FIBROUS CERAMIC INSULATION

Howard E. Goldstein
NASA Ames Research Center
Moffett Field, California

INTRODUCTION

In the late 60's and early 70's it became apparent that reusable heat shields would be required to provide thermal protection for the Space Shuttle Orbiter System. Ames Research Center therefore embarked on a program to develop an in-house competence in the technology of reusable ceramic fibrous insulation. Ames had for many years been one of the leading centers in the country for aeroconvective testing of heat shield materials using our extensive arc plasma test facility (Ref. 1). In order to contribute to the development of this new class of materials, which was expected to be used on the Space Shuttle, we felt that it was important to understand the materials properties and fabrication process. As our in-house capabilities improved we expanded our goals to include the development of higher temperature, more durable, stronger, rigid and flexible ceramic heat shield materials. The program led to significant new materials developments by the mid-1970's. Among those were improved coatings (Ref. 2), stronger, higher temperature tile materials (Ref. 3) and numerous contributions toward the supporting technology for aeroconvective and mechanical testing of the materials (Ref. 4).

The thrust of the program today is to develop improved reusable ceramic heat shield materials to enhance the Shuttle and enable development of new vehicles such as Advanced Space Transportation Vehicles, Aerobraking Orbital Transfer Vehicles and Advanced Military Spacecraft.

This paper will describe some of the materials that have been developed and their manufacturing processes, properties and applications.

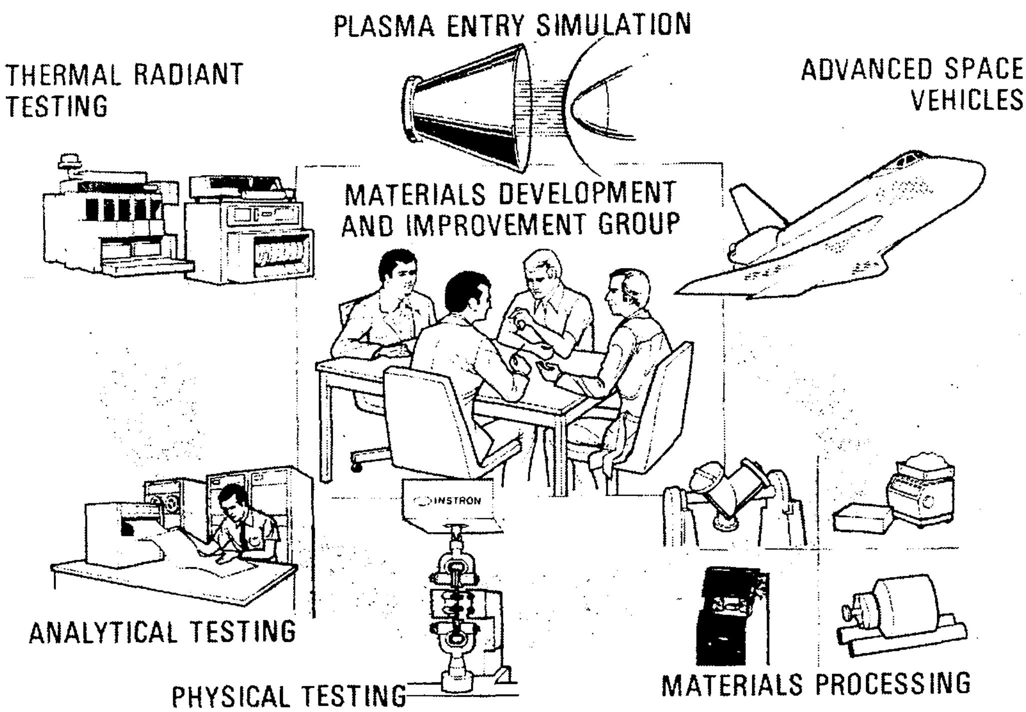
THERMAL PROTECTION MATERIALS DEVELOPMENT PROCESS

The development cycle of new materials from concept to system application is normally so lengthy that, from the start of a program like the Space Shuttle (1972) to its manufacturing phase (1978-1983), the possibility of incorporating new materials concepts is very remote.

The approach at Ames for the development of new materials for space transportation is depicted on this chart. The group is small, interdisciplinary and has all the necessary facilities within the organization to both develop and test new thermal protection materials. New materials are developed and screened internally. Only the reasonably mature innovations are presented to higher management for approval of procurement action for competitive commercial small-scale manufacturing. This essentially closed-loop system allows rapid transition from concept to finished prototype, shortening the development time for new materials considerably.

An example of how rapidly this can be accomplished is development of Fibrous Refractory Composite Insulation (Refs. 5 & 6). It was conceived in July 1977; patent disclosure was in April 1978; and a competitive procurement was awarded in January 1979 to pilot plant it. In January 1981 acceptable preproduction material was delivered by LMSC and in January 1982 first flight hardware delivery for installation on the third Space Shuttle was accomplished.

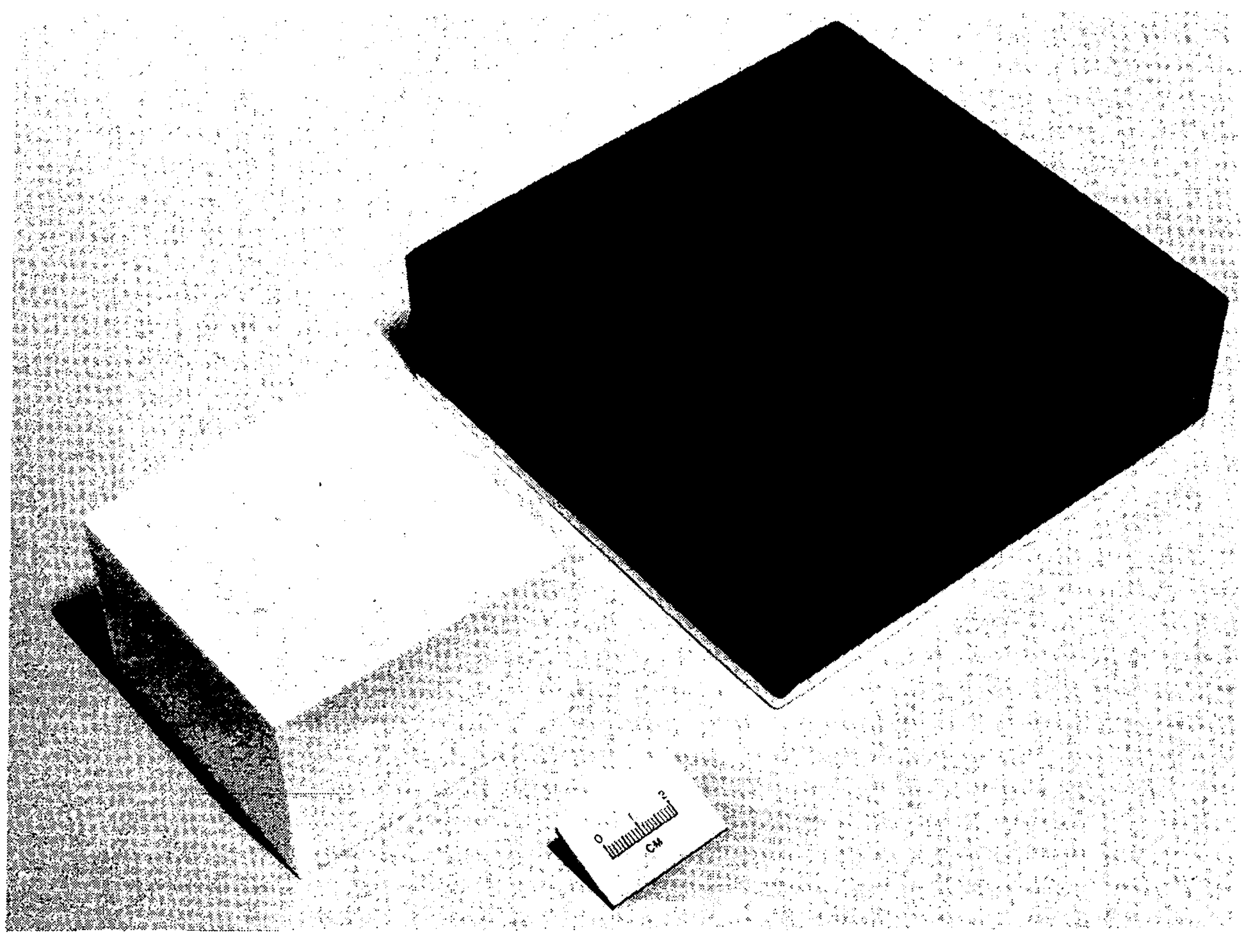
This extremely short time span from concept through flight hardware delivery is unusual in the field of material development and is attributed to a significant degree to the organization and management approach utilized in this program. Transfer of this technology to industry in a timely manner has been accomplished through an effective working relationship with the contractors that has evolved over a number of years.



FRCI-20-12 REUSABLE SURFACE INSULATION

This figure shows typical coated and uncoated Reusable Surface Insulation (RSI) tile. RSI is a generic name which describes any coated fibrous insulation materials used on the external surface of the Space Shuttle Orbiter. Among these materials are the rigid ceramics such as FRCI, a fiber-fiber rigid composite insulation; LI-900 and LI-2200 all silica rigid ceramic insulations; and flexible materials such as Fibrous Reusable Surface Insulation (FRSI), a Nomex felt blanket, and Advanced Flexible Reusable Surface Insulation (AFRSI), a glassy ceramic quilted material that will be described subsequently.

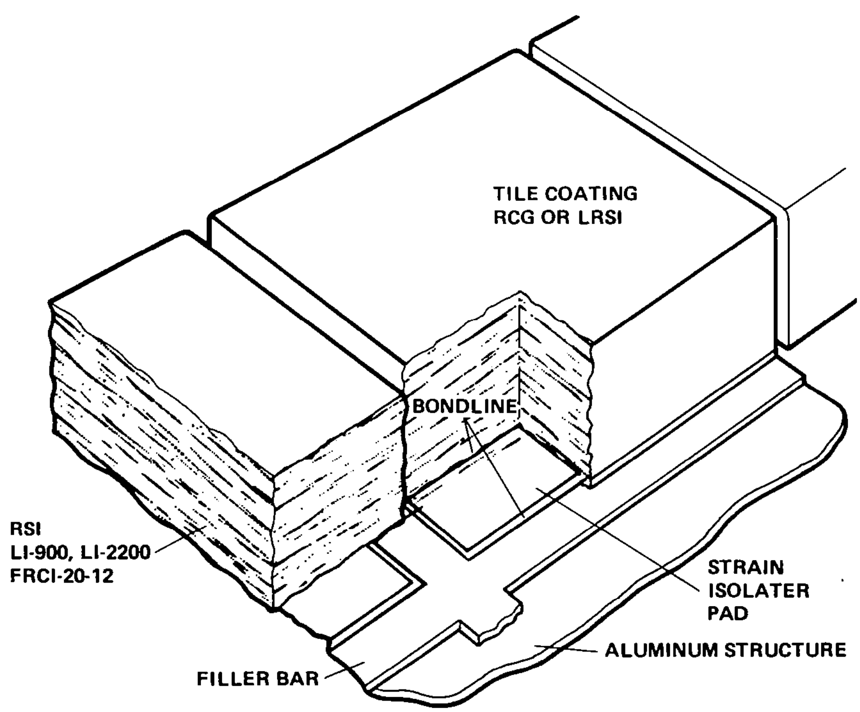
The material shown in this figure is a High Temperature Reusable Surface Insulation (HRSI) with the Reaction Cured Glass coating (Ref. 2). The specific tile material shown is FRCI-20-12 which was developed in the late 1970's by Ames (Refs. 5 & 6). LMSC, who developed the first all silica RSI (Ref. 7), manufactures all the rigid RSI materials for the Space Shuttle program. These rigid RSI materials are all fibrous bonded ceramics. They all are low density (0.12 to 0.35 gm/cm^3), extremely thermal-shock resistant, have high-temperature capability in excess of 1260°C and have very low thermal conductivities.



SPACE SHUTTLE RSI TILE SYSTEM

The tile system used on the Space Shuttle has been designed to meet many operational constraints. This cutaway drawing illustrates the various components of the system. Tiles are made of either pure silica fibers (LI-900 and LI-2200) or a composite of silica and aluminoborosilicate (FRCI) fiber. A Reaction Cured Glass coating (0.04 cm thickness) provides a handleable, high-emittance thermal control coatings. If undamaged, it is waterproof. Tiles are bonded with a silicone rubber to a Nomex felt strain isolation pad which in turn is bonded to the aluminum substrate. This strain isolation system prevents excessive thermal or mechanical stresses from being transferred from the rigid aluminum structure into the relatively fragile tiles. The silicone rubber adhesive and Nomex felt were chosen because they have maximum temperature capabilities in excess of 290°C and will not embrittle at temperatures as low as -56°C.

During development of the Space Shuttle Orbiter it became clear that a tougher system that would be less subject to debonding, more resistant to impact damage and have higher temperature capability than the original silica tiles was desirable. As a result of these perceived needs the LI-2200 (Ref. 3) was developed in the mid-seventies and the FRCI family of materials during the 1977-79 time period (Ref. 5 & 6). These materials have been implemented to correct design problems and to generally upgrade the system during development of the Shuttle Orbiter. The higher temperature stronger LI-2200 along with the adoption of a surface densification process for both LI-900 and LI-2200 helped correct a debonding problem discovered in late 1978 (Ref. 8). FRCI-20-12 will provide a weight savings over the earlier LI-2200 for certain areas of the Shuttle on the third and fourth orbiters.

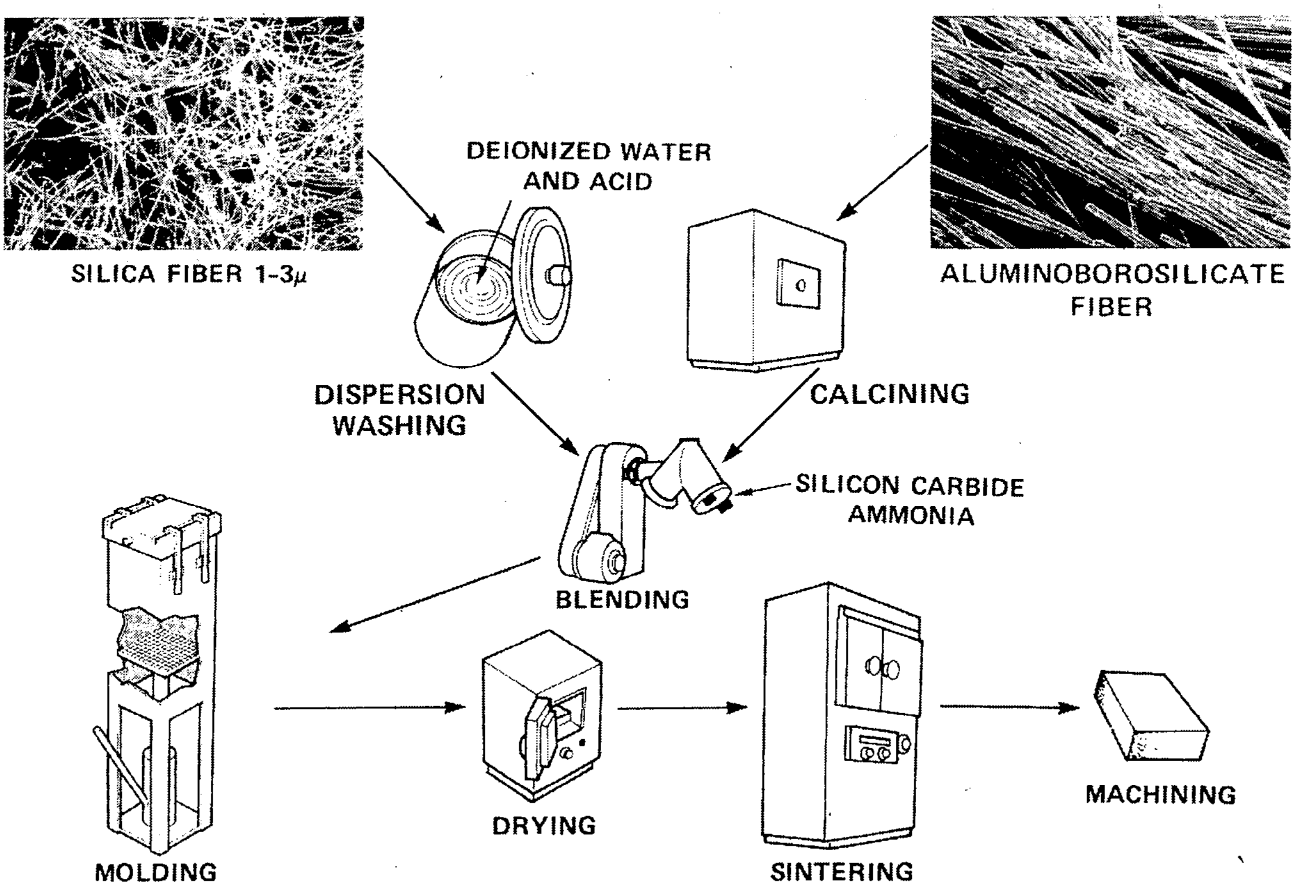


FRCI MANUFACTURING PROCESS

This figure illustrates the manufacturing process for FRCI. Silica fibers and aluminoborosilicate fibers are cleaned, mixed in deionized water to obtain a slurry, cast, dried, sintered and machined using numerically controlled machine tools to exact sizes. The tiles are then coated, dried and glazed with the appropriate ceramic coating, producing a fiber-fiber composite having controlled anisotropic properties. Strength and thermal conductivity in the plane perpendicular to the pressing direction are much higher than through the thickness, for instance.

Raw materials and processing parameters must be carefully controlled to obtain a reproducible product. The sintering temperature is typically controlled within ±10°C in order to be able to meet required density tolerances of ±10%. FRCI-20-12 is stable towards devitrification of the silica fibers at surface use temperatures above 1260°C as a result of both the careful control of the raw materials chemistry and the fiber to fiber ratios used.

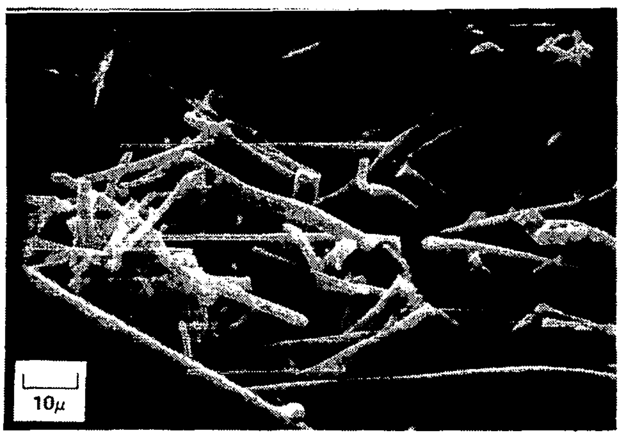
As noted earlier, LMSC is now manufacturing FRCI-20-12 for the Space Shuttle Orbiters after Columbia. Pilot plant contracts have been let to make small quantities of FRCI-40-20 a newer, higher temperature, stronger version of the material.



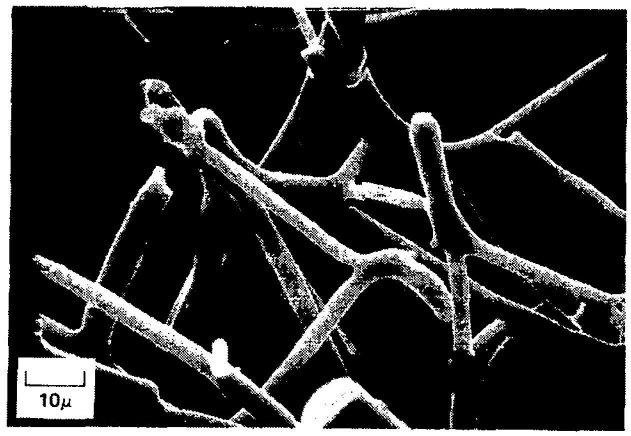
MICROSTRUCTURAL COMPARISON OF SILICA

(LI-2200) AND COMPOSITE (FRCI-20-20) RSI

This figure compares the microstructure of FRCI to LI-2200. One can see that much better fiber bonding occurs in the FRCI as a result of the fluxing of the silica by boron oxide vaporized from the aluminoborosilicate fiber during sintering. This improved bonding causes FRCI to have much higher strength than LI-2200. Small diameter fibers contribute to the material having a relatively high strain to failure (>0.5%). These two properties plus the low thermal expansion coefficient of FRCI result in it having extraordinarily good resistance to thermal shock. Typically, dropping a piece of FRCI at 1260°C into liquid nitrogen will cause no damage.



LI-2200 ρ = 0.352 g/cm^3 (22 lbm/ft^3)

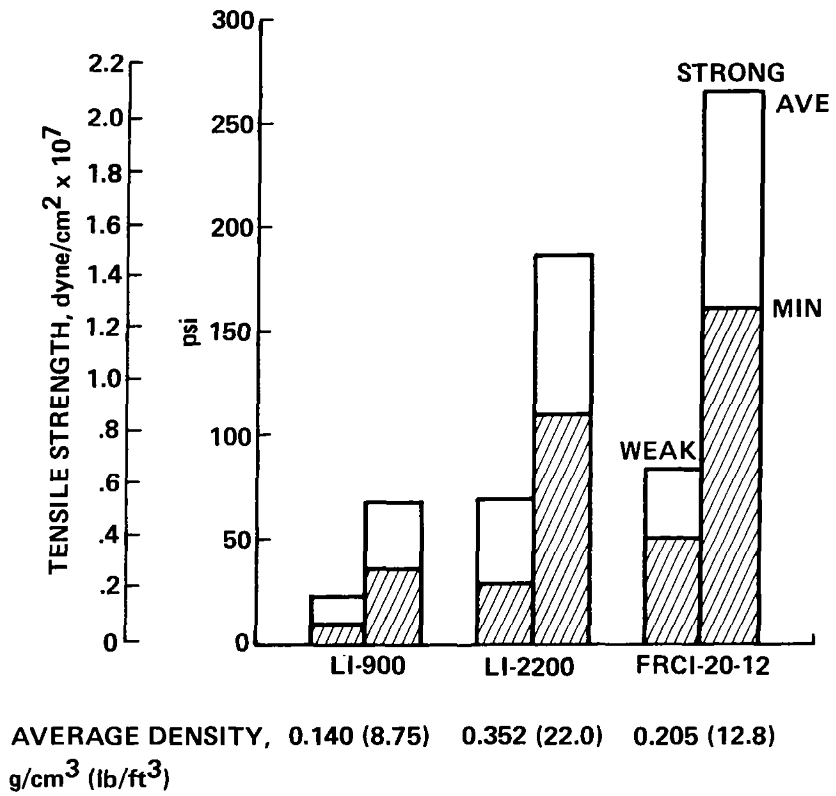


FRCI 20-20 ρ = 0.320 g/cm^3 (20 lbm/ft^3)

COMPARISON OF TENSILE STRENGTH OF FRCI AND ALL SILICA MATERIALS

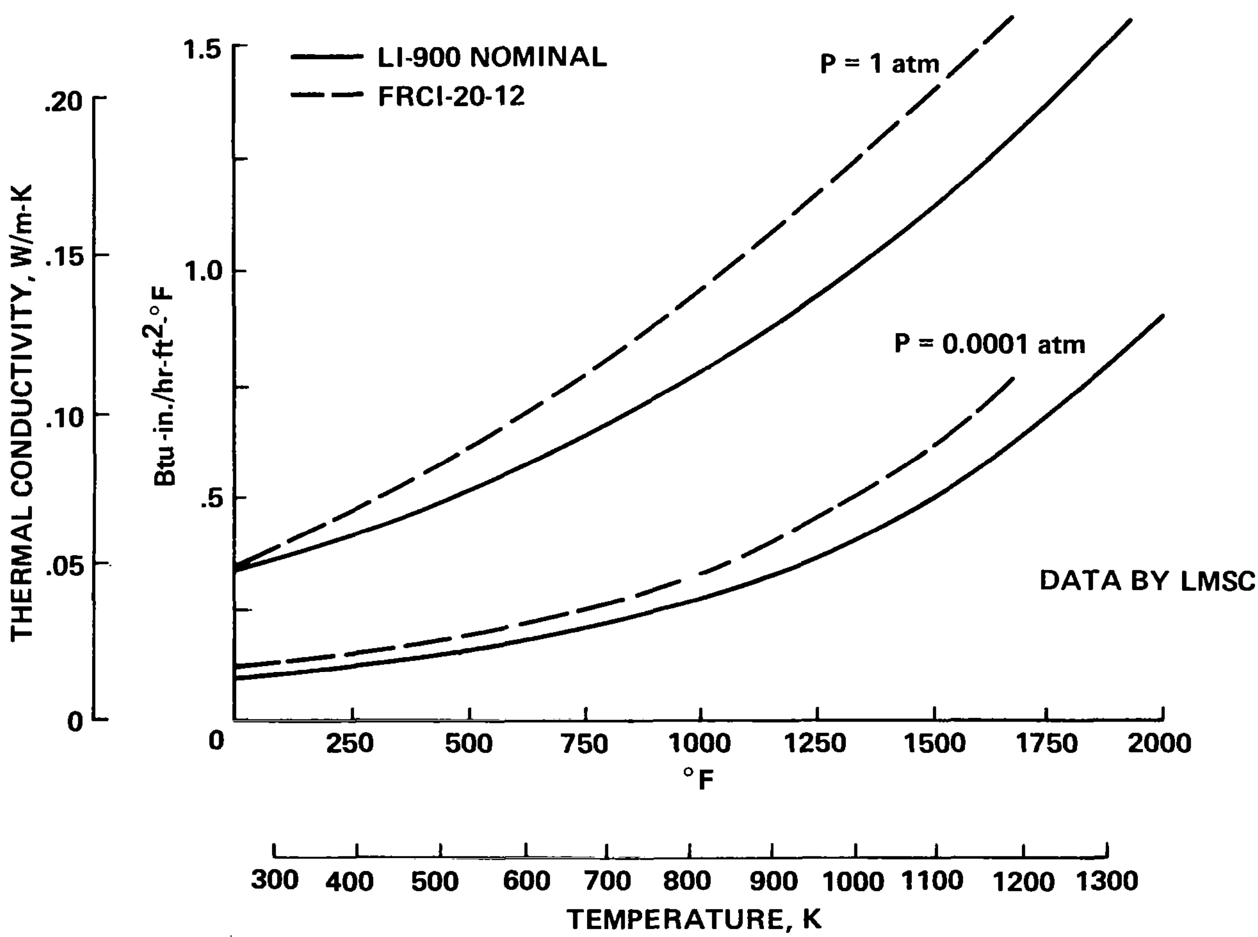
Average and minimum strength of FRCI-20-12 with LI-2200 and LI-900 in both in plane (strong) and through the thickness (weak) directions are shown. The important values for design are the minimums. FRCI-12 has a minimum 50% higher than LI-2200 and four times that of LI-900 even though its density is only 55% of LI-2200. These data demonstrate the important effect of improved bonding on strength.

Based on our experience with FRCI, which was the first fiber composite rigid insulation, studies are now being pursued to develop other such composites. These composites will have equivalent or improved strength and resistance to thermal shock with higher temperature capability. Materials with a continuous service capability of 1500 to 1650°C may be possible.



THERMAL CONDUCTIVITY OF FRCI COMPARED TO LI-900

The high temperature conductivity of both all silica RSI and FRCI is controlled by the average fiber diameter of the material. As this figure shows FRCI-20-12 has about a 10% higher thermal conductivity than LI-900. The difference exists because the aluminoborosilicate fibers are about 11 microns compared to 2-3 microns for silica. For practical purposes this difference in thermal conductivity is negligible since the uncertainty in the measurements is equivalent to the difference. Note also that the conductivity is both pressure and temperature dependent. At low pressure and high temperatures these materials have lower conductivities than any commercially available insulation with comparable temperature capability and density. No rigid commercial material has equivalent thermal shock resistance.

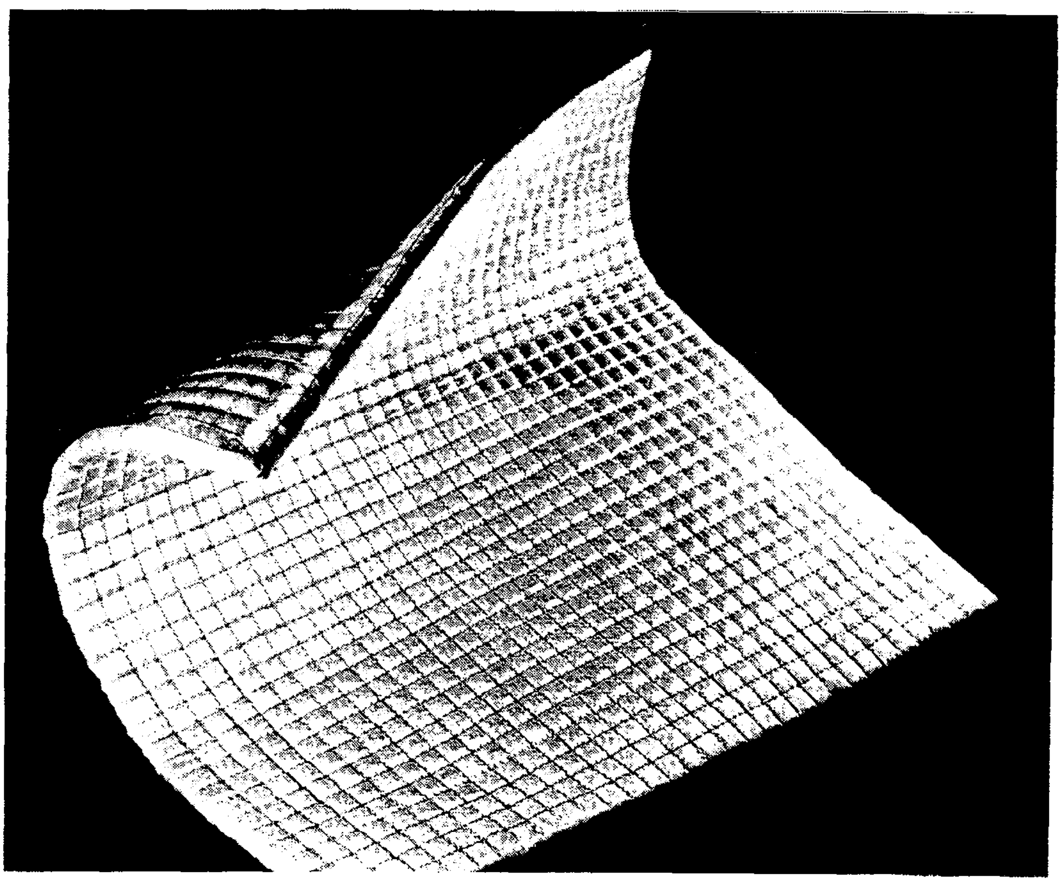


ADVANCED FLEXIBLE REUSABLE SURFACE INSULATION (AFRSI)

AFRSI is a quilt like material made of two layers of glass cloth with a layer of fibrous silica felt between them. The quilt, which varies in thickness from one to five centimeters, is sewn together with silica glass thread. It has a temperature capability in excess of 650°C. Similar materials have been used for many years to insulate jet engines.

AFRSI was conceived in 1975 as a result of test failures with the commercially available flexible ceramic insulations in simulated Space Shuttle launch environments. Shuttle launch acoustics, rain and aeroconvective heating were so severe that no commercial material could totally meet the requirements. Since the AFRSI concept is similar to commercial materials it could be manufactured using existing equipment and technology. Between 1975 and 1979 a series of arc plasma and wind tunnel tests and laboratory studies were performed to evaluate and modify the materials. Successive improvements were made by the manufacturer, Johns-Manville, at Ames direction.

In 1979 AFRSI was adopted for the Shuttle. About two square meters were installed on the Columbia between flights 1 and 2. The Orbiter maneuvering systems (OMS) pods on the second Orbiter Challenger are insulated with it and nearly all white tiles (approximately $185m^2$) will be replaced with it on Orbiters Discovery and Atlantis.



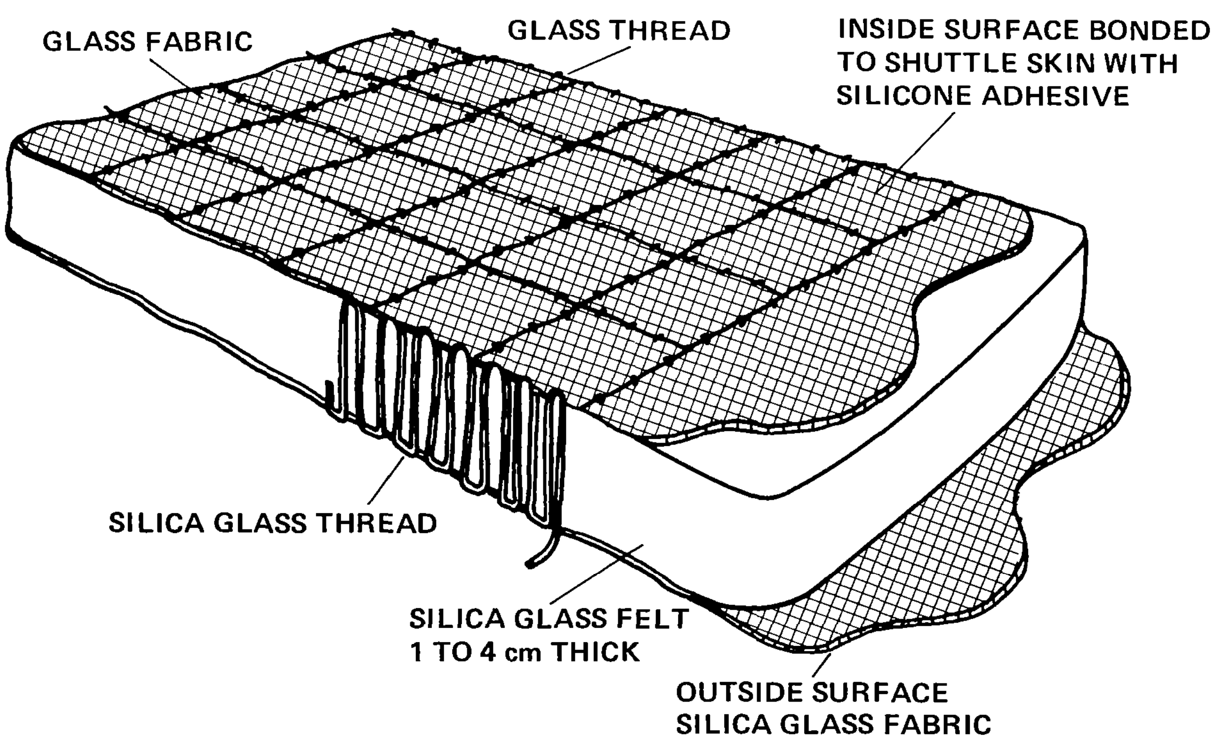
AFRSI CONSTRUCTION

The ARFSI external cover is 570 or 593 silica cloth. A fiberglass cover is used on the internal surface which is then bonded to the Shuttle skin with silicone resin. It is filled with silica fiber felt, having an effective density under 0.16 gm/cm^3. The composite is sewn together with Q-24 silica thread and treated with a silicone water repellent so that it will remain waterproof after long term exposure to surface temperatures above 600°C.

Transonic flow tests showed that heavy thread and relatively stiff cloth were required for AFRSI to survive the launch aeroacoustic environment. The failure mechanism for earlier versions was breaking of the sewing thread which allowed flutter of the outer cloth until the whole cover tore away. The failure mechanism with the current components is slow abrasion of the outer cloth which is easily seen before there is any risk of a catastrophic failure.

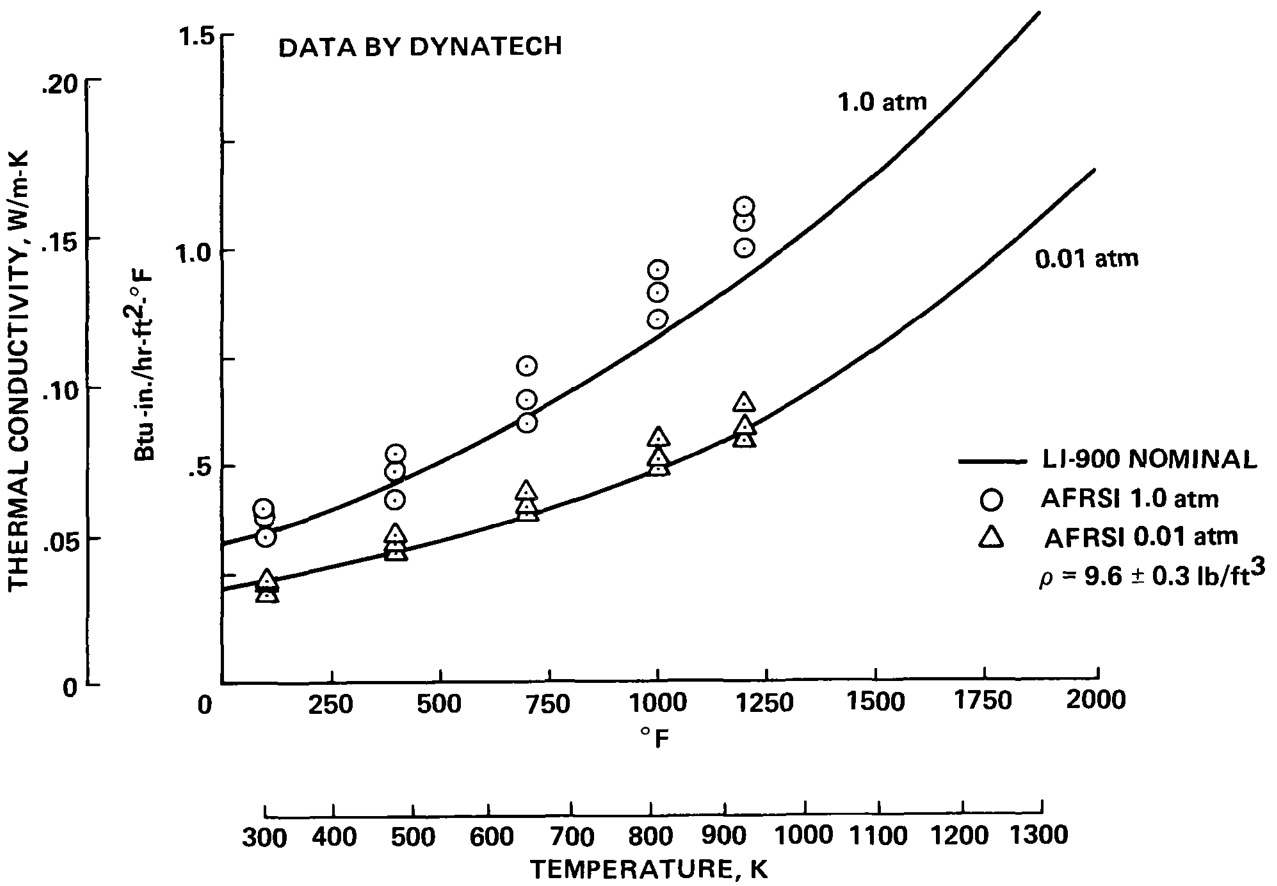
Temperature capability of AFRSI depends on the choice of cloth and thread, and the overall sequence of environments to which it is exposed. The original goal was to survive in excess of 650°C for 100 atmospheric entries after exposure to weathering on the launch pad and the orbital environment. Sequenced environmental testing has shown that current AFRSI has a maximum multiple use temperature of 750°C. Single use temperature is in excess of 1000°C.

AFRSI does not transmit stresses because of its construction and is totally resistant to thermal shock. Design of a load carrying structure using this material is much easier then with rigid RSI because strain compatibility with the substrate is not a concern.



THERMAL CONDUCTIVITY OF AFRSI

The thermal conductivity of AFRSI is essentially equivalent to that of rigid RSI because the same silica fiber is used in both. Conductivity at low pressures and high temperatures is exceptionally low. AFRSI optical properties can be easily tailored by coating, impregnating or changing the surface cloth to an appropriately opacified glass, without degrading temperature capability. This ability to tailor the properties should contribute to the potential for commercial applications.



CONCLUSION

New high technology fibrous ceramic insulators have been developed. These materials have unique properties in terms of thermal conductivity, resistance to thermal shock, temperature capability and controlled density. It is probable during the next few years that less expensive versions of these materials will become available in the marketplace, as applications develop to utilize their unique characteristics.

At Ames we are committed to advancing this technology by developing higher temperature, higher strength rigid fibrous ceramic insulation materials for use on advanced Space Transportation Systems. The goal for second generation flexible heat shield materials will be to have higher temperature capability and more resistance to the aeroacoustic environment experienced in transonic, supersonic and hypersonic flight regimes. It may be feasible to design these materials so that the drag and lift characteristics can be optimized in the flight regime of interest. The current materials are the benchmark on which we will base our future research. For the use of space to become truly economical future thermal protection systems must become less exotic, cheaper, and tougher. In the next decade we hope to provide materials to accomplish these goals.

REFERENCES

1. Larson, H. K., Centolanzi, F. J., Vojvodich, N. S., Goldstein, H. E., Covington, M. A., and Matting, F. W. Environmental Testing for Evaluation of Space Shuttle Thermal Protection Materials and Systems. NASA TMX-2273, Vol. II, Paper 10. Presented at NASA Space Shuttle Technology Conference, March 1971.

2. Goldstein, H. E., Leiser, D. B., Katvala, V. Reaction Cured Borosilicate Glass Coating for Low Density Fibrous Silica Insulation. Presented June 7, 1977 at the Boron in Glass Ceramics Conference, Alfred University, Alfred, New York. Published in Borate Glass Structure, Properties, Applications, Plenum Publishing Company, 1978.

3. Goldstein, H. E., Leiser, D. B., Smith, M., and Stewart, D. A. Opacified Silica Reusable Surface Insulation (RSI) for Thermal Protection of the Space Shuttle Orbiter. Presented August 25, 1977 at the Fifteenth International Thermal Conductivity Conference, Ottawa, Canada. Published in Thermal Conductivity 15, Plenum Publishing Company, 1978.

4. Larson, H. K., Goldstein, H. E.. Space Shuttle Orbiter Thermal Protection Materials Development and Testing. Presented March 3, 1978 at the 4th Aerospace Testing Conference of the Institute of Environmental Sciences, Los Angeles, Calif.

5. Leiser, D. B., Smith, M., Goldstein, H. E. Developments in Fibrous Refractory Composite Insulation. Ceramic Engineering and Science Proceedings. Volume I, No. 7-8 (B) July-August, 1980.

6. Leiser, D. B., Smith, M., and Goldstein, H. E. Fibrous, Refractory Composite Insulation. NASA Case No. ARC 11169-1, April, 1978. Patent No. 4,148,962, April 10, 1979.

7. Beaseley, R. M., Izu, Y. D., et al. Fabrication and Improvement of LMSC's All-Silica RSI. Presented at NASA Symposium on Reusable Surface Insulation for Space Shuttle, NASA TMX-2719, Vol. I, Nov. 1972.

8. Korb, L. J., Morant, C. A., Calland, R. M., and Thatcher, C. S. The Shuttle Orbiter Thermal Protection System, Ceramic Bulletin, pp. 1188 to 1193, Vol. 60, No. 11, 1981.