYED UP MATERIALS ARE COVERED WITH A PLASTIC FILM AND SUBJECTED TO HEAT AND HIGH PRESSURE IN AN AUTOCLAVE. (EXAMPLE - ABLATIVE CHAMBER)
- VACUUM BAG MOLDING - SIMILAR TO AUTOCLAVE MOLDING EXCEPT THAT AMBIENT PRESSURE IS USED IN PLACE OF AUTOCLAVE PRESSURE. (NON-STRUCTURAL AIRCRAFT PARTS)
- PULTRUSSION - PREPREG MOLDING MATERIAL IS DRAWN THROUGH A DIE IN WHICH RAPID CURING OCCURS. THIS PROCESS IS LIMITED TO MAKING STRAIGHT PIECES HAVING A CONSTANT CROSS SECTION (AUTOMOTIVE DRIVE SHAFTS)
- REACTION INJECTION MOLDING - PREFORMED FIBER MATERIAL IS PLACED IN A MOLD CAVITY. RESIN IS INJECTED INTO THE MOLD WHERE IMPREGNATION AND MOLDING OCCUR (AUTOMOTIVE AND ELECTRONIC STRUCTURAL PARTS)

Figure 24. Fabrication Processes

● **KEVLAR** -	A SYNTHETIC ORGANIC FIBER WITH A VERY HIGH TENSILE STRENGTH AND MODULUS. ON THE OTHER HAND IT DISPLAYS POOR PROPERTIES IN COMPRESSION AND HAS PROBLEMS WITH MATRIX ADHESION TO THE KEVLAR FIBERS. GENERALLY LIMITED TO TENSION APPLICATIONS
● **GRAPHITE** -	MADE FROM A SYNTHETIC ORGANIC FIBER AS A RESULT OF A STRESS - GRAPHITIZATION PROCESS. IT POSSES HIGH TENSILE AND COMPRESSIVE PROPERTIES
● **FIBERGLASS** -	MADE FROM SILICA AND WIDELY USED AS A REINFORCEMENT IN COMPOSITE MATERIALS. NOT AS STRUCTURALLY EFFICIENT AS THE ORGANIC FIBERS, BUT VERY COST EFFECTIVE
● **BORON** -	FIBER IS MANUFACTURED BY VAPOR DEPOSITION OF BORON ON A TUNGSTEN WIRE FILAMENT. CHARACTERIZED BY A HIGH MODULUS THAT SUITS IT FOR USE IN BOTH RESIN MATRIX AND METAL MATRIX COMPOSITES. VERY EXPENSIVE

Figure 25. Reinforcement Characteristics

- **EPOXY** - WIDELY USED BECAUSE OF ITS CONVENIENT TRANSFORMATION FROM A LIQUID TO A PLASTIC SOLID AND BECAUSE OF ITS ABILITY TO ADHERE TO A WIDE VARIETY OF REINFORCEMENTS. EPOXY MATRICES ARE ADVERSELY AFFECTED BY EXPOSURE TO RADIATION, HIGH TEMPERATURE, HUMIDITY, AND CERTAIN CHEMICALS

- **POLYIMIDE RESINS** - SIGNIFICANTLY LESS CONVENIENT TO USE IN COMPOSITE MATERIALS THAN EPOXIES. LESS AFFECTED BY HIGH TEMPERATURE AND CHEMICAL EXPOSURE

- **ALUMINUM** - DIFFICULT TO PRODUCE AND IS STRUCTURALLY LESS EFFICIENT THAN THE PLASTIC COMPOSITES. ON THE PLUS SIDE, ALUMINUM HAS A HIGHER TEMPERATURE LIMIT AND IS LESS AFFECTED BY CHEMICAL FACTORS BECAUSE OF ITS IMPERMEABILITY

- **CARBON** - VERY DIFFICULT TO PRODUCE AND VERY EXPENSIVE. ITS STRUCTURAL EFFICIENCY AT VERY HIGH TEMPERATURES IS UNMATCHED

Figure 26. Matrix Characteristics

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	TEMPERATURE LIMIT	SPECIFIC TENSILE STRENGTH	SPECIFIC STIFFNESS	SPECIFIC COMPRESSION	IN PLANE SHEAR	THERMAL EXPANSION	VAPOR PERMEATION	COST	COMMENTS
KEVLAR EPOXY	350°F	HIGHEST	MODERATE	LOWEST	LOWEST	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	LOW	USED PRIMARILY IN PRESSURE VESSELS
GRAPHITE EPOXY	350°F	HIGH	HIGH	HIGH	HIGH	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	HIGH	STIFFNESS APPLICATIONS
FIBERGLASS EPOXY	350°F	HIGH	LOW	MODERATE	HIGH	LARGE IN BOTH DIRECTIONS	HIGH	LOWEST	MOST WIDELY USED.NON-STRUCTURAL APPLICATIONS
HYBRID GRAPHITE KEVLAR EPOXY	350°F	HIGH	HIGH	MODERATE	LOW	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	MODERATE	USED PRIMARILY IN PRESSURE VESSELS
HYBRID GRAPHITE FIBERGLASS EPOXY	350°F	HIGH	MODERATE	MODERATE	HIGH	LARGE IN BOTH DIRECTIONS	HIGH	LOW	USED EXTENSIVELY IN AIRCRAFT SECONDARY STRUCTURE
GRAPHITE EPOXY/ METAL LAMINATION	350°F	MODERATE	MODERATE	HIGH	HIGH	LARGE (TRANS) SMALL (FIBER DIRECTION)	LOW	HIGH	HIGH BEARING STRENGTH
CARBON-CARBON	4000°F	LOW	LOW	LOW	LOW	SMALL IN BOTH DIRECTIONS (CONTRACTION)	HIGH	VERY HIGH	HIGH TEMPERATURE APPLICATIONS, BUT VERY EXPENSIVE NON-OXIDIZING
BORON EPOXY	350°F	HIGH	HIGH	HIGH	HIGH	MODERATE (FIBER) LARGE (TRANSVERSE)	HIGH	VERY HIGH	USED IN AIRCRAFT PRIMARY STRUCTURE
BORON POLYIMIDE	550°F	HIGH	HIGH	HIGH	HIGH	MODERATE (FIBER) LARGE (TRANS)	HIGH	VERY HIGH	USED IN HIGH PERFORMANCE AIRCRAFT
BORON ALUMINUM	700°F	LOW	MODERATE	LOW	MOD-ERATE	MODERATE BOTH DIRECTIONS	LOW	HIGH	R & D APPLICATIONS

Figure 27. Properties of Various Components

reader's quick reference and information and are not intended to supplant the information in Appendices B and C.

C. METHODOLOGY AND EVALUATION FORM

The next effort in Task II was to establish a methodology for the assessment of the component concepts. This was accomplished by preparing an evaluation form containing logic which led to the selection of components most likely to benefit from composite substitution.

Table IV shows an example of the "Task II Evaluation Form" for the oxidizer TPA on the LOX/LCH_4 engine. A detailed description of the parameters being evaluated in Table IV is found in Figure 28.

D. COMPONENT SELECTION

Each major component from the earth-to-orbit baseline engine (LOX/LCH_4, Cycle C) and the orbit-to-orbit baseline engine (OTV) underwent an evaluation in accordance with the methodology described in Table IV. Appendix D contains the evaluation forms for both engines. This evaluation narrowed the field of 92 major components to 12 components which could potentially benefit most from composite material substitution. The component selection rationale followed the steps shown below:

1. Ten parts were selected from each engine system solely on the basis of weight savings to be gained through composite substitution. (A total of 20 parts.)

2. The twenty parts were categorized and numbered based on percent of engine weight savings.

TABLE IV

Page 1 of 2

TASK II EVALUATION FORM

ENGINE: LOX/CH_4 WEIGHT (lb): 895 RANKING: 1 TEMP (^oF): -290 PRESSURE (PSI): 5262

COMPONENT: LO_2 TPA % ENGINE WEIGHT: 17 1400

PART	MATERIAL DENSITY ($lbs/in.^3$)	CURRENT WEIGHT (lbs)	LENGTH/ DIA (in.)	PROPOSED FAB METHOD	CRITICAL FAILURE MODE	PROPOSED MATERIAL	VOLUME FRACTION (%)
INDUCER HOUSING	.3	37	9.5/12.4	COMPRESSION MOLD,MACHINE	TENSION BENDING	HYBRID KEVLAR GRAPHITE EPOXY	100
INDUCER	.3	19	10.7/9.3	COMPRESSION MOLD OR REACTION INJECTION MOLD, MACHINE	TENSION HCF BENDING EROSION	GRAPHITE EPOXY	100
IMPELLER	.3	12	5/16.8	COMPRESSION MOLD OR REACTION INJECTION MOLD, MACHINE	TENSION HCF BENDING EROSION	GRAPHITE EPOXY	100
IMPELLER HOUSING	.3	475	15/24	AUTOCLAVE MOLD	TENSION BENDING	HYBRID KEVLAR GRAPHITE EPOXY	100

TABLE IV (cont.)

Page 2 of 2

NEW WEIGHT (lbs)	DELTA WEIGHT (lbs)	COST RATING	MAINTENANCE RATING	SELECTED/ EXCLUDED	JUSTIFICATION FOR EXCLUSION
16.2	-21	4.7	3.4	EXCLUDED	ANOTHER TPA HOUSING WAS SELECTED FOR DESIGN ANALYSIS
9.5	-10	4.9	3.4	EXCLUDED	NOT A MAJOR WEIGHT SAVING
6	-6	4.8	3.4	EXCLUDED	NOT A MAJOR WEIGHT SAVING
291	-184	3.4	3.5	SELECTED	

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Engine:	Either LOX/LH_2 OTV or LOX/LCH_4 Cycle C
Component:	Name of major component (i.e., turbopump)
Weight:	Baseline metallic weight of component
% Engine Weight:	Component weight/total engine weight
Ranking:	Each component is ranked according to percent of engine weight. The heaviest is ranked No. 1.
Temperature and Pressure:	Design conditions that the component experiences.
Part:	Subcomponent (i.e., shaft or rotor of the turbopump)
Material Density:	Current metallic density
Current Weight:	Subcomponent metallic weight (Estimated by obtaining the approximate volume of the subcomponent and multiplying it by the metallic density).
Length/Diameter:	Subcomponent envelope
Proposed Fabrication Method:	A fabrication process will be selected for the composite component on the basis of cost, quality level, and functional properties.
Critical Failure Mode:	Most likely mode of failure, determined by preliminary structural analysis. This assessment aids in the preliminary composite material selection.
Proposed Material:	A composite material will be selected as a substitute for the metallic part on the basis of the following: (1) propellant compatibility, (2) low temperature toughness, (3) elevated temperature and pressure stability and strength, and (4) storage deterioration characteristics. An extensive material properties literature search, in conjunction with consultation of material engineering specialists, will provide the information necessary to make these selections.
Volume Fraction:	Estimated percentage of the subcomponent which can be replaced with a composite material.
New Weight:	Obtained by multiplying the metallic volume by the composite density. The volume estimate will be refined in Task III if the structural analysis indicates any wall thickness changes.
ΔWeight:	Difference in weight between the baseline metallic part and its composite substitute.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 1 of 5)

Cost:

The cost factor assessment methodology is illustrated on Sheet 3 of this figure. It provides a relative cost comparison for rocket engine components made from composite materials. Manufacturing costs are broken down into four categories: materials, labor, facilities and tooling. Material cost data are obtained from material suppliers. Labor manhours are estimated on the basis of the part's complexity and the required fabrication process. Tooling costs are similarly estimated. Facility costs are determined by the process selected and are estimated only on a very general basis.

The tooling, material, and labor costs are weighted equally because these manufacturing expenses are totally recovered in the price of the part. The facility cost is assigned a weighted factor one fifth (1/5) that of other component costs as these are prorated over other products produced at the facility.

Industrial engineering man-hour data available in the Air Force Composite Materials Design Guide (Manufacturing, Volume III) are being evaluated for use in estimating manufacturing costs (labor and tooling). Proposed manufacturing flow sheets, vendors, and subcontractors are also being used as sources of manufacturing cost data.

Maintainability:

The maintainability assessment methodology is illustrated on Sheet 4 of this figure. It provides a relative maintainability comparison for rocket engine components made from composite materials.

The maintainability factor is broken down into three categories: life, frequency of repair, and cost of repair. The life of a particular component is estimated from the stability of the material in the operational environments and/or its low cycle fatigue properties. The frequency of repair is estimated from the wear on the component due to chemical or mechanical erosion (abrasion) and/or its high cycle fatigue properties. The cost of repair is estimated from the amount of refurbishment required to restore the part to an acceptable level of performance.

A weighting factor of one fourth (1/4) was used to assess the effects of the frequency of repair and the cost of repair maintainability factors. The life component of maintainability was weighted higher (1/2) than the other components because it directly determines any need for maintenance.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 2 of 5)

COST FACTOR ASSESSMENT

Item	Σ Component Cost Factor (1-5) x Weighting Factor (0-1)				=	Relative Cost (R)
	Material(1) +	Labor(2) +	Facilities(3) +	Tooling(4)	=	R
LOX Pump						
Housing	CF x 5/16 +	CF x 5/16 +	CF x 1/16 +	CF x 5/16 +	=	R^1
Shaft	CF x 5/16 +	CF x 5/16 +	CF x 1/16 +	CF x 5/16 +	=	R^2

Notes

(1) Material Cost Factor Scale: 1 $\geq$ \$10K; 5 $\leq$ \$100

(2) Labor Cost Factor Scale: 1 $\geq$ 1K Man-hours; 5 $\leq$ 10 Man-hours

(3) Facilities Cost Factor Scale: 1 $\geq$ \$500K; 5 $\leq$ \$10K

(4) Tooling Cost Factor Scale: 1 $\geq$ \$100K; 5 $\leq$ 1K

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 3 of 5)

MAINTAINABILITY ASSESSMENT

Item	Σ Maintainability Component (1-5) x Weighting Factor (0-1)			=	Rating (R)
	Life[1]	Frequency of Repair[2]	Cost of Repair[3]		R
LOX Pump					
Housing	MC x 1/2 +	MC x 1/4 +	MC x 1/4 +	=	R^1
Shaft	MC x 1/2 +	MC x 1/4 +	MC x 1/4 +	=	R^2

Notes

(1) Life Maintainability Factor Scale: 5 = Exceeds SOW Requirement
1 = Not Reusable

(2) Frequency of Repair Factor Scale: 5 = No Incidence of Repairable Damage
1 = Refurbishment Required for Reuse (For Each Cycle)

(3) Cost of Repair: 5 = Repair is Less than $\frac{\text{Replacement Cost}}{\text{Cycle Life}}$
1 = Repair Exceeds Replacement Cost

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 4 of 5)

Selected/Excluded:	All of the above-mentioned parameters will be evaluated for an acceptance-exclusion decision. ΔWeight will be given major consideration in this decision, with cost, maintainability, performance, and life being considered secondarily.
Justification for Exclusion:	This will consist of a brief explanation why a subcomponent did not meet the requirements for composite substitution.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 5 of 5)

3. Any parts which duplicated the technology needs of another part were eliminated from consideration (retaining the one with the highest percent of engine weight savings.)

4. Finally, the number of parts was narrowed based on cost, life, and maintainability.

Table V shows a list of the twelve selected components, along with information on weight savings, proposed composite material, and proposed fabrication method. It must be stressed that these twelve components were selected primarily on the basis of weight savings and secondarily on the basis of cost, maintainability, performance, etc. It should also be understood that the numbers in the "Change in Weight" (ΔWT) column in Table V were based solely on preliminary structural analysis at this point in time. These numbers, however, were considered sufficiently accurate to select the best "weight savers." A more precise ΔWT number was obtained by measuring the cross-sectional area of the twelve finished drawings during Task III.

TABLE V

Page 1 of 2

TASK II SELECTED COMPONENTS

ENGINE	% ENGINE WT SAVINGS	COMPONENT	PART	PROPOSED MATERIAL	PROPOSED FAB METH	Δ WT	COST	MAINT
1) OTV	3.9	NOZZLE DEPLOY SYSTEM	SHAFTS	GRAPHITE EPOXY	PULTRUSSION	-22.5	4.9	3.8
2) LOX/CH_4	3.6	LOX TPA	IMPELLER HOUSING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-184	4.8	3.5
3) OTV	3.2	VALVES AND ACTUATORS	VALVE BODIES	KEVLAR EPOXY	COMPRESSION MOLD	-18.2	4.8	2.8
4) LOX/CH_4	2.8	CH_4 TPA	IMPELLER HOUSING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-140	3.8	3.9
5) OTV	2.3	NOZZLE DEPLOY SYSTEM	SUPPORT RING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-13.5	4.7	5.0
6) OTV	2.3	VALVES AND ACTUATORS	SHAFTS, GEARS	FIBERGLASS POLYIMIDE	COMPRESSION MOLD	-12.8	4.8	3.6

TABLE V (cont.)

Page 2 of 2

ENGINE	% ENGINE WT SAVINGS	COMPONENT	PART	PROPOSED MATERIAL	PROPOSED FAB METH	Δ WT	COST	MAINT
7) LOX/CH_4	2.3	INJECTOR	HOUSING	KEVLAR EPOXY	COMPRESSION MOLD	-119	4.1	3.7
8) OTV	2.3	COMBUSTION CHAMBER	SUPPORT STRUCTURE	KEVLAR GRAPHITE EPOXY	AUTOCLAVE MOLD	-13.2	4.5	5.0
9) LOX/CH_4	2.1	LOX BOOST PUMP	HOUSING	KEVLAR GRAPHITE EPOXY	AUTOCLAVE MOLD	-106.7	4.3	3.2
10) LOX/CH_4	1.3	NOZZLE	JACKET	GRAPHITE EPOXY	AUTOCLAVE MOLD	-63.8	4.5	3.9
11) LOX/CH_4	1.2	GIMBAL	SEAT	GRAPHITE EPOXY	COMPRESSION MOLD	-62.8	4.6	4.5
12) LOX/CH_4	1.1	COMBUSTION CHAMBER	MANIFOLDS	KEVLAR EPOXY	COMPRESSION MOLD	-54.8	4.1	3.7

V. TASK III - CONCEPTUAL DESIGN ASSESSMENT

A. OBJECTIVES

The major objectives of Task III were to prepare conceptual design drawings (cross sections) of each of the twelve components selected in Task II and to perform appropriate structural analyses as required to obtain realistic weight estimates. A secondary objective was to visit outside vendors in order to supplement our knowledge of cost, life, fabrication, and maintainability.

B. STRESS ANALYSIS

Preliminary drawings of the twelve selected concepts were reviewed by both structural and material engineering specialists, and the following analysis steps were taken with respect to each drawing:

1. On- and off-axis material structural property calculations
2. Von Mises failure criteria for biaxial mechanical stability
3. Residual thermal stress calculations for interlaminar and coating-interfacial stability at cryogenic temperatures
4. Stress analysis calculations to determine minimum section requirements

C. FINAL DRAWINGS AND WEIGHT ESTIMATES

Subsequent to the structural analysis, the final cross-sectional drawings were prepared for each of the twelve selected components. These drawings, shown in Figures 29 through 40, contain fabrication notes and information on technology needs.

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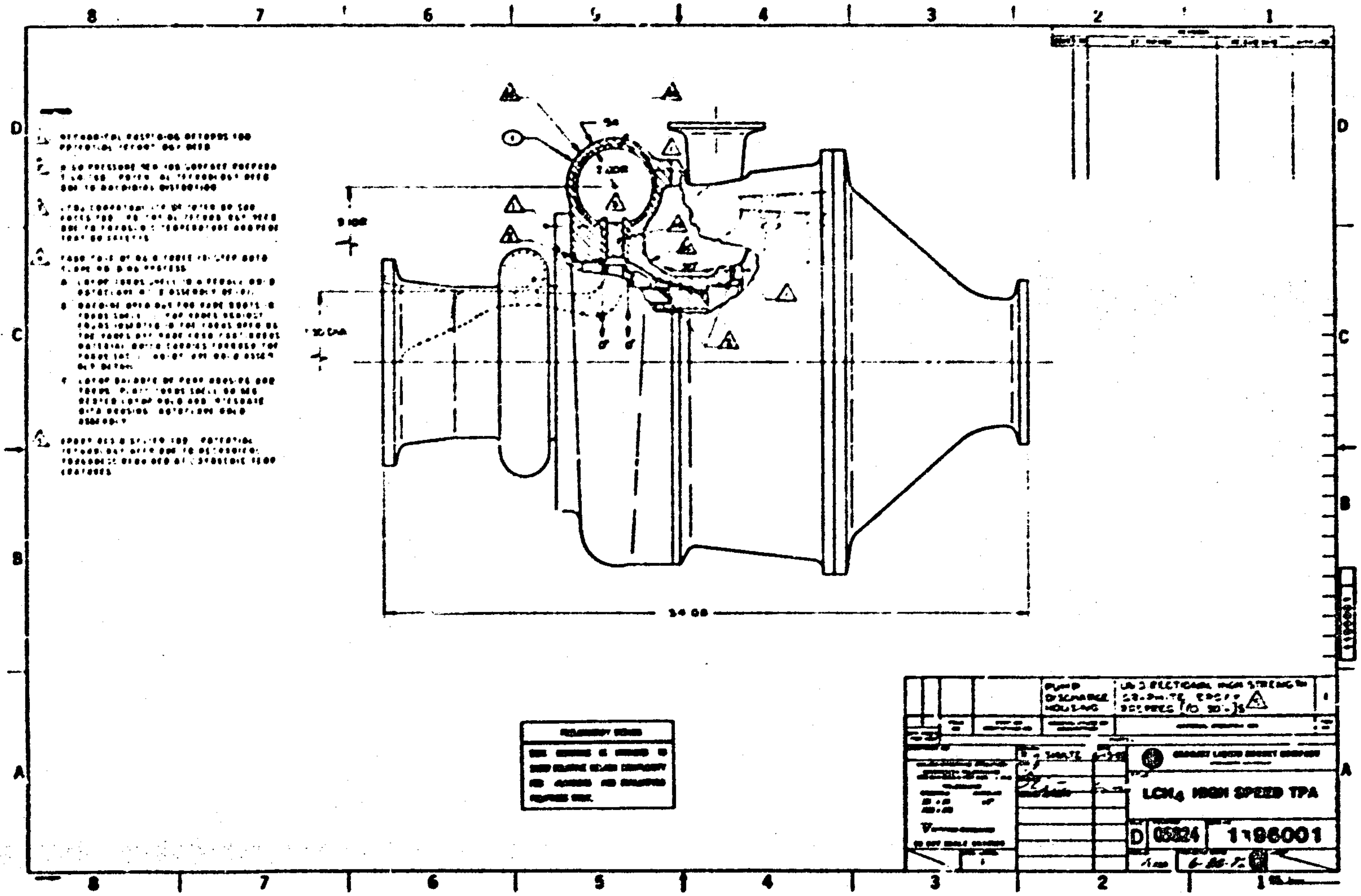

Figure 29. LCH$_4$ High-Speed TPA (ALRC Drawing No. 1196001)

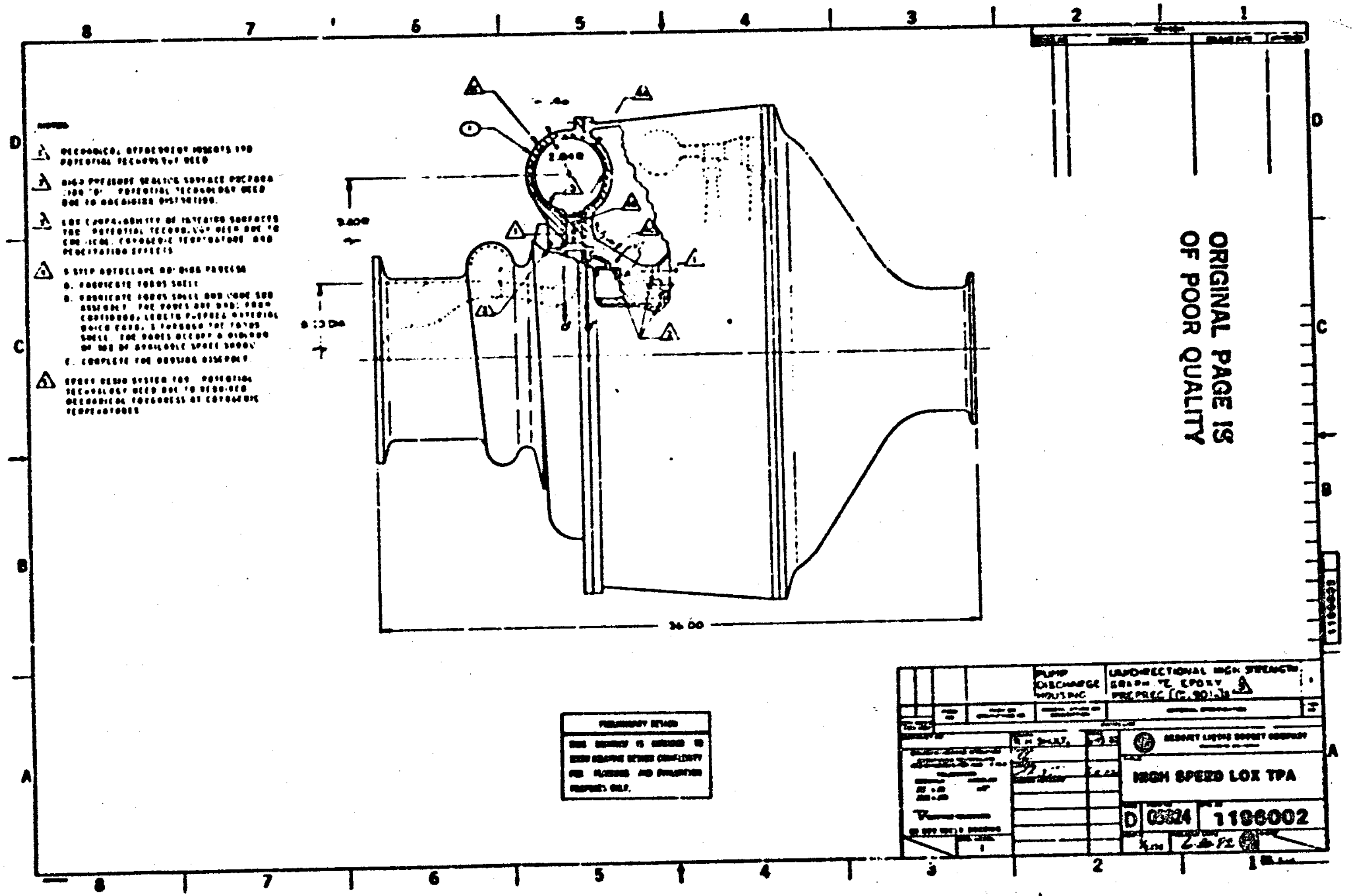

Figure 30. High-Speed LOX TPA (ALRC Drawing No. 1196002)

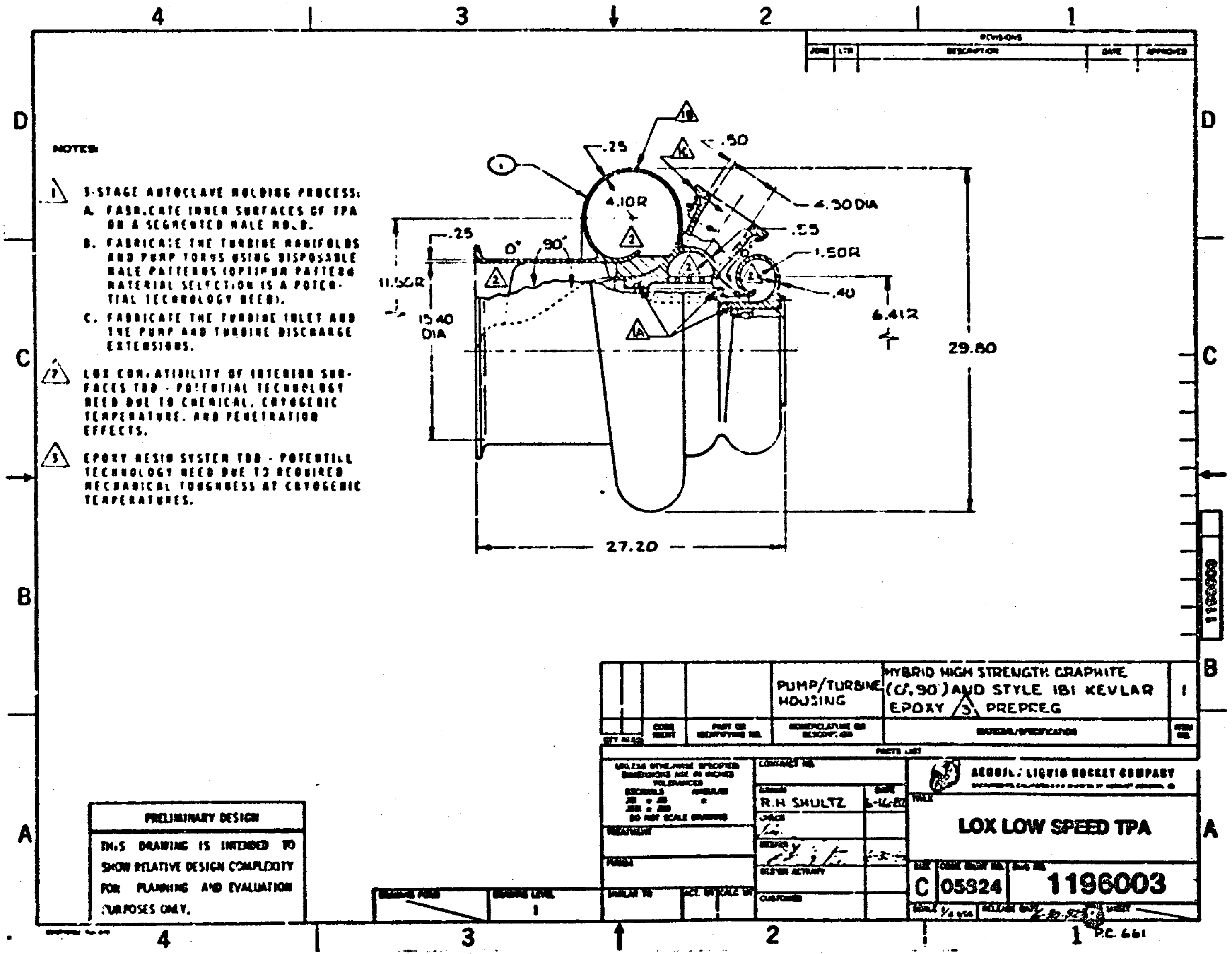

Figure 31. LOX Low-Speed TPA (ALRC Drawing No. 1196003)

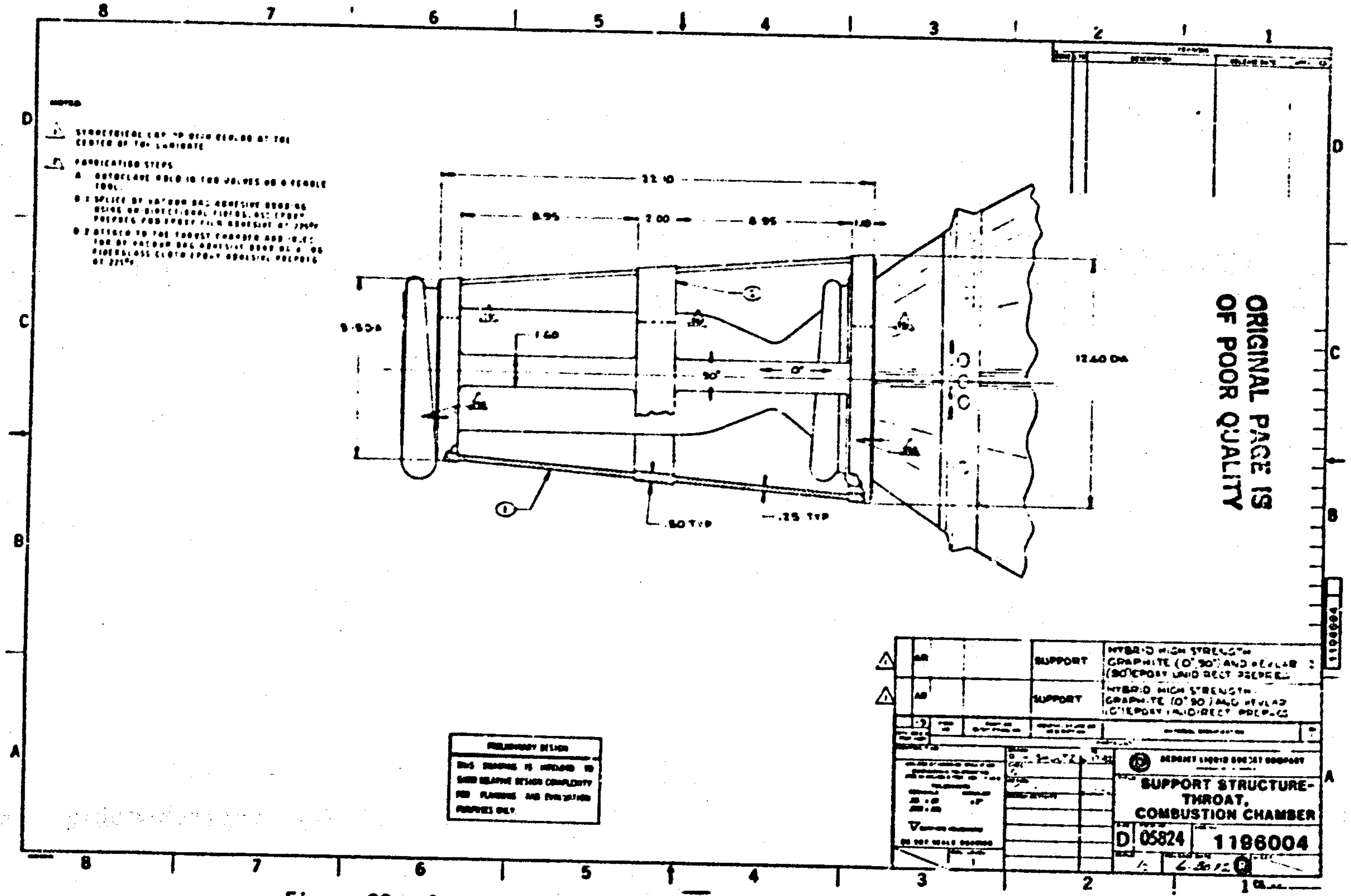

Figure 32. Support Structure - Throat, Combustion Chamber
(ALRC Drawing No. 1196004)

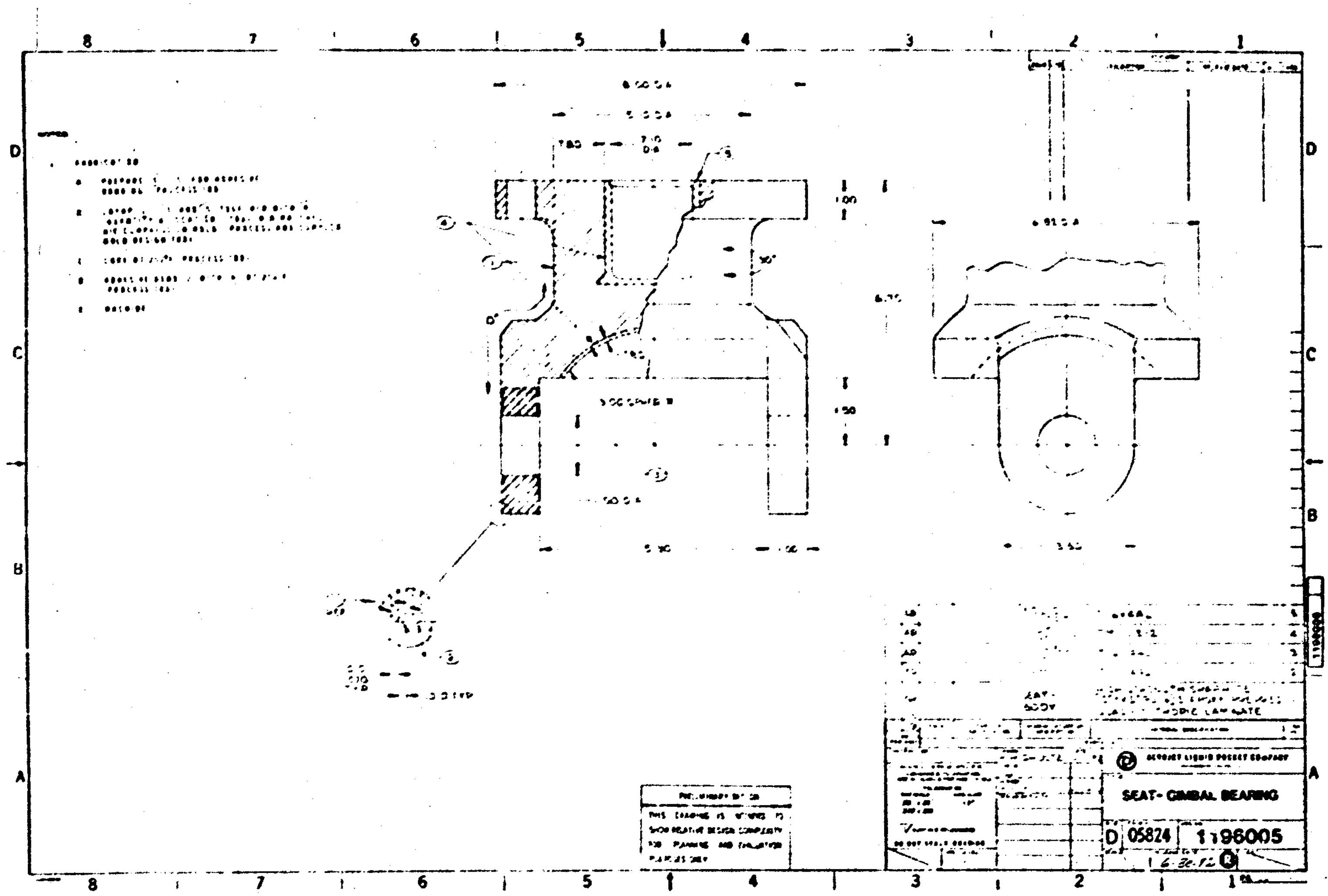

Figure 33. Seat - Gimbal Bearing (ALRC Drawing No. 1196005)

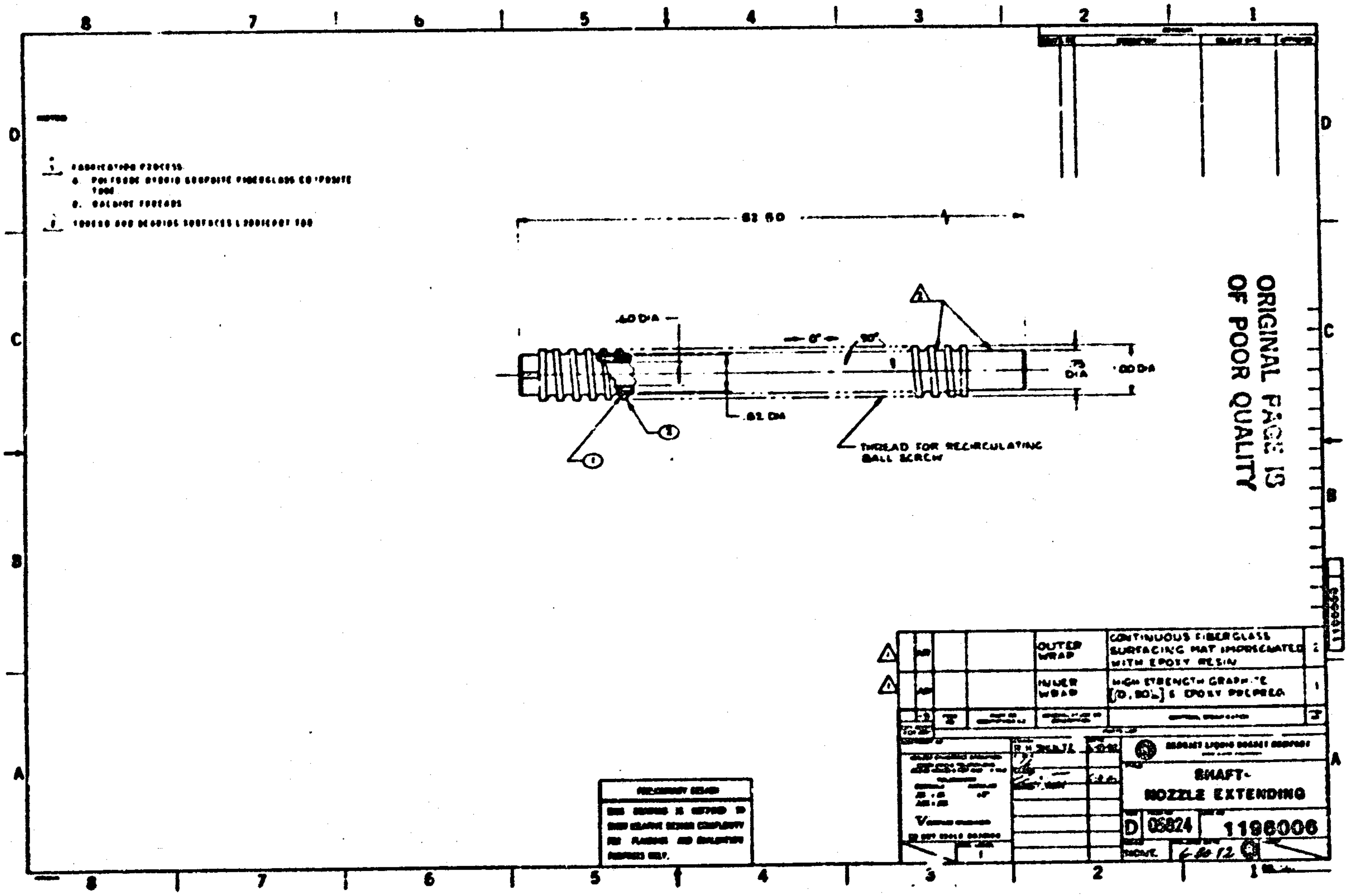

Figure 34. Shaft - Nozzle Extension (ALRC Drawing No. 1196006)

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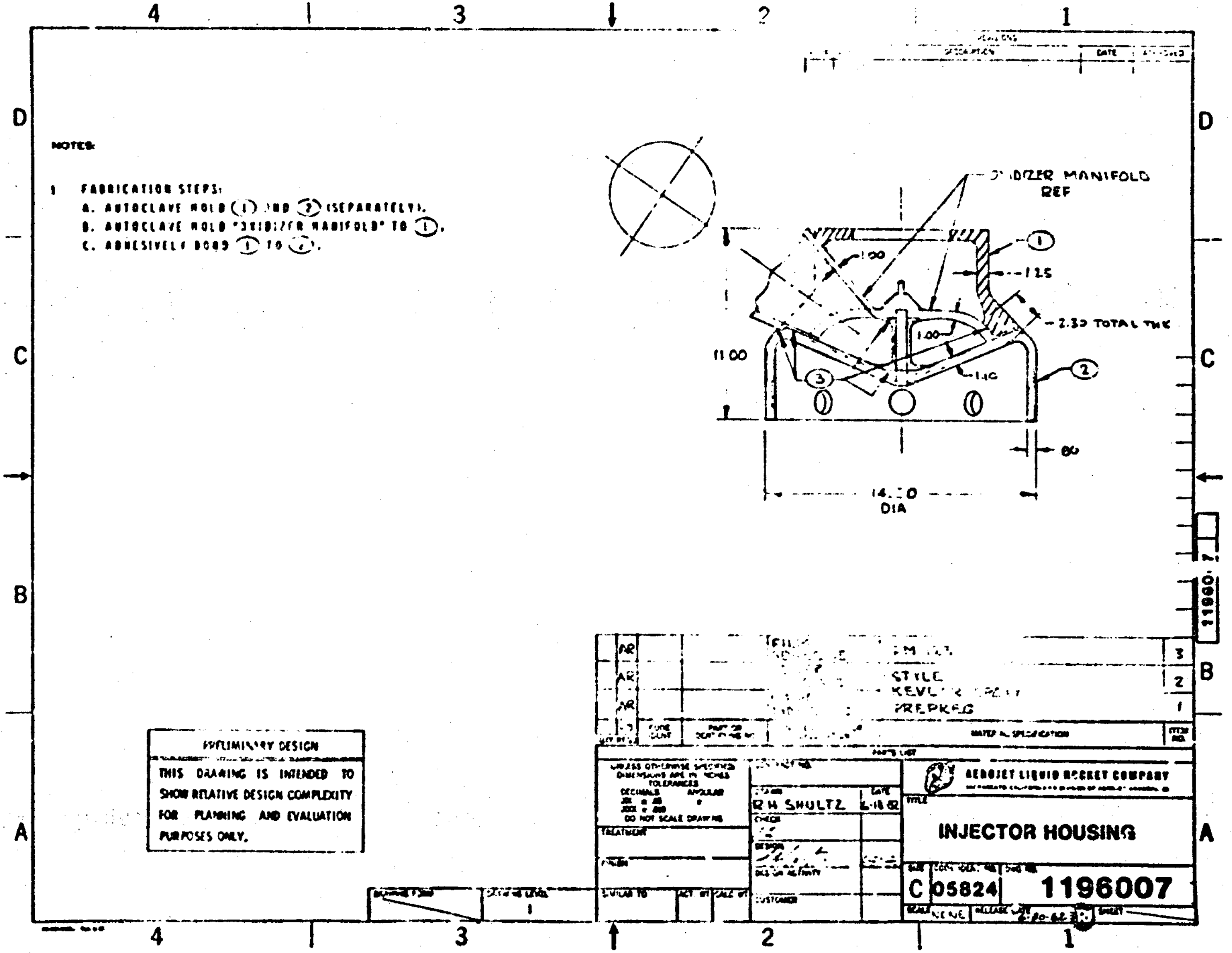

Figure 35. Injector Housing (ALRC Drawing No. 1196007)

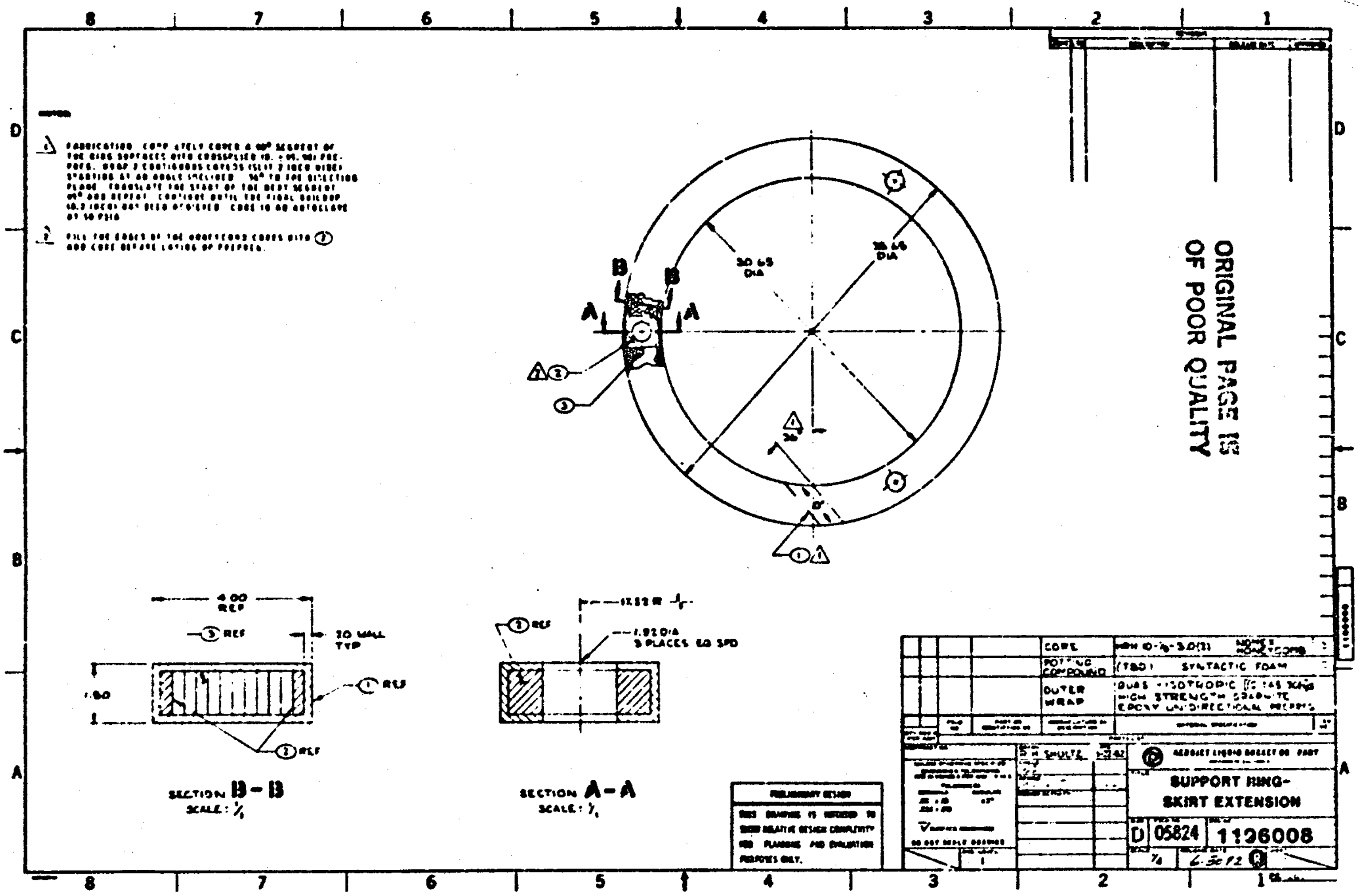

Figure 36. Support Ring - Skirt Extension (ALRC Drawing No. 1196008)

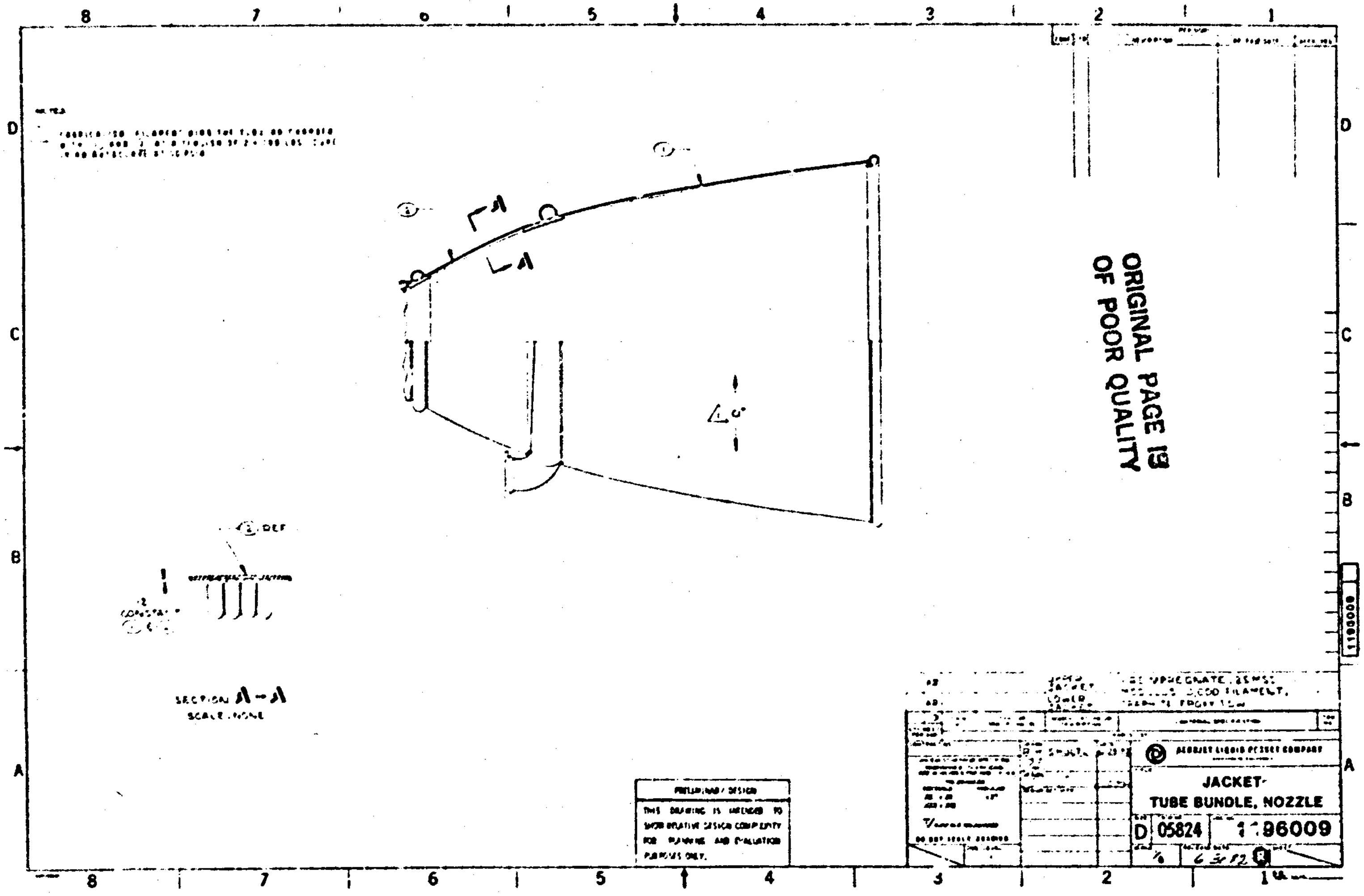

Figure 37. Jacket - Tube Bundle, Nozzle (ALRC Drawing No. 1196009)

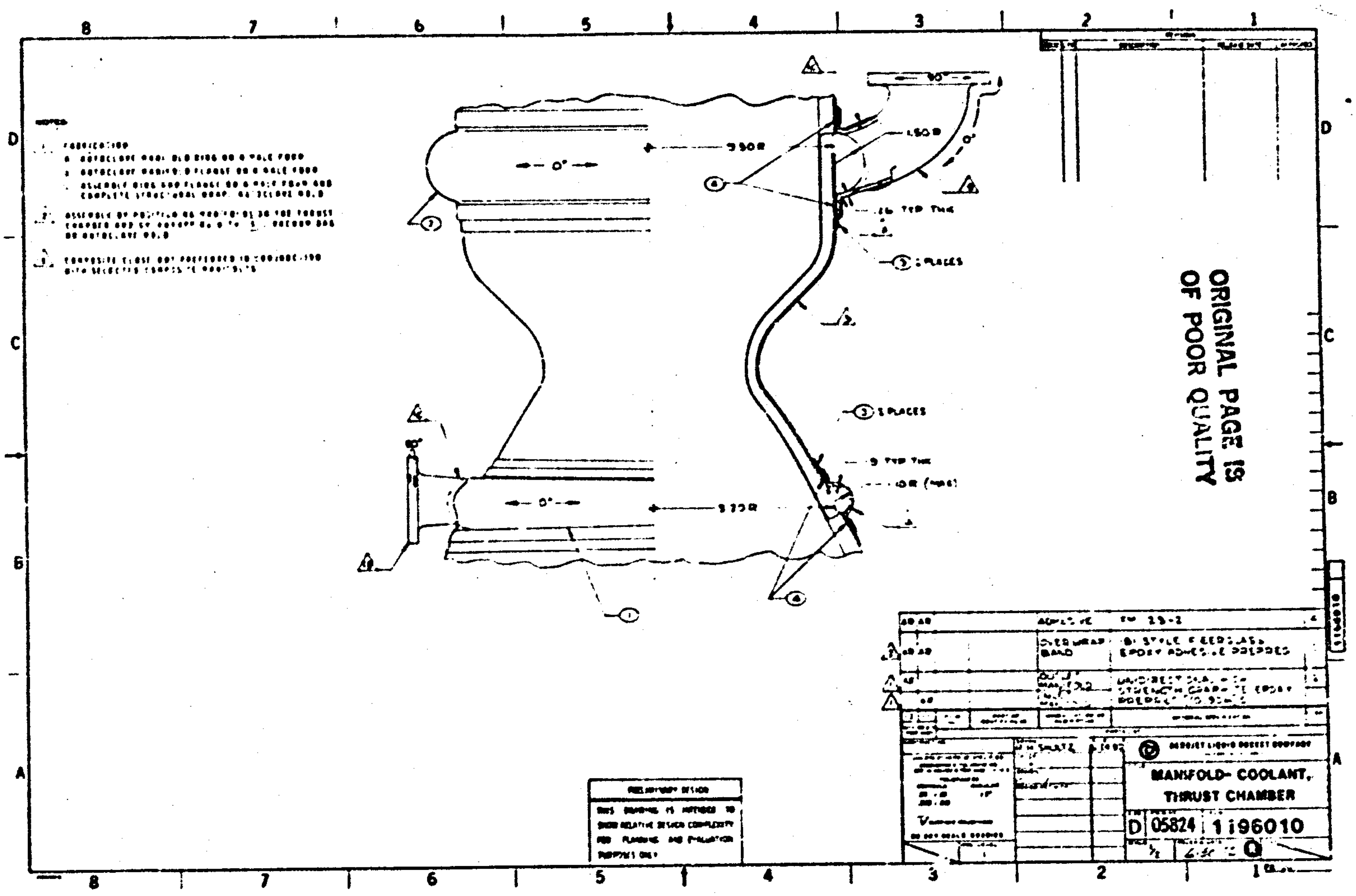

Figure 38. Manifold - Coolant, Thrust Chamber (ALRC Drawing No. 1196010)

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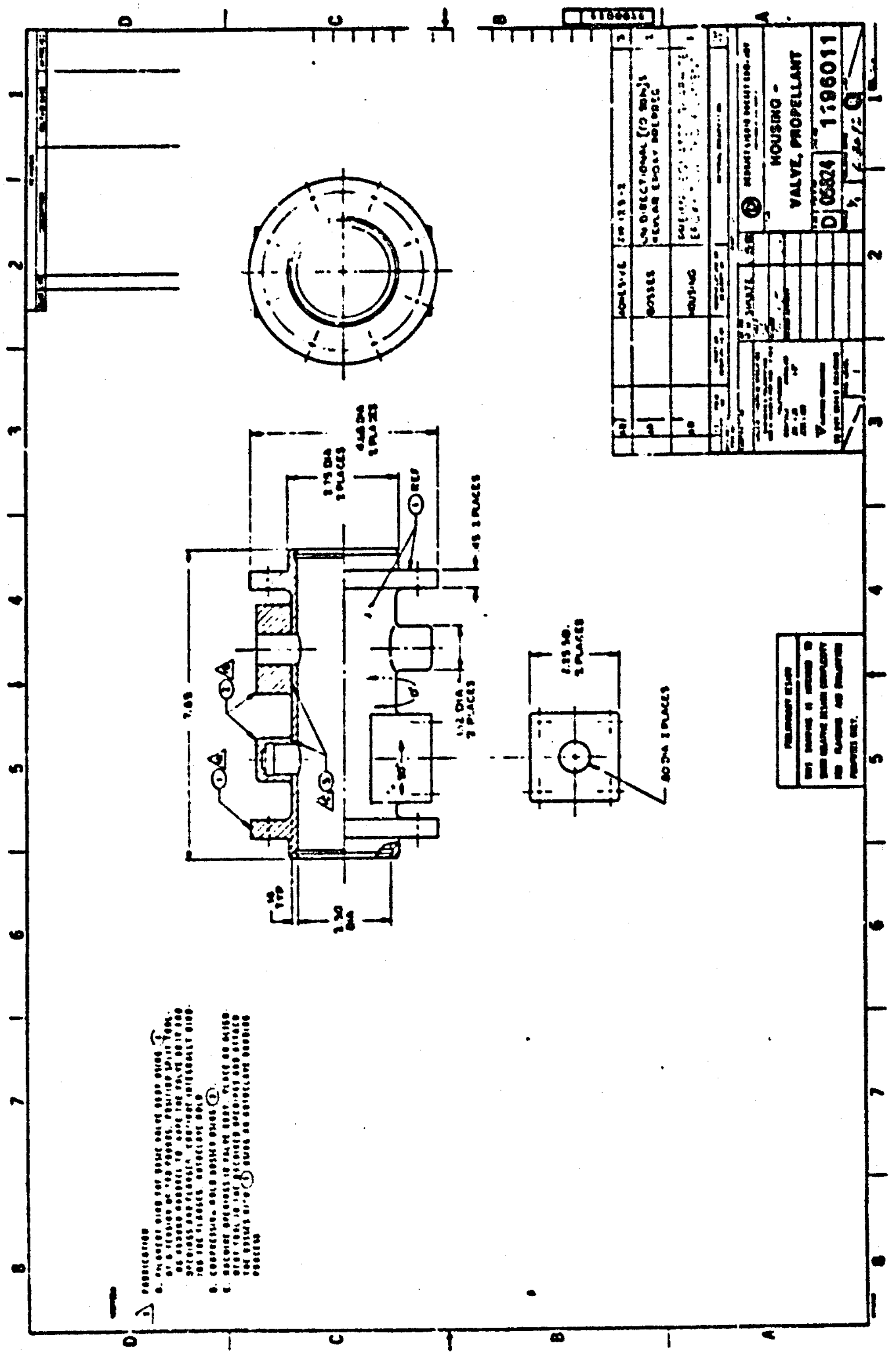

Figure 39. Housing - Valve, Propellant (ALRC Drawing No. 1196011)

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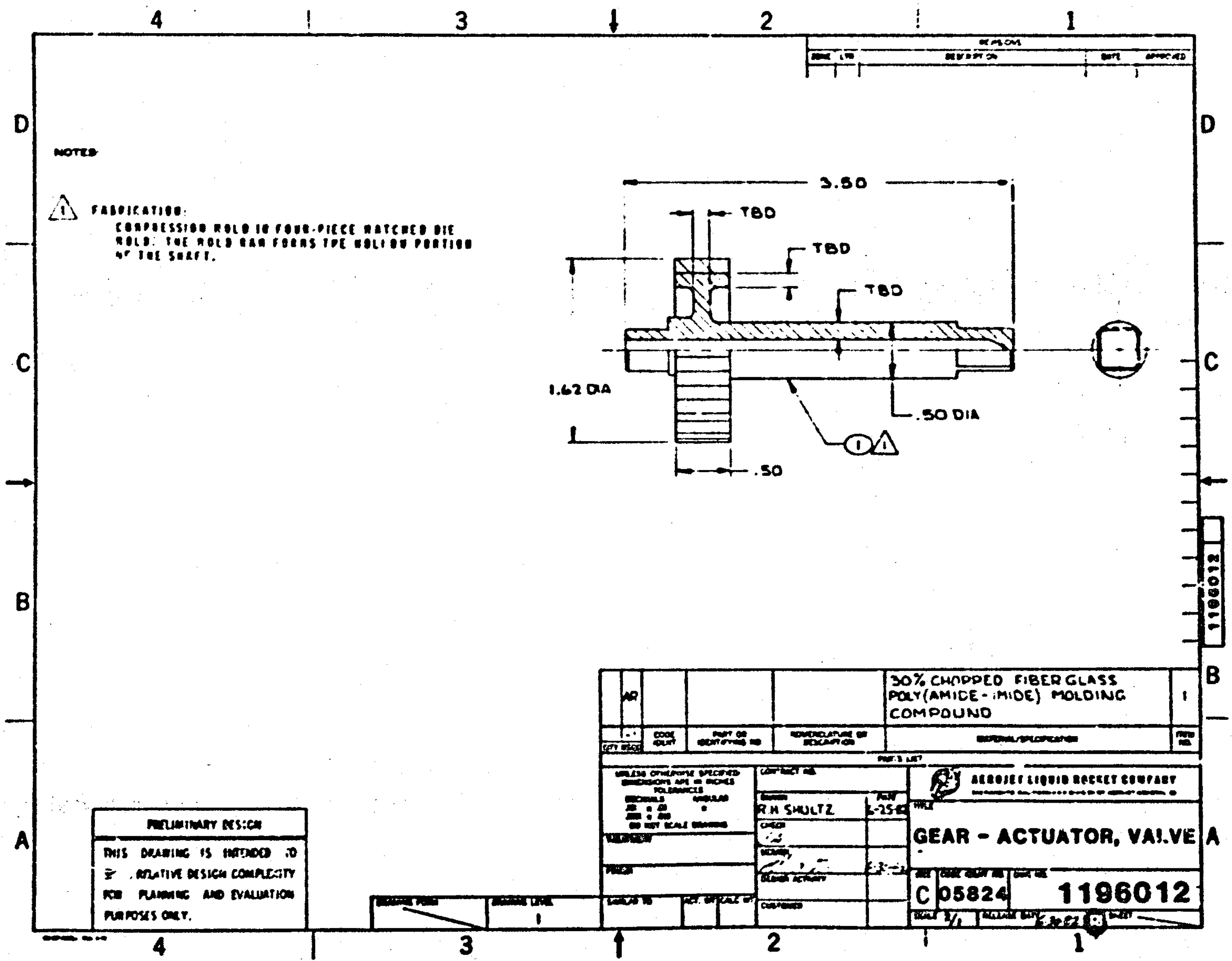

Figure 40. Gear - Actuator, Valve (ALRC Drawing No. 1196012)

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The weights of the composite-substituted components were then determined by using Simpson's rule to calculate part volume from the final drawing dimensions. Table VI contains data on component metallic weight, corresponding composite weight, and the percent weight savings achieved through composite substitution.

D. OUTSIDE VENDOR DESIGN INPUT CONCERNING REINFORCED PLASTIC COMPOSITES

The design concepts for the twelve selected parts benefited from consultation with a great variety of expert sources outside of ALRC during the course of the program. Table VII contains a complete list of every company contacted for consultation purposes.

A meeting was held with nonmetallic composite experts from the Aerojet Strategic Propulsion Company (ASPC) to review the twelve cross-sectional drawings from Task III. Their major comments were as follows:

1) Some of the more complex shapes would be a challenge from a fabrication standpoint, but are all considered feasible.

2) Extensive use of chopped molding compound (isotropic material) in low stress areas would promote the producibility of thick sections and complex surfaces where maintaining fiber alignment is difficult.

3) The use of woven fiber in low stress areas instead of unidirectional prepreg would aid in controlling fiber alignment.

TABLE VI

COMPONENT METALLIC WEIGHT VERSUS COMPOSITE WEIGHT

	Impeller Housing CH_4 High-Speed TPA	Impeller Housing LOX High-Speed TPA	Boost-Pump Housing LOX Low-Speed TPA	OTV Throat Support Structure	Gimbal Seat	OTV Nozzle Extension Shafts	Injecto Housing	OTV Skirt Support Ring	Nozzle Jacket	Combustion Chamber Manifolds	OTV Valve Housing	Valve Gear
	1196001	1196002	1196003	1196004	1196005	1196006	1196007	1196008	1196009	1196010	1196011	1196012
Metallic Weight (lb)	163	144	193	22	29	24	51	27	55	50	10	21
Composite Weight (lb)	34	49	97	5.6	13	4.9	24	14	11	11	2.6	4.6
% Weight Savings	79	66	50	75	55	80	53	48	80	78	74	78
Rank	3	8	11	6	9	1	10	12	1	4	7	4

TABLE VII

OUTSIDE VENDORS CONSULTED

VENDORS	SPECIALTY
1. AEROJET SOLID PROPULSION COMPANY	CARBON-CARBON AND FILAMENT WINDING
2. AFTON PLASTICS MOLDING COMPANY	PCTFE BARRIER COATINGS
3. AMERICAN AUTOMATED ENGINEERING INC.	AUTOCLAVE COMPRESSION AND TRANSFER MOLDING
4. CENTURY PLASTICS, INC.	VACUUM BAG MOLDING
5. DWA COMPOSITE SPECIALTIES, INC.	METAL MATRIX COMPOSITES MANUFACTURING
6. EDLER INDUSTRIES, INC.	AUTOCLAVE MOLDING
7. FIBIO, INCORPORATED	HARD AND CHOPPED-FIBER SPRAY LAY-UP
8. FIBERITE	COMPOSITE MATERIALS SUPPLIER
9. HAVIG-REINHOLD, INC.	AUTOCLAVE AND COMPRESSION MOLDING
10. HITCO	AUTOCLAVE MOLDING AND TAPE WRAPPING
11. M.C. GILL CORPORATION	BRAIDING
12. NETCO	METAL MATRIX COMPOSITES TESTING
13. PETERSON PRODUCTS	TRANSFER MOLDING
14. POLYMER DESIGN	RESIN CASTING
15. POLY-TRUSSIONS, INC.	PULTRUSSION
16. REYNOLDS AND TAYLOR	AUTOCLAVE MOLDING AND FILAMENT WINDING
17. RISDON CORPORATION	VACUUM DEPOSITED METALLIC COATINGS
18. SHIPLEY COMPANY, INC.	ELECTROLESS NICKEL COATING
19. SWEDOW, INC.	COMPRESSION MOLDING
20. 3M	COMPOSITE MATERIALS SUPPLIER

These comments were incorporated into the design of the components which were recommended for fabrication in Task V of this program.

In addition to the ASPC consultation, a trip was made to Los Angeles to meet with six fabricators of reinforced plastic composite materials. Appendix E lists the persons contacted during the visits, along with the product lines of the companies. Seven of the completed Task III drawings were reviewed by each of the contractors, and they were asked to assess their capabilities to make the parts together, listing the anticipated processing difficulties. They made comments on minor part-geometry redesign which would simplify fabrication and also indicated that they would like to be involved in the design of any part which would ultimately be fabricated at their facility. We also feel that if the bigger companies with composite design experience were involved in the design from the beginning, a lot of unnecessary and expensive supporting technology testing could be avoided in any follow-on fabrication program. All of the companies felt that the components would be satisfactory for manufacturing, and some of the companies prepared price quotes for inclusion in the Task V section of this report.

E. OUTSIDE VENDOR DESIGN INPUT CONCERNING METAL MATRIX COMPOSITES

Outside vendor consultations (Table VII) were made during the course of the program with regard to the application of metal matrix composites to the selected components. The companies visted were Nevada Engineering & Technology Corporation (NETCO), DWA Composite Specialities, and Aerojet Solid Propulsion Company. A summary of their major comments is presented in the following listing. (Also see Appendix E.)

V, D, Outside Vendor Design Input Concerning Reinforced Plastic Composites (cont.)

1) Selected parts too complex for fabrication by laying up MMC laminates and diffusion bonding.
2) TPA impeller housing is well beyond state of the art.
3) In complex shapes with multidirectional stress distributions, boron-aluminum and graphite aluminum become inefficient.
4) Valve housing could be fabricated from an aluminum-silicon carbide composite (powder metallurgy) such as DWA-AL. This material, however, possesses poor weldability.
5) MMC components would be lighter than those made from unreinforced metal but heavier than those made from RPC's.
6) No problems with permeability or compatibility.

Based on the recommendations of both outside expert sources and ALRC materials engineering experts, it was decided that reinforced plastic composites were preferable for fabricating the selected designs (Task V). Metal matrix composites are out of consideration at the present time because of their higher cost, lower specific strength, and greater fabrication difficulties. Table VIII contrasts the weights and fabrication risks of three individual components made from 1) RPC, 2) boron-aluminum, 3) silicon carbide-aluminum, and 4) baseline metal, respectively. The weights in Table VIII were determined analytically by performing a stress analysis to determine the appropriate wall thickness for each material. It can be seen that the RPC components are lighter in every case and pose far fewer fabrication difficulties.

If higher temperatures and greater performance become more important "drivers" than weight savings in future programs, it is possible that the use of certain MMC or ceramic materials would be indicated. For the present study, however, it is clear that RPC components are lighter and more cost-effective.

TABLE VIII

PLASTIC MATRIX VERSUS METAL MATRIX COMPARISON CHART

Material	LCH_4 TPA Discharge Housing - 1196001		Injector Housing 1196007		Valve Body 1196011	
	Weight (lb)	Fab. Risk	Weight (lb)	Fab. Risk	Weight (lb)	Fab. Risk
Reinforced Plastic Composite	34	Low	24	Low	1.3	Low
Crossplied Boron-Aluminum Composite	68	High	31	High	2.1	High
Silicon Carbide-Aluminum Particulate Composite	75	High	38	High	2.4	Moderate
Baseline Metal	163	Low	51	Low	5.0	Low

VI. TASK IV - CRITICALITY RANKING OF TECHNOLOGY NEEDS

A. OBJECTIVES

The first objective of Task IV was to define the technology needs involved in developing the twelve selected concepts and to evaluate those needs in terms of level of risk involved in bringing those technologies to operational status. The second objective of Task IV was to provide a criticality ranking of the identified technology needs and to justify the rankings with narrative and figures of merit.

B. TECHNOLOGY NEEDS

At the commencement of Task IV, a great deal of thought was given to defining the technological barriers that would need to be overcome in order to successfully build production rocket components out of reinforced plastic composites. A list of these technology needs is shown in Table IX.

Each of these technology needs was evaluated to establish the impact of required technology. Figure 41 is a schematic which outlines the steps taken during this evaluation. Each major component was examined to identify any parts that had not been developed. Except for rocket nozzles, where composite nozzles have been used, essentially all composite-substituted components fall into the new-with-composite screening category.

Those parts requiring further development were then evaluated in terms of the level of risk that would be involved in bringing them to operational status. The degree of risk was categorized between low (for components that are just short of being operational) to high (for components that have only been proposed or theorized). The sensitivity of each component to these risks was assessed in terms of cost, schedule, performance, life, weight, and commonality of technology. The results of this evaluation were

TABLE IX

TECHNOLOGY NEEDS LISTING

1.0	H_2 Compatibility	
2.0	O_2 Compatibility	
3.0	CH_4 Compatibility	
4.0	Low Temperature Toughness	
5.0	Fabrication	
	5.1	Mechanical Fastening
	5.2	Sealing Surface Finish
	5.3	Vane Manufacturing Method
	5.4	Vane Attachment Method
	5.5	Fabrication Sequence
	5.6	Barrier Coating Process
	5.7	Plumbing Connections
	5.8	Detail Joining Methods
	5.9	Detail Fabrication Methods
	5.10	Mold Design
6.0	Cryogenic Properties	
7.0	Interface Properties	
8.0	Metal Coating Interface Properties	
9.0	Differential Expansion Properties	
10.0	Solar Radiation Effects	
11.0	Low Cycle (Thermal) Fatigue	
12.0	High Cycle Fatigue (HCF)	
13.0	Bearing Surface Lubricant	

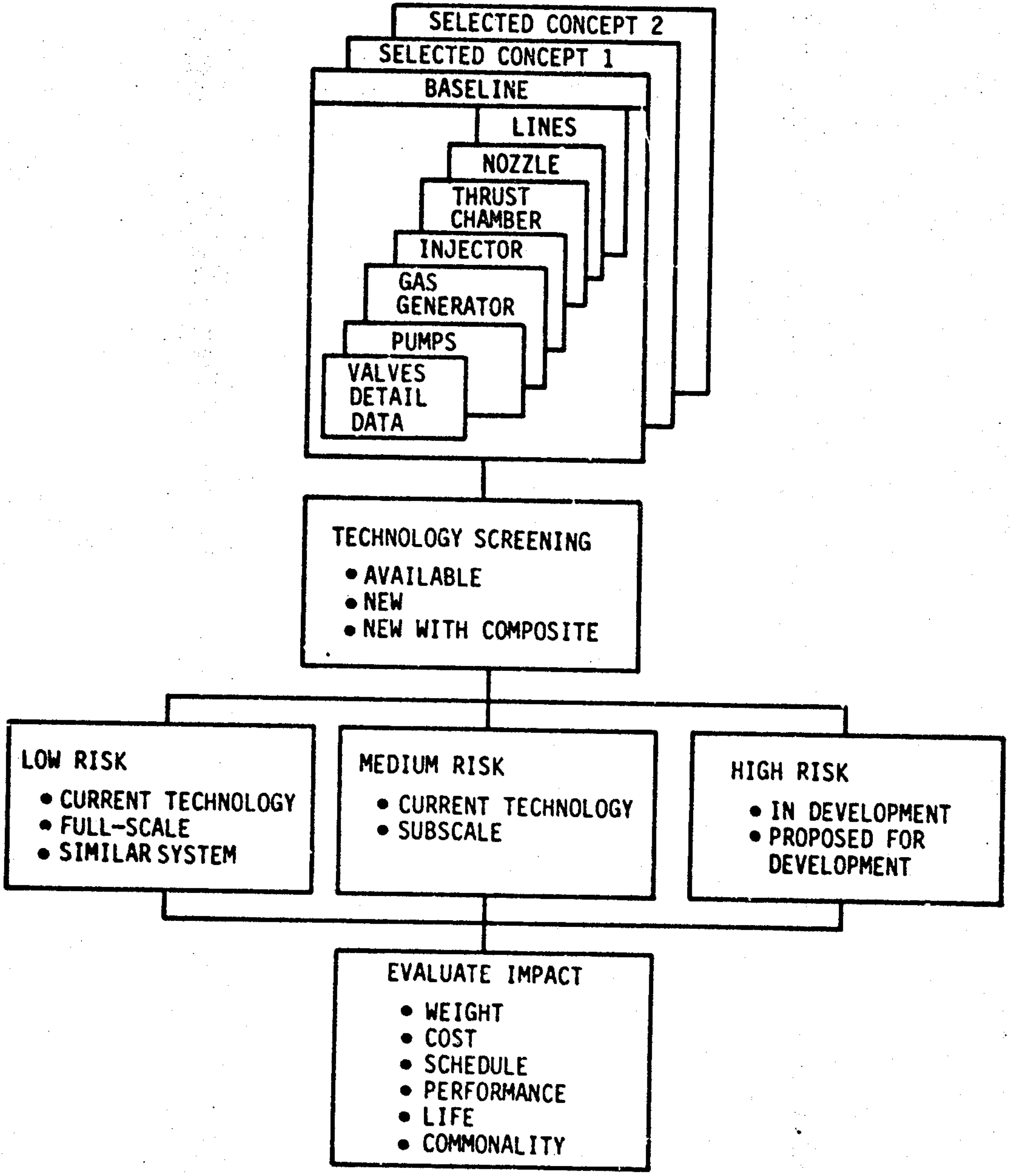

Figure 41. Technology Risk Assessment Procedure

documented in a series of "Technology Need Definition" forms. One of these forms was filled out for each of the categories shown in Table IX. This form defined the technology need, assessed its risk, suggested an approach to the problem, and proposed a solution. An example of one of these forms is shown as Figure 42 (Barrier Coating Process), and the balance is included as Appendix F in this report.

Many of the thirteen technology needs lend themselves to easy solutions and were only included out of a desire for thoroughness (i.e., solar radiation, bearing surface lubricant, etc.). It is believed that the balance of the technology needs can be solved through straightforward laboratory and test programs. This optimism about the ability to quickly solve the thirteen technology needs through technology programs is based on the following rationale:

1.0-3.0 <u>Propellant Compatibility</u> - Problems which can result from chemical incompatibility or from freeze-thaw cycling (causing cracks) will be precluded by the application of internal barrier coatings. (See 8.0 below.)

4.0 <u>Low Temperature Toughness</u> - Thermoset polymer matrix composites are brittle materials at room temperature. Evidence of this is seen in the resin microcracking that results from the residual thermal stress from curing at elevated temperature. These composite materials, however, exhibit a remarkable toughness capability because of the many individual fiber and resin interfaces, each of which is structurally redundant. This results in a fracture process that is progressive rather than sudden, as is characteristic of conventional brittle materials. Such behavior is characteristic of outstanding fracture toughness. Because the strength of polymer matrix composites is known to increase slightly at cryogenic temperatures, their fracture

ITEM: 5.6 - Barrier Coating Process

DESCRIPTION: High-performance plastic composites must be sealed in order to contain liquids and vapors.

ASSESSMENT OF RISK:

[✓ High] * Medium Low

*Microcracking occurs in the resin matrix of high-performance composite materials. These cracks result from residual and applied stresses. They render the resin matrix permeable to vapors and liquids.

APPROACH: Several barrier coatings (metal foils, plastic films, etc.) have been used successfully to seal composite materials. These coating materials and processes will be evaluated to select the optimum system for a given rocket engine component.

PROPOSED SOLUTION: Ductile barrier coatings are required to seal composite materials.

Figure 42. Technology Need Definition, Barrier Coating Process

toughness is not expected to decrease significantly at low temperatures because of any embrittling effects.

Structural element tests (including impact) at cryogenic temperatures are planned to confirm that this is true for the candidate composite materials and processes being considered for this program.

5.0 Fabrication - Any potential fabrication problems (i.e., fastening, barrier coating, sealing surface finish, etc.) will be solved through the development of manufacturing techniques during the technology programs. None of the identified fabrication technology needs pose a serious problem in view of the current state of the art with RPC's.

6.0 Cryogenic Properties - This is a low-risk technology need due to the existence of commercial composite materials which display high strength and good fracture toughness at cryogenic temperatures. Before finalizing any design, the structural and physical properties of the candidate material will be verified by structural testing at cryogenic temperatures.

7.0 Interface Properties - Strong adhesive bonds between two composite parts or between a composite and a metal part have been demonstrated successfully in the aircraft industry. The stability of these adhesive bonds at cryogenic temperatures will be analyzed, and each proposed combination will be tested to validate the predictions. In the event that the predicted structural performance is not attained because of poor adhesive bonding, other design alternatives will be investigated (i.e., bolting, riveting, sewing, etc.).

C-2

8.0 Metal Coating Interface Properties - The use of metallic barrier coatings is anticipated in order to protect the composite material from degradation caused by contact with the liquid rocket propellants. The large temperature excursions caused by cryogenic conditions are expected to result in significant bondline strain. This strain problem can be partially mitigated by tailoring the thermal expansion properties of the composite through control reinforcement and fiber volume (Ref. 8). Another technique which has been successfully used is to apply an elastomeric adhesive tie coat that approximates the expansion characteristics of the metal barrier (Ref. 9). A stable metal coating interface should result if the adhesive bond to the composite is strong enough to prevent separation during thermal excursions. The use of more than one tie coat adhesive introduces additional interfaces and reduces the stress at the two key interfaces for greater bond stability.

Satisfactory metal-lined tanks and propellant (LOX) lines of polymer composite have been fabricated and tested by the Martin Company under contract to NASA (Ref. 10 and 11).

9.0 Differential Expansion Properties - Differential expansion between contacting dissimilar materials results in interfacial stress. Stress rupture and disbonding are two harmful effects of differential expansion. A preliminary structural analysis performed at ALRC indicated that satisfactory dissimilar material interfaces can be developed over the temperature ranges anticipated (see 8.0 above).

10.0 Solar Radiation Effects - The surface of epoxy matrix composite materials is degraded by solar radiation. This degradation results in surface crazing and decreases the composites' chemical resistance. This appears to be a low-risk technology need since protective coatings are available to block solar radiation. The effectiveness of these coatings can be demonstrated in ultraviolet (UV) weatherometer exposure tests.

11.0 Low Cycle Fatigue (LCF) - Low cycle (thermal) fatigue results from structural damage in which thermal stress was a contributing factor. In composite materials, these stresses can result because of flaws in the material, dissimilar material interfaces, anisotropy, or poor bonding. Past experience shows that once the cause of the structural damage has been identified (through structural element testing), one can design around it. Examples of composite components in use today which are designed to successfully withstand low cycle thermal fatigue are 1) fiberglass LN_2 bottles, 2) natural gas vessels, and 3) parts in cryogenic wind tunnels.

12.0 High Cycle Fatigue (HCF) - High cycle (thermal) fatigue results from structural damage that is caused by stress-induced microstructural changes in the material. These changes occur generally because of some discrete mechanism that allows the stress to reach a destructive level. This mechanism depends upon a crack, void, disbond, or dissimilar material interface and a dynamic change in the level of stress due to vibration or movement.

In the case of RPC's, designing for HCF is a low-risk technology need. Example of RPC's used in HCF applications abound (i.e., gears, machinery, compressor blades, etc.). This serves to underscore the fact that composites are lighter, stiffer, and more structurally efficient than their metallic counterparts.

13.0 Bearing Surface Lubricant - Polymer composite materials abrade more easily than metallic materials because of the resin microcracking. A lubricant can be helpful in sealing the surface and providing a smooth, low friction surface to reduce abrasion damage due to sliding and rubbing. It should be a simple task to select a commercial lubrication system compatible with composite materials, the liquid rocket engine environment, and the vacuum conditions of space.

C. CRITICALITY RANKING OF TECHNOLOGY NEEDS

Using the weight data from Table VI and the information from the "Technology Needs Definition" forms, a "Technology Needs Cross-Reference Chart" was formulated (see Table I). This chart displays the number of components common to each technology and shows the percentage of weight reduction associated with the application of each technology need. This allows the ranking of technology needs as well as specific components in terms of weight reduction payoffs. It also displays our assessment of the risk associated with overcoming each technology barrier.

Since Table I is basically a compendium of the studies conducted in Tasks I through IV, it was used as a guide in selecting the follow-on tasks recommended for Task V of this study. Those selected for fabrication in Task V represent the components which provide the greatest percentage of weight savings through composite substitution and which also encompass the solution to a wide variety of technology needs.

VII. TASK V - RECOMMENDED TASKS

A. OBJECTIVE

The purpose of Task V was to recommend a minimum of two follow-on tasks involving component fabrication and testing. It was desired that the selected components not only show promising weight savings with composite substitution but that their construction also encompass the solution to a wide variety of technology needs, thus paving the way for a large number of composite substitutions in the future.

Another objective of Task V was to formulate a schedule and budget for the analysis, design, fabrication, and testing of the selected components.

B. RECOMMENDATIONS

The recommended follow-on tasks were selected by using the critical technology need ranking developed in Task IV (see Table I). This ensured that a combination of weight reduction and technology advancement features were incorporated into a minimum-cost, low-risk program.

The components selected for fabrication and further study in a follow-on program are as shown below:

PN	Component	% Weight Savings Rank	Number of Technology Needs Addressed
1196011	OTV Valve Housing	8	14
1196001	LCH_4 High-Speed TPA Impeller Housing	4	17
1196006	OTV Nozzle Extension Shafts	1	6
1196008	OTV Skirt Support Ring	5	4

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The OTV valve housing shows significant weight savings and requires the solution of fourteen technology needs. This component could be immediately useful on several engines while solving problems connected with many other components.

The LCH_4 high-speed impeller housing is the biggest weight saver on the 600K-lbF booster engine when made with composites. It also presents the most complications in terms of advancing the state of the art in composite fabrication technology. If this component could be successfully built, construction of any of the twelve components selected in Task III would be facilitated greatly.

The OTV extension shaft yields the greatest percentage of engine weight savings. At the same time, its fabrication process is fairly simple and would address the solution of only six technology needs. The extension shafts can be inserted directly into the OTV skirt support ring to form a subassembly. This support ring was also selected because it is simple to fabricate and shows a good weight savings.

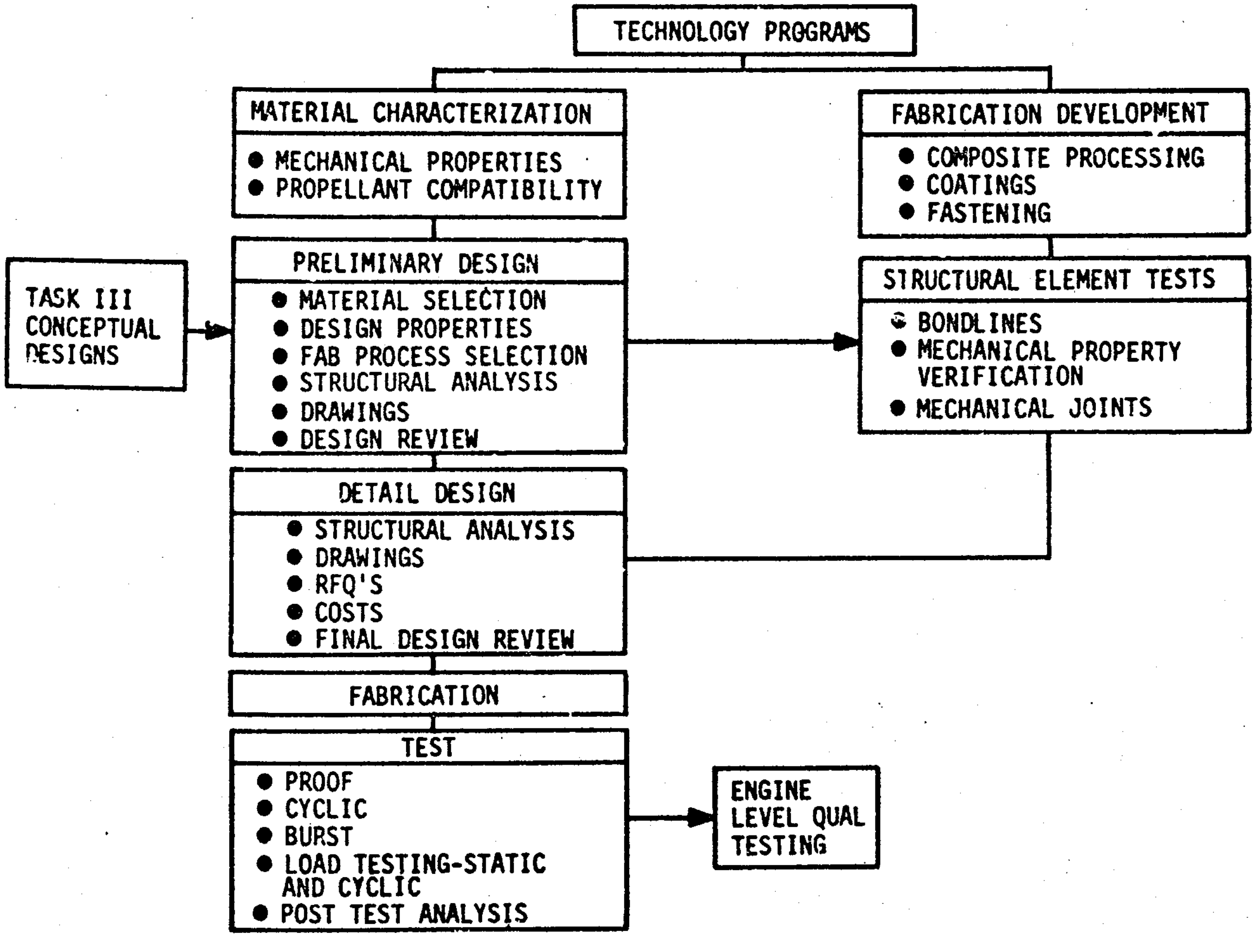
Notice should be taken that the four recommended tasks are not merely the four top weight savers based on the Task III weight analysis. They were selected not only to show good weight savings but also to cover the spectrum of technology needs from the simplest to the most complex. They may be fabricated either together or singly, depending on NASA's schedule and budgetary needs.

C. PROGRAM PLANS FOR THE SELECTED COMPONENTS

Table X shows a schematic representation of the general design and analysis steps that would be followed for any of the four recommended tasks.

TABLE X

DESIGN AND ANALYSIS STEPS FOR RECOMMENDED PARTS



VII, C, Program Plans for the Selected Components (cont.)

The proposed program for each recommended task consists of five elements: (1) technology programs addressing the technology needs identified for each selected part; (2) a preliminary design incorporating the results of the material characterization portion of the technology programs and the conceptual design from Task III; (3) a final design incorporating the results of the preliminary design and the fabrication development portion of the technology programs; (4) fabrication; and (5) testing and evaluation of the tested part.

Each recommended task is costed separately, with a breakdown by element to allow funding options for a follow-on activity.

Technology Programs

A general description of each technology need is given in Section VI,B of this report. These programs are concerned with (1) the determination of mechanical and physical properties of candidate materials, (2) the effect of propellant exposure on these properties, and (3) the development of fabrication techniques for application to the final design. The purpose of the programs is to minimize risk in the design by providing the data required for material selection, structural analysis, and the processing parameters required for fabrication of the part. Each program will be formulated to identify the candidate materials, test specimens, test procedures, special test equipment, and test parameters. The results of cryogenic mechnical tests will be evaluated for ductility and toughness values with respect to those at room temperature. Propellant compatibility tests results will be evaluated as to chemical reactions and the effect of static and cyclic exposure on mechanical properties.

Preliminary Design

The conceptual designs of Task III will be the basis for the development of a preliminary design that also incorporates the results of the material characterization portion of the technology programs (i.e., final material selection and design allowable properties). The Task III structural analysis hand calculations for the conceptual design will be refined to determine new section sizes and detail design features such as laminate orientations and thicknesses, bond lines, and mechanical joints. The preliminary design drawings will be reviewed with NASA for their approval.

Structural elements, based on the preliminary design, will be fabricated and mechanically tested to verify design property selection and the structural analyses. Failure to verify the conceptual design through structural element testing would require an iteration of the structural element tests.

Detail Design

The detail design will incorporate the results of the preliminary design and the structural element testing. A final computerized finite element structural analysis will be conducted to refine section sizes, bond areas, and mechanical joint details. Detail part and assembly drawings will be presented at a final review with NASA.

The detailed designs will be submitted to ALRC manufacturing and to outside suppliers that provided quotes for the study to finalize costs.

Fabrication

The selected fabricators will be monitored to assure conformance to drawing requirements and quality control procedures, including raw material inspection, process controls, and nondestructive inspection of fabricated parts.

Testing

The test plan for the completed part will be formulated to simulate the duty cycle. If the part requires pressure testing, it will be sealed by using the attachment method to the adjoining part as indicated in the component design. The part will be proof-tested prior to cyclic pressure-testing with the propellant. In the event of failure during cyclic testing, a destructive post-test failure analysis will be conducted in an effort to determine failure mode and to determine the degree of material degradation. If cyclic testing reaches full duration, the part will be visually and nondestructively inspected to determine material degradation. At this time, the part will either be destructively analyzed or burst-tested and destructively analyzed.

As each of the four recommended subcomponents is entirely different in function and fabrication complexity, it necessitates a separate budget, schedule, and test plan for each one. The paragraphs which follow describe a unique program plan for each of the recommended parts. These program plans consist of the following: 1) a conceptual drawing of the subcomponent, 2) a fabrication process flowchart, 3) a summary of the required technology and component testing, and 4) a detailed schedule and budget for each program plan.

1. OTV Valve Housing

The OTV valve housing, shown in Figure 43, was selected both for its significant engine weight savings (1.3%) and because its fabrication would address a total of fourteen technology needs. It is also a component which could be immediately useful on existing engines.

Figure 44 shows that the valve body would be filament-wound from graphite epoxy and thereafter autoclave-molded. The valve bosses would then be compression-molded separately from Kevlar-epoxy prepreg. After machining openings in the valve body, the bosses would be adhesively attached via an autoclave bonding process. The internal barrier coating could be performed on the mandrel before filament-winding the body, or they could be deposited internally by a variety of methods (i.e., electro deposition, vacuum deposition, etc.) after the valve body is completed. The specific barrier coating method selected would depend on the results of prior fabrication technology programs.

Figure 45 contains a summary of the material and fabrication technology tests which would be performed prior to fabricating the subcomponent. These tests would include 1) laboratory coupon tests to determine mechanical, thermal, and propellant compatibility properties, 2) fabrication and material process trials, and 3) structural element testing. After developing the technology and fabricating a valve housing, the housing would be proof-tested, cyclic pressure-tested (in LOX, LH_2, and LCH_4), and destructively burst-tested in LOX.

The schedule and budget for performing the technology, design, fabrication, subcomponent testing, and evaluation of the valve body are shown in Figure 46. The entire program would take place in a 13-month

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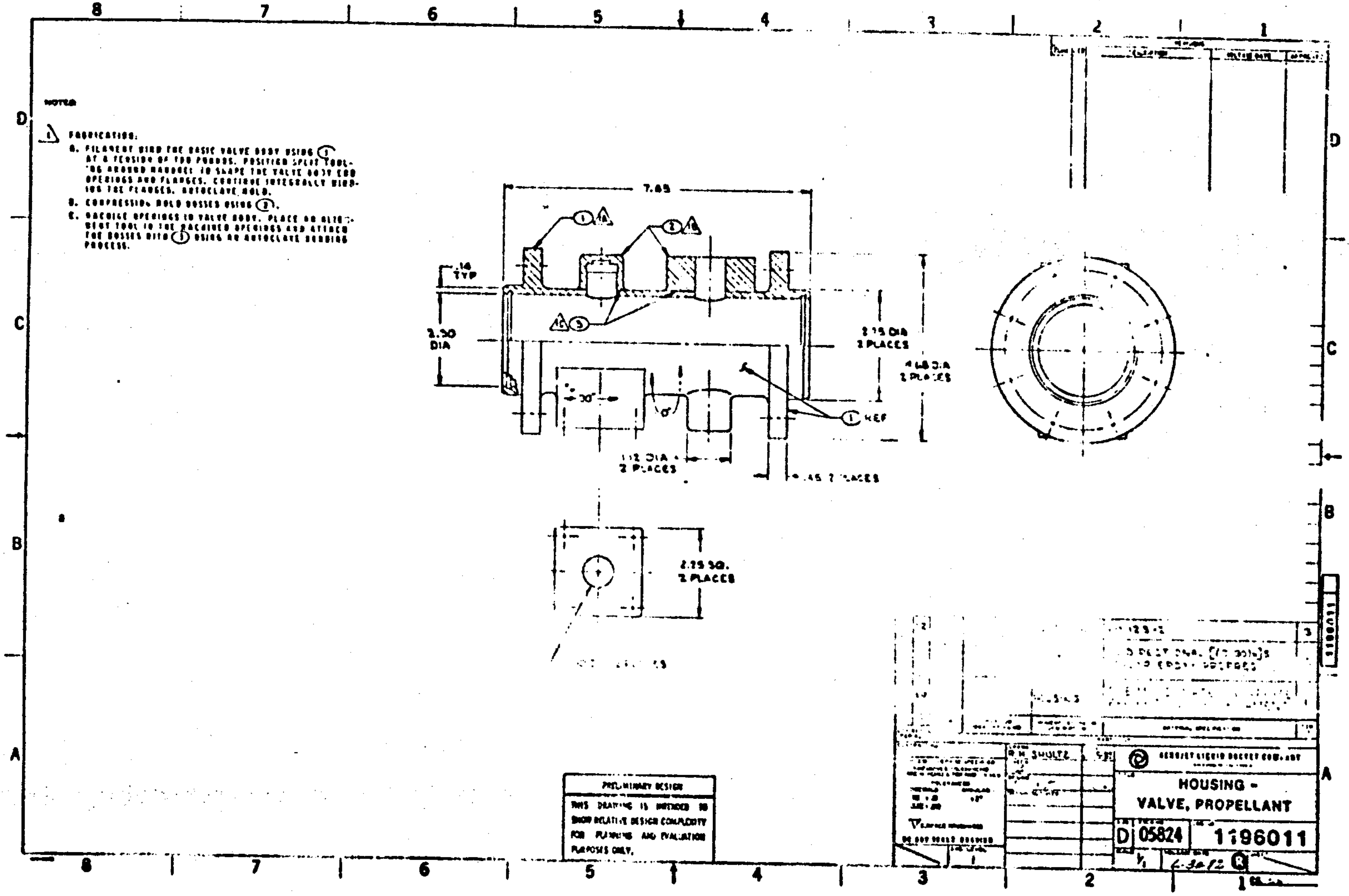

Figure 43. OTV Valve Housing

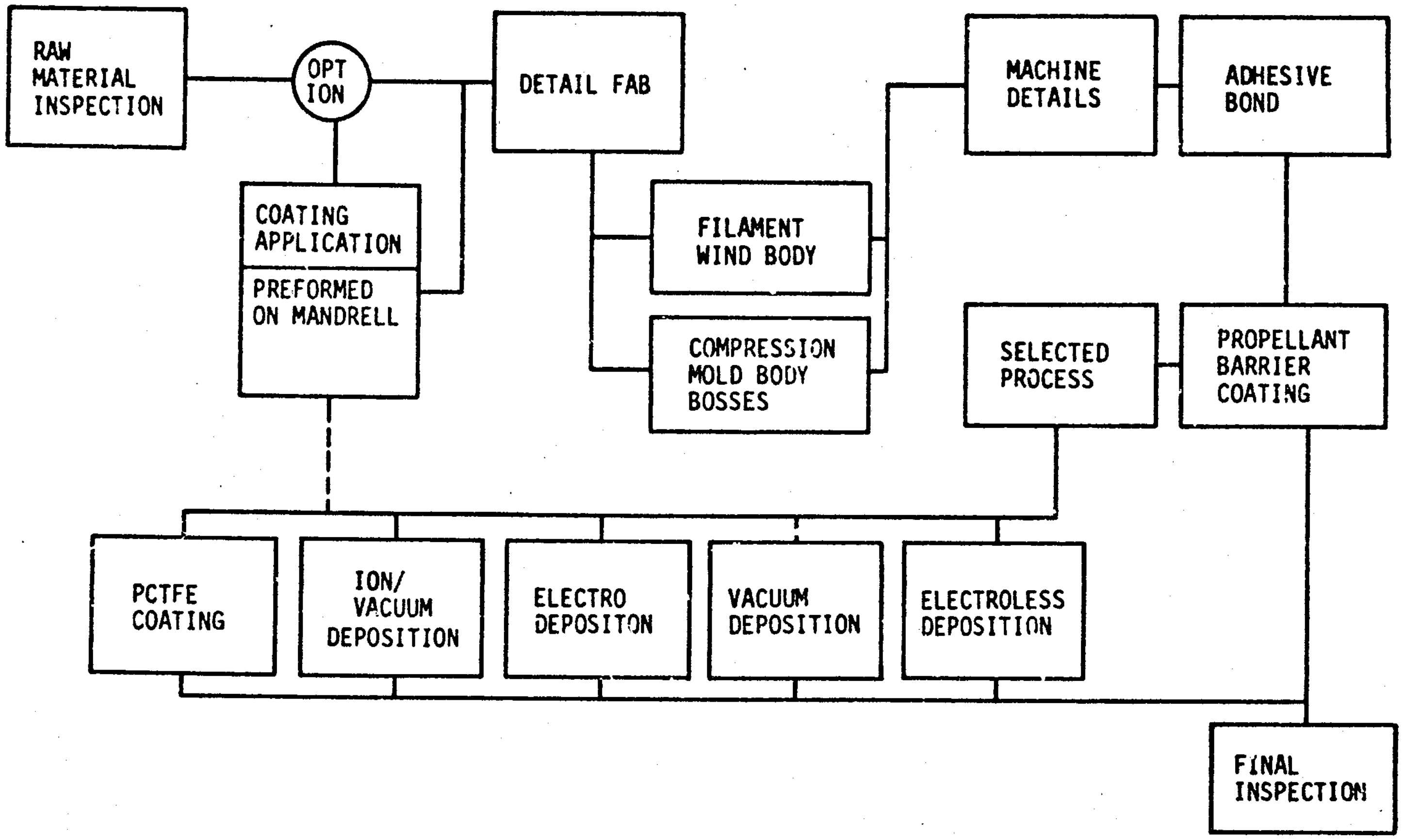

Figure 44. OTV Valve Housing Fabrication Process Flowchart

- COUPON TESTS
  - PROPELLANT COMPATIBILITY [(LOX, LCH_4, LH_2) (IGNITION SENSITIVITY AND LONG-TERM DEGRADATION EFFECTS)]
  - LOW TEMPERATURE TOUGHNESS [(STATIC AND CYCLIC FLEXURAL TESTS) (FLAWED AND UNFLAWED SPECIMENS)]
  - BARRIER COATINGS [(FLEXURAL TESTS FOLLOWING PROPELLANT EXPOSURE) (ADHESION TEST AT CRYOGENIC TEMPERATURE)]
  - THERMAL EXPANSION PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
  - STRUCTURAL PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
- STRUCTURAL ELEMENT TESTS
  - FABRICATION AND MATERIAL PROCESS TRIALS (BARRIER COATING PROCESS, SEALING SURFACE FINISHING DETAIL LAB METHODS, MACHINING, MOLD DESIGN, JOINING, PLUMBING CONNECTIONS)
  - LOW CYCLE (THERMAL) FATIQUE
  - COATING PROCESS OPTIMIZATION (BONDING AIDS AND COATING THICKNESS)
  - KEY INTERFACE SHEAR TESTS IN LN_2
  - CYCLIC PRESSURE AND BURST TESTS
- COMPONENTS TESTS
  - PROOF
  - CYCLIC PRESSURE TESTS (LOX, LCH_4, LH_2)
  - BURST TEST IN LOX

Figure 45. 1196011 Valve Housing Technology Program and Component Testing

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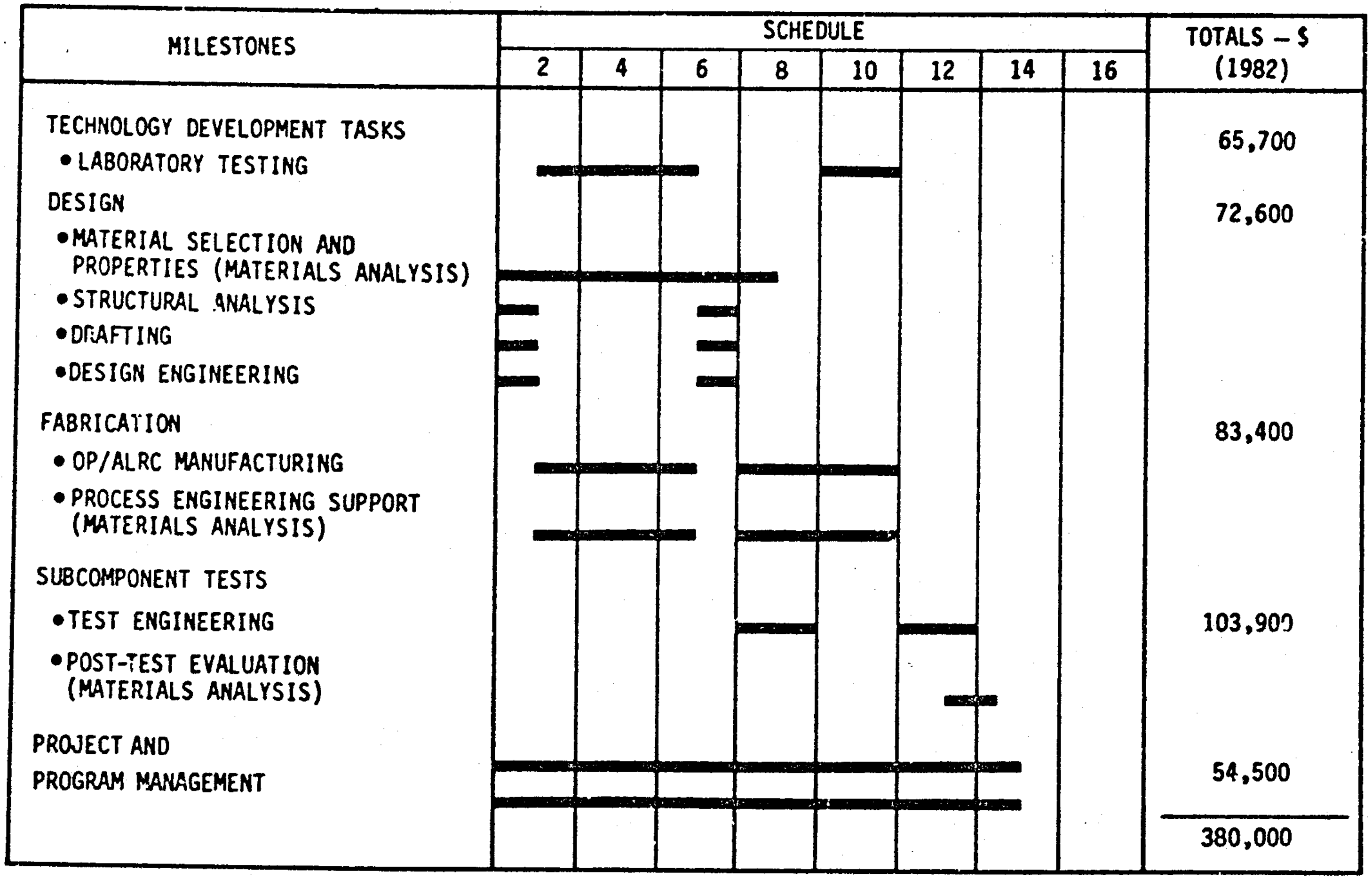

Figure 46. Schedule and Budget for the OTV Valve Housing

time frame and cost a total of $380K. The budget was figured on the basis of 1982 company wage rates and includes all management, travel, and reporting expenses. It should be noted that this program could just as easily be split into distinct segments (i.e., technology, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding.

2. LCH_4 TPA Impeller Housing

The impeller housing, shown in Figure 47, is the biggest engine weight saver on the 600K booster (2.5% engine weight savings) and is also the most complicated in terms of advancing the state of the art. Its complex shape and propellant exposure would result in the need to address seventeen technology needs before a housing could be successfully fabricated and tested. Its successful fabrication, however, would greatly facilitate the construction of any of the other subcomponents selected in Task III.

Figure 48 shows that the housing torus shell would be laid up in a female mold and autoclave-molded. The openings for the vane roots would be machined in the shell, and the vanes would be laid up against forms inserted in the torus opening and then autoclave-molded. After this, the balance of the pump housing and torus would be laid up and autoclave-molded. The method of applying the barrier coating would be determined as in the case of the OTV valve housing.

Figure 49 summarizes the material and fabrication technology tests which would be performed prior to fabricating the impeller housing. These tests would be similar to those performed for the OTV valve housing, with the addition of vane processing and attachment method testing. The final impeller housing would be proof-tested, cyclic pressure-tested in LCH_4, and destructively burst-tested in LN_2.

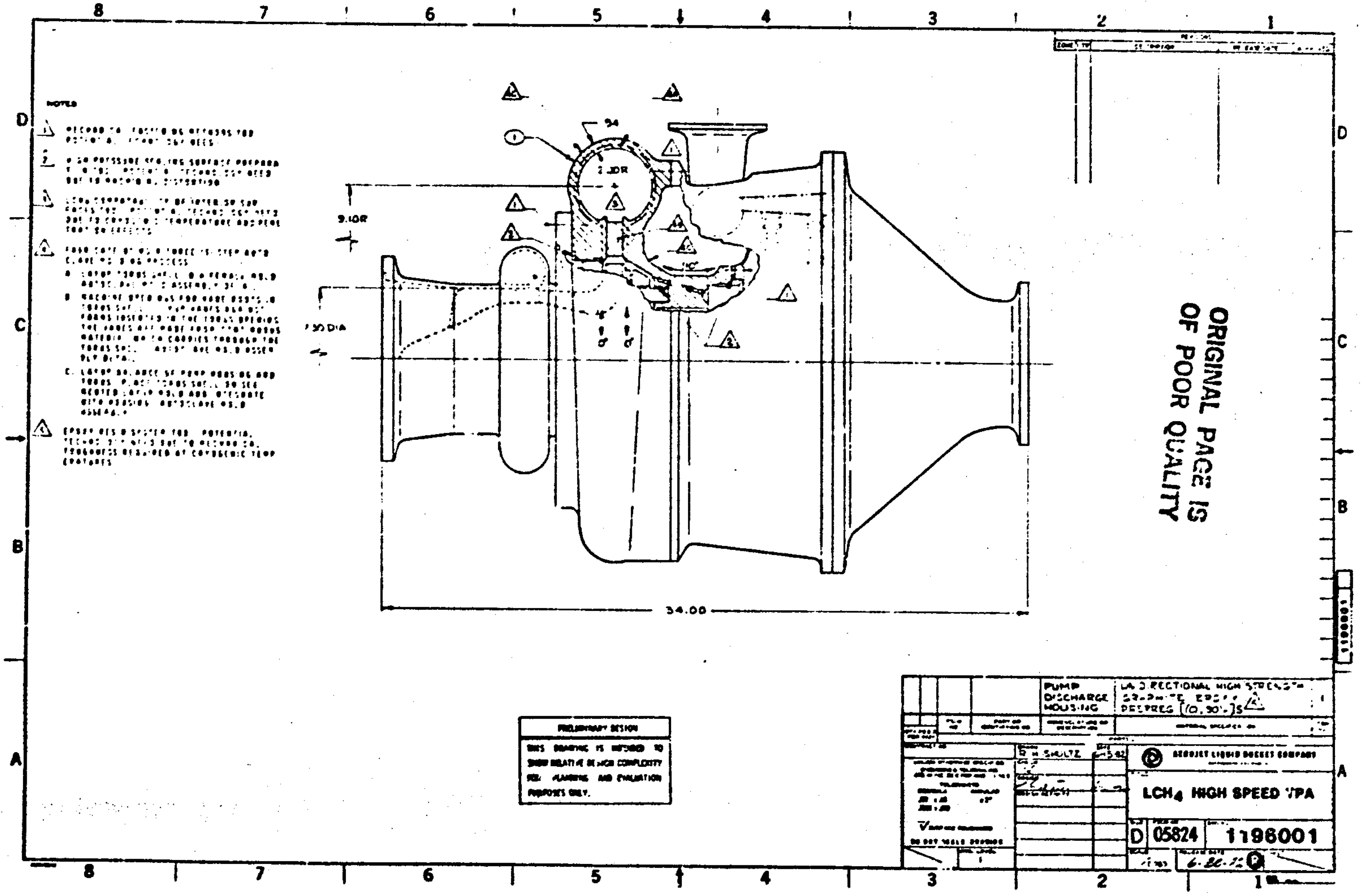

Figure 47. LCH_4 Impeller Housing

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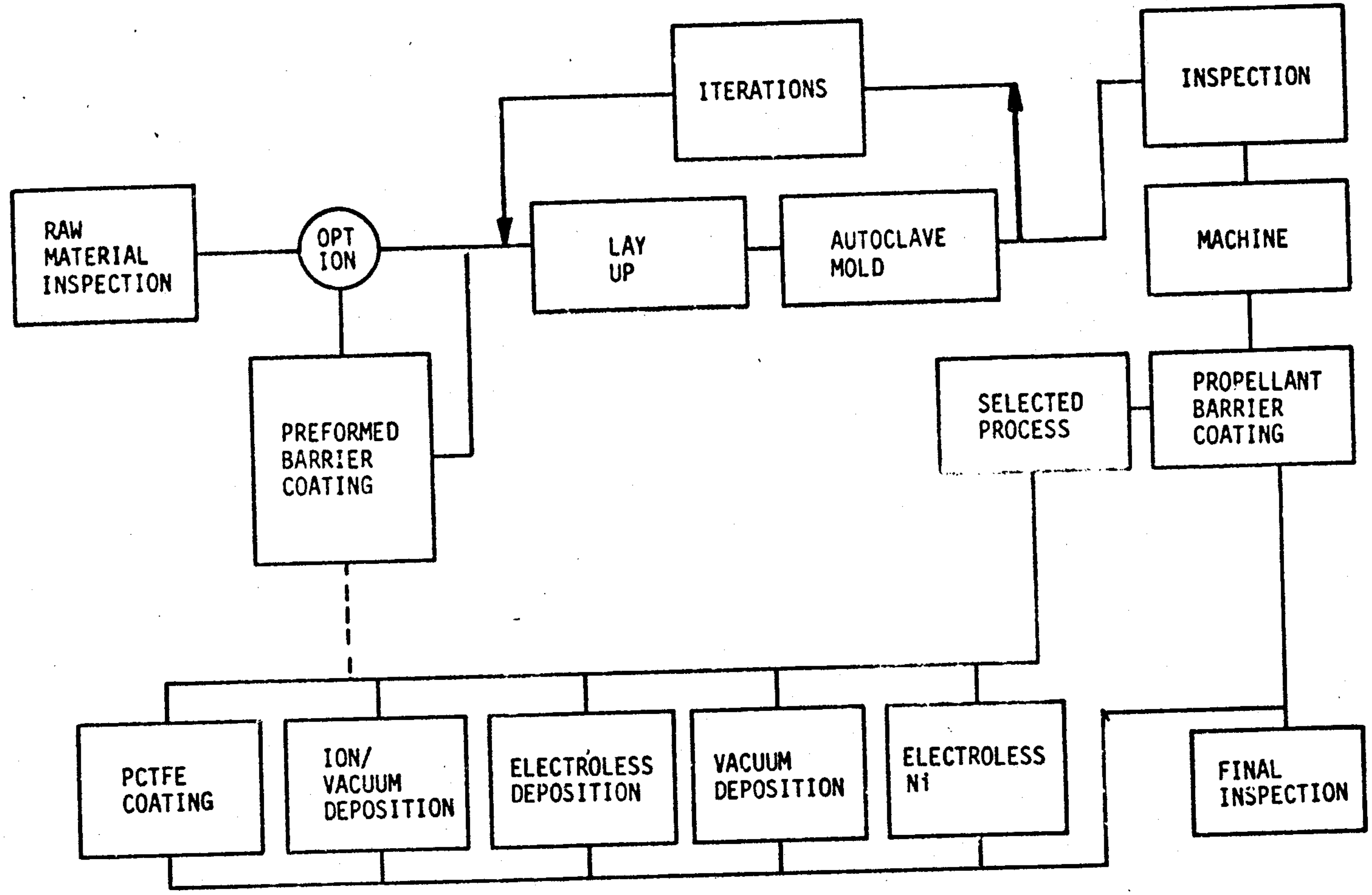

Figure 48. LCH_4 TPA Impeller Housing Fabrication Process Flowchart

- COUPON TESTS
  - PROPELLANT COMPATIBILITY (LONG-TERM DEGRADUATION EFFECTS IN LCH_4)
  - LOW TEMPERATURE TOUGHNESS [(STATIC AND CYCLIC FLEXURAL TESTS) (FLAWED AND UNFLAWED SPECIMENS)]
  - BARRIER COATINGS [(FLEXURAL TESTS FOLLOWING LCH_4 EXPOSURE) (ADHESION TESTS AT CRYOGENIC TEMPERATURE)]
  - THERMAL EXPANSION PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
  - STRUCTURAL PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
- STRUCTURAL ELEMENT TESTS
  - FABRICATION AND MATERIAL PROCESS TRIALS (MECHANICAL FASTENING, SEALING SURFACE FINISHING, VANE PROCESSING AND ATTACHMENT, FABRICATION SEQUENCING, BARRIER COATING PROCESSING, PLUMBING CONNECTIONS, DETAIL JOINING, MOLD DESIGN, MACHINING)
  - LOW CYCLE (THERMAL) FATIQUE
  - COATING PROCESS OPTIMIZATION (BONDING AIDS AND COATING THICKNESS)
  - KEY INTERFACE SHEAR TESTS IN LN_2
  - CYCLIC PRESSURE AND BURST TESTS
- COMPONENT TESTS
  - PROOF
  - CYCLIC PRESSURE TESTS (LCH_4)
  - BURST TEST (LN_2)

Figure 49. 1196001 LCH_4 TPA Discharge Housing Technology Program and Component Testing

The schedule and budget for developing the LCH_4 TPA impeller housing is shown in Figure 50. The program would have a duration of 16 months and cost a total of $448K. This is the most ambitious and costly of the recommended tasks, but its successful completion would solve the majority of identified technology needs connected with RPC substitution.

3. OTV Nozzle Extension Shaft

The OTV nozzle extension shaft, depicted in Figure 34, shows the greatest percentage of engine weight savings of any of the components selected in Task III (3.3%) and is also fairly simple to fabricate.

Figure 51 shows that the extension shaft would be fabricated by co-pultruding graphite fiber overwrapped with fiberglass. The threads would thereafter be machined in the fiberglass material overlay and lubricated. This simple process would result in a high-strength, lightweight, hollow extension shaft which could be used as part of a nozzle extension mechanism.

Figure 52 contains a summary of the material and fabrication technology testing which would be performed prior to fabricating the shaft. These tests would include 1) fabrication and material process trials, 2) structural properties testing at ambient and cryogenic temperatures (i.e., torsion, bending, tension, shear, and impact testing), and 3) durability tests at ambient temperature. The completed shaft would be subjected to vibration testing, cyclic testing (torsion and bending), and destructive torsion testing.

The schedule and budget for developing the OTV extension shaft are shown in Figure 53. The program would take place over 13 months

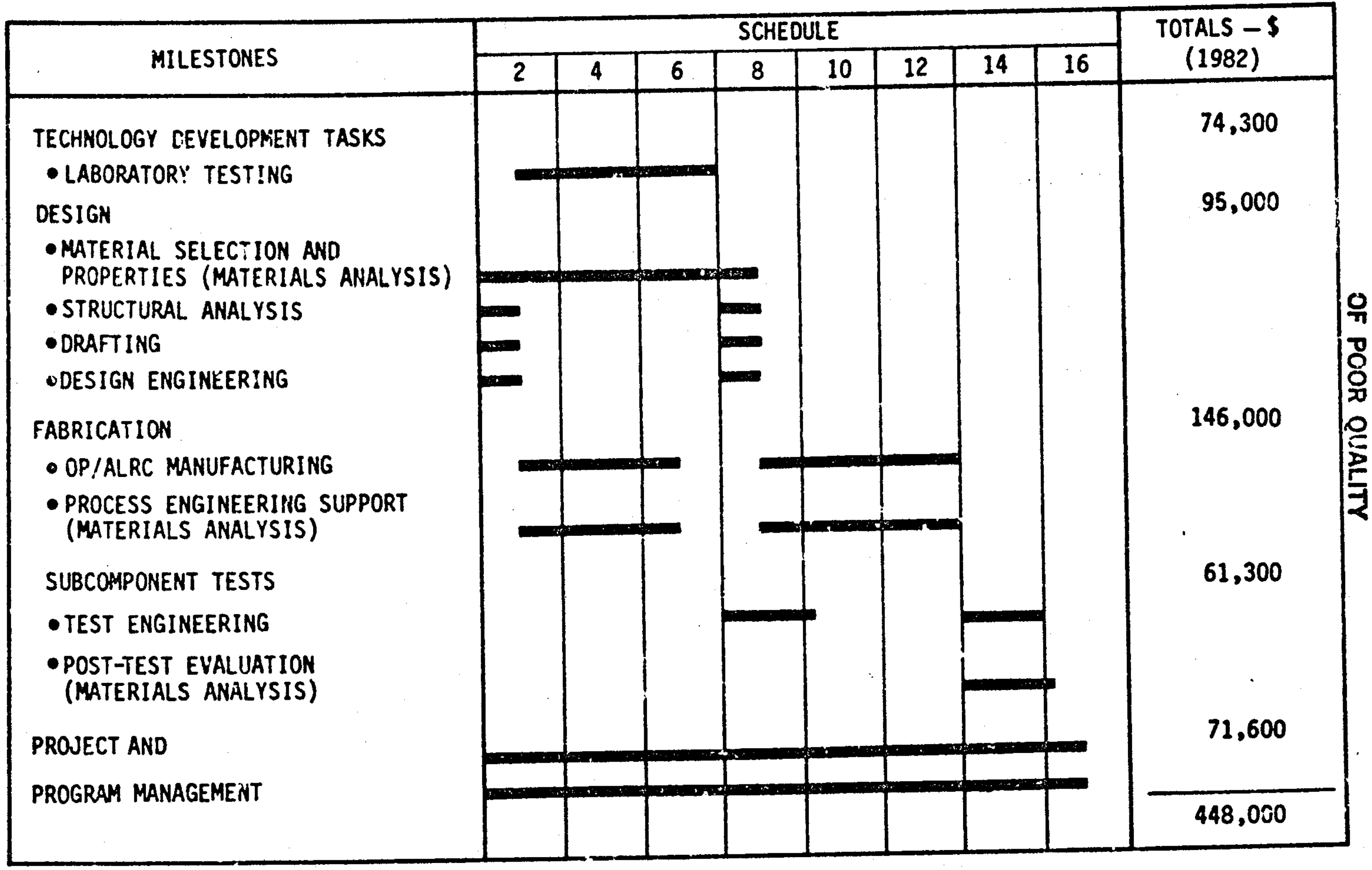

Figure 50. Schedule and Budget for the LCH_4 TPA Impeller Housing

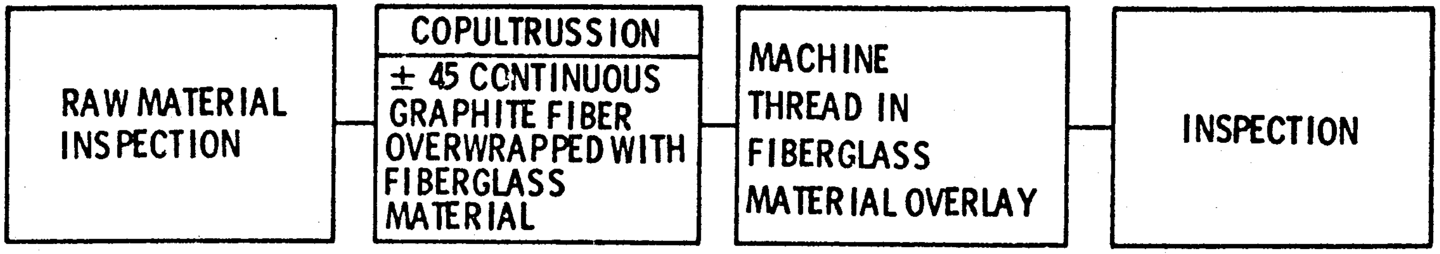

Figure 51. OTV Nozzle Extension Shaft Fabrication Process Flowchart

- STRUCTURAL ELEMENT TESTS
    - FABRICATION AND MATERIAL PROCESS TRIALS
    - STRUCTURAL PROPERTIES AT AMBIENT TEMPERATURE AND IN LN_2
        - TORSION (INTERLAMINAR SHEAR AND IN-PLANE SHEAR)
        - BENDING (STATIC AND CYCLIC)
        - AXIAL TENSION AND COMPRESSION
        - THREAD SHEAR
        - IMPACT
    - DURABILITY TESTS AT AMBIENT TEMPERATURE
        - UV WEATHEROMETER EXPOSURE
        - THREAD LUBRICANT EVALUATION IN VACUUM
- COMPONENT TESTS AT AMBIENT TEMPERATURE
    - VIBRATION TESTING
    - CYCLIC TESTING (TORSION AND BENDING)
    - DESTRUCTIVE TORSION TEST

Figure 52. 1196006 Shaft, Nozzle Extension Technology Program and Component Testing

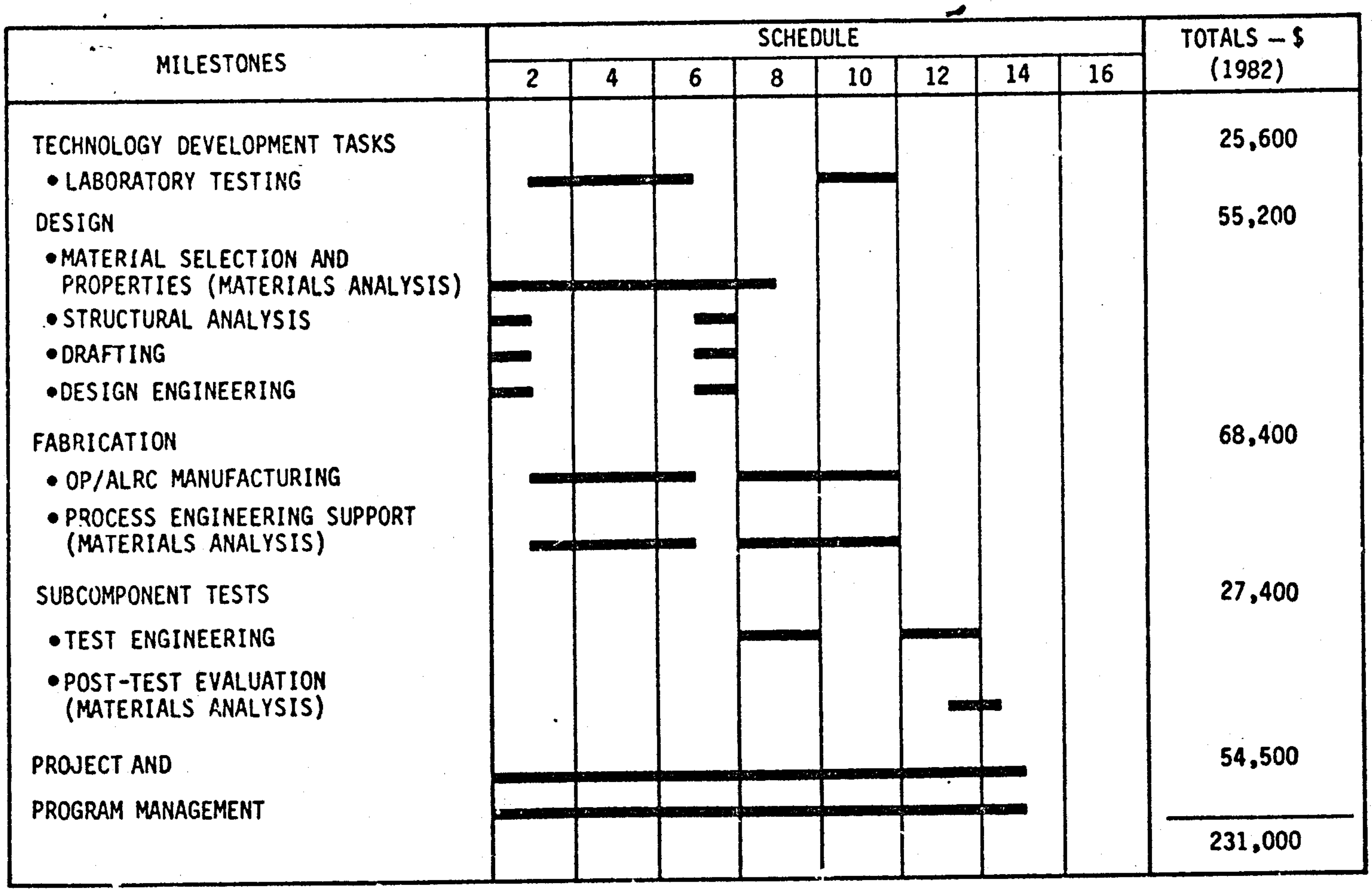

Figure 53. Schedule and Budget for the OTV Nozzle Extension

and cost a total of $231K. This is one of the simplest and least costly programs which could be performed and still result in significant weight savings.

4. OTV Skirt Support Ring

The OTV skirt support ring, shown in Figure 36, shows an engine weight savings of 2.2% and is also simple to fabricate. Additionally, it could be mated with the aforementioned extension shaft to form a subassembly.

Figure 54 shows that the support ring would be fabricated by machining a honeycomb core and tape wrapping the honeycomb with graphite-epoxy. The ring would then be cured in an autoclave mold and finish-machined.

Figure 55 contains a summary of the material and fabrication technology testing which would be performed prior to fabricating the ring. These tests would include 1) laboratory coupon tests to explore low temperature toughness and 2) structural element testing (i.e., fatigue, bending, and pull-out testing). The completed support ring would then be subjected to vibration testing, cyclic testing, and destructive bend testing.

The schedule and budget for developing the OTV skirt support ring are shown in Figure 56. The program would take place over 13 months and cost a total of $231K.

It has been found that combining the development programs for both the OTV nozzle extension shaft and the OTV skirt support ring results in certain economies due to commonality in the technology testing and

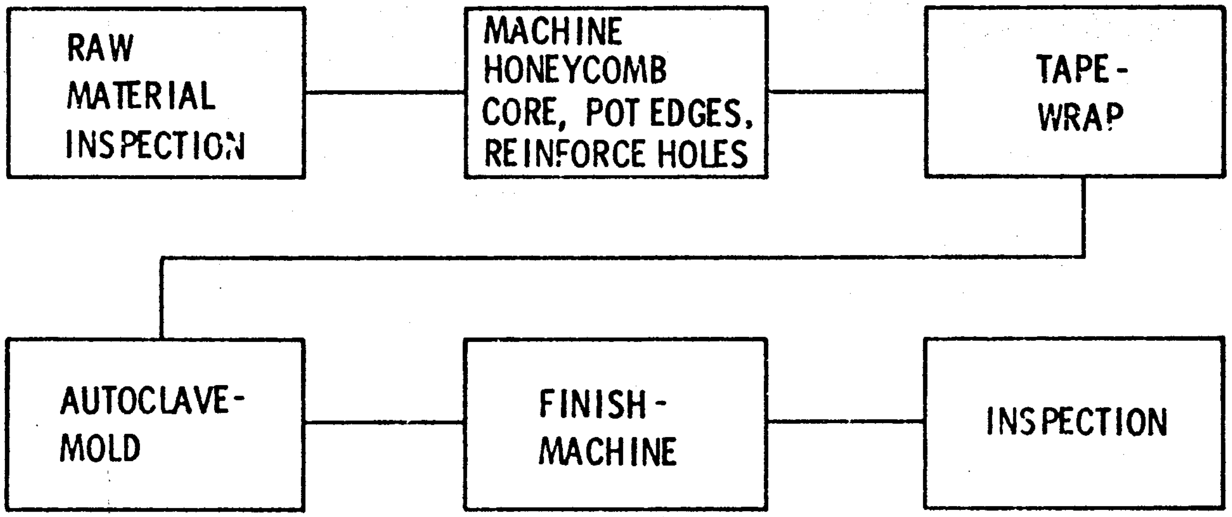

Figure 54. OTV Skirt Support Ring Fabrication Process Flowcart

- COUPON TESTS
    - LOW TEMPERATURE TOUGHNESS (STATIC AND CYCLIC FLEXURAL TESTS OF FLAWED AND UNFLAWED SPECIMENS AT LN_2 TEMPERATURES)
- STRUCTURAL ELEMENT TESTS
    - FABRICATION AND MATERIAL PROCESS TRIALS
    - LOW CYCLE (THERMAL) FATIQUE
    - BENDING
    - INSERT PULL-OUT AND TORQUE
- COMPONENT TESTS
    - VIBRATION TESTING
    - CYCLIC TESTS [INSERT (TORSIONAL AND AXIAL) AND RING (BENDING)]
    - DESTRUCTIVE BEND TEST

Figure 55. 1196008 Skirt Extension Support Ring Technology Program and Component Testing

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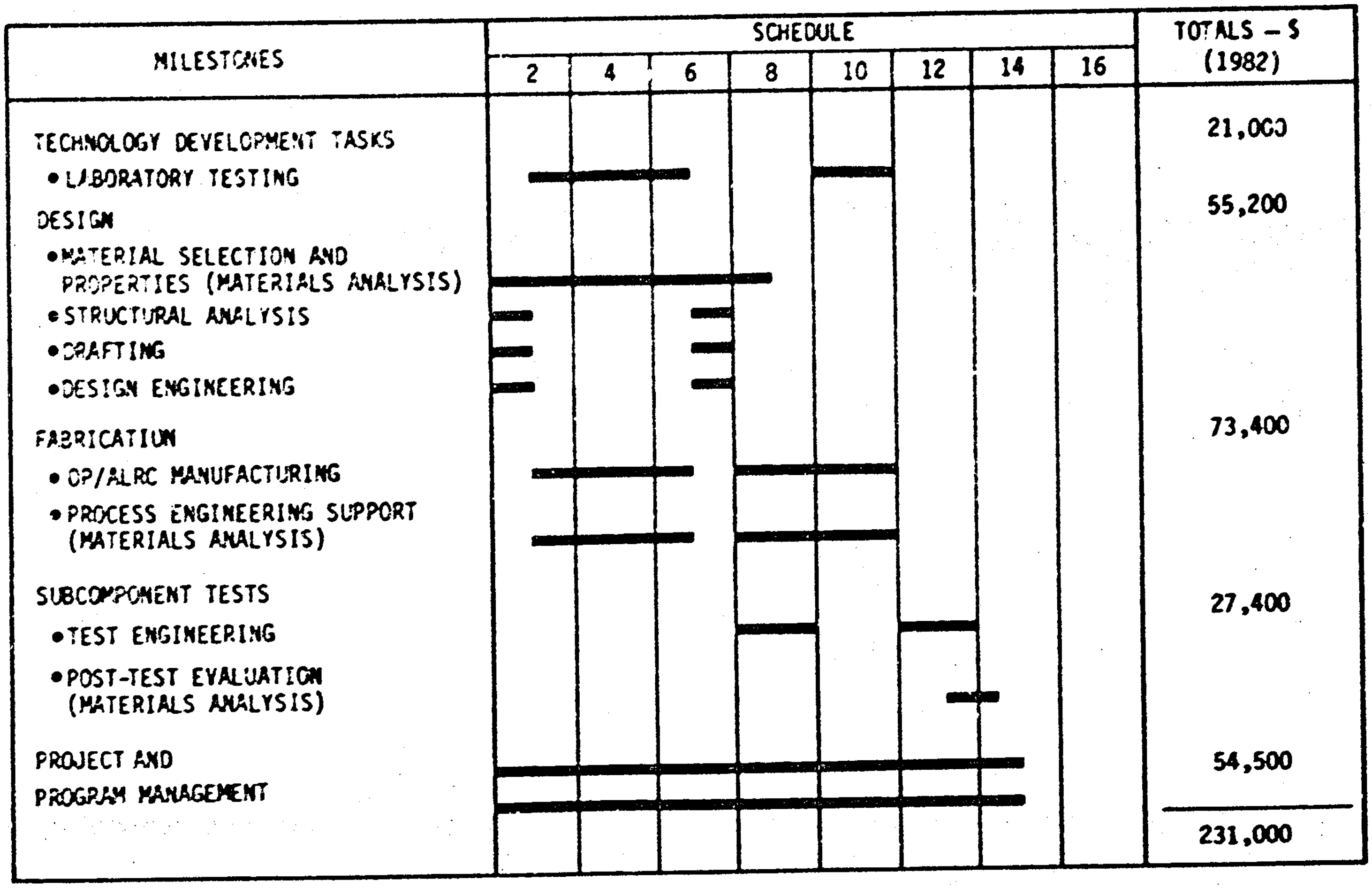

Figure 56. Schedule and Budget for the OTV Skirt Support Ring

subcomponent tests. Figure 57 shows that a combined program could be performed in the same 13-month time frame for a cost of $281K. An added benefit would be the ability to test the two components assembled together as a subassembly.

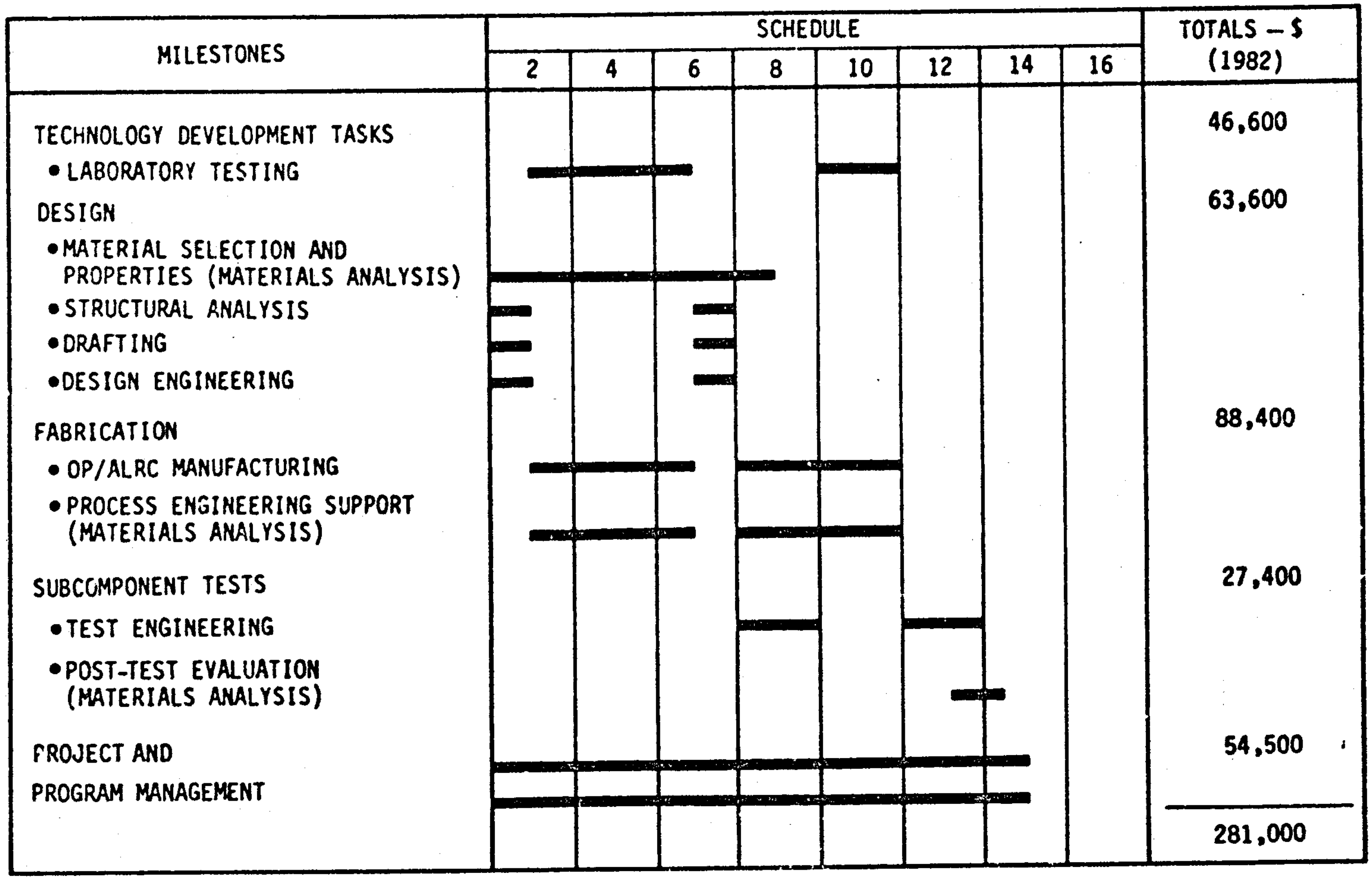

Figure 57. Schedule and Budget for Combining the Support Ring and Extension Shaft

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are drawn from this work:

1. Weight savings of up to 80% are possible on selected components when composite materials are substituted for metal.

2. Engine weight savings from 25 to 30% are possible with use of current composite technology. Future composite techno- may save 30 to 40% of the engine weight.

3. A variety of technology needs remain to be explored in substituting composite materials for metallic parts. These technologies can be developed through straightforward laboratory and fabrication test programs.

4. Reinforced plastic composites were selected over metal matrix composites because of their lower cost, greater fabricability, and higher specific strength. If high-temperature applications become more important, or if propellant compatibility becomes a major problem, the use of MMC's would be more clearly indicated.

5. A variety of follow-on programs could be performed to design, fabricate, test, and evaluate rocket engine subcomponents made from composite materials. The period of performance would range from 13 to 16 months, with the cost ranging from $231 to $448K for the simplest and the most complex tasks, respectively.

6. A follow-on program could just as easily be split into distinct segments (i.e., technology testing, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding (approximately $150K per year).

B. RECOMMENDATIONS

The following recommendations are made on the basis of the program results:

1. Conduct technology programs that address the fabrication, material properties, and propellant compatibility of reinforced plastic composites.

2. Fabricate and test an engine subcomponent which shows promising weight savings with the use of composite materials and which solves a wide variety of technology needs (together with, or separate from, the technology programs, depending on schedule and budget restraints).

3. Extend composite technology to additional rocket engine components as the technology is developed.

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APPENDIX A

COMPONENT REQUIREMENT FORMS

ADVANCED EXPANDER OTV
COMPONENT REQUIREMENTS

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Gimbal Assembly

Operating Pressure(s)	Subject to 15,000 lb_f thrust
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	-
Start/Shutdown Conditions	
Envelope (Length)	2.4 in.
Weight	3.3 lb_m
Material(s)	Tit/SS

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH$_2$
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Chamber

Operating Pressure(s)	Pc = 1200 psia
Operating Temperature(s)	
Propellant Flowrate(s)	Chamber coolant = 3.816 lb/sec, Tube Bundle Flowrate = .674 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	18 in.
Weight	47.3 lb_m
Material(s)	Zirconium Copper - EF Nickel Closeout

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Copper Nozzle

Operating Pressure(s)	17.55 psi (forward), 0.52 psi (aft)
Operating Temperature(s)	730°R
Propellant Flowrate(s)	.674 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	34.8 in
Weight	27 lbm
Material(s)	copper

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Injector

Operating Pressure(s)	POJ = 1434, PFJ = 1326, Pc = 1200 psia
Operating Temperature(s)	
Propellant Flowrate(s)	$\dot{W}_{ox}$ = 27.05 lb/sec $\dot{W}_f$ = 4.51 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	4.8 in.
Weight	30.6 lb_m
Material(s)	304L CRES

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Tube Bundle Nozzle

Operating Pressure(s)	2466 psia
Operating Temperature(s)	730°R
Propellant Flowrate(s)	0.674 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	30 in.
Weight	38.4 lb_m
Material(s)	347 CRES

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Radiation Nozzle

Operating Pressure(s)	Negligible
Operating Temperature(s)	2450°F
Propellant Flowrate(s)	31.56 lbm
Start/Shutdown Conditions	
Envelope (Length)	49.6 in.
Weight	80 lbm
Material(s)	C-103 Columbium Alloy

TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Nozzle Deployment System (3 shafts, DC Motor, Support Ring)

Operating Pressure(s)	Ambient
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	--
Start/Shutdown Conditions	
Envelope (Length)	60 in.
Weight	72 lb.
Material(s)	

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Propellant Flow, Control Valves
Modulating Poppet Valve } 8 Total

Operating Pressure(s)		16 psi - 1450 psi
Operating Temperature(s)		40°R - 600°R
Propellant Flowrate(s)		$\dot{W}_{ox} = 27.05$ lb/sec $\dot{W}_f = 4.51$ lb/sec
Start/Shutdown Conditions		______
Envelope (Length)		Prop Flow Control Valve 10.12" x 13.75" Mod Poppet Valve 6.4" x 10.9"
Weight		72.7 lb_m
Material(s)	● Bodies	(1) 6061-T6 Aluminum (2) A356-T6 Aluminum (3) 347 CRES (4) Nitronic 50 (5) A-286
	● Shafts	(1) A-286
	● Poppets	(1) A-286
	● Gears	(1) A-286 (2) 15-5 PH H1150 M
	● Springs	(1) 302 CRES
	● Seal	(1) Filled Teflon

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: LOX Boost Pump

Operating Pressure(s)		16-56 psia
Operating Temperature(s)		-320°F
Propellant Flowrate(s)		171 GPM
Start/Shutdown Conditions		
Envelope (Length)		4.6" X 5.0"
Weight		5.6 lb_m
Material(s)	Turbine Inlet & Housing	A356
	Pump Housing	A356
	Impeller & Shaft	15-5PH H1150 M CRES
	Bearings	440 C CRES

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : LH_2 Boost Pump

Operating Pressure(s)		18.5 - 50 psia
Operating Temperature(s)		-420°F
Propellant Flowrate(s)		456 GPM
Start/Shutdown Conditions		
Envelope (Length)		5" X 2.87"
Weight		8.5 lbm
Material(s)	Turbine Inlet & Housing	A356 Al
	Pump Housing	A356 Al
	Impeller & Shaft	Cast Ti 5Al 2.5 Sn ELI
	Bearings	440 C CRES
	Preload Springs	302 CRES

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : LOX TPA (Hi Speed)

Operating Pressure(s)		Pump 48-1487 psia Turbine 1512-1326 psia
Operating Temperature(s)		Pump 170°R Turbine 489°R
Propellant Flowrate(s)		194 GPM
Start/Shutdown Conditions		
Envelcpe (Length)		11.85° X 8.8"
Weight		26.9 lb_m
Material(s)	● Turbine Housing	(1) A-356 Aluminum (2) Cast 316 CRES (3) Nitronic 50
	● Turbine	(1) A-286
	● Pump Housing	(1) A-356 Aluminum (2) Cast 316 CRES
	● Seal Housing	(1) 6061 Aluminum (2) 347 CRES (3) Nitronic 50
	● Pump Impeller & Shaft	(1) 15-5 PH H1150M (2) INCC 718
	● Bearings	(1) 440 C CRES

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: LH_2 TPA (Hi Speed)

Operating Pressure(s)	Pump 49 - 2531 psia Turbine 2344-1522 psia
Operating Temperature(s)	Pump 40°R Turbine 535°R
Propellant Flowrate(s)	547 GPM
Start/Shutdown Conditions	
Envelope (Length)	11.05" x 7.52"
Weight	26.3 lb_m

Material(s)	• Turbine & Pump Housing (one piece)	(1) Cast 316 CRES (2) Nitronic 50
	• Pump Impellers	(1) Cast Ti BAl 2.5Sn ELI
	• Stators/Diffusers	(1) Cast Ti 5Al 2.5Sn ELI
	• Pump Inlet	(1) Cast Ti 5Al 2.5Sn ELI
	• Pump Inducer	(1) Cast or Wrought Ti 5Al 2.5SN ELI
	• Pump Shaft	(1) Wrought Ti 5Al 2.5Sn ELI
	• Turbine Exhaust Housing	(1) Cast 316 (2) Nitronic 50
	• Turbine	(1) A-286 CRES
	• Bearings	(1) 440 CRES

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Misc. Valves & Pneumatic Pack

Operating Pressure(s)	4000 psia
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	None
Start/Shutdown Conditions	
Envelope (Length)	
Weight	12.6 lbm
Material(s)	Titanium

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Lines

Operating Pressure(s)	18 - 1500 psia
Operating Temperature(s)	Tox = 140°R T_f = 40°R - 535°R
Propellant Flowrate(s)	Wox = 27.05 lb/sec W_f = 4.51 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	
Weight	27.0 lb_m
Material(s)	Titanium

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Ignition System

Operating Pressure(s)	1200 psia
Operating Temperature(s)	T_f = 550°R T_{ox} = 140°R
Propellant Flowrate(s)	$\dot{W}ox$ = .0609 lb/sec $\dot{W}_{H2}$ = .00152 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	
Weight	9.2 lb_m
Material(s)	SS/Nickel

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components : Miscellaneous*

Operating Pressure(s)	
Operating Temperature(s)	
Propellant Flowrate(s)	
Start/Shutdown Conditions	
Envelope (Length)	
Weight	37 lb
Material(s)	

*Electrical Harness - 12.5 lb
Service Lines - 6.5 lb
TPA Protective Bulkhead - 0.4 lb
Attachment Hardware - 15.0 lb
Instrumentation - 2.6 lb

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Engine Controller

Operating Pressure(s)	Ambient
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	-
Start/Shutdown Conditions	
Envelope (Length)	16.8" x 10" x 8"
Weight	35 lbm
Material(s)	Aluminum

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	1200 psia
Thrust (Vac)	15,000 lb_f
Isp (Minimum) (vac)	475.4 sec.
Propellants	LOX/LH_2
Duty Cycle (Burns)	1200 thermal cycles
Cumulative Life	10 hrs.
Mixture Ratio	6.0
Weight	574.4 lb_m

Components: Heat Exchanger

Operating Pressure(s)	1500 - 2300 psia
Operating Temperature(s)	535°R
Propellant Flowrate(s)	Very small amount
Start/Shutdown Conditions	
Envelope (Length)	
Weight	5.0 lb
Material(s)	

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LOX/LCH$_4$ ENGINE (CYCLE C)
COMPONENT REQUIREMENTS

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components : Gimbal System

Operating Pressure(s)	Transmits 600K lb$_f$ thrust
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	--
Start/Shutdown Conditions	--
Envelope (Length)	6.6" Long
Weight	207 lbm
Material(s)	Tit/SS

TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Injector

Operating Pressure(s)	Pc = 4300 psia
Operating Temperature(s)	
Propellant Flowrate(s)	$\dot{W}ox$ = 1432.7 lb/sec $\dot{W}f$ = 508.43 lb/sec
Start/Shutdown Conditions	--
Envelope (Length)	D = 15.4" L = 10.2"
Weight	611 lbm
Material(s)	Body - Inconel 625 or ARMCO Nitronic -50 Manifolds - CRES 347 or Nitronic -50 Injector Face - Inconel 625

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Combustion Chamber

Operating Pressure(s)	Pc = 4300 psia
Operating Temperature(s)	
Propellant Flowrate(s)	W_T = 1784.51 lb/sec
Start/Shutdown Conditions	--
Envelope (Length)	L' = 15.5" D = 15.44"
Weight	428 lbm
Material(s)	Zirconium Copper

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Nozzle

Operating Pressure(s)	6 psi
Operating Temperature(s)	1580°R
Propellant Flowrate(s)	$\dot{W}_T$ = 1784.51 lb/sec
Start/Shutdown Conditions	-
Envelope (Length)	L = 111.2" Dex = 76.4"
Weight	264 lb_m
Material(s)	Nitronic 50 or A-286

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Gas Generator

Operating Pressure(s)	Pc = 4200 psia
Operating Temperature(s)	1860°R
Propellant Flowrate(s)	$\dot{W}_{ox}$ = 44.75 lb/sec $\dot{W}_f$ = 111.87 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	D = 10.5" x L = 14.3"
Weight	76 lbm
Material(s)	Inj. body - Nitronic 50 Chamber - Inconel 625

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Oxidizer Valves

Operating Pressure(s)	Up to 5300 psi
Operating Temperature(s)	Cryo
Propellant Flowrate(s)	Main $\dot{W}ox$ = 1432.7 lb/sec GG $\dot{W}ox$ = 44.75 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	Pump Valve D = 3.1" GG Valve D = 2"
Weight	155 lbm
Material(s)	Aluminum and A-286

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components : Fuel Valves

Operating Pressure(s)	Up to 8000 psi
Operating Temperature(s)	Cryogenic
Propellant Flowrate(s)	Main $\dot{W}f$ = 508.43 lb/sec GG $\dot{W}f$ = 111.87 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	Main Pump Valve Diam = 3.4" GG Valve Diam = 2.7"
Weight	133 lbm
Material(s)	Aluminum & A-286

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Oxidizer Boost Pump

Operating Pressure(s)		P_D = 231 psia
Operating Temperature(s)		Tox = 166°R Pump Tox = 166°R Turbine
Propellant Flowrate(s)		W_{pump} = 1396.5 lb/sec W_{Turb} = 215 lb/sec
Start/Shutdown Conditions		
Envelope (Length)	D_{env} = 26.7"	Line Inlet D = 15.4" Outlet D = 8.2"
Weight	L_{env} = 27.2"	311 lbm
Material(s)	• Shaft	Inconel 718, 15-5 PH H1150M
	• Impeller & Turbine	7075 T-73, Al Alloy
	• Housing	A356 T6, Al Alloy
	• Bolts	A-286
	• Housing Liner	FEP Teflon Fused Coating
	• Bearings	CRES 440C; Haynes Star J Alloy PM

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Fuel Boost Pump

Operating Pressure(s)		P_D = 135 psia
Operating Temperature(s)		207°R
Propellant Flowrate(s)		$\dot{W}_{pump}$ = 495.4 lb/sec $\dot{W}_{turb}$ = 99 lb/sec
Start/Shutdown Conditions		
Envelope (Length)	L_{env} = 20.9" D_{env} = 21.9"	Line Inlet D = 10.3" Outlet D = 7.3"
Weight		103 lbm
Material(s)		All materials same as low speed LOX TPA except teflon coating is not required.

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure		4300 psia
Thrust (S.L.)		600,000 lb_f
Isp (Minimum) (S.L.)		309.1 sec.
Propellants		LOX/LCH_4
Duty Cycle (Burns)		100
Cumulative Life		10 hrs.
Mixture Ratio		2.82
Weight		5075 lb_m

Components : Oxidizer Main Pump

Operating Pressure(s)		5262 psia
Operating Temperature(s)		T_{pump} = 166°R T_{turb} = 1860°R
Propellant Flowrate(s)		W_{pump} = 1396.5 lb/sec W_{turb} = 156.61 lb/sec
Start/Shutdown Conditions		D_{Lin} in = 8.2 in. D_{LOut} = 3.1 in
Envelope (Length)	D_{env} = 26.9" L_{env} = 36"	
Weight		895 lbm
Material(s)	● Shaft	A-286
	● Impeller	Inconel 718
	● High-Pressure	ARMCO
	Pump & Turbine Hsg.	Nitronic-50
	● Inducer Housing	Inconel 718
	● Turbines	Inconel 718
	● Bolts (pump)	A-286
	● Bolts (turbine	Waspaloy
	● Bearings	CRES 440C

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Fuel Main Pump

Operating Pressure(s)	7953 psia
Operating Temperature(s)	T_{pump} = 207°R T_{turb} = 1860°R
Propellant Flowrate(s)	$\dot{W}_{pump}$ = 495.4 lb/sec $\dot{W}_{turb}$ = 156.61 lb/sec
Start/Shutdown Conditions	
Envelope (Length) D_{env} = 23.3 in. L_{env} = 34 in.	D_{Lin} = 7.3" D_{Lout} = 3.4"
Weight	661 lbm
Material(s)	5 Al - 2.5 Sn ELI Titanium Alloy All other materials the same as high speed LOX TPA

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Hot Gas Manifold

Operating Pressure(s)	363 psia
Operating Temperature(s)	1780°R
Propellant Flowrate(s)	156.61 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	D = 6.6"
Weight	23 lbm
Material(s)	Inconel 625

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Low Pressure Line

Operating Pressure(s)	15 psia Ox 24 psia CH$_4$
Operating Temperature(s)	Cryo
Propellant Flowrate(s)	$\dot{W}_{ox}$ = 1396.5 lb/sec $\dot{W}_f$ = 495.4 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	D_{ox} = 15.4" D_f = 10.3"
Weight	253 lb
Material(s)	

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components : High Pressure Lines

Operating Pressure(s)	4000-8000 psia
Operating Temperature(s)	166°R - 1860°R
Propellant Flowrate(s)	$\dot{W}_{ox}$ = 1396.5 lb/sec $\dot{W}_f$ = 495.4 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	Varied - See Calcs
Weight	383 lbm
Material(s)	

TABLE III-I

COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components : Ignition Systems

Operating Pressure(s)	
Operating Temperature(s)	
Propellant Flowrate(s)	
Start/Shutdown Conditions	
Envelope (Length)	
Weight	40 lbm
Material(s)	

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH_4 Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb_f
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH_4
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb_m

Components: Misc. (Frames, fastener, harness, instrumentation, etc).

Operating Pressure(s)	
Operating Temperature(s)	
Propellant Flowrate(s)	
Start/Shutdown Conditions	
Envelope (Length)	
Weight	174 lbm
Material(s)	

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Controller

Operating Pressure(s)	Ambient
Operating Temperature(s)	Ambient
Propellant Flowrate(s)	-
Start/Shutdown Conditions	
Envelope (Length)	
Weight	130 lb
Material(s)	Aluminum

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Pressurization System

Operating Pressure(s)	
Operating Temperature(s)	
Propellant Flowrate(s)	Very Small Amount
Start/Shutdown Conditions	
Envelope (Length)	
Weight	138 lb.
Material(s)	

TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH$_4$ Engine (Cycle C)

Chamber Pressure	4300 psia
Thrust (S.L.)	600,000 lb$_f$
Isp (Minimum) (S.L.)	309.1 sec.
Propellants	LOX/LCH$_4$
Duty Cycle (Burns)	100
Cumulative Life	10 hrs.
Mixture Ratio	2.82
Weight	5075 lb$_m$

Components: Interpropellant Seal

Operating Pressure(s)	5262 psia
Operating Temperature(s)	Pump - 166°R Turbine - 1860°R
Propellant Flowrate(s)	Pump - 1396.5 lb/sec Turbine - 156.61 lb/sec
Start/Shutdown Conditions	
Envelope (Length)	
Weight	90 lbm
Material(s)	

APPENDIX B

REINFORCED PLASTIC COMPOSITE PROPERTIES

POLYMER MATRIX COMPOSITES

MATERIAL IDENTIFICATION	MATERIAL CONSTANTS					ALLOWABLE STRENGTH				MATERIAL COST $/LB
	ρ lbs/in^3	E_x psi	E_y psi	E_s psi	ν_x	Tension Ksi	Compression Ksi	Inplane Shear Ksi	Inter-Laminar Ksi	
1. Graphite epoxy prepreg crossplied (0,90)S	.056	11.5×10^6	11.5×10^6	$.8\times10^6$	.04	100	100	13	13	45
2. Kevlar epoxy Style 181 cloth prepreg	.047	5×10^6	5×10^6	3.3×10^5	.19	50	23	6	3	15
3. Graphite epxoy prepreg crossplied (+45)S	.056	2.5×10^6	2.5×10^6	5.5×10^6	.8	23	23	59.3	13	45
4. Unidirectional Kevlar epoxy prepreg	.054	11×10^6	8×10^5	3.3×10^5	.34	170	40	8.7	6	15
5. Graphite epoxy prepreg Quasi-isotropic laminate (0, ± 45, 90)S	.056	12×10^6	12×10^6	3.1×10^6	.21	105	84	37	13	45
6. 30% chopped fiberglass in Poly (amide - imide)	.067	1.92×10^6	1.92×10^6	3.25×10^6	.38	24	24	-	21.4	20
7. Unidirectional high modulus graphite epoxy prepreg	.056	25×10^6	1.7×10^6	$.65\times10^6$	.30	110	100	9	10	100
8. Unidirectional Boron Epoxy Prepreg	.073	30×10^6	2.7×10^6	$.7\times10^6$	.21	192	353	15.3	13.0	200
9. Fiberglass epoxy Prepreg crossplied (0,90)S	.070	4.7×10^6	4.7×10^6	$.3\times10^6$	.26	140	91	17	9.5	5

APPENDIX C

METAL MATRIX COMPOSITE PROPERTIES

METAL MATRIX COMPOSITES

MATERIAL IDENTIFICATION	MATERIAL CONSTANTS					ALLOWABLE STRENGTH				MATERIA COST
	ρ lbs/in^3	E_x psi	E_y psi	E_s psi	ν_x	Tension Ksi	Com-pressior Ksi	Inplane Shear Ksi	Inter-Laminar Ksi	$/LB
Crossplied Boron/Aluminum	.095	25.5x10^6	25.5x10^6	5.6x10^6	.27	172	172	18.0	18.0	325
Silicon Carbide/Aluminum	.103	18x10^6	18x10^6	--	.26	80	120	--	--	200

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APPENDIX D

TASK II EVALUATION FORMS

LOX/LCH$_4$ 600K BOOSTER
EVALUATION FORMS

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262

COMPONENT: LO_2 TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Inducer Housing	.3	122	9.5/12.4	Compression mold, machine	Tension Bending,	Hybrid Kevlar Graphite Epoxy	100
Inducer	.3	84	10.7/9.3	Compression mold or reaction injection mold, machine	Tension HCF Bending Erosion	Graphite Epoxy	100
Impeller	.3	51	5/16.8	Compression mold or reaction injection mold, machine	Tension HCF Bending Erosion	Graphite Epoxy	100
Impeller Housing	.3	144	15/24	Autoclave mold	Tension Bending	Hybrid Kevlar Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
90.7	-31.3	4.7	3.4	Excluded	Not a major weight saving
41.7	-42.3	4.9	3.4	Excluded	Not a major weight saving
25.4	-25.6	4.8	3.4	Excluded	Not a major weight saving
49	-95	3.4	3.5	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262

COMPONENT: LO_2 TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Inlet Housing	.3	66	10/27	None	Tension Bending	None	
Turbine Vanes	.3	62		None	Tension Compression Bending HCF	None	
Turbine Rotors	.3	217	7/14	None	Tension Compression Bending HCF	None	
Shaft (2 pc)	.3 .3	87 58	17.2/4 31/.7	Autoclave mold, machine	Torsion Bending HCF	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
68.4	-76.6	4.5	2.7		A similar part has been selected for analysis.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262

COMPONENT: LO_2 TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	2.1 1.9	80 mm 75 mm	None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-			Excluded	Ball bearings are not an effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953

COMPONENT: CH_4 TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Inducer Housing	.18	79	9.4/11	Autoclave mold, machine	Tension Bending	Hybrid Kevlar Graphite Epoxy	100
Inducer	.3	63	4.7/6.8	Compression reaction or injection mold, machine	Tension Bending HCF Erosion	Graphite Epoxy	100
Impeller	.3	40	4.0/9.4	Compression reaction or injection mold, machine	Tension Bending HCF Erosion	Graphite Epoxy	100
Impeller Housing	.3	163	13.5/ 21.4	Autoclave mold	Tension Bending	Hybrid Kevlar Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
52.4	26.6	4.6	3.9	Excluded	Not a major weight saving
19.9	-43.1	4.9	4.0	Excluded	Not a major weight saving
19.9	20.1	4.7	4.0	Excluded	Not a major weight saver
34	-129	3.9	3.9	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953

COMPONENT: CH_4 TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Inlet Housing	.3	46	14.8/ 20.3	None	Tension Bending	None	
Turbine Vanes	.3	42	.9/16	None	Tension Bending Compression HCF	None	
Turbine Rotors	.3	138	7.3/16	None	Tension Bending Compression HCF	None	
Shaft (2 pc)	.3 .3	53 33	17/3.1	Autoclave mold	Torsion Bending HCF	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite applications. Improved performance. No near term weight saving.
40.6	-54.4	4.5	3.2	Excluded	A similar part has been selected for analysis.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953

COMPONENT: CH_4 TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	1.2 .5	60 mm 45 mm	None		None	

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 611 RANKING: 3 TEMP (°F): -290 PRESSURE (PSI): 4300

COMPONENT: Injector % ENGINE WEIGHT: 12 -260

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Body	.3	373	6.2/20	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Face	.3	17	.18/15.4	Mold, carbonize, machine	Bending LCF	Carbon/ Carbon	100
LOX Manifold Cover	.3	33	3/15	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Fuel Manifold Cover	.3	33	3.8/20.6	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
282	-91	4.6	4.0	Excluded	Not a major weight saving
21.6	+4.7	4.5	4.4	Excluded	Not a major weight saving
25	-8	4.9	3.2	Excluded	Not a major weight saving
25	-8	4.9	3.7	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 611 RANKING: 3 TEMP (°F): -290 PRESSURE (PSI): 4300

COMPONENT: Injector % ENGINE WEIGHT: 12 -260

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.3	51	22.6/24	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Acoustic Cavity	.3	100	-	Mold, cargonize, machine	Tension	Carbon/ Carbon	-

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
24	-27	3.7	3.6	Selected	
130	+30	4.5	4.4	Excluded	Not a major weight saving.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 383 RANKING: 4 TEMP (°F): -290 PRESSURE (PSI): 4000-8000

COMPONENT: High Pressure Lines % ENGINE WEIGHT: 8 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)*	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	30	12/64	Tape Wrap (tubes)	Tension LCF Buckling	Hybrid Graphite Kevlar Epoxy	
	.3	178**	75/60				
	.3	40**	25/4				
Flanges	.3	80	50/4	Compression mold or reaction injection mold, machine, adhesive bond	Tension Bending Bearing	Graphite Epoxy and metal laminate	
	.3	16**	20/2				
Flex Joints	.3	40		Not a composite application		-	-
		384					

30 lbs (tubes)
80 lbs (flanges)
40 lbs (flex joints)

* All lines
** hot gas line - not composite application

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
12.8	-17.2	4.7	4.0	Excluded	A similar part has been selected for analysis
47.6	-32.4	4.8	4.8	Excluded	A similar part has been selected for analysis

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 364 RANKING: 5 TEMP (°F): -250 PRESSURE (PSI): 4300

COMPONENT: Combustion Chamber % ENGINE WEIGHT: 7 1000

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Liner	.3	154	27/19	Molding, Carbonization, Machine	LCF Compression Induced	Carbon/ Carbon	100
Close-Out	.3	61	27/19	Vacuum bag or autoclave bond	Tension Bending	Graphite Epoxy	95-100
Manifolds	.3	50	4.8/23	Compression or autoclave bond	Tension	Kevlar Epoxy	95-100
Support Structure	.3	99	25/25	Autoclave mold	Tension, Bending	Hybrid Graphite Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
171	+65	3.2	3.9	Excluded	Not a major weight saving
24	-37	4.7	3.9	Excluded	Not a major weight saving
11	-39	4.1	3.7	Selected	
39.6	-59.4	4.6	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 328 RANKING: 6 TEMP (°F): 1120 PRESSURE (PSI): 6

COMPONENT: Nozzle % ENGINE WEIGHT: 6

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tube Assembly	.3	109	100/76	None	Tension Bending	None	
Manifold	.3	93	57/5.7	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	
Manifold	.3	49	30.5/4	Autoclave mold, machine	Tension	Kevlar Epoxy	
Reinforcing Rings	.3	22	-	Autoclave mold, adhesive bond	Tension	Kevlar Epoxy	

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
				Excluded	High temperature metal matrix composite application. Improved Improved. No near term weight saving.
58.5	-34.5	4.6	3.7	Excluded	Not a major weight saving
-31	-18	4.7	3.7	Excluded	Not a major weight saving
10.5	-11.5	4.7	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 328 RANKING: 6 TEMP (°F): 1120 PRESSURE (PSI): 6

COMPONENT: Nozzle % ENGINE WEIGHT: 6

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Jacket	.3	55	100/76	Wrap and autoclave mold	LCF, Axial Bending	Graphite Epoxy	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
11	-44	4.5	3.9	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 311 RANKING: 7 TEMP (°F): -290 PRESSURE (PSI): 231

COMPONENT: LO_2 Boost Pump % ENGINE WEIGHT: 6

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing Hybrid	.1	193	27/26.7	Autoclave mold, machine	Tension Bending	Hybrid Kevler Graphite Epoxy	
Inducer Bolt	.3	7	15.4/ 1.5	None	Tension Compression Shear	None	
Turbine	.1	12	7.9/9.4	Compression or reaction injection mold, machine	Tension Compression Bending HCF	Graphite Epoxy	
Shaft	.3	50	22.8/3.9	Autoclave mold, machine	Torsion Bending HCF	Graphite Epoxy	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
97	-96	4.3	3.2	Selected	
-	-			Excluded	Low interlaminar shear properties limit the effectiveness of threads made of current technology composite materials and no weight saving results.
6	-6	4.9	3.4	Excluded	Not a major weight saving
27	-33	4.6	3.5	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 311 RANKING: 7 TEMP (°F): -290 PRESSURE (PSI): 231

COMPONENT: LO_2 Boost Pump % ENGINE WEIGHT: 6

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	1	100 mm	None	Bearing Tensile	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-			Excluded	Current technology composite materials are not effective in ball bearing applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 253 RANKING: 8 TEMP (°F): -260 PRESSURE (PSI): 15-24

COMPONENT: Low Pressure Lines % ENGINE WEIGHT: 5 -290

Part	Material Density (lbs/in³)	Current Weight (lbs)*	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	12	11.4/ 7.3	Autoclave mold, machine	Tension Bending LCF	Hybrid Kevlar Graphite Epoxy	50-99
	.3	19	13.3/ 10.3				
	.3	54	23/ 15.4	Compression mold, machine	Tension Bending Bearing	Graphite Epoxy Metal Lamination	50-70
	.3	100	80/8.2				
Flanges		68					
				Not a composite application			
	185 (tubes) 68 (flanges)						

*All lines

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
71	-113	4.6	4.0	Selected	
41	-27	3.6	4.8	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 204 RANKING: 9 TEMP (°F): Ambient PRESSURE (PSI): 600K lbf thrust

COMPONENT: Gimbal % ENGINE WEIGHT: 4

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Seat	.18	29	4.7/4.0	Compression or resin injection mold, machine	Bearing Compression	Graphite Epoxy and Metal Lamination	90-95
Body	.3	166	4.0/4.2	Compression or resin injection mold, machine	Bending Bearing	Graphite Epoxy and Metal Lamination	90-95
Block	.3	7	1.4x2.3	Compression or resin injection mold, machine	Compression Bearing	Graphite Epoxy and Metal Lamination	90-95
Shaft	.3	2	4.2/1.0	Compression or resin injection mold, machine	Torsion Bearing Bending	Graphite Epoxy and Metal Lamination	90-95

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
13	-16	4.6	4.5	Selected	
114	-52	4.5	4.5	Excluded	Not a major weight saving
5	-2	4.9	4.5	Excluded	Not a major weight saving
1.6	-.4	4.8	4.5	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 174 RANKING: 10 TEMP (°F): - PRESSURE (PSI):

COMPONENT: Miscellaneous % ENGINE WEIGHT: 3.5

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)

---

*Not analyzed for composite material applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 155 RANKING: 11 TEMP (°F): -290 PRESSURE (PSI): to 5300

COMPONENT: LOX Valves % ENGINE WEIGHT: 3

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bodies	.1	80	13/13	Reaction or injection mold, machine	Tension	Kevlar Epoxy	95-100
Balls	.3	38	-/5.4	Reation or injection mold, machine	Bending	Graphite Epoxy	95-100
Shafts	.3	13		Pultruded or autoclave molded	Torsion	Graphite Epoxy	100
Miscellaneous	.3	24		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
60.9	-19.1	4.8	2.8	Excluded	Not a major weight saving
25	-13	4.8	3.0	Excluded	Not a major weight saving
6.2	-6.8	4.9	3.6	Excluded	Not a major weight saving
				Excluded	Nonstructural parts that would not be cost effective if manufactured from composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 138 RANKING: 12 TEMP (°F): - PRESSURE (PSI): -

COMPONENT: Pressurization System % ENGINE WEIGHT: 3

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
						*	

*Not analyzed for composite material application. High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 133 RANKING: 13 TEMP (°F): -260 PRESSURE (PSI):

COMPONENT: CH_4 Valves % ENGINE WEIGHT: 2.6

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bodies	.1	70	14.3/16	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95-100
Balls	.3	33	4.4/6.5	Reaction injection or compression mold, machine	Bending	Graphite Epoxy	99-100
Shafts	.3	11	13/1	Pultruded or autoclave molded	Torsion	Graphite Epoxy	100
Miscellaneous	.3	19		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
64	-9	4.9	3.9	Excluded	Not a major weight saving
21.7	-11.3	4.7	3.9	Excluded	Not a major weight saving
5.2	-5.8	4.7	3.9	Excluded	Not a major weight saving
-	-			Excluded	Nonstructural parts that would not be cost effective if manufactured from composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 130 RANKING: 14 TEMP (°F): Ambient PRESSURE (PSI): Ambient

COMPONENT: Controller % ENGINE WEIGHT: 2.5

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.1	42	-	Autoclave or vacuum bag mold, machine	Bending	Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
32	-10	4.9	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 103 RANKING: 15 TEMP (°F): -250 PRESSURE (PSI): 135

COMPONENT: Fuel Boost Pump % ENGINE WEIGHT: 2

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.1	62	21/22	Autoclave mold, machine	Tension Bending	Hybrid Kevlar Graphite Epoxy	95-100
Inducer	.1	15	5.6/ 10.2	Compression or reaction injection mold	Bending HCF Erosion	Graphite Epoxy	100
Turbine	.3	4	5.7/2.3	Compression or reaction injection mold	Bending HCF Erosion	Graphite Epoxy	100
Inducer Bolt	.3	.5		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
42	-20	4.4	4.2	Excluded	Not a major weight saving
7.5	-7.5	4.8	4.0	Excluded	Not a major weight saving
2.0	-2.0	4.8	4.0	Excluded	Not a major weight saving
				Excluded	Low interlaminar shear properties limit the effectiveness of threads made of current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 103 RANKING: 15 TEMP (°F): -250 PRESSURE (PSI): 135

COMPONENT: Fuel Boost Pump % ENGINE WEIGHT: 2

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	21	17.2/ 2.3	Autoclave mold	Torsion	Graphite Epoxy	100
Bearings	.3	.3	40 mm	None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
10	-11	4.87	3.15	Excluded	Not a major weight saving
				Excluded	Ball bearings are not an effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH$_4$ WEIGHT (lbs): 90 RANKING: 16 TEMP (°F): -290 PRESSURE (PSI): 5262

COMPONENT: Interpropellant Seal % ENGINE WEIGHT: 2 1400

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
						*	

*Not analyzed for composite material applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 76 RANKING: 17 TEMP (°F): -260 PRESSURE (PSI): 363

COMPONENT: Gas Generator % ENGINE WEIGHT: 1.5 -290, 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Injector Body	.3	8	5.6/12.7	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95
Manifold	.3	13	5.6/10.5	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95
Cone	.3	5	1.5/12.7	Reaction injection or compression mold, machine	Compression Bending	Graphite Epoxy	95
Chamber	.3	25	7.2/12.8	Mold, carbonize; machine	Tension Bending	Carbon/ Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
6.0	-2	4.7	4.0	Excluded	Not a major weight saving
9	-4	4.7	3.2	Excluded	Not a major weight saving
3.3	-1.7	4.9	3.6	Excluded	Not a major weight saving
25	+0.0	4.4	4.4	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 76 RANKING: 17 TEMP (°F): -260 PRESSURE (PSI): 363

COMPONENT: Gas Generator % ENGINE WEIGHT: 1.5 -290, 1400

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Elements	.3	25	7.4/1.3	Compression Mold	Compression	30% Chopped fiberglass poly (Amide-imide)	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
9.5	-15.5	4.5	4.0	Excluded	Not a major weight savings

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 40 RANKING: 18 TEMP (°F): PRESSURE (PSI):

COMPONENT: Ignition System % ENGINE WEIGHT: .7

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)

*Not analyzed for composite material applications
*

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH_4 WEIGHT (lbs): 23 RANKING: 19 TEMP (°F): 1300 PRESSURE (PSI): 363

COMPONENT: Hot Gas Manifold % ENGINE WEIGHT: .5

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Manifold	.3	23	-	Mold, carbonize, machine	Tension	Carbon/ Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
29.4	+5.4	3.2	3.9	Excluded	Not a major weight saving

15K CTV EVALUATION FORMS

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Nozzle-Radiation Cooled
WEIGHT (lbs): 80
% ENGINE WEIGHT: 14
RANKING: 1
TEMP (°F): 245°
PRESSURE (PSI): Negligible

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Nozzle	.3	80	65/50	Molding, Carbonization, Machining	Beam Bending, Interlaminar Shear Stress	Carbon/ Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
130	+50	3.2	3.9	Exclude	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Valves & Actuators

WEIGHT (lbs): 72.8
% ENGINE WEIGHT: 12.6

RANKING: 3

TEMP (°F): -370° to 140°

PRESSURE (PSI): 16-1450

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
2 Valve Bodies	.18	10	6.8/4	Compression mold, machine	Tension	Kevlar Epoxy	95-100
4 Actuator Bodies	.18	29	11/2.4	Compression mold, machine	Tension	Kevlar Epoxy	100
Actuator End Closures	.18	7.8	.7/2.4	Compression mold, machine	Bending	Kevlar Epoxy	100
4 Gates	.3	5.0	2.2	Compression mold, machine	Bending	Graphite polyimide amide	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
2.6	-7.4	4.8	2.8	Selected	
8.7	-20.3	4.8	4.0	Excluded	Not a major weight saving
2.2	-5.6	4.8	5.0	Excluded	Not a major weight saving
1.8	-3.2	4.8	3.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Valves & Actuators

WEIGHT (lbs): 72.8
% ENGINE WEIGHT: 12.6
RANKING: 2
TEMP (°F): -370° to 140°
PRESSURE (PSI): 16-1450

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shafts	.3	10	2.5	Compression mold, machine	Shear	Graphite Epoxy	100
Gears	.3	10	-	Compression mold, machine	Bending	Graphite Epoxy	100
Springs	.3	1	5/3	None	Shear	None	

P-5

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
3.6	-6.4	4.8	3.6	Selected	
3.6	-6.4	4.8	3.6	Selected	
-	-	-	-	Excluded	Springs are not a cost effective application for composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 72 RANKING: 4 TEMP (°F): Ambient PRESSURE (PSI): Ambient
COMPONENT: Nozzle Deployment System % ENGINE WEIGHT: 12.5

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
3 Extension Shafts	.3	24	53/1	Pultrusion	Tension, Compression	Graphite Epoxy	100
Support Ring	.3	27	1/37	Autoclave mold	Tension Bending	Graphite Epoxy	100
Gear Box	.3		3.5/3	None		None	
Ball Screws	.3	21	3/3	None		None	
Flex Shafts	.3		.5/25	None		None	

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OF POOR QUALITY

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
4.9	-19.1	4.9	3.8	Select	
14	-13	4.6	5.0	Select	
				Exclude	Nonstructural parts that would not be cost effective if manufactured from composite materials.
-	-				
-	-				

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Combustion Chamber

WEIGHT (lbs): 74.3
% ENGINE WEIGHT: 13

RANKING: 2 TEMP (°F): 1000° PRESSURE (PSI): 1200

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Liner	.3	20.4	22/8.4	Molding, Carbonization, Machining	LCF, Compression Induced	Carbon/ Carbon	100
Close-Out	.3	9.4	22/10	Vacuum bag or autoclave mold	Tension, Bending	Graphite Epoxy	95-100
Manifolds	.3	22.5	3/11 3/30	Compression or autoclave mold	Tension	Kevlar Epoxy	95-100
Support Structure	.3	22	24/12	Autoclave mold, machine	Bending (axial) Tension (radial)	Hybrid Graphite Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
33	+12.6	3.2	3.9	Excluded	Not a major weight saving
3.7	-5.7	4.7	3.9	Excluded	Not a major weight saving
14	-8.5	4.7	2.8	Excluded	Not a major weight saving
5.6	-16.4	4.5	5.0	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Nozzle-Tube Bundle
WEIGHT (lbs): 38.4
% ENGINE WEIGHT: 6.6
RANKING: 5
TEMP (°F): 270°
PRESSURE (PSI): 2466

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tube Assembly	.3	29.4	34.4/ 36.6	Tape wrap tubes*	Tension, LCF, Buckling	Hybrid Graphite Kevlar Epoxy	20-30
4 Reinforcing Rings	.3	3	35/2 29/2 24/2 18/2	Autoclave mold	Tension	Kevlar Epoxy	100
Manifold	.3	6	1.3/12	Compression mold, adhesive bond	Tension	Kevlar Epoxy	100

* Reinforcement of Tubes

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
*	*	–	–	Excluded	Not a major weight saving
1.2	-1.8	4.7	5.0	Excluded	Not a major weight saving
3.8	-2.2	4.5	3.1	Excluded	Not a major weight saving

* Negligible weight benefit from overwrapping steel tube bundle with composite.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Propellant Lines
WEIGHT (lbs): 37
% ENGINE WEIGHT: 6.4
RANKING: 6
TEMP (°F): -290°
-420
PRESSURE (PSI): 18-1500

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	9	35/2.5 30/1.5	Tape wrap	Tension, Bending	Hybrid Kevlar, Graphite Epoxy	90-100
Flanges	.3	10	1.5/4 1/2	Compression mold, adhesive bond	Tension, Bending	Graphite Epoxy Metal Laminate	50-75
Flex Joints	.3	18	2.5/3 2/2	None	Tension Bending	Hybrid Kevlar, Graphite Epoxy	90-100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
3.8	-5.2	4.7	4.0	Excluded	Not a major weight saving
6	-4	4.7	4.6	Excluded	Not a major weight saving
7.6	-10.4	4.7	4.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Controller
WEIGHT (lbs): 35
% ENGINE WEIGHT: 6
RANKING: 7
TEMP (°F): Ambient
PRESSURE (PSI): Ambient

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Case	.1	11	17x8x10	Autoclave mold		Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
8.4	-2.6	5.0	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Injector

WEIGHT (lbs): 30.6 RANKING: 8 TEMP (°F): PRESSURE (PSI): 1200-1434
% ENGINE WEIGHT: 5.3

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Body	.3	21	3.2/6.5	Compression or reaction injection mold	Tension	Kevlar Epoxy	95-100
Face	.3	1.0	05/5.6	Molding, carbonization, machine, adhesive bond	LCF, Bending	Carbon/ carbon	100
Co-axial Elements	.3	1.2	.18/2.3	Reaction injection mold or compression mold, or pultruded/ wrapped tube	Tension, Compression	Graphite Epoxy	100
Manifold	.3	5	2.3/7.9	Compression or reaction injection mold	Tension	Kevlar Epoxy	95-100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
16	-5	4.7	3.8	Excluded	Not a major weight saving
1.0	+.3	4.7	4.4	Excluded	Not a major weight saving
.5	-.7	4.7	3.1	Excluded	Not a major weight saving
3.8	-1.2	4.7	3.6	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Injector

WEIGHT (lbs): 30.6 RANKING: 8 TEMP (°F): PRESSURE (PSI): 1200-1434
% ENGINE WEIGHT: 5.3

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
2 Clevises	.3	2.4	2.9/1.6	Compression or reaction injection mold	Tension, Bending, Shear, Bearing	Graphite Epoxy, 10% Steel	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.8	-.6	4.7	4.8	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LOX TPA

WEIGHT (lbs): 25.1 RANKING: 9 TEMP (°F): -290 PRESSURE (PSI): 48-1487
% ENGINE WEIGHT: 4.7 30 1326-1512

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Pump Housing	.1	5.4	33/6.2	Compression mold, machine	Tension, Bending	Hybrid Graphite Kevlar Epoxy	95-100
Seal Housing	.1	7.0	5/1/4.2	Compression mold, machine	Tension, Bending	Kevlar Epoxy	100
Turbine Housing	.1	4.0	3.9/8.8	Compression mold, machine	Tension, Bending	Hybrid Graphite Kevlar Epoxy	95-100
Impeller	.1	.2	1/18	Compression or reaction mold	HCF, Tension, Bending	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
2.4	-3	4.7	3.8	Excluded	Not a major weight saving
5.3	-1.7	4.8	3.5	Excluded	Not a major weight saving
1.8	-2.2	4.8	4.0	Excluded	Not a major weight saving
.1	-.1	4.9	3.8	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LOX TPA

WEIGHT (lbs): 25.1
% ENGINE WEIGHT: 4.7

RANKING: 9

TEMP (°F): -290
30

PRESSURE (PSI): 48-1487
1326-1512

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	2.0	5.8/1.2	Spiral tape wrap, autoclave mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Turbine	.3	4.0	2.8/6.3	Compression or resin injection mold	HCF, Tension, Bending	Graphite Epoxy	100
Bearing	.3	2.5		None	Tension Bearing	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
.9	-1.1	4.7	3.9	Excluded	Not a major weight saving
2	-2	4.9	3.8	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH_2 TPA

WEIGHT (lbs): 21.5 RANKING: 10 TEMP (°F): -420 PRESSURE (PSI): 49-2531
% ENGINE WEIGHT: 4.6 75 2344-1522

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Propose. Fab. Meth.	Critical Failure Mode	Proposed Material	Volume Fraction (%)
LH_2 Inlet Housing	.18	4.0	2.8/5.8	Compression reaction or injection mold, machine	Tension, Bending	Hydrid Kevlar Graphite Epoxy	95-99
Pump Housing	.18	8.5	6.8/6.6	Compression mold, machine	Tension, Bending	Graphite Epoxy	95-99
Inducer	.18	.1	1.6/3.8	Compression mold, resin injection, machine	HCF, Tension, Bending	Graphite Epoxy	100
Impellers	.18	3.0	1.3/3.4	Compression mold, resin injection, machine	HCF, Tension, Bending	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.8	-2.2	4.9	4.0	Excluded	Not a major weight saving
3.8	-4.7	4.8	4.0	Excluded	Not a major weight saving
.05	-.05	4.9	3.6	Excluded	Not a major weight saving
1.5	-1.5	4.9	3.6	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH_2 TPA

WEIGHT (lbs): 21.5 RANKING: 10 TEMP (°F): -420
% ENGINE WEIGHT: 4.6 75

PRESSURE (PSI): 49-2531
2344-1522

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Exit Housing	.1	3.7	2.0/3.8	Compression mold, machine	Tension, Bending	Graphite Epoxy	100
Shaft	.3	1.4	7.8/.8	Tape wrap, machine	HCF, Tension, Bending	Graphite Epoxy	100
Turbines	.3	.6	.9/2.8	Compression mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Bearings	.3	.2	12 mm 40 mm	None	Bearing Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.4	-2.3	4.8	4.3	Excluded	Not a major weight saving
.7	-.7	4.7	3.3	Excluded	Not a major weight saving
.3	-.3	4.9	3.8	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 12.6 RANKING: 11 TEMP (°F): PRESSURE (PSI):
COMPONENT: Misc. Valves and Pneu. Pack % ENGINE WEIGHT: 2.2

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
						*	

*Not analyzed for composite material applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Ignition System
WEIGHT (lbs): 9.2
% ENGINE WEIGHT: 1.6
RANKING: 12
TEMP (°F)
PRESSURE (PSI): 1200

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
						*	

*Not analyzed for composite material applications

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH_2 Boost Pump

WEIGHT (lbs): 8.5 RANKING: 13 TEMP (°F): -420 PRESSURE (PSI): 18.5-50
% ENGINE WEIGHT: 1.4

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine-Impeller Housing	.1	3.6	2.3/5.6	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	95-100
Exit Housing	.1	4.1	2.7/5	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	100
Turbine-Impeller	.1	.3	1.4/4.4	Compression mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Impeller Bolt	.3	.1	2.5/.3	None	Tension, Compression	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.6	-2.0	4.8	3.7	Excluded	Not a major weight saving
1.8	-2.3	4.8	3.7	Excluded	Not a major weight saving
.15	-.15	4.9	3.6	Excluded	Not a major weight saving
				Excluded	Low innerlaminar shear properties limit the effectiveness of threads made of current technology composite materials and no weight savings results.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH_2 Boost Pump

WEIGHT (lbs): 8.5 RANKING: 13 TEMP (°F): -420 PRESSURE (PSI): 18.5-50
% ENGINE WEIGHT: 1.4

Part	Material Density (lbs/in^3)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	.4	3.8/.6	Autoclave mold, machine	Tension, Bending	Graphite Epoxy	100
Bearings	.3	.08	17mm	None	Bearing Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
.19	-.22	4.7	3.3	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LOX Boost Pump

WEIGHT (lbs): 5.6 RANKING: 14 TEMP (°F): -320 PRESSURE (PSI): 16-56
% ENGINE WEIGHT: 1.0

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine-Impeller Housing	.1	2.4	1.9/5.5	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	95-100
Exit Housing	.1	2.7	3.4/3.1	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	100
Impeller Shaft	.1	.3	3.4/3.1	Compression mold	Tension, Bending	Graphite Epoxy	100
Bearings	.3	.08	15 mm	None	Bearing, Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.05	-1.35	4.8	3.2	Excluded	Not a major weight saving
1.2	-1.5	4.8	3.2	Excluded	Not a major weight saving
.15	-.15	4.7	3.5	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Heat Exchanger

WEIGHT (lbs): 5
% ENGINE WEIGHT: .8

RANKING: 15 TEMP (°F): 70 PRESSURE (PSI): 1500-2300

Part	Material Density (lbs/in³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Outer Shell	.3	3.5	3/6.4	Tape Wrap	Tension	Graphite Epoxy	100
Inner Shell	.3	1.5	3/4.0	Autoclave mold, adhesive bond, machine	Tension	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.75	-1.75	4.7	3.6	Excluded	Not a major weight saving
.75	-.75	4.7	3.6	Excluded	Not a major weight saving

APPENDIX E

VENDOR TRIP MEMOS

Aerojet
Liquid Rocket
Company

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Materials Analysis

REPORT NO. MA-82-144
DATE 25 June 1982

WORK REQUESTED BY D. C. Judd	DEPT. 9733		PAGE 1 OF 4
SUBJECT Trip Report - Composite Material Fabricators (June 21-22)			TABLES: 2 FIGURES:
PROGRAM Composite Material Applications to Liquid Rocket Engines	W.O. NO. 2418-03-000		ENCLOSURES:
PART NAME Conceptual Design Assessment	PART NO. Task III	S/N	MATERIAL Composites

PURPOSE:

To meet with fabricators of composite materials to present ALRC conceptual designs for composite parts, to obtain their comments on producibility, and to assess their fabrication capabilities.

SUMMARY:

Six contractor facilities were visited during a two day trip to Los Angeles. In these meetings it was explained that a significant weight savings (between 30 and 40 percent) can be realized by substituting composite materials for metals in liquid rocket engines. All six contractors indicated that they would be interested in helping ALRC develop rocket engine parts.

DISTRIBUTION DL Xors DE Lemke RW Michel CJ O'Brien HO Davis (ASPC)	REPORT BY E. W. Carter E.W. Carter
	REVIEWED BY G. R. Janser G.R. Janser
	APPROVED BY for V. FRICK, MANAGER, MATERIALS ANALYSIS SECTION

INTRODUCTION:

The current NASA contract to study composite material applications in liquid rocket engines has provisions for recommending designs for a minimum of two parts for a follow-on development program. A description of this follow-on program is required including detail fabrication plans. During the visits to the six subcontractor facilities, subcontractor participation in the follow-on program was discussed. The preliminary designs of seven rocket engine parts to be made with composites were reviewed. Each contractor was asked to assess his capability to make the parts together with anticipated processing difficulties.

DISCUSSION:

The preliminary designs reviewed by the six subcontractors fall into three categories of producibility:

(1) Parts whose fabrication is straightforward.

(2) Parts that require a process development program to establish parameters for controlling fiber geometry.

(3) Parts that require redesign in order to successfully fabricate (Note 1A, Table I).

Table I summarizes the position of each subcontractor on these parts; it shows the processes available at each facility for manufacturing the part and the contractor's opinion of producibility. For five of the designs (1196001, 1196002, 1196003, 1196005, and 1196007), the complexity of the parts and the lack of design detail make the assessment of producibility difficult. Two of these designs (1196003 and 1196005) had enough obvious difficulties to establish that a redesign would be necessary. It was assumed that the redesigned part would be satisfactory for manufacturing if the subcontractor consulted with the designer.

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Swedlow Inc. indicated that they could assume responsibility for part design. This suggestion was made during the review of the injector housing (1196007). They feel that the high pressures and propellant flows dictate extraordinary methods of structural analysis.

Four subcontractors (Swedlow, HITCO, Reynolds and Taylor, and M.C. Gill) have excellent facilities for producing parts using composite materials. Two contractors (Swedlow and HITCO) also have the capability to design with composite materials.

The subcontractors have indicated that the response time to an RFQ for participation in a development program would be three weeks or less. To prepare a quote, they would require an SOW and a detail design of the part to be developed. Additional technical meetings would be helpful to discuss program requirements and familiarize the subcontractors with rocket engine components. HITCO made the suggestion that one development part might be a mock-up combining the design features and technology needs of several parts. This approach would concentrate the objectives of the program in one part and set of tooling to reduce costs.

Table II lists the persons contacted during the visits along with the product lines of the companies.

CONCLUSIONS:

1. All six contractors have potential to help ALRC build rocket engine parts out of composite materials.

2. HITCO, Swedlow, and M.C. Gill are large diversified manufacturers with significant manufacturing research capability. Reynolds and Taylor's capabilities emphasize job shop production.

3. Poly-Trussions and Fibco are limited respectively to pultrusion or vacuum bag and compression molding.

RECOMMENDATION:

1. Prepare an SOW defining subcontractor support requirements for follow-on composite effort.

2. Coordinate SOW with candidate subcontractors and obtain quotations for inclusion in follow-on proposal to be prepared in Task V (7/15-9/15).

TABLE I

SUMMARY OF SUBCONTRACTOR POSITIONS REGARDING PRODUCIBILITY AND DESIGN*

ROCKET ENGINE PART	REYNOLDS & TAYLOR	SWEDLOW	FIBCO	M.C. GILL	POLY-TRUSSIONS	HITCO
1196001 LCH$_4$ High Speed TPA	1B, 1C, 1E, 3A, 3B, 3C, 3F, 4	1B, 1C, 1D, 3A, 3B, 3F, 4	2A	1B, 1C, 1E, 3A, 3B, 3E, 3F, 4	2A	1B, 1C, 1E, 3A, 3B, 3F, 4
1196002 High Speed LOX TPA	1B, 1C, 1E, 3A, 3B, 3C, 3F, 4	1B, 1C, 1D, 3A, 3B, 3F, 4	2A	1B, 1C, 1E, 3A, 3B, 3E, 3F, 4	2A	1B, 1C, 1E, 3A, 3B, 3F, 4
1196003 LOX Low Speed TPA	1A, 1B, 1E, 3A, 3B, 3C, 3F, 4	1A, 1B, 1D, 3A, 3B, 3F 4	2A	1A, 1B, 1E, 3A, 3B, 3E, 3F, 4	2A	1A, 1B, 1E, 3A, 3B, 3F, 4
1196004 Support Structure Throat Combustion Chamber	1B, 3B, 3F, 4	1B, 3B, 3F, 4	1B, 3B, 3F, 4,	1B, 3B, 3F, 4	2A	1B, 3B, 3F, 4
1196005 Seat-Gimbal Bearing	1A, 1E, 3A, 3B, 3C, 3F, 3G, 4	1A, 1D, 3A, 3B, 3F, 3G, 4	2A	1A, 1E, 3A, 3B, 3F, 4	2A	1A, 1E, 3A, 3B, 3F, 3G, 4
1196006 Shaft-Nozzle Extension	1B, 3B, 3F, 3G, 4	1B, 3B, 3F, 3G, 4	1B, 3B, 3F, 3G, 4	1B, 3B, 3E, 3F, 3G, 4	2B, 3D, 4	1B, 3B, 3F, 3G, 4
1196007 Injector Housing	1B, 1C, 1E, 3A, 3B, 3C, 3F, 4	1A, 1B. 1D, 3A, 3B, 3F, 4	2A	1B. 1C. 1E, 3A, 3B, 3F, 4	2A	1B, 1C, 1E, 3A, 3B, 3F, 4

* See Notes on next page for legend explanation.

TABLE I (cont'd)

NOTES

1 PRODUCIBLE

A. Extensive part-geometry redesign is required. Consideration should be given to structural requirements because of their effect on fiber geometry and fiber misalignment tolerances. Extensive use of chopped molding compound (isotropic material) in low stress areas would promote the producibility of thick sections and complex surfaces where it is difficult to maintain precision fiber alignment.

B. A series of concurrent and congruent processing and fabrication steps are required.

C. Minor part-geometry redesign would simplify fabrication.

D. Subcontractor would prefer to assume basic design responsibility for the part.

E. Subcontractor would prefer to act as a design consultant to guide producibility.

2 OUT OF MANUFACTURING SCOPE

A. Lack processing facilities.

B. Fabrication with graphite fiber must be segregated to prevent electrical equipment malfunctions.

3 PROCESSES

A. Compression molding
B. Autoclave molding
C. Transfer molding
D. Pultrusion
E. Braiding
F. Hand lay-up
G. Wrapping, winding

4 Subcontractor would like to submit a quote to be included in the Composite Material Applications Study Contract Final Report.

TABLE II

COMPANIES AND PERSONS CONTACTED

COMPANY	PERSONS CONTACTED	PRODUCTS
Reynolds and Taylor 2109 South Wright Street Santa Ana, CA (714) 540-4850	Mike Furry Vice President-Fabrication	Wings of composite material for the Israel smart bomb - Transfer molded stringers and integral fiberglass stress skins.
Swedlow, Inc. 12122 Western Avenue Garden Grove, CA (714) 893-7531	George Greenwald Manager Design Joe Kertesz Production Engineering Supervisor Glenn Cook Project Engineer Earl Gruhn Tony Chevalier Production Engineers John Progue Contract Administrator	Aircraft canopies, structural shapes, microwave antenna
Fibco Plastics, Inc. 6899 Oran Circle Buena Park, CA (714) 522-1161	Tony Rivera	Radomes, microwave antenna

TABLE II (cont'd)

COMPANY	PERSONS CONTACTED	PRODUCTS
M.C. Gill Corporation 4056 Easy Street El Monte, CA (213) 443-6094	Steven Gill Vice President-Production	Aircraft interiors Cargo containers Aircraft flooring Aircraft ducting
Poly-Trussions Inc. 3050 Daimler Street Santa Ana, CA (714) 557-5802	Richard Kostner Vice President	Pultrusions
HITCO 1600 West 135th Street Gardena, CA (213) 321-8080	Donald Dwyler Product Manager	Ablative nozzles and exit cones Aircraft interiors 767 Flap track covers (Kevlar, Graphite, Fiberglass) Radomes Submarine fairings Carbon/Carbon Composites

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Reynolds and Taylor
2109 SOUTH WRIGHT ST

Location: Santa Ana, Ca.

Telephone: 714-540-4850

persons contacted: [illegible], President; [illegible] Supt. & Smith Vice President Fabrication; Don Harrison, Sales

business scope: Subcontractor of Reinforced Plastic parts to the Aerospace Industry

processes used: Autoclave, Vacuum bag, Compression, Resin injection molding

related experience: Production contracts with Hughes Aircraft, Raytheon, Litton, TRW Space Systems, Aerojet. They also make parts for engineering studies. Much of their work is with advanced composites.

Interest in Aerojet/NASA contract: yes

Remarks: Three divisions: Machining, Composites, Materials. They suggested a visit to observe their facilities. Sending a brochure describing the company.

6-10-82 Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

Company: Peterson Products

Location: 1325 Old Country Rd
Belmont, Ca

Telephone: (415) 591-7311

persons contacted: Ken Anderson, manager

business scope: Job shop supplier of reinforced plastic parts to the building, electronics, and aerospace industries

process used: Vacuum, compression molding, and resin transfer molding (reaction injection molding).

related experience: 3 R&D-type development contracts with Lockheed, Ford Aerospace, IBM. Received Navy contract a few years ago.

Interest in Aerojet/NASA contract: yes

Remarks: Sending a Bidder Policy Letter

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Poly-Trusions Inc.

Location: 3050 Daimler St.
Santa Ana

Telephone: (714) 557-5802

persons contacted: Dell Miller, Engineer

business scope: Manufacturing of commercial fiberglass pultrusions.

processes used: Pultrusion and minor amounts of compression molding

related experience: No direct. They appear to have considerable expertise in pultrusion and knowledge of how to process graphite and Kevlar.

Interest in Aerojet/NASA contract: Yes, Poly-Trusions would like to help us develop the nozzle deployment system actuator rods. They [illegible] pultrusion [illegible] while

Remarks: Tube with .090 in thick integral fiberglass [illegible] into which screw thread would be ground. This approach has been used in the past to make [illegible] in actuator systems.

(over)

Dell estimated that between 5 and 10 thousand dollars of tooling would be required and perhaps a week of machine trials to optimize the part. Dell is sending a company brochure.

Dell suggested Reynolds and Taylor as a plastic fabricator of aerospace parts.

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Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Swedlow Inc.

Location: 12122 Western Ave
Garden Grove, Ca

Telephone: (714) 893-7531

1:26 Bill return call

Persons contacted: John Pogue Contract Adm. & Joe Sullivan, Marketing
Bill Yamaguchi

Business scope: Contract supplier of assorted reinforced plastic parts for government and commercial products.

Processes used: Hand lay-up, vacuum, autoclave, hydroclave, compression molding (max capability 2000 ton, 56×60 in)

Related experience: Many contracts with Aerojet Strategic and Tactical Companies supplying ballistic missile components. They have done design and prototype contracts for the Navy.

Interest in Aerojet/NASA contract: Yes, would be interested in helping us develop advanced composite rocket engine parts. Sending a brochure and Engineering data book.

Remarks:

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

Company: HITCO

Location: 1600 W. 135th Street
Gardena, Ca

Telephone: (213) 321-8080

persons contacted: Bill Curran, Contract Administrator
Don Dwer, Pat Dempsey

business scope: Fabricator of High Temp. AEROSPACE Structures

processes used: Autoclave, Hydroclave, Compression Molding

related experience:

Interest in Aerojet/NASA contract: yes

Remarks:

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Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Century Plastics, Inc

Location: 1435 S. Santa Fe
Compton Ca.

Telephone: (213) 637-1121

persons contacted: Irv. Green, Principal and General Manager

Business scope: Job shop fabricator of reinforced plastic parts, primarily for electrical applications.

processes used: Vacuum Bag molding, Autoclave molding. Compression Molding (1500 ton capacity)

related experience: Autoclave molded a prototype spyder part of Kevlar epoxy for the L-1011. Developed a graphite stiffened part for FMC.

Interest in Aerojet/NASA contract: Yes.

Remarks: Employ a retired Lockheed Engineer as a consultant three days a week. The consultant is an instructor at the Harvey Mudd Institute. He would like the consultant to be present when we visit their facility to discuss our requirements.

6-9-82

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Fibco Plastics Inc.

Location: 6899 Oran Circle
Buena Park, Ca

Telephone: (714) 522-1161

persons contacted: ~~Tom~~ Tony Rivera. Father owns company. Father started company 22 years ago and has the primary technical expertise

business scope: Job shop fabricator of small production runs and prototype parts.

processes used: Hand lay-up, Vacuum ~~and autoclave~~ molding, and compression molding

related experience: Have made parts for Aerojet in Buena Vista and El Monte. Have frequently quoted work from Azusa. Manufacture radomes for EA-6 and P-3 aircraft, NASA, and the Navy. They supply the 11 foot radome covers for the Navy Terrier missile system.

Interest in Aerojet/NASA contract: yes.

Remarks: We should discuss our technical requirements with Tom's father. They are sending us some literature describing the technical capabilities of the company.

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

Company: M.C. Gill Corp.

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Location: 4056 Easy Street
El Monte, Ca

Telephone: (213) 443-6094

persons contacted: Dennis Watts, manager of commercial aircraft division, Steven Gill, manager of the Witchita operations.

business scope: Job shop manufacturer of reinforced plastic parts for the commercial aircraft industry.

processes used: Vacuum, autoclave, and compression molding.

related experience: They have conducted manufacturing development programs involving graphite epoxy and Kevlar epoxy McDonald Douglas and the Dahagren labs of the US Navy.

Interest in Aerojet/NASA contract: They have studied polyimide resin and have quoted several jobs for McDonald Douglas. They are especially interested in pursuing a development program using polyimide resins.

Remarks: They have a process development lab in El Monte and we would be welcome to participate in any experiments conducted for us.

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Aerojet
Liquid Rocket
Company

Materials Analysis

REPORT NO. MA-82-156
DATE 21 September 1982

WORK REQUESTED BY D. C. Judd	DEPT: 9772	PAGE 1 OF 4
SUBJECT Application of Metal Matrix Composites to Selected Engine Parts		TABLES: FIGURES:
PROGRAM Composite Materials Application to Liquid Rocket Engines	W.O. NO. 2418-05-000	ENCLOSURES:
PART NAME	PART NO. / S/N	MATERIAL

PURPOSE:

To consult with metal matrix composite fabricators to determine the state-of-the-art for application to selected liquid rocket engine parts.

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REPORT BY G.R. Janser
G. R. Janser

REVIEWED BY

APPROVED BY
V. RICK MANAGER MATERIALS ANALYSIS SECTION

DISCUSSION:

The writer and Ed Carter visited Nevada Engineering and Technology Corp. (NETCO) of Long Beach, California, and DWA Composite Specialities, Inc. of Chatsworth, California, on 10 September, for consultation with regard to the application of metal matrix composites to the subject program.

NETCO

The NETCO contacts were Leroy Davis, President, and Jack Williamson. The purpose of visiting NETCO was twofold. In addition to the aforementioned consultation, NETCO is expected to be a source for mechanical and physical property data for proposed designs. NETCO is under contract to the Department of Defense Metal Matrix Composites Information Analyses Center (MMCIAC) to collect, evaluate, store and disseminate metal-matrix property and processing data. Mr. Davis was asked to provide MMCIAC cyrogenic property data for support for the design activity of the anticipated composites follow-on contract. He stated that there was very little cryogenic information; and since this activity is just getting underway, the material is not fully organized for immediate retrieval. Mr. Davis is placing the writer on distribution for the MMCIAC bulletin and will determine the availability of cryogenic data at a later date.

When the drawings were presented, Messrs. Davis and Williamson stated that they preferred not to comment on the viability of the design from the standpoint of fabrication from metal matrix composites due to their complexity as compared to their experience. They recommended consulting with either AVCO, DWA or MCI for fabricability information. They believed that DWA would be the best source for this information and did offer an opinion that fabrication would be very difficult.

Mr. Williamson wanted to comment on the design with regard to reinforced plastic (RPC) materials since he is also marketing director for Reynolds and Taylor, a company which had declined to respond to an RFQ from ALRC on the subject RPC designs. He said he would persuade his associates at Reynolds and Taylor to reconsider their no-bid position.

DWA

The DWA contacts were Joe Dolowy, President, Bill Harrigan, General Manager-Operations and Roy Levin, Manager-Manufacturing Development. After the writer and Ed Carter described the composites contract, Joe Dolowy stated they were already somewhat familiar with the program since they had consulted with Rocketdyne on their parallel effort. Their examination of the drawings resulted in a unanimous opinion that the parts could not be fabricated by laying-up metal matrix laminates and diffusion bonding. They said that not only could the parts not be layed up due to the small and varying radii, but that hot gas isostatic pressing (HIP) for diffusion bonding would be a development program in itself. They specifically stated that the most complex part, the pump housing, was well beyond the present state of metal matrix composite fabrication capability. It was also their opinion that for complex shapes with multi-directional stress distributions, boron-aluminum becomes inefficient and that graphite-metal composites present the same problem in addition to the problem of very low transverse and shear strength. They proposed fabricating from their proprietary aluminum-silicon carbide reinforced composite material, DWA-Al. This material is a powder metallugry product, which is consolidated into semi-finished stock prior to being processed by conventional metal shaping techniques such as forming, extrusion, forging and machining. The material possesses poor weldability by the GTAW process and is considered by DWA to be unweldable by the electron beam process. Weld deposits are porous and have the same properties as those deposited on unreinfoced aluminum alloys. DWA stated that they have made good progress in reducing weld porosity, and presented photomicrographs showing porosity limited to the weld deposit heat affected zone interface. They expect to further improve weld soundess and are currently developing composite weld rods for producing reinforced, higher strength weld deposits. This development has led to their initiating a casting program. DWA could not provide assurance that these technologies would be sufficiently developed for application for our follow-on contract.

The writer inquired whether the aluminum graphite composite, which can be tailored to match the expansion coefficient of the RFP material, could be applied as liners for the interior of RFP parts. Their response was negative.

Mr. Dolowy said that DWA would provide a written cost estimate for the one part, the valve body. He would propose to machine the part from an extrusion and gave a preliminary estimate of $50,000.

CONCLUSIONS AND RECOMMENDATIONS:

1. Fabrication of the candidate parts by diffusion bonding of metal matrix composite laminates would be very difficult and is considered a high risk item.

2. A material such as the DWA-A1 composite offers the lowest risk in the application of metal matrix materials to the unwelded, candidate parts. Welded designs must account for reduced strength and some weld porosity.

dwa composite specialties, inc.

16 September 1982

Aerojet Liquid Rocket Company
P.O. Box 13222
Sacramento, CA 95813

Attention: Messrs. Ed Carter and George Janser

Subject: Meeting at DWA 10 September 1982

Gentlemen:

With regard to your visit of last week, we have reviewed the structures discussed and have reached similar conclusions to those reached during the meeting. Of the five structures considered: 1) the LCH_4 High-speed TPA appears to be well beyond the present state of MMC fabrication capability; when truly "castable" forms of discontinuous composites become available, large toroidal or volute type structures will become do-able. 2) & 3) The Support ring and nozzle extending shafts were only considered in passing, since they didn't offer any appreciable weight saving or technology challenge; both could be impacted with metal matrix. 4) Injector Housing represents a significant challenge to present discontinuous reinforced MMC fabrication technology. Utilizing forged DWAl 20® for the bottom third and top third of the part while handling the oxidizer manifold as a separate problem seems most efficient (fabricate as a separate "pressure-vessel" type structure, utilizing conventional material, or possibly superplastically formed DWAl 20®). Forged "cup"®"complex-base" cylinder shapes have been produced with DWAl 20®. The most significant problem with the injector housing would evolve from assembling the three subcomponents; brazing and welding both seem reasonable, but a development program would be advised. If necessary, selective circumferential reinforcing could be applied, using graphite epoxy; this could also aid in assembling the subcomponents. 5) Housing-valve, propellant - represents the second structure discussed 10 September, with reasonable options for MMC demonstration. Extruded, heavy-wall cylinders represent a straightforward approach, but necessitates significant machining to create bosses, attach-points and flanges. An alternative fabrication process could utilize ring-rolling to decrease the required machining, but this would necessitate higher tooling costs.

In reviewing the Aerojet selected hardware, my associates and I felt the DWAl 20® (isotropic particulate-reinforced P.M. composite) would be most appropriate. Although our experience with boron-aluminum-type composites exceeds all other material systems when axi-symmetric, rather complex-shaped parts (with multi-directional stress distributions) are desired, B-Al tends to

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become inefficient. Also, the complexities of fabrication with continuous, stiff fibers limit available processes. The graphite-metal composites were not considered for similar reasons, with the added problem of very-low transverse and shear strength. The ability to utilize many conventional metal-working processes and to yield isotropic mechanical properties, has finalized the recommendation of DWAl 20® materials.

In response to questions generated during the meeting, attached are several tables showing mechanical properties and costs of various MMC systems. A generalized development effort for the valve housing might require five or six months, with initial extrusion experiments yielding 8-inch long x 2.2" ID x 4.8" OD samples. Subsequent machining would create the final product. A $35K to $45K effort should be sufficient.

The injector housing structure, which would involve a much greater analysis effort, separate tools, and an assembly task would necessitate a ten to twelve-month effort. Initially, the design concept and part sizes would be finalized with the selection of material for the oxidizer manifold. Forging, or hot-forming tools for the top and bottom sections will be produced, then axisymmetric tool-verification parts generated. Mechanical property levels verified from the "tool try" parts following NDT, would create mechanical-property data. The assembly technique would be demonstrated (braze, or weld with option of Gr-Epoxy overwrap, or adhesive bond) with a final assembly, proof test, and inspection sequence. This program would require support to about $100K.

I hope your MMC study program with NASA is a success. We at DWA would be happy to support Aerojet Liquid Rocket in any design, trade-off, or prototype hardware efforts using any metal-matrix composite materials. We look forward to your comments on this letter.

Very truly yours,

DWA COMPOSITE SPECIALTIES, INC.

J.F. Dolowy, Jr.
President

JFD:ls
80611

cc: T.D. Lynch

APPENDIX F

TECHNOLOGY NEEDS DEFINITION FORMS

TECHNOLOGY NEED DEFINITION

ITEM:

1.0 - H_2 Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to hydrogen.

ASSESSMENT OF RISK:

High	Medium	Low
*		

* Freeze-thaw cycling of hydrogen rocket propellant (and other vapors) trapped in composite material has the potential to cause severe structural damage. The glass transition temperature of epoxy resin used in high performance structural composites have glass transition temperatures above ambient. At use temperatures below the glass transition, mechanical properties show improvement. Also at cryogenic temperatures, hydrogen is chemically unreactive and not a cause of resin degradation.

APPROACH:

The effects of mechanical property degradation resulting from freeze-thaw cycling can be demonstrated. The rate of degradation should depend upon the permeability of the composite. It is believed impractical to control mechanical property degradation by resin selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

TECHNOLOGY NEED DEFINITION

ITEM:

2.0 - O_2 Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to LOX.

ASSESSMENT OF RISK:

High *	Medium	Low

*1. If freeze-thaw (also condensation) cycling occurs.
2. Most organic polymers used as matrices in high performance composite materials are expected to fail LOX impact requirements (MSFC-SPEC 106).

APPROACH:

Poly (amide-imide) resin matrix may pass LOX impact requirements. It is believed impractical to control degradation caused by freeze-thaw cycling through material selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

TECHNOLOGY NEED DEFINITION

ITEM:

3.0 - CH_4 Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to methane.

ASSESSMENT OF RISK:

High *　　　　Medium　　　　Low **

* If freeze-thaw (also condensation) cycling occurs.
** 1. Temperature too low for chemical degradation.
2. Methane absorption will not make worse the effects of any polymer transitions occurring because of low temperature.

APPROACH:

It is believed impractical to control degradation of mechanical properties due to freeze-thaw cycling through material selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

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TECHNOLOGY NEED DEFINITION

ITEM:

4.0 - Low Temperature Toughness

DESCRIPTION:

Select composite materials that are thermal shock and impact resistant.

ASSESSMENT OF RISK:

High Medium Low *

* Composite materials have inherent toughness properties because of their energy absorbing fracture characteristics. These characteristics increase slightly at cryogenic temperatures to improve toughness performance.

APPROACH:

Fiberglass reinforcement and graphite fiber reinforcement are used successfully in cryogenic structural applications. Fiberglass is preferred for applications requiring thermal insulation. Graphite is preferred for applications requiring higher thermal conductivity or greater stiffness.

PROPOSED SOLUTION:

Select composite materials on the basis of room temperature structural properties and validate their structural performance at cryogenic temperatures by conducting structural element tests.

TECHNOLOGY NEED DEFINITION

ITEM:

5.1 - Mechanical Fastening

DESCRIPTION:

Bonded metallic inserts for composite materials may pull out because of thermal contraction at cryogenic temperatures.

ASSESSMENT OF RISK:

High Medium Low *

* Mechanically anchored inserts are available that do not pull out easier because of shrinkage.

APPROACH:

Review applications of mechanical fasteners to make sure that bonded inserts are not used where insert shrinkage would result in an attachment failure.

PROPOSED SOLUTION:

Avoid using bonded metallic inserts in composites at cryogenic temperatures.

TECHNOLOGY NEED DEFINITION

ITEM:

5.2 - Finish of Fluid Sealing Surfaces

DESCRIPTION:

Smooth surfaces are required for O-rings and seals. Machining high performance composite materials may not meet the finish requirements for seals.

ASSESSMENT OF RISK:

High	Medium	Low *

* Coatings can be used to improve the finish of machined composite materials.

APPROACH:

Select coating compounds for use with lubrication seals.

PROPOSED SOLUTION:

Coatings to upgrade the finish of machined composite surfaces will be used.

TECHNOLOGY NEED DEFINITION

ITEM:

5.3 - Vane Manufacturing Method

DESCRIPTION:

Select a manufacturing process to mold the TPA stator vanes.

ASSESSMENT OF RISK:

High Medium Low *

* Alternate methods for molding the stator vanes are available.

APPROACH:

Allow the manufacturer of the TPA housing to determine the best manufacturing method for this part.

PROPOSED SOLUTION:

The stator vanes may be molded in-place (in situ) or molded separately and bonded in place.

TECHNOLOGY NEED DEFINITION

ITEM:

5.4 - Vane Attachment Method

DESCRIPTION:

An adhesive bonding process must be developed if the manufacturer elects to mold these details separately.

ASSESSMENT OF RISK:

High Medium Low *

* Adhesives for bonding composite materials at cryogenic temperatures are available.

APPROACH:

The manufacturer of the TPA assembly will select an adhesive and bonding process that will satisfy the structural requirements of the design disclosure.

PROPOSED SOLUTION:

The shear stress between the stator vanes and the turbine manifold shell may exceed the interlaminar shear capability of the composite. In this case more composite material will be required to reduce this stress.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.5 - Residual Thermal Streses

DESCRIPTION:

Determine the effect that the cure cycle has on the residual stress of each design.

ASSESSMENT OF RISK:

High Medium * Low

* Distortion and ply failure due to thermal stress at cryogenic temperatures can be avoided by controlling the fiber orientation.

APPROACH:

Analyze the effects that the fabrication process has on residual stress. Design the process and laminate to minimize thermal distortion and failure.

PROPOSED SOLUTION:

Control residual thermal stress through design analysis and process control.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.6 - Barrier Coating Process

DESCRIPTION:

High performance plastic composites must be sealed in order to contain liquids and vapors.

ASSESSMENT OF RISK:

High * Medium Low

* Microcracking occurs in the resin matrix of high performance composite materials. These cracks result from residual and applied stresses. They render the resin matrix permeable to vapors and liquids.

APPROACH:

Several barrier coatings (metal foils, plastic films, etc.) have been used successfully to seal composite materials. These coating materials and processes will be evaluated to select the optimum system for a given rocket engine component.

PROPOSED SOLUTION:

Ductile barrier coatings are required to seal composite materials.

TECHNOLOGY NEED DEFINITION

ITEM:

5.7 - Plumbing Connections

DESCRIPTION:

Propellant line connections are a primary source of propellant leaks. Composite materials are expected to cause more leak problems than metals because they scratch and distort more readily.

ASSESSMENT OF RISK:

High	Medium	Low *

* Viton, Kryton, Teflon, Kel-F, and metal foils are materials available to seal propellant line connections.

APPROACH:

Evaluate seals and O-rings to determine the most effective method to produce leak-resistant plumbing connections.

PROPOSED SOLUTION:

More extensive use of metals in flanges will be necessary if leak-resistant connections using composites fail.

TECHNOLOGY NEED DEFINITION

ITEM:

5.8 - Adhesive Bonding

DESCRIPTION:

Adhesives and adhesive prepregs which join composite materials in liquid rocket engine applications must satisfy the same compatibility requirements as the composite.

ASSESSMENT OF RISK:

High *	Medium	Low

* Melt processible PCTFE and poly (amide-imide) might provide propellant compatible adhesive systems (TBD). Otherwise barrier coatings will be required.

APPROACH:

Freeze-thaw cycling damage is not as serious a problem for adhesive bonding applications because resin microcracking does not occur. Propellant exposure tests may indicate that a protective barrier will only be required for LOX.

PROPOSED SOLUTION:

Barrier coating, liner, etc.

TECHNOLOGY NEED DEFINITION

ITEM:

5.9 - Fabrication Methods

DESCRIPTION:

Alternative methods are available to mold composite materials (compression, autoclave, resin injection, etc.).

ASSESSMENT OF RISK:

High Medium Low *

* An analysis of the structural effects of alternative processes may indicate a change in the structural capability of the part.

APPROACH:

The effects of processing must be validated in structural tests. A trade-off between structural performance and producibility will be made.

PROPOSED SOLUTION:

Revised design allowables will be issued if the choice of a process affects the structural properties of the material.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.10 - Mold Design

DESCRIPTION:

A mold to produce composite parts should be capable of meeting all the design objectives specified for the part.

ASSESSMENT OF RISK:

High	Medium *	Low

* Analysis of the mold performance before building the mold will reduce costly iterations in process and mold design to solve problems involving producibility.

APPROACH:

An analysis of the mold performance should be made to determine if any design changes are needed. The analysis should investigate the effects of compaction, flow, temperature rise, cure uniformity, cool down, and concentration of reinforcement and resin on residual thermal stress, shrinkage, and voids.

PROPOSED SOLUTION:

Redesign the mold until analysis indicates that the part is satisfactory or lower the part specification to reflect what is possible before releasing the mold design for fabrication.

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TECHNOLOGY NEED DEFINITION

ITEM:

6.0 - Cryogenic Properties

DESCRIPTION:

Some commercial composite materials have useful structural properties at cryogenic temperatures. Their outstanding fracture toughness is due to microcracking of the resin matrix to relieve residual thermal strain.

ASSESSMENT OF RISK:

High	Medium	Low *

* Commercial composite materials have met the requirements of application at cryogenic temperature because of good fracture toughness and moderate increases in mechanical properties.

APPROACH:

Candidate composite materials will be tested at cryogenic temperatures to determine their structural properties. Structural tests following cryogenic temperature cycling will also be conducted to evaluate the stability of the fiber matrix bond.

PROPOSED SOLUTION:

Commercial composites will not be applied beyond their temperature limits. Efforts will be made to obtain composite materials having improved fracture toughness properties at cryogenic temperatures.

TECHNOLOGY NEED DEFINITION

ITEM:

7.0 - Interface Properties

DESCRIPTION:

Many kinds of interfaces occur in composite materials. Interfacial instability may occur because of corrosion, stress, debonding, etc.

ASSESSMENT OF RISK:

High *	Medium	Low

* The low temperature stability of adhesive interfaces because of thermal stress is a familiar problem, especially acute for metallic interfaces.

APPROACH:

Tests will characterize the stability of composite material interfaces in liquid rocket engine applications. These tests will determine which kinds are acceptable in design and which are not.

PROPOSED SOLUTION:

Unstable interfaces can not be used because of the potential for progressive structural failure. Metallic parts would replace composite parts in any applications involving unstable interfaces.

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TECHNOLOGY NEED DEFINITION

ITEM:

8.0 - Metal Coating Interface Properties

DESCRIPTION:

Cycling temperature and pressure can fail the metallic barrier coating protecting the composite. Two techniques may impart more durability to the protective barrier: (1) Metallized plastic film, (2) Elastomeric adhesive.

ASSESSMENT OF RISK:

High Medium * Low

* Elastomeric adhesives have demonstrated low temperature bonding capability to metal and metalized plastic film. Their performance at cryogenic temperatures needs to be determined (~~TDB~~).
TBD

APPROACH:

Evaluate the bond stability by cycling the test specimens between ambient and cryogenic temperature. Specimens consist of (1) metal bonded to composite with an elastomeric adhesive and (2) metallized film bonded to composite with an elastomeric adhesive. Failure of the elastomeric adhesive bond will result in a more sophisticated approach to stabilize the bond. A tie coat adhesive, approximating the thermal expansion of the metal, will be evaluated with the elastomeric adhesive.

PROPOSED SOLUTION:

Composite materials can not be used in applications requiring protective coatings if the tests above and the supporting analysis indicate that the barrier coatings fail to meet the strain cycling requirements.

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TECHNOLOGY NEED DEFINITION

ITEM:

9.0 - Differential Expansion Properties

DESCRIPTION:

The thermal expansion properties must be known in order to analyze the thermal stresses affecting design.

ASSESSMENT OF RISK:

High Medium Low *

* The anisotropic thermal expansion coefficients (α_x and α_y) can be used to calculate residual thermal stress.

APPROACH:

Thermal expansion data will be obtained from the material suppliers or from ALRC lab tests.

PROPOSED SOLUTION:

Without this data the analysis of thermal effects to support design will be less accurate.

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TECHNOLOGY NEED DEFINITION

ITEM:

10.0 - Solar Radiation Effects

DESCRIPTION:

Protective coatings are needed to protect the surface of plastic matrix composites from polymer degradation.

ASSESSMENT OF RISK:

High Medium Low *

* The absorption of radiation by the reinforcement limits damage to the surface. In most applications the most serious effect is cosmetic.

APPROACH:

Select protective coatings that are compatible with the rocket engine environment for use on surfaces exposed to solar radiation.

PROPOSED SOLUTION:

If coatings are not used to protect against radiation, small losses in strength will occur due to surface degradation.

TECHNOLOGY NEED DEFINITION

ITEM:

11.0 - Low Cycle (Thermal) Fatigue

DESCRIPTION:

Cycling temperatures can result in structural failure.

ASSESSMENT OF RISK:

High Medium * Low

* Distortion and ply failure due to thermal stress can be avoided by controlling the reinforcement orientation.

APPROACH:

Conduct a thermal-stress analysis to identify any structural elements that exceed allowable ply stresses.

PROPOSED SOLUTION:

Without this analysis the chances of LCF failures increase.

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TECHNOLOGY NEED DEFINITION

ITEM:

13.0 - Bearing Surface Lubricant

DESCRIPTION:

A lubricant applied to the nozzle extension shaft threads will reduce friction, stress, and wear.

ASSESSMENT OF RISK:

High Medium Low *

* Surfaces of plastic composite materials errode faster than metal surfaces for a variety of reasons. Lubricants will reduce friction and wear.

APPROACH:

Select a commercial lubrication system compatible with composite materials, the liquid rocket engine environment, and the vacuum conditions of space.

PROPOSED SOLUTION:

Without a lubrication system, the useful life of the shaft will be shortened due to excessive wear.