

9.0 PROPULSION SYSTEMS PANEL DELIBERATIONS

The Propulsion Systems Panel was established because of the specialized nature of many of the materials and structures technology issues related to propulsion systems. This panel was co-chaired by Carmelo Bianca, MSFC, and Bob Miner, LeRC. Because of the diverse range of missions anticipated for the Space Transportation program, three distinct propulsion system types were identified in the workshop planning process: liquid propulsion systems, solid propulsion systems and nuclear electric/nuclear thermal propulsion systems.

9.1 LIQUID PROPULSION SYSTEMS SUBPANEL ACTIVITIES

The Liquid Propulsion Systems Sub-panel was chaired by Larry Johnston, MSFC.

Eight global issues were identified and 25 specific issues/technology requirements quad charts were prepared by the Liquid Propulsion Systems subpanel.

The initial global issues identified were:

- Combustion Chamber Materials
- Propellant-Compatible Materials
- Fabrication Techniques
- Turbopump Materials
- Nozzle Materials
- Bearing Materials
- Data Base
- Lightweight Insulations

The specific issues/technology requirements developed for each of the subpanel topics were presented by the lead member of each of the subpanels (Paul Munafa for Materials, Larry Johnston for Structures and Walt Karakulko for Operations). Ensuing discussions resulted in additions to both global and specific issues and the final list developed by the panel is shown in Figure 9.1. The number in parentheses which follows the issues listed in Figure 9.1. indicates the number of times each issue was raised in the liquid propulsion system quad charts.

LIQUID PROPULSION SYSTEMS PANEL

ISSUES/TECHNOLOGY REQUIREMENTS

| | |
|---|------|
| • IMPROVED FABRICATION PROCESSES | (11) |
| • IMPROVED ANALYSIS & TEST METHODS | (4) |
| • PROPELLANT COMPATIBLE MATERIALS (ENABLING) | (6) |
| • IMPROVED BEARING & SEAL MATERIAL & FABRICATION PROCESSES (ENABLING) | (7) |
| • IMPROVED COMBUSTION CHAMBER MATERIALS DEVELOPMENT (ENABLING) | (7) |
| • IMPROVED TURBOPUMP MATERIALS | (4) |
| • IMPROVED NOZZLE MATERIALS | (4) |
| • DEVELOP GLOBAL MATERIALS & PROCESSES DATA BASE | (3) |
| • LIGHTWEIGHT STRUCTURAL MATERIALS DEVELOPMENT | (2) |
| • LIGHTWEIGHT INSULATION MATERIALS DEVELOPMENT (ENABLING) | (1) |
| • IMPROVED ENGINE HARDWARE | (4) |
| • IMPROVED PROJECTILE SHIELDING | (1) |
| • IMPROVED PROPELLANTS | (1) |

Figure 9.1 Liquid Propulsion Panel Global Issues List

The subpanel then prioritized the specific issues/technology requirements to define the highest priority issues which would be provided to the Propulsion Systems Panel Co-chairman, Carmelo Bianca, and subsequently presented to the workshop as part of the Propulsion Systems Panel report. Prior to undertaking that task, Tom Herbell, Lewis Research Center, presented a briefing on ceramic composite technology research being conducted at Lewis for application to liquid rocket turbopump parts. He cited the benefits of composites - higher turbine inlet temperatures and extended service life - and indicated the funding requirements over a period of time that would be required to establish the technology base.

While prioritizing, the subpanel raised a number of additional issues, which are listed below:

- What criteria should be used to select top priority technologies: near-term (materials compatibility) vs. longer-term (composite materials) technologies?

- Propellant management technology issues should be raised as a comment.
- Launch costs are again increasing the importance of performance.
- Technology programs have insufficient funds to carry technology far enough and program managers are unwilling to take risk with new technologies (fear of failure syndrome).
- Technology sharing with Air Force should be encouraged.

The specific issues and technology requirements included in the Panel Summary Report were:

- *Improved fabrication processes for rocket engine components:* Plasma spray forming, platelet technology, diffusion bonding, tubular construction, near-net-shape fabrication, precision castings, superplastic forming, electroforming, laser-welded coolant tubes, and joining processes.

- *Improved analysis and test methods:* Durability modeling in one computer code and accelerated test techniques
- *Propellant-compatible materials:* Hydrogen-resistant alloys, improved materials for rubbing in an oxygen environment, environmentally-compatible materials for cleaning, and methods to neutralize the effects of nitrogen-tetroxide on materials.
- *Improved bearing and seal materials and fabrication processes:* Cryogenic rolling-element bearing materials, bearing cage materials, improved seal materials, foil bearings, dual-property bearing race processing, application of ceramic materials to cryogenic bearings, and the application of nanocrystalline materials to bearings.

9.2 SOLID PROPULSION SUBPANEL ACTIVITIES

The objective of the Solid Propulsion Subpanel, chaired by Raymond Clinton, MSFC, was to assess the state of the art in solid propulsion materials, structures and manufacturing processes, compare this to needs identified prior to and during the plenary session of the workshop and determine the areas where additional technology effort should be expended to meet these needs.

The Solid Propulsion Subpanel divided into ten task teams representing each of the basic elements of solid rocket motors. These task teams were: 1) motor cases, 2) propellants, 3) nozzles, 4) bondlines, 5) nondestructive evaluation, 6) motor case insulation, 7) materials properties, 8) analysis, 9) adhesives, and 10) hybrid motors.

The task teams prepared inputs prior to the workshop regarding the state of current technology and the needs in each of the ten areas. As a result of this thorough assessment of current technology and future propulsion system needs, a preliminary determination of the technology required to satisfy these needs was completed. A total of 90 technology needs were defined by the task teams. In order of greatest number, these

were: bondlines - 25; analysis - 14; propellants - 13; nozzles - 8; NDE - 7; motor case insulation - 6; materials properties - 6; motor cases - 5; adhesives - 4; and hybrid motors - 2. The Liquid Propulsion Subpanel added to this list four additional needs in NDE and motor cases. After review and combination of the needs, the following list resulted: 1) bondlines/propellant - 42; 2) nozzles - 28; 3) motor cases - 11; 4) motor case insulation - 7; 5) hybrid rocket propulsion - 2.

Presentations in the following areas in which additional technology effort was determined to be needed were made:

- Motor cases
 - Improved case materials/forms
 - Improved case joints/attachments
 - Self insulating case
- Propellant/Bondlines
 - Material and process variability
 - Bondline design for inspectability
 - Propellant and bondline failure criteria
 - Propellant test techniques
- Insulation
 - TPE insulator fabrication technology and bondline characterization for large motors
- Nozzles
 - Process understanding, optimization and control for ablative nozzle components
 - Robust ablative nozzle material and process development
- Analytical issues
 - Material response characterization and constitutive modeling of ablative materials
- Hybrid propulsion
 - Hybrid propulsion feasibility demonstration

The two white papers in Section 9.4 address issues discussed by the solid propulsion

subpanel. They were submitted by subpanel members subsequent to review and are included for information.

9.3 NUCLEAR PROPULSION SYSTEMS SUBPANEL ACTIVITIES

The Nuclear Propulsion Subpanel of the Propulsion Panel was chaired by Bob Miner, LeRC, and co-chaired by James Stone, LeRC. This subpanel was organized to assess nuclear propulsion materials and structures technology issues. The subpanel meetings began with presentations on Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) systems and materials. The titles and authors of the presentations were:

- "Fuels Development for Nuclear Propulsion Systems," by Bruce Matthews, Los Alamos National Laboratory
- "Materials for Space Nuclear Thermal Propulsion Systems" and "Refractory Alloys for Space Nuclear Electric Propulsion Systems," by Roy Cooper, Oak Ridge National Laboratory
- "Fuel Materials Issues Involved in the Development of Nuclear Thermal Rockets" and "Non-Fuel Materials Issues Involved in the Development of Nuclear Thermal Rockets," presented by Bob Long, Babcock & Wilcox

The primary driving force behind renewed interest in space nuclear propulsion is SEI. The Stafford Synthesis Group labeled nuclear thermal propulsion an enabling technology for SEI. During 1991, an interagency (NASA/DOE/ DoD) technical panel has been evaluating nuclear thermal propulsion concepts as well as planning a joint technology development project in nuclear propulsion. The present plan calls for demonstrating Technology Readiness Level (TRL) six for NTP and TRL five for NEP by the year 2006.

Currently, the state of the art in nuclear technology is defined by the NERVA/ROVER nuclear rocket programs from the 1960s and 1970s for NTP and the latest results on SP-100 for NEP.

New NTP systems for SEI require the reactor to operate at temperatures (3000 K exhaust temperature) beyond the capabilities of current fuels and materials technology used in the NERVA/ROVER program. Advances in materials systems hold the potential to significantly reduce NTP mass and realize the full impulse power potential of these concepts. Five major NTP subsystems can be identified: propellant tank, propellant pump, radiation shield, nuclear heat source, and thruster nozzle. Although no detailed designs exist for these systems or sub-systems, candidate materials for construction of these subsystems can be identified and developed. *The high operating temperatures for the fuels and core materials is the major technical feasibility issue for NTP reactors.*

For NEP systems, five major subsystems can be identified: nuclear heat source, radiation shield, power conversion, thermal management, and electric thruster. High-performance space nuclear electrical power systems will place severe demands on candidate alloys for fuel cladding and structural applications. Alloy selection criteria of major importance include creep strength, producibility, weldability and tolerance to radiation effects. Qualification of refractory alloys could be the pacing, and possibly the limiting, technology need of the space nuclear electric propulsion program. High burnup at end of life and accompanying swelling of the major fuels and cladding materials are technical feasibility issues for NEP reactors. The SP-100 engine operates at 1375 K and has a seven-year operating lifetime. However, for significantly higher operating temperatures and a target lifetime of seven years for NEP applications, presently-available alloys appear inadequate. New alloys will be required to achieve the goal of TRL five by 2006.

Ground testing was identified as the most critical need for qualifying nuclear propulsion systems. Construction of new facilities and refurbishment of present facilities will be necessary. These facilities range from fuel manufacturing plants to environmentally-safe, terrestrial-based propulsion systems test facilities. These new facilities may prove to be very difficult to design, fabricate and most importantly, afford.

Fuels and coatings were deemed the highest priority for NTP propulsion systems. This is because: (1) NTP was selected by SEI as the propulsion system of choice for Mars missions, and (2) nuclear fuels and coatings are the very foundation of nuclear propulsion. A description of the desired characteristics for NTP fuels and coatings follows:

- ~100% fission product retention
- Thermal stability (low mass loss at $T \geq 3000$ K in H_2 over five hours)
- High melting point (> 3400 K)
- High fuel density
- Thermal shock resistance
- Slow degradation mechanisms
- Chemical compatibility with coating and matrix materials
- High surface area to volume ratio
- Fabricability

The recommended actions to produce these fuels and coatings are:

- Reduce concepts by defining criteria, eliminating non-performers, down-selecting, and combining designs
- Initiate R&D on issues common to proposed fuels and coating technologies
- Construct test facilities
- Initiate R&D to demonstrate evolutionary improvement in safety and performance (increase time & temperature)
- Initiate fabrication and characterization development
- Initiate prototypical fuel element testing
- Generate data to:
 - Support engineering designs
 - Qualify operating margins
 - Predict reliability

- Complete safety analyses

The Nuclear Propulsion Subpanel assigned the second highest priority to NEP refractory alloys and described the desired characteristics for NEP refractory alloys as follows:

- Lifetime greater than two years at temperatures greater than 1500 K
- Compatibility with candidate fuels
- Compatibility with working fluids and coolants
- High strength at operating temperatures
- Resistance to radiation damage
- Readily fabricated into complex components

The actions necessary to produce NEP refractory alloys are:

- Reduce candidate concepts and select candidate materials
- Develop materials specifications
- Optimize fabrication methods
- Establish supply infrastructure
- Generate preliminary data base for:
 - Radiation damage effects
 - Compatibility with coolant & working fluids
 - High temperature mechanical properties
- Refurbish facilities to support the above

NEP fuels and claddings were assigned the third highest priority, and the desired characteristics for them are:

- High burnup: 10-25% at end of life for liquid metal cooled and 3-5% for gas cooled reactors
- Low fission gas release and swelling
- Fuel/cladding/fission product compatibility

- Fuel cladding integrity
- High creep strength for cladding materials
- Fuel element integrity for thermionic conversion systems
- Benign off-normal performance

The actions necessary to produce NEP fuels and claddings efficiently are:

- Reduce concepts by defining criteria, eliminating non-performers, down selecting, and combining designs
- Develop and test stable, comparable, high temperature fuels
- Start prototypical, high-burnup irradiation testing program
- Construct ground testing facilities
- Generate data to:
 - Support engineering designs
 - Qualify operating margins
 - Predict reliability
 - Complete safety analysis

Lightweight, high-temperature, and high-performance radiator materials were given the fourth highest priority, but are key for NEP systems. Increased weight reduces the

NEP thrust-to-mass ratio and also results in more initial mass to Low Earth Orbit. These radiator materials should have the following characteristics:

- $T > 1000$ K
- High specific conductivity
- Protection from alkali metals
- High strength/stiffness
- High emissivity/coating

The actions necessary to produce lightweight, high-temperature, and high-performance radiator materials are:

- Carbon/carbon
 - Select most robust high conductivity fiber
 - Develop composite architecture to reduce weight and increase through-thickness conductivity
 - Develop light protective liner
 - Optimize surface emissivity
- Graphite/copper
 - Optimize interfacial bonding
 - Develop joining process
 - Optimize surface emissivity
- Fabricate subscale radiator segment

9.4 PRESENTATIONS

9.4.1 Hybrid Rocket Propulsion by Allen L. Holzman, United Technologies/Chemical Systems