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INTEGRATED MODULAR ENGINE FOR UPPER STAGE PROPULSION

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Abstract

The vision of revolutionary new launch systems that significantly reduce the cost of payload delivery to orbit and retain America's leadership in space has been with us for a long time. However, arguments for new upper stages still fall short because the magnitude of promised improvements has not overcome the barrier of development costs. The evolution of new technologies, innovative engine architectures, and development strategies provides the opportunity to develop a modern, more operationally cost-effective upper stage system at an affordable cost.

Engine concepts characterized by modular architecture, incorporating advanced aerodynamic nozzles and advanced components, were evaluated for their merits with respect to ease of development, low unit production costs, and their contribution to greatly reduce operations, schedules, and costs. This paper describes the process for identifying the most important overall upper stage propulsion requirements. The results of defining requirements, conducting preliminary designs and trade studies, and completing assessments for a minimum-risk, cost-effective upper stage Integrated Modular Engine (IME) is presented.

Introduction

The IME study, U.S. Air Force Headquarters Space System Division Contract F04701-91-C-0076, was a 6-month program to study and conceptually design an operational IME. The study defined an IME propulsion system for an Advanced Upper Stage (AUS) vehicle. This IME design was used to quantify payoffs and advantages, and to identify key technical areas for further development and demonstration in a follow-on effort. The IME design presented is well-grounded, having been subject to extensive objective trade-offs in all the critical areas.

Current Air Force space missions are performed using either the Inertial Upper Stage (IUS) or the Centaur upper stages. The IUS is a solid-motor powered space transfer system; the Centaur is powered by Liquid Oxygen/Liquid Hydrogen (LOX/LH_2) RL-10 rocket engines. Both designs were originally configured over 30 years ago, are mature, and have reasonable reliability and safety records. Both systems were designed and developed in an era where the focus was principally on maximizing performance, minimizing weight, and achieving high design reliability.

In recent years, a new focus (in launch vehicle and space transfer system design) has been applied to understanding, investigating, and defining methodologies and approaches for drastically reducing the costs associated with designing, developing, and operating space launch and transfer systems. The goal is for an order of magnitude reduction in payload delivery costs for DOD, NASA, and the commercial space industry to enable a significant increase in the utilization of space.

Today, a number of factors are driving in the direction of a favorable decision to develop a new propulsion system. New materials are available to reduce the weight of highly stressed and high-temperature parts. New fabrication methods can significantly reduce production costs. Requirements emphasis has shifted from performance at any cost to an increased emphasis on reduction of production and operation costs. The above emphasis has been achieved in the IME design while, at the same time, realizing high performance. The IME preliminary design presented has high performance, is producible, has minimal operability requirements, and can be developed at an order of magnitude reduction to conventional propulsion system development programs.

The AUS studies by Aerospace Corporation have an initial launch capability schedule for operational capability in the year 2002. This permits application of many new technologies to reduce production costs and improve operability features.

The IME study is the next logical step in the progression of studies and was contracted by Rocketdyne for the Air Force Space Systems Division as an advanced propulsion system design effort concentrating on the engine. The Aerospace Corporation was specified to provide mission and vehicle inputs to the program. The objectives of the study are: (1) investigate advanced space

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transfer engine candidates and options, (2) define an advanced upper stage space transfer engine (the IME) for future Air Force missions, and (3) complete assessments on performance, operability, reliability, risk, technology needs, and the development program and production costs.

Approach

The basic approach taken in the IME design process was to identify and prioritize customer requirements and to direct the design to satisfy these requirements. The Quality Function Deployment (QFD) process was used as the primary method of implementing the approach and was supported by reviews with the customer and vehicle contractors during the design process. The house of quality showing requirements and design strategies to meet those requirements is shown in Fig. 1. The result of customer inputs and interactions was a set of requirements which emphasized reliability, safety, operability, and cost. A minimum value was set for specific impulse but the priority of attaining values in excess of the minimum was low. Engine length was not a strong driver (all configurations, except single bell fixed nozzles, met the

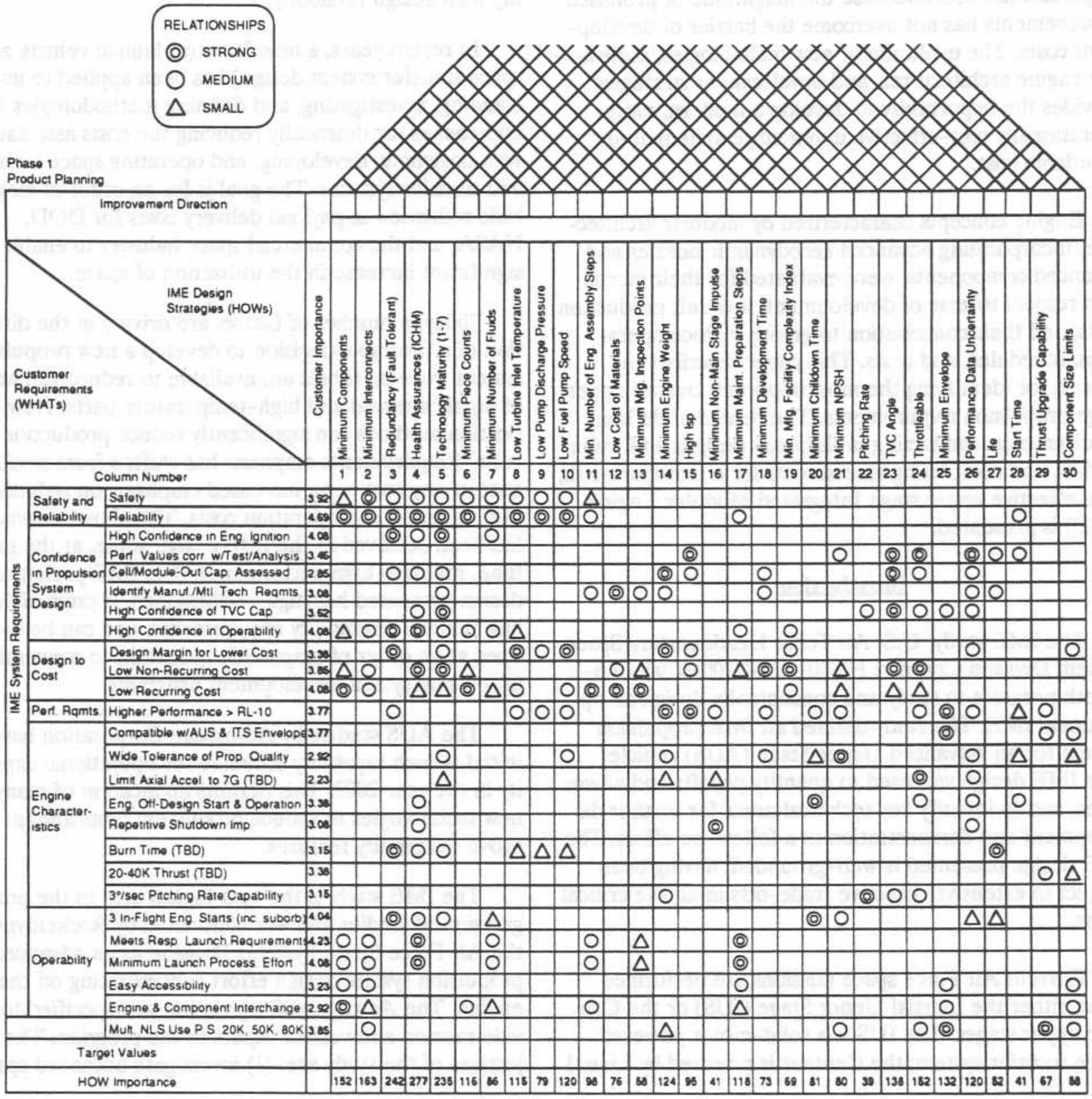


Fig. 1. IME Program House of Quality

length constraint) so that advanced nozzles were not attractive.

A primary driver in the IME design was the recognition that significant improvements in propulsion system reliability, operability, cost, and performance could be achieved by driving the IME design to provide features that benefit the overall propulsion system. In other words, the propulsion system definition was enlarged to include Thrust Vector Control (TVC), the Reaction Control System (RCS), and the propellant feed system as shown in Fig. 2. This novel approach was implemented by designing the engine to eliminate vehicle subsystems which are normally required for engine support and by using the engine to accomplish, more effectively, functions traditionally provided by other subsystems.

IME Design Features

Design requirements/goals specified by Aerospace Corporation, the vehicle integration contractor designated by the Air Force, are listed in Table 1.

The resulting IME is shown in Fig. 3, with characteristics presented in Table 2. The IME design focused on addressing operability concerns. Figure 4 shows the operability features of the propulsion design. Two other versions of the IME evolved with additional features. An alternative IME design, which eliminates chill down for both propellants, is shown in Fig. 5. This design includes

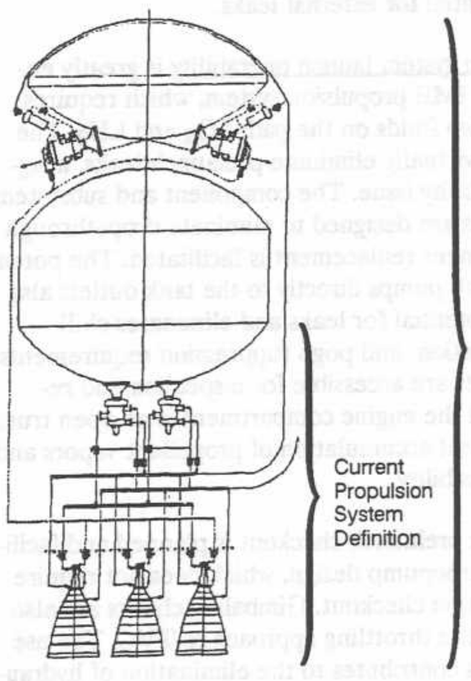


Fig. 2. Expanded Propulsion System Definition Enhances Operability Opportunities

Table 1. IME Requirements

Propellants	O_2/H_2
Thrust (lbf)	30,000
Specific impulse (sec)	>470
Reliability	0.995
Operability	High
Production and development costs	Low

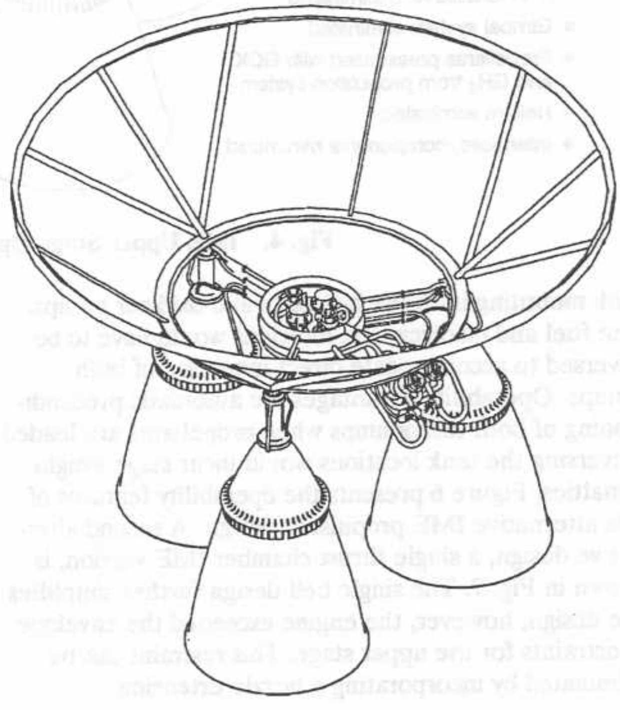


Fig. 3. IME Propulsion System

Table 2. IME Performance

Specific impulse (sec)	480
Chamber pressure (psia)	1,746
Mixture ratio	6.0
Nozzle expansion ratio	700:1
Engine cycle	Hybrid cycle Fuel-expander cycle Oxidizer-high MR preburner
Engine length (in.)	87.7
Engine diameter (in.)	136
Engine weight (lb)*	1,048

*Aerospace Corporation analysis indicated vehicle weight is reduced by 482 lb as pneumatic, hydraulic, and helium systems are eliminated. These eliminated subsystems reduce vehicle cost by $5 million (Rough Order of Magnitude [ROM] estimate).

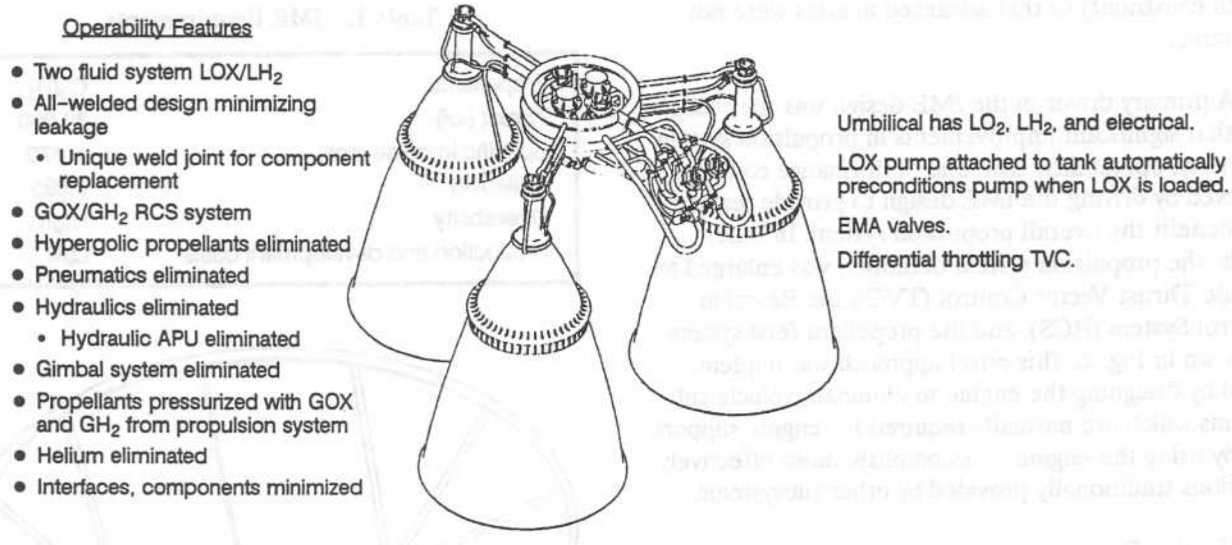


Fig. 4. IME Upper Stage Operation Concerns Are Minimized

tank mounting both the hydrogen and oxidizer pumps. The fuel and oxidizer tank locations would have to be reversed to accommodate direct mounting of both pumps. Operability advantages are automatic preconditioning of both turbopumps when propellants are loaded. Reversing the tank locations would incur stage weight penalties. Figure 6 presents the operability features of this alternative IME propulsion design. A second alternative design, a single thrust chamber IME version, is shown in Fig. 7. The single bell design further simplifies the design, however, the engine exceeded the envelope constraints for the upper stage. This restraint can be eliminated by incorporating a nozzle extension.

The IME features, listed in Table 3, are discussed in the following subsections relative to the benefits they provide with respect to the IME study.

Reliability and safety are enhanced by the following design features. A second, spare turbopump set is activated if the first set fails or approaches failure conditions. The system only requires nominal power when maximum TVC is demanded. Turbomachinery and combustion devices nominally operate about 30% below their design points, thereby significantly enhancing the normal design margins.

The propulsion system has a greatly reduced number of parts. The use of Electromechanical Actuators (EMAs) eliminates the entire hydraulic system, which includes a storable propellant-driven Auxiliary Power Unit (APU) and/or pneumatic actuators and related systems. Wraparound ducts with flex joints, gimbal actuators, and bearings are eliminated by the throttling chambers. The helium system is eliminated by the selected power cycle, which provides pressurants for both propellant tanks and for a GO_2/GH_2 RCS and eliminates the seal purge on the oxidizer turbopump. An H_2/O_2 heat exchanger is also replaced by a GO_2/LO_2 unit for added safety. The use of zero Net Positive Suction Head (NPSH) pumps opens the possibility of eliminating all tank pressurizing systems. The jet boost pumps have no moving parts and the main turbopumps feature a novel design that reduces the parts count by an order of magnitude. An all-welded assembly was designed to reduce the potential for external leaks.

Propulsion system launch operability is greatly enhanced by the IME propulsion system, which requires loading only two fluids on the pad: LO_2 and LH_2. The welded joints virtually eliminate prelaunch leaks, a significant operability issue. The component and subsystem interface welds are designed to eliminate drop-through so that component replacement is facilitated. The potential to mount all pumps directly to the tank outlets also reduces the potential for leaks and eliminates chill down, recirculation, and pogo suppression requirements. All components are accessible for inspection and replacement and the engine compartment is an open truss design to prevent accumulation of propellant vapors and facilitate accessibility.

Automatic prelaunch checkout is planned and facilitated by the turbopump design, which does not require torque or position checkout. Gimbaling checks are also eliminated by the throttling approach to TVC. The use of EMA valves contributes to the elimination of hydraulic and pneumatic systems. To qualitatively evaluate operability improvements, a schedule for a current upper stage was compared to an IME upper stage. The

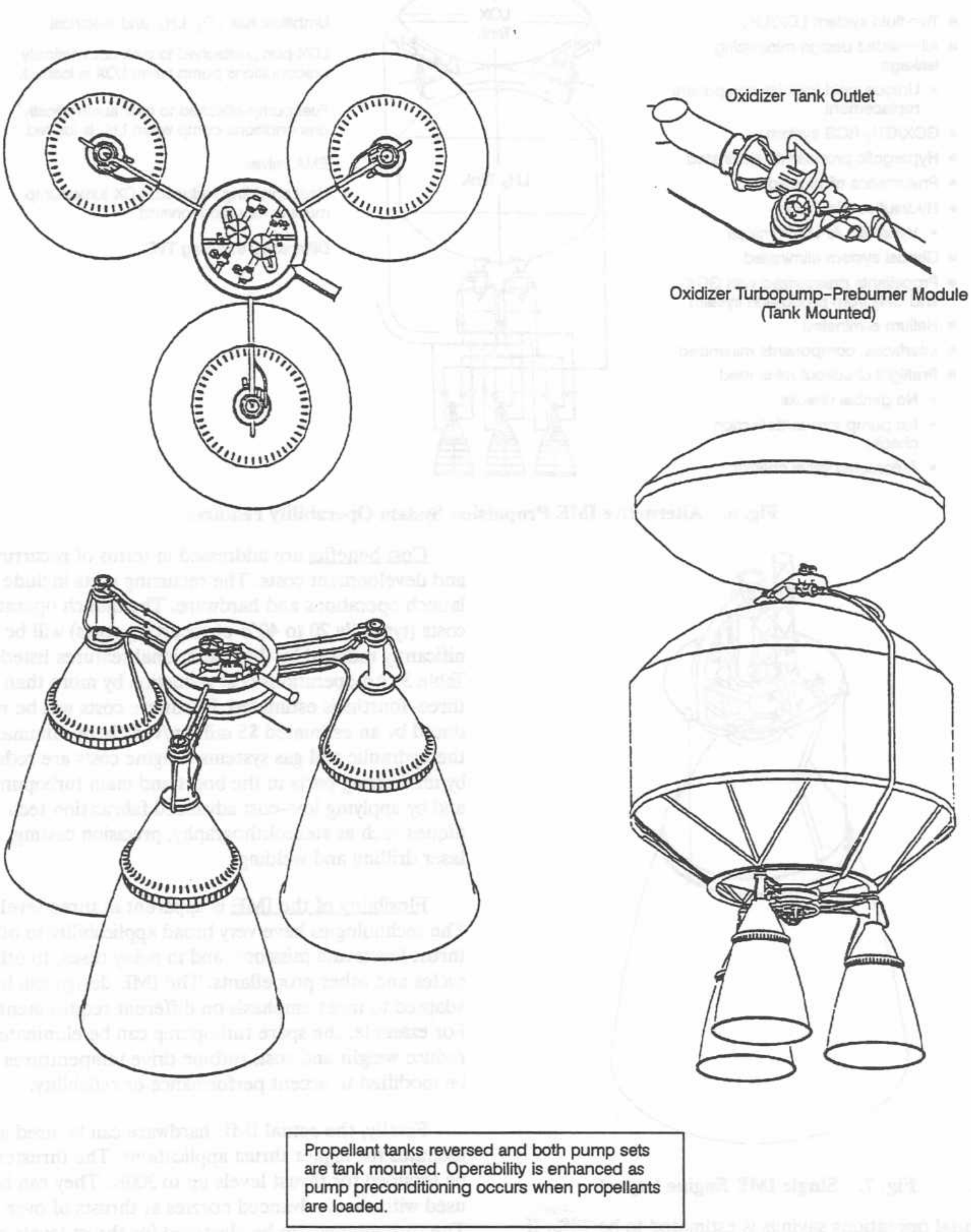
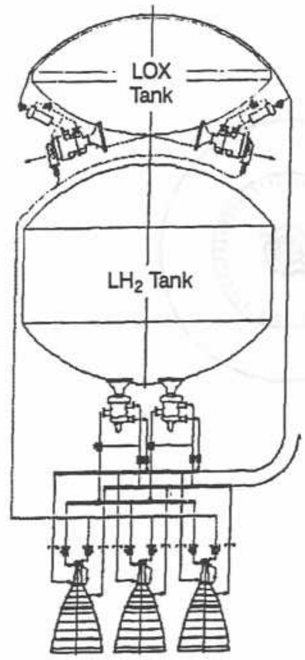


Fig. 5. IME Alternate Configuration

Operability Features

- Two fluid system LOX/LH_2
- All–welded design minimizing leakage
  - Unique weld joint for component replacement
- GOX/GH_2 RCS system
- Hypergolic propellants eliminated
- Pneumatics eliminated
- Hydraulics eliminated
  - Hydraulic APU eliminated
- Gimbal system eliminated
- Propellants pressurized with GOX and GH_2 from propulsion system
- Helium eliminated
- Interfaces, components minimized
- Preflight checkout minimized
  - No gimbal checks
  - No pump torque/deflection checks
  - Automated valve checks



Umbilical has LO_2, LH_2, and electrical.

LOX pump attached to tank automatically preconditions pump when LOX is loaded.

Fuel pump attached to tank automatically preconditions pump when LH_2 is loaded.

EMA valves.

Heat shielding reduced, LOX turbopump module mounted forward.

Differential throttling TVC.

Fig. 6. Alternative IME Propulsion System Operability Features

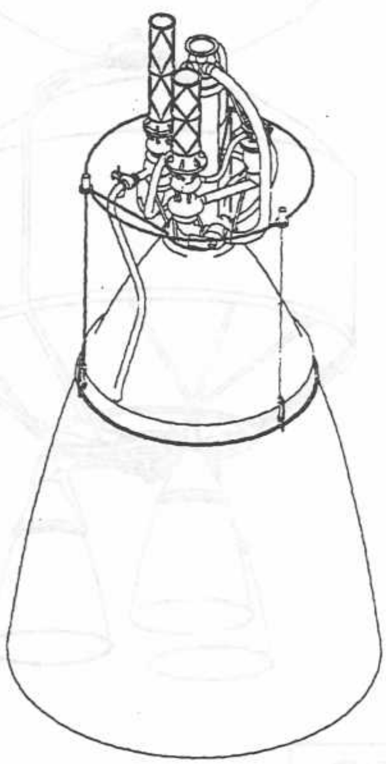


Fig. 7. Single IME Engine Layout

potential operations savings is estimated to be 78%. If the IME/AUS is combined with a booster stage designed to be similarly efficient with respect to launch operations, then major facility support systems and operations can be eliminated.

Cost benefits are addressed in terms of recurring and development costs. The recurring costs include launch operations and hardware. The launch operations costs (typically 20 to 40% of recurring costs) will be significantly reduced by the operational features listed in Table 3. An operations cost reduction by more than three–fourths is estimated. Hardware costs will be reduced by an estimated $5 million/vehicle by eliminating the hydraulic and gas systems. Engine costs are reduced by minimizing parts in the boost and main turbopumps and by applying low–cost advanced fabrication techniques such as stereolithography, precision casting, and laser drilling and welding.

Flexibility of the IME is apparent at three levels. The technologies have very broad applicability to other thrust levels and missions, and in many cases, to other cycles and other propellants. The IME design can be adapted to meet emphasis on different requirements. For example, the spare turbopump can be eliminated to reduce weight and cost; turbine drive temperatures can be modified to accent performance or reliability.

Finally, the actual IME hardware can be used as modules for higher thrust applications. The thrusters can be grouped for thrust levels up to 300K. They can be used with short advanced nozzles at thrusts of over 80K. The turbopumps can be clustered for thrust levels of up to 150K.

The performance of the IME propulsion system exceeds the National Launch System (NLS) requirements.

Table 3. IME Features/Benefits

Feature	Benefit*
Hybrid cycle	
Fuel: Expander cycle	R, P
Oxidizer: Oxidizer-rich preburner cycle	P
No LO_2/GH_2 heat exchanger	R
GO_2 and GH_2 available	
Propellant tank pressurization	R, O, C
Reaction control	O
Two turbopump sets - one is spare	R
Integral jet boost pumps	
Zero NPSH	O, P
Propellant tank mounted LO_2 pump	O
Propellant tank mounted LH_2 pump alternate	O
Simplified main pumps	
Hydrostatic bearings	O, R
Very few parts	R, C, P
Purgeless oxidizer turbopump	O, P
Three thrust chambers	P
TVC by moderate throttling	O, P, R
Fixed nozzles	R, O, C
Electromagnetic valve actuators	O, C
Health monitoring	
Automated checkout	O
Redundancy activation	R
Potential for future adaptive control	R
Only two fluids required - LO_2 and LH_2	O, C, R, P
No hydraulic system	
No pneumatic system	
No storable propellants	
No pogo suppression system	O, P, C
Rapid chill down	O
All-welded joints	O, R

*O: Operability, R: Reliability, C: Cost, P: Performance (I_{sp}, weight, length)

The specific impulse exceeds the required minimum by 10 seconds. The weight of the engine, in the context of other propulsion system elements which have been eliminated and features to enhance reliability and operability, is low. The three thrust chamber bell nozzle design significantly reduces propulsion system length, for the same high performance area ratio, over a single conventional thrust chamber bell nozzle design. The engine dimensions comfortably fit the stage requirements.

Conclusions

An IME system design was developed that meets all Air Force design requirements. Quality Function Deployment methodology was used to refine propulsion requirements, evolve design strategies, and develop an exceptionally capable propulsion system. The modular design is adaptable to a wide range of applications via adding additional thrust chamber and turbopump modules. The propulsion system attributes enhance performance, operability, and reliability. In addition, technologies were identified, risks were minimized via backup positions, and a cost-effective development program was developed.

The design approach that treats the engine as an integrated part of the propulsion system results in significant operability, reliability, and cost benefits. The application of advanced design and fabrication concepts also provides major benefits.