$\sigma^s_{\omega,j}$ and $P_{\omega,j}(s',s)$, which depend on particle size. The radiant intensity from plumes at an altitude of 6.1 km is about 20% larger than from plumes at sea-level because the temperatures of the former remain higher over a longer distance along the plume and because the plumes are slightly larger.

Conclusions

The following conclusions on the influence of scattering on IR signatures of realistic rocket plumes can be drawn from the numerical results presented herein.

1) The IR signature of rocket plumes is sensitive to radiation scattering. The six-flux solutions are more realistic and are more sensitive to scattering than gas-only, pseudogas, and two-flux solutions because the six-flux model considers scattering into and out of the line of sight.

2) The effect of scattering is a function of particle size. Particles with diameters near 1.0-μm influence the broadside signature more than smaller or larger particles.

3) High altitude plumes emit larger IR signatures than sea-level plumes for the same nozzle exit conditions. This occurs mainly because they are larger.

4) Al_2O_3 is a weak absorber/emitter in the 2000-5000 1/cm wavenumber band; consequently the source of the plume signature is due to gas emission. Particle scattering influences the signature by changing its directional pattern.[10]

In terms of modeling, this study shows a strong need for accurate determination of the particle size as a function of position throughout the plume for accurate signature predictions. The six-flux model, which is the most realistic of the scattering models considered herein, predicts a strong sensitivity of the signature magnitude to the particle size.

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Ultralight Reactive Metal Foams in Space: A Novel Concept

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LARGE-scale engineering projects increasingly have become a focus of attention in space development planning. Such projects typically would require much greater total payload tonnages than any undertaken previously. Therefore, the question of the density, strength, and stiffness of the materials chosen for use in such projects becomes of greatly increased importance. In current space activities, aluminum alloys are the materials of choice for most structural applications. Aluminum alloys are used in spite of the difference in densities of aluminum and magnesium (2.70 g/cm^3 vs 1.74 g/cm^3, respectively), partly because the increased chemical activity of magnesium makes high-strength magnesium alloys much more susceptible than aluminum alloys to environmental degradation in the terrestrial environment. Additionally, the Young's modulus of magnesium (45 GPa, 6.5×10^6 psi) is significantly less than that of Al (70 GPa, 10×10^6 psi) and the maximum yield strengths of wrought Al alloys (e.g., 525 MPa, 76 ksi for 7175-T66) are substantially above those of wrought Mg alloys (e.g., 305 MPa, 44 ksi for ZK60A-T5). Both Mg and Al alloys are susceptible to stress corrosion cracking,[1] and more than one Apollo mission has been affected by the stress corrosion failure of aluminum alloy or titanium alloy components.[2-4]

In large-scale space applications which do not involve crew quarters or other water- or oxygen-containing environments, as, for example, in solar power satellites, chemical reactivity is no longer as important as density, strength, and stiffness and the associated cost of transporting the required mass of structural materials to the desired orbit. A proposed solar power station might require 1000 metric tons of structural aluminum girders, but approximately only 500 metric tons of girders if Mg-Li alloys (1.35 g/cm^3) were substituted for aluminum alloys (2.70 g/cm^3). This reduction is payload mass might well be worth the additional difficulty of dealing with a more reactive material on Earth. As will be seen, there may, in fact, be an approach to the problem of the inherent reactivity of light metals which simultaneously ameliorates the problem of their low moduli of elasticity and makes their handling on Earth relatively straightforward.

Although there are certain exceptions, e.g., U and Pu, the relationship of increasing chemical reactivity with decreasing density appears to be generally true, as shown in Fig. 1. This figure shows the oxidation potential at unit activity[5] plotted vs the density at 25°C[6] of 25 metallic elements, including all those commonly used in alloys for terrestrial structural applications. Although the observed activity of certain elements, e.g., Al and Cr, is in practice lessened by the presence of passive adherent oxides, it is clear from this graph that as density decreases, reactivity increases. Thus Mg alloys are the lightest that can be used on Earth for any sort of structural application. All the elements lighter than Mg—that is, Ca, Na, K, and Li—have such great reactivities that they cannot be used themselves as structural materials on Earth. Because Li is very soluble in Mg,[7] attempts have been made to develop Mg-Li alloys for structural purposes, and indeed such alloys

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as LA141A (Mg, 14 wt % Li, 1 wt % Al) with a density of 1.35 g/cm^3 (Ref. 8) were at one time produced commercially (by Brooks and Perkins, Detroit, Michigan). However, due to environmental and other problems (including stress corrosion) this alloy was withdrawn and is no longer produced commercially in the United States.

Because of their high oxidation potential and the concomitant fact that they are not used in structural applications, very little metallurgical effort has been aimed at developing high strength Li, Na, K, or Ca alloys. Indeed many uses of these materials (as, for example, in batteries) depend upon their high chemical reactivity. All four of these elements possess cubic crystal structures at ambient temperatures and in pure form exhibit very great ductility. Because of their great chemical reactivity and associated low solubility for other elements, however, there are not many metallic elements which can be used as additions to Li, Na, K or Ca to produce improved strength through solution-hardening, although, as has been mentioned, Li and Mg do show substantial solubility. Because of the limited solubility of reactive metals for other elements, it is virtually certain that precipitation hardening processes similar to those currently used in producing high-strength aluminum alloys, rather than solid solution strengthening, would have to be used to produce alloys with yield strengths substantially greater than those of the pure elements, which are themselves quite soft. In the case of Mg-Li-Al alloys, such heat treatments have been used to give ultimate tensile strengths of over 310 MPa (45 ksi).[8] In Mg-Li-Al alloys, the precipitating phase responsible for this hardening is $MgLi_2Al$.[8] Apparently, no detailed investigations have ever made on the maximum strengths attainable through age-hardening reactions for Li, Na, K, or Ca alloys.

These ultralight, reactive metals—Li, Na, K, and Ca—all exhibit low moduli of elasticity. Remembering that the Young's modulus of aluminum is approximately 70 GPa (10×10^6 psi) the moduli of Li, Na, K, and Ca are, respectively, 4.9 GPa (0.7×10^6 psi), 6.8 GPa (1×10^6 psi), 3.5 GPa (0.5×10^6 psi),[9] and 22.1 -26.2 GPa (3.2 -3.8×10^6 psi).[10] Thus, even if high strengths could be developed, these metals in solid form would show very low stiffnesses. Since the theoretical strengths of solids are proportional to the square root of the elastic moduli, it is unlikely that very high strengths could be produced in alloys based upon Li, Na, or K. Theoretically, however, calcium alloys could be made as strong as aluminum alloys on a strength-to-weight basis. Because the stiffness of beams is proportional to both the elastic modulus of the beam material and the second moment of inertia of the beam cross section, it is possible to increase beam stiffness substantially by shifting the beam cross-sectional area away from the neutral axis. This shift in cross-sectional area is routinely done in terrestrial construction through the use of I-beams or other beam shapes to produce structural members of increased stiffness-to-weight ratio. In the case of ultralight reactive metals, because of their low melting points, one possible way of substantially increasing the cross-sectional area is by means of foaming so as to produce a porous material of substantially increased volume. If, for example, beams of square cross section are being considered, when the cross-sectional area is increased by a factor of ten through foaming, assuming that the effective modulus of the beam material were to be decreased by this same factor, the resulting beam stiffness (as measured by its deflection under a given load) would still be raised by a factor of ten. This result occurs because for square beams the second moment of the beam cross section increases as the square of the beam cross-sectional area.

As it happens, even though Li has an extremely low modulus, Mg-Li alloys of up to 14 wt % Li exhibit a modulus that is only slightly lower than that of Mg. Mg-15Li-1Al for example, has a modulus of 42.7 GPa (6.2×10^6 psi) and a density of 1.35 g/cm^3.[8] With the assumptions above, if a beam of this alloy were expanded by foaming to ten times its cross-sectional area, then the resulting square beam stiffness would be equivalent to that of a solid aluminum square beam which weighed five times as much per unit length or to that of a foamed aluminum beam that weighed 1.6 times as much per unit length. These results are due to the fact that for simply loaded beams the beam deflection varies inversely as the product of modulus and the second moment of the beam cross-sectional area.

Foamed metals and metal sponges can be and are produced on earth by a variety of methods,[11-16] including both powder metallurgy and metallic hydride or carbonate decomposition occurring within the molten metal, which is usually made more viscous by addition of materials such as glass fibers, as well as by directional solidification techniques. However, it is evident that due to the lack of significant gravitational forces on orbiting structures, gas-foaming methods, especially of large structures, would appear to be more readily achievable in space than on Earth and that in this situation glass fiber additions would not be needed. The foaming of metals in orbit has been proposed repeatedly,[17-19] but apparently never before in conjunction with the use of ultralight reactive metals to produce stiff structural units of truly exceptional low weight.

Thus, for example, the use of preformed solid shapes, composed of Mg-14Li-1Al admixed and compacted together with a foaming agent such as barium hydride, which decomposes upon heating to produce substantial quantities of gas, would enable this material to be handled in a compact form while in the terrestrial environment as well as during launch. In orbit, these solid compact shapes could be foamed by heating them in a chamber whose inner dimensions were those of the desired structural unit, whether single beam or more complex truss or trapezoidal shape. Of course, the residue of the foaming agent, e.g., Ba, would remain in the foam, but assuming a 10:1 increase in volume, the foaming agent typically would comprise 1% or less of the metal foam by weight.

The alloy Mg-14Li-1Al has been chosen as an example because both density and modulus data are known for this material. Indeed, this alloy can be handled readily in bulk in the terrestrial environment without undue difficulty. With a 10:1 increase in volume by foaming, the resulting density of LA141A would be 0.135 g/cm.^{3} Since even higher lithium contents than 14% could be considered for use in space, the foam density could readily be made even less than 0.135 g/cm.^{3}

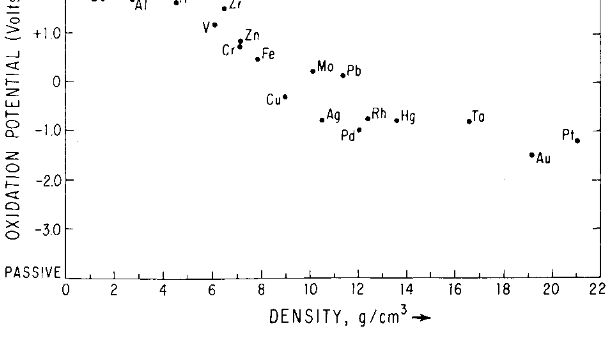

Fig. 1 **Relationship between density and oxidation potential for 25 metallic elements.**

Additionally, it is not expected that metal foams would be seriously degraded by ultraviolet radiation or the presence of tenuous gases in near-Earth orbits. This later conclusion follows because such gases (at 300 km orbits) are extremely rarified. If the rate of reaction is assumed to be proportional to gas pressure, then the approximately 10^{-11} decrease in pressure that occurs in going from sea level to 300 km would effectively reduce reaction to a level near zero. With the reasonable assumption that chemical reaction rates will be proportional to pressure, even materials which were degraded with extreme rapidity at sea level would be only minimally affected at 300 km. It should also be pointed out that by constructing large scale space structures of reactive metal foams, the likelihood of any material reaching the surface of the Earth in the event of orbital failure would be very greatly reduced by the reactivity of these foams during reentry. Finally, in the case of Mg-Li-Al alloys, it is known that this material possesses exceptional resistance to hypervelocity impacts by small particles.[8] It is possible, therefore, that foam of such material could be considered as a hyperballistic armor material for crew quarters or other critical, permanent space installations, provided that suitable care were taken regarding the susceptibility of such foams to oxygen and water. It is worth noting also that metal foams may have substantial heat-transfer advantages compared to bumper sheet stand-off micrometeriod shielding designs.[20]

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Errata

Modeling Slag Deposition in the Space Shuttle Solid Rocket Motor

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