OPERATIONALLY EFFICIENT SPACE-BASED INTEGRATED PROPULSION MODULE

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ABSTRACT

Space-based propulsion systems, for lunar and Mars missions, will require operability to be a prime design requirement. Propulsion system processing is tedious, time consuming, and uses many people with sophisticated support equipment to verify flight system readiness. An operable system is defined as having simple flight readiness processes and checkouts. Since the rocket engine propulsion system represents one of the most complex systems in a space-based vehicle, a study was made to identify propulsion system operational problems.

This paper uses descriptions of major operations problems encountered in today's launch vehicles as a point of departure for this study. Lessons learned from the Space Shuttle, expendable launch vehicles, and satellite maintenance reveal activities that are time consuming, costly, difficult, and potentially dangerous. Operational functions are much more difficult in space, have a large impact on cost, and unscheduled operations could result in a missed launch window.

Launch and satellite flight certification problems are related to projected space-based propulsion system operations issues. Space-based propulsion systems may be reusable with long periods of space exposure and storage between firings. The space-based propulsion system operability study approach is described, and tradeoffs are presented on operability. Operations driven requirements focus on minimizing or eliminating processing and checkout operations.

This paper presents a concept description of a zero maintenance, space-based, integrated propulsion module system. This system is operationally efficient, minimizing operational activities. The resulting propulsion system is simpler, more reliable, has enhanced component out capability, and is more operable than a conventional unintegrated engine system.

INTRODUCTION

The Lunar Excursion Module (LEM), NASA's last man-rated, space-based propulsion vehicle, landed and launched from the moon six times without firing rooms or anything else. These successful missions epitomize the effectiveness of minimizing propulsion system operational requirements. The LEM vehicle used single operation propulsion systems; one for landing and one for launch. However, the ground-based operational checkouts performed on the LEM at the beginning of the mission were massive. Also, a simple low performance propulsion system was used and this level of risk is not acceptable today. The return to the moon and future Mars missions envision propulsion systems with engine out capability, multiple firings, and reuse after long periods of space storage. These requirements add to the burden of providing an operationally efficient propulsion system.

This paper begins with descriptions of major operations problems encountered in today's launch vehicles. The focus is limited to propulsion system launch operational concerns. The Space Shuttle, with its reusable propulsion system, provides an extensive database on operability. In addition, expendable launch vehicles and satellite maintenance add to this database. Note that these systems all begin with extensive ground-based checkouts. Ground operations for contemporary launch vehicles have become a large part of vehicle recurring costs per flight, ranging from 20 to 45% for expendable and reusable vehicles. Operations for space-based propulsion systems will have a major impact on the effectiveness of future manned space efforts and the selection of competing modes; i.e., space-based mode, direct mode, and rendezvous or docking mode.

SPACE BASING

The success of a propulsion system deployed in space—lunar or Martian environments—depends on the ability of the various subsystems to perform their functions effectively. The propulsion system must be able to operate with flexibility and be maintained expeditiously. Finally, the propulsion system must be independent from complex support and logistics procedures. The Apollo program incorporated built-in propulsion system redundancy in all but one propulsion system, the LEM ascent stage. Next generation manned space-based propulsion systems are assumed to have engine out and fault tolerance capability on all propulsion systems.

Operational functions are much more difficult in space. Extravehicular activity or robotic operation will be used to conduct any nonautomated operational activity. Personnel, equipment, consumables and spares must also be boosted into space to support operational activity. The resulting cost means these activities must be minimized.

Space-based operations, if conducted in the same manner as current ground operations, would have prohibitive recurring costs per flight. Unscheduled operations could have a major impact on launch schedules. The effect of missing a planetary launch window could cause a delay of months to years.

CONCERNS

The Operationally Efficient Propulsion System Study (OEPSS),[1] developed a list of 23 concerns for launch systems. Reviewing this list for space-based propulsion systems reveals there is synergism with most of the concerns on the list. Only two items, ocean recovery and retractable umbilical carrier plates, are not applicable. A list, amended from launch vehicle concerns, of space-based propulsion system (vehicle) concerns, follows.

Space-Based Propulsion System Concerns

- Closed aft compartments
- Fluid system leakage
- External
- Internal
- Hydraulic system for valve actuators and TVC
- Multiple propellants
- Hypergolic propellant safety
- Accessibility
- Sophisticated heat shielding
- Excessive components/subsystem interfaces
- Lack of hardware integration
- Separate OMS and RCS
- Pneumatic system for valve actuators
    - Actuation
    - Purging
    - Spin-up
    - Pressurization
- Gimbal system requirements
- High maintenance turbopumps
- Ordinance operations
- Propellant tank pressurization systems
- Excessive interfaces
- Conditioning/geysering (LOX tank forward)
- Preconditioning system
- Expensive commodity usage - helium
- Lack of hardware commonality
- System contamination

This list identifies operations problems that have driven ground-based operations activities to exorbitant levels, severely restricting our ability to achieve routine space access. Overlaying the difficulties of space-based operations means that most of the above concerns must be eliminated.

The concerns listed reveal that many of the operational complexity issues must result from the system design. As the basis for the concerns list stems from launch operations experience, it is abundantly clear that operations issues were not fully appreciated or addressed during the design process. A simplified overview of propulsion system design process would be instructive.

PROPULSION SYSTEM DESIGN PROCESS

A mission is defined, a mission architecture is determined, prime contractor(s) are chosen, and finally major subsystem contracts are initiated. Propulsion system requirements pass through this trickle-down process. For a new mission, such as the Apollo and Space Shuttle programs, costly and schedule-intensive engine development programs were completed. Propulsion system requirements evolved and focused around performance, development cost, schedule, and reliability. The relatively long engine development program length sometimes results in selection of the engine design very early in the process.

A manned spacecraft such as the LEM had nine major subsystems. These elements are listed below. The propulsion subsystem consisted of the rocket engines (one descent and one ascent engine), six propellant tanks, three helium tanks, helium pressurization modules, heat exchangers, and a supercritical helium pressurization module. Interface and integration were achieved through specifications and interface control drawings. These multiple subsystems were treated as independent entities. At this subsystem level many operational issues, for example accessibility, excessive components/subsystem interfaces, and lack of hardware integration, were difficult to address in the larger context of the integrated vehicle.

Lunar Module Major Subsystems

- Guidance, navigation, and control
- Crew provisions/displays
- Environmental control
- Electroexplosive devices
- Instrumentation
- Electrical power
- Main propulsion
- Reaction control
- Communications

An examination of the LEM major subsystems reveal at least two areas where integrating the systems could be beneficial operationally: the main propulsion and reaction control systems. Combining these systems could significantly reduce operational activities for both subsystems. The Propulsion Subsystem alone includes components (rocket engines, propellant tanks, etc.) which were procured from separate contractors. Interface and integration were maintained through specifications and interface control drawings. This process, with its many interfaces, aggravates operations concerns. Clearly a change in the design process to include operability will be required for true space-based propulsion system requirements. Let us begin with redefining the propulsion system.

Propulsion System Definition

Current practice defines a propulsion system from the inlet to the engine to the nozzle exit. Resources or utilities required to operate the engine, such as purges, electrical power, and hydraulic power, are supplied by the vehicle or incorporated on the engine system. An artificial interface for these utilities, defined by the interface control document, "hand off" these utility responsibilities to the next subsystem or the vehicle integrator.

A suggested new propulsion system definition would be from the vehicle propellant tank inlet to the engine system exhaust exit. Figure 1 graphically describes the two propulsion system definitions. Within these boundaries as much integration as possible would be incorporated to simplify or eliminate operations concerns. Multiple subsystems and suppliers can be embodied in this definition; however, a higher degree of total propulsion system integration design and management would be required.

INTEGRATED DESIGN PROCESS

The system integration management process must include an operability element or focus. To achieve space-based operational efficiency, the principles of Total Quality Management (TQM) need to be applied to product quality; that is, quality cannot be inspected into product, it must be designed into it. Likewise, operational efficiency cannot be added on to a product; it must be designed into it. Operations must not just support the design: It must be one of the factors that drive the design from the conceptual beginning to the final production output. The TQM approach is illustrated in the design/build/operations cycle shown in Fig. 2 . Space-based propulsion systems must be produced using an integrated design process that includes design, operations, and manufacturing working in an integrated manner.

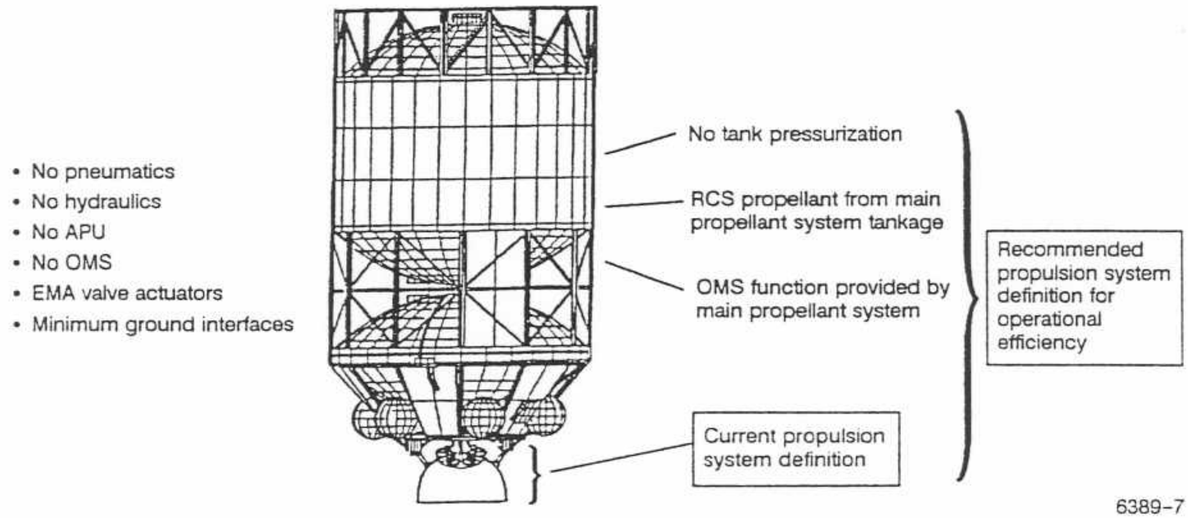


Figure 1. Propulsion System Definition

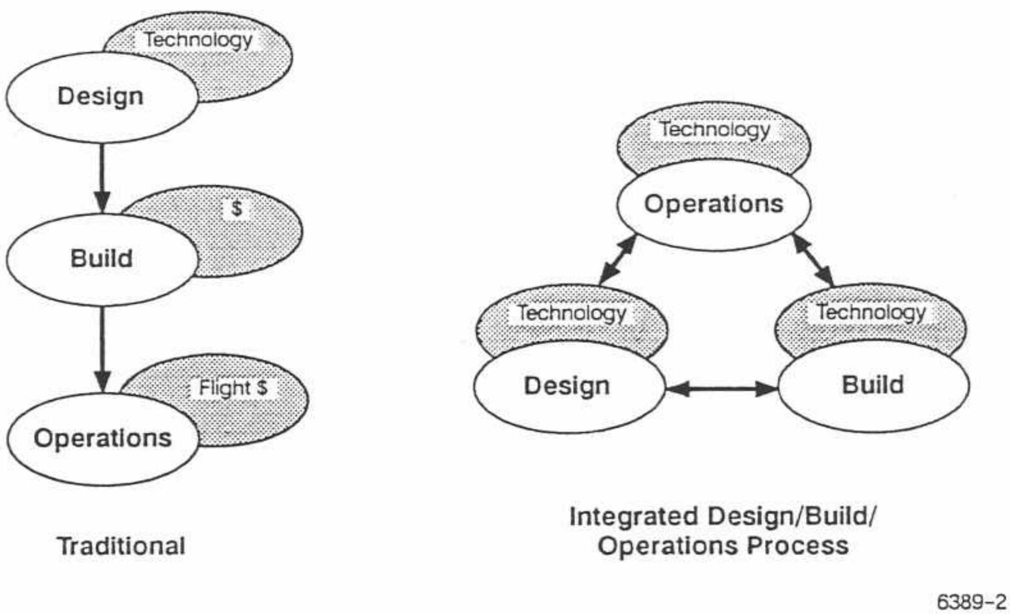


Figure 2. Total Propulsion Design/Build/Operations Process

SPACE-BASED PROPULSION REQUIREMENTS

The basic requirement for space-based propulsion is to eliminate or minimize operations. Design goals can be formulated based on the above requirement and are listed below.

Space-Based Propulsion Design Goals.

- Eliminate EVA operations
- No in-space assembly
- Eliminate in-space replacements
- Eliminate inspections
- No fluid transfers except propellants
- No hydraulics
- Eliminate pneumatics
- Single propellant combination
- Integrate propellants with reaction control systems, life cycle, power, and thermal systems

REDUNDANCY

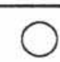
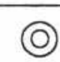
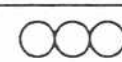
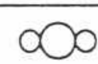
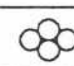
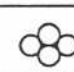
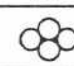
The added dimensions of propulsion system reusability, long-term storage, and operation at long distances from the earth increase the importance of redundancy and fault tolerance in the propulsion system. Several space propulsion system components and engine system arrangements were examined for their effects.

Redundant component engine clusters were evaluated for space-based propulsion applicability. In this approach, instead of having multiple independent parallel engines, the components (thrust chamber and turbopumps) are configured in parallel. A component failure, such as a single turbopump, would not have as great an impact on the thrust capability of the overall propulsion system, since the remaining pumps and all the thrust chambers remain on line. With independent engines, a single pump failure causes the shutdown of an entire engine. Components configured in parallel will improve overall propulsion system reliability. Additional benefits include easier component accessibility and improvements in throttling capabilities.

A summary of the cluster configurations analyzed is presented in Table I. This summary includes the number of turbopump (T/P) sets, number of thrust chamber (T/C) sets, and the geometric T/C arrangement. A single independent engine and a four independent engine cluster are included for references to evaluate the relative benefits of the parallel component layouts.

A simplified schematic for the three T/C and two T/P configuration is presented in Fig. 3. The detailed ducting through the coolant circuits and turbines was deleted from this schematic so the basic principle

Table I. Cluster Configurations Analyzed

Number of T/P Sets	Number of T/C Sets	T/C Pattern
1*	1	
2	2	
2	3	
3	3	
2	4	
4	4	
4*	4	

*Independent Engine(s)

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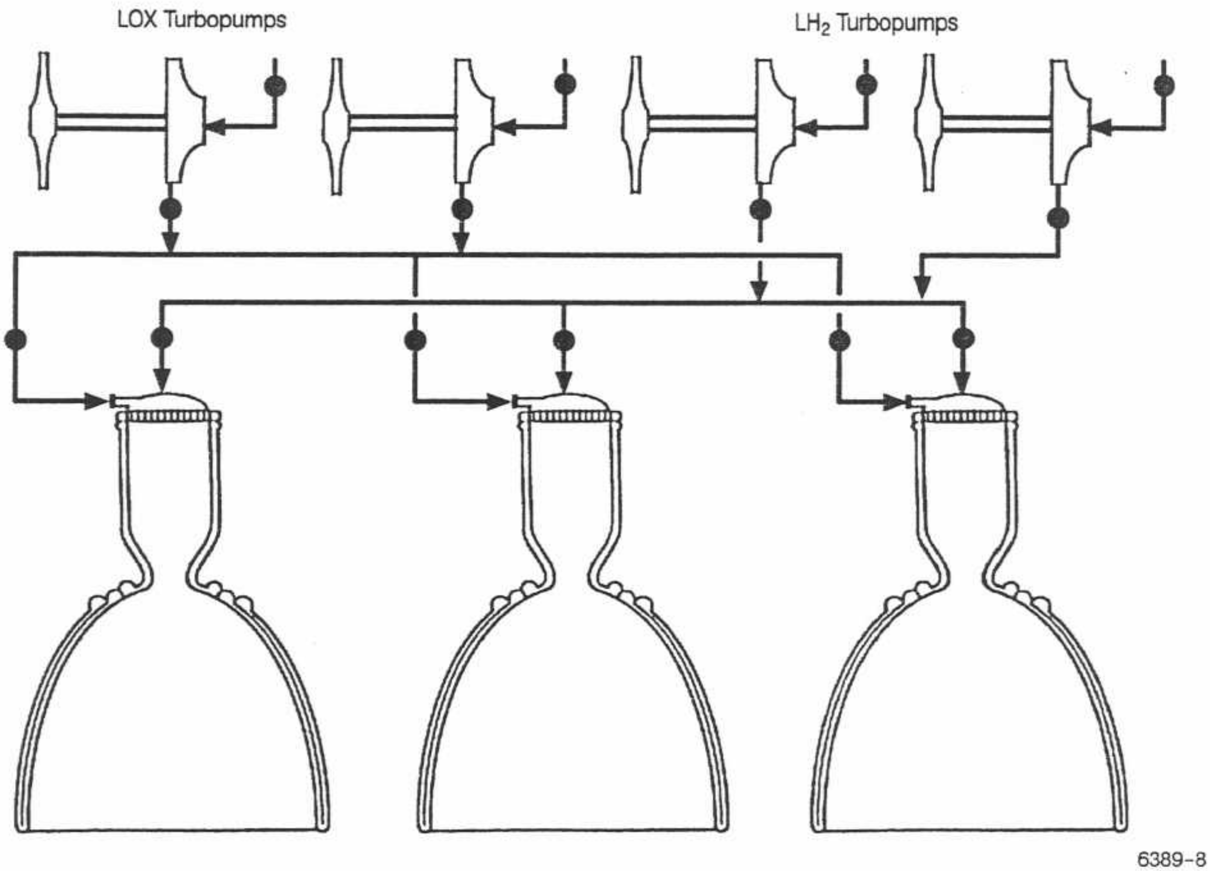


Figure 3. Integrated Propulsion System—Simplified Schematic.
Three Thrust Chamber/Two Turbopump Set Configuration

behind manifolded parallel components could be more easily understood. The T/Ps feed common manifolds that are plumbed to the T/Cs. Isolation valves around each component enable failed components to be "valved" out of the system, thus minimizing the impact of the failures.

Failure Accommodation

A total propulsion system thrust of 80 klbf was assumed for these analyses. A minimum of 40 klbf was also assumed to be required to complete a mission. If the system thrust after component failure dropped below 40 klbf, the mission was lost.

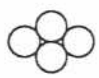
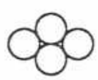
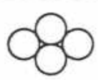
The impact of the various combinations of single component and double component failures was assessed for the seven configurations studied. The results of these hypothetical situations are summarized in Tables II and III. For illustrative purposes the ramifications of the various combinations of failures for the two–T/P and four–T/C configuration will be presented.

With the two–T/P and four–T/C configuration, four 20 klbf T/Cs are arranged in a square pattern. For a single T/C failure, both the failed T/C and the opposing T/C are valved out of the circuit. The minimum mission thrust of 40 klbf is still achieved. It is necessary to shut down the opposing T/C to maintain the correct thrust vector, since gimballing would require excessive angles for the three remaining T/Cs.

A single T/P (LH_2 or LOX) failure would be accommodated by valving that T/P out and running the four T/Cs at reduced thrust. The total thrust could vary from 40 lbf to some higher value, based on how much the flow rate from the remaining T/P could be safely increased.

A simultaneous failure of two T/Cs can occur for opposing or adjoining units. If they are opposing T/Cs, they are both simply valved off and the mission proceeds with the remaining T/Cs each at 20 klbf. If

Table II. Integrated Space Propulsion System Single Failure Tolerance

Concept	Configuration T/P–T/C	T/C Pattern	Single Failure			
			1 T/C Lost		1 T/P (LH_2 or LOX) Lost	
1*	1–1		Mission lost	–	Mission lost	–
2	2–2		Operational	Remaining T/C F = 40K Q = 50%	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
3	2–3		• Center T/C fails–operational • O.B. T/C fails–mission lost	• Remaining 2 T/C F = 53.4K • Shut opposing T/C, F = 26.7K	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
4	3–3		• Center T/C fails–operational • O.B. T/C fails–operational	• Remaining 2 T/C F = 40K • Shut opposing T/C, F = 40K	Operational	$53.6 \leq F \leq 80K$ $100 \leq Q \leq 150\%$
5	2–4		Operational	Shut opposing T/C, F = 40K	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
6	4–4		Operational	Shut opposing T/C, F = 40K	Operational	$60 \leq F \leq 80K$ $100 \leq Q \leq 133\%$
7*	4–4		Operational	Shut opposing T/C, F = 40K	Operational	Shut opposing engine, F = 40K

*Independent Engine(s)

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adjoining T/Cs fail, the mission is lost because the remaining T/Cs do not have the gimballing capability to provide the correct thrust vector through the vehicle center of gravity.

For a double failure involving one T/C and one T/P, these two components and the opposing T/C are valved out and the mission continues at 40 lbf (or greater if the remaining T/P can run at a higher operating speed).

If one LOX and one LH_2 T/P fail, they will be isolated from the system and the mission will continue as in the scenario above. Finally, if two turbopumps fail and both are either LOX or LH_2 pumps, the mission is lost.

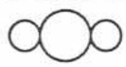
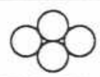
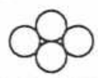
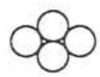
These permutations of the component failure modes are addressed for each of the seven configurations in Tables II and III. The doubling of the thrust chambers in the 4–4 configuration to a 4–8 (four turbopump sets and eight thrust chambers) allows double failures in all situations with full operational capability. This integrated system is shown in Fig. 4.

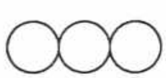
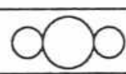
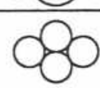
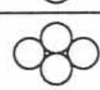
The integrated system, shown in Fig. 4, describes a zero maintenance, space-based, integrated propulsion module system. This space-based propulsion module system is operationally efficient, minimizing operational activities. The resulting propulsion system is simpler, more reliable, has enhanced component out capability, and is more operable than a conventional unintegrated engine system.

Operations Enhancing Technology

The Space-Based Propulsion System Concerns list provides a basis to identify technology areas that would enhance operability. The Operationally Efficient Propulsion System Study (OEPSS)[1] developed a technology list for mitigating launch system concerns. Space-based propulsion systems again show synergism with the operations enhancing technology list. All launch-related operations enhancing technologies are

Table III. Integrated Space Propulsion System Double Failure Tolerance

Concept	Configuration T/P–T/C	T/C Pattern	Double Failure			
			2 T/Cs Lost		1 TC and 1 T/P Lost	
1*	1–1		–	–	Mission lost	–
2	2–2		Mission lost	–	Operational	F=40K
3	2–3		• 2 O.B. T/C fail-mission lost • Center & O.B. T/C fail-mission lost	• F=26.7K • –	• Center T/C fails-operational • O.B. T/C fails-mission lost	• F=40K • Shut opposing T/C F=26.7K
4	3–3		• Mission lost	–	Operational	F=40K Q=75%
5	4–4		• Mission lost	–	Operational	Shut opposing T/C F=40K Q=100%
6	4–4		• Mission lost	–	Operational	Shut opposing T/C F=40K Q=67%
7*	4–4		• Mission lost	–	• Mission lost	• Shut opposing engines F=40K • Shut both engines F=40K • –

Concept	Configuration T/P–T/C	T/C Pattern	Double Failure			
			2 T/Ps Lost 1 LH_2 and 1 LOX		2 T/Ps Lost 2 LH_2 or 2 LOX	
1*	1–1		Mission lost	–	–	–
2	2–2		Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$	Mission lost	–
3	2–3		Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$	Mission lost	–
4	3–3		Operational	$53.6 \leq F \leq 80K$ $100 \leq Q \leq 150\%$	Operational	F=40K Q=150%
5	2–4		Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$	Mission lost	–
6	4–4		Operational	$60 \leq F \leq 80K$ $100 \leq Q \leq 133\%$	Operational	$40 \leq F \leq 80K$ $100 \leq Q \leq 200\%$
7*	4–4		• Failure in same engine-operational • Failure in opposing engine-operational • Failure in adjacent engine-mission lost	• Shut opposing engine F=40K •Shut both engines F=40K • –	• Failure in opposing engine-operational • Failure in adjacent engines-mission lost	• F=40K • –

*Independent Engine(s)

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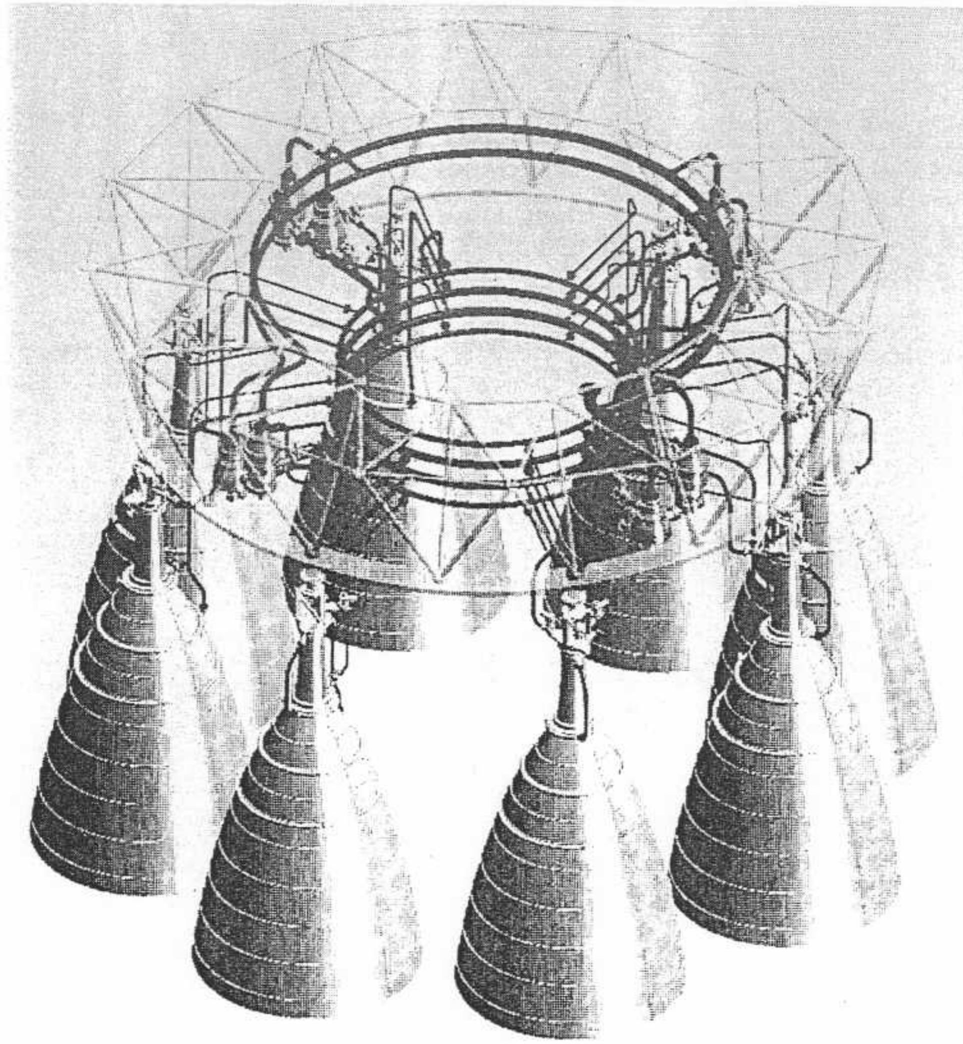

Figure 4. Integrated Propulsion Module System

applicable. The addition of some space-based specific technology areas results in the following list for space-based operations enhancing technologies.

Space-Based Operations Enhancing Technologies

- No leakage mechanical joints
- Electric Motor Actuator (EMA)
- Automated leak detection
- Automated internal leak detection
- Combined O_2/H_2 systems (propulsion, RCS, OMS, fuel cell)
- No purge pump seals
- No flight purge combustion chamber
- Flash boiling tank pressurization
- Nonintrusive instrumentation
- Automated visual inspection
- Differential throttling
- Low NPSH pumps
- Large flow range pumps
- Oxidizer-rich turbine in LOX turbopump
- Hermetically sealed inert engine (initial earth launch)
- Health monitoring for space-based propulsion system
- Automated preflight readiness checkout for space-based system

Technology programs successfully concluded and incorporated into a space-based propulsion system would significantly reduce the operations activity content of such a system. The result would be routine space-based flight operation.

Summary and Conclusion

The launch systems of today have a high operations content and related high cost and low flight rates. As there are no man-rated, space-based propulsion systems in operation at this time, we must infer space-based systems will be based on this current launch system legacy. This approach has been shown to be unusable since space basing will not have the resources of current ground launch systems. The complex propulsion systems on current launch systems are a major part of this problem.

Operations activity must be significantly improved for space-based propulsion systems if the goals of the Space Exploration Initiative are to be achieved. This paper's study results provide the following conclusions:

(1) The success of a propulsion system deployed in space to a lunar or Martian environment depends on the ability of the various subsystems to perform effectively. The propulsion system must be able to operate with flexibility and be maintained expeditiously. A propulsion system must be independent from complex support and logistics procedures.

(2) Space-based propulsion systems must be produced using an integrated design process that includes design, operations, and manufacturing working in an integrated manner.

(3) Operational functions are much more difficult in space. Extravehicular activity or robotic operation will be used to conduct any nonautomated operational activity.

(4) The basic requirement for space-based propulsion is to eliminate or minimize operations.

(5) The Space-Based Propulsion System Concerns list identifies operations problems that have driven ground-based operations activities to exorbitant levels, severely restricting our ability to achieve routine space access. The concerns list reveals that many of the operational complexity issues must result from the system design. Overlaying the difficulties of space-based operations means that most of the above concerns must be eliminated.

(6) The added dimensions of propulsion system reusability, long-term storage, and operation at long distances from Earth mean that issues of maintenance, redundancy, and fault tolerance increase in importance. An integrated design approach, with built-in redundancy, is a potential solution that can also incorporate solutions to space-based operational concerns.

(7) Technologies to improve operability must be identified and pursued.

Reference

1. "Operationally Efficient Propulsion System Study" (OEPSS), NASA/KSC Contract NAS10-11568, G. S. Wong, Rocketdyne Division, Rockwell International, RI/RD90-149-1, -2, -3, -4, and -5, April 1990.

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