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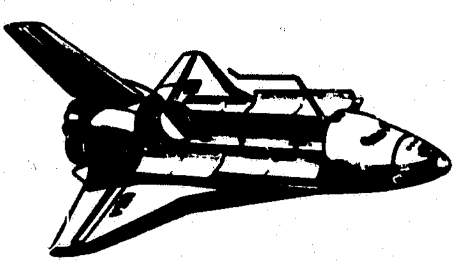
Orbit Transfer Vehicle Engine Study Phase A, Extension I

Contract NAS 8-32999
Study Plan Update
31 July 1979

Prepared For:
George C. Marshall Space Flight Center
National Aeronautics And Space Administration



Aerojet
Liquid Rocket
Company

REPORT 32999-SP2

31 July 1979

ORBIT TRANSFER VEHICLE ENGINE STUDY
PHASE"A", EXTENSION 1

CONTRACT NAS 8-32999

STUDY PLAN UPDATE

Prepared for

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National Aeronautics and Space Administration
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FOREWORD

This study plan update is submitted for the Orbit Transfer Vehicle Engine Study, Phase "A", Extension I per the requirements of Contract NAS 8-32999, Data Procurement Document No. 559, Data Requirement No. MA-01. This work is being performed by the Aerojet Liquid Rocket Company for the NASA/Marshall Space Flight Center. The study authority to proceed was received on 20 July 1979.

The study program consists of engine system, programmatic, cost and risk analyses of OTV engine concepts. These evaluations will ultimately lead to the selection and conceptual design of the OTV engine for use by the OTV vehicle contractor.

The NASA/MSFC COR is Mr. D. H. Blount. The alternate COR is Mr. J. F. Thompson. The ALRC Program Manager is Mr. L. B. Bassham and the Study Manager is Mr. J. A. Mellish.

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I. INTRODUCTION

The Space Transportation System (STS) includes an Orbit Transfer Vehicle (OTV) that is carried into low Earth orbit by the Space Shuttle. The primary function of this OTV is to extend the STS operating regime beyond the Shuttle to include orbit plane changes, higher orbits, geosynchronous orbits and beyond. The NASA and the DOD have been studying various types of OTV's in recent years. Data have been accumulated from the analyses of the various concepts, operating modes and projected missions. The foundation formulated by these studies established the desirability and the benefits of a low operating cost, high performance, versatile OTV. The OTV must be reusable to achieve a low operating cost. It is planned that an OTV have an Initial Operating Capability (IOC) in 1987.

The OTV has as a goal the same basic characteristics as the Space Shuttle, i.e., reusability, operational flexibility, and payload retrieval along with a high reliability and low operating cost. It is necessary to obtain sufficient data, of a depth to assure credibility, from which comparative systems analyses can be made to identify the performance, development, costs, risks and program requirements for OTV concepts. The maximum potential of each concept to satisfy the mission goals will be identified in the OTV systems studies initiated in FY-79.

An assessment of the above factors will be made by the NASA to determine the candidate approaches for matching the OTV concepts to mission options within resource and schedule requirements. The original Phase "A" effort and this study extension will provide the necessary data on OTV engine concept(s) based on 1980 technology required to objectively select, define, and design the preferred OTV engine.

II. STUDY PLAN

This section describes the approach to a program for the continuation of a study of oxygen/hydrogen engines for Orbit Transfer Vehicle (OTV) applications. This study extension will provide preliminary design data, plans and cost information which will complement the data generated to satisfy the original Statement of Work on Contract NAS 8-32999, dated 6 July 1978. This engine data, together with system studies, will ultimately lead to the characterization and design of O_2/H_2 engines for the OTV.

A. OBJECTIVES

The major objectives of the Phase "A" engine study extension are: (1) optimize an advanced expander cycle engine for OTV applications, (2) investigate the feasibility of providing low-thrust capability within the same expander cycle engine, (3) provide additional safety, reliability, development risk, cost and planning data on OTV engine candidates, and (4) provide design and programmatic parametric data on the OTV engines for use by NASA and OTV system contractors. The original and engine study extension, in conjunction with the system studies, will provide comparative data on engine design alternatives and identify engine requirements, concepts and approaches recommended for further study on a subsequent conceptual design phase.

Specific study objectives are:

- Prepare a study plan update (submitted herein).
- Perform analytical studies to optimize the advanced expander cycle engine thrust chamber geometry and cooling, engine cycle and controls.
- Investigate the feasibility and design impact of providing extended low thrust operating capability in the advanced expander cycle and identify technology requirements.

II, A, Objectives (cont.)

- Perform in-depth analysis to provide comparative data on development risk, crew safety, and mission reliability for both advanced expander cycle and staged combustion cycle OTV engine candidates.

- Prepare a work breakdown structure (WBS), planning (schedules) and detailed cost estimate for a 20,000 lb thrust staged combustion cycle engine for comparison with the data generated under Contract NAS 8-32999 for the advanced expander cycle engine.

- Support the OTV systems studies contrractors in the application of OTV engine parametric data and provide updated engine design information.

- Prepare a final report at the completion of the study which documents the technical details and programmatic assessments resulting from the study.

II, Study Plan (cont.)

B. STUDY PROGRAM SCHEDULE

The study plan schedule is shown on Figure 1. This figure shows the major milestones for the initiation and completion of the study tasks. The program consists of five major tasks and a reporting task per the SOW. Also shown are the milestones for the submittal of the Study Plan update, Bi-Monthly Status Reports, Task I and II reports, Performance Reviews and the Study Final Report. The milestones and reporting dates presented below were mutually agreed upon at the orientation briefing held at NASA/MSFC on 16 July 1979.

- Program Start - 20 July 1979
- Study Plan Submittal
  - First Submittal - with the proposal
  - Second Submittal - two weeks after contract initiation (3 August 1979).
- Bi-Monthly Status Report (4 are planned)
  - First Submittal - 15 September 1979.
  - Subsequent Submittals - 15th day of the month on a bi-monthly basis (i.e., 15 November 1979, 15 January 1980 and 15 March 1980).
- Task I Report - four months after the contract extension initiation (20 February 1980)
- Orientation Briefing - prior to the initiation of work. (Conducted on 16 July 1979 at NASA/MSFC)

Those milestones identified from the contract statement of work are:

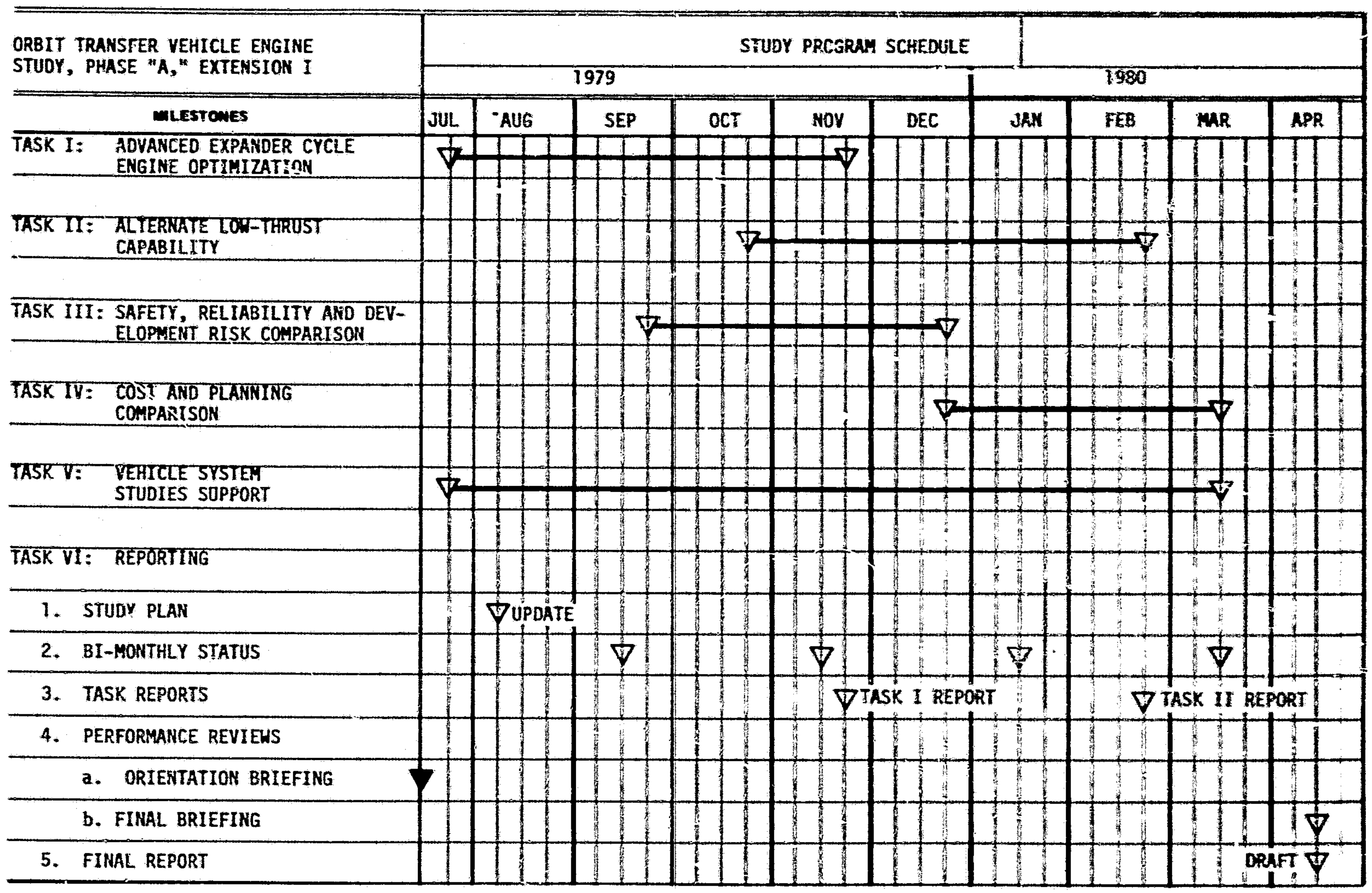


Figure 1. Study Program Schedule

II, B, Study Program Schedule (cont.)

- Technical Completion: 15 March 1980
- Final Report Draft: 10 April 1980
- Final Report Approval: 20 April 1980
- Final Report Publication: 16 May 1980

The schedule shows that the support of the vehicle system contractors (Task V) will be a continual effort throughout the study requiring the establishment of lines of communication between the vehicle contractor and ALRC. The advanced expander cycle engine optimization (Task I) will be well underway before the initiation of other study tasks to assure that the best engine is evaluated. The effect of the adoption of extended low-thrust operation upon this optimized engine will be evaluated in Task II. The cost and planning comparison (Task IV) will be initiated after the safety, reliability and development risk analyses (Task III) are complete to be sure that all factors are considered.

II, Study Plan (cont.)

C. STUDY MANAGEMENT ORGANIZATION

The study team is shown on Figure 2. Mr. L. B. Bassham, the program manager was also the program manager for the initial Contract NAS 8-32999 Phase "A" Study efforts and all related company efforts on the OTV. He is utilizing personnel from the prior Phase "A" effort to staff this program. This team has a demonstrated capability for the conduct of such studies as indicated on the initial Phase "A" contract and similar programs.

Mr. J. A. Mellish, the study manager, was the study manager for the initial Phase "A" study effort under Contract NAS 8-32999. He was also the study manager for the Space Tug Storable Engine Study (Contract NAS 8-29806), the project engineer on the Advanced High Pressure Engine Study (Contract NAS 3-19727), (LO_2/LH_2 APS Study for Space Tug (Purchase Order M4M3XDX-649707), Engine Study for the Transtage Interim Upper Stage System (Purchase Order RC4-370534), and the Advanced Engine Study for Mixed-Mode Orbit-Transfer Vehicles (Contract NAS 3-21049).

The assigned engineering specialists have either assisted directly in these past and on-going studies or have demonstrated their capabilities on other engine system studies. These include the Unconventional Nozzle Trade-Off Study (Contract NAS 3-20109), the Dual Throat Thruster Cold Flow Analysis (Contract NAS 8-32666), the ongoing Dual-Fuel, Dual-Throat Engine Preliminary Analysis (Contract NAS 8-32967), and the Phase B, Space Shuttle Main Engine Definition Study (Contract NAS 8-26188).

Since most of the engineering specialists are the same individuals who held similar areas of responsibility in the initial contractual efforts, there is a continuity of effort between the original study and this extension. These people understand the problem and can proceed with minimum "start up" time.

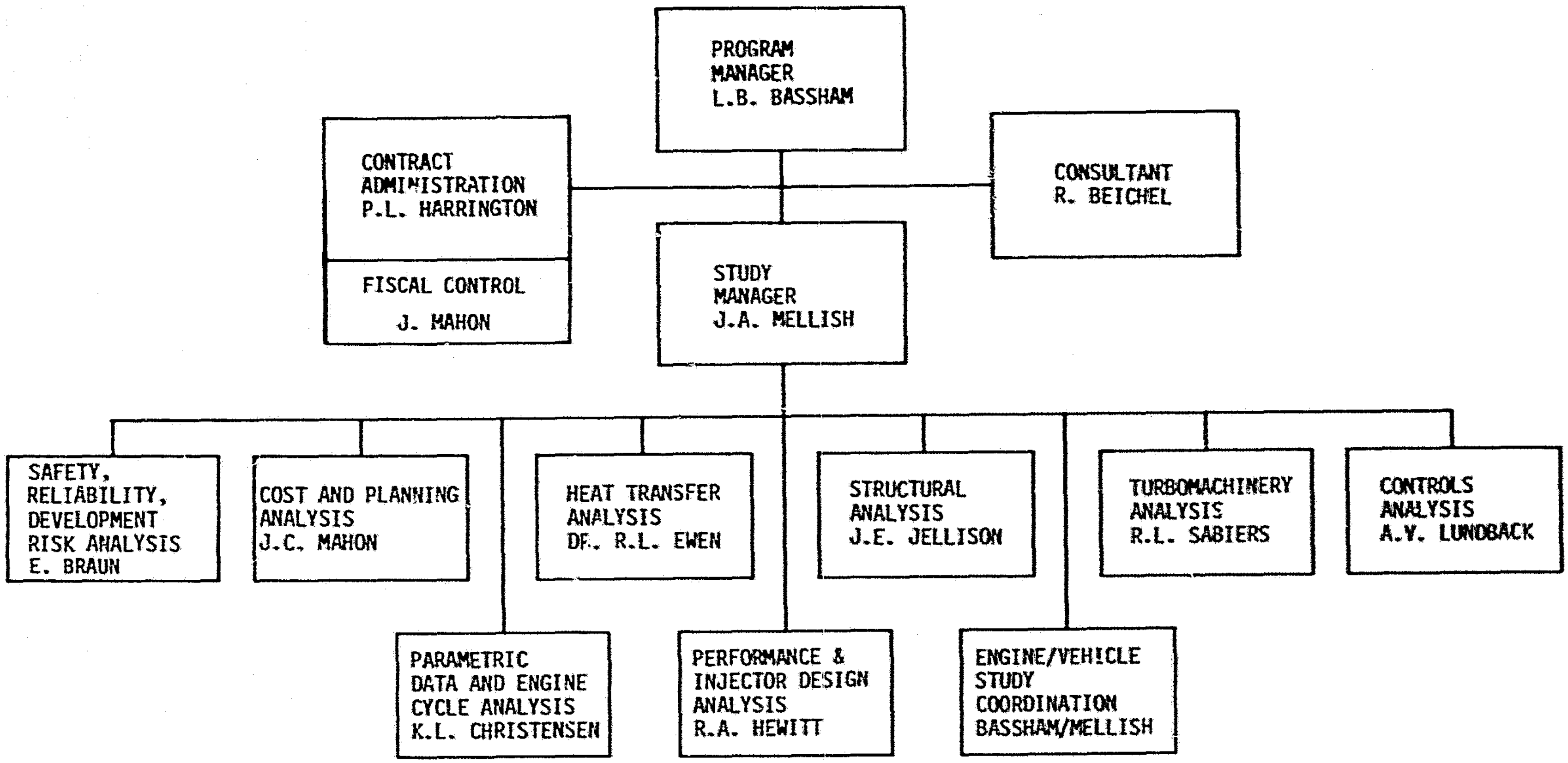


Figure 2. Study Management Organization

Mr. L. B. Bassham, the program manager, has complete authority and responsibility for the direction of this study and all Orbit Transfer Engine related programs at ALRC. He has the authority and responsibility to represent and commit ALRC on all matters related to the subject program. He is the individual to whom NASA/MSFC can look to for completion of the contract requirements. He is responsible for the program performance in terms of:

- Technical success
- Contract compliance
- Costs and schedule

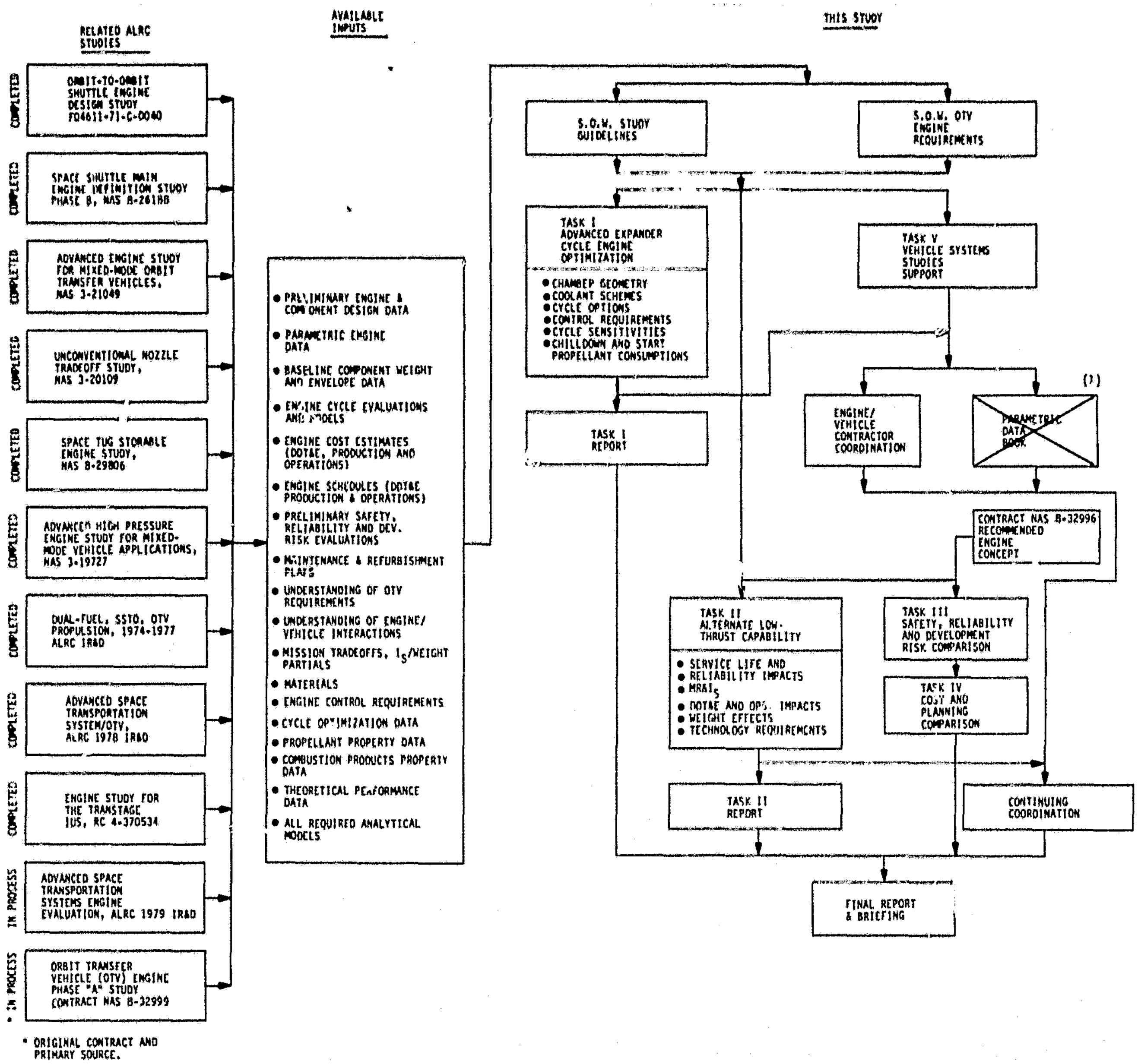
Mr. Bassham has served as program manager on the majority of NASA technology programs for the past five years. Prior to this, he was the project engineer on several technology programs. His extensive experience obtained during the design, development and demonstration phases of programs for advanced engines is fully applicable to this program.

D. STUDY FLOW LOGIC AND TECHNICAL APPROACH

This section describes the overall approach for the performance of the study program. To accomplish the program objectives, the study is composed of five (5) major tasks and a reporting task. The study logic diagram depicting these tasks, major inputs, related studies, task interrelationships and principal reporting outputs is shown on Figure 3. The time phasing of each of these major tasks is shown on Figure 1. Each task is discussed in detail in Section II,E, which presents individual task logic diagrams showing subtasks and task outputs.

ALRC's approach to this study is similar to that utilized on many past programs for NASA/MSFC, NASA/LeRC, NASA/JSC and AFRPL. The most recent of these, conducted for MSFC, is, of course, the initial Phase "A" study efforts of Contract NAS 8-32999. This initial work and the study extension are logical follow-ons to the earlier studies which included the Design Study of RL-10 Derivates (Ref. 1), an Orbit-to-Orbit Shuttle Engine Design Study (OOS) (Ref. 2), the Space Tug Storable Engine Study (Ref. 3), and the Advanced Space Engine Preliminary Design program (Refs. 4 and 5). The data analyses and results from these previous studies will be utilized as much as possible to aid in performing this study. These, and the studies listed on Figure 3, provide analytical methods or useful data which will be used or updated to meet the OTV engine study requirements. Thus, the resources are primarily applied to the new issues resulting in a cost effective study program.

ALRC in-house efforts have supported the Advanced Space Transportation System definition efforts for the past six years. Recent emphasis on the OTV have led to the formulation and computer modeling of various OTV engine candidates on ALRC sponsored efforts. These engine models are capable of generating parametric delivered performance, weight and envelope



[(1)]This subtask has been deleted.

Figure 3. Study Logic Flow Diagram

data for engines such as, the dual-expander, tripropellant and O_2/H_2 bell nozzle engines. In addition, the O_2/H_2 bell nozzle engine models perform the engine steady-state cycle power balances for gas generator, staged combustion and expander cycle engines. The expander cycle option in this model will be used to conduct the cycle analyses required in Task I, Advanced Expander Cycle Engine Optimization.

The primary inputs available to the study are also shown on the study logic diagram (Figure 3). Much of the supporting information is available from the initial Phase "A" efforts. In particular, the engine weight, performance, envelope and cost parametric data, and the schedular information are available from the previous work. The parametric data have been generated for advanced expander cycle staged combustion cycle and gas generator cycle OTV engine candidates. Only the expander and staged combustion cycle engine data is of interest in this study extension. Detailed cost estimates for the advanced expander cycle engine are available and will be used as a reference point for the comparisons in Task IV.

To support the Phase A OTV Engine Study Engine Requirements and Concepts Selection Review held at MSFC on 24 October 1978, ALRC conducted in-house studies to evaluate the effects of safety (man-rating), mission reliability and engine development risk on the engine cycle selection. This information will be updated as necessary, documented and used in the conduct of Task III.

Task I will be initiated upon the authority-to-proceed (ATP) and will optimize the advanced expander cycle engine combustion chamber geometry, coolant scheme, and engine cycle. The results of this task will be documented in a task report and updated information provided to the vehicle contractor(s).

II, D, Study Flow Logic and Technical Approach (cont.)

Task V, Vehicle Systems Study Support, will also be initiated upon the ATP date. The initial subtask will be to establish communication between ALRC and the systems contractor(s). The engine parametric data is already available for the OTV engine cycle candidates and is presented in the final report on the prior study efforts. The support task will be a continual level-of-effort throughout the program to update information, answer questions, and clarify data and design characteristics of the engines. NASA/MSFC will be kept informed of verbal and written communcations through the bi-monthly reports, in addition to being sent copies of written communications.

Task II, Alternate Low-Thrust Capability, will be initiated after the advanced expander cycle optimization process is nearly completed, approximately three (3) months after ATP. This task will assess the impact of a low-thrust option, within the same basic engine, upon the engine service life, reliability, weight, DDT&E cost and operations cost. The performance (specific impulse) and operating mixture ratio at the low-thrust point will be established. Technology programs required to bring the engine, with its low-thrust "kit", into being will be identified. All task results will be documented in a task report.

Task III will not be initiated until the start of the third program month in order to take advantage of the data from Task I. As discussed previously, the ALRC in-house studies will be updated as required and the comparative safety, reliability and risk between an advanced expander cycle engine (Contract NAS 8-32999 recommendation) and the staged combustion cycle engine (Contract NAS 8-32996 recommendation) will be established. To accomplish this and the Task IV Cost and Planning Comparison, the recommended design characteristics for the engine evolved from Contract NAS 8-32996 are required.

II, D, Study Flow Logic and Technical Approach (cont.)

Task IV will provide a work breakdown structure, engine schedules and programmatic information through the DDT&E, production and operations phases, and a cost estimate for a staged combustion cycle engine as detailed by Contract NAS 8-32996. This data will be compared to that prepared for the advanced expander cycle engine under Contract NAS 8-32999. This task will be initiated after the completion of Task III approximately five (5) months after ATP.

A Final Report Draft, which documents all study assumptions, trade-offs, rationale, results and recommendations, will be submitted approximately nine (9) months after ATP. This report draft will be submitted for NASA approval at about the time of the final briefing, which will be held on a date to be mutually agreed upon.

E. DETAILED TASK DESCRIPTIONS

1. Task I: Advanced Expander Cycle Engine Optimization

This task will be initiated upon receipt of the authority to proceed and will use the advanced expander cycle engine data and characteristics recommended for Contract NAS 8-32999 under Statement of Work paragraphs 6.2.2 and 6.2.3 as the point of departure. The task logic diagram is shown on Figure 4.

The initial subtask to be undertaken is the chamber geometry optimization. As shown by the task diagram, this optimization will be performed at three (3) thrust levels for a nominal engine mixture ratio of 6.5 and maximum engine length with the extendible nozzle in the stowed position of 60 inches. A mixture ratio of 6.5, rather than 6.0, was selected on the basis of performance analysis results obtained on the prior contractual efforts. Heat transfer analyses will be undertaken to establish the variation in the chamber coolant jacket pressure drop and coolant outlet temperature with combustion chamber length and contraction ratio. Values selected in the initial study efforts were a chamber length of 18 inches and a contraction ratio of 3.66. These selections were based upon the results of analyses performed in past efforts (Refs. 1, 2 and 6).

Performance analyses have shown that a minimum chamber length of about 12 inches is required to meet the Phase "A" energy release efficiency (ERE) goal of 99.5%. Longer chambers result in higher hydrogen coolant outlet temperatures and hence, increase turbine inlet temperatures. For a given set of pump discharge pressures, this lowers the turbine pressure ratio and increases the thrust chamber pressure. Chamber pressure increases result in higher area ratios and performance (I_s) for an engine with a fixed length constraint. However, longer chambers reduce the length of the nozzle that can

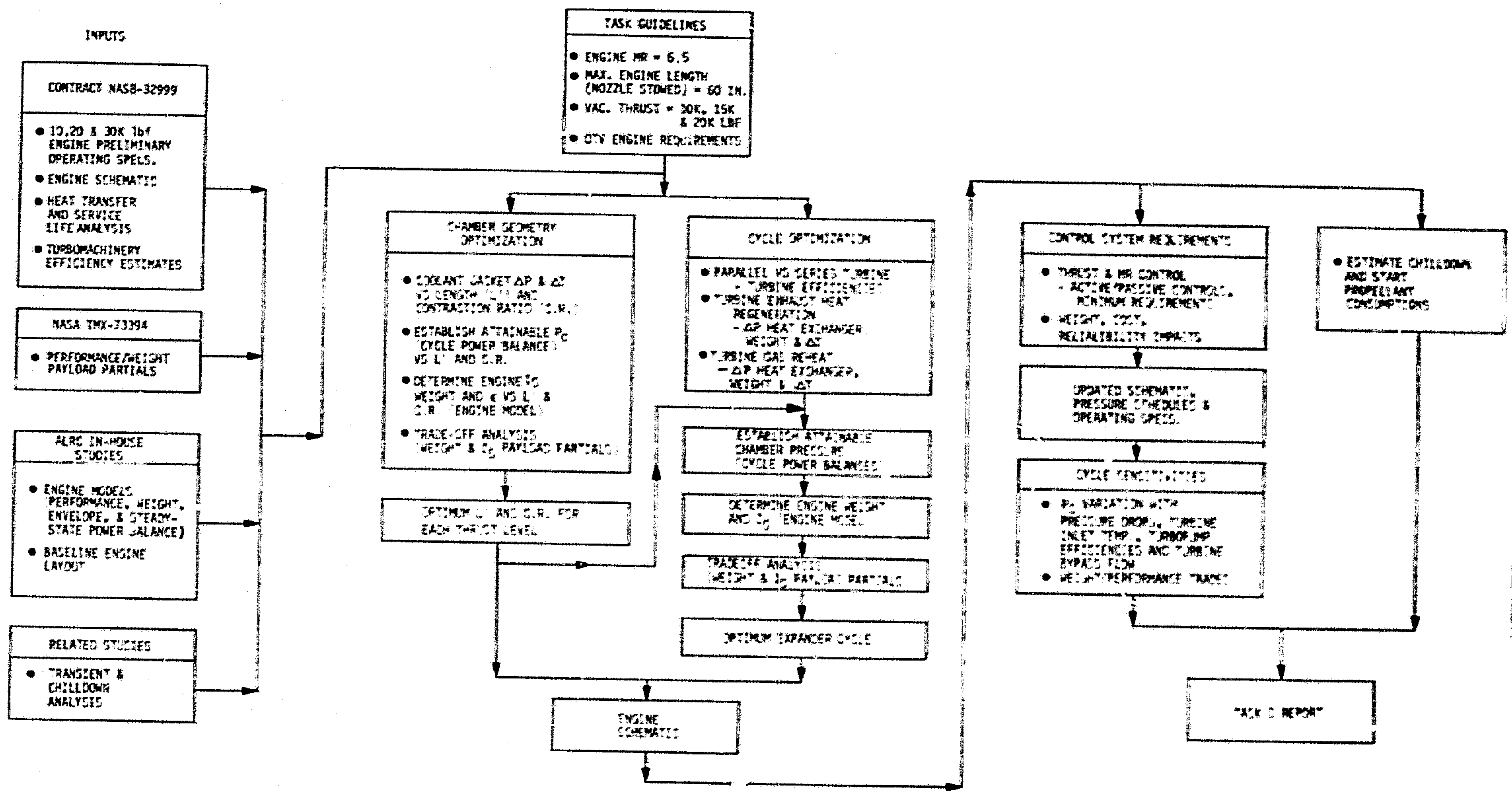


Figure 4. Task I: Advanced Expander Cycle Engine Optimization

be fit into the available envelope and hence, reduce the area ratio and lower performance. Longer chambers also result in greater engine weight.

The chamber contraction ratio also affects the attainable chamber pressure because it influences the coolant jacket pressure drop and coolant temperature rise which influence the cycle power balance. Increasing the chamber contraction ratio also results in a heavier chamber and engine weight.

The thrust chamber pressures selected at each thrust level, during prior contractual efforts, will be used for the intial heat transfer analyses. The chamber length and contraction ratio will be varied at each thrust level and chamber pressure operating point to obtain the coolant jacket pressure drop and coolant temperature rise data. The influence of the operating chamber pressure upon these chamber cooling results will then be established. The chamber length will be varied over a range from 12 to 30 inches, contraction ratio from 2.5 to 5.0 and chamber pressure $\pm$ 200 psia about each nominal point.

Power balances will be performed using the results of the heat transfer analyses to establish the attainable chamber pressure as a function of chamber length and contraction ratio. Delivered performance and engine weight will then be calculated at these chamber pressures by using the existing ALRC engine model. A typical output from this model is shown on Table I. Weight and specific impulse tradeoffs will be made by using the payload partials derived from NASA TMX-73394. These partials are:

	AMOTV	APOTV
$\Delta W_{PL}/\Delta I_S$, lb/sec	+73	+60
$\Delta W_{PL}/\Delta W_{ENG}$, lb/lb	-1.1	-1.1

<u>TABLE I</u>

TYPICAL ENGINE DATA MODEL OUTPUT

ENGINE PERFORMANCE

1.THRUST(LBF)	10000.00
2.CHAMBER PRESSURE(PSIA)	1300.00
3.MIXTURE RATIO	6.00
4.TOTAL FLOWRATE(LBM/SEC)	21.05
5.LOX FLOWRATE(LBM/SEC)	18.04
6.FUEL FLOWRATE(LBM/SEC)	3.01
7.ISP ODE(SECONDS)	491.31
8.NOZZLE EFFICIENCY	.9880
9.ENERGY RELEASE EFFICIENCY	.9950
10.KINETIC EFFICIENCY	.9937
11.BOUNDARY LAYER LOSS (LB)	160.06
12.ISP DELIVERED(SECONDS)	475.13
13.THRUST TO WEIGHT RATIO	22.93

ENGINE SIZE (IN AND IN**2)

1.GIMBAL LENGTH	3.536
2.INJECTOR LENGTH	2.828
3.CHAMBER LENGTH	18.000
4.NOZZLE LENGTH	95.636
5.ENG LENG STOWED	60.000
6.ENG LENG DEPLYD	120.000
7.EXIT DIAMETER	61.453
8.THROAT RADIUS	1.092
9.AREA RATIO	792.
10.CU AREA RATIO	8.
11.TUBE BNDL AREA RATIO	121.
12.PERCENT BELL	86.47
13.X/RT	87.57
14.PERCENT RAO	165.59

ENGINE WEIGHTS (LBM)

1.GIMBAL	8.35
2.INJECTOR	10.68
3.CHAMBER	39.78
4.COPPER NOZZLE	13.28
5.TUBE BNDLE NOZZL	29.49
6.RAD NOZZLE	84.54
7.NOZZLE DEPLOY SYS	48.36
8.FUEL RICH PREBRNRS	.00
9.VALVES AND ACTUATORS	54.74
10.LOX BOOST PUMP	5.05
11.LH2 BOOST	2.15
12.LOX TPA (HI SPD)	17.37
13.LH2 TPA (HI SPEED)	20.14
14.MISC. VALVES	4.76
15.LINES	23.33
16.IGNITION SYSTEM	11.00
17.ENGINE CONTROLLER	35.00
18.MISCELLANEOUS	28.90
19.HEAT EXCHANGER	3.44
20.TOTAL ENGINE WEIGHT	436.17

The following data matrix is planned for analyses:

Thrust, K lbf	Chamber Length	Contraction Ratio
10	12	3.66
10	18	3.66
10	24	3.66
10	30	3.66
10	18	2.5
10	18	5.0
15	12	3.66
15	18	3.66
15	24	3.66
15	30	3.66
15	18	2.5
15	18	5.0
20	12	3.66
20	18	3.66
20	24	3.66
20	30	3.66
20	18	2.5
20	18	5.0

Data displays such as those shown by the sketches on Figure 5 and 6 will be constructed. These will identify an optimum chamber length and contraction ratio at each thrust level which will be used in the other study efforts requiring defintions of engine characteristics.

The baseline expander engine cycle selected in the prior study effort is a parallel turbine drive concept. This cycle will be used

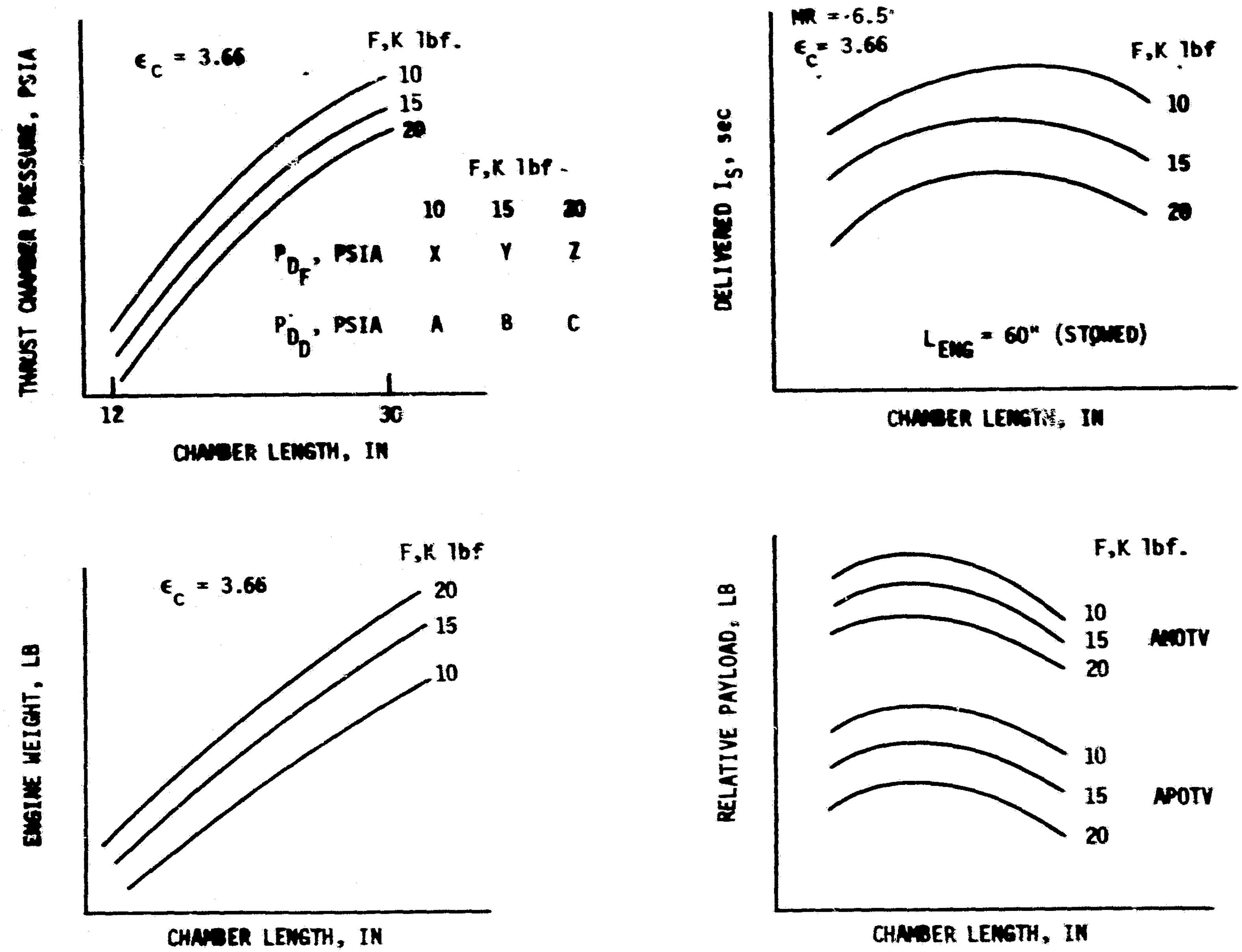


Figure 5. Chamber Length Optimization

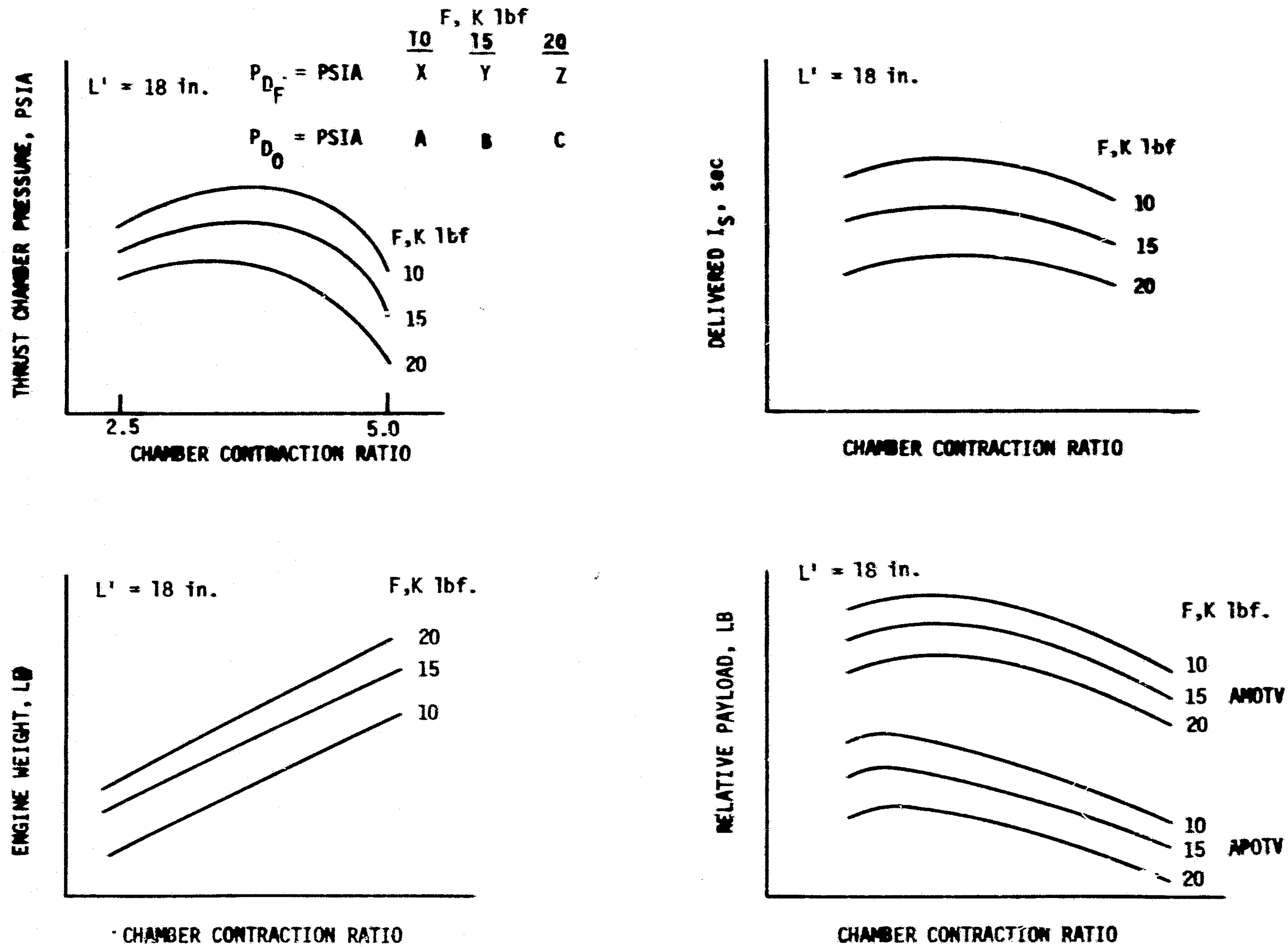


Figure 6. Chamber Contraction Ratio Optimization

for the chamber optimization but variations in the cycle will be analyzed in another subtask. As a minimum, concepts to be considered are: series turbine flow path, turbine exhaust heat regeneration and turbine exhaust reheat. Schematics of the cycle concepts are shown on Figure 7. The turbine exhaust heat regeneration analyses will be conducted for the most promising of the series or parallel flow turbine cases.

The primary issue in the parallel vs series turbine cases is whether the increase in oxidizer pump turbine efficiency, created by the higher flow in-series oxidizer pump turbine, will make up for the pressure ratios of the turbines being in series. The oxidizer turbine inlet temperature is reduced for the series turbine case. The advantages of independent parallel turbine development versus the development of series turbines must also be considered. If the series turbine offers a performance advantage it will be traded against the development complexity.

The key issues in both the turbine exhaust heat regeneration and turbine exhaust gas reheat evaluations are the additional heat exchanger pressure drop, hydrogen temperature pickup and the weight of the heat exchanger. Heat transfer analyses will be performed to evaluate the practicality of such heat exchangers and weight estimates made. Cycle power balance analyses will be conducted for a baseline set of pump discharge pressures to establish the attainable chamber pressure. Delivered performance and engine weight calculations will then be performed and the relative payload capability determined through tradeoff analyses.

The results of the cycle optimization will be discussed informally with the NASA/COR and a cycle recommendation made. A schematic of the selected optimum expander cycle will be prepared and used in other task efforts.

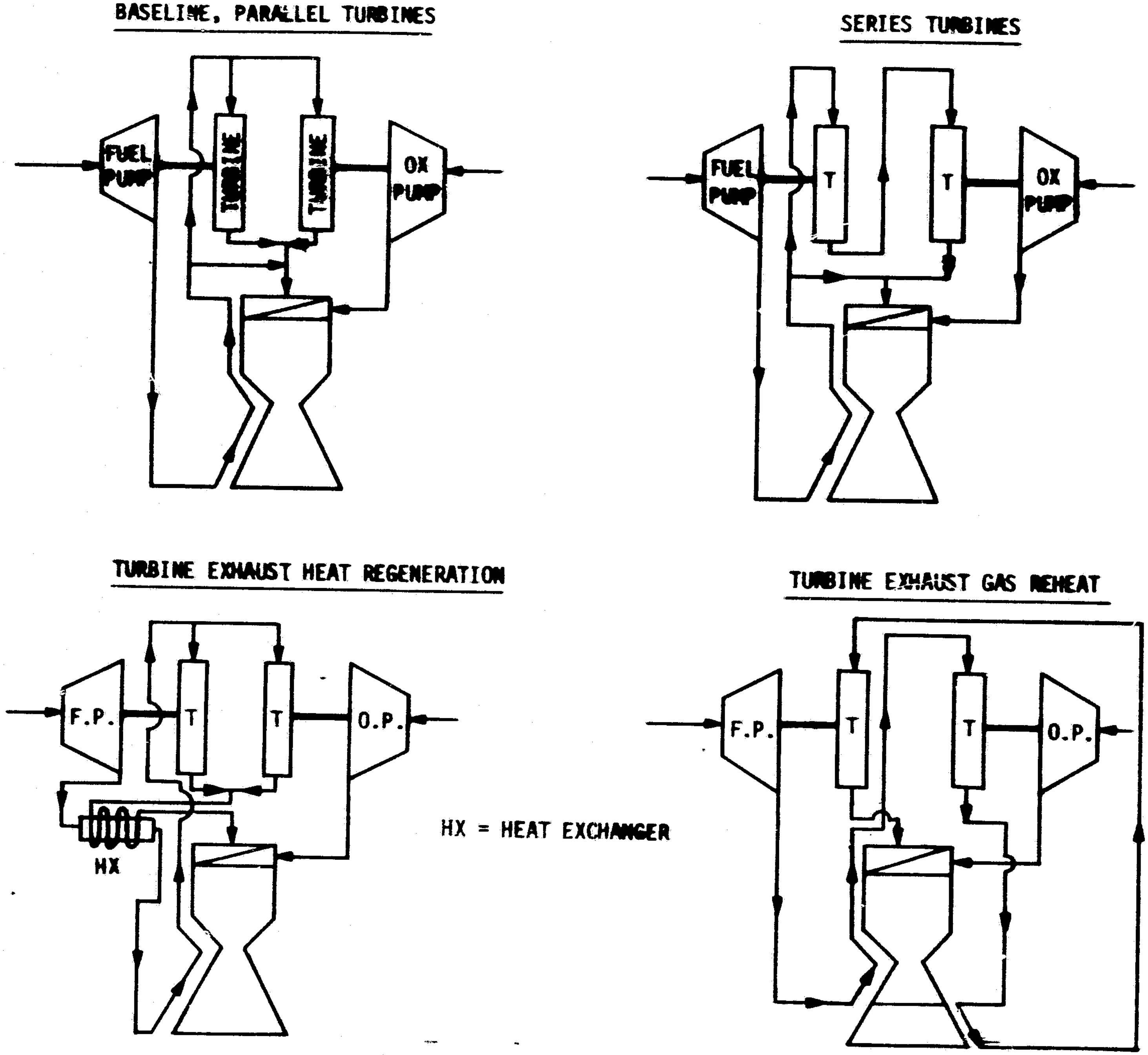


Figure 7. Cycle Evaluations

The selected engine cycle will be evaluated to define a preliminary control system. Initial emphasis will be placed on an active control system that would have a high probability of starting, controlling and shutting down the engine safely, while achieving desired performance characteristics. The control system will then be reduced in complexity in an attempt to achieve a passive control concept. This simplification effort will include subjective evaluations of the effects of changes on performance, cost, weight and reliability. The reliability aspect will be considered in terms of crew safety and mission success but will not involve numerical predictions. The anticipated "minimum" control system is expected to include both active and passive elements. This effort will be performed on a qualitative basis, relying upon review of prior work (Refs. 1 through 5) and simple calculations to provide selection guidance and assess impact. Based upon the controls analyses, updated engine pressure schedules and operating specifications, such as shown on Tables II and III will be prepared at thrust levels of 10K, 15K and 20K lbf. The operating specifications will be in sufficient detail to permit checks and calculation of the engine cycle power balances.

The sensitivity of the cycle power balance to changes in component pressure drops, pump and turbine efficiencies, turbine inlet temperature and turbine bypass flow rates will be established. Statistical deviations in these parameters will be determined and the effect upon engine chamber pressure, performance and weight established for each thrust level nominal operating point. This in turn will be transformed into relative payload variations using the payload partials previously discussed.

Engine chilldown and start propellant consumptions will be estimated for the selected cycle. This will be accomplished by reviewing the results of past analyses (Refs. 1, 2, 4 and 5) and updating these analyses as necessary to reflect the engine cycle selected.

TABLE II

TYPICAL ADVANCED EXPANDER CYCLE ENGINE PRESSURE SCHEDULE

PRESSURE SCHEDULE (PSIA)

	FUEL CIRCUIT	LOX CIRCUIT
1.PUMP INLET	25.96	62.00
2.PUMP PRESSURE RISE	2912.[illegible]	1522.86
3.PUMP DISCHARGE	2938.[illegible]	1584.86
4.LINE PRESSURE DROP	40.00	40.00
5.VALVE INLET	2898.65	1544.86
6.VALVE PRESSURE DROP	28.98	15.45
7.VALVE OUTLET	2869.67	1529.41
8.LINE PRESSURE DROP	40.00	--
9.COOLANT JACKET INLET	2829.67	--
10.COOLANT JACKET PRESSURE DROP	137.00	--
11.COOLANT JACKET OUTLET	2692.67	--
12.LINE PRESSURE DROP	40.00	--
13.TURBINE INLET	2652.67	--
14.TURBINE PRESSURE RATIO(PIN/POUT)	1.88	--
15.TURBINE OUTLET	1413.04	--
16.LINE PRESSURE DROP	.00	--
17.TCA INJECTOR INLET	1413.04	1529.41
18.TCA INJECTOR PRESSURE DROP	113.04	229.41
19.TCA INJECTOR FACE	1300.00	1300.00
20.TCA PRESSURE DROP	.00	.00
21.CHAMBER PRESSURE	1300.00	1300.00

FLOWRATES (LBM/SEC) TEMP DROP (DEGREES R) (FC=FUEL CIRCUIT) (OC=OX CIRCUIT)		HORSEPOWERS AND EFFICIENCIES (FC=FUEL CIRCUIT) (OC=OX CIRCUIT)	
1.FC TURBINE FLOW	2.45	1.FC TURB HORSEPOW	890.55
2.OC TURBINE FLOW	.38	2.OC TURB HORSEPOW	150.70
3.FC TURBINE TEMP DROP	108.83	3.FL PUMP SHP	890.55
4.OC TURBINE TEMP DROP	108.83	4.OX PUMP SHP	150.70
		5.FC TURBINE EFF	.67
		6.OC TURBINE EFF	.74
		7.FUEL PUMP EFF	.60
		8.OX PUMP EFF	.69

ENGINE SPECIFIED ABOVE OPERATING AT MR= 7.0

PC(PSIA)= 1260.99
TOTAL FLOWRATE (LBM/SEC)= 21.13
LOX FLOWRATE (LBM/SEC)= 18.49
H2 FLOWRATE (LBM/SEC)= 2.64
DELIVERED ISP (SECONDS)= 473.32

@FIN

TABLE III

PRELIMINARY ADVANCED EXPANDER CYCLE ENGINE OPERATING SPECIFICATION

ENGINE

Vacuum Thrust, lb	10,000
Vacuum Specific Impulse, sec.	475.1
Total Flow Rate, lb/sec.	21.05
Mixture Ratio	6.0
Oxygen Flow Rate, lb/sec.	18.04
Hydrogen Flow Rate, lb/sec.	3.01

THRUST CHAMBER

Vacuum Thrust, lb	10,000
Vacuum Specific Impulse, sec.	475.1
Chamber Pressure, psia	1,300
Nozzle Area Ratio	782
Mixture Ratio	6.0
Throat Diameter, in.	2.184
Chamber Diameter, in.	4.18
Chamber Length, in.	18.0
Chamber Contraction Ratio	3.66
Nozzle Exit Diameter, in.	61.1
Percent Bell Nozzle Length	87.1
Nozzle Length, in.	95.6

MAIN PUMPS	LOX	LH_2
Total Outlet Flow Rate, lb/sec	18.04	3.01
Volumetric Flow Rate, gpm	114	307.1
NPSH, ft.	137	1,321
Suction Specific Speed, $(RPM)(GPM)^{1/2}/(ft)^{3/4}$	20,000	8,000
Speed, RPM	75,000	100,000
Discharge Pressure, psia	1,625	3,200
Head Rise, ft.	3,159	103,408
Number of Stages	1	3
Specific Speed, $(RPM)(GPM)^{1/2}/(ft)^{3/4}$	1,900	692
Head Coefficient	0.47	0.60
Impeller Tip Speed, ft/sec	465	1,360
Impeller Tip Diameter, in.	1.42	3.11
Efficiency, %	69	60

MAIN PUMP TURBINES	LOX TPA	LH_2 TPA
Inlet Pressure, psia	2,818	2,818
Inlet Temperature, °R	665	665
Flow Rate, lb/sec	0.357	2.473
Gas Properties		
C_p, Specific heat a constant pressure, BTU/lb °R	3.543	3.543
γ, Ratio of Specific Heats	1.397	1.397
Shaft Horsepower (1)	154.7	971.5
Efficiency, %	74	67
Pressure Ratio (Total to Static)	1.976	1.976
Turbine Bypass Flow, lb/sec	0.18	

(1) Includes 3% Horsepower penalty for boost pump drive flow.

The analyses and results of all Task I efforts will be summarized in a task report and submitted to NASA approximately four (4) months after contract initiation. This task report will be detailed enough to be incorporated as a section in the final report.

2. <u>Task II: Alternate Low-Thrust Capability</u>

This task will investigate the feasibility and design impact of providing a low-thrust option within a 10K lb thrust expander cycle engine. The low-thrust capability will be in a 1K to 2K lb thrust range. The design impact will be assessed in terms of changes in engine weight, cost, performance, service life and reliability of the basic 10K lb thrust engine. The task will use the updated engine design characteristics resulting from Task I analyses and will be conducted at a nominal engine mixture ratio of 6.5 and a maximum engine length with the extendible nozzle in the stowed position of 60 inches. The task logic network is shown on Figure 8.

The initial subtask in this analyses is to establish the thrust level and mixture ratio for the low-thrust operation so that the more detailed analyses can be conducted at a given off-design operating point. This will be accomplished by reviewing the pumped-idle mode results of Reference (1) and conducting preliminary cycle, heat transfer and turbomachinery analyses over the desired low thrust operating range. Heat transfer analyses will establish feasibility of cooling the chamber at high and low thrust with minimum compromise to the basic engine design, as measured in terms of coolant jacket pressure drop and coolant bulk temperature rise. System analyses will establish minimum injector pressure drops at the high and low thrust end points and assess the impacts to pump discharge pressure requirements for the basic engine. The turbomachinery analyses will establish the feasibility of operating the rotating machinery at the two thrust extremes and identify pump design areas requiring modifications. Based upon these preliminary analyses, a low-thrust level value and mixture ratio will be selected and carried into more detailed design analyses.

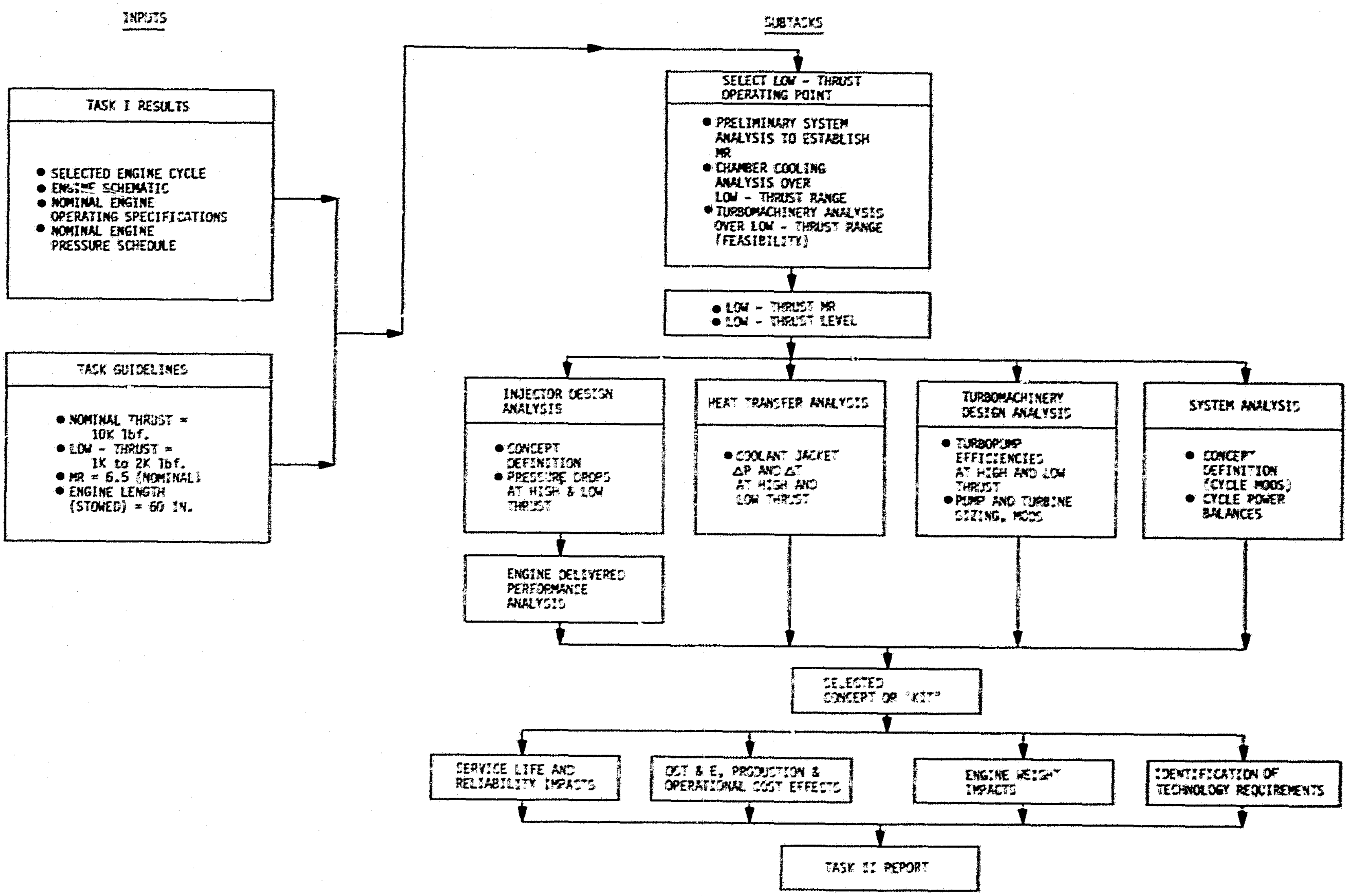


Figure 8. Task II: Alternate Low-Thrust Capability

The injector design analysis will investigate the design modifications required to a basic injector to provide the low-thrust capability. Dual manifolding, injector segmenting and other such schemes will be screened and a candidate concept selected. The concept selection will be based upon minimum system complexity, minimum compromise in the required injector pressure drop at high thrust, and minimum impact upon the basic engine delivered performance. An injector concept selection will be made in harmony with the other analyses being conducted in parallel. The delivered performance for the selected concept will be established at both the high and low-thrust operating points.

Heat transfer analyses will be conducted to establish the coolant jacket pressure drops and coolant bulk temperature rises of an engine which operates at two thrust extremes. These data are required for the engine pressure schedule, to establish turbine inlet temperatures, and to conduct power balance analyses which will establish the pump discharge pressure requirements of the modified engine. Based upon the heat transfer results, an assessment of the impact of the dual thrust requirement upon the engine service life will be made.

Turbomachinery analyses will be conducted at both the high and low thrust extremes to define component efficiencies and establish design modifications required to make the dual-thrust operation feasible. Turbine design and flow area requirements and "kitting" of the turbopump will be investigated. Cycle modifications which may simplify component designs such as, a small pump recirculation flow will be considered in the design analyses.

The controls defined during Task I will be evaluated to determine whether any critical flow control elements or control loops would require revision to accommodate the additional low thrust capability. Any significant effects or modifications will be identified.

The outputs of these analyses will be a recommended concept or "kit", if feasible and definition of the impact of the dual thrust requirement on the basic engine in terms of service life, reliability, cost and weight. The technology which should be pursued to bring the dual-thrust engine into being will also be identified.

The assumptions, analyses, and results will be documented in a task report which will be submitted approximately seven (7) months after contract extension initiation. This report will be prepared in sufficient detail to be incorporated as a section to the final report.

3. Task III: Safety, Reliability and Development Risk Comparison

This task will evaluate the impact of the engine cycle selection (advanced expander cycle vs staged combustion cycle) upon crew safety, mission reliability and engine development risk. The task logic diagram is shown on Figure 9.

ALRC has conducted in-house studies, similar to those requested by this task, to aid in the cycle selection presented at the Phase A OTV Engine Study Engine Requirements and Concept Selection Review held at NASA/MSFC on 24 October 1978.

Reliability analyses will be used to establish component redundancy and single engine reliability requirements for both expander and staged combustion cycle engines. These engine reliabilities are then used

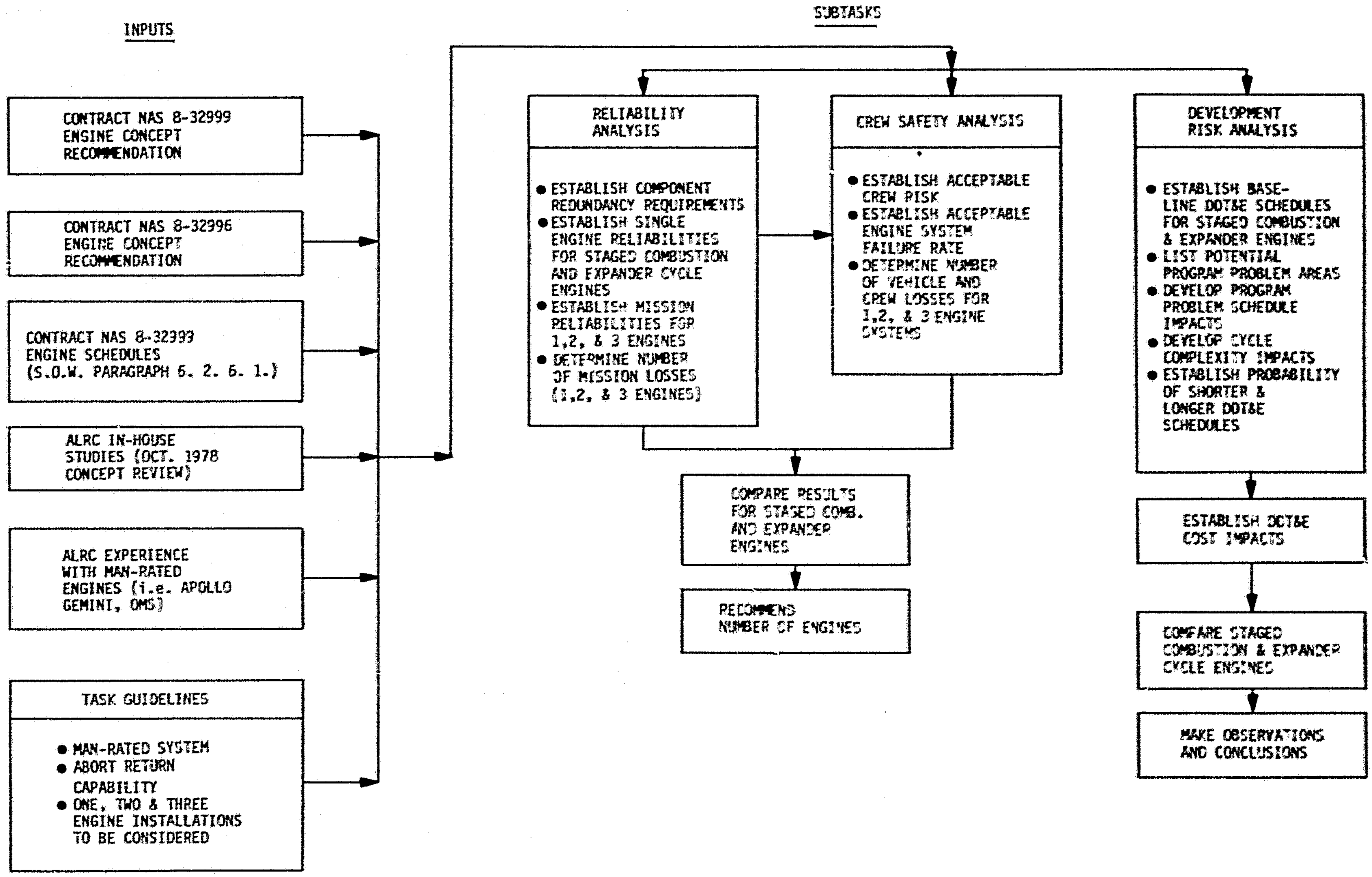


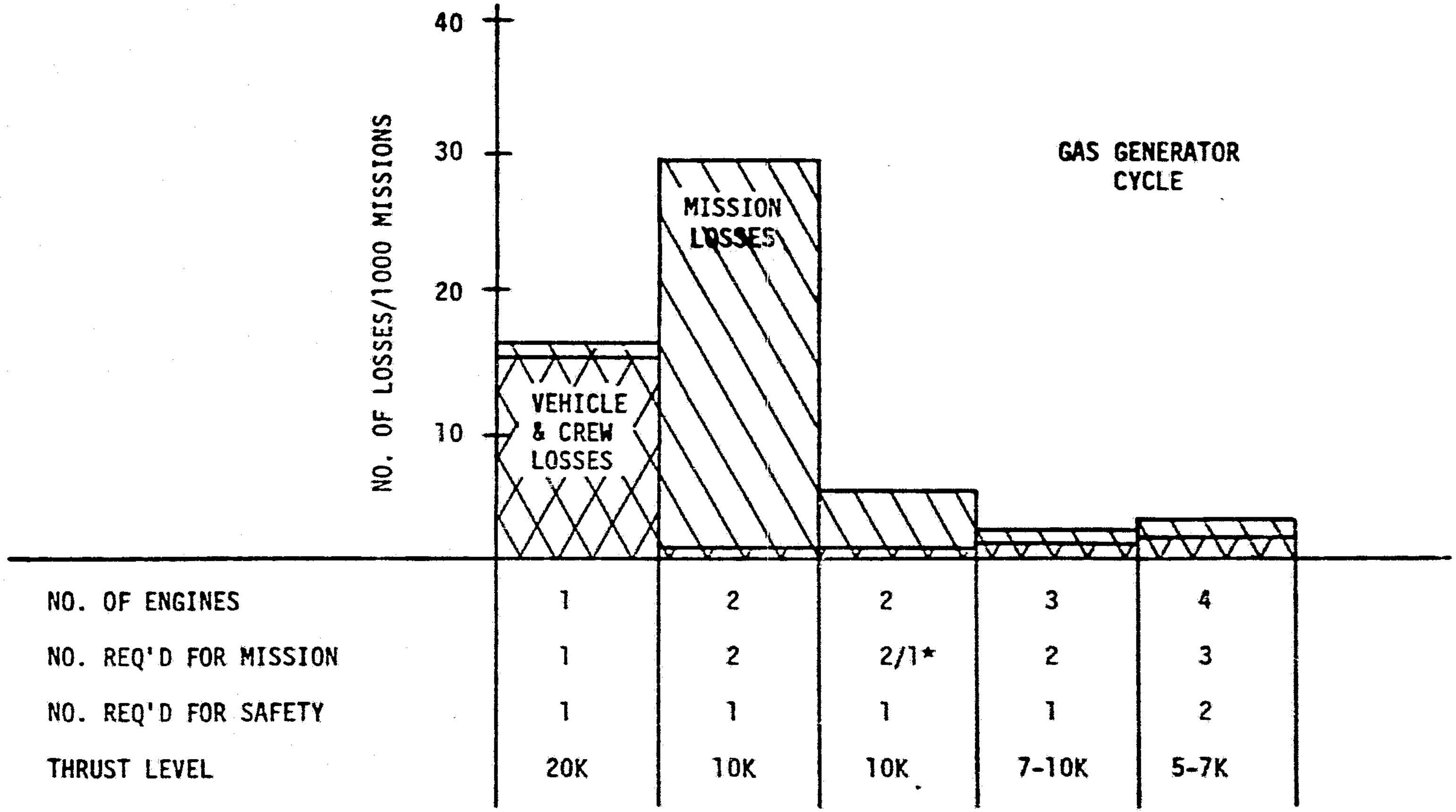
Figure 9. Task III: Safety, Reliability and Development Risk Comparison

to calculate the OTV mission reliability for one, two and three engine installations, along with the anticipated losses for a given number of missions (e.g. losses per 1000 missions).

Crew safety analysis uses historical data and experience to establish an acceptable crew risk level. This and the engine reliability data is then used to calculate the acceptable engine failure rate. The number of vehicle and crew losses anticipated are then calculated for 1, 2 and 3 engine installations. A typical display is shown on Figure 10. In this fashion, an engine number is chosen which minimizes the risk to the crew while still gaining acceptable mission reliability. The staged vs expander engine data will be compared, the number of engines recommended and conclusions made.

To conduct the development risk analysis, preliminary, nominal risk, DDT&E schedules will be established for the critical engine components of the expander and staged combustion cycle engines. Typical potential problem areas which historically arise during the development of these components will be listed and estimates of the schedule time required for their solution made. In addition, cycle complexity factors relating such parameters as component operating pressures will be derived. These complexity factors will be used to assist in establishing the increase in potential risk and adjustments to the schedule times required to solve problems.

Shorter and longer DDT&E schedules will also be considered and the impacts discussed in the preceding paragraph evaluated for each. It is anticipated that the longer schedule will reduce risk and hence, have less overall impact. Since schedule changes affect the eventual total DDT&E cost, cost impact estimates will be made for both the staged combustion vs expander cycle engines.



*2 ENGINES REQUIRED FOR FIRST BURN ONLY

Figure 10. OTV-Mission and Vehicle/Crew Risk

The data will be compared, observations and conclusions made and presented in the final briefing and report.

4. Task IV: Cost and Planning Comparison

Engine plans, schedules and costs will be prepared for a 20K lb thrust staged combustion engine cycle in this task. This will permit a consistent evaluation of both the advanced expander cycle and staged combustion cycle engines by a single contractor. The advanced expander cycle engine programmatics and costs were evaluated by ALRC during the initial efforts on Contract NAS 8-32999. The analysis to be conducted in this task duplicates that performed under Contract NAS 8-32999, Statement of Work paragraphs 6.2.5, 6.2.6 and 6.2.7. The task logic diagram is shown on Figure 11.

Some preliminary analyses were conducted with ALRC in-house funds to support the October 1978, Engine Concept Review for Contract NAS 8-32999. The previous contract and in-house efforts will, of course, form the foundation for the conduct of this task.

The initial subtask is the establishment of a Work Breakdown Structure (WBS) for the staged combustion cycle engine. This WBS is already available since it was established in concert with NASA/MSFC very early in the primary program. This WBS was then modified to accommodate the advanced expander cycle engine in the costing efforts. The primary modification was the dropping of WBS item 1.1.3, Preburner/Gas Generator. Otherwise the WBS is the same. The WBS and dictionary that will be used in this study are as defined by the attachments to NASA/MSFC letter EP24(78-54) dated 15 August 1978.

Preliminary nominal DDT&E schedules will be established for development risk evaluations in Task III. These will be prepared in more

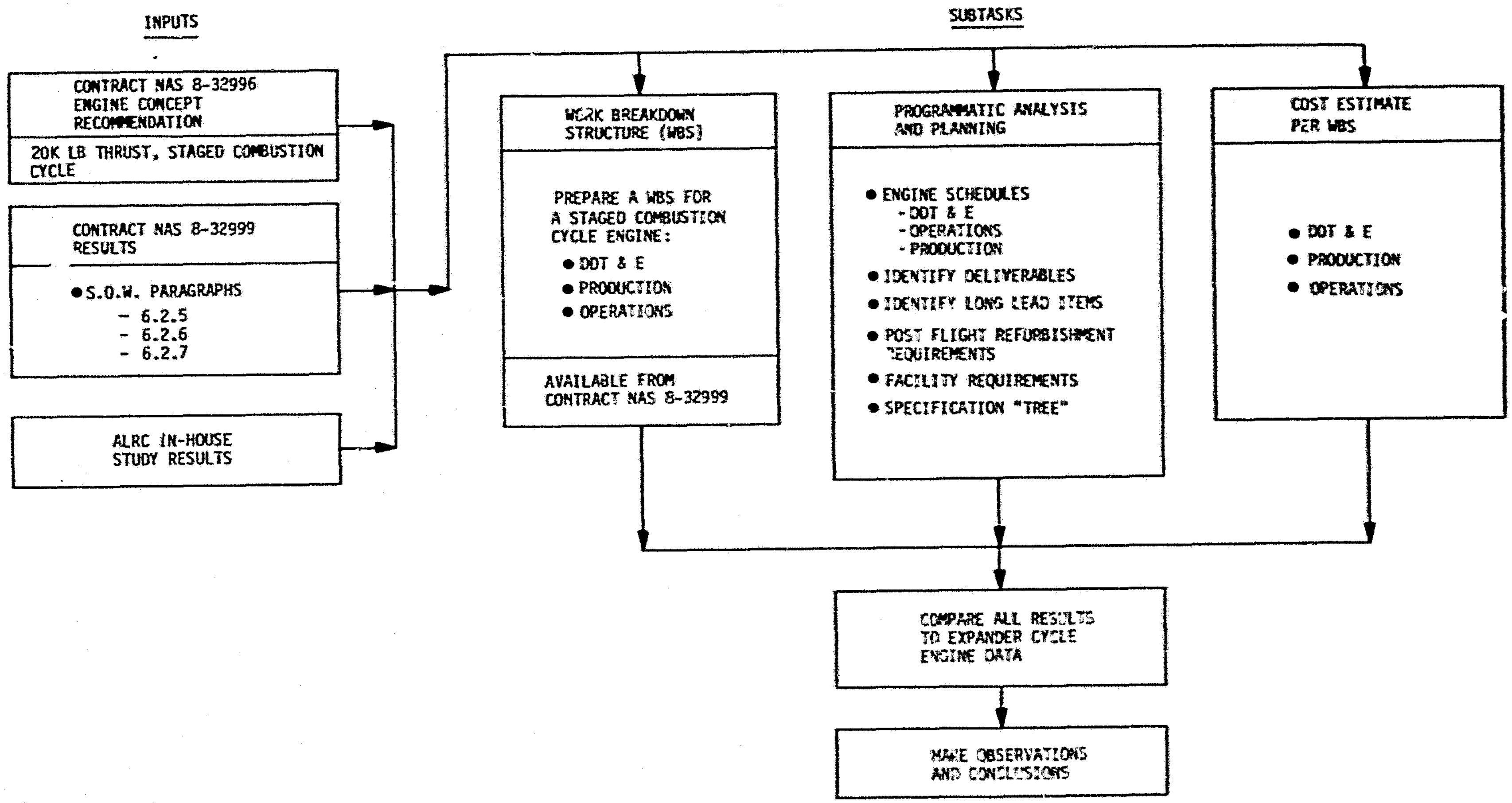


Figure 11. Task IV: Cost and Planning Comparison

detail for the DDT&E phase to coincide with the lowest WBS level and also extended to cover the production and operations phases. The programmatic analysis will include the identification of deliverable and long lead items and a summary listing of these will be prepared.

A brief analysis will be conducted to identify the differences in post-flight maintenance and refurbishment operations for the staged combustion cycle engine vs the expander cycle engine. This will be accomplished by the review and modification of the previously prepared expander cycle engine maintenance and refurbishment task descriptions.

Facility requirements peculiar to the staged cycle will be identified and ROM cost estimates made for new facilities.

Configuration end items such as, the basic rocket engine assembly, nozzle assembly and engine controller will be identified and the preliminary specification "tree", setup for the advanced expander cycle engine, will be modified for the staged combustion cycle.

The final subtask is the engine cost estimate which will be made for the DDT&E, Production and Operations phases. This cost estimate will be made to the lowest identified WBS level for each program phase. The DDT&E and Production costs will be spread by year over the anticipated schedules and the Operations cost estimate will be made for one year.

All data resulting from this task will be compared to the advanced expander cycle engine information. Observations and conclusions will be made on the basis of these comparisons and presented in the final briefing and report.

5. <u>Task V: Vehicle Systems Studies Support</u>

This task will supply support to the OTV System Studies contractor(s) in accord with the task logic diagram shown on Figure 12. This task will be a continual level of effort throughout the study program.

Lines of communication will be established between ALRC and the vehicle contractor(s). The ALRC interfaces will be Mr. Larry Bassham, the program manager and Mr. Joe Mellish, the study manager. Phone numbers for these two individuals are shown on the task logic figure. Mr. Bassham will be the primary contract and Mr. Mellish will act in his absence.

Engine parametric and schedule data available from Contract NAS 8-32999 under Statement of Work paragraphs 6.2.3 and 6.2.6.1 are presented in the final report on the intiial study efforts. The types of data available are shown as inputs on the task logic network.

The requirement for a Parametric Data Book was deleted by NASA/MSFC and the vehicle contractors will use the information contained in the interim final report for this contract. Therefore, initial emphasis will be placed upon assisting the vehicle contractors in the application of the data contained in this final report.

Coordination with the systems contractor will be a continual study effort to update information, answer questions, clarify data and discuss and clarify engine design characteristics. NASA/MSFC will be kept informed of verbal and written communications through the bi-monthly status reports. NASA/MSFC will be sent copies of all written communications.

This engine/vehicle contractor communication system proved to be very effective during ALRC's participation in the Space Tug studies (Contract NAS 8-29806).

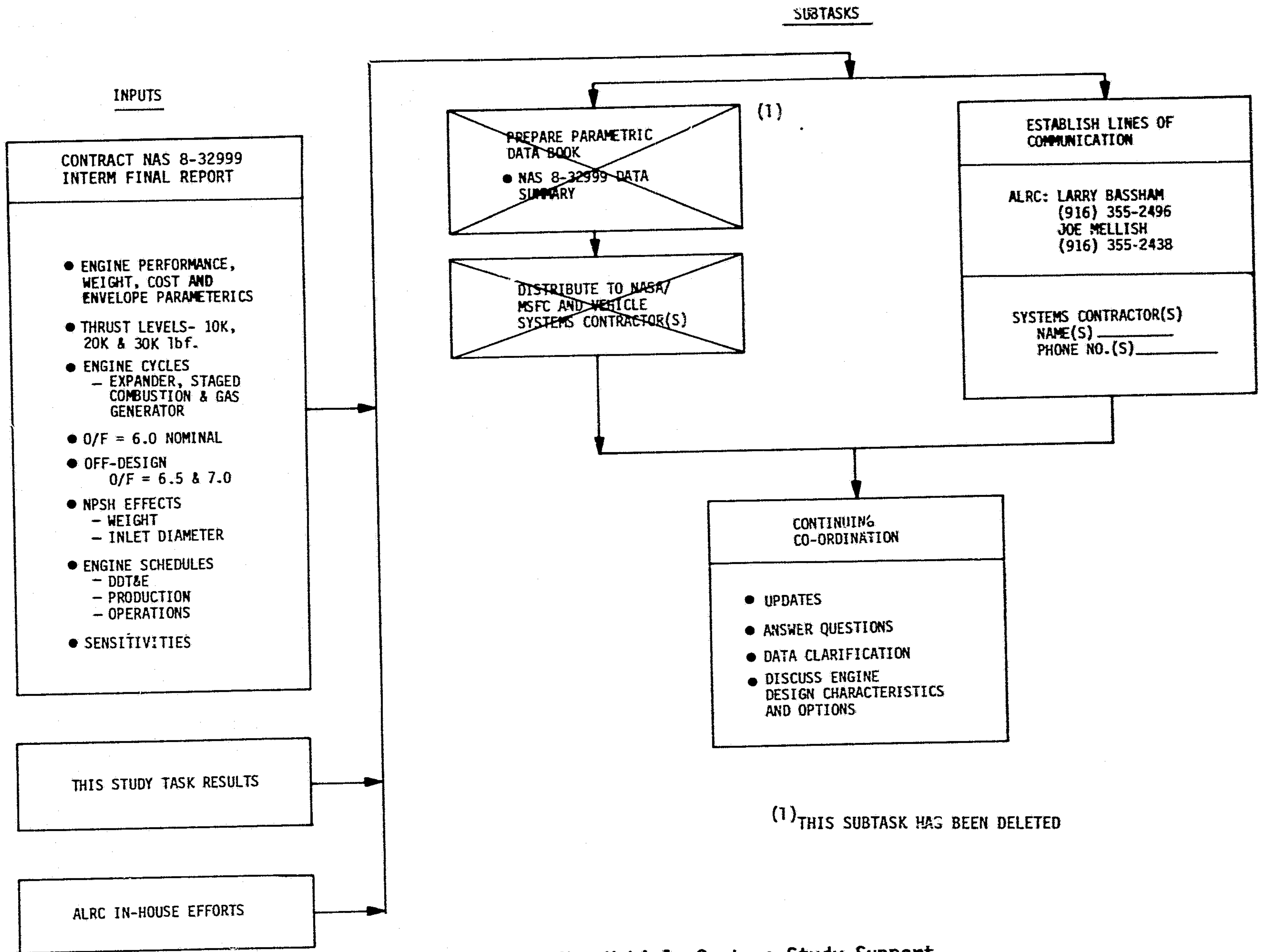


Figure 12. Task V: Vehicle Systems Study Support

6. Task VI: Reporting

The reporting requirements as required by the Statement of Work are:

- Study Plan
- Bi-Monthly Status Reports
- Final Report
- Task Reports
  - Task I Report
  - Task II Report
- Parametric Data Book (Deleted)
- Performance Reviews
  - Orientation Briefing
  - Final Briefing

The reporting requirements flow chart is presented on Figure 13.

a. Study Plan

The study plan was submitted with the proposal and is updated and resubmitted herein for the approval of the NASA COR two weeks after authority-to-proceed per the requirements of Data Procurement Document (DPD) 559, DR-MA-01. This second submittal reflects the changes resulting from contract negotiations and agreements reached at the orientation briefing.

b. Bi-Monthly Status Reports

Bi-Monthly status reports will be submitted during each two months of the contract performance. They will contain discussions of technical progress, status against planned work schedule, problem areas, work planned for the next reporting period and man-hour expenditures.

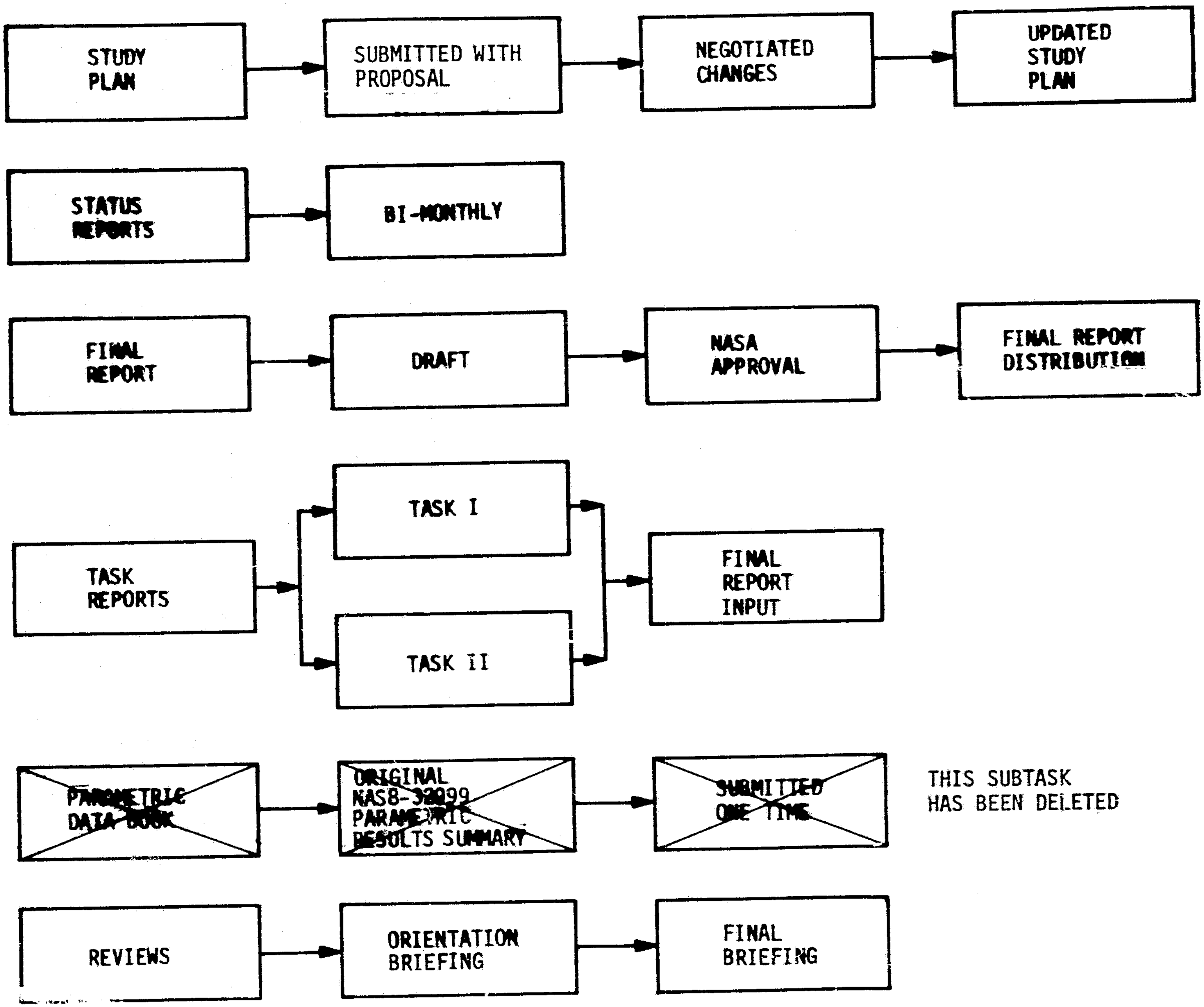


Figure 13. Task VI: Reporting

The initial submission will be on the 15th of Sept. 1979. Subsequent submittals will follow every two months after per DPD559, DR-MA-02. No report is required in the last month of the contract and four bi-monthlies are planned.

c. Final Report

The final report draft will be submitted per the requirements of DPD559, DR-MA-05 approximately nine months after contract initiation. This report will contain all study extension results, supporting data, assumptions, rationale, conclusions, and recommendations. It will be an integrated compilation of the data generated for each study extension task.

It is planned to submit the final report in two volumes:

- Volume I - Executive Summary
- Volume II - Study Results

The final report will be printed and distributed after corrections to the draft are made and approval is received from the NASA/COR.

d. Task Reports

Two task reports will be written documenting the results and analyses conducted in support of Task I and II of the study extension. These reports will be prepared in sufficient detail to be utilized as the basis for reporting on the tasks in the final report.

The Task I report will be submitted four months after the initiation of the contract extension. This report shall contain a discussion on each subtask and present the rationale for selections and the operating parameters for the baseline advanced expander cycle engine. As a minimum, the parameters displayed will be chamber pressure, nozzle area ratio, vacuum specific impulse, flow rates, operating pressures, pump horsepowers and efficiencies, turbine efficiencies, coolant jacket pressure drop and coolant temperature rise, and all other parameters required to determine the engine cycle power balance such as, the hydrogen gas ratio of specific heats and specific heat at constant pressure.

The Task II report will be submitted seven months after the initiation of the contract extension. This report will contain a discussion of the results obtained from each subtask and clearly indicate what design and cost impact the low thrust option requirement has upon the baseline engine. The technology effort required to bring the dual level thrust engine into being will also be identified.

e. Performance Reviews

(1) Orientation Briefing

A briefing covering the study plan was given at NASA/MSFC on 16 July 1979. This briefing covered the approach to conducting the study tasks, the study schedule and major milestones, the manhours allotted to each study task and the study management organization.

(2) Final Briefing

A briefing covering all the study analyses and results will be given at NASA/MSFC per the requirements of DPD559, DR-MA-03. This review will be held approximately nine months after beginning work on a date to be mutually agreed upon.

F. MANPOWER PLAN

The Orbit Transfer Vehicle Engine Study, Phase "A", Extension I, has been planned and structured by the major tasks defined by the Statement of Work. This provides both control of scope and accurate manpower estimates by task.

Figure 14 tabulates the manhours that will be applied to each major task in monthly increments and a total. Thus, the ALRC Program and Study Managers and the NASA COR are provided with a total overview of the program and a control of resources for each task.

The manhours previously allocated for the preparation of the Parametric Data Book have been redistributed in Task I per the instructions of the NASA COR.

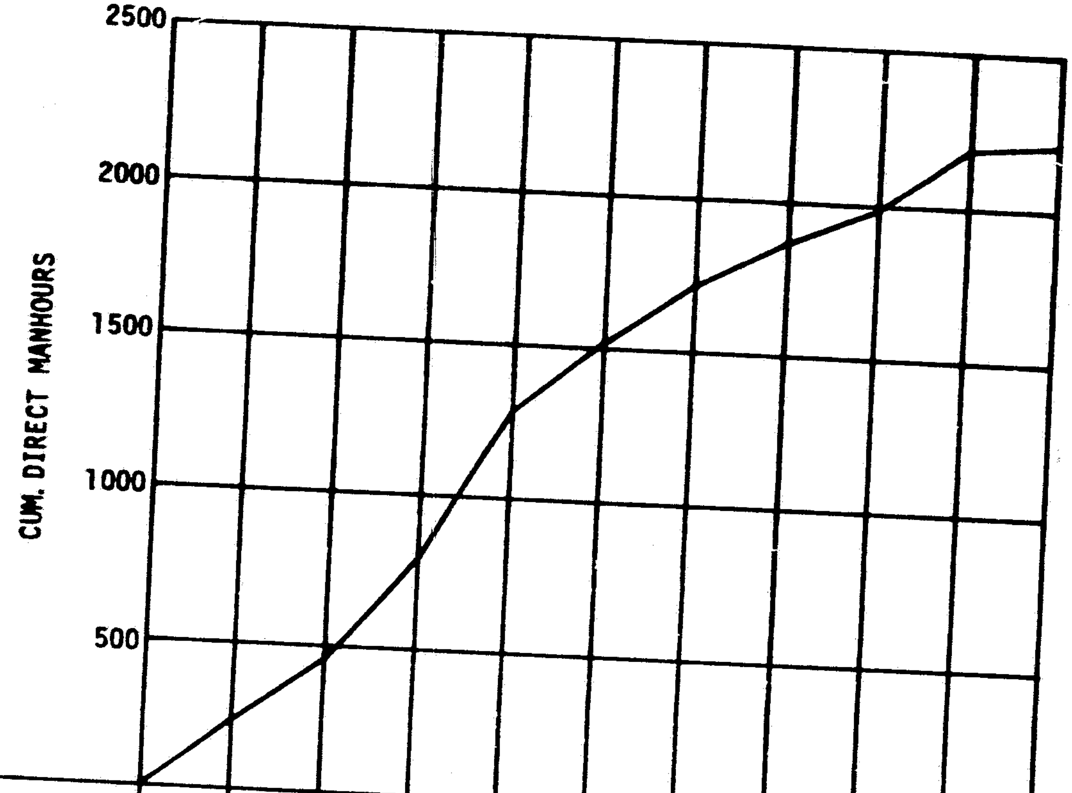
Figure 15 is a summary of the total program manhours which are planned to be expended by monthly increment and a cumulative total. The actual rate of expenditure versus this plan provides a measure of performance and study completeness at any point in the schedule.

TASK	MANHOURS	1	2	3	4	5	6	7	8	9	10(1)	TOTAL
CY		1979						1980				
MONTH		J AUG SEP OCT NOV DEC JAN FEB MAR APR M										
		PROGRAM MONTH										
I: ADVANCED EXPANDER CYCLE ENGINE OPTIMIZATION	SH	103	140	216	62							521
	HH	8	8	14	5							35
	TOTAL	111	148	230	67							556
II: ALTERNATE LOW-THRUST CAPABILITY	SH				239	117	125	39				520
	HH				12	6	4	4				26
	TOTAL				251	129	129	43				546
III: SAFETY, RELIABILITY AND DEVELOPMENT RISK COMPARISON	SH			60	62	60						182
	HH			1	1	1						3
	TOTAL			61	63	61						185
IV: COST AND PLANNING COMPARISON	SH						21	21	21			63
	HH						1	1	1			3
	TOTAL						22	22	22			66
V: VEHICLE SYSTEM STUDIES SUPPORT	SH	10	10	10	10	10	10	10	10			80
	HH	1	1	1	0	1	1	1	1			7
	TOTAL	11	11	11	10	11	11	11	11			87
VI: REPORTING	SH	101	33	40	83	42	33	72	75	195	4	678
	HH	12	8	6	10	6	7	7	10	19	3	88
	TOTAL	113	58	46	93	48	40	79	85	214	7	766
TOTAL PROGRAM	SH	214	183	326	456	229	189	142	106	195	4	2044
	HH	21	17	22	28	14	13	13	12	19	3	162
	TOTAL	235	200	348	484	243	202	155	118	214	7	2206

SH = SALARY HOURS
HH = HOURLY HOURS

(1) HOURS SHOWN IN THE TENTH PROGRAM MONTH ARE FOR FINAL REPORT DISTRIBUTION

Figure 14. Task Manhours by Month



PROGRAM MONTH		1	2	3	4	5	6	7	8	9	10
DIRECT HOURS	INC	235	200	348	484	243	202	155	118	214	7
	CUM	235	435	783	1267	1510	1712	1867	1985	2199	2206
CUM %		11	20	35	57	68	78	85	90	99.7	100
MONTH		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	ARP	MAY
CY		1979						1980				

Figure 15. Summary of Program Manhours

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