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8.0 VEHICLE SYSTEMS PANEL DELIBERATIONS

The Vehicle Systems Panel addressed materials and structures technology issues related to launch and space vehicle systems not directly associated with the propulsion or entry systems. The Vehicle Systems Panel was comprised of two subpanels - Expendable Launch Vehicles & Cryotanks (ELVC) and Reusable Vehicles (RV). Tom Bales, LaRC, and Tom Modlin, JSC, chaired the expendable and reusable vehicles subpanels, respectively, and co-chaired the Vehicle Systems Panel. The following four papers are discussed in this section.

- "Net Section Components for Weldalite™ Cryogenic Tanks," by Don Bolstad
- "Built-up Structures for Cryogenic Tanks and Dry Bay Structural Applications," by Barry Lisagor
- "Composite Materials Program," by Robert Van Siclen
- "Shuttle Technology (and M&S Lessons Learned)," by Stan Greenberg

8.1 PRESENTATION SUMMARIES

8.1.1 AL-LI TECHNOLOGY STATUS

Presentations described current capabilities in fabricating aluminum-lithium (Al-Li) parts for launch vehicle components and cryotanks. Much of the material presented illustrated specific components that have been created for the Advanced Launch System (ALS).

The ALS program has pursued advances in the following:

- Net-shape development
- Weld processing
- Efficient manufacturing
- Weld sensor development
- Tank fabrication and testing

Tank fabrication activities are primarily focused on reducing manufacturing and materials costs. Al-Li materials have lower weight (potential reduction of 15% or more) and density, and higher strength and modulus of elasticity than conventional aluminum alloys. To decrease machining scrap in the fabrication process, companies are exploring methods to extrude large sections in near-net shapes from Al-Li. Several extruded components have been demonstrated by the ALS program.

Laboratories are also exploring methods of creating built-up structures from Al-Li. Initially, much of the work in built-up Al-Li structures focused on cryogenic tank applications, but now application to dry-bay structures is being examined. The payoffs for advancing technology in this area are expected to be lower vehicle dry weight and lower system costs due to reduced machining requirements. Examples of built-up Al-Li structures manufactured for the ALS were provided. Continued work is required in built-up Al-Li structures. Fracture and fatigue characteristics are several of the areas to be studied.

8.1.2 COMPOSITES TECHNOLOGY

Composite matrix and reinforcing materials include a range of polymers, metals and ceramics. In the case of space transportation vehicles, high temperature strength is sought through composites. Composites are therefore enabling in some vehicle programs (e.g. NASP) and offer excellent commercialization potential for a variety of applications, including cryogenic tankage, actively-cooled structures and high-temperature heat shields. Currently, 400 material fabricators and suppliers, 150 universities and research centers and 12 government entities research composites, although not all for space applications.

Composites technologies have rapidly advanced in recent years, although a national plan is needed to better implement composites technology in the building of space structures. Such a plan was developed by the Aerospace Industry Association (AIA), in its report entitled "Key Technologies for the 90's," which provided roadmaps for composites technologies. Implementation of the roadmaps is uncertain, however, and the organization is currently developing a National Composites Strategic Plan. Key issues associated with implementation of a national plan include:

- International competition
- Supplier vulnerability
- High product cost
- Evolving national educational policy
- Government budget and structure uncertainty
- Pace of technology implementation

The most significant requirement is involvement of the composites community to support a unified national agenda.

8.2 SUBPANEL ACTIVITIES

Many of the issues and technologies discussed by each subpanel were pertinent to both reusable and expendable systems, although the subpanels addressed technology issues differently because the applications required a different perspective. Cost was a consideration which differed the most between reusable and expendable applications. For example, material cost is a stronger driving force for expendable vehicles, which require construction of a new vehicle for every mission. For reusable vehicles, mission costs associated with vehicle mass are the primary life cycle cost driver and material costs are not as significant.

The subpanel sessions yielded a number of proposed activities. To better specify each of the specific issues and to obtain a consensus of the members, the subpanels considered each issue on its merits, evaluated the content of all of the submissions and identified the specifics of the subpanels' broad interests. The result of this effort was a constrained list of 20 specific issues for the ELVC subpanel and 23 for the RV subpanel. These issues are discussed further in the following sections.

8.2.1 EXPENDABLE LAUNCH VEHICLES AND CRYOTANKS SUBPANEL

The 13-member Expendable Launch Vehicles & Cryotanks subpanel included individuals with a wide cross section of skills and experience, and with both industrial and government affiliations. The diversity of the subpanel was very advantageous for assessing ELVC materials and structures technology.

In reaching a consensus, the subpanel concentrated on three major areas of concern:

- Materials development
  - Advanced metallics
  - Composites
  - Thermal protection system (TPS) / insulation
- Manufacturing technology
  - Near-net shape metals technologies
  - Composites
  - Welding
- Non-destructive evaluation methods and processes

Table 8.2.1 Priority Technology Issues for Expendable Launch Vehicles & Cryotanks

1. Advanced structural materials
2. Al-Li technology
3. Near-net shape fabrication technology for vehicle structures
4. Near-net shape metals technology
5. Near-net shape extrusions for structural hardware
6. Near-net shape forgings
7. Near-net shape spin forgings
8. Welding
9. In-space welding/joining
10. Composites technology for cryotanks and dry-bay structures
11. Joining technology for composite cryotanks
12. Tooling approach for manufacturing large diameter cryotanks
13. Develop a cure methodology for large composite cryotanks
14. State-of-the-art buckling structure optimizer program
15. State-of-the-art "shell of revolution" analysis program
16. NDE for advanced structures
17. In-line inspection of composites
18. Scale-up of launch vehicles
19. Launch vehicle TPS/insulation beyond 27.5 ft. diameter
20. Design and fabrication of thin-wall cryotanks for space exploration (5-20 ft. dia.)

Priority concerns of the Expendable launch vehicles and cryotanks Sub-Panel:

1. The primary near-term issue regarding Al-Li is availability of funding to ensure incorporation in the National Launch System.

- Production capability is in place for 8090, Weldalite and 2090 Al-Li alloys
- Near-net shape processes have been defined; scale-up activities are underway
- Program management decisions are required to exploit the potential of Al-Li alloys

This issue addresses producibility of Al-Li alloys for the National Launch System. The subpanel expressed concerns about the maturity of specific Al-Li alloys and progress in near net shape processes and scale-up activities. The subpanel would like to see program managers at NASA, DoD and the NLS Joint Program Office recognize the full potential of Al-Li alloy systems, and NLS program funding sufficient to allow program managers to act in a timely and definitive way to support Al-Li technology maturation for use in the NLS.

2. NASA materials technology programs should include research on expendable launch vehicles and cryotanks.

- A focused materials and structures technology program for launch vehicles is necessary.
- Sustained programs to support user needs and long-term NASA missions are clearly needed.

3. Structural analysis and optimization programs are needed.

The subpanel stressed a need for additional efforts at *all* levels in the area of structural analysis and optimization, computational methods and experimental verification, particularly for long duration and complex space environmental conditions.

4. Non-destructive evaluation (NDE) techniques and methods must be exploited to assure integrity, reliability and cost reductions.

This issue emphasizes the need to (1) define and develop NDE capabilities that enhance the production of advanced materials systems, including composites, and (2) verify the integrity and inherent quality of flight system hardware. These technologies, techniques and capabilities are required for expendable launch vehicle and cryotank applications to achieve reliability in operations and to provide necessary cost reductions.

5. Joining and bonding techniques and concepts must be developed and characterized for future large launch vehicle applications.

This statement emphasizes the need to develop advanced joining and bonding concepts for the large vehicle, cryotank and dry-bay applications envisioned for future system applications. This statement applies to both evolving composite systems and built-up intermetallic structures.

8.2.2 REUSABLE VEHICLES SUBPANEL

The Reusable Vehicles (RV) subpanel agreed to include vehicles meant for multiple missions or for repeated mission events, as expected with Mars exploration missions. Although an actual quantity of repeated missions was not agreed upon, most agreed that the set of critical issues (e.g., fracture mechanics and safe-life analysis) are the same for five to 10 missions as they are for 50 to 100 missions. Ideally, reusable vehicles are those which can return from flight, undergo inspection, and fly again in a reasonable time. Several panel members suggested the analogy of a commercial aircraft.

In creating a list of highest priority issues, the primary framework for discussion was future reusable vehicles requirements. The four most pertinent requirements for reusable vehicles were defined:

- Low cost
- High reliability
- Low maintenance
- On-time launch or deployment capability

The RV subpanel identified several technologies required for envisioned and existing missions and vehicle programs. Materials technology was the primary focus of subpanel discussions. Within the context of existing programs which require reusable vehicles such as NLS, SEI, NASP, SDIO/SSTO, Al-Li and composites technologies received the most attention.

Materials

As previously mentioned, metallics and composites were the primary topics discussed by the subpanel. Because of its near-term potential for upcoming missions, Al-Li technology was discussed in great detail, particularly for cryogenic tank applications. The benefits of Al-Li alloys were stressed, particularly:

- Lightweight as compared to conventional aluminum alloys
- High strength at cryogenic temperatures

The subpanel agreed that the technology for Al-Li must be advanced and that Al-Li alloys need focused development in the near term to impact planned launch vehicle designs. One clear Al-Li technology issue was that although several alloys are currently under development, *specific knowledge about any one alloy has not progressed to a point where a vehicle designer can safely baseline Al-Li for any particular application*. The subpanel recommended that Al-Li development follow a two-pronged path. One or two alloys should be chosen and fully characterized to enable evaluation for specific program needs. Simultaneously, a continuing effort should be supported to improve Al-Li characteristics such as strength-to-weight ratios, transverse strength and isotropy.

Composites were also discussed in detail by the RV subpanel. Recall that prior to the individual subpanel meetings, Robert Van Siclen presented an industry perspective on composites technology for space applications. The issues addressed in this presentation were enhanced by a discussion of potential applications of composites to reusable vehicle systems. In particular, application of composites technology to cryogenic tankage was addressed.

Table 8.2.2 Priority Technology Issues for Reusable Vehicles

- Cryogenic tankage
- Cryogenic tankage with LH_2
- Cryogenic tankage with LO_2
- Launch vehicle TPS/insulation
- Durable passive thermal control devices and/or coatings
- Development and characterization of processing methods to reduce anisotropy of material properties in Al-Li
- Durable thermal protection system
- Unpressurized Al-Li structures (interstages, thrust structures)
- Near net shape sections
- Pressurized structures
- Welding and joining
- In space joining
- Micrometeoroid and debris hypervelocity shields
- State-of-the-art shell buckling structure optimizer program to serve as a rapid design tool
- Damage tolerant design for composite structures
- Test philosophy
- Reduced load cycle time
- Optimized system engineering approach to ensure robustness
- Structural analysis methods
- Optimization of structural criteria
- Develop an engineering approach to properly trade material and structural concepts selection, fabrication, facilities and cost
- Maintenance and refurbishment philosophy

Through use of composites technology for NASP applications, much has been learned about composites and hardware manufacture for cryogenic hydrogen tanks using composites. By building a prototype composite cryogenic H_2 tank, NASP has advanced the state of the art in composites technology and suggested that Al-Li may not be the only alternative for reusable vehicle cryotanks. Composites and Al-Li alloys should be competed at all levels. The subpanel agreed that the benefits of composites for cryogenic tanks (in particular, weight savings, high strength properties and lower part count) warrant a level of effort that will allow continued research in composites technology for cryogenic applications. However, issues such as penetration effects (sealing), H_2 compatibility (liners) and H_2 leakage must be priorities for research to assess the realistic potential of composites. An example of composite material for cryotank applications is 8551-7 graphite-fiber-reinforced toughened resin.

The potential of composites for LO_2 tanks and the primary issue associated with composite LO_2 tanks – flammability protection – were also discussed. The hydrogen content in composite resins requires that tank liner technology be advanced to seal the resin from the LO_2. Technology issues for liners involve safety from microcracking and permeability. Also, non-ignition source level sensors must be developed to reduce risk with composite LO_2 tanks. The greatest benefit of composite cryotanks is expected to be a 10-15% reduction in tank weight and the associated significant cost savings. However, the realistic potential for composite LO_2 tanks was not readily conceded by the entire subpanel.

Metal matrix composites (MMC) technologies are being pursued by the NASP program, especially titanium-based composites, because of their potential as hot structure materials. Many MMC properties must be better characterized to allow lower risk decisions regarding use of MMC on vehicle systems. A better mathematical characterization of nonlinear structural stress properties must also be gained.

Advanced thermal protection system materials are needed which are durable, lightweight and can be used in an increasing spectrum of erosion environments. High temperature, high-strength reusable spray-on foams acceptable to the Environmental Protection Agency are needed for cryogenic tanks. Limited work in this area has recently been started. Maintenance costs are also very important criteria for TPS system selection. Many current systems are adhesively attached, which makes them very expensive to remove for inspection.

Structural Concepts
For reusable structures, low structural weight is one of the most important design considerations. Safe designs are needed which offer the lowest possible structural design weight to maintain low operational costs. A fundamental means of achieving low structural weight is to use advanced lightweight materials like those previously mentioned in conventional structures. Another is to develop structural optimization techniques which will lessen design conservatism while not exceeding acceptable risk levels.

For actively-cooled structures, innovative structural designs are needed to lower structural weight and improve cooling effectiveness, which would allow lower coolant flow rates and reduce liquid coolant weights. Though primarily a design consideration and not a technology, this requirement identifies the need for less-expensive and faster computational structural analysis methods to reduce uncertainty and enhance the capability of designers to include more sophisticated computer models into the design process.

Fabrication and Manufacturing
Most of the discussion of fabrication techniques focused on advanced metallics, specifically Al-Li. Recall that two papers were presented before the entire VSP panel which described the state of the art in manufacturing capability by providing examples of existing structures using advanced materials. Because of concern that machining wastes large quantities of expensive material, different methods of fabricating parts were discussed.

For Al-Li alloys such as 2090, technology is lacking in cryotank manufacturing areas including stretch-forming gores, spur domes and large-scale extruded net sections. The Soviets claim that they have extruded a 0.8 m x 10.0 m section from an Al-Li material with better properties than 2090 and Weldalite™.

Design, Analysis and Certification
Though not necessarily a technology issue, the test philosophy commonly employed for advanced structures technology development efforts does not include a strong commitment to test structures to failure. Such a test philosophy must be developed, as well as a simple, probabilistic approach to derive structural design criteria.

Another fundamental design philosophy discussed was the design margins for vehicle systems. A design with margins beyond what is required would permit more robust vehicles than vehicles built to operate at existing structural design limits. In the latter case, low structural weight will be a primary design criteria and advanced structures will need to operate reliably under the most extreme limits of their design. To ensure safety with reduced design margins, better non-linear structural analysis tools will be needed.

Non-Destructive Evaluation
Techniques to inspect and evaluate the fidelity of vehicle components without causing damage to parts are vital to lowering the cost of planned and existing vehicle systems. Current post-flight methods used to ensure recertification for follow-on flights of many reusable vehicles require large-scale disassembly, inspection and testing (e.g., Shuttle Orbiter). These labor-intensive activities produce significant increases in operation costs for the vehicle. Space vehicle developers should perhaps look to non-space industry philosophies to realize "lessons-learned."

Though not identified in the final list of critical issues, in-situ health monitoring was also identified as an important materials and structures consideration for reusable space vehicles.

8.3 PRESENTATIONS

8.3.1 Built-up Al-Li Structures for Cryogenic Tank and Dry Bay Applications by Barry Lisagor, LaRC