LOW-THRUST CHEMICAL ROCKET ENGINE STUDY

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Low-Thrust Engine Study Program, Contract NAS 3-21940

A number of studies have forecast the need for large space structures such as microwave antennas and reflectors in geosynchronous equatorial orbit (GEO). These structures would be launched to low earth orbit (LEO) in a stowed condition using the Space Shuttle and subsequently transferred to GEO using a high energy space propulsion system. There are two options available for placement of these types of payloads in GEO. In the first option, the LEO-to-GEO transfer would be accomplished with the payload in the stowed condition, followed by manned or automated deployment and assembly in GEO. Either high or low thrust could be used for the transfer. In the second option, manned or automated deployment and assembly would be carried out in LEO, followed by a LEO-to-GEO transfer with the payload in the assembled condition. Here, low thrust would be required in order to preclude high inertia loading which would cause damage to the assembled payload. Chemical engine systems suitable for the low-thrust option have not received in-depth attention and it is the purpose of this work to provide the data necessary for orbit-transfer-vehicle studies utilizing low-thrust chemical propulsion.

The major objectives of this Low-Thrust Chemical Rocket Engine Study are to provide parametric data and preliminary designs on liquid rocket engines for low thrust cargo orbit-transfer-vehicles and to identify those items where technology is required to enhance the designs. These data and the systems analyses will ultimately lead to the identification of low-thrust OTV engine requirements so that the engine design and development phase can be initiated.

Low-Thrust Engine Study Program
Contract NAS 3-21940

- APPLICATION

  CARGO ORBIT-TRANSFER VEHICLE (COTV)

- PRIMARY OBJECTIVES

  1. PROVIDE PARAMETRIC DATA AND PRELIMINARY DESIGNS ON LIQUID ROCKET ENGINES

  2. IDENTIFY TECHNOLOGY REQUIREMENTS

Specific Objectives

Specific study objectives are:

- Provide fundamental propellant property, combustion property and performance data for O_2/H_2, O_2/RP-1 and O_2/CH_4 engine concepts.
- Establish the combined thrust level and chamber pressure range over which film and regeneratively cooled low-thrust chamber designs are feasible.
- Devise six engine system concepts. (Initial efforts considered only conventional cooling schemes and will be updated on about 15 July 1980 to include advanced cooling concepts).
- Generate parametric performance, weight and envelope data for viable concepts based upon historical data and conceptual evaluations. The first data dump (9 May 1980) was based upon conventional cooling techniques and will be updated to include the advanced cooling schemes.
- Select concepts and design points for preliminary design.
- Prepare preliminary designs of two concepts. One uses oxygen hydrogen propellants and the other oxygen/hydrocarbon.
- Update the parametric data based upon the preliminary design results and provide this data in a format suitable for use by OTV vehicle system contractors.

Specific Objectives

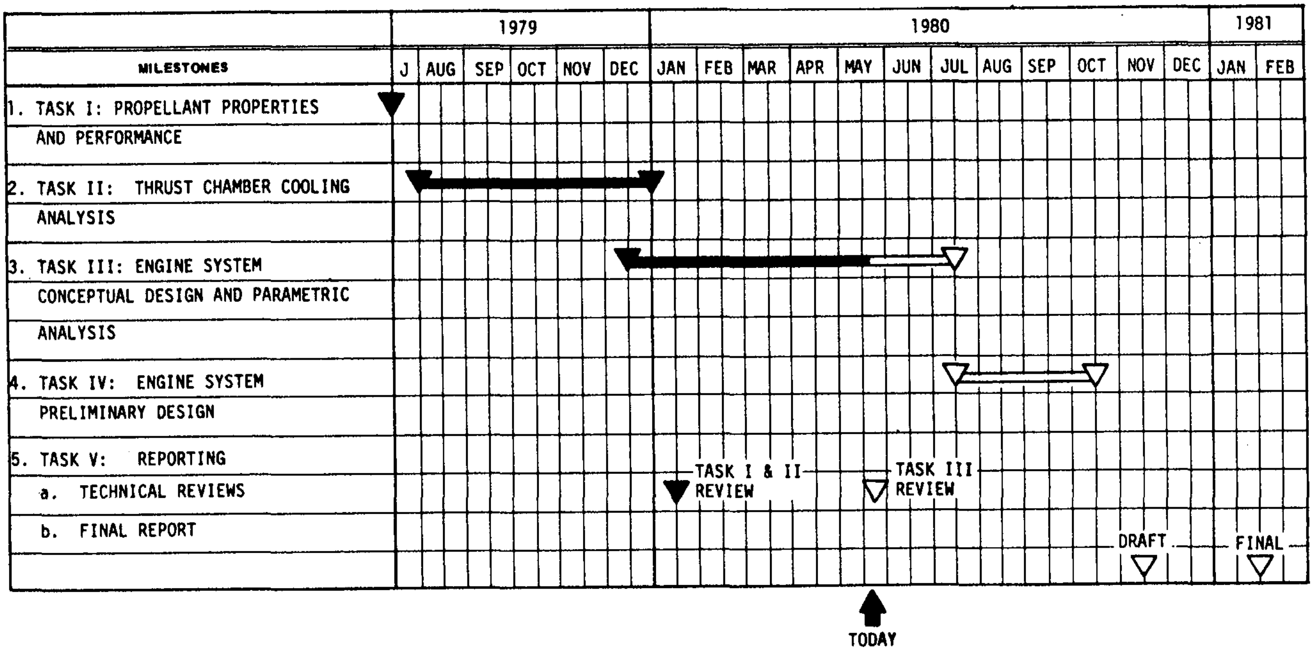
	DELIVERY DATES
1. PROVIDE PROPELLANT PROPERTY AND PERFORMANCE DATA (TASK I)	10 SEPT 1979
2. ESTABLISH FEASIBLE THRUST AND CHAMBER PRESSURE RANGES FOR FILM AND REGEN COOLING (TASK II)	17 JAN 1980
3. EVALUATE SYSTEM CONCEPTS AND DEVISE ENGINE CONCEPTS (TASK III)	23 MAY 1980
4. PROVIDE PARAMETRIC DATA (TASK III)	9 MAY & 15 JULY 1980
5. PREPARE PRELIMINARY DESIGNS OF TWO CONCEPTS (TASK IV)	15 OCT 1980
6. UPDATE PARAMETRIC DATA (TASK IV)	15 OCT 1980

Low-Thrust Chemical Rocket Engine Study Schedule

The current study schedule is shown on the figure. This schedule reflects the changes to accommodate the additional Task III work involved in evaluating advanced cooling schemes.

In Task I, properties and/or theoretical performance of the subject propellants and propellant combinations over the low-thrust range of interest were determined. Task II involved analyses to establish the combined thrust level and chamber pressure range over which film and regeneratively cooled low-thrust chamber designs are feasible. In Task III, engine system concepts are devised and evaluated over the thrust chamber cooling feasibility range to establish a feasible design range for the engine system concepts. Parametric data (performance, weight, etc.) are generated for the viable concepts to assist in the selection of concepts and design points for preliminary design. In Task IV, preliminary design will be accomplished on two concepts (one hydrogen-oxygen and one hydrocarbon-oxygen) and the parametric data for the selected concepts will be updated to reflect the results of the preliminary design effort.

Low-Thrust Chemical Rocket Engine Study Schedule



Low-Thrust Engine Study Cases

The original study guidelines specified that the engines would be either regeneratively cooled or film cooled and combined regen/film cases were not included in the analyses. In addition, only the fuels were considered as coolants. The contract is currently being modified to include other cooling schemes.

Low-Thrust Engine Study Cases

Propellant Combination	O/F	Cooling Method	Coolant	Thrust Study Range (LBF)	Chamber Pressure Study Range (PSIA)
H_2/O_2	6.0	Regen	H_2	100-3000	20-1000
H_2/O_2	6.0	Film	H_2	100-3000	20-1000
RP-1/O_2	3.0	Regen	RP-1	100-3000	20-1000
RP-1/O_2	3.0	Film	RP-1	100-3000	20-1000
CH_4/O_2	3.7	Regen	CH_4	100-3000	20-1000
CH_4/O_2	3.7	Film	CH_4	100-3000	20-1000

Task I Propellants and Parametric Ranges

The thrust ranges were shown on the previous chart and other ranges are shown here. One dimensional equilibrium (ODE) specific impulse data was generated over a range of area ratios from 1 to 1000 although a nominal value of 400:1 is used in the conduct of Tasks II and III. Mixture ratio (O/F) ranges are also shown and the nominal values for each propellant combination were shown on the previous chart.

Task I Propellants And Parametric Ranges

- PROPELLANTS - O_2, H_2, RP-1, CH_4
- PROPELLANT COMBINATIONS
  O_2/H_2, O_2/RP-1, O_2/CH_4
- PARAMETRIC RANGES

CHAMBER PRESSURE:	20 TO 1000 PSIA
AREA RATIO:	1 TO 1000
MIXTURE RATIO	
O_2/H_2:	4 TO 7
O_2/RP-1:	2.6 TO 3.2
O_2/CH_4:	3.4 TO 4.0

Task II Thrust Chamber Cooling Analysis Objectives

The key objective of the Task II cooling analysis was to identify feasible operating ranges using conventional cooling techniques and design criteria. As mentioned previously, the study is being extended to include advanced cooling methods.

Task II Thrust Chamber Cooling Analysis Objectives

- DETERMINE THE COMBINED THRUST LEVEL AND CHAMBER PRESSURE RANGE OVER WHICH LOW-THRUST CHAMBER DESIGNS ARE FEASIBLE USING CONVENTIONAL COOLING METHODS AND DESIGN CRITERIA.

- PROVIDE HEAT TRANSFER AND HYDRAULIC PARAMETRIC DATA FOR USE IN ENGINE SYSTEM ANALYSIS EFFORT IN TASKS III AND IV.

Task II Cooling Analysis Guidelines

Some of the cooling analysis guidelines specified by the SOW are shown. The chambers analyzed are a slotted design configuration and the study also imposed practical limits on these designs such as,

Minimum slot width = .03 in.
Maximum slot depth/width = 4 to 1
Minimum web thickness = .03 in.
Minimum wall thickness = .025 in.
Minimum channel depth = .035 in.

Task II Cooling Analysis Guidelines

- 90% BELL NOZZLES (ϵ = 400:1)
- COOLANT INLET TEMPERATURE

  H_2 = 37.8 °R
  RP-1 = 537 °R
  CH_4 = 201 °R
- POSSIBLE BENEFIT OF CARBON DEPOSITION ON HOT GAS SIDE WALL SHALL BE NEGLECTED.
- COOKING LIMIT

  RP-1 = 1010°R
  CH_4 = 1760°R
- SERVICE LIFE

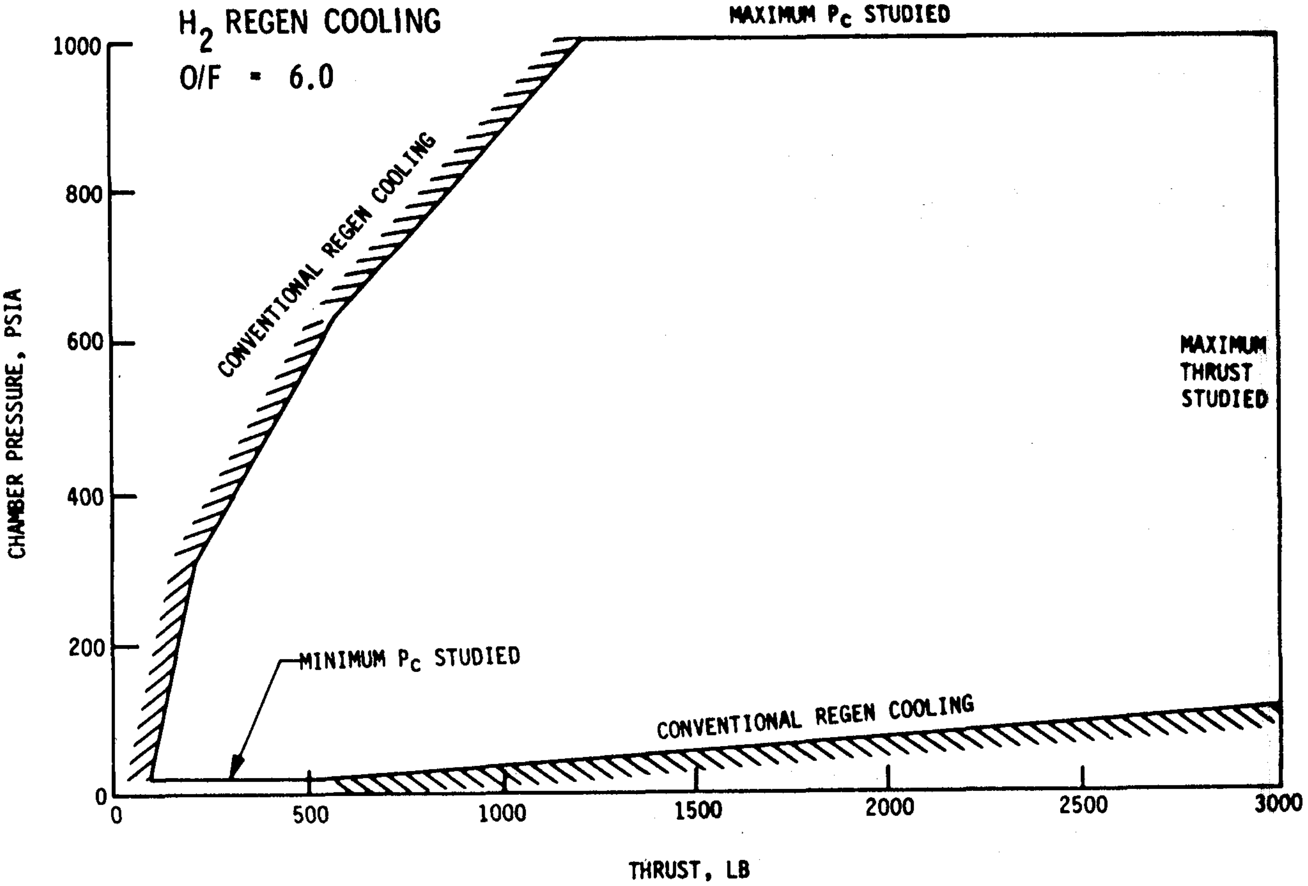
  FIVE THERMAL CYCLES TIMES A SAFETY FACTOR OF FOUR.

$$\text{ENGINE RUN TIME} = \frac{\text{5000 LB-HRS}}{\text{THRUST, LBS}}$$

O_2/H_2 Regen Cooled Engine Operating Region

Hydrogen provided the largest operating map on a thrust-chamber pressure plot. Channel Mach number limits and channel depth considerations constrain operation at low thrust-high Pc and high thrust-low Pc combinations. The feasible cooling map with hydrogen covers both the supercritical and subcritical pressure regimes. The critical pressure of hydrogen is 188 psia and coolant jacket exit pressure was held above this value to obtain a practical design solution. This will penalize pressure-fed systems with regen cooled engines because of the high hydrogen tank pressure. Thrusts greater than 3000 lb and chamber pressures greater than 1000 psia were not considered in this study although they would be feasible.

O_2/H_2 Regen Cooled Engine Operating Region



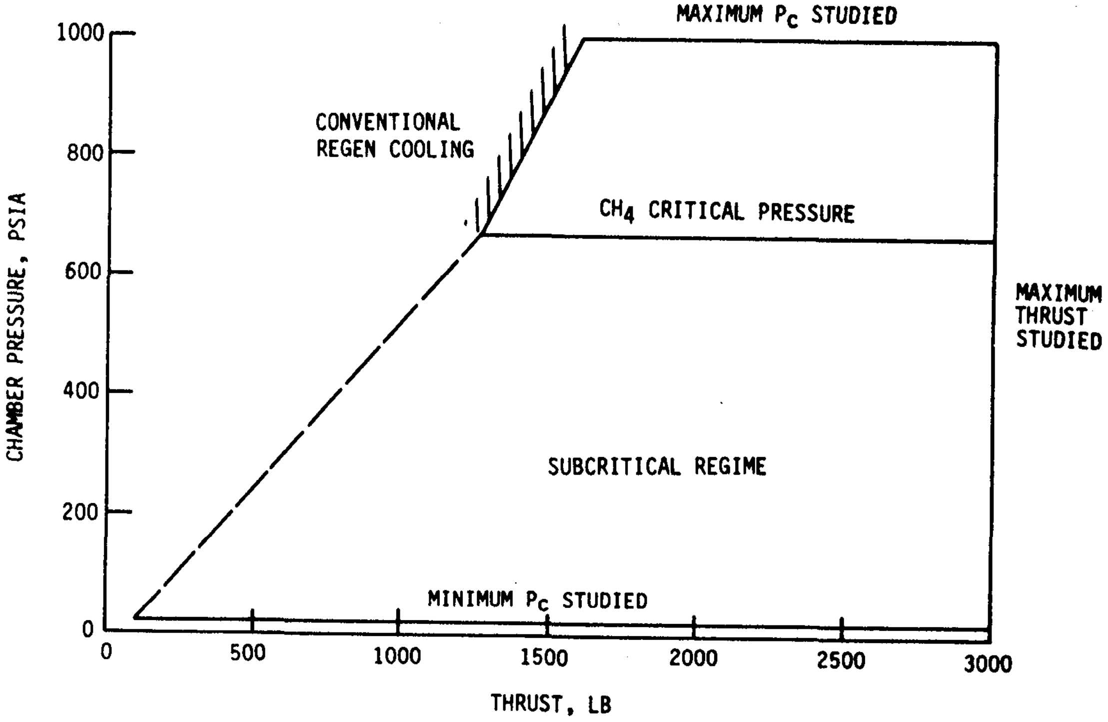
O_2/CH_4 Regen Cooled Engine Operating Region

Methane provided a smaller feasible cooling map with the channel Mach number limiting operation to a higher thrust and pressure region. Feasible designs could not be obtained with the CH_4 below its critical pressure (i.e. 667 psia). However, engine system analysis in the subcritical pressure regime was continued by keeping the coolant jacket outlet pressure above critical. This places the burden upon the CH_4 pumping system.

O_2/CH_4 Regen Cooled Engine Operating Region

CH_4 REGEN COOLING

O/F = 3.7



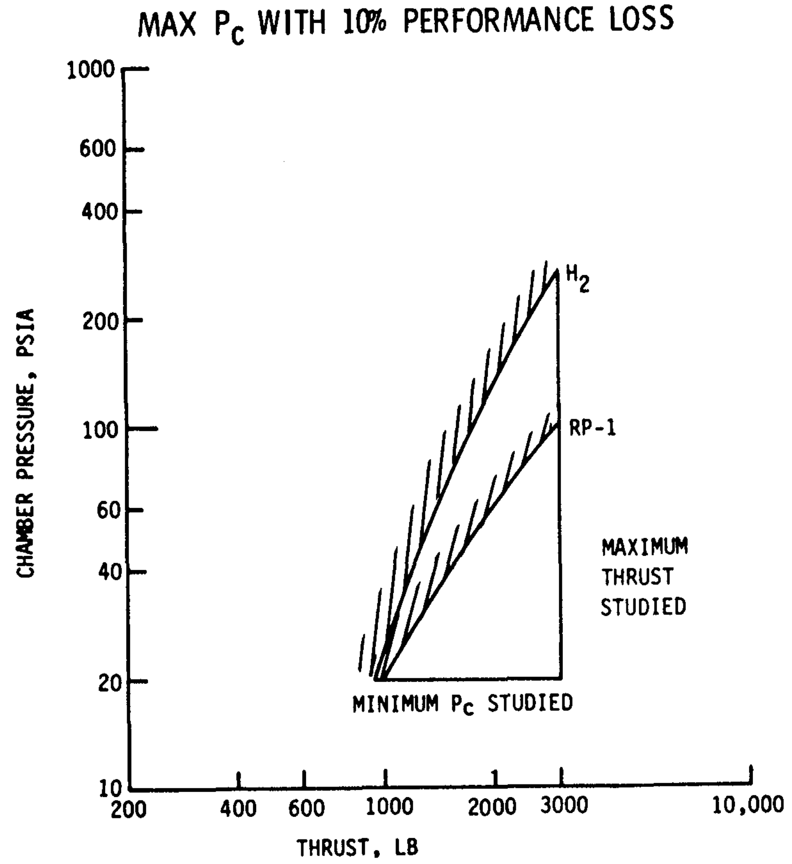
Film Cooling Analyses Results

The results of the film cooling studies to establish the upper chamber pressure limit, based upon a 10% performance degradation, are shown. This performance degradation is based upon a comparison to the performance of an engine requiring no film cooling.

Hydrogen and RP-1 cannot be used as film coolants at thrusts below about 1000 lbf and their chamber pressure ranges are very limited. Hydrogen is penalized by the low wall temperature (1800°F) obtainable with compatible materials, and RP-1 is penalized by the long chamber lengths required to achieve a minimum study specified energy release efficiency of 98%. RP-1 film cooled engines were dropped from further study because of this small operating range. Lower limit chamber pressures corresponding to a 3 percent performance degradation were found to be approximately at or below the specified minimum chamber pressure of 20 psia.

The feasibility of methane film cooling is highly dependent upon the kinetics of the methane decomposition. However, this analysis was beyond the scope of the current effort. The sensitivity of the results to the chemistry model assumption was assessed at a thrust of 1000 lbf and a chamber pressure of 300 psia. Assuming no CH_4 decomposition and thus, no coolant reaction with the entrained core gases, the coolant requirement exceeds 50% of the fuel and the performance loss exceeds 20%. With the complete decomposition assumption, the required coolant flow is about 33% of the fuel flow and performance loss is 10%. Because of this uncertainty, NASA/LeRC has elected to temporarily drop CH_4 film cooled engines from the analysis. Data is required to verify the models.

Film Cooling Analyses Results



Cooling Analyses Conclusions

The study showed that regen cooling with RP-1 was not feasible over the entire thrust and chamber pressure ranges. The thermal data showed that the RP-1 bulk temperature exceeded the study coking temperature limit of 1010°R. This result might change if chamber coatings, possible benefits from carbon deposition on the hot gas side wall or a purified RP-1 were considered. These were not within the current study scope but will be considered in the extension efforts.

Based upon the results presented, O_2/H_2 and O_2/CH_4 regen engine systems and O_2/H_2 film cooled engines were selected for further study in the system analysis. Advanced cooling schemes and investigations will also be considered for all propellants in further study efforts.

Cooling Analyses Conclusions

- VIABLE CONCEPTS WITH CONVENTIONAL COOLING METHODS:
  - O_2/H_2, H_2 REGEN COOLED
  - O_2/H_2, H_2 FILM COOLED
  - O_2/CH_4, CH_4 REGEN COOLED
- RP-1 REGEN COOLANT TEMPERATURE EXCEEDED 1010°R COKING LIMIT OVER ENTIRE THRUST AND PRESSURE RANGES.
- EXTEND STUDY DESIGN CRITERIA TO CONSIDER ADVANCED COOLING SCHEMES.

Task III Engine System Conceptual Design and Parametric Analysis

Task III involves the screening and evaluation of candidate concepts, the selection of concepts for further analyses, generation of parametric data for the concepts and the selection of two concepts for preliminary design analyses in Task IV. The concepts undergoing evaluation are presented on the following six charts. The thrust and chamber pressure operating ranges are as defined by the cooling analysis results, unless this range is further restricted by cycle or concept limits which are determined in conducting this task. Parametric data is generated over the feasible thrust and chamber pressure ranges at the nominal propellant combination mixture ratios and an area ratio of 400:1. The concept weights are estimated by scaling historical component weight data in this size range.

Task III Engine System Conceptual Design And Parametric Analyses Objectives

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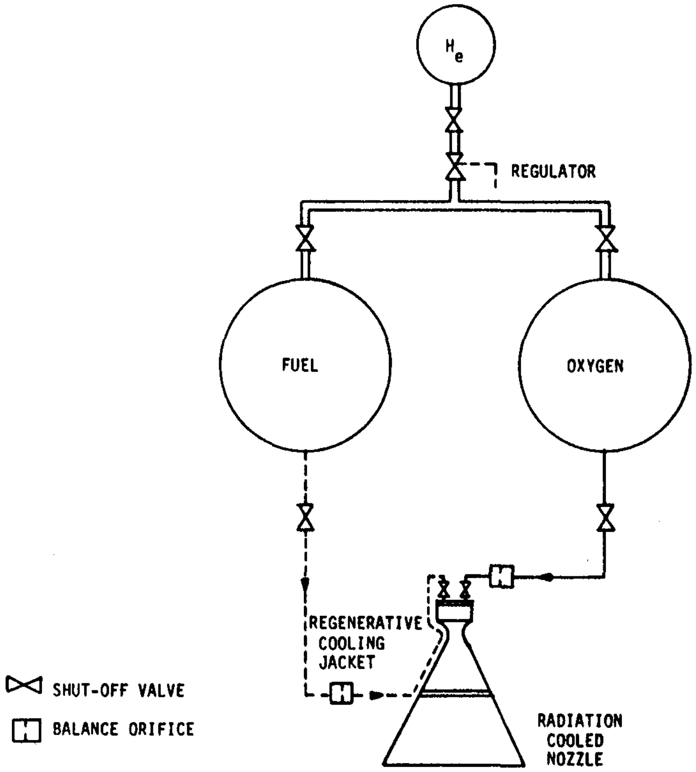
- ASSESS THE FEASIBILITY OF VARIOUS DESIGN APPROACHES.
- ESTABLISH OPERATING RANGES.
- DETERMINE ADVANTAGES AND DISADVANTAGES OF CONCEPTS.
- ASSESS TECHNOLOGY REQUIREMENTS.
- PREPARE PARAMETRIC DATA ($\epsilon = 400$) (WEIGHT, PERFORMANCE & ENVELOPE).

Pressure-Fed Concept

The simple pressure-fed system concept is shown on the figure. In this concept the engine run tanks are pressurized to the required pressure levels by a regulated helium source. It should be noted that the concept is applicable to both regen and film cooled engines.

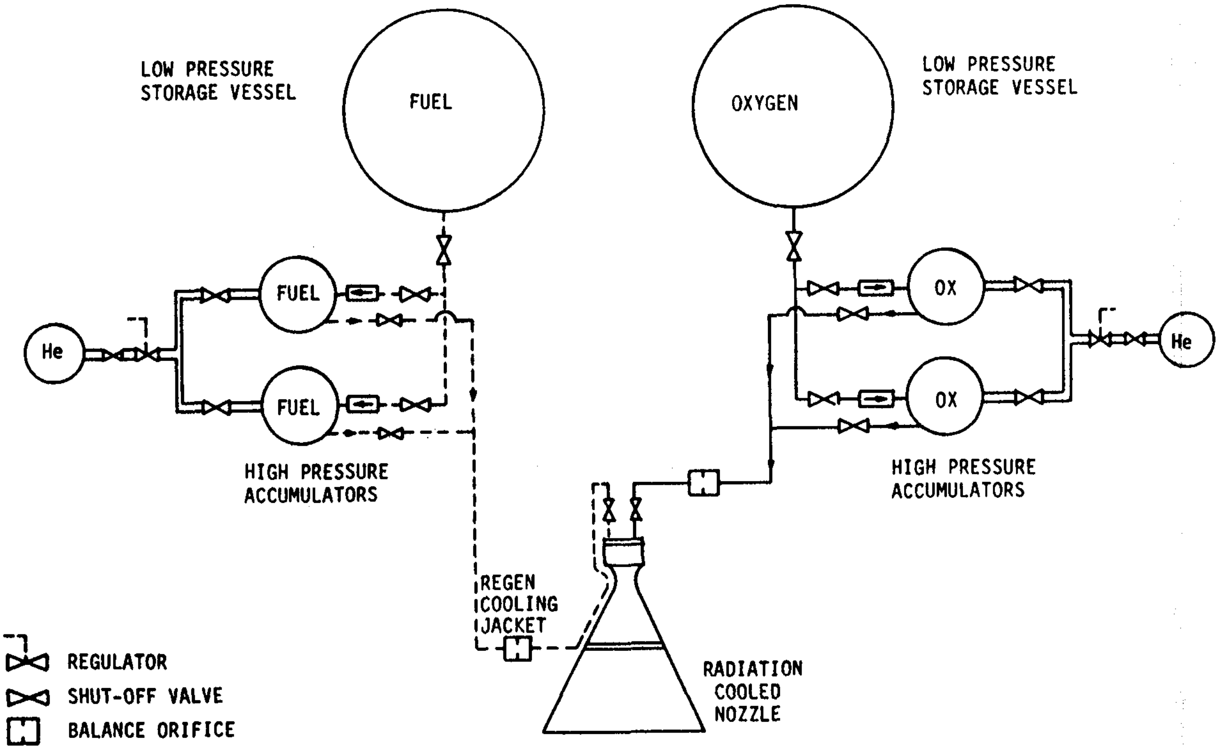
Pressure-Fed Concept



Parallel Accumulator Concept

A parallel pressurized tank concept is shown on the schematic. In this concept, both the fuel and oxygen are stored in low pressure main propellant tanks. Two small parallel accumulators in each propellant feed system are located downstream of these main propellant tanks. These accumulators are alternately filled from the main propellant tank and pressurized to provide the engine propellant supply. When the propellant is expelled, the tank is vented and then refilled from the main tank. While one tank is being filled, the engine runs off of the parallel tank. The advantage of this system over the basic pressure-fed concept is a reduction in the high pressure tankage weight. The accumulators are sized to provide the apogee burn. Again, the engine can be either regen or film cooled.

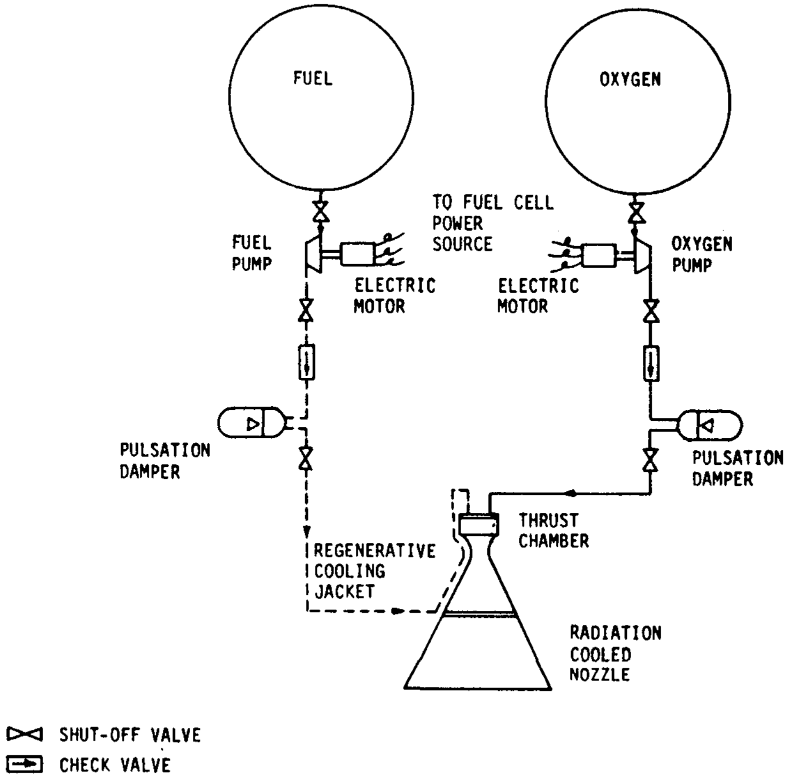
Parallel Accumulator Concept (Pressure-Fed)



Auxiliary Power Source (Fuel Cells) Concept

The figure shows a pump-fed concept in which the pumps are driven by electric motors with fuel cells as the power source. Analysis has indicated that the weight of batteries is prohibitive. The concept shown has a pulsation damper (very small accumulator) downstream of the pumps. This component will be required if positive displacement pumps are selected in component screening analysis. This concept is also applicable with film or regen cooling.

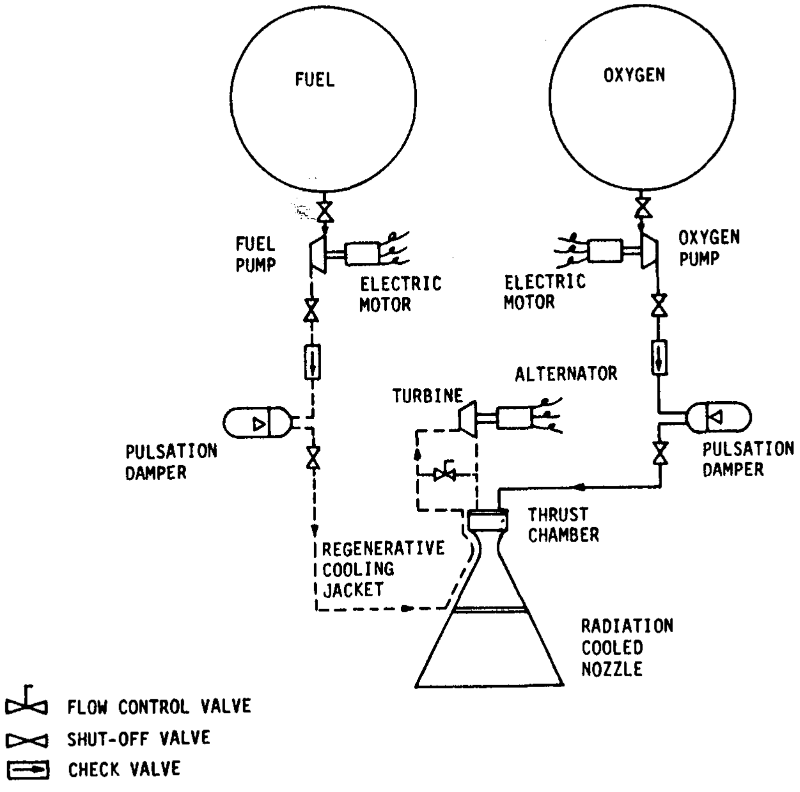
Auxiliary Power Source (Fuel Cells) Concept



Turboalternator Concept

The figure shows a pump-fed concept with an electric motor drive using a turboalternator as the power source. This concept has potential application with heated hydrogen or methane as the turbine drive fluid. A small amount of the heated fuel bypasses the turbine. This bypass flow provides the power control. Cycle power balances were performed to determine if the maximum operating chamber pressure of this system is different than the cooling limits. This is discussed with a later chart.

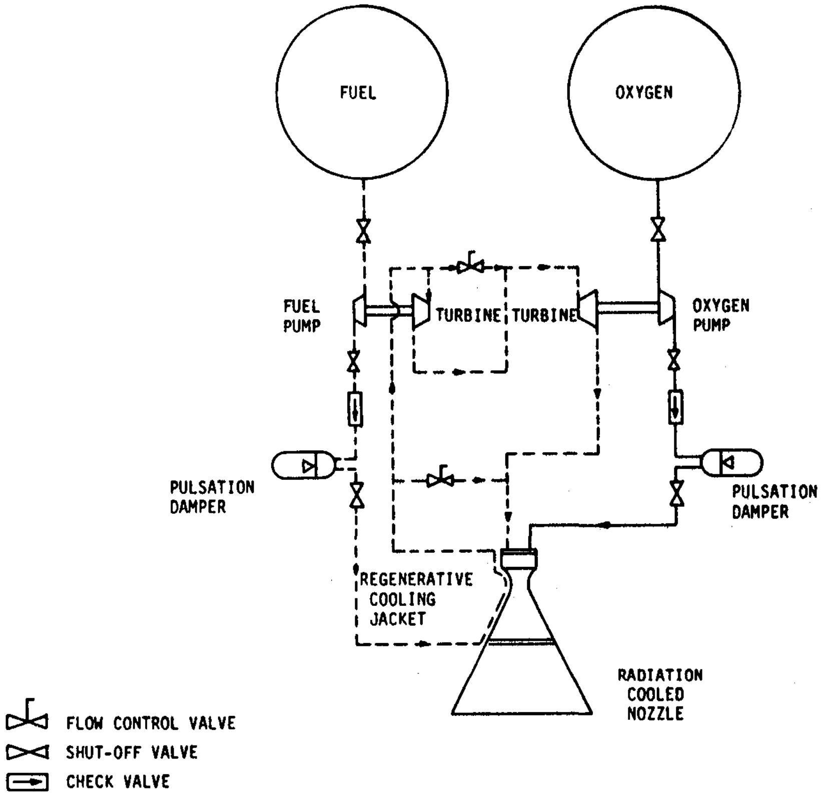
Turboalternator Concept



Expander Cycle Concept

An expander cycle pump-fed concept is shown on the schematic. This concept is also applicable with heated hydrogen or methane as the drive fluid for the turbines. A series turbines cycle arrangement was selected because the full flow oxygen turbine is much more efficient than the extremely low flow oxygen turbine in a parallel arrangement. The fuel turbine bypass valve shown on the figure is used to provide mixture ratio control and the valve bypassing flow around both turbines is for power control. This is the simpliest pump-fed system because it does not require any additional components.

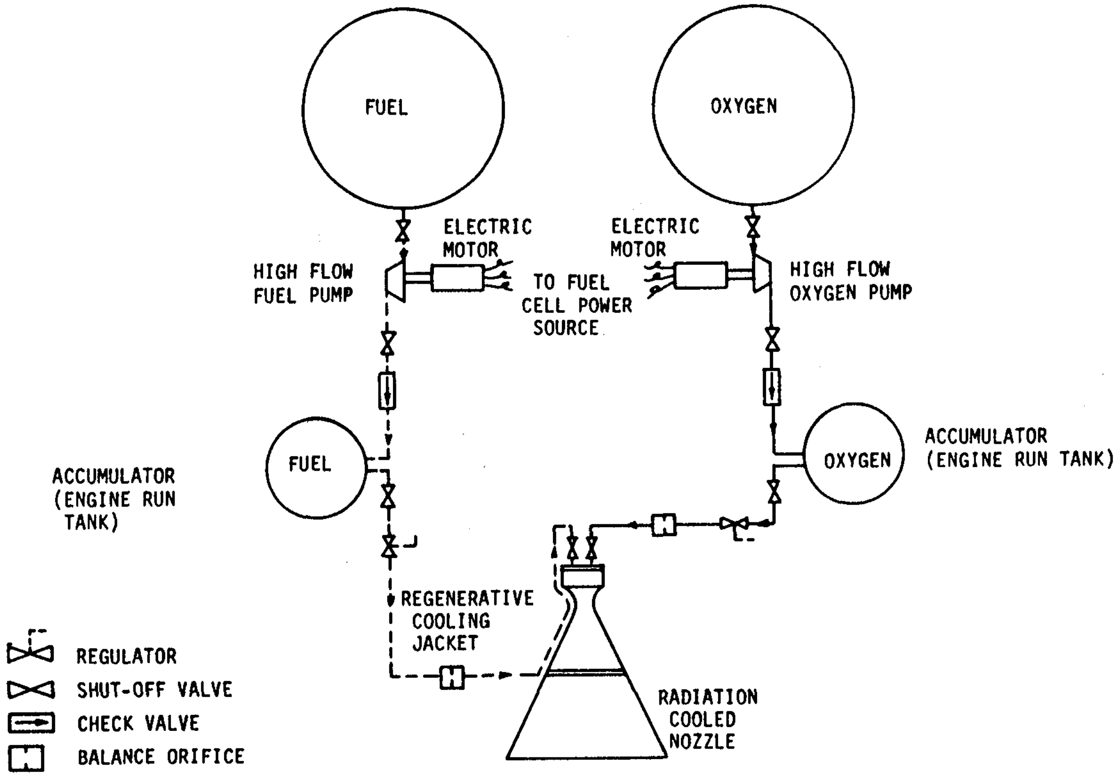
Expander Cycle Concept



Pump-Filled Feed System Tank Concept

A pump-filled tanks engine feed system concept is shown schematically. In this concept, the engine run tanks are filled by pumps from the low pressure main vessels during mission coast periods. The possible advantage of this concept is that the pump flows can be much higher than the engine flows which may provide a more suitable operating regime for the pumps (i.e., the pump design is not restricted by the engine thrust level). A regulator is shown downstream of the engine run tanks to maintain constant engine pressures. Without this regulator, the chamber pressure and engine thrust would decay as the propellant is expelled. This system is applicable with regen or film cooled engines.

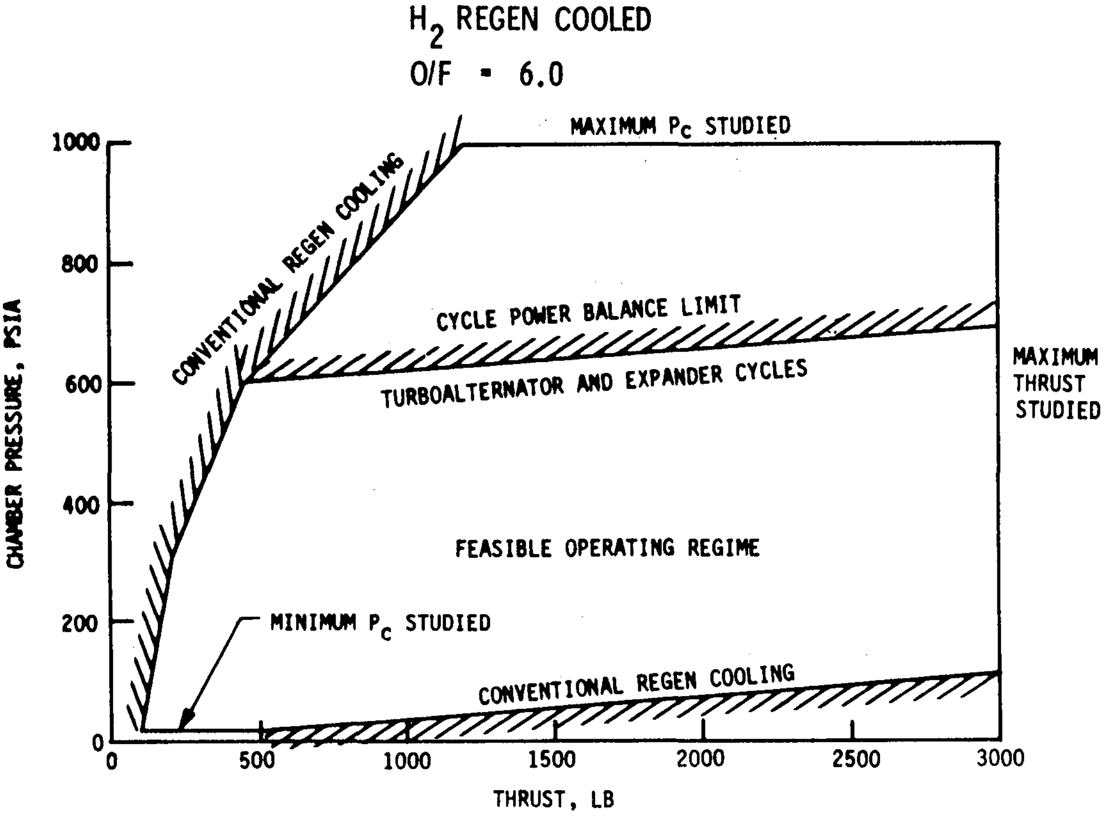
Pump-Filled Feed System Tank Concept



O_2/H_2 Turboalternator and Expander Cycle Operating Regime

The figure shows cycle power balance limits for both the turboalternator and expander cycle concepts superimposed on the feasible cooling map. For these two cycles, the operating region is reduced even further. The power balance is limited by the coolant jacket pressure drop, turbine inlet temperature and component efficiencies. For pump-fed systems using an auxiliary power source (i.e. fuel cells), operation to 1000 psia is possible although the power requirements are very large. Engine parametric data was run over the feasible operating regimes as defined by either the cooling or power balance limits. Advanced cooling schemes may extend these limits.

O_2/H_2 Turboalternator And Expander Cycle Operating Regime



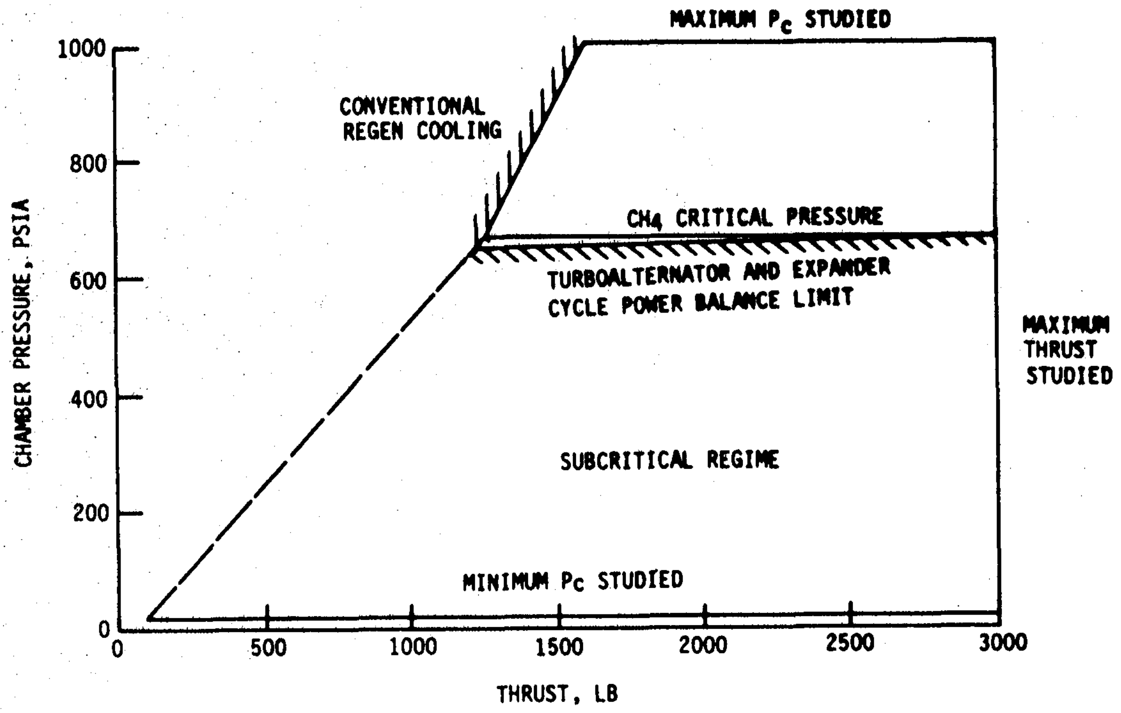
O_2/CH_4 Turboalternator and Expander Cycle Operating Range

This operating map is similar to that described for O_2/H_2 except the engine combined power balance and coolant limit occured at a lower thrust level (~1300 psia). In conducting these power balances, the coolant jacket exit pressure was maintained above the critical pressure of CH_4. This, of course, put the burden upon the methane pumping system.

O_2/CH_4 Turboalternator And Expander Cycle Operating Range

CH_4 REGEN COOLING

O/F = 3.7



Turboalternator Cycle Performance Parametrics

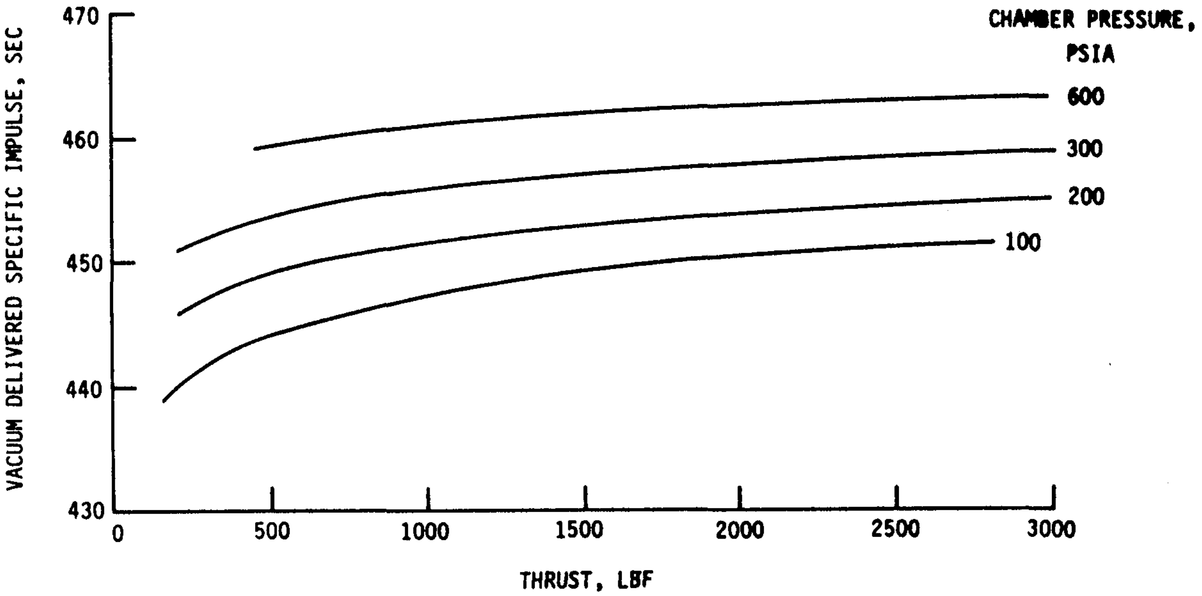
Typical parametric data generated by the study is shown on this and the following two charts. The engine delivered performance data for a turboalternator cycle is shown as a function of both thrust and chamber pressure. This data is also applicable for an O_2/H_2 expander cycle. Performance decreases with both decreasing thrust and chamber pressure because of the kinetic loss increases. The energy release efficiency also decreases with chamber pressure. With LO_2/GH_2 propellants, energy release efficiencies (ERE) greater than 98% can be achieved. An ERE of .995 at 1000 psia and .992 at 100 psia is considered typical of the state-of-the-art for LO_2/GH_2 propellants.

Turboalternator Cycle Performance Parametrics

O_2/H_2 PROPELLANTS

O/F = 6.0

ϵ = 400:1



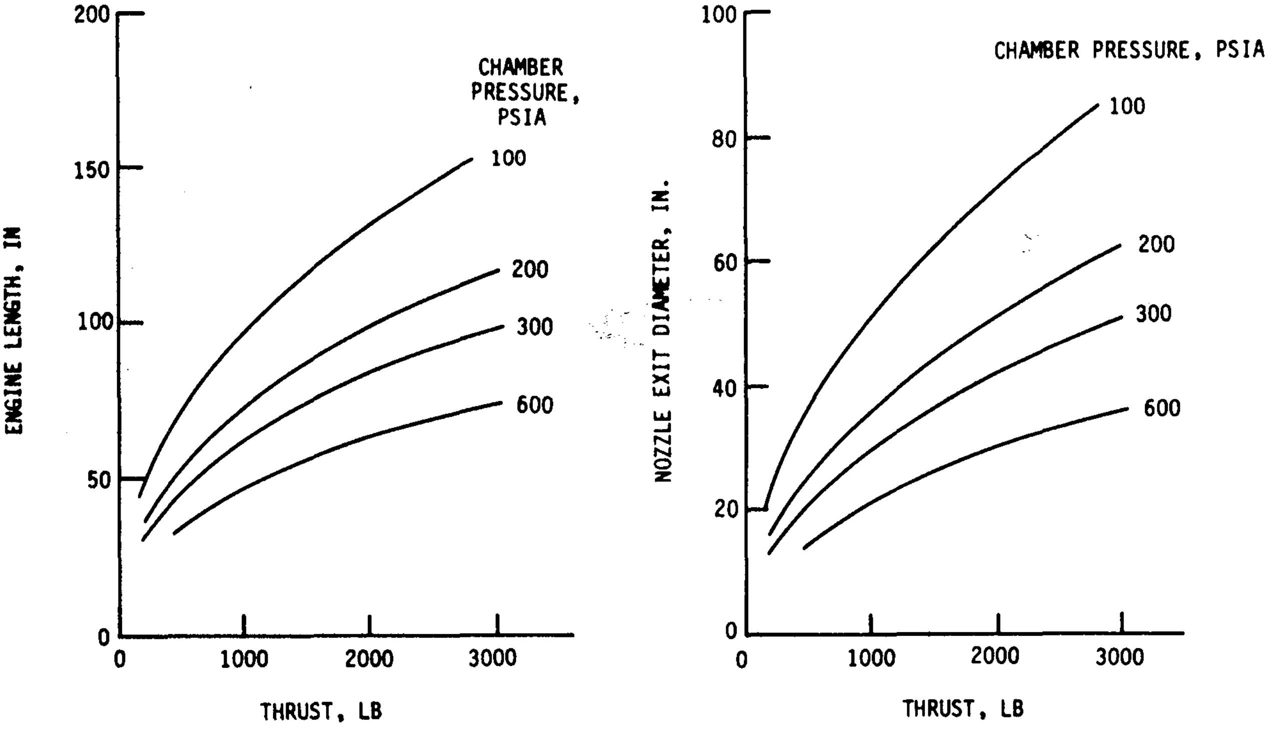
Turboalternator Cycle Envelope Parametrics

The engine envelope (total length and nozzle exit diameter) is shown as functions of thrust and chamber pressure for the turboalternator cycle. This data is also applicable to an expander cycle engine. The data shows that the nozzles get very large at high thrust and at low chamber pressures. This, of course, gets reflected in the engine weight and is discussed with the following chart.

If short engine lengths are required to minimize the length of the COTV, high chamber pressure, low thrust operation is desirable. This increases the incentive to look at advanced cooling schemes.

Turboalternator Cycle Envelope Parametrics

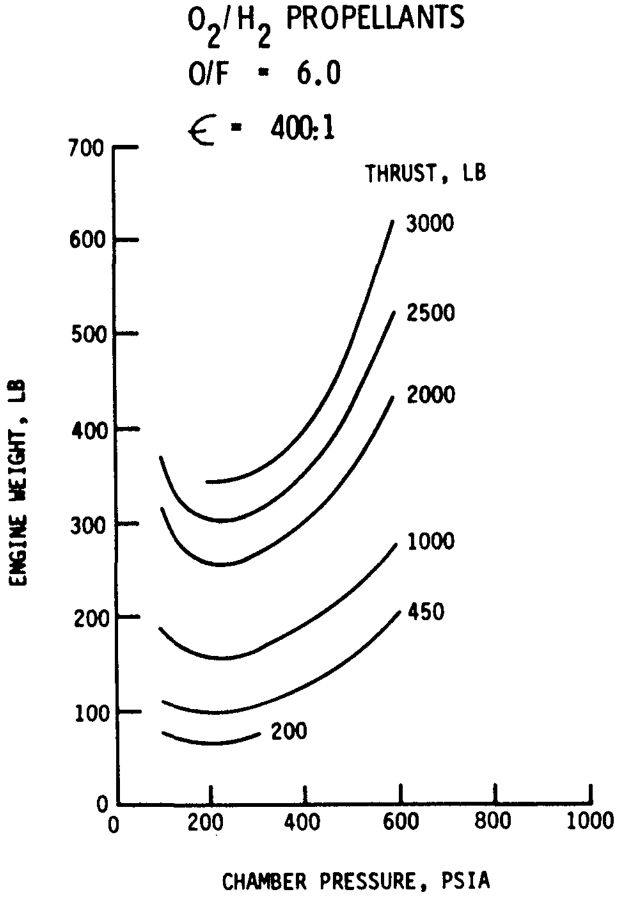
O_2/H_2 PROPELLANTS
$O/F = 6.0$
$\epsilon = 400:1$



Turboalternator Cycle Weight Parametrics

The engine weight data for the turboalternator cycle is shown on the figure as a function of chamber pressure. Engine weight increases as chamber pressure decreases below 200 psia because the nozzle becomes the dominant component weight. As expected, this is amplified as the engine thrust increases. As thrust and chamber pressure increase, the alternator and electric motors become the dominant heavy components. This is particularly evident at a thrust level of 3000 lbs and a chamber pressure of 600 psia.

Turboalternator Cycle Weight Parametrics



Task IV Engine System Preliminary Design Objectives

Task IV takes the outputs of all previous task analyses and molds them into a final end product: the preliminary design of two engine concepts. One of these designs will be of an oxygen/hydrogen engine and the other of an oxygen/hydrocarbon engine.

Based upon the component design analyses, layouts, performance and cycle balance, baseline engine performance, weight and envelope data will be calculated for each of the two engine concepts at an area ratio of 400:1. This data will be used to modify the weight and envelope scaling equations and adjust the performance loss calculations in the parametric engine models. The parametric data generated for these two engine concepts will then be updated and the performance, weight and envelope data presented as functions of thrust, chamber pressure and area ratio. The thrust and chamber pressure ranges will be the feasible design ranges established in Task III and the area ratio range will be 200 to 1,000.

Task IV Engine System Preliminary Design Objectives

- PRELIMINARY DESIGN OF TWO ENGINE CONCEPTS
  - O_2/H_2
  - O_2/HYDROCARBON
- UPDATE ENGINE PARAMETRIC DATA
  - THRUST & P_c PER TASK II AND III RESULTS
  - ϵ = 200 TO 1000

Major Technology Requirements

During the course of the study,recommendations for advanced technology or further study efforts which would enhance the concepts will be identified. Those items which have been identified at this point in the study are shown on the figure.

Advanced cooling schemes are required if O_2/RP-1 engines are to become viable low-thrust candidates. If the performance losses associated with film cooled engines are too high and engine envelope is a system design driver, then advanced cooling schemes are required for all propellant combinations to increase the operating chamber pressures at low-thrust.

If a pump-fed system is selected for this application, the development of high efficiency pumps in this small size range is required because experience in certain sizes is either non-existent or very limited.

The 100 to 3000 lbf thrust range being studied is too broad because problems or design drivers may vary significantly in this range. Engine/vehicle study effort should be continued to better define the engine thrust requirement and to focus on the real issues.

Major Technology Requirements

- DEVELOP ADVANCED COOLING SCHEMES TO EXTEND REGENERATIVE COOLING LIMITS.
- DEVELOP LOW SPECIFIC SPEED, HIGH HEAD RISE, LOW FLOW, HIGH EFFICIENCY TURBOPUMPS.
- CONDUCT FURTHER EFFORT TO REDUCE THE THRUST AND CHAMBER PRESSURE RANGES.