DATA SHEET

Use of Aluminum-Beryllium Composites ON the ORBCOMM Satellite

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ABSTRACT

Newly developed metal matrix composites of aluminum and beryllium (Al-Be) have been used in the primary structure of Orbital Sciences Corporation's ORBCOMM communication satellites. Hot Isostatically Pressed and extruded Al-Be materials used in these spacecraft have a two-phase microstructure that combines the stiffness and light-weight of beryllium with the ductility and fabrication ease of aluminum and the synergistic strengthening effect of the dual phases. The ORBCOMM spacecraft has undergone a rigorous qualification testing program that included modal identification (to verify structural stiffness), ultimate static loading, vibration testing to levels typical of a Pegasus launch, separation shock loading to over 600 g's at greater than 1000 Hz, and thermal cycling between -35°C and +40°C. The aluminum-beryllium composite structure survived these environments with no cracking, no detrimental permanent deformation, and no degradation in material properties. Furthermore, the first two ORBCOMM satellites have been launched into low earth orbit by OSC's Pegasus launch vehicle, and have been operating for over a year. This paper will further describe the spacecraft structure, design drivers that led to the selection of this material, its fabrication process, results of qualification testing, and a cost comparison to other materials.

Keywords: Metal Matrix Composites, Aluminum-Beryllium, AlBeMet, Space Applications, Structures

INTRODUCTION

Looking for better and less costly methods of sending satellites into orbit is keeping material's scientists and metallurgists on a never-ending quest: finding metals and alloys that offer a combination of high strength, light weight, rigidity, and the ability to be fabricated into shapes and sizes to suit the application. Conventional metals, alloys, and some composites often don't have the properties to meet these demanding requirements. AlBeMet®, a metal matrix composite of aluminum and beryllium, combines the high modulus and low density of beryllium with the strength, ductility, and fabrication characteristics of aluminum. The composites promise to fulfill many of the needs of satellites and other spacecraft structures.

AlBeMet® composites produced by Materion Brush Beryllium & Composites are being used for the major structural components of a satellite system being produced by Orbital Sciences Corporation (OSC). The initial system is expected to consist of a constellation of 28 small satellites in low earth orbit that will provide seamless, two-way, real-time messaging between any two points on the globe. In addition, with sophisticated global positioning system navigation technology, users will be able to accurately determine their position or that of their remotely located assets. Stranded boaters or hikers can send highly accurate position information to rescuers. Mobile equipment owners can monitor locations of all vehicles in a fleet of trucks, ships, or railroad cars with the ORBCOMM satellite system. Farmers can effectively manage large irrigation systems by monitoring temperature, water pressure and other parameters important to the irrigation program.

The first two ORBCOMM satellites were launched in April, 1995 on a Pegasus small launch vehicle. The satellites became fully operational a few months later and limited service has already begun. Full service, with complete global coverage is scheduled for early in 1997 with three more Pegasus launches, each consisting of eight ORBCOMM spacecraft stacked on top of one another.

Spacecraft Configuration

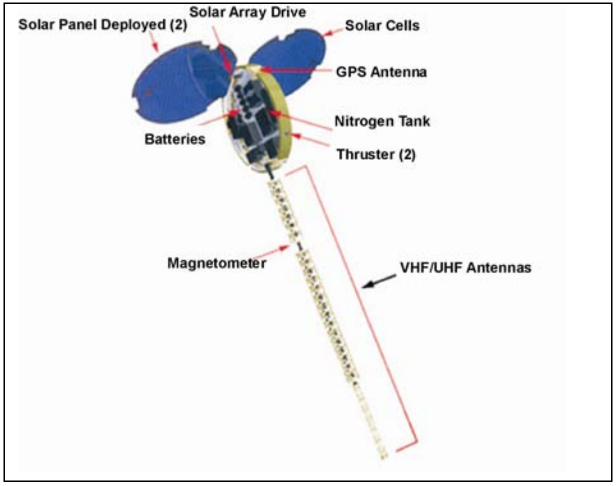
With the exception of the first two spacecraft, each of the 28 spacecraft in the ORBCOMM constellation is planned to be identical and to consist of three major components identified in Figure 1 in the deployed configuration:

- A flat 1.04 m (41 in) diameter by 152.5 mm (6 in) high housing that contains the spacecraft's computers, attitude control system, propulsion system, and communications payload
- Two deployable, articulated solar panels for providing power to the spacecraft
- A segmented, deployable boom supporting the subscriber, UHF, and gateway antennas for communication with the ground

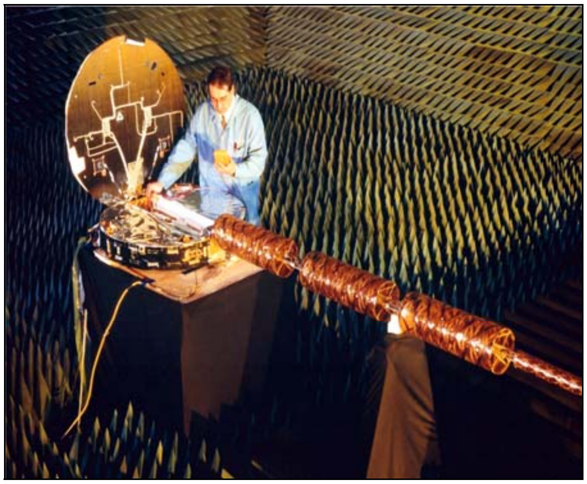
For launch, the solar panels and the antenna boom are folded into the spacecraft structure, allowing multiple spacecraft to be stacked on top of each other. Non-explosive separation bolts attach the spacecraft to each other at three points on the interface.

The primary spacecraft ring consists of three arched 25 mm (1 in) thick AlBeMet® sandwich panels fastened together by three AlBeMet® separation brackets. The brackets incorporate 12.5 mm (0.5 in) thick upper and lower flanges to hold the separation bolts and the shear bearings to provide a stiff load path between spacecraft structures when they are stacked together for launch. Four dip-brazed vertical gusset panels connect the upper and lower flanges to provide a rigid structure that also allows access to the separation bolts during spacecraft integration. The outer two vertical gussets are machined into C-channels to accommodate the arched ring segments that are both bonded and riveted into the channels. Brazed AlBeMet® brackets connect payload shelf to the primary spacecraft ring. Since the payload mounting shelf is not in the primary stiffness path of the stacked configuration, it can be fabricated from standard aluminum. Bonded AlBeMet® pieces are also needed for the rectangular tube used as the support structure for the antenna boom segments.

Figure 1 – ORBCOMM Spacecraft Configuration



ORBCOMM Assembly



Discussion

Design Requirements. The design of the ORBCOMM spacecraft and the choice of its materials was ultimately driven by the requirement to survive all launch vehicle imposed loads (1) with the minimum weight possible. From this system-level requirement, material requirements for stiffness, strength, and ductility were derived.

Stiffness Requirements. To reduce the magnitude of the dynamic transient loads accompanying the launch and to avoid launch vehicle guidance problems, the combined stack of eight ORBCOMM satellites is required to have a bending frequency of no less than 20 Hz. In addition, under dynamic loading, the maximum deflection at the top of the stack of eight satellites can be no greater than 6.3 mm (0.25 in) to avoid violating the Pegasus fairing envelope.

Both of these requirements result in the need for high stiffness, as measured either by the natural vibration frequency (proportional to $[EI/M^{1/2}]$ or by deflection (proportional to $1/EI$). Since the geometric stiffness (i.e. effective inertia, I, for the stacked configuration) is limited by the available payload fairing diameter and is further compromised by the added compliance of joints between spacecraft, a high intrinsic stiffness (i.e. modulus, E) is required. Initial stiffness sizing performed by OSC indicated that a modulus value higher than that of aluminum, greater than 69 GPa (10 Msi), would be required.

Strength Requirements. In addition to needing maximum rigidity in the satellite stack, the high loads resulting from the Pegasus launch transient mean that a high strength material is needed for the spacecraft construction as well. Initial sizing analyses conducted by OSC indicated that yield values at least as high as those of 6061 aluminum, 273 MPa (40 ksi) or higher, would be required. In particular, high loads were expected for the flange pieces which support both the preload forces from the separation bolts and the dynamic bending loads associated with launch.

Ductility Requirements. Although non-explosive separation bolts are used to connect the spacecraft together in the launch configuration, shock loads at the interface are high because a significant amount of stored strain energy in the preloaded bolts is released within a few milliseconds when separation is initiated. Therefore, brittleness was a concern in the design and material selection for the spacecraft. The dynamic nature of the shock loading could not be easily correlated to crack growth rates or material strength, so no requirement for fracture toughness could be derived from the loading. Instead, a substantial ductility, as evidenced by elongation to failure greater than 5%, was deemed indicative of sufficient resistance to shock loading and was desired for the materials selected for the spacecraft.

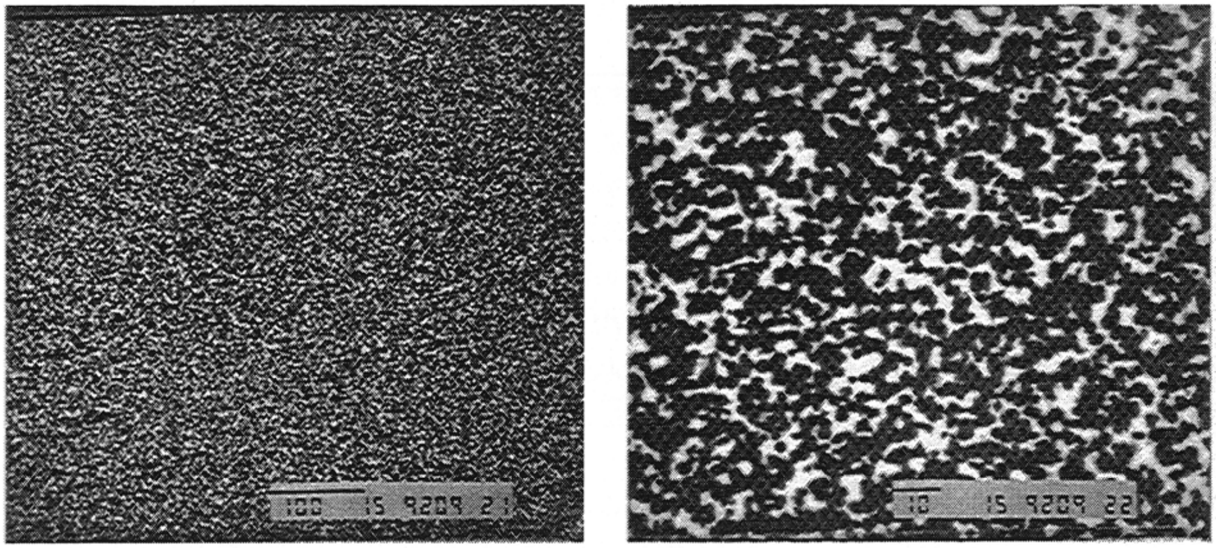
Materials Selection. Initially, aluminum was considered for the primary spacecraft ring and bracket structure, but aluminum options could not meet the stiffness requirements within the allowable mass budget. Magnesium provided only a marginally stiffer structure for the same weight. A more costly beryllium structure could easily have met the stiffness requirements (with over six times the specific stiffness of aluminum), but beryllium presented considerable problems for the shock and dynamic loading because of its brittleness.

A unidirectional graphite/epoxy structure could be fabricated with high modulus fibers and result in a specific stiffness of over five times that of aluminum, but such a structure would also result in highly anisotropic properties. The ORBCOMM ring structure requires both hoop and shear stiffness to resist bending of the satellite stack; the specific stiffness of a composite layup tailored to these requirements would be reduced to less than twice that of aluminum. Furthermore, the ORBCOMM separation brackets require thick sections and nearly isotropic properties to resist the separation bolt preload forces. Consequently, there was significant concern about the ability to fabricate a graphite/epoxy composite into this configuration easily.

AlBeMet® composites ultimately provided the unique combination of stiffness, strength, and high ductility along with light weight that met all the ORBCOMM structure requirements. With a modulus in the range of 145-180 GPa (21-26 Msi) and a density in the range of 2.1-2.26 g/cc (0.076-0.082 lbm/in^3) AlBeMet® has a specific stiffness that is 2.5 to 3.5

that of aluminum. More importantly, the stiffness is isotropic, and ideally suited to the requirements of the ORBCOMM primary structure. AlBeMet's two-phase microstructure, shown in Figure 2, consists of elongated discrete or semi-continuous beryllium particles within a continuous aluminum matrix. Due to the mutual insolubility of the two phases in each other, the microstructure is quite stable, and little noticeable change can be observed after heat treatment (2).

Figure 2 – AlBeMet® microstructure showing semi-continuous beryllium phase (dark) within continuous aluminum phase (light). Bars indicate 100µm (left) and 10µm (right).



The material can be characterized as an engineered composite material because of the potential synergistic combination of beryllium's high modulus and load bearing capability with aluminum's toughness and ductility. For example, strength of some AlBeMet® composite materials is higher than that of either of the parent metals because of the nature of the load sharing between the two phases and the impedance to dislocation motion and plastic flow presented by the phase boundaries. Strength and elongation properties of AlBeMet® composites are compared with those properties of 6061 aluminum and pure beryllium in Figure 3.

As in most composite systems, AlBeMet's atomic-based properties like density, modulus and coefficient of thermal expansion follow the Rule of Mixtures averaging, with properties varying monotonically with the proportion of constituent phases. Modulus and coefficient of thermal expansion (CTE) values for AlBeMet® are shown in Figure 4.

In addition to the stiffness and strength advantages that AlBeMet® has over aluminum, it also provides improved thermal properties as well. In particular, AlBeMet's thermal expansion coefficient is up to 40% lower than that of aluminum, resulting in lower thermally induced stresses and deflections. This property was of particular importance in the selection of a material for the ORBCOMM antenna boom. In this structure, the use of AlBeMet® significantly decreased the thermally induced deformation of the boom, and provided greater antenna accuracy.

Figure 3. Comparisons of typical strength and elongation to failure for 6061 aluminum, AlBeMet® and pure beryllium.

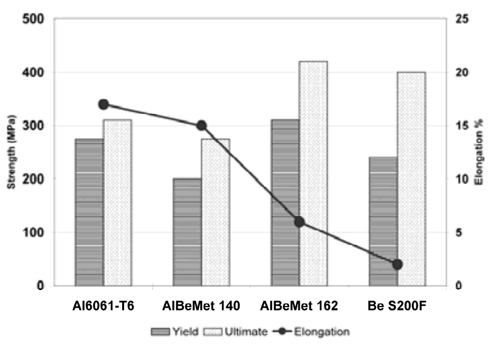
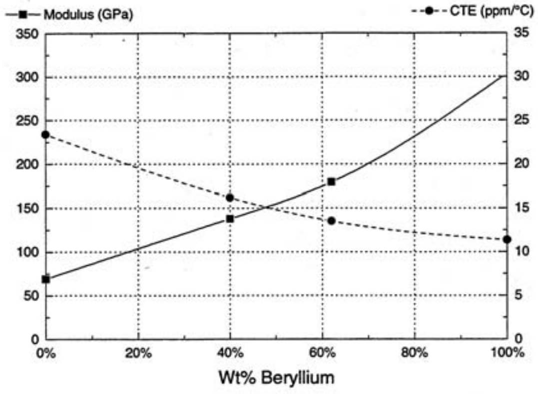


Figure 4. Modulus and Coefficient of Thermal Expansion (CTE) as a function of beryllium content for aluminum beryllium materials.



AlBeMet® grades 150 and 162 (corresponding to 50 wt% and 62 wt% Be respectively) were chosen for the ORBCOMM structures because they are nearly as stiff as steel (E = 145-180 GPa or 21-26 Msi), lighter than aluminum (p ≡ 2.19 g/cc or 0.079 lbm/in^3) and less costly than pure beryllium. The AlBeMet® 162 grade is more completely characterized (3, 4), and was specified for the critical components in the ORBCOMM spacecraft – the separation brackets and the payload deck brackets. These structures demanded the higher strength that the 162 grade could provide. Mechanical properties of the hot isostatically pressed (HIP'd), extruded, and cross-rolled sheet of AlBeMet® 162 are listed in Table I. In the formed and heat treated condition, nearly isotropic strength was attainable with sufficient ductility (greater than 6%) to indicate that brittleness would not be a major concern. The less-demanding structures – face sheets for the honeycomb panels of the spacecraft ring and the antenna boom – are fabricated from the 150 grade. The honeycomb itself is 5052 aluminum.

Table I. Typical Properties of AlBeMet® 162 in the HIP'd, Extruded or Rolled Condition.

Alloy Condition	Heat Treatment	Yield Strength MPa (ksi)	Ultimate Strength MPa (ksi)	Elongation %
HIP'd	None	242 (35.1)	306 (44.4)	2.56
	593°C/24 hr	433 (32.8)	287 (41.6)	2.71
Extruded-L	None	562 (81.5)	609 (88.4)	1.44
	593°C/24 hr	328 (47.6)	439 (63.7)	9.40
Extruded-T	None	558 (81.0)	607 (88.1)	0.24
	593°C/24 hr	314 (45.6)	345 (50.0)	6.12
Rolled-L	None	399 (57.8)	463 (67.2)	5.09
	593°C/24 hr	314 (45.5)	413 (59.9)	7.75
Rolled-T	None	374 (54.3)	453 (65.7)	2.62
	593°C/24 hr	319 (46.3)	406 (58.9)	6.39

L=Longitudinal to work direction T=Transverse to work direction

Fabrication. Fabricating AlBeMet® materials is quite similar to fabricating aluminum. The principal fabrication difference is the need for a facility that can handle beryllium-containing materials to remove the fine, airborne beryllium particles that could pose a health risk to some people. Forming is also similar to aluminum production in that the same tooling and temperature ranges can usually be used for forming at an elevated temperature, typically over 200°C (400°F). Forming rate is slightly slower for the AlBeMet® materials if severe deformation or bending is required. Gentle curves such as those of the ORBCOMM honeycomb ring panels were formed at the same rate as that used for aluminum panels.

Coating. Like aluminum, the AlBeMet® materials form a protective oxide film on freshly machined surfaces, except the film on AlBeMet® is much more tenacious. For this reason, immediate coating after machining or grinding parts is critical. Coating the AlBeMet® surface resists corrosion and also provides a continuous bonding surface. Precleaning and proper coating application are critical for the primer, usually a phenolic-based epoxy compound, that is subsequently cured at 120°C (250°F).

Once the machined surfaces are stabilized by coating, coated parts may be stored for months, if necessary. After storage, a simple alcohol wipe removes any dust or fingerprints prior to further assembly operations. A quality fabricator can therefore furnish the product in a condition that the assembler/customer does not have to interface with the AlBeMet® materials in his subsequent assembly or mounting operations.

Joining. The AlBeMet® materials can be joined by both electron beam welding and dip brazing methods. For the ORBCOMM spacecraft structure, brazing was chosen because of consistency and quality of the joints. Expert fabricators of AlBeMet® materials, such as Peregrine Falcon Corp., have developed proprietary programs involving higher temperatures and longer times then those used for aluminum to obtain high-quality brazed joints.

Design of joints for this metal matrix composite is quite different from those used for aluminum. Aluminum usually fails in a ductile manner, so bending occurs before failure, which usually occurs in the joint. With AlBeMet® materials, the metal is stiffer, so the joint is designed so the parent metal breaks before the joint fails. In this fail-safe design, the joints are not the weak members in the design and will therefore take the stress build-up without failing.

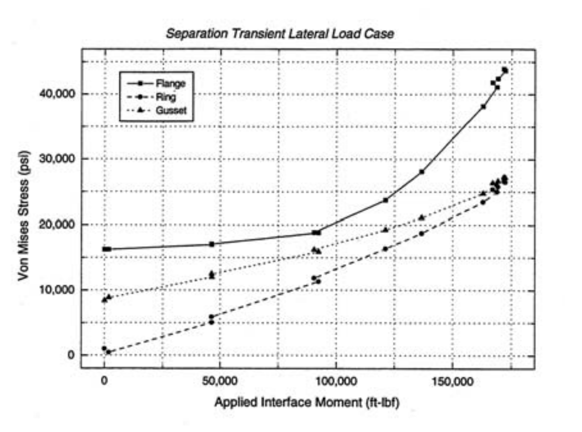
Testing. Exhaustive testing of the ORBCOMM spacecraft structures was conducted by simulating all flight loads for all critical components including the separation event. These tests included modal identification testing, axial and lateral static loading conditions, anticipated axial and lateral vibration, shock loads, and thermal cycling loads.

Modal testing identified all the significant mode shapes and natural frequencies of the ORBCOMM spacecraft, and verified the in-situ stiffness of the AlBeMet® material. Modal properties agreed with predicted values and indicated that with AlBeMet®, the stacked spacecraft would have a natural frequency of 21Hz, meeting the 20Hz minimum requirement. In addition, the modal testing verified deflection analysis that indicated that the satellite stack would not violate the Pegasus fairing dynamic envelope.

Static load simulation of the launch environments was achieved using hydraulic actuators within a static loads test stand. Some of the recorded stresses for the separation transient lateral load case are shown in Figure 5. A peak stress of 300 MPa (43.9 ksi) was recorded in the lower flange under ultimate loading, resulting in a margin of safety of 0.45, based on UTS for the extruded bracket in the longitudinal direction (5). Slightly lower stresses were recorded in the ring panels and vertical gussets. Despite the nonlinear stress increase due to complex load transfer through the brackets, upon removal of the loads, stresses returned to their initial values indicating that no yielding or permanent deformation had occurred.

Random vibration testing was conducted over the range from 20 Hz to 2000 Hz in both the spacecraft axial and lateral directions. Typical results for an accelerometer placed on the payload shelf are shown in Figure 6. Resonance from the spacecraft's payload shelf diaphragm mode is clearly seen at 70 Hz, but at higher frequencies, the measured vibration levels are lower than the input levels.

Figure 5. Measured Von Misses stresses in the ORBCOMM separation bracket flange, cylindrical ring, and separation bracket gusset during simulated launch static loads testing.



This phenomenon was observed in most of the vibration responses and may indicate that the AlBeMet® composite material is providing a measure of internal damping to reduce the vibration (6).

Figure 6. Axial vibration response power spectral density at the ORBCOMM spacecraft payload shelf center under axial excitation.

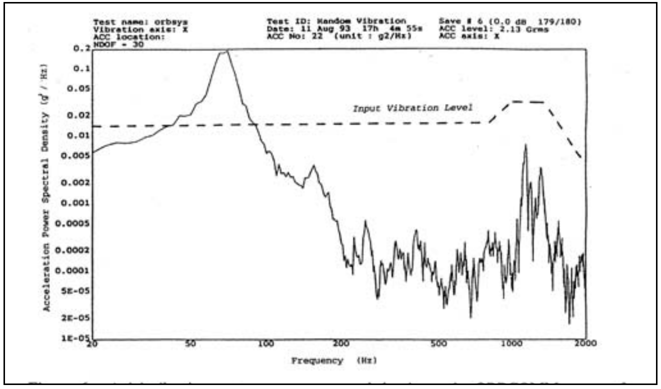
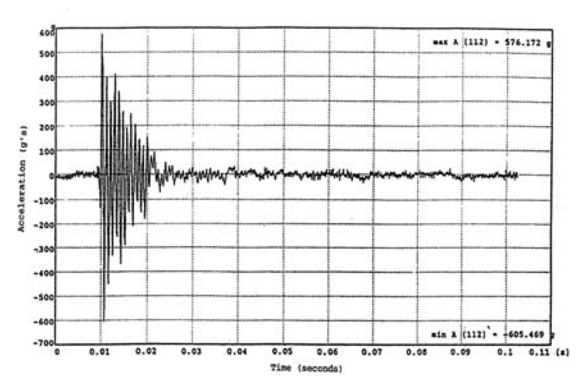


Figure 7. Accelerometer response at the ORBCOMM spacecraft separation bracket flange during separation shock loading.



Shock loading of the spacecraft was accomplished by simultaneously releasing the three separation bolts that connect two spacecraft and recording the resulting accelerations at the separation bracket flanges and at other locations on the spacecraft. While the release mechanism is non-explosive, shock levels are still high because of the stored strain energy in the bolts and in the brackets due to the preloading of the separation bolts. Typical accelerometer measurements at the separation bracket flange are shown in Figure 7. A peak acceleration of 600 g's was recorded at a frequency of about 1000 Hz. Despite this very high acceleration, this short duration shock pulse did not appear to affect the AlBeMet® material in any way. Even after repeated separation tests, no cracks were observed in the separation bracket flanges or vertical gussets originating with the shock loading. The strength and load bearing capacity of the AlBeMet® composite did not seem to be compromised either, since no yielding or permanent deformation was observed during subsequent bolt preloading or further static loads testing.

Thermal cycle qualification testing was conducted for twenty cycles over the range of -35°C (-31°F) to +40°C (104°F) with dwell times of over 1 hour at each end of the cycle. No detrimental deformation or material behavior was observed during this testing.

Cost Comparison. Based on Materion Brush Beryllium & Composites metrics for the fabricated material, AlBeMet® provides about 75% of the properties of beryllium at about one half the price. A more specific comparison can be made for the finished structure, including machining and post-fabrication costs based on OSC data. Besides the ORBCOMM spacecraft, OSC designed, built, tested, and launched another spacecraft (called MicroLab) using the same general structural arrangement (ring structure, separation brackets, deployable solar panels, and deployable antenna boom). Although the payload was different (a optical sensor for a scientific experiment), MicroLab was also launched on Pegasus and was subjected to the same launch environments as the ORBCOMM spacecraft. However, separate constraints on the schedule and the payload led to the selection of magnesium for its primary structure. The two spacecraft primary structures are compared in Table 2. For a given weight of finished structure, the AlBeMet® structure is three times stiffer than the magnesium structure (per pound of material) at only slightly over 25% higher unit cost. In the demanding satellite market, this performance is well worth the slight additional cost.

Table 2. Comparison of cost and properties for ORBCOMM and MicroLab structures.

Spacecraft	**Unit**	**ORBCOMM**	**Microlab**
Material		AlBeMet®	Magnesium
Cost*	$	$23,000	$30,000
Weight	Kg (Lab)	4.54 (10.0)	7.62 (16.8)
Unit Cost	$/Kg ($/Lb)	5000 (2300)	4000 (1800)
Modulus	Gap (Msi)	158 (23)	43.4 (6.3)
Density	g/cc (Lbm/in^3)	2.1 (0.079)	1.7 (0.065)
Specific Stiffness	10^{6}m (10^6 in)	7.39 (291)	2.46 (97)

*Finished primary structure cost including all machining and post-fabrication costs.

CONCLUSIONS

The ORBCOMM qualification test program demonstrated that AlBeMet® materials can withstand the critical launch load environments and conditions for a structure of this type. In particular:

- AlBeMet's modulus allowed the stacked ORBCOMM spacecraft to meet the Pegasus' 20 Hz natural frequency requirement.
- AlBeMet's strength was more than sufficient to provide ample structural margin under the worst-case predicted static loading from Pegasus.
- AlBeMet® showed no degradation after extended vibration loads typical of a Pegasus launch.
- AlBeMet's ductility was sufficient to prevent cracking under the shock loading conditions of spacecraft separation.
- AlBeMet® showed no degradation after extended thermal cycling typical of the space environment.

In addition, AlBeMet® proved to be cost-effective for this application. The ORBCOMM spacecraft's use of AlBeMet® materials may pave the way for more widespread use of the material in other space-related structures.

REFERENCES

1. Pegasus Launch System: Payload User's Guide, Release 3.00, Orbital Sciences Corporation, Dulles, VA, 1993.
2. F.C. Grensing and D. Hashiguchi, "Properties of Wrought Aluminum-Beryllium", Advances in Powder and Particulate Materials, MPIF, Vol.4, 1993.
3. F.C. Grensing and D. Hashiguchi, "Mechanical and Thermal Properties of Aluminum-Beryllium AM162", Advances in Powder Metallurgy and Particulate Materials, MPIF, 1995.
4. D. Hashiguchi and F.C. Grensing, "Ternary Aluminum-Beryllium", Advances in Powder Metallurgy and Particulate Materials, MPIF, 1995.
5. "ORBCOMM Qualification Static Loads Test Report", OSC Technical Document, TD-1711, June, 1994.
6. "ORBCOMM Development Random Vibration Test Report", OSC Technical Document, TD-1786, Jan. 1995.

Note:
Handling Aluminum-Beryllium in solid form poses no special health risk. Like many industrial materials, beryllium-containing materials may pose a health risk if recommended safe handling practices are not followed. Inhalation of airborne beryllium may cause a serious lung disorder in susceptible individuals.
The Occupational Safety and Health Administration (OSHA) has set mandatory limits on occupational respiratory exposures. Read and follow the guidance in the Material Safety Data Sheet (MSDS) before working with this material. For additional information on safe handling practices or technical data on Aluminum Beryllium materials, contact Materion Brush Beryllium & Composites.