AIAA 93-1891

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AIAA/SAE/ASME/ASEE
29th Joint Propulsion
Conference and Exhibit
June 28–30, 1993 / Monterey, CA

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Abstract

An Integrated Modular Engine (IME) system conceptual design has been developed for meeting the upper stage propulsion requirements. This design was used to identify key technical areas for further development and demonstration. A number of factors are favorable for introducing advanced technologies: new materials are available, controls and health monitoring are vastly more capable, and new fabrication methods are coming on-line. Furthermore, recent innovative integrated propulsion system architecture designs leverage the benefits throughout the stage. All needed technologies are compatible with near-term initial launch capability around the year 2000. These technologies do not require extensive, time-consuming, or expensive development programs to bring these technologies to fruition. This paper describes those technologies that need to be developed to support an IME development program which would result in an affordable propulsion system applicable to a wide range of missions, i.e., upper stage, space-based, transfer, lunar lander, lunar ascent, and Mars lander propulsion systems.

Introduction

A preliminary design of an Integrated Modular Engine (IME) propulsion system for upper stage applications was developed for the Air Force in 1992. Details on the evolution and design drivers leading to this configuration are presented in Reference 1. The primary design was a 30,000-lb-thrust LO_2/LH_2 propulsion system powered by a hybrid expander cycle using three bell thrust chambers and two turbopump sets. The modular architecture is adaptable 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; its specific physical arrangement is adaptable to various vehicle and mission requirements. Figure 1 presents two propulsion system designs from the study, one configuration using differential throttling for thrust vector control (TVC) and the second configuration using gimballing for TVC. All approaches integrate three major propulsion system attributes: enhanced performance, operability, and reliability.

High performance was achieved using a combination of high chamber pressure and high area ratio nozzles. The IME modular architecture is adaptable to multiple configurations which are driven by requirements (i.e., number of nozzles, turbopumps, module locations, etc.). A conventional bell nozzle was chosen as the most understood and modeled. Propulsion system launch operability was enhanced by having a system that requires loading only two fluids on the pad: LO_2/LH_2 (i.e., the stage eliminates pneumatics, hydraulics, and helium purges). Reliability improvements include a simple design and a backup turbopump module. In addition, stage integration is enhanced by using gaseous hydrogen and oxygen from the engine for tank pressurization (if required) and reaction control system (RCS) thrusters, eliminating the need for a stage storable propellant system.

The aforementioned design served as the foundation for determining emerging technologies that would make an IME propulsion system a reality. The requirements for each application must be considered and a "best" configuration evolved for each situation, particularly with regard to the location of components and gimballing versus differential combustor throttling for TVC.

Three characteristics also evolved from the Air Force contract study that helped define the resultant propulsion system. These characteristics are an enlarged propulsion system paradigm, modularity, and operational efficiency. Described in the following is a description of how IME needed technologies were determined based on the IME preliminary design.

Approach

The propulsion system paradigm, normally defined as from the engine inlet to the nozzle exit, was enlarged to include all components from the propellant tank inlet to the engine nozzle exit. This redefined propulsion system definition permits the combining of stage and engine resources (battery power, etc.) and integration of other systems such as the RCS. The use of modules and the enlarged paradigm allows component and module placement at optimum locations within the stage. Artificial interfaces between the engine and the stage are eliminated.

A propulsion system requirements list was developed with Air Force staff, Aerospace Corporation staff, and technical consultants. Rocketdyne facilitated developing the requirements list using the Quality Function Deployment

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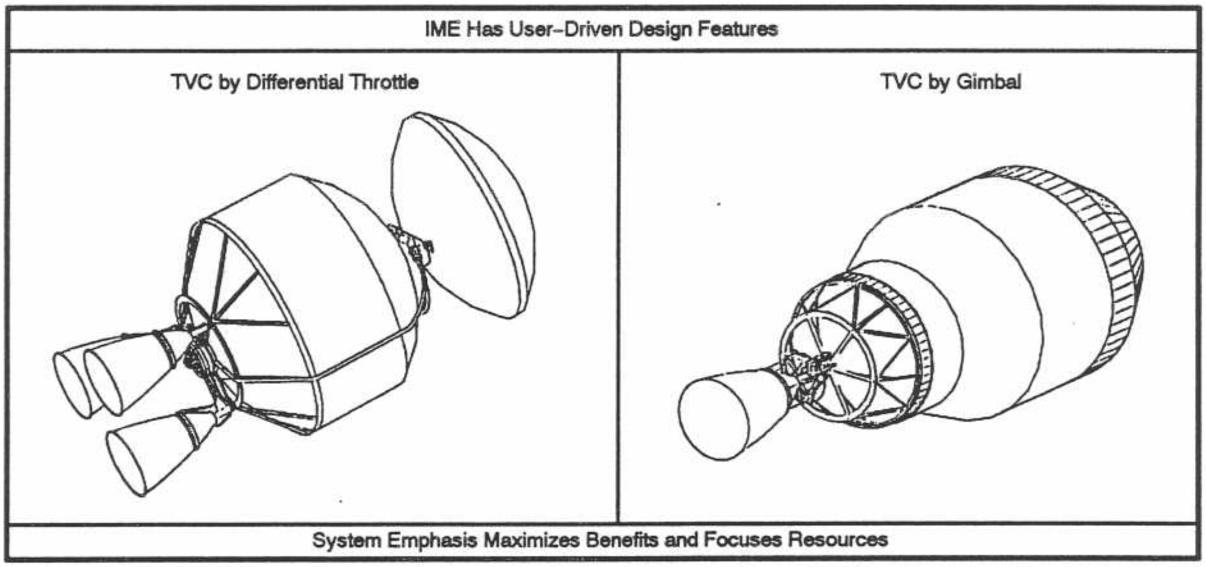


Fig. 1. IME Propulsion System Designs

(QFD) process. The QFD process is a powerful tool for refining propulsion requirements, evolving design strategies, and developing an exceptionally capable propulsion system meeting these requirements. A conference with a cross-functional staff of the customer provided an upper stage wants (requirements) list. Rocketdyne facilitated this process but did not provide direct input in order to assure that the customer requirements were truly reflected. The Rocketdyne technical staff presence at the session did assist in maximizing the transfer of information requirements (i.e., clarification questions were asked if required on specific requirements).

The resultant list is representative of what this customer wanted. A process corollary would be an automobile customer survey where the buyer comments on the engine characteristics he or she would like. In this example, the automobile buyer is the upper stage vehicle provider.

The QFD-derived customer wants (requirements) list for the IME program asks for a propulsion system that is currently unavailable (i.e., the customer has a need for an improved upper stage propulsion system while, at the same time, maintaining a conservative approach [low risk, low uncertainty, high confidence]). The IME program requirements list is presented in Table 1. This is not a generic list but is a list for a specific upper stage system application. This requirements list was affinitized into six general areas. The smaller group or affinity list describes, in general terms, areas for propulsion system improvement.

The five affinitized headings describe propulsion system areas essential to satisfying customer requirements. The first four items from the affinitized list are usually present in a propulsion system specification. Reliability and safety, confidence in design, cost, and performance are normal propulsion system specification description areas. The fifth heading "operability" is generally not included in propulsion system specification descriptions.

Operability is defined at 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 launch system schedule and cost. As current launch systems are mature and operations issues continue, it is apparent that operability cannot easily be retrofitted. Therefore, a heavy emphasis on operability was incorporated on the IME program from the start.

After customer requirements are defined, the QFD process focus shifts to satisfying these requirements. A QFD team consisting of cross-functional Rocketdyne staff and Air Force representatives defined characteristics or design requirements satisfying the customer requirements. These design strategies are listed in Table 2. The characteristics of the resulting IME propulsion system evolving from the requirements and design strategies is presented in Fig. 2.

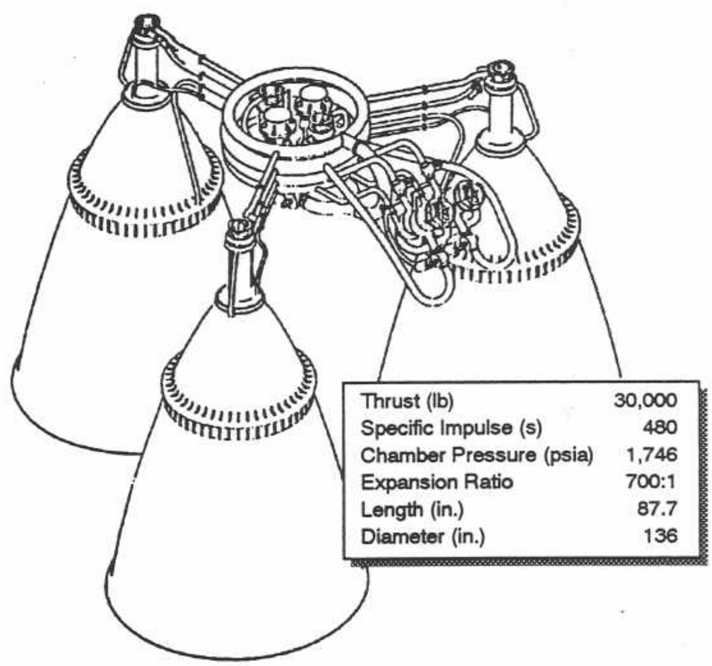
The IME preliminary design described in Fig. 2 includes advanced technologies and concepts. The next step was to recommend a rapid technology development path using a propulsion system test bed. A test bed approach would demonstrate system propulsion system operation, interaction, and performance. Individual component technologies would be

Table 1. IME Program Customer Wants (Requirements)

Affinitized Requirements	Customer Requirements
Safety and reliability	Safety Reliability
Confidence in propulsion system design	High confidence in engine ignition Performance values correspond with test/analysis Cell/module out capability assessed High confidence of TVC capability High confidence in operability
Design to cost	Design margin for lower cost Low nonrecurring cost Low recurring cost
Performance requirements engine characteristics	Specific impulse higher than 446 s Compatible with advanced upper stage envelope Wide tolerance of propellant quality Limit axial acceleration to 7 g's Engine off-design start and operation Repetitive shutdown impulse Burn time (TBD) 20,000- to 40,000-lb thrust (TBD) 3-deg/s pitching rate capability
Operability	Three in-flight starts (including suborbital) Meets launch responsiveness requirement Minimum launch process effort Easy accessibility Engine and component interchange Multiple National Launch System use

Features

- Two Fluid System LOX/LH_2
- Expander Fuel Side
- Oxygen-Rich Preburner Oxidizer Side
- All Welded Design Minimizes Leaks
- No Purges/Hypergolics, Pneumatics, Hydraulics, Helium, Gimbal System
- TVC by Differential Throttling
- EMA Valves
- Propellant Tanks Pressurized with GOX and GH_2 from Propulsion System
- GOX/GH_2 RCS System
- Pump
- Preconditioning when Propellants are Loaded (Tank Mounted Pump Option)



System Emphasis Maximizes Benefits and Focuses Resources

Fig. 2. IME Propulsion System Characteristics

Table 2. IME Program Hows (Design Strategies)

Affinitized Design Strategies	Rocketdyne Design Strategies
Ability to meet or exceed minimum needs	Minimum engine weight Minimum NPSH High specific impulse Minimum envelope Minimum chilldown time Throttling Start time
Reasonable operating parameters	Low turbine inlet temperature Low pump discharge pressure Low fuel pump speed
Fewer parts	Minimum interconnects Minimum number of fluids Minimum components Minimum piece count
Fewer controls	Health assurance Redundancy (fault tolerance)
Design margin	Life Thrust upgrade capability Component size limits
Manufacturing operation	Minimum number of assembly steps Minimum manufacturing steps Minimum manufacturing facility complexity
Functional effectiveness	Pitching rate TVC angle Minimum maintenance preparation steps Minimum non-main stage impulse
Technical risk	Technology maturity Low cost of materials Minimum development time Performance data uncertainty

demonstrated in a system environment. A listing of component and subsystem technology demonstrations is shown in Table 3. This list shows the component or subsystem, the demonstration objectives, and special facility provisions. Table 4 provides a list of component benefits resulting from incorporating specific technologies. A technology test bed would enhance the subsequent development program, reducing program risk, reducing program schedule, and minimizing cost.

The IME program presupposed certain technologies, already in development or technologies that need to be developed, will be available for the IME design. Four technologies were identified where development is needed for the IME: advanced materials, oxygen-rich preburner characteristics, turbopump technology, and controls and health monitoring.

Advanced materials includes materials and processing to be used in the turbomachinery and thrust chamber areas. These materials would expand component operating envelope and rapid prototyping manufacturing processes would greatly shorten the time to implement design changes.

The oxidizer-rich preburner enables a wider engine system operating range, provides a source of gaseous oxygen for tank pressurization and RCS systems, and simplifies the overall propulsion system. Simplification occurs when the turbopump turbine is driven with the same propellant which it pumps and concerns about mixing oxidizer and fuel propellants within the unit are eliminated. This allows the fuel and oxidizer turbopumps to be designed without intermediate seal and purge requirements.

Table 3. Component/Subsystem Technology Demonstrations

Component/Subsystem	Demonstrate	Special Facility Provisions
EMA valves	Response Repeatability Cryo compatibility Power requirement Weight	Cryo propellants
Precombustor	Durability, performance Stability	High-pressure LO_2, GH_2
Oxidizer turbopump	Durability, performance GO_2 compatibility Operating range Zero NPSH	High-pressure ambient or warm GO_2 Low-pressure LO_2
Fuel turbopump	Durability, performance Operating range Zero NPSH	High-pressure ambient or warm GHe Low-pressure LH_2
Thrust chamber assembly	Fabricability Ignition, start, shutdown Durability, performance	High-pressure ambient or warm GO_2 and GH_2 Vacuum optional
Controller, instrumentation, software	Durability, performance Accuracy	Simulators for controlled components and propulsion system

Table 4. Component/Subsystem Benefits

Component/Subsystem	Benefit	Technology
Turbopumps	Tank pressurization system eliminated Chilldown eliminated Reliability, cost Preflight physical checks eliminated Purge eliminated	Zero NPSH Very low parts count Hydrostatic bearings GO_2 driven oxidizer turbopump (OTP) turbine
Injector	Low cost, rapid prototype	Laser drilled
Combustor	Low cost, rapid prototype Long life, high margin, reliability Gimbal/actuator system eliminated Wraparound flex ducts eliminated Preflight physical checks eliminated Improved reliability	Stereolithography Conformal channels Throttling for TVC Laser ignition
Precombustor	OTP drive eliminates purge Enables GO_2/GH_2 RCS—eliminates additional hypergolic propellants Facilitates injector throttling for TVC Potential for higher performance Facilitates tank–mounted OTP to eliminate prechill	GO_2–rich
Valves	Hydraulic system eliminated	Electromechanical actuators

Turbomachinery is the critical component for providing high thrust–to–weight ratio propulsion systems. Typically, turbomachinery is expensive and complex, with a large number of parts, elaborate seals, mechanical bearings and, in some cases, gear trains. Simplified turbomachinery is needed.

Controls and health monitoring includes control, diagnostics, and onboard real–time propulsion system safety monitoring to supplement redlines. Controls and heath monitoring implementation during development would increase component behavior understanding, decrease hardware losses, and improve turnaround time and safety. These characteristics would decrease the schedule risk to the program.

The need for system–level testing to complete demonstration of these technologies is as strong as, or perhaps stronger than, the requirement to demonstrate basic operation at the component level. Drivers to this position are requirements to determine system–level interactions and system–level operability. Experience has shown that component operation in the presence of system interactions is the only approach to truly demonstrate the feasibility of the concepts. This is especially true for closed cycle systems where system interactions are strong. A system–level technology test bed was suggested in the IME program to complete the development of these technologies. Operability is also best demonstrated with system level testing. In addition, operability must be considered at the beginning of the development program as it is difficult to improve operability of a developed system.

The complete IME propulsion system development program includes incorporation of developing technologies, incorporation of operational efficiency features, and system integration. This systems approach produced a short (4 year), cost–effective development plan for the IME program. In addition, backup positions were defined for each technology area which, while modestly affecting performance, allow IME program objectives to be realized with conventional approaches.

The 30 design strategies listed in Table 2 are solutions to customer requirements. These design strategies also indicate desired characteristics for technology improvement. One characteristic predominates on this list. The adjective "minimum" was used in approximately 45 percent of the design strategies. Minimums included components, interconnects, pieces, fluids, assembly steps, inspection, weight, non–main stage impulse, maintenance, development time, chilldown time, NPSH, and envelope. This "minimization" feature will result from all technology development tasks. A grouping of the QFD process "minimums" and the four IME program identified technology areas is presented in Table 5.

The broad interdependence of "minimum" to technology areas shows the technology development process should focus on achieving "minimums" or simplification wherever possible. Minimum components, operations, etc., must be incorporated into the IME propulsion system.

Although Table 5 shows the primary items minimized by each technology, many of the above "minimums" apply to several of the technology areas (i.e., a minimum piece count is a desirable feature for processes, turbomachinery, preburner, and controls). This interrelationship confirms the need for a system focus on propulsion system development. For example, a technology that features a turbopump with minimum interconnects has advantages; however, if it is difficult to manufacture the technology it is only enhancing one area at the expense of another. A system focus views component technology interrelationships for the total propulsion system. System integration of technologies is the only approach for optimizing the total propulsion system.

Table 5. Technology Areas versus "Minimum" Design Strategies

Advanced materials and processes	Minimum piece count Minimum number of assembly steps Minimum manufacturing steps Minimum manufacturing facility complexity Minimum interconnects Minimum components
Turbomachinery technology	Minimum number of fluids Minimum chilldown time Minimum NPSH
Oxygen-rich preburner	Minimum maintenance preparation steps Minimum engine weight Minimum envelope
Controls	Minimum development time

Conclusions

The IME program identified technologies needing development in order to execute an effective IME development program. These technologies were advanced materials and processes, an oxygen-rich preburner, turbopump technology, and controls and health monitoring.

The QFD process aided in the defining the primary characteristic for technology development. The adjective "minimum" was used in approximately 45 percent of the design strategies devised for the IME propulsion system. Minimums included components, interconnects, pieces, fluids, assembly steps, inspection, weight, non-main stage impulse, maintenance, development time, chilldown time, NPSH, and envelope.

The recommended technology development approach was to utilize a technology test bed system. Included in this test bed system would be provision for incorporating operability in all phases of the program. Propulsion system operability can be enhanced while also improving system performance, weight, and cost.

Applying advanced technologies to the total stage provides synergistic benefits which far exceed benefits derived from improving only the engine.

Reference

1. Harmon, T. J. and R. P. Pauckert, "Integrated Modular Engine for Upper Stage Propulsion," AIAA 92-3693, AIAA Joint Propulsion Conference, Nashville, TN, 1992