INTEGRATED MODULAR ENGINE CONFIGURATION OPTIONS*

T. J. Harmon and G. L. Briley
Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

ABSTRACT

Engine concepts characterized by modular architecture, advanced technologies, and enhanced operability features were evaluated for inherent merits with respect to ease of development, low production costs, and applicability to a wide range of missions (i.e., upper stage, space-based, transfer, lunar lander, lunar ascent, and Mars lander propulsion systems). Two widely different propulsion system applications, a launch vehicle upper stage and a lunar lander vehicle, were developed around a common propulsion system architecture. These Integrated Modular Engine (IME) systems include propellant tanks, propellant distribution, and the rocket engines. This approach focused on automating and minimizing operations required for preparing and placing a propulsion system into operation. The versatility of the IME system architecture is described along with options to further integrate stage or vehicle functions.

INTRODUCTION

The IME configuration options paper was derived from results of an Air Force upper stage propulsion study contract.[1] The IME study was a six-month program to evaluate and conceptually design an operational IME. The study defined an IME propulsion system for a National Launch System (NLS) Upper Stage (NLSUS) vehicle. This IME design was used to quantify payoffs and advantages, and to identify key technical areas for further development. The IME program offered the opportunity to build upon previous integrated architecture's[2] and apply the principles of Continuous Process Improvement (CPI) to a second generation system. Rocketdyne's approach to include operability in the design process demonstrated that an operations driven design architecture enhances the design.

DISCUSSION

The upper stage IME propulsion system concept design was for a 30,000-lb thrust class system using LO_2/LH_2 propellants. The IME propulsion system study produced a conceptual design which has high performance, is producible, and has modular elements. The resulting modular design had two primary characteristics, it was adaptable to a wide range of applications and was highly operable.

Key propulsion system features were operability, integration, and modularity. Operability was achieved through simplification (i.e., minimizing components), integrating the propulsion system in the stage, and addressing operations concerns early in the design process. A careful review of the need for redundant components was made in order not to burden the system with added operations to check out those redundant components. System integration permitted a single turbopump set to provide propellants to the thrust chambers. Propellants are ducted to each thrust chamber via propellant manifolds. Conventional engine systems have a complete set of components for each thrust chamber assembly. The modular architecture provides adaptability to a wide range of configurations and applications via adding or subtracting thrust chamber and turbopump modules. The IME propulsion system is a concept, not a specific design, and its specific physical arrangement is dictated by vehicle and mission requirements. Thus, it was a short step to evolve the design from upper stage applications to other applications such as space-based, orbit transfer, lunar lander, lunar ascent, and Mars lander propulsion systems.

CONCEPT DESIGN APPROACH

The Quality Function Deployment (QFD) methodology was used to refine propulsion requirements, evolve design strategies, and develop an exceptionally capable propulsion system. QFD is a powerful methodology for linking customer requirements to design strategies. In addition, the QFD process elicits information on the relative importance of customer requirements. This systematic process was implemented at the beginning of the IME program and its results guided the design process.

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Customer and Rocketdyne interactions during the QFD process produced an enlarged set of requirements. These requirements, while compatible with contract document requirements, were more definitive and revealed an emphasis on operability, reliability, safety, and cost. Figure 1 shows graphically the design evolution process that occurred during the study. Applying QFD methodology with its expanded requirements disclosed the originally proposed IME concept, a horizontal flow nozzle approach, was not an optimum design.

An innovative feature in the IME design synthesis process was the recognition that significant propulsion system improvements would result if the design process used a three element concurrent approach. Therefore, the design, manufacturing, and operations elements were considered at the beginning of the concept design process. Operability implementation in a propulsion system means designing the propulsion system to minimize components, eliminate subsystems, and use the propulsion system to accomplish, more effectively, functions traditionally provided by other subsystems (i.e., eliminating storable propellants by substituting a GH_2/GO_2 Reaction Control System [RCS]). The increased focus on operations pushed the design toward a simpler, more operationally efficient design architecture. These same operations features would simplify the manufacturing process. This "enhanced" design, the modular bell design, was found to be adaptable to a wide range of applications via adding or subtracting thrust chamber and turbopump modules.

Customer requirements drive the propulsion system architecture solution, however, the relative importance of design strategies for meeting requirements showed where the design emphasis should be focused. Design strategies meeting customer requirements were grouped into four areas: reliability and safety, costs (operations and acquisition), performance, and technology level. Figure 2 shows the relative weighting factor (emphasis) of these design areas. The most important areas were reliability/safety and cost. Performance received a modest ranking while technology was the least important area.

Cost was subdivided into acquisition costs and operability costs. It was observed that operability, reliability, and safety elements are synergistic. For example, a highly operable system drives a design toward simplicity. Also, a high reliability requirement drives a design toward simplicity. Simplicity enhances operability, reliability, safety, and acquisition cost. This intertwining of operations, reliability, safety, and cost focused the IME conceptual design process. The modest ranking of performance had the following characteristic brought out in the QFD process: performance was important and a minimum performance level was established, however, higher performance over the minimum was not to be pursued if other characteristics were compromised to achieve that higher performance. The low emphasis on technology showed that the system must use proven components. Some flexibility existed in

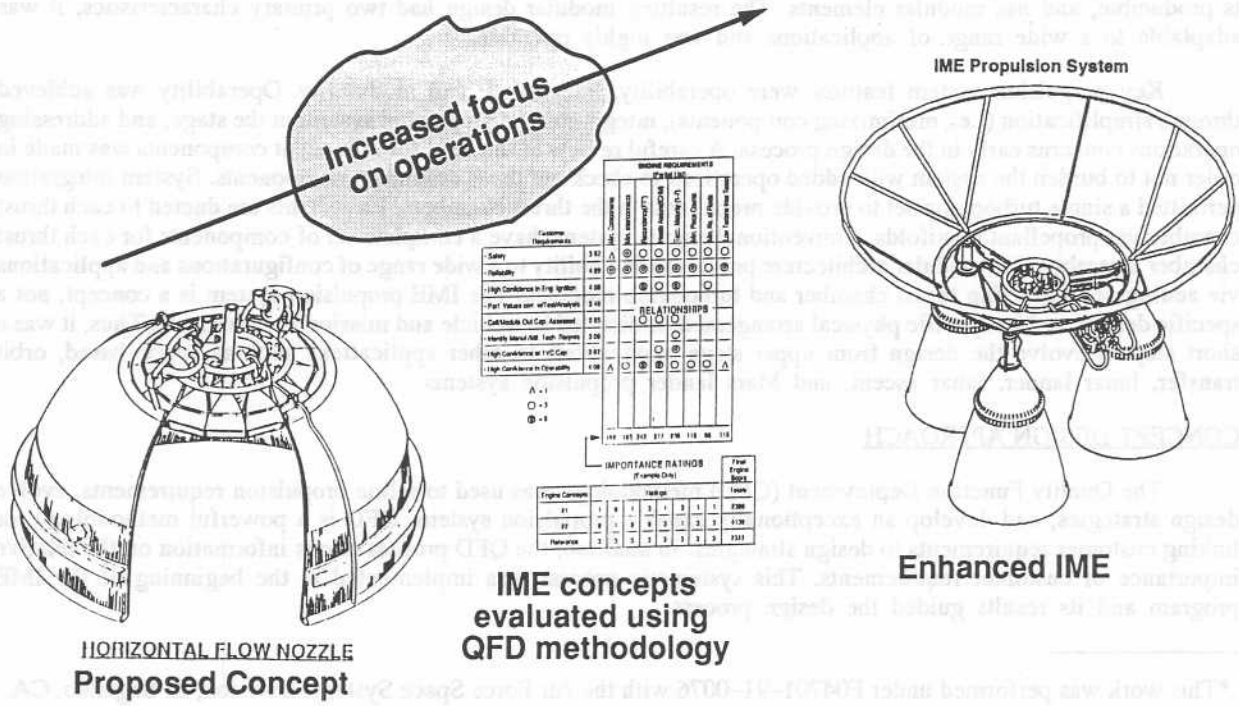


Figure 1. IME Design Evolved Through QFD Process

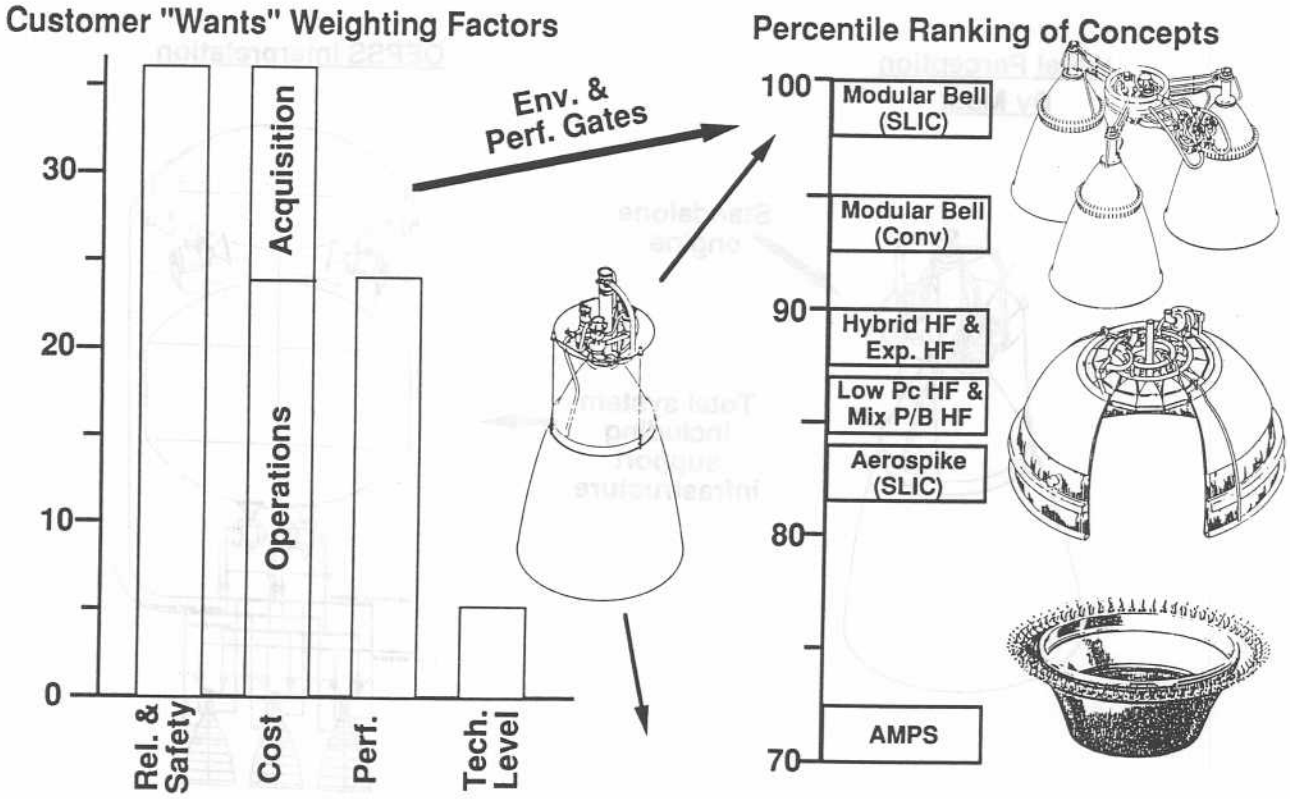


Figure 2. Requirements Drive the Architecture Solution

this area as the IME Initial Launch Capability date was defined as the year 2002. Technologies that could be proven within that time frame could be included in the design.

When propulsion system concepts were ranked against customer weighting factors (reliability and safety, costs, performance, and technology level), the different propulsion system concept rankings showed the modular bell design to be higher than the reference horizontal flow design. While the propulsion system is a major element of a total stage, there are stage influences that also impact the reliability and safety, costs, performance, and technology level. For example, eliminating propulsion system helium purges (a propulsion system operations enhancement) while maintaining stage helium for tank purges or pressurization fails to take full advantage this propulsion system feature. An optimum use of the propulsion system in the stage requires integrating the propulsion and upper stage systems.

Current practice defines a propulsion system from the engine inlet to the nozzle exit. Other stage elements (i.e., the RCS, tank pressurization system, etc.) impact stage operability. As the entire upper stage defines stage operability it suggests the propulsion system definition should include other related elements such as tankage, propellant/fluid management systems, and the engine (including RCS). Figure 3 graphically describes the two propulsion system definitions. Maximizing integration within the enlarged boundary can simplify or eliminate operability concerns. This design approach was used on the IME and led to propulsion system modularization and innovative component placement. The resulting IME system (stage) was a highly operable, modular, upper stage system.

IME CONCEPTUAL DESIGN

The IME design benefits are summarized in Table I. The IME propulsion system is a two fluid (LOX and LH_2) system using three thrust chambers and two turbopump sets. The number of bell thrust chambers was requirements driven. One turbopump set is operational with the second set in a standby mode. Thrust vector control is by differential throttling. The engine features a hybrid cycle with an expander cycle driving the hydrogen turbopump and a LOX-rich preburner driving the oxygen turbopump. Interpropellant seals and purges between the pump and turbines are not required. The oxidizer pumps are tank mounted. Tank mounting the turbopump allows automatic pump preconditioning when LOX is loaded. An alternate configuration would also allow tank mounting

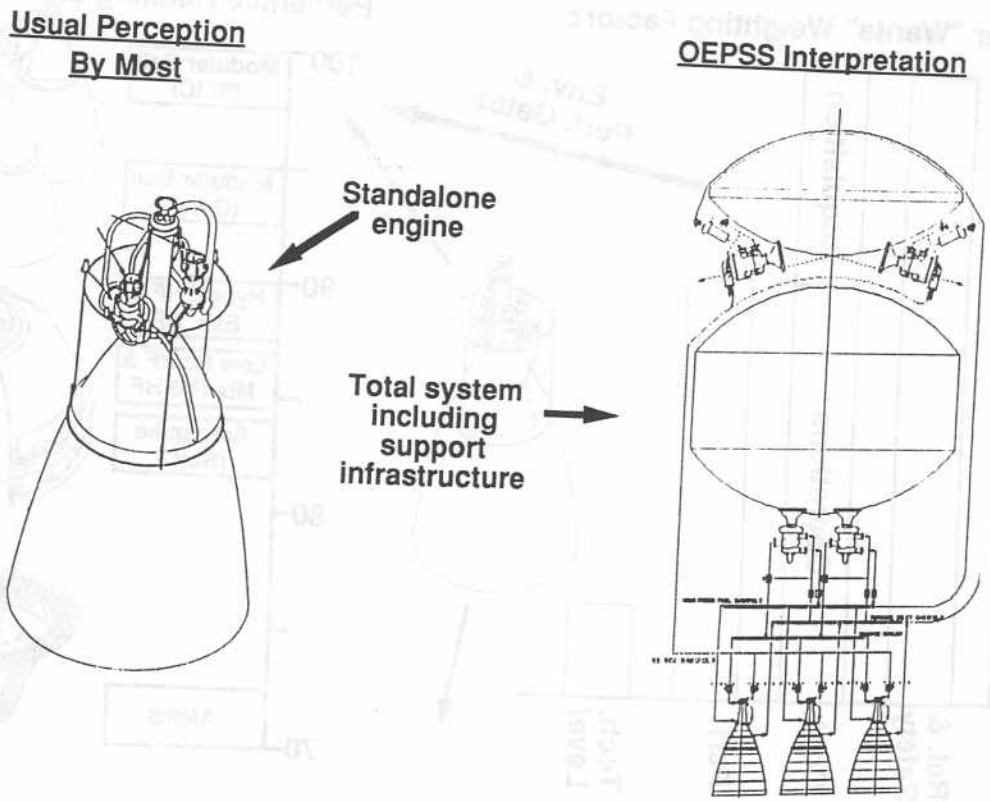


Figure 3. What Is a Propulsion System?

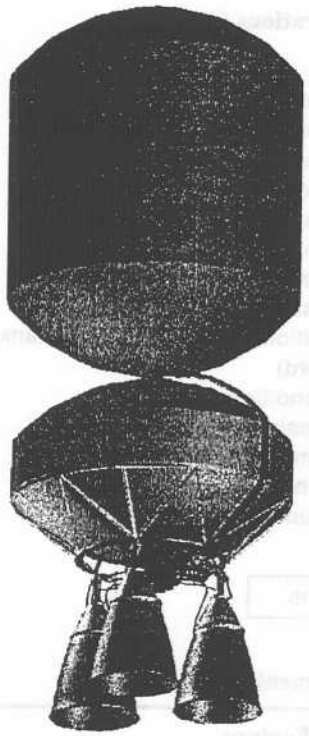
Table I. IME Modular Bell Benefits

Characteristic	Modular Bells
Minimum components, piece count, and assembly and inspection steps	Fewest components and assembly and inspection steps
Component size limits (thrusters)	Near optimum for fabrication and development
Specific impulse	Highest of concepts
Engine weight*	Slightly more but within acceptable range
Thrust vector control pitch rate	Within acceptable range
Performance data uncertainty	Best, minimum performance variation
Development time	Minimum development time and minimum new technology
Overall	Best choice — superior in major areas

*Installed weights TBD

the hydrogen pump and automatic fuel pump preconditioning. The propulsion system eliminates purges, pneumatics, and hydraulics. The propulsion system also supplies gaseous hydrogen and oxygen for tank pressurization (if needed). In addition, the gaseous hydrogen and oxygen could also be used to supply small GH_2 and GO_2 RCS thrusters, eliminating the need for a storable propellants (hydrazine or monomethylhydrazine and nitrogen tetroxide) RCS.

The IME system shown in Fig. 4 met all Air Force design requirements. The propulsion system attributes of high performance, operability, and reliability were achieved without compromising the system. The IME system would reduce by orders of magnitude the launch site support requirements



- Thrust 30,000 lbs.
- Specific Impulse 480 sec.
- Reliability 0.9953
- LOI 0.80
- Engine Length 88 in.
- Engine Diameter 136 in.

Figure 4. Operations and Operability Enhanced IME Architecture

The modular approach to the propulsion system means components are not necessarily mounted on the thrust chamber. A conventional propulsion system has all the engine components attached to the thrust chamber. The IME uses one turbopump set to supply propellant to all three thrust chambers. Disconnecting the turbopumps from thrust chamber mounting allows optimum placement of this major subsystem. Cryogenic systems must have the turbopumps conditioned to the fluid operating condition for successful operation. With conventional engine systems, a complicated recirculation or propellant bleed system is necessary to condition the turbopumps. The modular IME architecture allows placement of the turbopumps at the propellant tank outlet. This approach automatically conditions the turbopumps when propellants are loaded into the propellant tank.

OPERABILITY FEATURES

The IME architecture approach recognized that system improvements would result by focusing on incorporating operability enhancements which would mitigate or eliminate operations concerns. Operability is defined as those activities required to bring a propulsion system to the launch ready point. Current launch experience has shown that the activity required to bring a propulsion system into operation represents a significant part of a lunch system schedule and costs. The Operationally Efficient Propulsion System Study (OEPSS), a NASA Kennedy Space Center (KSC) sponsored study,[3] developed an experience-based list of operation concerns from expendable manned launch vehicles, expendable unmanned launch vehicles, and recoverable reusable launch vehicles. A review of this database showed most of the launch concerns are applicable to an upper stage propulsion system. This list of operations concerns is presented in Table II. The IME design addresses 18 of those 23 concerns, as indicated by the circle around the concerns list number.

A discussion of how each concern was addressed in the IME design is presented in Table III.

IME PROPULSION SYSTEM FAMILY

The IME modular propulsion system concept is a flexible architecture in that the design is modular and can be adapted to meet emphasis on different requirements. For example, the IME design can be adapted to meet emphasis on different requirements (i.e., eliminate the spare turbopump to reduce weight and cost, modify turbine drive temperatures to accent performance or reliability, etc.). Also the IME architecture can be adapted to higher thrust applications through the addition of more thrust chamber and turbopump modules.

Table II. IME Focused on OEPSS Operations Concerns

No.	
1	Closed aft compartments
2	Fluid system leakage
	• External
	• Internal
3	Hydraulic system
4	Ocean recovery/refurbishment
5	Multiple propellants
6	Hypergolic propellants (safety)
7	Accessibility
8	Sophisticated heat shielding
9	Excessive components/subsystems
10	Lack of hardware integration
11	Separate OMS/RCS
12	Pneumatic systems
13	Gimbal system
14	High maintenance hardware
15	Ordnance Operations
16	Retractable T-O umbilical carrier plates
17	Propellant tank pressurization system
18	Excessive interfaces
19	Conditioning/geysering (LOX tank forward)
20	Preconditioning system
21	Expensive commodity usage -- helium
22	Lack hardware commonality
23	System contamination

IME addresses 18 concerns

Table III. IME Operability Enhancements/Features

Concern	Feature
Fluid system leakage	The IME design is an all welded design, minimizing the potential for propulsion system leakage.
Hydraulic system	Thrust vector control is accomplished through differential throttling.
Multiple propellants	The IME upper stage is a two-fluid system, oxygen and hydrogen.
Hypergolic propellant	RCS can use GOX/GH_2 thrusters supplied from the IME propulsion system, eliminating the requirement for hypergolic propellant on the stage.
Sophisticated heat shielding	The modular design permits limited, local heat shielding of the modules. Simple spray-on heat shield can be used.
Excessive components/ subsystem interfaces	Interfaces are minimized by designing a two-fluid propulsion system.
Hardware integration	A very high level of hardware integration is achieved in the propulsion system design and in the vehicle by defining the propulsion system to include tankage, propellant/fluid management systems, and the engine.
Separate OMS and RCS	The RCS could use IME propulsion propellants. The RCS propellants, gaseous H_2 and O_2, would be supplied by the IME (charging small tanks) during its operation. These tanks would be recharged each time the propulsion system is operated.
Pneumatic system	Pneumatic systems are eliminated on the IME propulsion system.
Gimbal system	The thrust chambers are fixed and thrust vector control is accomplished through differential throttling.
High maintenance hardware	Elimination of the helium supply system for tank pressurization, pneumatic, and hydraulic system, and the use of simple, low-cost innovative concept (SLIC) turbopumps (simple design with a minimum of components and no maintenance requirement).

The modular bell design was shown to have the highest percentile ranking for the IME study (reference Fig 2). This result was due to a specific design requirement limiting propulsion system length. Except for this limited length requirement, the IME single bell concept met all the vehicle requirements. The features shown for the modular bell system also apply to the single bell concept. This system level flexibility (i.e., multiple or single thrust chambers, multiple components, and optimum component placement) shows the IME concept is a unique concept architecture.

A brief evaluation has shown the IME architecture is adaptable to other in-space applications. Specifically space transfer and lunar and Mars descent and ascent systems. In-space systems must be extremely operable as the infrastructure for maintenance, checkout, and repair in space will be extremely limited. The operations driven design approach used developing the IME concept design will be applicable to in-space systems. These applications (upper stage, space-based, orbit transfer, lunar lander, lunar ascent, and Mars lander propulsion systems) are shown in Fig. 5.

CONCLUSION

A family of modular propulsion systems has been defined which can be tailored to specific design applications. These applications are upper stage, space-based, orbit transfer, lunar lander, lunar ascent, and Mars lander propulsion systems.

The QFD process aided in defining the primary propulsion system characteristics. The QFD methodology allows the design process to incorporate refined requirements, evolve design strategies, and develop an exceptionally capable propulsion system. The modular design that evolved is adaptable to a wide range of applications. Key propulsion system features were operability integration and modularity.

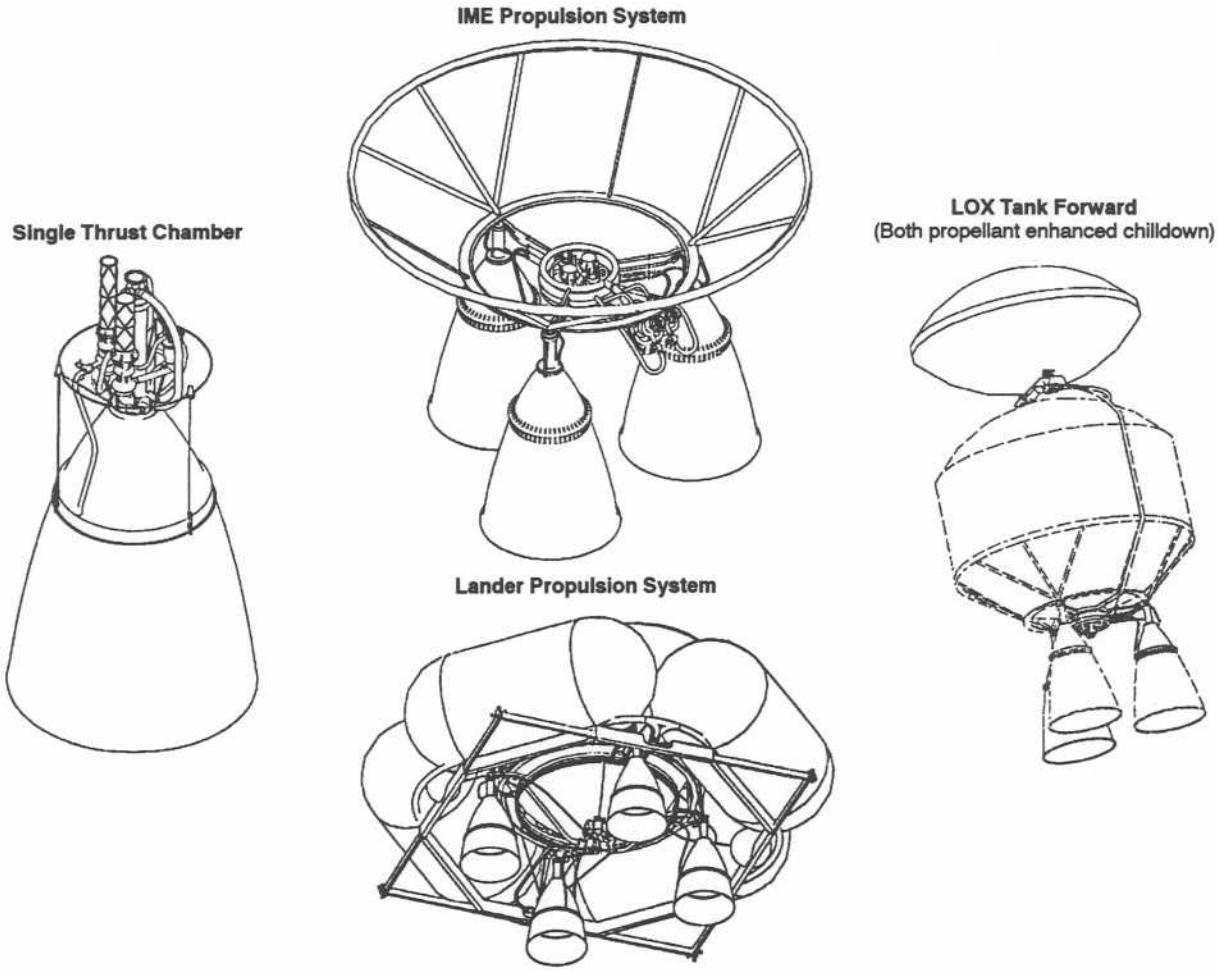


Figure 5. IME Propulsion Architecture Concept Family

The focus on automating and minimizing operations evolved into an integrated modular propulsion system architecture that incorporated the following features: (1) a simple design with few components, (2) an integrated system with optimum component placement, and (3) a modular system with component sizes readily adaptable to other applications.

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