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RI/RD89-186

ADVANCED LAUNCH SYSTEM PROPULSION FOCUSED TECHNOLOGY LIQUID METHANE TURBOPUMP TECHNICAL IMPLEMENTATION PLAN

25 MAY 1989

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Rockwell International

Rocketdyne Division

Rockwell International

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Rockwell International Corporation
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Canoga Park, California 91303

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NASA

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16. Abstract

This document presents the Technology Implementation Plan, in compliance with Contract Data Requirement Number 15 of Contract Number NAS 8-37594. The work to be accomplished during the 40-month program to develop reliable, low cost turbopumps for the ASL program is defined. Time phasing of the effort is presented and the interrelationship of the tasks is defined. Major subcontractors are identified and their role in the program is described.

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268

TABLE OF CONTENTS

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FIGURES

TABLES

Key Words/Acronyms

ALS	Advanced Launch Systems
APTF	Advanced Propulsion Test Facility
ATCM	ALS Turbopump Cost Model
CDRL	Contract Data Requirements List
CER	Cost Estimating Relationship
CH_4	Methane
CMS	Condition Monitoring System
CO_2	Carbon Dioxide
COTR	Contracting Officers Technical Representative
CRM	Cost, Reliability & Maintainability
DN	Diameters x Revolutions per Minute
DOD	Department of Defense
ECM	Electrochemical Machine
EDL	Engineering Development Laboratory
ELI	Extra Low Interstitial Elements
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
GEAE	General Electric Aircraft Engine Division
GG	Gas Generator
GSE	Ground Support Equipment
HCF	High Cycle Fatigue
HEE	Hydrogen Environment Embrittlement
HII	Hitchcock Industries, Inc.
ID	Inside Diameter
IR&D	Independent Research and Development
LCF	Low Cycle Fatigue
LCH_4	Liquid Methane
L/O	Liftoff Seal
LOX	Liquid Oxygen
LOX/HC	Liquid Oxygen/Hydrocarbon
MCR	Management Consulting Research, Inc.
MSFC	Marshall Space Flight Center
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NASA	National Aeronautics and Space Administration
OD	Outside Diameter
PCC	Precision Castparts Company
PCO	Procuring Contracting Office
PDR	Preliminary Design ReviewRFP Request for Proposal
RI	Rockwell International
RPM	Revolutions per Minute
SL	Sea Level
SSC	Stennis Space Center
SSFL	Santa Susana Field Laboratory
SSME	Space Shuttle Main Engine
SOW	Statement of Work
STAS	Space Transportation Architecture Study
STBE	Space Transportation Booster Engine
STE	Special Test Equipment
STEM	Scanning Transmission Electron Microscope
STME	Space Transportation Main Engine

TBD	To be Determined
TDR	Test Data Review
TORR	Test Operational Readiness Review
TRR	Test Request Review
USAF	United States Air Force
VAC	Vacuum

INTRODUCTION

Within the last decade it has become increasingly evident that the Nation needs a space transportation system that can place payloads into orbit at a substantially reduced cost compared with currently active systems. The need is supported by expanding military as well as commercial utilization of space. To meet this emerging requirement, NASA and the Air Force have initiated effort toward the definition of an Advanced Launch System (ALS). Phase A and A' studies addressing the vehicle and propulsion design parameters have been concluded, and proposals for detail characterization of the propulsion systems in a Phase B effort are currently under evaluation.

The system being studied includes a stage and a half liquid rocket propulsion system, with 580,000-lb vacuum thrust LOX/LH_2 engines (STME) in the core, operating for full duration, and ideally 750,000-lb thrust LOX/LCH_4 booster engines (STBE) operating for partial duration. The economics of the overall program dictate that maximum use be made of commonality between the STME and STBE engines to minimize development costs and maximize per part production rates. Accordingly, the groundrule has been adapted by NASA and the Air Force that components optimized for STME application be used for the STBE engines, with some compromises in the STBE thrust and performance. Studies performed by Rocketdyne revealed that an STME engine will develop an acceptable 502,000 lb of thrust with minor modifications to the LOX turbine.

Parallel with the Phase B studies of the STME and STBE engines, NASA and the Air Force have initiated several advanced component development programs to establish the base for low-cost production and operations approach, and to provide a validated model for cost projection. Rocketdyne has been awarded the contract by NASA MSFC to develop the methodology for producing a reliable, low-cost liquid methane turbopump for the STBE engine. The contract start date was May 12, 1989. This document presents the plans for conducting the 40-month program.

In accordance with the groundrules noted above, the overall approach will be to optimize the design as an LH_2 turbopump for a 580,000-lb vacuum thrust STME engine, and define its performance characteristics when operating as an STBE methane turbopump with appropriate structural margins. Minor modifications in the design parameters may be adapted to enhance methane characteristics with customer approval.

The requirement for use of International System of Units has been waived for this document.

OBJECTIVE

The objective for this program is to focus on innovative integration of all functional disciplines of design, manufacturing, materials, fabrication processes, and producibility to define and demonstrate a highly reliable, easily maintained, low cost liquid methane turbopump as a component for the STBE engine using the STME oxygen turbopump. A cost model is to be developed to predict the recurring cost of production hardware and operations. A prime objective of the program is to design the liquid methane turbopump to be common with an LH_2 turbopump optimized for the STME.

PROGRAM SUMMARY

The program is structured in two major phases. Phase I is a 1-year study with the principal objectives of establishing the methodology of producing reliable turbopumps with low production and operations cost and producing a preliminary design of the turbopump. A preliminary cost model to facilitate accurate prediction of recurring turbopump costs is to be generated. The Phase I effort will be initiated with a 3-month trade study, in which the benefits of alternate design and fabrication approaches are evaluated. A 3-month turbopump conceptual definition effort follows, in which the results of the trade study will be applied to formulate conceptual configuration and manufacturing plans. During the final 6 months, a preliminary design of the turbopump will be produced, materials and processing will be selected, and manufacturing and quality approaches will be defined. Effort will be expended throughout the year to generate a user friendly, accurate model, capable of predicting recurring turbopump production and operation costs.

Phase II is a 28-month effort to detail design and fabricate one prototype methane turbopump plus selected spares, and to provide hardware and test support to testing to be conducted by NASA at SSC. A detailed cost model will be developed and anchored with actual cost data generated during the program. The detail design task includes generation of shop drawings of the turbopump components and assembly aids, as well as a test cart with turbopump mounting provisions and instrumentation panels for SSC testing. The design will be substantiated prior to turbopump testing by performing structural tests on key components, testing the bearings and seals in a test rig, and testing pump models and full-size components in air and water. Prototype fabrication will include fabrication of components for the turbopump assembly and spares as well as fabrication of the test cart. The turbopump will be assembled in the cart and all instrumentation will be routed to connector panels to simplify the activation effort at SSC.

Program reviews will be held on a quarterly basis. In addition, major reviews will be held on completion of conceptual, preliminary, and detail designs, at completion of design substantiation, prior to delivery of the assembled turbopump and upon completion of testing at SSC.

The efforts in both phases of the program will be performed using the principles of total quality management. Specifically, the design phases will take advantage of the benefits of simultaneous engineering approach.

KEY PROGRAM AND PROGRAM CONTROL ELEMENTS

LOGIC DIAGRAM AND MASTER MILESTONE SCHEDULE

Program activities are summarized in the program master schedule and schedule of major control points (milestones) (Figures 1 and 2), the time phased program logic flowcharts (Figures 3 and 4), and the time-phased man-loading by skills (Figures 5 and 6). The program is organized into two phases. The objective of Phase I is to generate a preliminary design for a low cost, highly reliable turbopump and a preliminary cost model. This study period is 12 months. Phase II has the objectives of detail design, fabrication, and testing of the prototype turbopump in parallel with other analytical and test substantiation activities to demonstrate cost and reliability. The preliminary cost model will be further developed by additional input from the substantiation testing and further studies. This Phase II period is scheduled for 28 months.

WORK BREAKDOWN STRUCTURE (WBS)

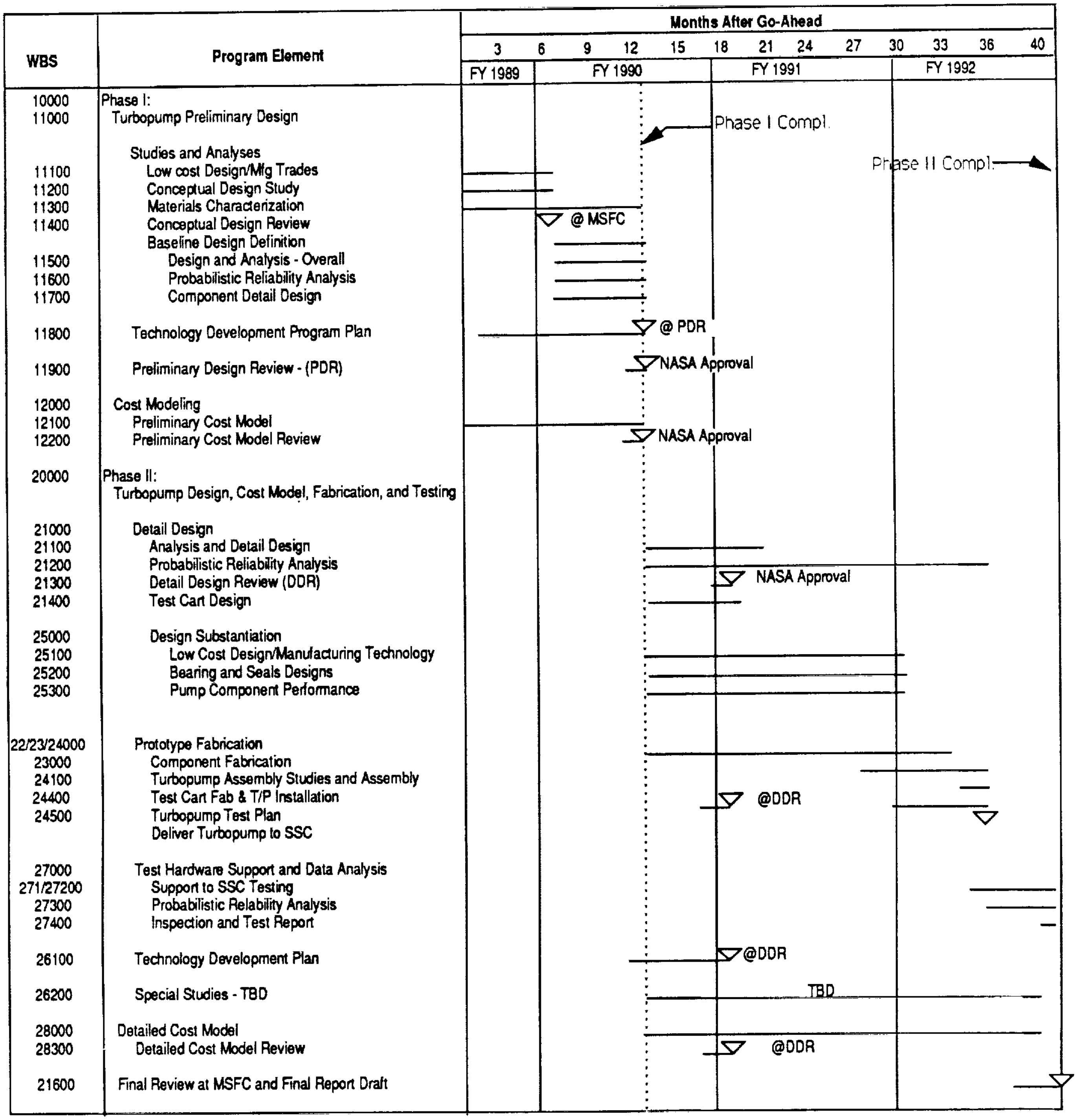
The WBS (Figure 7) provides a structure for the orderly planning and tracking of program activities. The WBS may be further subdivided to allocate resources, provide cost substantiation data, and schedule to specific efforts.

PROGRAM MANAGEMENT

The program manager is responsible for effective program administration. The program management team will use a system of in-place program management tools. Principal among these will be cost and schedule accounting analysis programs for tracking work element expenditures and schedule actuals versus planned values. The program control function will operate the earned value control system and appraise the program manager of performance variances to allow timely responsive action.

RISK MANAGEMENT

Rocketdyne experience in programs requiring technology development indicates the need for recognizing areas of potential risk and anticipating the contingencies necessary for proceeding with alternate plans, if required. Risk reduction methods include: (1) parallel development of alternate approaches, (2) early prototype development, and (3) development of computer models to verify development items in advance of fabrication.



WBS	Program Element
10000	Phase I:
11000	Turbopump Preliminary Design
	Studies and Analyses
11100	Low cost Design/Mfg Trades
11200	Conceptual Design Study
11300	Materials Characterization
11400	Conceptual Design Review
	Baseline Design Definition
11500	Design and Analysis - Overall
11600	Probabilistic Reliability Analysis
11700	Component Detail Design
11800	Technology Development Program Plan
11900	Preliminary Design Review - (PDR)
12000	Cost Modeling
12100	Preliminary Cost Model
12200	Preliminary Cost Model Review
20000	Phase II: Turbopump Design, Cost Model, Fabrication, and Testing
21000	Detail Design
21100	Analysis and Detail Design
21200	Probabilistic Reliability Analysis
21300	Detail Design Review (DDR)
21400	Test Cart Design
25000	Design Substantiation
25100	Low Cost Design/Manufacturing Technology
25200	Bearing and Seals Designs
25300	Pump Component Performance
22/23/24000	Prototype Fabrication
23000	Component Fabrication
24100	Turbopump Assembly Studies and Assembly
24400	Test Cart Fab & T/P Installation
24500	Turbopump Test Plan
	Deliver Turbopump to SSC
27000	Test Hardware Support and Data Analysis
271/27200	Support to SSC Testing
27300	Probabilistic Relability Analysis
27400	Inspection and Test Report
26100	Technology Development Plan
26200	Special Studies - TBD
28000	Detailed Cost Model
28300	Detailed Cost Model Review
21600	Final Review at MSFC and Final Report Draft

Figure 1. Master Schedule, Liquid Methane T/P

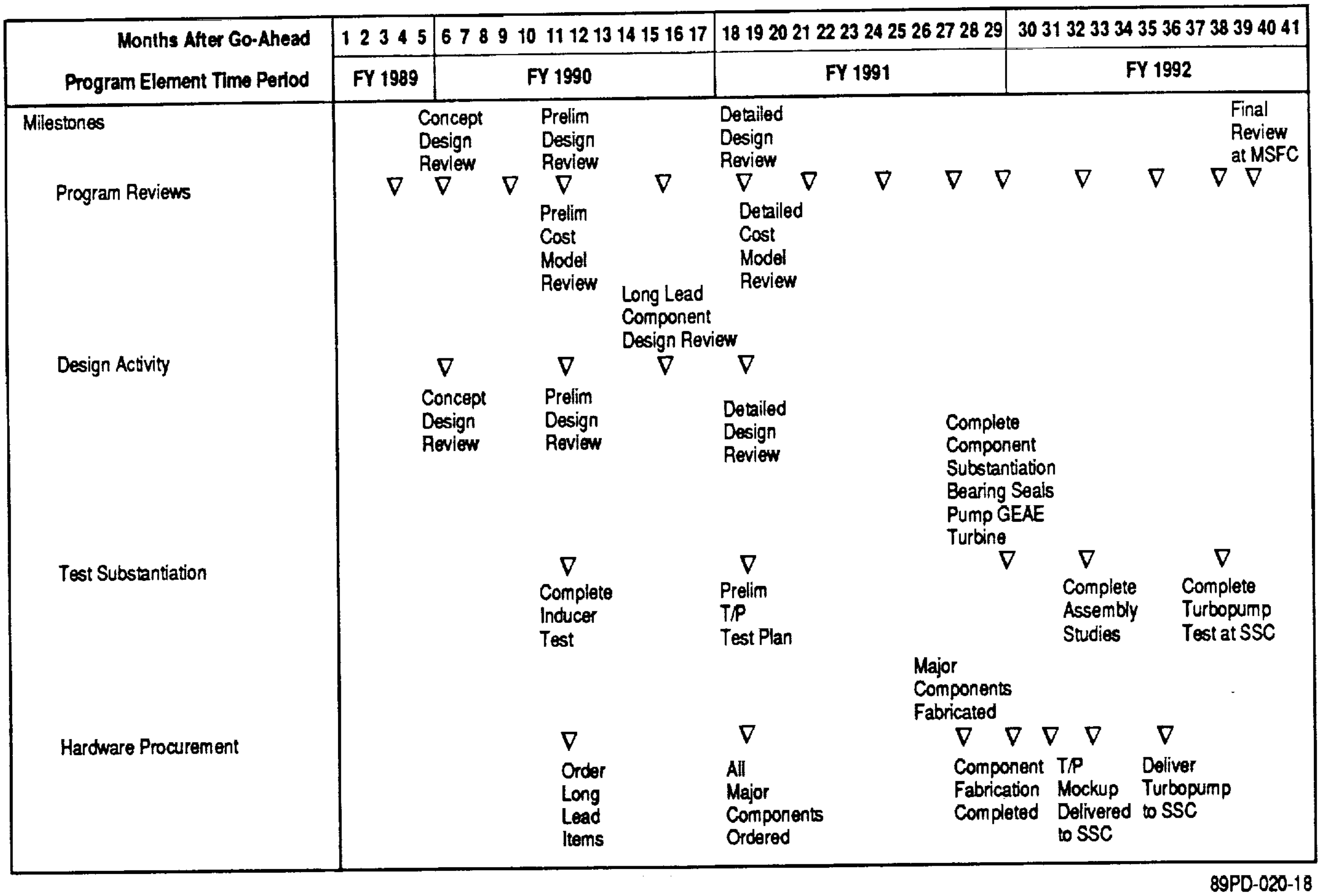


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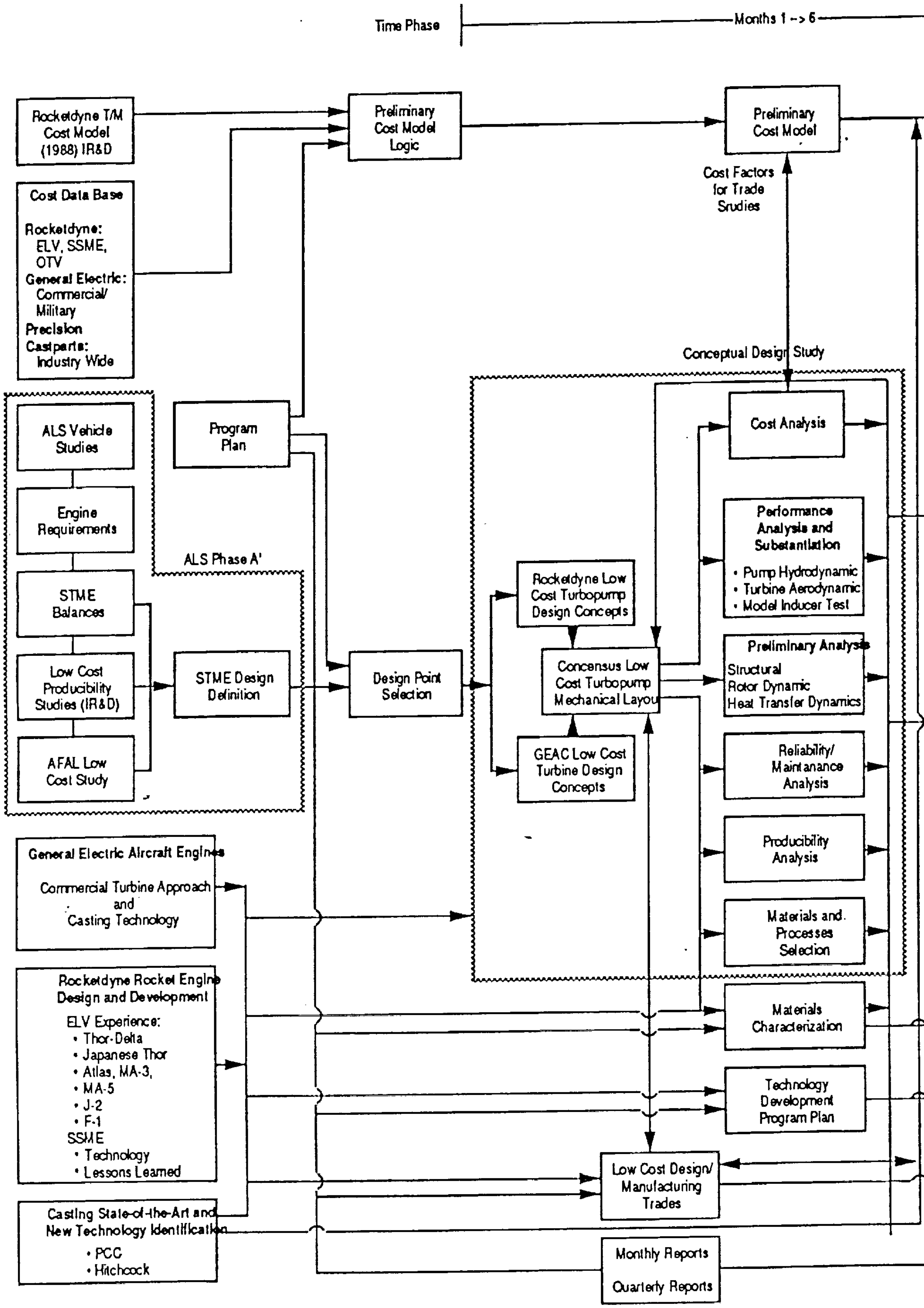
Figure 2. Schedule of Major Control Points, "Milestones"

The approach to contingency planning is to carry alternate concepts through the analysis and preliminary design phases. Substantiation tests and analyses will be used to resolve any uncertainties. The approach to fallback positions is to identify a reduced level of performance (e.g., less cost saving) as a fallback position that still allows the program to proceed.

There are two potential problem/technical risk areas (Table 1) where we have identified specific parallel, alternate paths for the blisk and the cast inducer. For both of these risk areas, the program can proceed without achieving the prime approach, but the projected cost in production will be higher. Lower order risks will be identified and tracked during the program.

SUBCONTRACTORS

Rocketdyne has assembled an outstanding team for the specific purpose of achieving the goals of this program. These team members, General Electric Aircraft Engine Division (GEAE), Precision Castpart Company (PCC), Hitchcock Industires, Inc. (HII), and Management Consulting Research, Inc. (MCR)



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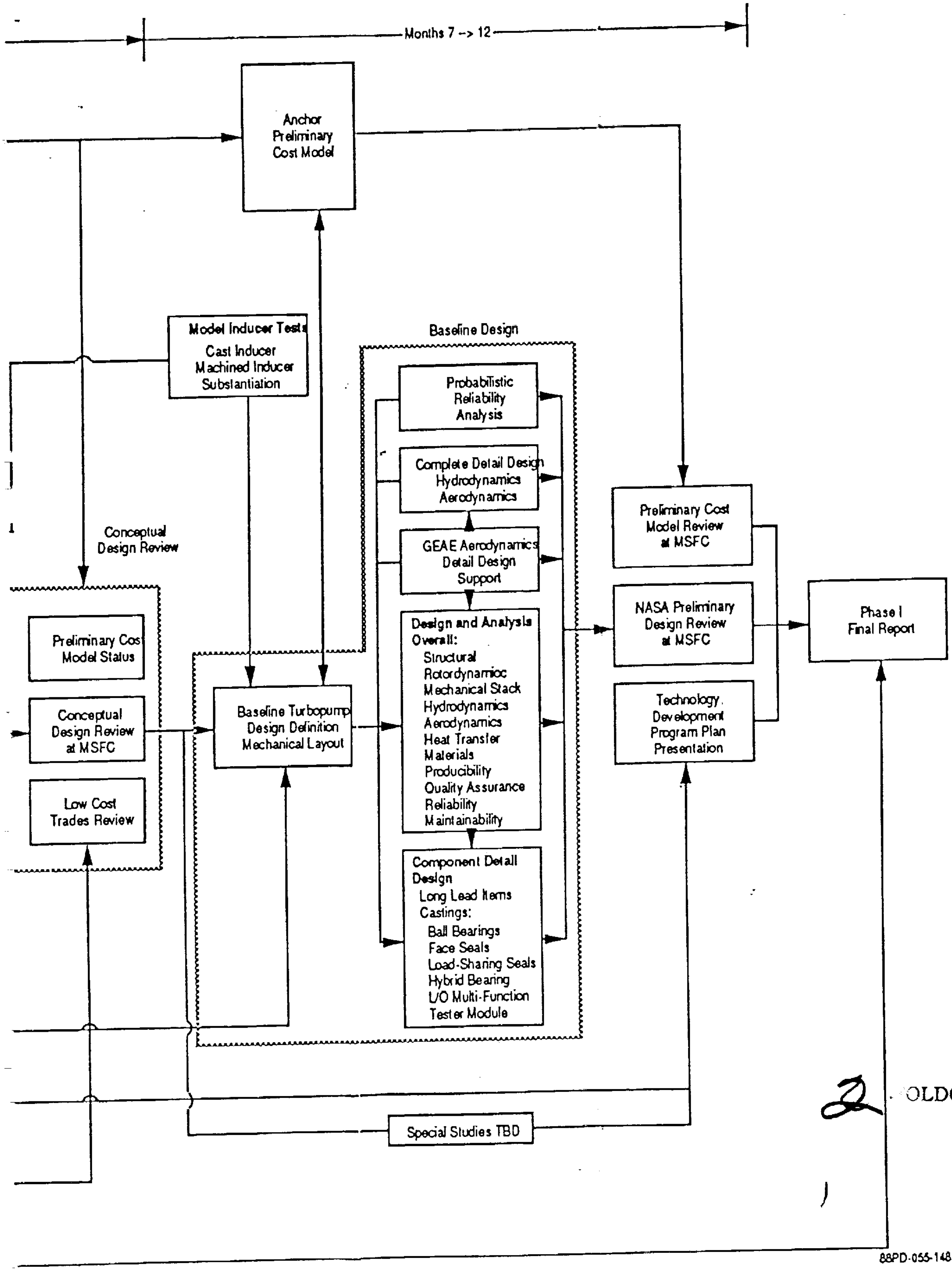

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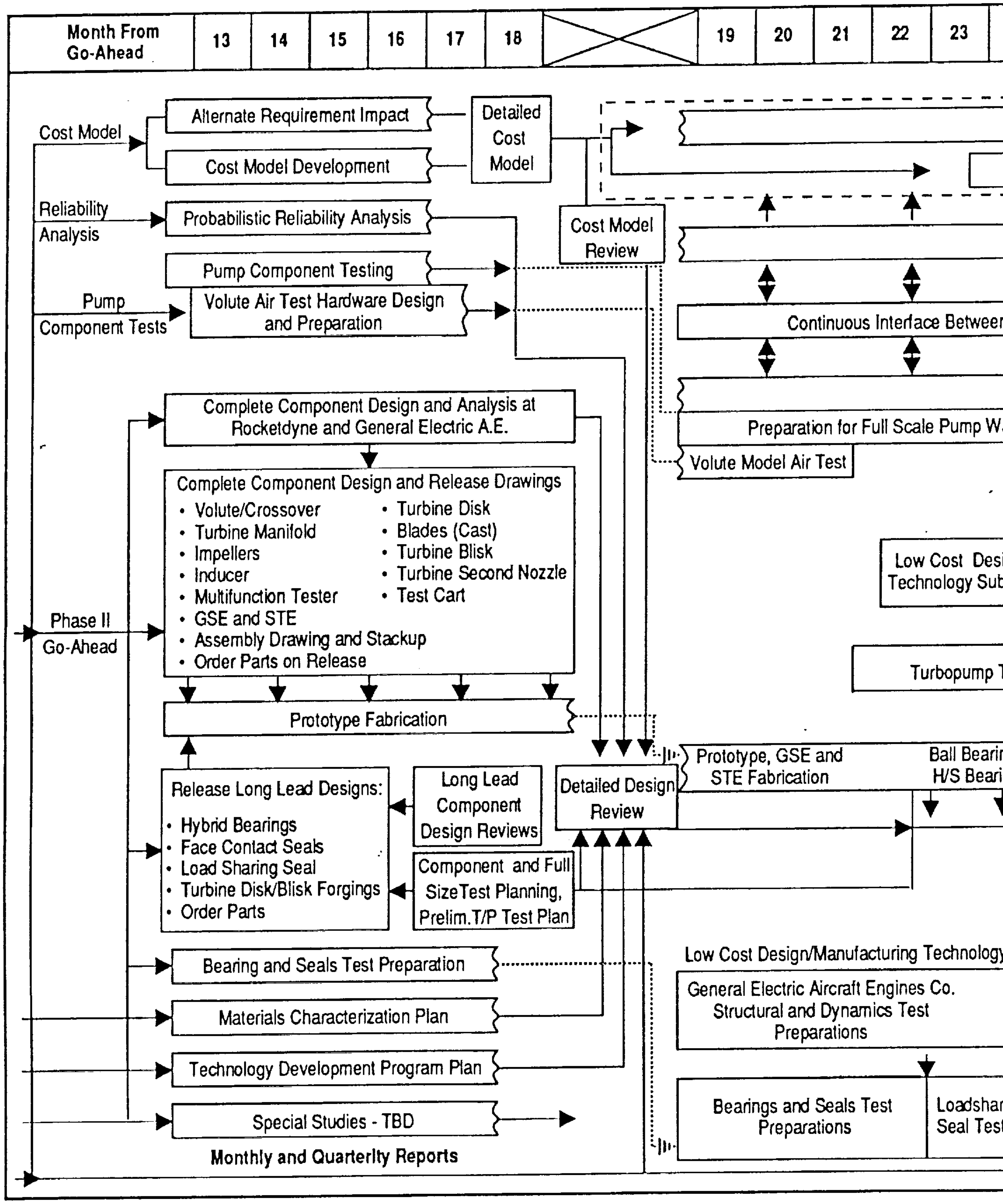
Figure 3. Program Logic, Phase I



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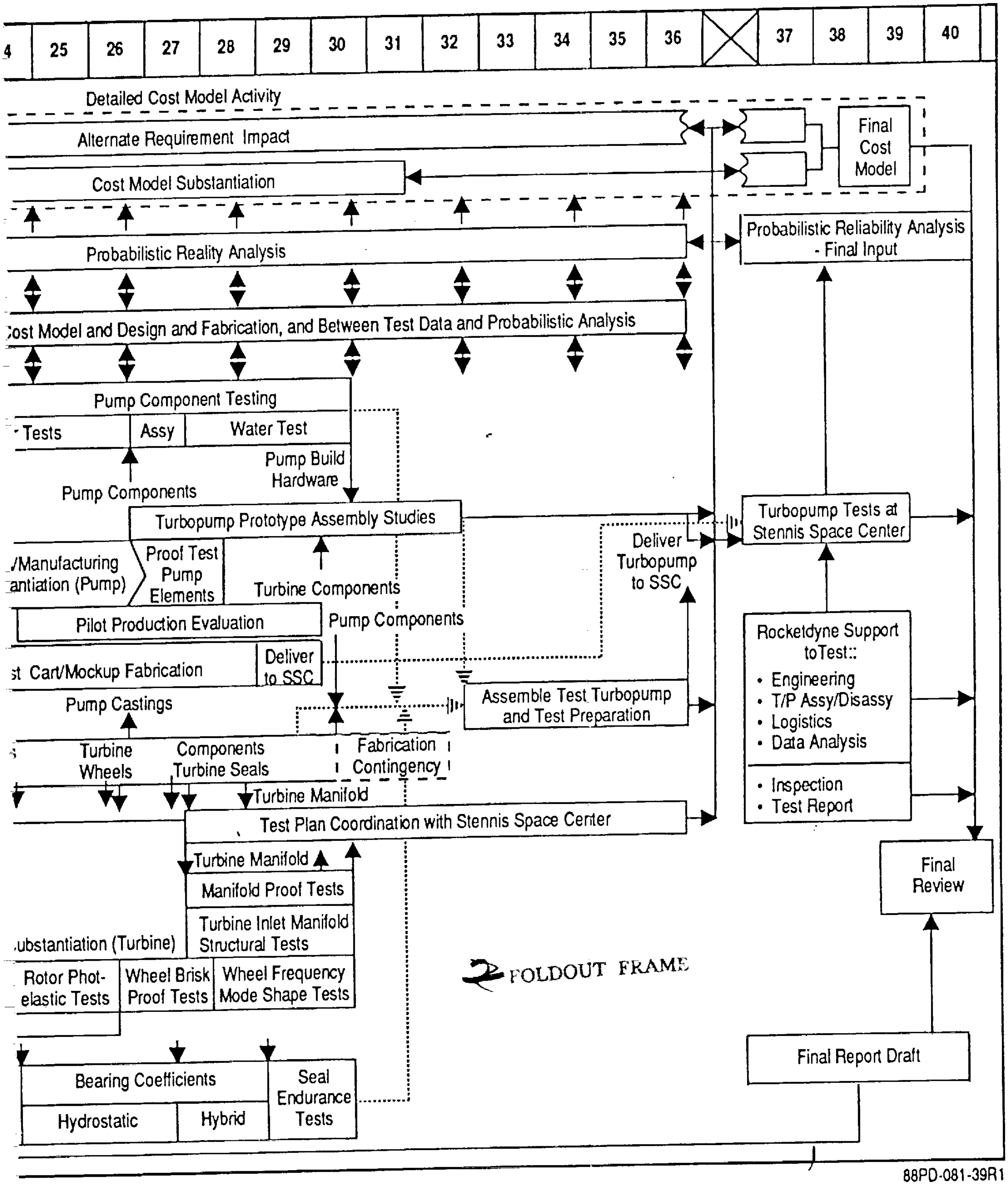

Figure 4. Program Logic, Phase II

W B S	TASK IDENTIFICAION	PROGRAM-CALENDER	PROGRAM MONTH												PHASE I
			1 05-89	2 06-89	3 07-89	4 08-89	5 09-89	6 10-89	7 11-89	8 12-89	9 01-90	10 02-90	11 03-90	12 04-90	TOTAL
	PHASE I														
11000	PRELIMINARY DESIGN														
	ROTATING MACHINERY		910	1116	1614	1885	1686	1793	2069	2176	2175	2204	2234	2433	22295
	ENGINEERING DESIGN TECHNOLOGY		434	434	721	1007	1010	1092	1449	1317	1315	1306	1182	1288	12555
	MATERIALS ENGINEERING AND TECHNOLOGY		161	162	231	232	234	327	285	285	284	304	302	280	3087
	ENGINEERING DEVELOPMENT LABORATORY				44	44				396	440	572	528		2024
	MANUFACTURING ENGINEERING		57	234	237	235	234	257	201	184	184	184	264	264	2535
	QUALITY/RELIABILITY/MAINTAIN./SAFETY		80	80	80	80	60	80	60	60	60	60	60	100	860
	INSTRUMENT ENGINEERING		27	36	36	35	36	36	18	18	17	18	18	18	313
	TOTAL		1669	2062	2963	3518	3260	3585	4082	4436	4475	4648	4588	4383	43669
12000	COST MODELING														
	ADVANCED PROGRAMS ENGINEERING		89	90	89	90	89	45	36	36	35	36	36	148	819
13100	PROGRAM AND BUSINESS DEVELOPMENT														
	BUSINESS MANAGEMENT		239	239	165	165	165	165	165	165	165	165	165	165	2128
	PROGRAM MANAGER		76	76	76	76	76	76	76	76	76	76	76	76	912
	SUPPLIER MATERIAL SUPPORT		75	75	75	75	75	75	75	75	75	75	75	75	900
	TOTAL		390	390	316	316	316	316	316	316	316	316	316	316	3940
13200	PRODUCT MANAGEMENT														
	PRODUCT MANAGER		72	71	72	71	72	71	72	72	71	72	71	72	859
	PROJECT ENGINEER		148	147	148	148	147	148	148	147	148	148	147	148	1772
	DESIGN MANAGER		148	147	148	148	147	148	148	147	148	148	147	148	1772
	TASK MANAGERS		8	8	8	8	8	8	8	16	16	17	16	16	137
	CONTRACTOR INTERFACE		32	32	33	32	32	32	33	32	32	32	33	32	387
	ENGINEERING OPERATIONS		402	307	184	184	182	184	198	198	198	197	198	198	2630
	TOTAL		810	712	593	591	588	591	607	612	613	614	612	614	7557
13300	SIMULTANEOUS ENGINEERING AND SUPPORT														
	QUALITY ENGINEERING								60	60	60	60	60	60	360
	RELIABILITY AND MAINTAINABILITY		30	30	30	30	30	30	30	30	30	30	30	30	360
	SAFETY		36	116	6	46	46	6	6	6	46	46	6	6	372
	MANUFACTURING		20	19	95	20	19	56	20	19	56	20	19	56	419
	DATA REQUIREMENTS		10	31	12	93	94	65	16	45	81	38	40	97	622
	FACILITIES AND INDUSTRIAL ENGINEERING		30	46	30	30	30	30	30	30	30	50	50	50	436
	TOTAL		126	242	173	219	219	187	162	190	303	244	205	299	2569
	TOTAL EFFORT, MHRS		3084	3496	4134	4734	4472	4724	5203	5590	5742	5858	5757	5760	58554

Figure 5. Time Phased Manloading, Phase I

W B S	TASK IDENTIFICAION — PROGRAM MONTH / CALENDER DATE	13 05-90	14 06-90	15 07-90	16 08-90	17 09-90	18 10-90	19 11-90	20 12-90	21 01-91	22 02-91	23 03-91	24 04-91	25 05-91	26 06-91	2 07-9
	PHASE II OPTION															
21000	DETAILED DESIGN	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	ROTATING MACHINERY	2961	2838	2717	2225	2226	2225	965	392	339	159	160	159	161	160	16
	ENGINEERING DESIGN TECHNOLOGY	1817	1817	1814	1872	1870	1871	239	98	97	60	61	60	61	60	6
	MATERIALS ENGINEERING AND TECHNOLOGY	267	268	318	318	328	328	20								
	INSTRUMENT ENGINEERING	80	81	80	81	80	81									
	QUALITY/RELIABILITY/MAINTAIN./SAFETY	80	80	80	159	264	372	528	451	328	213	118	38			
	PACKAGING ENGINEERING DESIGN				80	81	80									
	MANUFACTURING ENGINEERING	4032	2503	2505	2505	1655	1657	1691	917	920	917	917	918	919	920	91
	TOTAL	9237	7587	7514	7240	6504	6614	3443	1858	1684	1349	1256	1175	1141	1140	113
22000/ 23000/ 24000	PROTOTYPE FABRICATION	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	ROTATING MACHINERY	297	308	213	197	273	275	212	226	333	580	640	618	662	621	66
	ENGINEERING DESIGN TECHNOLOGY						30		50	51	101	100	101	100	101	12
	MATERIALS ENGINEERING AND TECHNOLOGY						10		16	16	16	16	16	16	16	2
	INSTRUMENT ENGINEERING							83	85	83	84	85	83	83	85	8
	ENGINEERING DEVELOPMENT LABORATORY-TEST														88	9
	MANUFACTURING ENGINEERING	3344	488	485	486											1
	QUALITY/RELIABILITY/MAINTAIN./SAFETY				2	9	31	15	16	11	6	5	1			
	PACKAGING ENGINEERING DESIGN														131	13
	TOTAL	3641	796	698	685	282	346	310	393	494	787	846	819	861	1042	112
25000	DESIGN SUBSTANTIATION	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	LOW COST DESIGN/MFG TECHNOLOGY(25100)						161	302	458	587	499	498	589	537	499	49
	BEARINGS AND SEALS DESIGNS(25200)	441	440	441	305	305	631	631	1299	1108	1168	812	1521	1443	1399	138
	PUMP PERFORMANCE(25300)	975	533	373	106	110	926	311	926	971	207	40	40	145	417	123
	TOTAL	1416	973	814	411	415	1718	1244	2683	2666	1874	1350	2150	2125	2315	311
26100	TECHNOLOGY DEVELOPMENT PROGRAM PLAN				XXXXXX	XXXXXX	XXXXXX									
	MATERIALS ENGINEERING AND TECHNOLOGY				40	40	81									
26200	SPECIAL STUDIES	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	ROTATING MACHINERY	36	35	37	36	36	35	36	37	35	36	36	37	35	36	3
26300	FINAL REVIEW/REPORT															
	ROTATING MACHINERY															
	ENGINEERING DESIGN TECHNOLOGY															
	MATERIALS ENGINEERING AND TECHNOLOGY															
	QUALITY/RELIABILITY/MAINTAIN./SAFETY															
	TOTAL															
27000	TEST HARDWARE AND SUPPORT DATA ANALYSIS															
	ROTATING MACHINERY															
	ENGINEERING DESIGN TECHNOLOGY															
	MATERIALS ENGINEERING AND TECHNOLOGY															
	INSTRUMENT ENGINEERING															
	ENGINEERING DEVELOPMENT LABORATORY-TEST															
	LOGISTICS															
	QUALITY/RELIABILITY/MAINTAIN./SAFETY															
	TOTAL															
28000	COST MODEL	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	ADVANCED PROGRAMS ENGINEERING	216	217	216	216	217	216	216	297	432	296	298	296	700	296	70
29100	PROGRAM AND BUSINESS MANAGEMENT	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	BUSINESS MANAGEMENT	147	147	147	147	147	147	147	147	147	147	147	147	147	147	14
	PROGRAM MANAGER	76	76	76	76	75	76	76	76	76	76	76	76	76	75	7
	SUPPLIER MATERIAL SUPPORT	75	75	75	75	75	75	75	75	75	75	75	75	75	75	7
	TOTAL	298	298	298	298	297	298	298	298	298	298	298	298	298	297	29
29200	PRODUCT MANAGEMENT	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	PRODUCT MANAGER	76	77	76	77	75	77	76	77	76	77	76	77	76	75	7
	PROJECT AND DEVELOPMENT ENGINEERING	377	377	377	377	377	376	377	378	376	378	377	377	377	376	37
	DESIGN MANAGER	76	77	76	77	75	77	76	77	76	77	76	77	76	75	7
	TASK MANAGEMENT	50	51	50	50	50	51	50	50	51	50	50	50	51	50	5
	CONTRACTOR INTERFACE	20	20	20	20	21	20	20	20	20	20	20	20	20	20	2
	ENGINEERING OPERATIONS	227	226	226	227	226	227	146	150	148	149	147	149	147	149	14
	TOTAL	826	828	825	828	824	828	745	752	747	751	746	750	747	745	75
29300	SIMULTANEOUS ENGINEERING & SUPPORT	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXXXXX	XXX
	QUALITY	114	114	114	114	114	113	48	48	48	48	48	48	48	48	4
	RELIABILITY AND MAINTAINABILITY	57	114	114	119	57	57	23	12	14	9	11	11	29	72	11
	SAFETY	24	24	24	45	45	45	9	9	9	9	9	9	23	23	2
	MANUFACTURING	65	84	84	93	72	72	27	23	24	22	23	23	33	48	6
	DATA REQUIREMENTS	43	238	124	131	40	218	34	301	121	133	41	218	31	90	12
	FACILITIES AND INDUSTRIAL ENGINEERING	76	76	76	76	75	76	76	76	76	76	76	76	76	75	7
	TOTAL	379	650	536	577	403	580	216	469	291	297	208	385	239	355	44
	TOTAL EFFORT, MHRS	16049	11384	10938	10331	9018	10716	6508	6787	6647	5688	5038	5910	6146	6226	760

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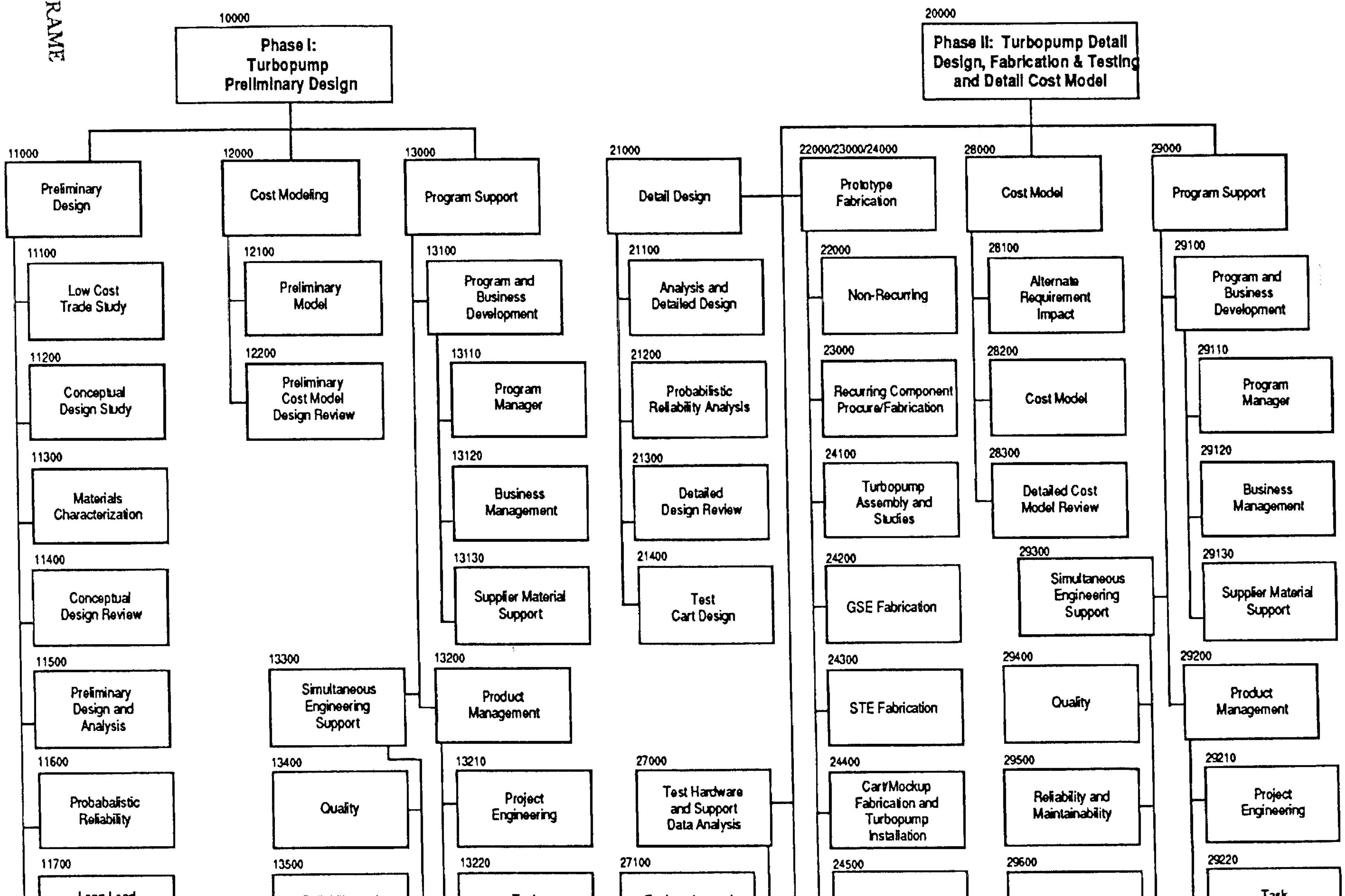
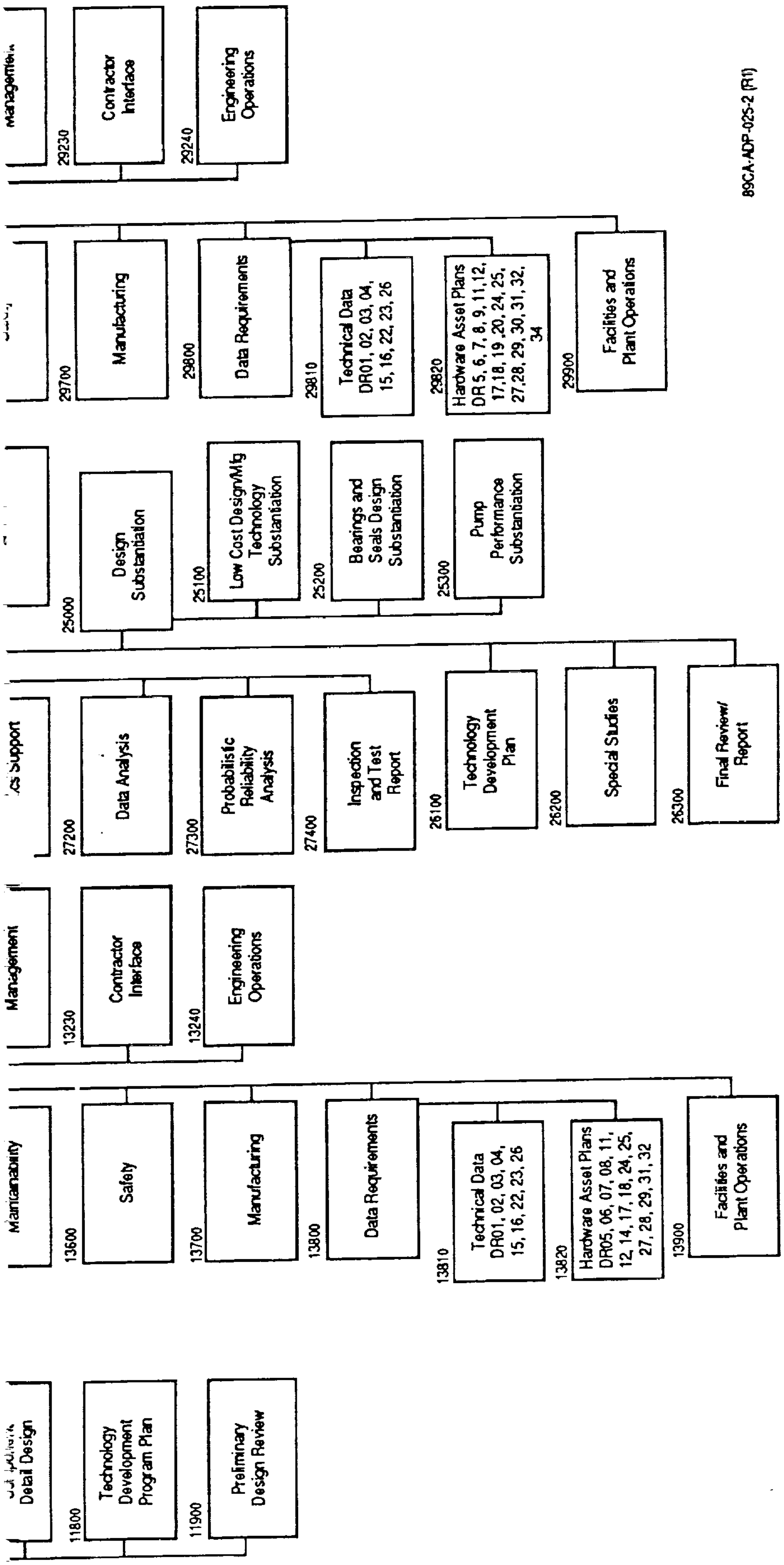
28 08-91	29 09-91	30 10-91	31 11-91	32 12-91	33 01-92	34 02-92	35 03-92	36 04-92	37 05-92	38 06-92	39 07-92	40 08-92	PHASE II TOTAL
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX			
181	181	293	293	292	294	292	293	137	71	70			20244
61	60	60	61	60	61	161	242	206	141	141			13111
													1847
													483
							20	40	80	170			3021
													241
917	919	920	918	555	554	554	557	554	556				30898
1159	1160	1273	1272	907	909	1007	1112	937	848	381			69845
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX					
682	378	378	378	399	317	318	157						9131
101	101	113	114	153	154	113	114						1717
56	16	20											236
84	85	83											1006
							330	330					660
	80	80	80	80	80	80							5461
40	40	40	40	40	40								346
131													392
1094	700	714	612	672	591	511	601	330					18949
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX					
498	1116	1062	827	1067	1067	773	362	362					11762
1400	40												14767
785	815												8914
2683	1971	1062	827	1067	1067	773	362	362					35443
													161
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
35	37	36	36	35	36	37	35	36	36	37	35	36	1006
										XXXXX	XXXXX	XXXXX	
										360	488	480	1328
										20	120	161	301
										81	140	141	362
											80	205	285
										461	828	987	2276
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
161	161	161	161	161	161	161	161	833	1075	1152	1055	1045	6448
								340	406	429	542	538	2255
												165	166
								40	120	82	80		322
												330	330
16	16	16	16	16	16	16	16	16	80	80	80	80	464
										320	360	328	1008
177	177	177	177	177	177	177	177	1229	1681	2063	2117	2487	10993
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
699	297	216	50	100	100	166	452	453	166	166	453	166	8313
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
147	147	147	147	147	147	147	147	147	147	147	147	147	4116
76	76	76	76	76	76	76	76	75	76	76	76	76	2125
75	75	75	75	75	75	75	75	75	75	75	75	75	2100
298	298	298	298	298	298	298	298	297	298	298	298	298	8341
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
76	77	76	77	76	77	76	77	75	77	76	77	76	2138
377	377	377	378	376	377	378	376	377	377	377	377	373	10551
76	77	76	77	76	77	76	77	75	77	76	77	76	2138
51	50	50	50	51	50	50	51	50	50	50	51	50	1408
20	20	20	20	20	20	20	20	21	20	20	20	20	563
148	148	148	149	148	147	149	149	147	149	148	148	149	4617
748	749	747	750	747	748	749	750	745	750	747	750	743	21415
XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
48	48	48	48	48	48	48	48	48	48	48	48	32	1723
123	80	114	114	0	0	0	0	0	0	0	0	0	1242
29	29	29	28	28	28	41	41	41	18	18	18	17	695
67	52	64	63	25	25	30	30	30	22	22	22	20	1223
31	37	78	77	40	38	31	40	38	31	37	41	34	2437
76	76	76	76	76	76	76	76	75	76	76	76	65	2115
374	322	409	406	217	215	226	235	232	195	201	205	169	9434
7267	5711	4932	4428	4220	4141	3944	4022	4621	3974	4354	4686	4886	186176

2 FOLDOUT FRAME

Figure 6. Time Phased Manloading, Phase II

FOLDOUT FRAME





FOLDOUT FRAME

Figure 7. WBS for ALS Turbopump Program

Table 1. Potential Problem Areas/Inherent Technical Risks

Potential Problem Areas and Inherent Technical Risks	Risk Abatement Approach	Impact of Invoking Contingency, Work Around or Fallback
Blisk dynamics may be unacceptable	Use parallel, alternate firtreed disk with damping	Higher cost in production
Cast inducer blade thickness distribution may not meet suction requirements	Use back-up machined inducer verified by model testing	Higher production cost

89PD-020-17

provide the experience, skills, and resources required to successfully conduct the program. Specific tasks are described under Detailed Discussions. The management of these important contributors will be aided by a dedicated subcontract procurement department to control all contractual matters; a data management function to track and document all subcontractor data items; and an automated financial control system to manage subcontractor commitments nd technical earned value. Clearly defined work statements, a negotiated budget, and a subcontract data requirements document that flows down appropriate CDRL items will be used. The program manager will direct all subcontractors using the above approach.

INTEGRATION WITH OTHER TECHNOLOGY PROGRAMS

Rocketdyne will review and evaluate the health monitoring concepts which will emerge from the Rocket Engine Condition Monitoring Demonstration Program conducted concurrently with this program for the Government by Pratt and Whitney. Sensors which benefit the methane turbopump reliability and maintainability will be incorporated in the design.

CONTRACT DELIVERABLES

The contract deliverables for this program are listed in Table 2. Major items include one turbopump and critical spares, facility interface hardware and test cart, ground support equipment (GSE), and special instrumentation sensors. All items will be prepared by proper cleaning and packaging prior to delivery.

GOVERNMENT-FURNISHED PROPERTY (GFP) AND PROPELLANTS

A list of GFP planned for this program is presented in Table 3. The major items listed refer to use of the Multifunction Tester Modules for bearing and seal design substantiation testing and propellants for use in bearing and seal component substantiation tests.

Table 2. Contract Deliverables

Item	Qty
• **Assembled Test Turbopump**	1
• **Critical Spares**	
Bearing, Pump, Ball Bearing	6
Bearing, Turbine, Ball Bearing	6
Bearing, Hydrostatic, Pump	1
Bearing, Hydrostatic, Turbine	1
Seal Floating Ring	2
Ring, Mating	1
Firtree Bladed Wheel	1
Lock, Inducer Nut	3
Lock, Hydrostatic Bearing, Pump	18
Lock, Hydrostatic Bearing, Turbine	36
Lock, 2nd Stage Nozzle Bolt	54
Seal, Metal, Pump Housings	6
Seal, Metal, Hydrostatic Bearing, Pump	3
Seal, Metal, Hydrostatic Bearing, Pump	3
Seal, Metal, Hydrostatic Bearing, Turbine	6
Seal, Metal, Hydrostatic Bearing Turbine	6
Seal, Metal, Floating Seal Housing	3
Spring, Bearing Preload	14
Bolt, Hydrostatic Brg, Pump	12
Bolt, Hydrostatic Brg, Turbine	24
Bolt, 2nd Stage Nozzle	36
Bolt, Turbine Manifold	76
Bolt, Inlet	48
Fiber-optic Deflectometer Probe	2
• **Facility Interface Hardware & Test Cart**	
Propellant Inlet Duct	1
Propellant Discharge Duct	1
Turbine Inlet Duct	1
Turbine Discharge Duct	1
Turbine Discharge Orifice	3
Turbine Discharge Transition Duct	1
Seal, Falicity to Propellant Inlet Duct	6
Seal, Propellant Inlet Duct to Pump	6
Seal, Propellant Discharge Duct to Pump	6
• Facility Interface Hardware (Continued)	
Seal, Propellant Discharge Duct to Facility	6
Seal, Turbine Inlet Duct to Facility	6
Seal, Turbine Inlet Duct to Pump	6
Seal, Turbine Discharge Duct to Pump	6
Seal, Turbine Discharge Duct to Orifice	6
Seal, Orifice to Turbine Discharge Trans	6
Seal, Turbine Trans Duct to Facility	6
Fastener Set Prop Inlet Duct	2
Fastener Set Prop Dischg Duct	2
Fastener Set Turb Inlet Duct	2
Fastener Set Turbine Dischg Duct	2
Turbopump Cart	1
• **Turbopump Deliverable Instrumentation**	
Torque/Speed Sensor Probe and Associated Signal Condition Device	1
Fiber Optic Deflectometer Probe and Associated Signal Cond Device	2
Non-Intrusive Speed Sensor and Associated Signal Condition Device	1
Isotope Wear Detector	2
Hi-Frequency Press Transducer and Associated Signal Condition Device	6
Resistance Temperature Measuring Device (RTD)	4
Proximeter, Shaft Radial Position and Associated Signal Condition Devices	4
Proximeter, Shaft Axial Position and Associated Signal Condition Devices	4
Accelerometers, Pump Housing	6
Low Frequency Pressure Transducer	23
• **GSE**	
Press, Test Plate Set Turbopump	1
Shipping Container, Test Cart	1
Shipping Container, Interface Ducts	5
Closure Set, Turbopump	1

89PD-020-1

HARDWARE REQUIREMENTS FOR SUBSTANTIATION ACTIVITIES

The hardware requirements for substantiation activities planned in this program is given in Table 4. The list includes the model and full-size pump test hardware, turbopump components for producibility and reliability/performance tests at Rocketdyne and GEAE, bearing and seal test hardware, and materials and parts for low cost materials characterization and technology enhancement programs.

Table 3. ALS Government Furnished Property and Propellants

<table>
<tr><th colspan="7">ALS Government Furnished Property</th></tr>
<tr><th rowspan="2">Item Description</th><th rowspan="2">Part Number (Location)</th><th rowspan="2">J Number</th><th rowspan="2">Contract Number</th><th rowspan="2">Qty Reqd</th><th colspan="2">Time Frame Utilized</th></tr>
<tr><th>From</th><th>To</th></tr>
<tr><td>Test Module, Multifunction Tester Load Sharing Seal</td><td>7R034500 (Rocketdyne)</td><td>0036524</td><td>F04611-86-C-0103</td><td>1</td><td>23</td><td>29</td></tr>
<tr><td>Test Module, Multifunction Tester Hybrid Bearing Face Seal</td><td>7R034530 (Rocketdyne)</td><td>0036526</td><td>F04611-86-C-0103</td><td>1</td><td>23</td><td>29</td></tr>
<tr><td colspan="7">Note: Time Frame is in Months From Go-Ahead; From: Start of Assy, To: Finish of Test</td></tr>
</table>

<table>
<tr><th colspan="2">Government Furnished Propellants</th></tr>
<tr><th rowspan="3">Item Description</th><th>Quantity (WBS 25000)</th></tr>
<tr><th>Months From Go-Ahead</th></tr>
<tr><th>23-29</th></tr>
<tr><td>Propellants/Pressurants</td><td></td></tr>
<tr><td>Liquid Hydrogen (k-lb)</td><td>---</td></tr>
<tr><td>Gaseous Nitrogen (k-scf)</td><td>1,692.0</td></tr>
<tr><td>Helium (k-scf)</td><td>665.0</td></tr>
<tr><td>Liquid Nitrogen (tons)</td><td>140.0</td></tr>
<tr><td>Liquid Oxygen (tons)</td><td>---</td></tr>
<tr><td>Liquid Methane (k-gal)</td><td>79.5</td></tr>
</table>

89PD-020-2

SPECIAL TEST EQUIPMENT

The list of special test equipment planned for this program (Table 5) includes all the special test fixtures and testers required to conduct this program.

Table 4. Substantiation Hardware Requirements

Substantiation Hardware Requirements	Time Frame Utilized	
	From	To
• Hydrodynamic (pump) test activity at Rocketdyne Engineering Development Lab		
Air test fixture (model) (STE)	15	22
Water test fixture (model)	9	12
Water test fixture (full scale)	27	30
• Structural (pump) test activity at Rocketdyne Engineering Development Lab		
Proof spin test fixture	24	30
Burst spin test fixture	24	30
Proof and burst pressure test fixture	21	30
• Structural (turbine) test activity at GEAE		
Rotor photoelastic test fixture	25	26
Proof and burst spin test fixture	27	30
Proof and burst pressure test fixture	25	30
• Mechanical elements (seals and bearings) test activity at Rocketdyne Engineering Development Lab		
Multifunction tester and modules (STE) (GFP)	18	29
Note: Time Frame is in Months from Go-Ahead — From: Start of Assembly, To: End of Testing		

89PD-020-3

Table 5. Program Special Test Equipment

Items	Qty	Remarks
• Test Module, Multifunction Tester, Load Sharing Seal	1	Modify 7R034500 Module J#O036524 Assumed to be Available From Contract F04611-86-6-0103 Need Date: 18th Month After Contract Go-Ahead
• Test Module, Multifunction Tester, Hybrid Bearing and Face Seal	1	Modify 7R034530 Module J#O036526 Assumed to be Available From Contract F04611-86-6-0103 Need Date: 18th Month After Contract Go-Ahead
• Air Tester, Model Pump	1	To be Fabricated for Air Flow Test Verification of Hydrodynamic Components

89PD-020-4

DETAILED DISCUSSION OF TECHNICAL IMPLEMENTATION PLAN

1.0 PHASE I: TURBOPUMP PRELIMINARY DESIGN

1.1 Preliminary Design (WBS 11000)

The output of this 12-month task is a preliminary design of a liquid methane turbopump for the STBE engine which maximizes common components with the STME LH_2 turbopump. The turbopump will be designed to meet the parameter ranges noted in Table 6.

Table 6. Turbopump Design Parameters

	As a LH_2 Turbopump	As a LCH_4 Turbopump (Approximate)
Pump		
Inlet pressure, psia	27 ± 3.0	46
Inlet temperature, R	37 ± 1.0	210
Inlet flow rate, lbm/s	189.0 ± 2.0	458
Discharge pressure, psia	3586.0 ± 375.0	3900
Turbine		
Inlet pressure, psia	1676.0 ± 573.0	2335
Inlet temperature, R	1700.0 ± 100.0	1600
Inlet flow rate, lbm/s	47.0 ± 4.0	111
Discharge pressure, psia	433.0 ± 138.0	555
Working fluid	O_2/H_2	O_2/CH_4

89PD-020-5

The departure point for achieving a reliable, low-cost liquid methane turbopump will be the implementation of total quality management principles in the execution of the program, starting with the preliminary design phase. The following specific design guidelines will be key to achieving the reliability and cost objectives:

1. Design for moderate parameters
2. Design for increased margin
3. Simplify the design
4. Design for short recurring lead time
5. Design to use low-cost materials and processes

6. Match tolerances to the process
7. Address cost and failure history of current and past rocket engine turbopumps.

The preliminary design will be performed using the simultaneous engineering process to assure producibility, inspectability, and maintainability. Preliminary design will be comprised of the following subtasks: Studies and Analyses, which include trade and conceptual design studies as well as critical material characterizations needed for the design of the turbopump. Parallel with this, a development plan will be defined for those technologies which are considered necessary to the success of the ALS program, but which cannot be matured on this program. The final element of the Phase I activity will be formulating a preliminary version of the cost model.

Studies and Analyses

The following tasks will be performed under Studies and Analyses:

1. Low-cost trade study
2. Conceptual design study
3. Materials characterization
4. Conceptual design review
5. Preliminary design and analysis
6. Probabilistic reliability analysis
7. Long-lead component detail design.

Each of these subtasks will be discussed in detail in the following. Note that Studies and Analyses has not been assigned a WBS number to provide a total of the subtasks. This was done to limit the number of subtiers in the WBS structure, so that the last two digits in the WBS numbers may be used to register costs by functional groups. Also the total costs of the subtasks under Studies and Analyses is of less importance than the cost of the individual subtasks.

1.1.1 Low Cost Trade Study (WBS 11100). The main objective of this initial program task will be to identify the cost/reliability/maintainability (CRM) drivers and design methodology to achieve the program goals.

Independent conceptual turbine designs by Rocketdyne and GEAE in the first months of the study, with subsequent integration of these design concepts, will provide an innovative atmosphere from which to begin the design process. Some of the trade studies identified to date include those listed on Table 7.

Table 7. Turbopump Trade Study

- Turbopump assembly
  - Pump inlet pressure and rotor speed
  - Integral shaft/disk vs separate
  - Inboard vs outboard bearings
  - Flange designs and low cost seals and fasteners

- Component Studies
  - Pump
    - Two vs three stage pumps
    - Cast vs forged inducers and impellers
    - Volute design: double discharge vs double tongue
    - Performance variability vs dimensional tolerances
    - Cost vs performance of small inducer tip clearances
  - Turbine
    - Conventional machined firtree disks vs integrally bladed disk (blisk)
    - Shrouded vs unshrouded blades
    - Constand vs variable section blades
    - Single vs double rotor
  - Materials and Processes
    - Cast vs forged bladed disks
    - ECM vs conventionally machined blades for blisk
    - Modified A286 disks vs alternatives

89PD-020-6

An example of trade study activity early in the program will be the evaluation of a cast versus machined inducer for the turbopump. Later in the Phase I activity, the model inducers will be fabricated and tested in water to substantiate the design, determine the performance impact, and further quantify the CRM factors. Each trade study will attempt to provide a quantitized approach for comparison of the options under study, and overall cost, reliability and maintainability (CRM) impacts to the engine and vehicle will be evaluated.

1.1.2 Conceptual Design Study (WBS 11200). The conceptual design study of the proposed turbopump will be performed during the first 6 months after go-ahead. The conceptual design study will result in a conceptual design developed from the low cost trade study and supported by performance and structural analysis and test, by materials and processes selection, by mechanical layouts and producibility, and by reliability and maintainability studies. A description of these activities follows.

1.1.2.1 Performance Analysis and Substantiation. During the Phase I performance analysis and substantiation task, trade studies will be performed to support the selection of the final turbopump configuration. Since the attainable suction performance is a dominant factor in establishing speed and therefore the size of the turbopump, and in keeping with the goal of maintaining methane and hydrogen commonality, inducer definition and empirical design substantiation must be accomplished early in the program. The inducer will be designed to accommodate the selected hydrogen inlet pressures within the range of 24 psia to 30 psig, and which can operate well below the 46 psia design point inlet pressure for methane. Detail design, fabrication, and water testing of model-sized inducers is included in this early task. The stator and impeller inlet flowfields will be defined during this test series and preliminary hydrodynamic design of the impellers, crossover, and diffuser/volute will be completed. Initial profiles for the turbine nozzles and blades will be defined.

The selection of the baseline inducer design will be made by testing models of two inducers designed using material properties for a casting and for a machined forging. Stators will be designed to match the two inducer designs and tested with the model inducers.

The test series outlined in Table 8 includes performance testing to select the inducer design and laser velocimeter surveys upstream and downstream of the inducer for the selected design. The laser data will define the time-averaged and unsteady flow fields presented to both the stator and the impeller, and will be used to verify the leading edge designs of these components and provide input to both steady and unsteady loading analyses.

Table 8. Six-Inch Model Inducer Stator Performance Tests

Test Series	InducerDesign	Test Description	Flow Range (% Design)	NPSH	Purpose
1	Forged/machined	H - Q	50 - 130	Nominal	Define inducer head-flow characteristic
2	Forged/machined	Cavitation	80 - 120	Nominal to 20% head loss	Define suction performance characteristic
3	Cast	H - Q	50 -130	Nominal	Define inducer head-flow characteristic
4	Cast	Cavitation	80 - 120	Nominal to 20% head loss	Define suction performance characteristic
5	Selected baseline	Laser survey at inducer discharge	100	Non-cavitating	Define Impeller inlet flow field

89PD-020-7

1.1.2.2 Preliminary Structural Analysis. The structural design will promote increased durability by simplified direct load path definition, minimizing stress concentrations, avoiding detrimental hardware natural frequencies, and providing thermal isolation. The simplified structure will allow the use of highly reliable simplified structural analysis tools, such as shell and finite element methods.

Rotordynamic analyses will be conducted using coupled finite-element models of the housing and rotating assembly. Linear critical speed and stability analyses will establish the basic rotordynamic margins and determine the rotordynamic coefficient requirements for the bearings and seals. Rotor internal loads will be determined and nonlinear analyses will establish the effects of rubbing, sideloads, etc. to ensure that adequate rotordynamic margins are preserved as the design evolves.

1.1.2.3 Materials and Process Selection. Principal issues to be addressed in this subtask are the selection of titanium alloy for the impellers, use of cast steel vs aluminum alloy for the volute and crossover and selection of materials for the turbine components. Titanium alloys are preferred for pump rotating components because of their high strength to weight ratio. Because of its extensive characterization in liquid hydrogen, 5-2.5 Ti ELI is baselined for the impellers. A promising alternate is 6-4Ti, either regular or ELI grade. Results of IR&D work currently in progress will be used to make a decision.

In selecting the material for the volute and crossover, consideration will be given to producibility, cost, weight, and corrosion issues stemming from potential ocean recovery exposure.

Although HEE is not an issue in the methane turbine because of the low partial pressure of hydrogen in the combusted gas, its impact will have to be considered to make the turbine capable of operating in the LOX-hydrogen environment of the STME engine. Material selections will be directed toward avoiding the necessity of applying protective platings and coatings. Materials will be chosen that are well characterized for the operating environment. Assessment of existing characterization will be made by reference to MIL-HBK-5E, Rocketdyne Materials Properties Manual (Publication #572K) and other published data bases (e.g., MSFC-SPEC-522A, MIL-STD-899, and MSFC-SPEC-250). If insufficient data exist, additional data will be generated before hardware fabrication.

1.1.2.4 Conceptual Mechanical Layout. A conceptual layout will be prepared to define the turbopump mechanical arrangement. The layout will be updated throughout the conceptual phase to reflect the results of low cost trade studies, structural and performance analysis, and fabrication methods and material selections. CAD/CAED will be used to allow rapid updating and incorporation of selected designs made for trade studies into the baseline conceptual layout.

1.1.2.5 Producibility Analyses. A detailed analysis of the conceptual turbopump design as it develops will be performed to determine the applicability of the least costly manufacturing processes required for fabrication.

1.1.2.6 Reliability/Maintainability Analysis.

Reliability Analyses. The implementation of the reliability engineering task during the conceptual design phase will be focused primarily on supplementing the simultaneous engineering development effort by identifying all potential failure modes of concern, and quantifying the reliability performance expectations of candidate design configurations. This effort will involve: (1) analysis of historical turbopump reliability performance data; (2) deterministic quantification of reliability-enhancing design improvements; (3) failure modes, effects, and criticality analysis (FMECA); and (4) probabilistic analyses.

An FMECA will be conducted, and updated, to identify failure modes of concern in candidate design configurations. The inclusion of estimated reliability performance levels from the historical data analysis will enable prioritization of the reliability concerns. This will permit a methodical design engineering approach to optimizing the turbopump design for high reliability and low cost.

An additional element of the reliability analysis will be the quantification of cyclic-fatigue-induced variability upon expected reliability performance over anticipated life cycle. The probabilistic analysis approach will be used to quantify the cycle influence.

Maintainability Analyses. The maintainability engineering effort during the conceptual design phase will involve analyses to quantify and optimize design issues to: (1) improve part mean-time-between-failure (MTBF); (2) reduce mean-time-to-repair (MTTR); and (3) minimize support equipment and personnel requirements. This effort will utilize the quantified reliability estimates of failure rates (i.e., MTBF), and assess the proposed designs for inspectability [or condition monitoring system (CMS) monitorability] and accessibility. Frequency of repair will quantitatively be evaluated against options that affect time to repair (e.g., fault isolation, accessibility, modularization, special test equipment, etc.).

1.1.3 Materials Characterization (WBS 11300). The materials characterization programs will be used to substantiate material, process, and design concepts.

High Strength, Modified A-286, Producibility and Characterization. This task will demonstrate the producibility of full-scale turbine disks of modified A-286 processed for high strength, and develop properties data suitable for use as a preliminary design data base. Forge tooling and processing will be developed at the forging source for the full-scale turbopump disk. Disks will be sectioned for grain flow evaluation, and test bars machined from all areas of the forging. The bars will be in radial, tangential, long, and short transverse directions. High cycle fatigue (HCF), low cycle fatigue, notched, and unnotched tensile data will be generated for a range of temperatures below -400°F to 1150°F. Based on the information gained, suitable design and processing modifications will be made for production of turbopump hardware.

Electrochemical Machining (ECM) Effects on High Strength, Modified A-286. This task will quantify the effects of ECM on the HCF properties of high strength modified A-286, and so provide a preliminary design data base for the blade areas of the disk. The same material will be used as in the previously presented producibility and characterization task, and the results will be compared to conventionally machined HCF test results. Between them, the two tasks will provide a comparative HCF data base (Table 9).

Table 9. Comparative HCF Data for Modified High Strength A286

Machining	Test Type	-400	RT	+1150	Rationale
Conventional	Tensile	√	√	√	Baselines
Conventional Conventional ECM ECM	HCF R = -1 HCF, Other R's HCF R = -1 HCF, Other R's		√ √ √ √		Direct Comparison of Conventional Machining Versus ECM Confirmation of Goodman Diagram
Conventional Conventional	HCF R = -1 HCF, Other R's	√ √			Data for Analysis of Cryogenic Areas Confirmation of Goodman Diagram
ECM ECM	HCF R = -1 HCF, Other R's			√ √	Data For Disc Rim and Blade Analysis Confirmation of Goodman Diagram

89PD-020-8

Casting Surface Quality Optimization. A test program using a simple mold (Figure 8) will be conducted to assess methods of obtaining optimum casting surface quality. The mold will have provision for insertion of ceramic cores in the base, as shown. Thickness changes allow for varying solidification rates within the casting. It is planned to pour castings in candidate investment casting alloys 718, 625, 347, and Mod A-286, using at least three different mold investment materials and two different pouring temperatures for each alloy.

1.1.4 Conceptual Design Review (WBS 11400). A conceptual design review will be held at NASA-MSFC after the first six months of Phase I. The review will present the status of the cost model, the status of the conceptual design, identify design/material substantiation issues, and recommend a baseline conceptual turbopump design to address the long lead procurement requirements of selected items for Phase II substantiation and planned turbopump testing. Approval for detail design of selected long lead components will be sought from the NASA-MSFC COTR at this time.

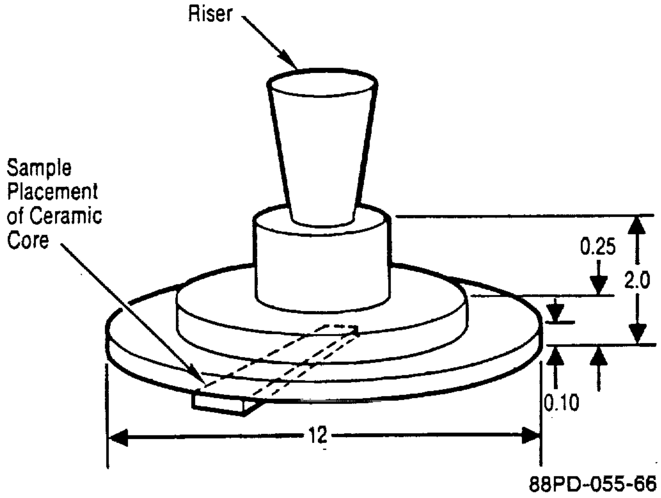


Figure 8. Casting Surface Quality Test Mold

1.1.5 Baseline Design Definition

1.1.5.1 Preliminary Design and Analysis (WBS 11500). During the baseline design definition in the last half of Phase I, the conceptual pump design will be updated and refined to yield a completed mechanical layout with supporting analytical and detailed component designs. This information will serve as the basis for the preparation of the detailed component drawings and specifications after the preliminary design review has been completed.

All turbopump components will be evaluated to provide the required reliability and structural margins for a durable, low cost turbopump design. The most critical expected operating conditions include all environmental, dynamic, thermal, tolerance buildup, surging effects, and defect size considerations. The level of complexity to be used in the structural analysis models is dependent on the complexity of the part geometry and loading. In addition to the deterministic analysis on all hardware, reliability will be quantitatively determined for all components. After an initial screening, a detailed probabilistic analysis will be performed on selected life critical components. GEAE will support the Rocketdyne design effort mainly in the areas of turbine design analysis and will perform detailed probabilistic analysis on the turbine disk and blades. In addition, GEAE will support pump design analysis, material and processes selections, and recommend producibility features for reduced cost.

The rotordynamic analyses initiated during conceptual design will be extended and completed during the preliminary design phase. The effects of sideloads, rubbing, eccentricities, and other nonlinearities will be evaluated with extensive parametric studies to ensure that substantial margins are maintained throughout the design evolution. Rotor deflections will be determined for bearing, seal, inducer, and turbine design. Internal rotor loads will be determined for subsequent rotating assembly stress analysis. The resulting design will provide ample margins that can be reliably achieved with production hardware.

1.1.5.2 Probabilistic Reliability Analysis (WBS 11600). A preliminary probabilistic design review will be conducted for each component to initially assess hardware reliability. This review will entail screening every component at the piece part level based on the following categories: component criticality (potential failure modes), preliminary deterministic assessment of design margins, hardware complexity, component sensitivity to operating environment, and input variable uncertainty evaluation.

1.1.5.3 Long Lead Component Detail Design (WBS 11700). Once the low cost trade study identifies and integrates the various design options potentially available to the design of the turbopump, and develops the conceptual design, the baseline design will have been selected. From this design, selected components will have been determined to be long lead items based on the requirements of the substantiation studies and the final prototype hardware. After approval from the NASA-MSFC COTR at the conceptual design review, Rocketdyne will proceed to detail the long lead components in parallel with the baseline design layout and analysis. These components are items necessary to the substantiation testing prior to prototype testing and are expected to include the hybrid and face contact seal designs, the ball bearings, and the turbine blisk and disk forgings. The detail drawings will be completed and checked, but will not be released until after authority is given to proceed into Phase II. No prototype hardware is expected to be procured during Phase I. The only items to be procured during the Phase I activity will be the model inducer test elements and any materials required in the materials characterization and manufacturing studies.

The hydrodynamic, aerodynamic, structural, and producibility analyses initiated during the conceptual design period, will be carried to sufficient detail in this task, to permit initiation of long lead casting drawings. The in depth analyses and preliminary detail design activity at this point in the program yield the dual advantages of NASA receiving a well substantiated design at PDR, and facilitating an earlier design release in Phase II, which reduces schedule risk to develop quality castings.

1.2 Technology Development Program Plan (WBS 11800)

Plans for technology development programs will be generated during the contract. These will address presently immature technologies, which require long term development and proof of concept for rocket engine hardware, but offer potential cost savings for phase C/D turbopumps. Concepts to be considered include: (1) cast, integrally bladed rotors (blisks), (2) bi-cast firtree bladed wheel, where precast blades are set in a mold and metal poured to form the disk and capture the blades into it, (3) inertia welding development for disk-to-shaft and/or disk-to-disk joining, (4) casting development towards an integral inducer-cum-impeller, and (5) methods of forming/attaching turbine blade shrouds.

Cost savings and risk potential for such design and fabrication technologies will be quantitized and program plans developed for the most promising candidates. These plans will be reported at PDR.

1.3 Preliminary Design Review (WBS 11900)

A preliminary design review (PDR) will be held at the conclusion of Phase I during month twelve of the contract. This review will include presentation of progress of both the preliminary turbopump design and the preliminary cost model and plans to complete Phase II.

The turbopump portion of the review will present the baseline and alternate design options considered. Both design and fabrication options under evaluation to support the selected design will be presented. A review of the studies and tradeoffs conducted to select the preliminary design and the results achieved will be summarized and the selection process by which the design and fabrication processes were chosen will be presented. This will include the technical evaluations and analysis conducted by Rocketdyne and GEAE personnel during the Phase I effort. Supporting technology analysis and evaluations in materials and processes at Rocketdyne and supported by PCC and others will be reviewed. A technical description of the turbopump design and the features related to low cost, high reliability, and ease of maintenance will be covered including a summary of the analysis supporting the preliminary design. Operational parameters will be reviewed and basic assumptions key to the structural, hydrodynamic, and aerodynamic analysis will be included. Predicted operational capability relating to projected STME and STBE and vehicle service applications will be discussed. Design layout drawings and the parts lists of the recommended baseline design will be reviewed including the stackup of the turbopump layout.

1.4 Cost Modeling (WBS 12000)

Rocketdyne will develop the ALS turbopump cost model (ATCM) which will predict the theoretical first unit and recurring costs for a flight version of the ALS turbopump assembly. The model will utilize a part cost methodology based on an analysis of historical data. The analysis will result in cost estimating relationships (CERs) utilized by the model to estimate costs. Our team member, Management Consulting and Research, Inc. (MCR), will provide expertise to ensure logical, auditable, and statistically significant CERs. MCR has developed similar models for NASA, DOD, and the aerospace industry.

1.4.1 Preliminary Cost Model (WBS 12100) The preliminary cost model will utilize an existing Rocketdyne model as a starting point and refine the model to meet the requirements for the ATCM. Historical data analysis and bottom-up estimates will be used to refine the CERs used in the model. This activity will focus heavily on production impacts, modeling of new processes, and support level estimating. Next, the model will be anchored to actual data from the RS-27 program. Also, the uncertainty of the model will be defined utilizing a Monte Carlo simulation to establish a confidence interval for the turbopump cost estimate.

Finally, the product team will complete an evaluation of the government requirements and their cost impacts. In addition, the product team will recommend alternates to these specifications with equivalent reliability.

1.4.2 Preliminary Cost Model Review (WBS 12200). NASA will be kept informed of the ATCM progress. Rocketdyne will solicit NASA inputs in order to guide the development of the model by participating in the NASA Cost Working Group. At the preliminary design review Rocketdyne will present the existing model that will contain the basic part cost CERs. In addition, the preliminary results, including anchoring and uncertainty results, will be presented. Also, Rocketdyne will present the status of the modules being developed and the program plan to complete Phase II.

2.0 PHASE II: TURBOPUMP DESIGN, FABRICATION AND TESTING (WBS 20000)

2.1 Detail Design (WBS 21000). Rocketdyne with design and producibility support from GEAE personnel will complete a detailed design and analysis of the turbopump assembly configured during the Phase I preliminary design. Included in this effort will be the detail design of any GSE and special test equipment required to install, service, and operate the turbopump assembly in the SSC test cell. The definition of these requirements is contained in Interface Control Document (ICD) DPD DR-28. The turbopump will be designed to interface with the GFP gas generator scheduled for use in turbopump testing at SSC. Rocketdyne supported by GEAE will provide completed drawings of all turbopump components and assembly drawings, as applicable, to completely define the components and the assembly requirements per DRD DR-29.

Recommended test plans will be developed by Rocketdyne for the component and turbopump test programs. The test plans will comply with the DRD DR-30 for the turbopump testing. All test plans will be presented to NASA-MSFC at times appropriate to the schedule for testing during Phase II. The test plans will include a description of the test elements and tester hardware, interface requirements and facilities to be used, propellant requirements, projected instrumentation requirements, and a test objectives and operational matrix defining the test activity planned.

In the design of the turbopump, Rocketdyne will provide as an integral part of the design analysis and layout an instrumentation package to measure hardware performance and operating characteristics. Selection considerations of the candidate sensors for incorporation into the turbopump design will use the Air Force Astronautics Laboratory (AFAL) study entitled "Rocket Engine Condition Monitoring System Study."

2.1.1 Analysis and Detail Design (WBS 21100). A detailed design analysis will be made of the turbopump and related GSE and STE for each component, subassembly, and assembly, for all turbine and pump components; performance and identification of operating loads for mechanical, thermal, dynamics, flow, structural, rotordynamics and axial and radial load control including bearings and seals performance. Heat transfer analyses will be performed to determine critical deflections, fits and clearances. Natural frequencies of features subject to dynamic loading will be eliminated. Preliminary stress calculations initiated during Phase I will be concluded using detail forcing functions calculated by performance analysts. Processing specifications and drawing material callouts will be prepared. All Drawings and specifications will be released through the formal Rocketdyne release system after review by product team members. Component and subassembly design reviews will be held at Rocketdyne, as required, to review the design and analysis methods and address critical design issues as they arise.

2.1.2 Probabilistic Reliability Analysis (WBS 21200). The detailed probabilistic design analysis is a more in-depth assessment of life-critical failure modes associated with the turbopump design. In general, the basic analysis will be updated on those components where a minimum reliability estimate can be assessed using deterministic analysis and approximate reliability calculations.

A detailed probabilistic analysis will be made of those life-critical components identified by the preliminary analysis. Each component failure mode will be characterized by an analytical failure model (e.g., HCF, LCF, and fracture). Both component failure modes and input parameter uncertainties (life drivers) defined in the preliminary analysis, together with statistically characterized material properties, will be used to predict component failure probabilities. The predicted component reliability can be obtained from the failure probability prediction and compared to the reliability allocation goal, where a pass/fail assessment will be made.

Life-driver sensitivity studies will be conducted for all designs to assess the impact of input parameter variability. The life-driver sensitivities will be used to define testing that effectively quantifies life driver uncertainty, anchor failure models, or verify component responses. Component testing and turbopump system test data will augment the reliability estimates as the program matures. Component test histories will be used to improve reliability values using Bayesan statistics..

2.1.3 Detailed Design Review (WBS 21300). At the completion of the detailed design, Rocketdyne will conduct a detailed design review at NASA-MSFC per DRD DR-27 requirement. This review is projected to be held 6 months from the start of Phase II. The review will include a detailed description of the turbopump design, the assumptions and calculated environments used in the design and analysis, and a summary of the analysis supporting the design. The proposed fabrication approach and projected schedule for all hardware will be presented, as well as a recommendation of critical item spares to support the turbopump test program and any other applications required during substantiation activities.

A detailed test plan will be presented which will include the turbopump description, interface requirements, projected instrumentation requirements, propellant needs, and test matrix, with objectives and operational requirements for each test. In addition to this plan, a summary of all other test activities including component, model and full size substantiation testing will be presented. The test plans and objectives of each program will be presented in the format previously described. A recommended test plan for the materials characterization needed to support full-scale development will be prepared on this contract and submitted at the DDR. Statistical bases for existing data will be derived from MIL-HBK-5E guidelines, Rocketdyne internal document MPTB00-004, and the methods developed at Rocketdyne to establish reliability and confidence levels for upper and lower bounds of fracture mechanics data. The analysis techniques and reliability goals will be matched to the requirements for statistical quality of material property data, and recommendations made as to where upgrades are needed.

2.1.4 Test Cart Design (WBS 21400). A test cart will be detail designed in this task which will be used to support the turbopump during shipping and installation at SSC and which will function as a mounting device for the turbopump during testing. All instrumentation sensors on the turbopump will be routed to electrical connectors mounted to instrumentation panels which minimizes the time required to install and check-out the turbopump in the SSC facility.

Informal drawings will also be prepared under this subtask to partially machine the components which form the principal external structure of the turbopump, which will be used to fabricate a mockup of the turbopump for initial facility fit-ups.

2.2 Detailed Cost Model (WBS 28000)

The detailed ATCM will include modifications to the preliminary model to increase the model accuracy and automate certain relationships defined during the analysis of historical data in Phase I. One of the modifications includes expanding the production rate and quantity CER from Phase I into a detailed separate module. The support labor calculations will be expanded into a detailed module in Phase II. Another modification includes integrating the impact of the alternative requirements into the CERs as defined by the product team. The model will be substantiated utilizing actual cost data from the ALS turbopump assembly fabrication. At the completion of the ATCM, Rocketdyne will hold a cost model review.

2.2.1 Alternate Requirements Impact (WBS 28100). In Phase I, the product team will have identified, ranked, and quantified (preliminary) the cost impact of the government requirements. In Phase II, each specification with a significant cost impact will be studied, estimated, and incorporated into the model through modifications in the CERs addressing changes in tasks, processes, materials, or methods of operation. Detailed analysis of the specifications and alternates, which preserve turbopump reliability, will be conducted using ACTM, and a final set of specifications will be recommended.

2.2.2 Cost Model (WBS 28200). The ATCM will be substantiated at three levels and the government supplied with data to perform independent estimates. First, ATCM logic and structure will be substantiated through a building-block approach employing a number of intermediate logic validation steps. Next, the data used to generate the CERs will be carefully analyzed to ensure logical CERs with statistical significance. In addition, an existing performance control system track costs during the ALS turbopump fabrication at the necessary level of detail.

The third level of substantiation will include a comparison of actual ALS turbopump assembly and fabrication costs to the ATCM results. Also, the Rocketdyne bottom-up cost model developed with discretionary funds, will be used to substantiate the cost impacts of the alternate requirements. At the conclusion of the substantiation, the uncertainty of the model will be re-evaluated to establish a confidence interval for the cost estimate. In addition, the government will be supplied with data to perform independent cost checks that Rocketdyne will use to run the GE-PRICE code.

2.2.3 Detailed Cost Model Review (WBS 28300). Rocketdyne will continue to participate in the NASA Cost Working Group during the detailed design. At the detailed design review, Rocketdyne will present the ATCM results including the impact of the government requirements, as well as alternate approaches, the substantiation and uncertainty, and the data requested by the government for independent assessments of the cost.

2.3 Design Substantiation (WBS 25000)

A key objective of this Focused Technology Program is to demonstrate that low-cost turbopump components can, in fact, be produced, and that they will both meet the reliability/ruggedness criteria and operate with acceptable performance.

2.3.1 Low Cost Design/Manufacturing Technology (WBS 25100). This task aims to substantiate that the key components which are instrumental in attaining low cost, meet the *dimensional* and *structural properties* needed to attain the high reliability program goals.

The components addressed in this task and the tests planned for each component are presented in Table 10. All components will receive a thorough dimensional evaluation to ensure that drawing tolerances are met and to document part-to-part variation. The first article of each cast component will be sectioned, and material properties will be determined.

Table 10. Low Cost Design/Manufacturing Technology Substantiation

Component \ Test Program	Dimensional	Material Properties	Proof Spin	Burst Spin	Proof Pressure Test	Burst Pressure Test	Frequency and Modeshape	Photo Elastic	Producibility
Cast Inducer	X	X	X	X			X		
Machined Inducer (Backup)	X	(FORG)							
Cast Impeller	X	X	X	X			X		
Volute	X	X			X	X			
Integrally Cast INCO 625 Turbine Manifold/Nozzle	X	X			(GEAE)	(GEAE)			
Fir-tree-Mounted Turbine Wheel									
Cast 713 Blades	X	X							
TMP A286 Disc	X	(FORG)							
Wheel Assembly			(GEAE)						
ECM'D A286 Blisk	X	(FORG)	(GEAE)	(GEAE)*			(GEAE)	(GEAE)	
Turbopump Assembly Study									X
Pilot Production Evaluation (Turbine Manifold)									X

89PD-020-9

To establish blade critical frequencies and mode shapes, the selected inducer and the cast impellers will be submitted to vibration tests. They will also be proof spun, and one unit will be spun to burst. The two main housings of the turbopump, the integrally cast pump volute/crossover, and the turbine manifold/nozzle will be subjected to the same physical substantiation process. In addition to the first article dimensional and materials test, one unit of each will be strain gaged and burst tested, and all units will be proof pressure tested. The pump components testing will be conducted at Rocketdyne. The turbine manifold and wheels proof and burst testing, and all turbine components structural testing will be performed by GEAE.

GEAE will also perform all physical and dynamics tests on the ECM'd blisk. These will include blade and disk frequency and mode shape tests; photoelastic model tests of the wheels (including blading).

This task will characterize critical complex castings by defining NDE indication size distributions and providing fracture mechanics material properties data. The information will support design integrity verification. The destructive analysis will facilitate determining the material integrity of critical locations and the castings in general. Distributions of indication size and location will be generated. To define threshold stress intensity, crack growth rates, and fracture toughness, fracture mechanics properties testing of selected areas of the castings will be conducted at temperatures ranging from -400°F to room temperature. The results of the analyses will verify the level of margin achieved for each critical casting.

A pilot production study will be conducted under this WBS, in which 5 turbine manifolds will be cast and finish machined. The hands-on effort and support costs to accomplish this task will be closely monitored for substantiating cost model analyses and "standard hours" methodology.

Another study prior to turbopump assembly will be conducted using the CAD system simulation to develop the step-by-step assembly procedures and tooling required to assemble the turbopump. The completed study will be used to train the assembly mechanics and the actual assembly times compared to that predicted by the study.

2.3.2 Bearing and Seal Design (WBS 25200). The durability, performance and life of the bearing and face seal designs will be demonstrated by test and the data compared to analysis for verification. Posttest hardware assessments will determine design integrity and confidence in the final product. The program plan is to develop a liquid methane data base for the proposed design and assess the need for design modifications. These data will envelop the turbopump requirements and support the bearing and seal detailed design.

The methane turbopump generates loads that will be distributed between the hybrid bearings and annular seals. The machine life is enhanced by multiple load-carrying devices and damping provided by hydrostatic fluid-film devices. The major concern for this type of rotor support system is that the eccentricities between support locations will interact to induce large misalignment loads. Special care will be taken structurally and thermally in the mounting concentricities and in selecting bearing and seal locations to prevent excessive loading between the elements that may result in reduced life and reliability. Technology needs include determination of the dynamic coefficients of the bearing and annular seal designs to support critical rotordynamic analyses. Expanding the wear life data base for bearings and face seals is also required, in addition to quantifying the benefits obtainable by use of wear resistant materials. Because low cost and extended life are both program goals, material selections for high reliability and low maintenance are important issues.

Verification of the rotordynamic coefficients and basic performance predictions for the impeller interstage annular seal will be accomplished by comparison of the data acquired on a similar seal during AFAL LOX/Hydrocarbon Turbomachinery Technology contract testing. The hybrid face seal will be tested to empirically determine basic performance data and endurance. The demonstration testing is required to verify the sealing surface wear rate will not be excessive and that the sealing surfaces separate properly.

The multifunction tester will be used to determine the stiffness and damping coefficients of a hybrid bearing at turbopump operating conditions in liquid methane. These data, and the measured flows, will be compared to state-of-the-art computer code results for model substantiation and used to support rotordynamic analyses. This tester will also be used to verify bearing and face seal life, durability and transient start/stop cycle capability. Full-scale test modules will be designed for this tester to accommodate all proposed configurations. The tester measures load, pressure and temperature gradients, rotor and test article displacements, flow and life for comparison with analytical calculations.

The multifunction tester will determine the dynamic coefficients through use of a magnetic bearing as a rotor control and loading device. The magnetic bearing can be used to produce asynchronous excitation of the test article. The test procedure consists of perturbing the test article with a known radial displacement and measuring the associated support response while sweeping the nonsynchronous frequency range from near zero to slightly above maximum design speed while at a constant shaft speed. This process is repeated at several shaft speeds and pressures to determine the coefficients at all desired frequencies. Other shaft components not mounted in the module calibrated support, such as a face seal, may be evaluated during the coefficient testing without distorting the data.

The ball bearing stiffness will be calculated from the rotordynamic coefficient data obtained after testing the hybrid bearing. The stiffness of the hydrostatic bearing is assumed to vary linearly with pressure and not with speed. The stiffness of the ball bearing when maintained at constant temperature should change with speed and not pressure. This method should yield results as accurate as any procedure to date for a reasonable cost.

The tester also has the capability of applying loads for life and load-sharing substantiation. The hybrid bearing and face seal testing consists of 30 starts, where speed is ramped to approximately 9500 rpm with the bearing supply pressure proportional to speed to simulate a pump fed hydrostatic bearing and under constant static radial and axial loads applied by the magnetic bearings. A second magnetic bearing imposes axial motion which simulates the predicted turbopump behavior to concurrently verify the face seal endurance and the axial load capacity of the ball bearing. A 200 second dwell at near 9,500 rpm will follow each start test to acquire 6,000 second of life duplicating actual stresses and sliding velocities. All testing will be performed at APTF at SSFL. The initial test matrix is defined in Table 11.

Table 11. Bearing and Seal Tests

Test	Configuration	Objective	Module	Build	Speed Krpm	Pressure ΔP_{psi}	Excitation Frequency	Radial Load, lb	Axial Load, lb	Starts	Duration Min
1	Hybrid Bearing	Coefficients	1	1	6 8 9.5	2000 2500 3000	Sweep	-	-	1	10
2-31	Hybrid Bearing and Face Contact Seal	Endurance/ Load-Share Demo	1	1	0-9.5	0-3000 500	Synch	500	1000	30	3.3

* CH_4 Load Sharing Seal, Hydrostatic Bearing and Ball Bearing Data Provided From Liquid Oxygen/ Hydrocarbon Turbomachinery Technology Contract With AFAL (Contract F04611-86-C-0103)

89PD-020-10

To achieve the bearing and seal procurement and fabrication requirements of Phase II, detailed designs must be defined in Phase I. In the event the rotordynamic requirements are not met, the bearing design can be altered to provide the desired load-sharing effect. Rocketdyne has an IR&D-funded program with the Center for Space Power at Texas A&M University to perform basic hydrostatic bearing geometry optimization and research. The generic data acquired from this program will support anchoring the design process. This program will also provide Rocketdyne with a complementary hydrostatic bearing analysis code for comparative evaluation of the test results.

2.3.3 Pump Performance (WBS 25300). The Phase II performance substantiation tests will include model and full size pump components testing. This testing will characterize the influence of low-cost production configurations on performance and operational parameters.

During the Phase II performance substantiation task, inducer and stator, and the volute area distribution will be optimized on models. Performance variability will be defined on full-size hardware.

A second-stage model will be fabricated to the same scale as the inducer and stator tested in Phase I. The impeller will be machined open-faced from aluminum and the front shroud attached by brazing. The diffuser/volute will be constructed from plexiglass and in sections so as to allow changes to be easily made to the volute area distribution. This model will be tested in air with sufficient instrumentation at the impeller discharge to define the radial load generated by the volute and the area distribution optimized to minimize the radial load. At the completion of this test series, the stage performance will be defined. Table 12 outlines the model air tests.

Table 12. Pump Model Stage Air Tests

Test Series	Test Description	Flow Range (% Design)	Purpose
1	Radial Load	Design	Optimize Diffuser/Volute Design
2	H - Q	0 - 130	Define Overall Pump Head-Flow Characteristics

89PD-020-11

Two builds of the full-size pump will be tested at 3100 rpm in the water loop of the pump test facility. One of these builds will be extensively instrumented to define the pressure distributions throughout the pump. Performance comparisons coupled with dimensional data will provide indications of performance variability. This test series is outlined in Table 13.

Table 13. Full-Size Pump Water Calibration Testing

Test Series	Test Description	Flow	NPSH	Pump Build	Purpose
1	H-Q and Cavitation	80 -120	Nominal to 10% Head Loss	Build No. 1	Test Pump Performance and Variability
2	H-Q and Cavitation	80 -120	Nominal to 10% Head Loss	Build No. 2	

89PD-020-12

2.4 Prototype Fabrication (WBS 22000, 23000, 24000)

2.4.1 Nonrecurring Material Procurement. (WBS 22000). The procurement of nonrecurring material, such as tooling required for fabricating castings and forgings and for manufacturing and assembling pumps, will be initiated in Phase II. All procurement and fabrication will be controlled by Material Control Plan DRD DR-23 and Manufacturing Plan DR-22 described in Section 3 and a quality assurance plan meeting the intent of NHB.4 (1B)5300 DR-17.

2.4.2 Component Procurement and Fabrication (WBS 23000). Hardware will be procured to support the fabrication of one complete turbopump assembly with hardware for additional critical spares and support for component test and substantiation programs. Control of procurement and fabrication will be as described for nonrecurring material procurement. Costs of recurring and nonrecurring components will be closely monitored as part of the data substantiation for cost model support.

2.4.3 Turbopump Assembly and Studies (WBS 24100). The procedures required to assemble, disassemble, and deliver the turbopump will be written by a simultaneous engineering team. The team will thoroughly study the assembly and disassembly processes using innovative techniques including extensive use of CAD. The resulting mature procedures will greatly reduce the time and risk associated with turbopump assembly. Delivered hardware is described in Table 2, Contract Deliverables. This task will also include studies to measure rotor and housing, dynamic characteristics to verify analytical models, and rotor balancing sensitivity evaluations and low-cost approaches to such balancing.

2.4.4 GSE Fabrication (WBS 24200). The GSE equipment required to transport and check the pump, will be fabricated and delivered. The proposed GSE is listed in Table 2, Contract Deliverables.

2.4.5 STE Fabrication (WBS 24300). The STE required for the program will be procured. This STE, which consists of three nondeliverable testers, is listed in Table 5, Program STE.

2.4.6 Test Cart/Mockup Fabrication and Turbopump Installation (WBS 24400). A test cart will be fabricated in this task which will be used to support the turbopump assembly during shipping and installation at SSC and will serve as a mounting structure for the turbopump during testing. All instrumentation sensors on the turbopump or on the transition pieces at the pump and turbine inlet and discharge will be routed to instrumentation panels located on the test cart. The cart will be mounted on wheels for ease of transportation and will have provisions for handling by an overhead crane.

A mockup of the turbopump external components will be fabricated and assembled with the transition pieces to the cart and delivered to SSC approximately 8 months prior to delivery of the turbopump test article, to permit facility fitups. The cart will be returned to Rocketdyne, where the test article turbopump will be installed and all instrumentation sensors will be connected to the instrumentation panels.

2.4.7 Test Plan (WBS 24500). The final recommended test plan will be submitted four weeks before delivery of the test turbopump. The test plan will define the three months testing at SSC and will contain, at a minimum, a test matrix defining test by test objectives and operating conditions, test hardware description, instrumentation list, redline definition, facility interface requirements, and propellant requirements. The proposed baseline instrumentation is listed in Table 14. A hazards analysis will also be prepared to evaluate the potential damage to the pump test cell.

Table 14. Turbopump Instrumentation List

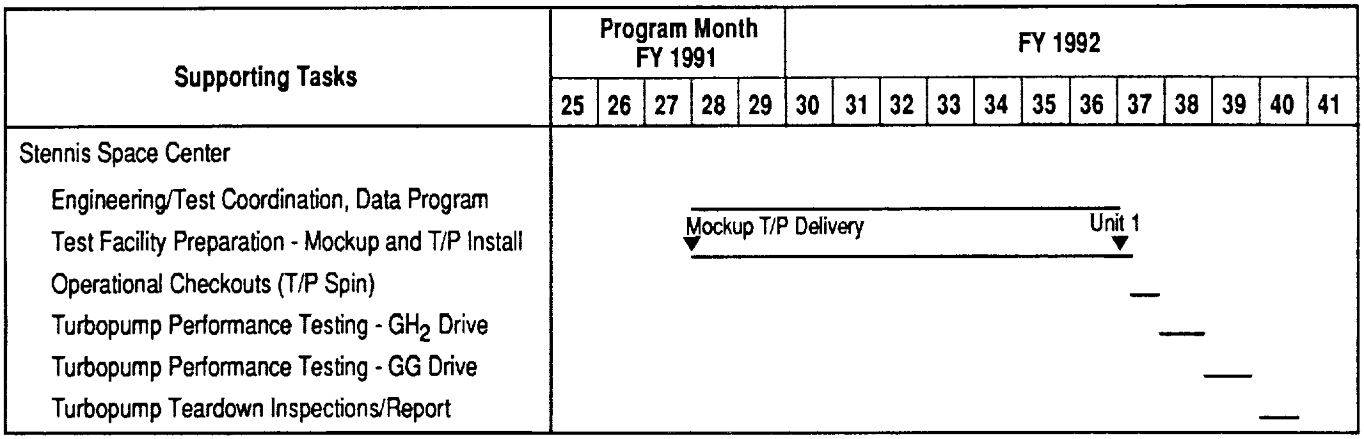
Measurement	Transducer	Qty	Transducer Supplied By	Remarks
Pump Torque/Speed	Torque/Speed Sensor	1	R/D	
Pump Speed (Back-Up)	Non-Intrusive Speed Sensor	1	R/D	
Ball Bearing Condition	Fiberoptic Deflectometer	2	R/D	
Ball Bearing Wear	Isotope Wear Detector	2	R/D	
Pump Inlet Static Pressure	Facility Low Freq Pressure Transducer	2	R/D	
Pump Discharge Static Pressure	Facility Low Freq Pressure Transducer	2	R/D	
First Stage Pump Static Pressure	Facility Low Freq Pressure Transducer	6	R/D	
Second Stage Pump Static Pressure	Facility Low Freq Pressure Transducer	6	R/D	
First Stage Discharge Dynamic Pressure	Hi-Freq Pressure Transducer	2	R/D	Redundant
Second State Discharge Dynamic Pressure	Hi-Freq Pressure Transducer	2	R/D	Redundant
Pump Discharge Dynamic Pressure	Hi-Freq Pressure Transducer	2	R/D	
Hydrostatic Bearing Supply Pressure	Facility Low Freq Pressure Transducer	2	R/D	
Ball Bearing Down Stream Pressure	Facility Low Freq Pressure Transducer	2	R/D	
Ball Bearing Down Stream Temperature	RTD	2	R/D	
Pump Inlet Temperature	RTD	1	R/D	Redundant
Pump Discharge Temperature	RTD	1	R/D	
Turbine Inlet Pressure	Low Freq Facility Transducer	2	R/D	
Turbine Inlet Temperature	Thermocouple	2	R/D	
Turbine Pressure U/S Disk No. 1	Low Freq Facility Transducer	1	R/D	
Rotor Axial Position - Inlet End	Proximeter	1	R/D	
Rotor Axial Position - Discharge End	Proximeter	2	R/D	
Rotor Radial Position - Pump End	Proximeter	2	R/D	
Rotor Radial Position - Turbine End	Proximeter	2	R/D	
Pump Housing Acceleration	Accelerometers	6	R/D	

89PD-020-13

2.5 Test Hardware Support and Data Analysis (WBS 27000)

2.5.1 Engineering and Logistic Support (WBS 27100). The ALS turbopump will be assembled in the Canoga Park facility, packaged and shipped during program month 36, to the SSC for evaluation testing at the NASA test site.

A Rocketdyne engineering team has been assigned to develop the turbopump ICD with the NASA SSC. This effort will be closely coordinated by project and program managers in order to meet the turbopump schedule testing effort at NASA. In addition, system integration, as applicable to the turbopump test effort, will be finalized prior to the installation of the turbopump into the SSC test stand. An on-site coordination schedule has been established by Rocketdyne to assist in the turbopump development installation, and testing activity requirements at SSC (Figure 9).



89PD-020-14

Figure 9. ALS Turbopump Testing Overall Schedule

The Rocketdyne Engineering and Logistics organizations will develop the handling and maintenance specifications for turbopump packaging, shipment, and installation into the NASA test stand. These specifications will include methods to ensure that all interface connections between the facility and the ALS turbopump are adequately defined, including required pretest operations such as pressure testing, torque checks of the rotor, spares parts lists, GSE and STE, and definitions of the installed instrumentation. These specifications will also define the specific methods and operations documentation for possible replacement of certain subassembly components in the turbopump should the need arise. Rocketdyne will also provide on-site engineering support during the actual testing phases for turbo-pump operations at the SSC.

2.5.2 Data Analysis (WBS 27200). Prior to installation of the ALS turbopump at the SSC, the gas generator to power the ALS turbine will have been checked and be ready for integration into the turbopump operations system. Rocketdyne will coordinate the operational sequence controls of the gas generator at the SSC to establish the control logic for the gas generator turbine power operation. The overall operations and control sequence will be presented at the pretest operational readiness review (TORR).

The ALS turbopump will be installed during the last quarter of Fiscal Year 1991 with initial checkout testing scheduled to begin in program month 37. A series of ambient temperature GH_2 turbine-powered tests are planned, Table 15, to validate the integrity of the turbopump and assess the facility integration, chilldown, sequence control, head versus flow, and minimum net positive suction head. Following these series of tests, the gas generator will be connected to the turbine inlet, and four tests are planned to validate the turbopump operation using hot-gas products from the gas generator to power the turbine.

Table 15. ALS Turbopump Systems Test Matrices

ALS Turbopump Performance and Operational Test Matrix J. C. Stennis Space Test Center		
Test No.	**Test Type**	**Test Objective**
Facility / Turbopump Operational Checkouts GH_2 Turbine Drive		
1	Static	T/P Facility Chilldown Facility Integration/Function PC - Data Processing
2	Spin	T/P Checkout to 60% N - NOM Q/N Ambient GH_2 Turbine Drive Validation Sequence Control 1st Critical Speed Verifcation Facility Resistance Adjustment
3	Spin	T/P Checkout - to 100% N - NOM Q/N Ambient GH_2Turbine Drive Validation Sequence Control Critical Speeds Verification
4	Spin	Minimum NPSH - at 100% N, NOM Q/N Sequence Control
Turbopump Performance Testing With Gas Generator Turbine Drive		
5	Spin	T/P Checkout to 60-80% N - NOM Q/N Gas Generator Hot Gas Turbine Drive Sequence Control
6	Spin	T/P Checkout to 100% N - NOM Q/N Gas Generator Hot Gas Turbine Drive Sequence Control
7	Spin	T/P Duration at 100% N - NOM Q/N Gas Generator Hot Gas Turbine Drive Duration Capability
8	Spin	T/P Duration at 100% N - NOM Q/N Facility - T/P Duration Capability Repeatability Gas Generator Hot Gas Turbine Drive

89PD-020-15

2.5.3 Probabilistic Reliability Analysis (WBS 27300). System reliabilities verification will be achieved by statistically characterizing specific test data and/or turbopump testing histories and incorporating these data into the component reliability/failure models. Condition monitoring and engineering-requested test instrumentation (an outcome of the preliminary and detailed probabilistic analyses) will be installed on the turbopump during system-level testing. The instrumentation and the data processing system will provide both the reduced test data and the proper data format. Test data obtained will quantitize the variance/uncertainty of pump operating conditions; statistically characterize component thermal, pressure, flow, or vibration environments; define component stress/strain responses; and improve reliability prediction by statically incorporating the turbopump test histograms in the reliability estimate. All test data obtained will be used to control/reduce failure model input parameter uncertainty, anchor the failure model stress response, and/or update the reliability estimate for life-critical components.

2.5.4 Inspection and Test Report (WBS 27400). A plan will be developed to disassemble the ALS turbopump after the 8-test matrix is completed at program month 39. To involve the entire product team in the hands-on inspection of the hardware items, disassembly is planned at the Canoga Park facility. Detailed disassembly measurements will be taken as part of the disassembly procedures to assess any wear patterns or areas of specific concerns. Photographs of individual parts, in the case of assemblies, will be taken to document the conditions. The turbopump will be disassembled systematically to uncover each critical area for inspection.

A final summary report will be submitted after the inspection has been completed and will include a test history, observations, performance value, disassembly documentation, conclusions, and applicable recommendations for future design considerations.

2.6 Technology Development Program Plan (WBS 26100)

The plans developed in WBS 11800 will be updated as required. Programs will be added or deleted, based on potential payoffs and risk assessments. Revised plans will be reported at DDR and in the final review and final report.

2.7 Special Studies (WBS 26200)

Rocketdyne has included 1000 man-hours on the Phase II budget to perform special studies that may become necessary during the design and fabrication effort. The special studies will be conducted at the direction of the (COTR), based on needs identified by NASA or Rocketdyne.

3.0 FINAL REVIEW/REPORT (WBS 26300)

A review of the entire program technical effort is scheduled for presentation at NASA-MSFC during program month 40. The review will focus on the results of all specific tasks completed during the program effort. The final substantiated version of the ATCM will be discussed, and the model predictions will be compared to the ALS turbopump assembly actual costs. All specific technical areas within the program will be documented in a final report.