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Chapter 16

A HISTORY OF HEAT SHIELDS FOR MANNED SPACE FLIGHT*

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The history of manned space flight from the first supersonic flight in 1947 to the first Space Shuttle flight in 1981 is closely related to the evolution of heat shield materials and cross-range maneuverability requirements. During this period there were parallel lines of development: aeronautics and astronautics. The Space Shuttle resulted from the combined advances in these two fields.

Early advances came quickly as new materials were tested. The X-2, designed to go higher and faster than the X-1, tested a new nickel stainless-steel alloy (monel-K) for heat resistance. The X-15, built by North American Aviation and possibly the best known of all the X-series rocket planes, was designed as a Mach 6 vehicle; the nickel-steel alloy, Inconel-X, could withstand 649°C (1200°F). To prevent the Inconel skin from buckling during planned Mach 6 to Mach 8 flight tests, a heat shield was required. Ablation, a method pioneered more than ten years earlier, used a planned sacrificial loss of the exterior material to protect the interior.

The ablative material selected was MA-25s, developed by Martin Marietta in Baltimore. This material was based on a silicone resin (GE 652) developed by Dr. Modic of General Electric Silicone Products Department (no other resin system was evaluated because no alternate commercial silicone resin could be identified).

In early 1967 patches of ablator were applied and flight tested. Later in the year the entire plane was sprayed with ablator by James Ruff under the lead of Charles K. Mullen, both of Martin Marietta. On Oct. 3, 1967, Major William J. Knight of the U.S. Air Force flew the ablator-covered X-15A-2 to a record Mach 6.72 or 7300 km/hr (4534 miles/hr). The ablator was subsequently stripped from the plane. "Even before the X-15 was flown, the technology was developing so fast that in 1956 and 1957 the NACA and Air Force were considering a rocket-boosted airplane that would fly initially up to Mach 12 or 14 and eventually to orbital speeds. This work finally developed in the X-20 (Dyna-Soar) project" [1, p.6].

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Following the Oct. 4, 1957 launch of *Sputnik 1*, the X-20 project was reoriented and directed to proceed to orbital-flight capability immediately. However, by 1958, studies showed the simpler ballistic approach advanced 13 years earlier by H. D. Allen offered greater chances of success in a shorter time. The X-20 was not simply a victim of changing policies, it had already encountered problems related to increasing weight from increasing the size of structural members due to the inability to control structural temperatures with its planned metallic re-radiation system and active thermal control system.

Material advances alone could not solve the problem of manned re-entry, since the kinetic energy involved would vaporize any known material. During the early 1950s few agreed on the proper approach to manned space flight. In 1956, the Air Research and Development Command (ARDC) advanced two proposals: a "Manned Glide Rocket Research System" and a "Manned Ballistic Rocket Research System." At this time X-series research aircraft had only investigated flight regimes through Mach 3. The best thinking and computer solutions extrapolated this meager data into the, as yet undefined, hypersonic region. A major drawback at the time was that everyone thought in terms of streamlined shapes; they thought a pointed streamlined configuration was best. In fact, it was not best for re-entry.

H. J. Allen, head of the High Speed Research Division at Ames, reasoned that the kinetic energy is converted into heat—two types of heat: compression and friction. Pointed cone shapes were heated to excess because the viscous layer generates most of the heat, and because it was attached to the surface of the cone, the material increased in temperature beyond a survivable level. With a blunt-shaped configuration, the shock wave would be greatly strengthened, and would at no point attach to the entry body. Also, a blunt-faced body would more evenly distribute the heat reaching the surface and render it less prone to local hot spots. Switching the source of heat generation from boundary layer to a "stand-off" shock wave did not completely solve the problem. Heat-shielding methods were still needed: heat-sink or ablation. Heat sinks were, by virtue of their density, much heavier than the comparatively light ablative compounds.

In 1955, Dr. Arthur Kantrowitz and his team at Avco Manufacturing Corporation used shock tubes and high temperature electric arcs to simulate the re-entry heating conditions, so that the behavior of materials exposed to the severe environment could be studied. The first known man-made object recovered intact from space was an RVX-1 re-entry vehicle (nose cone) in 1955. This unmanned re-entry vehicle, which flew at ICBM speeds and range, was covered with AVCOITE, a quartz-based material that had successfully incorporated the experimental "ablative" concept.

The AVCOITE absorbed the heat of reentry and dissipated it by vaporizing, thus exhibiting some of the characteristics of ablation; planned sacrificial loss to protect the interior, mass transfer cooling, and convective blockage by thickening the boundary layer.

The re-entry capsules for Mercury, Gemini and Apollo relied on blunt-faced ablative heat shields for protection. The evolution is summarized below:

	Mercury	**Gemini**	**Apollo**
Material	Epoxy Phenolic Wound Tape	Corning DC 235	Avco 5026-39
Density (lb/cu ft.)	114	54	33
Area (ft^2)	32	45	365

The Mercury capsule, built by McDonnell, used an epoxy-phenolic wound tape for its blunt re-entry face, where heating rates were highest. This heavily glass-reinforced ablation shield was used in conjunction with re-radiative metallic shingles on the sides of the cone where heating rates were lower. Rene 41, a nickel-cobalt alloy, was used on the sides of the cone, and beryllium heat-sink shingles were used on the recovery canister, where heating rates were higher [1, p.95].

Gemini, the same shape as Mercury but larger, (18 ft. 5 in. long by 10 ft. in diameter versus 11 ft. long by 6 ft. in diameter), was also built by McDonnell of titanium and beryllium. The ablative heat shield was a Dow Corning Silicone based material (DC 235) in a blind honeycomb [2, p.210].

The Apollo Command Module, built by North American Aviation, was constructed with an inner structure of stainless-steel honeycomb bonded between aluminum alloy sheets. The outer structure is a three-piece heat shield of brazed honeycomb stainless steel, attached with fiberglass stringers with Q felt insulation, filling the gap between inner and outer structure [2, p.217; 3, p.545]. The outer honeycomb was filled with an epoxy novolac, and Avco material (Avco 5026-39). This honeycomb had larger openings than that used on Gemini. The Gemini honeycomb was filled by using vacuum to cause the ablator to flow into the honeycomb, whereas each opening in the Apollo heat shield was individually filled.

All during this time work was being done on lifting bodies which promised to be the best of both worlds: high drag when needed, yet able to glide to a controlled landing. In order to learn more about cross-range maneuverability and the heat shielding requirements, the Air Force began, in 1961, a project called Spacecraft Technology and Advanced Re-entry Test (START). Two versions of the Air Force's SV-5 were built & tested by Martin Marietta: the unmanned 1/3-scale PRIME (Precision Recovery Including Maneuvering Re-entry) and the X-24, a full-scale manned subsonic version, which tested handling and dead-stick landings.

PRIME, launched by an Atlas, tested ablative materials (ESA-3560 on the body, ESA-5500 on the leading edges, carbon-phenolic on the nose and teflon, which is rf transparent, over the antennas) as well as cross-range capability. By the time this project and NASA's HL-10, M2-F1, and M2-F2 lifting body research was completed, state-of-the-art heat shield technology permitted the Shuttle Orbiter, built by Rockwell, to be a delta wing design (even greater cross-range capability) instead of a lifting body.

The requirement for the Orbiter heat shield to be reusable, led to the development of the ceramic re-radiation tiles for the lower surface, and carbon-carbon for the leading edges and nose. The ceramic tile material existed only in the laboratory and required major development. Actually, when the Space Shuttle first flew, there were only three areas of true state-of-the-art technology: the main engines, the orbiter ceramic tile heat shield, and the external tank's thermal protection system.

Since the External Tank for the Space Shuttle is not recovered, and an extremely large volume of cryogenic fluids must be protected, an entirely different kind of thermal protection system developed. The ET uses both spray-on foam insulation (SOFI) and a highly filled ablator. The SOFI (primarily CPR-UPJOHN CPR-488 and North Carolina Foam Industries NCFI 22-65) serves both as an insulation for the cryogens and as an ablative material for low to medium heating rate areas. The ablators include Martin Marietta's MA-25S (basically the same material sprayed on the X-15) and SLA-561 (super-light ablator). The SLA-561 is derived from the materials tested on PRIME and later developed by Eric Strauss for use on the Viking Mars lander. Two trends can be clearly seen in the evolution of heat shields for manned space flight: continually increasing area to be protected and dramatically reduced density.

The area protected by the thermal protection systems for the Shuttle Orbiter and External Tank is more than an order of magnitude greater than for any previous vehicle. The Orbiter has 11,895 sq. ft. of TPS (9 lb/cu ft), which is designed to last 100 flights. The ET, jettisoned after each flight, has over 16,000 sq. ft. of TPS. Over 14,000 sq. ft of SOFI on the ET has a density of only 2.3 lb/cu ft. The ET is also the first manned space vehicle component that is mass produced. The advent of routine flights of the Space Shuttle resulted from the evolution of heat shield materials and technology. The Shuttle's roots are in the lessons learned from developments in aeronautics and astronautics—from ballistic re-entry and lifting bodies, as well as the early work from high speed planes. As manned presence in space broadens in scope, and flight and production experience increases, the development of heat shield materials will continue to evolve.

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