Materials in Thermal Protection Systems [TPS] of Aerospace Vehicles

All the orbiters were covered in TPS materials which protected the shuttles from the heat of re-entry and also cold temperatures experienced when in space, a temperature range of -121-1,649°C. There is a complicated array of materials which comprise the TPS to help keep the astronauts and payload safe during flights.

The TPS covered essentially the entire orbiter surface, and consisted of seven different materials in varying locations based on amount of required heat protection:

- Reinforced carbon–carbon (RCC), used in the nose cap, the chin area between the nose cap and nose landing gear doors, the arrowhead aft of the nose landing gear door, and the wing leading edges. Used where reentry temperature exceeded 1,260 °C (2,300 °F).
- High-temperature reusable surface insulation (HRSI) tiles, used on the orbiter underside. Made of coated LI-900 silica ceramics. Used where reentry temperature was below 1,260 °C.
- Fibrous refractory composite insulation (FRCI) tiles used to provide improved strength, durability, resistance to coating cracking and weight reduction. Some HRSI tiles were replaced by this type.
- Flexible Insulation Blankets (FIB), a quilted, flexible blanket-like surface insulation. Used where reentry temperature was below 649 °C (1,200 °F).
- Low-temperature Reusable Surface Insulation (LRSI) tiles, formerly used on the upper fuselage, but were mostly replaced by FIB. Used in temperature ranges roughly similar to FIB.
- Toughened unipiece fibrous insulation (TUFI) tiles, a stronger, tougher tile which came into use in 1996. Used in high and low temperature areas.
- Felt reusable surface insulation (FRSI). White Nomex felt blankets on the upper payload bay doors, portions of the mid fuselage and aft fuselage sides, portions of the upper wing surface and a portion of the OMS/RCS pods. Used where temperatures stayed below 371 °C (700 °F).

Each type of TPS had specific heat protection, impact resistance, and weight characteristics, which determined the locations where it was used and the amount used.

The shuttle TPS has three key characteristics that distinguish it from the TPS used on previous spacecraft:

Reusable

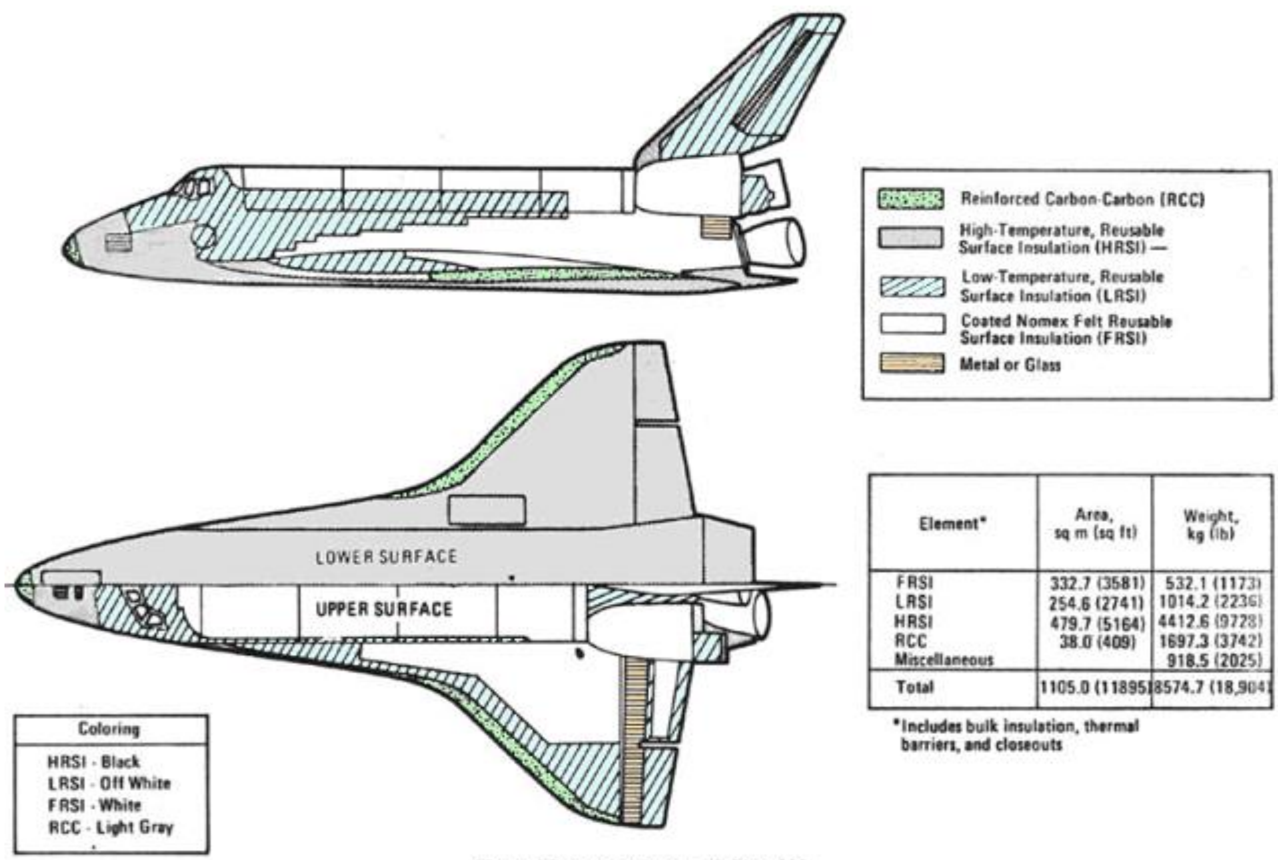
Previous spacecraft generally used ablative heat shields which burned off during reentry and so couldn't be reused. This insulation was robust and reliable, and the single-use nature was appropriate for a single-use vehicle. By contrast, the reusable shuttle required a reusable thermal protection system.

Lightweight

Previous ablative heat shields were very heavy. For example, the ablative heat shield on the Apollo Command Module comprised about 15% of the vehicle weight. The winged shuttle had much more surface area than previous spacecraft, so a lightweight TPS was crucial.

Fragile

The only known technology in the early 1970s with the required thermal and weight characteristics was also so fragile, due to the very low density, that one could easily crush a TPS tile by hand.



Element*	Area, sq m (sq ft)	Weight, kg (lb)
FRSI	332.7 (3581)	532.1 (1173)
LRSI	254.6 (2741)	1014.2 (2236)
HRSI	479.7 (5164)	4412.6 (9728)
RCC	38.0 (409)	1697.3 (3742)
Miscellaneous		918.5 (2025)
Total	1105.0 (11895	8574.7 (18,904

*Includes bulk insulation, thermal barriers, and closeouts

Thermal Protection System, Orbiter 102

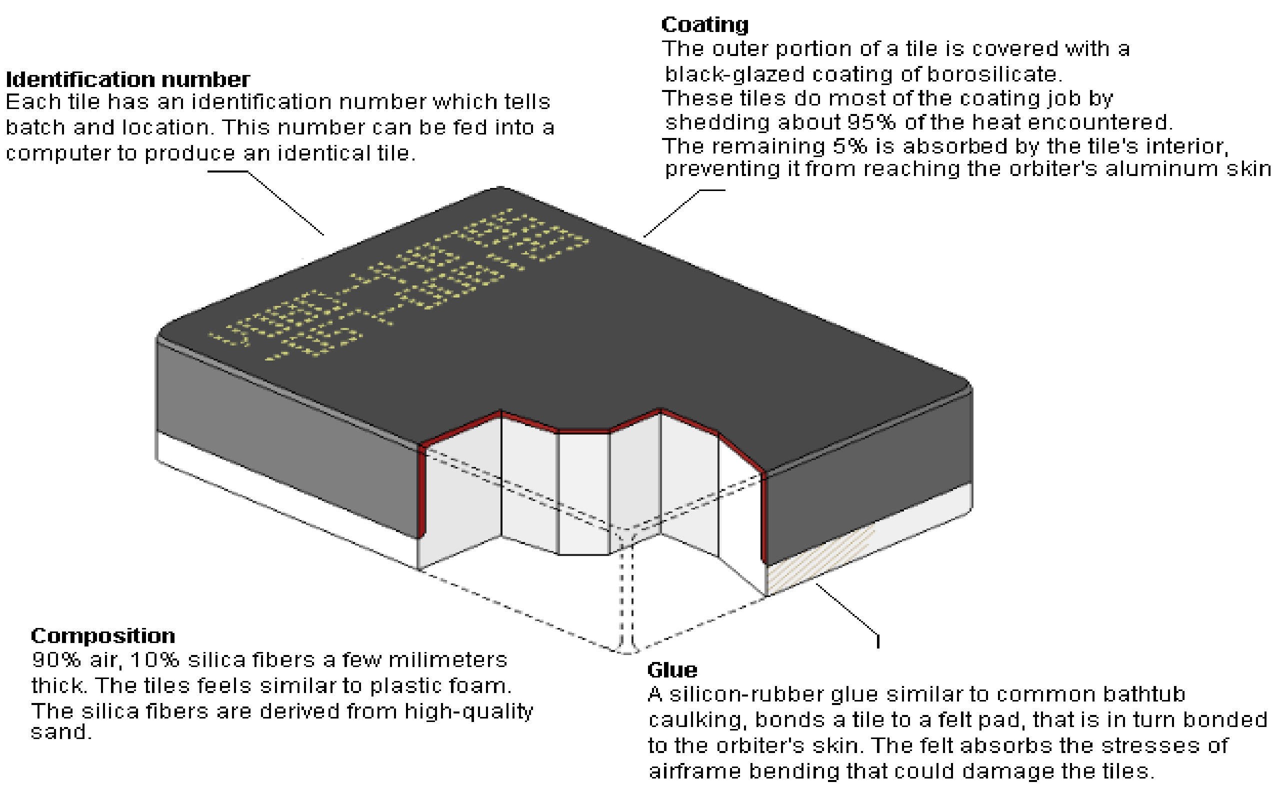
Tile types

High-temperature reusable surface insulation (HRSI)

It can withstand temperatures up to 1,260 °C (2,300 °F). There were 20,548 HRSI tiles which covered the landing gear doors, external tank umbilical connection doors, and the rest of the orbiter's under surfaces. They were also used in areas on the upper forward fuselage, parts of the orbital maneuvering system pods, vertical stabilizer leading edge, elevon trailing edges, and upper body flap surface. They varied in thickness from 1 to 5 inches (2.5 to 12.7 cm), depending upon the heat load encountered during re-entry. Except for closeout areas, these tiles were normally 6 by 6 inches (15 by 15 cm) square. The HRSI tile was composed of high purity silica fibers. Ninety percent of the volume of the tile was empty space, giving it a very low density (9 lb/cu ft or 140 kg/m^3) making it light enough for spaceflight.

The uncoated tiles were bright white in appearance and looked more like a solid ceramic than the foam-like material that they were.

The black coating on t was Reaction Cured Glass (RCG) of
which tetrasilicide and borosilicate glass were some of several ingredients. RCG was applied to all but one side of the tile to protect the porous silica and to increase the heat sink properties. The coating was absent from a small margin of the sides adjacent to the uncoated (bottom) side. To waterproof the tile, dimethylethoxysilane was injected into the tiles by syringe. Densifying the tile with tetraethyl orthosilicate (TEOS) also helped to protect the silica and added additional waterproofing.



An uncoated HRSI tile held in the hand feels like very light foam, less dense than Styrofoam, and the delicate, friable material must be handled with extreme care to prevent damage. The coating feels like a thin, hard shell and encapsulates the white insulating ceramic to resolve its friability, except on the uncoated side. Even a coated tile feels very light, lighter than a same-sized block of Styrofoam. As expected for silica, they are odourless and inert.

HRSI was primarily designed to withstand transition from areas of extremely low temperature (the void of space, about −270 °C or −454 °F) to the high temperatures of re-entry (caused by interaction, mostly compression at the hypersonic shock, between the gases of the upper atmosphere & the hull of the Space Shuttle, typically around 1,600 °C or 2,910 °F).

Fibrous Refractory Composite Insulation Tiles (FRCI)

The black FRCI tiles provided improved durability, resistance to coating cracking and weight reduction. Some HRSI tiles were replaced by this type.

Toughened unipiece fibrous insulation (TUFI)

A stronger, tougher tile which came into use in 1996. TUFI tiles came in high temperature black versions for use in the orbiter's underside, and lower temperature white versions for use on the upper body. While more impact resistant than other tiles, white versions conducted more heat which limited their use to the orbiter's upper body flap and main engine area. Black versions had sufficient heat insulation for the orbiter underside but had greater weight. These factors restricted their use to specific areas.

Low-temperature reusable surface insulation (LRSI)

White in color, these covered the upper wing near the leading edge. They were also used in selected areas of the forward, mid, and aft fuselage, vertical tail, and the OMS/RCS pods. These tiles protected areas where reentry temperatures are below 1,200 °F (649 °C). The LRSI tiles were manufactured in the same manner as the HRSI tiles, except that the tiles were 8 by 8 inches (20 by 20 cm) square and had a white RCG coating made of silica compounds with shiny aluminum oxide. The white color was by design and helped to manage heat on orbit when the orbiter was exposed to direct sunlight.

These tiles were reusable for up to 100 missions with refurbishment (100 missions was also the design lifetime of each orbiter). They were carefully inspected in the Orbiter Processing Facility after each mission, and damaged or worn tiles were immediately replaced before the next mission. Fabric sheets known as gap fillers were also inserted between tiles where necessary. These allowed for a snug fit between tiles, preventing excess plasma from penetrating between them, yet allowing for thermal expansion and flexing of the underlying vehicle skin.

Prior to the introduction of FIB blankets, LRSI tiles occupied all of the areas now covered by the blankets, including the upper fuselage and the whole surface of the OMS pods. This TPS configuration was only used on *Columbia* and *Challenger*.

Non-tile TPS

Flexible Insulation Blankets/Advanced Flexible Reusable Insulation (FIB/AFRSI)

Developed after the initial delivery of *Columbia* and first used on the OMS pods of *Challenger*. This white low-density fibrous silica batting material had a quilt-like appearance, and replaced the vast majority of the LRSI tiles. They required much less maintenance than LRSI tiles yet had about the same thermal properties. After their limited use on *Challenger*, they were used much more extensively beginning with *Discovery* and replaced many of the LRSI tiles on *Columbia* after the loss of *Challenger*.

Reinforced Carbon-Carbon (RCC)

The light gray material which withstood reentry temperatures up to 1,510 °C (2,750 °F) protected the wing leading edges and nose cap. Each of the orbiters' wings had 22 RCC panels about ¼ to ½ inch (6.4 to 12.7 mm) thick. T-seals between each panel allowed for thermal expansion and lateral movement between these panels and the wing.

RCC was a laminated composite material made from carbon fibres impregnated with a phenolic resin. After curing at high temperature in an autoclave, the laminate was pyrolized to convert the resin to pure carbon. This was then impregnated with furfural alcohol in a vacuum chamber, then cured and pyrolized again to convert the furfural alcohol to carbon. This process was repeated three times until the desired carbon-carbon properties were achieved.

To provide oxidation resistance for reuse capability, the outer layers of the RCC were coated with silicon carbide. The silicon-carbide coating protected the carbon-carbon from oxidation. The RCC was highly resistant to fatigue loading that was experienced during ascent and entry. It was stronger than the tiles and was also used around the socket of the forward attach point of the orbiter to the External Tank to accommodate the shock loads of the explosive bolt detonation. RCC was the only TPS material that also served as structural support for part of the orbiter's aerodynamic shape: the wing leading edges and the nose cap. All other TPS components (tiles and blankets) were mounted onto structural materials that supported them, mainly the aluminum frame and skin of the orbiter.

Nomex Felt Reusable Surface Insulation (FRSI)

This white, flexible fabric offered protection at up to 371 °C (700 °F). FRSI covered the orbiter's upper wing surfaces, upper payload bay doors, portions of the OMS/RCS pods, and aft fuselage.

Gap fillers

Gap fillers were placed at doors and moving surfaces to minimize heating by preventing the formation of vortices. Doors and moving surfaces created open gaps in the heat protection system that had to be protected from heat. Some of these gaps were safe, but there were some areas on the heat shield where surface pressure gradients caused a crossflow of boundary layer air in those gaps.

The filler materials were made of either white AB312 fibers or black AB312 cloth covers (which contain alumina fibers). These materials were used around the leading edge of the nose cap, windshields, side hatch, wing, trailing edge of elevons, vertical stabilizer, the rudder/speed brake, body flap, and heat shield of the shuttle's main engines.

On STS-114, some of this material was dislodged and determined to pose a potential safety risk. It was possible that the gap filler could cause turbulent airflow further down the fuselage, which would result in much higher heating, potentially damaging the orbiter. The cloth was removed during a spacewalk during the mission.

The nose cap, the area between the nose cap and the nose landing gear doors, arrowhead aft of the nose landing gear door and the outer edges of the wings are produced from a reinforced carbon-carbon (RCC) composite. This composite is able to withstand high temperatures and was used to protect areas of the shuttle that would rise above 1,260°C. For temperatures below this, NASA used rigid silica tiles/fibrous insulation.

The tiles used were based on work carried out by the *Lockheed Missiles & Space Company* who had a patent disclosure which described a reusable insulating tile made from ceramic fibers which could be used during re-entry as a guard against high temperatures. A reusable insulation system that could be directly bonded to a lightweight aluminium airframe was very attractive to NASA and so the focus of the generation of the TPS was diverted towards using tiles.

The large portion of the TPS is comprised of High-Temperature Reusable Surface Insulation (HRSI) and Low-Temperature Reusable Surface Insulation (LRSI). The main difference between HRSI and LRSI is the surface coatings used on them.

On the HRSI tiles, a black borosilicate glass coating was used to protect areas of the shuttle which reached up to 1,260°C. A white coating was used on the LRSI tiles which had the optical properties required to maintain on-orbit temperatures for vehicle thermal control purposes. The areas of the shuttle covered with LRSI reached temperatures up to 649°C.

Heat-resistant superalloys and their applications

Superalloys are nickel-, iron-nickel-, and cobalt-base alloys generally used at temperatures above about 1000ºF (540ºC). The iron-nickel-base superalloys such as the popular alloy IN-718 are an extension of stainless steel technology and generally are wrought. Cobalt-base and nickel-base superalloys may be wrought or cast, depending on the application/composition involved. A large number of alloys have been invented and studied; many have been patented. However, the many alloys have been winnowed down over the years; only a few are extensively used. Alloy use is a function of industry (gas turbines, steam turbines, etc.).

Figure 1.1 compares stress-rupture behaviour of the three alloy classes (iron-nickel-, nickel-, and cobalt-base). Appropriate compositions of superalloys can be forged, rolled to sheet, or otherwise produced in a variety of shapes. The more highly alloyed compositions normally are processed as castings. Fabricated structures can be built up by welding or brazing, but many highly alloyed compositions containing a large amount of hardening phase are difficult to weld. Properties can be controlled by adjustments in composition and by processing (including heat treatment), and excellent elevated-temperature strengths are available in finished products.

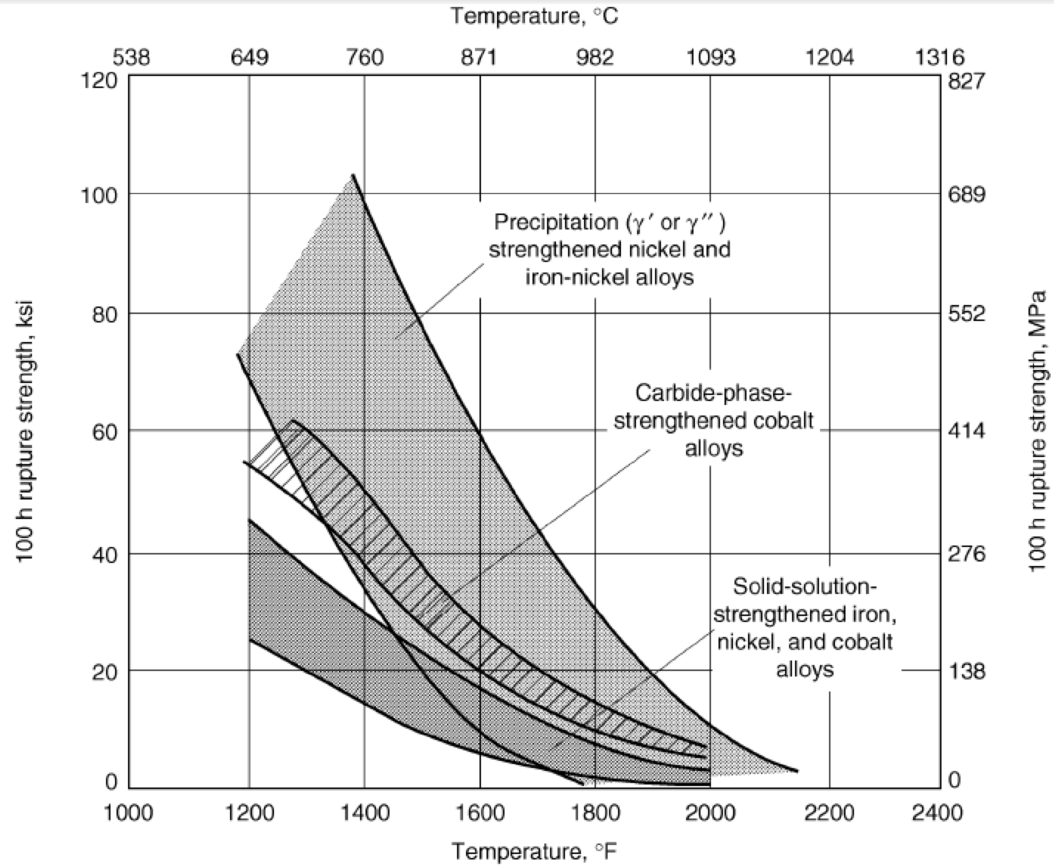


Fig. 1.1 Stress-rupture strengths of superalloys

Superalloys are used widely in high-temperature environments where materials must resist corrosion and retain their strength, toughness and structure. Each superalloy is manufactured carefully, balancing key compositional elements to give desirable properties for a range of industrial applications.

For example, within the aerospace industry, nickel superalloys have many essential applications. They are employed within the hottest areas of jet engines, where temperatures can regularly exceed 1200°C. Materials in this area must be able to withstand those conditions without compromising the structural integrity of the engine. Such superalloys are perfect for the job, as they are engineered to offer superior resistance against corrosion and oxidation at elevated temperatures.

Jet engine applications

When using superalloys in jet engines, it's important to look to a nickel-based product, one with high levels of chromium, iron, titanium and cobalt. INCONEL alloy 601 is a good example of this. It has 58% nickel and 20-23% chromium, as well as all the other necessary key elements. In particular, it has the addition of aluminium, which enables the alloy to resist high-temperature oxidation and aqueous corrosion. It also has a high mechanical strength and can be readily machined and welded, making it a very versatile material for jet engine use.

The introduction of better superalloys has helped to develop the jet engine. As the materials are manufactured with increasingly better properties – such as increased high-temperature resistance and corrosion resistance – design engineers are able to make improvements to jet engine performance, including higher thrust and lower fuel consumption.

Processing chemicals and waste

Back down on the ground, there are other environments that rely on superalloys and their exceptional heat resistance. In the processing industries, these kinds of high-performance materials are integral to systems we all rely on.

Waste fluid treatment plants, for example, are necessary but difficult environments. They are highly corrosive and very hot. INCONEL alloy C-276 is known for its outstanding corrosion resistant in the most inhospitable of atmospheres. Its composition is such that it can withstand even the most severe system. It has a low carbon content, which minimises carbide precipitation during welding to help it maintain its corrosion resistance in as-welded structures, enhancing its usefulness. It also has a high level of molybdenum (15-17%), which gives the alloy strength, as well as better resistance to pitting and crevice corrosion. As well as waste treatment, this superalloy is used in pollution-control systems, chemical processing, and pulp and paper production, thanks to its unique characteristics.

Oil and gas extraction

The oil and gas industry has some incredibly corrosive, high-temperature situations to deal with. The materials used in these systems are paramount to the safe extraction of essential resources, and therefore they must be up to the job. Nickel superalloys are used for both onshore and offshore extraction projects, for everything from pumps and valves to process-control equipment.

One of the key materials used is INCONEL alloy 625, a flagship nickel alloy due to its exceptional properties. This material offers high strength, outstanding corrosion resistance and high-temperature resistance. It has a unique composition, with nickel, chromium, molybdenum and niobium that gives it particularly superior resistance to severely corrosive environments. One of its key uses, though it has many, is in pipelines used for gathering sour gas. It's also used in the separation of extracted fluids in the processing equipment for liquefied natural gas production.

Important Characteristics Superalloy

• When temperatures go above about 1000 ºF (540 ºC), ordinary steels and titanium alloys are no longer strong enough for application. Steels also may suffer from enhanced corrosion attack.

• When the highest temperatures (below the melting temperatures, which are about 2200 to 2500 ºF (1204 to 1371 ºC) for most alloys) must be achieved and strength is the consideration, then nickel-base superalloys are the materials of choice.

• Nickel-base superalloys can be used to a higher fraction of their melting points than just about any other commercially available materials. Refractory metals have higher melting points than superalloys but do not have the same desirable characteristics as superalloys and are much less widely used.

• Cobalt-base superalloys may be used in lieu of nickel-base superalloys, dependent on actual strength needs and the type of corrosive attack expected.

• At lower temperatures, and dependent on the type of strength needs for an application, iron-nickel-base superalloys find more use than cobalt- or nickel-base superalloys.

• Superalloy strength properties are directly related not only to the chemistry of the alloy but also to melting procedures, forging and working processes, casting techniques, and, above all, to heat treatment following forming, forging or casting.

• Iron-nickel-base (sometimes designated nickel-iron-base) superalloys such as IN-718 are less expensive than nickel-base or cobalt-base superalloys.

• Most wrought superalloys have fairly high levels of the metal chromium to provide corrosion resistance. In the cast alloys, chromium was high to start but was significantly reduced over the years in order to accommodate other alloy elements that increased the elevated temperature strength of superalloys. In the superalloys based on nickel, the aluminum content of the alloys increased as chromium decreased. Thus, the oxidation resistance of nickel superalloys remained similar to original levels or even increased. However, resistance to other types of corrosion attack decreased.

• Superalloys have great oxidation resistance, in many instances, but not enough corrosion resistance. For many applications at the highest temperatures, above about 1400 _F (760 _C), as in aircraft turbines, superalloys must be coated. For very long-time applications at temperatures at or above about 1200 _F (649 _C), as in land-based gas turbines, superalloys may have to be coated.

• Coating technology is an integral part of superalloy development and application. Lack of a coating means much less ability to use superalloys for extended times at elevated temperatures.

• Many alloy elements are added to superalloys in minuscule to major amounts, particularly in the nickel-base alloys. Controlled alloy elements could be as many as 14 or so in some alloys.

• Nickel and cobalt as well as chromium, tungsten, molybdenum, rhenium, hafnium, and other elements used in superalloys are often expensive and strategic elements that may vary considerably in price and availability over time.

Applications of Superalloys

The high-temperature applications of superalloys are extensive, including components for aircraft, chemical plant equipment, and petrochemical equipment. The gas temperatures in gas turbine engines in the hot sections (rear areas of the engine) may rise to levels far above 2000 ºF (1093ºC). Cooling techniques reduce the actual component metal temperatures to lower levels, and superalloys that can operate at these temperatures are the major components of the hot sections of such engines.

The significance of superalloys in today’s commerce is typified by the fact that, whereas in 1950 only about 10% of the total weight of an aircraft gas turbine engine was made of superalloys, by 1985 this figure had risen to about 50%. Table 1.3 lists some current applications of superalloys. It will be noted, however, that not all applications require elevated-temperature strength capability. Their high strength coupled with corrosion resistance has made certain superalloys standard materials for biomedical devices. Superalloys also find use in cryogenic applications.