History and experience of overcoming thermal barriers in rocket and space technology: 1. Ballistic missiles

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Abstract. This paper considers the history of overcoming “thermal barriers” in rocket and space technology. “Thermal barriers” do not let individual subassemblies, units of spacecrafts or whole spacecrafts to perform their task due to out-of-limit thermal loads. Designers of rockets and spacecrafts regularly face “thermal barriers” with special features related to intensity, intermittency, and duration of thermal loads. However, a universal solution for overcoming these barriers does not exist yet. In searching for such solutions, new ideas are born, methods and tools of mathematical modeling and experimentation are developed and perfected, new materials and technologies are created. This is the first paper in a series of papers devoted to the study of this problem.

1. Introduction
In rocket and space technology, thermal processes make a decisive influence on the onboard system's layout, the choice of materials, and technological solutions. During the operation of rocket engines and power plants, the flight of rockets and spacecrafts in the atmospheres of the Earth and other planets at high speed, spacecraft motion in the outer space, temperature gradients are so severe that regular operation is impossible without taking certain protection measures. Thermal protective coating (TPC) is the main measure ensuring the required thermal regimes.

Thermal protection design is a complex multi-disciplinary problem encompassing the problems of aerodynamics, thermal physics, mechanics, and material science. The pioneering research of ablative TPC of re-entry vehicles of long-range ballistic missiles (LRBM) was conducted in the USSR and the USA in the middle of the 1950s. In the design of LRBM and spacecrafts, this avenue of research had become principal.

The goal of the series of studies is to analyze the current state of thermal protection to identify ways to improve durability and reduce coating mass by using new materials and better analyzing specifics of heat transfer in the coatings.

2. “Thermal barrier” in the way of creating LRBM
The appearance of the “thermal barrier” term is related with the name of a renowned aerospace scientist Theodore von Kármán. When he analyzed the problems of hypersonic flight, he made the following conclusion, “At such speeds, even in rarified air, the surface will be heated to the temperatures none of the known materials can withstand. The problem of the thermal barrier is much more complicated than the problem of sound barrier” [1].
After the end of WWII, the USSR and the USA started creating LRBM based on the German experience in that area. However, a “thermal barrier” in the form of harsh thermal and dynamic loads on the structure of rockets moving at high speed in a relatively dense atmosphere stood in the way of creating these rockets.

2.1. USSR missiles
The search for solutions to the “thermal barrier” problem can be considered for the example of creating the first-generation Soviet LRBM directed by S. P. Korolyov in OKB-1 (table 1).

| Missile name, index | Max range, km/max altitude, km/max velocity, m/s / striking velocity, m/s | Shape and dimensions, mm, of the re-entry vehicle | Re-entry vehicle mass, kg/payload | Thermal protection / Material of the re-entry vehicle body |
|---------------------|-----------------------------------------------------------------|----------------------------------|--------------------------------|--------------------------------------------------------|
| R-1 (8A11)          | 320/100/1650/800/1100                                           | Pointed cone, length – 2100      | 1000 / Conventional explosives | None / Low-carbon steel                                 |
|                     | 600/170/2170/700/1000                                           | Pointed cone, length – 2255 + 1792 aerodynamic stabilizer (skirt), base diameter 1390 | 1500 / Conventional explosives | Layer of asbestos cardboard between steel shells / Low-carbon steel |
| R-5 (8A62)          | 1200/300/3000/2200                                             | Pointed cone, length – 5250, base diameter 1650 | 1425 / Conventional explosives | 6 mm mineral coating / Low-carbon steel                 |
| R-5M (8K51)         | 1200/300/3000/1100                                             | Pointed cone, base diameter 1650 | 1300 / Nuclear 0.3; 1.0 Mt | Asboplastic (Asbestos fabric + phenol-formaldehyde resin) / Steel |
| R-7 (8K71)          | 8835/1360/6510/5000                                            | 1956-1957: Pointed cone, (cone half-angle 11°), length – 7200, base diameter 2590, tip 1635. 1958: Cone, length – 5505, base diameter 2420, tip 765, semi-spherical blunting, radius 300 | 1957: 5370 / Thermonuclear 5.0 Mt 1958: 3700 / Thermonuclear 3.0 Mt; | 1956-1957 Glass fiber reinforced plastic with phenol-formaldehyde resin / Steel 1958-1959 Asboplastic with phenol-formaldehyde resin / Steel |
| R-7A (8K74)         | 1959: 12000/??/?/??                                            | Dual-cone, length – 3070, base diameter 2420, semi-spherical blunting, radius 300 | 3000 / Thermonuclear 3.0 Mt; 2400 / 1.65 Mt | Asboplastic (Asbestos fabric + phenol-formaldehyde resin) / Steel |

In the R-1 (8A11) missile, which was an improved design of the German A-4 (V-2) missile, with the 320 km maximum range, steel was widely used [2, 3]. The conical base of the re-entry vehicle was manufactured from 6 mm low-carbon steel. Under aerodynamic heating, the surface temperature reached 600 °C. This is far from the melting point around 1500 °C, but the permissible temperature of such steels where their load-carrying capacity is reduced by half during long-term operation is just 470-
500°C [4]. Hence, the possibility of using cheap and accessible low-carbon steel was related to the short duration of over-the-limit temperatures.

The R-2 missile (8Zh38) created in 1949 was designed for the 600 km range. Because of the increased velocity of atmosphere re-entry, thermal and dynamic body loads grew so much that keeping the structural layout similar to that of R-1 no longer made any sense. On the R-2, re-entry vehicle separated after the engine shutdown, which had become a revolutionary solution in the missile technology [5]. The new structural layout of the missile allowed reducing the missile weight.

The first twelve test launches of missiles in October-December of 1950 failed. For seven missiles, re-entry vehicles were damaged due to overheating at the descent stage [2]. So, the strength and thermal insulation of the re-entry vehicle body had to be improved. For the R-2 missile, the re-entry vehicle was 2255 mm and had a 1792 mm long aerodynamic stabilizer (skirt) with a base diameter of 1390 mm. The conical shell of the re-entry vehicle body was comprised of three layers. Outer and inner layers with a thickness of 6 mm were made from low-carbon steel, while a 5 mm asbestos cardboard layer was supposed to protect the missile payload from overheating.

Without many-fold range increase of the guided LBRMs, deterring potential enemies and ensuring the safety of open launch sites on the homeland territory for the 6-hour long launch preparation was unfeasible. Besides, the fueled state time was limited to 20 minutes because of the evaporation of oxygen serving as a liquid oxidizer.

It was supposed that the new R-3 rocket (8A67) with the 3000 km range, whose draft project was presented in 1949, would have none of these drawbacks. Dramatic details of that stage of Soviet missile technology were described in [6]. It was found out soon that none of the steels and alloys were fit for making the body of the unusually long re-entry vehicle. Naturally, the joint flight of the re-entry vehicle with the missile body to improve the efficiency of the conventional payload explosion due to the kinetic effect, as proposed by some of the customer’s representatives, was out of the question. The use of temperature-resistant materials (such as tungsten and molybdenum) was also out of the question because of absolutely unacceptable mass, cost, and manufacturing parameters. The required theoretical basis of thermal and thermal-structural calculations was yet to be created. The implementation of the R-3 missile project was postponed under the pretext of creating an intercontinental missile.

The project of the R-5 (8A62) missile with a detachable re-entry vehicle and the range of 1200 km was started in OKB-1 in 1951. The 5250 mm long re-entry vehicle of the R-5 missile had the shape of a pointed cone with the diameter of the aerodynamic stabilizer base 1650 mm. Although satisfactory results were obtained during tests in 1953-1955, the range was less than 1000 km due to re-entry vehicle destruction under aerodynamic heating. For thermal protection of the re-entry vehicle steel body, thermal-resistant 6 mm thick mineral coating based on sublimating (evaporable) high-enthalpy materials type of silicon carbide TO-2 was used on R-5 for the first time [2].

On an improved variant of the R-5 missile, the R-5M (8K51) missile, a nuclear warhead (an analog of the 300 kt RDS-6 bomb) had to be installed [2]. During the design of the R-5M, the re-entry vehicle length was reduced, and the striking velocity was cut down in half (down to 1100 m/s). Thus, dynamic and thermal body loads were reduced, while the warhead's colossal power massively surpassed the contribution of kinetic energy in target destruction. It can be assumed that the “metallurgical” approach to thermal protection of the re-entry vehicle remained the weak spot of the improved design. In conditions of high temperatures and vibrations, reliable fixture of ceramic (mineral) coatings to the metallic body having a massive difference of linear thermal expansion coefficients was hard to ensure.

In light of this, we should highlight a brilliant achievement – the decision of Soviet material scientists and Bauman Moscow Higher Technical School graduates V. N. Iordansky and G. G. Konradi (NII-88), as well as their colleague A. A. Severov (OKB-1) to use an ablating TPC from asboplastic (polymer composite material) for protection of the re-entry vehicle steel body. Successful tests of the M5RD missile with this coating took place in July-October of 1956 [2].

Surprisingly, both components (asbestos fabric and phenol-formaldehyde resin) were known. From the standpoint of weight, such a simple, reliable, and, in some sense, elegant engineering solutions
proved to be very efficient compared to known foreign heat accumulation systems of the same purpose. Besides, this solution had unique self-regulation of protection characteristics.

Heating of polymer composite material above certain temperatures caused decomposition and gasification of the polymer resin taking away heat from outside (endothermic effect). The heat spent on physical-chemical transformations was diverted to the surrounding space by gaseous decomposition products. As heating intensified, decomposition of polymer composite intensified, filtration of decomposition products through the porous frame increased, injection of the product in the boundary layers intensified. So, the heat flux density on the surface decreased. With increased porosity of the surface layer, its thermal conductivity decreased, and emissivity increased. Thus, the amount of heat that could be transferred to the payload through the coating was decreased. However, the protective effect of this coating sharply decreased with the disappearance of the polymer matrix. So, TPC parameters like local layer thickness had to be agreed with the intensity and duration of the thermal load.

In 1950, OKB-1 started research on intercontinental ballistic missiles (ICBM). In 1954, the research results on topics N-3 and T-1 formed the basis of the R-7 (8K71) ICBM project meant to carry a 5.5 t re-entry vehicle with a 5 Mt thermonuclear charge for the distance of 8000 km. The “Semyorka” R-7 was supposed to strip the USA of invulnerability [7]. In the variant of the year 1956, the re-entry vehicle was shaped like a 7200 mm long pointed cone with the 1635 mm long tip. TPC was made out of glass fiber reinforced plastic with phenol-formaldehyde resin. The coating technology turned out to be very labor-intensive, and its quality was far from perfect. Before the test, cracks on the side surface were found [8].

It is commonly believed that the first successful test of the R-7 missile took place on August 21, 1957. However, its re-entry vehicle did not reach the target. By some estimates, it broke during the flight 15…20 seconds away from the calculated impact time [2, 7]; by other estimates, it broke at the altitude of 11 km at the flight speed of 5000 m/s. Now it can be stated with high certainty that the TPC of the sharp cone did not prevent destruction when the air plasma temperature at the front critical point exceeded 8000 °C.

At the end of 1957, radical changes were made to the re-entry vehicle structure. A pointed tip was replaced with a conical tip with a 300 mm radius semi-spherical blunting, and its length was reduced to 765 mm. The total re-entry vehicle length became 5505 mm [8]. Probably, new TPC was made out of asboplastic upon the experience of the M5RD tests. As a result of these measures, the re-entry vehicle with the second stage of the R-7 missile reached the target with the 80 km overshoot at the 11-th launch on January 30, 1958. On March 29, 1958, a fully successful test took place [7].

In 1959-1961, to increase the range to 12000 km and then to 16000 km, the mass of the re-entry vehicle of the modernized “Semyorka” missile, the R-7A (8K74), was reduced by more than two times. The length of the re-entry vehicle was 3070 mm. The biconical shape of the re-entry vehicle was its distinguishing feature. Based on the fact that the R-7 (8K71) and R-7A (8K74) missiles were ultimately fitted with conical re-entry vehicle with semi-spherical blunting, Soviet specialists managed to make sense of specifics of hypersonic flow around sharp and blunted bodies and used ablating TPC on them for the first time.

2.2. USA missiles

It is revealing that the USA did not have a reliable solution to the problem of thermal protection of the re-entry vehicle warhead of guided LRBMs from the end of the 1940s to the second half of the 1950s. Back at the end of the 1940s, the Americans concluded on the impracticality of creating a military-purpose intercontinental-range rocket-powered aircraft of the "Silver Bird" type proposed by a German engineer E. Sänger [9]. He believed that the aircraft flight would be characterized by "bouncing" from the atmosphere, some sort of ricocheting, with periodic elevation in the near space to cool the heated body by radiating away excess heat.

However, calculation disproved the concept of E. Sänger. Indeed, for gliding aircraft descent with a velocity higher than 2 km/s (M>6), heat fluxes on the surface should be less than usual, but the heating duration is much greater, inevitably melting any metallic body. Therefore, during that period and the
years after, the USA developed cruise missiles Snark (SM-62), Regulus (SSM-N-8), Regulus-II (SSM-N-9), Navaho (SSM-A-5), Matador (MGM-1), Mace (CGM/MGM-13) and other missiles whose velocity was less than $M=3$, thus excluding the need for thermal protection [10].

In 1944, the USA started analyzing the possibility of combat application of guided LBRM. By studying captured German hardware, the Americans created a two-stage missile V-2/WAC Corporal, dubbed Bumper, based on the V-2 missile. In February 1949, the second stage of this missile reached the altitude of 392.6 km (244 miles) and hypersonic speed of 2300 m/s (5150 mph), corresponding to $M=7$, during descent in the atmosphere [11]. As a result of aerodynamic heating, the body of the Bumper missile was fully destroyed. It became evident that hypersonic aerodynamics has specifics that had not been studied yet.

It cannot be stated that the “thermal barrier” had put a block on the ideas to overcome it. In 1951, H.J. Allen from the NACA Ames Research Laboratory made an important conclusion on specifics of hypersonic flow around the body. In 1952, H.J. Allen and an aerodynamicist A.J. Eggers, Jr. verified these conclusions experimentally and formulated them as the “blunt body theory” [11-13]. The theory's essence is that a blunted body will radiate away most of the thermal energy related to the hypersonic motion of the body in the atmosphere.

Detached shock waves, bow shocks, physic-chemical transformation in the boundary layer, and other phenomena had become a subject of increasingly in-depth theoretical and experimental investigations. The results of these investigations successively explained the relationship between shapes of bodies, their flow regimes, and heat exchange intensity [13-18]. To date, these studies are still relevant due to solutions of new applied problems [19-24].

Despite many problems of hypersonic flight, the USA continued the development of new guided LRBM at the beginning of the 1950s. Specialists of NACA, General Electric, Bell Aircraft, AVCO Manufacturing Corporation tried implementing the “blunted body theory” in re-entry vehicles and studying variants of thermal protection with liquid coolant circulation (water or sodium), porous cooling and accumulation of heat exerted during aerodynamic heating. They could use hypersonic wind tunnels at NACA Langley and Ames research centers, test facilities with plasma torches and gas burners, computers, and flying models. The variant with the accumulation of heat seemed to have the most promise. The re-entry vehicle body was designed to be in the shape of a blunted cone with the half-angle of 60º made from nickel-chromium and cobalt alloys, graphite, beryllium, and copper. Even gold and silver were considered based on the assumption that the warheads would be few [13, 14].

The discrepancy of the experimental investigation was that manufacturing-friendly and relatively cheap copper having the best heat accumulation parameters was 4 times heavier than graphite and about 5 times heavier than beryllium. Graphite was rejected because of high propensity to oxidation, evaporation, and cracking; nickel-chromium alloys like Inconel X were rejected due to intensive heating to limit temperatures. Fitting the missiles with such re-entry vehicle warheads was stalling because designers still had doubts about flight stability, strong deceleration of movement, visibility of the heated surface in the infrared range, risk of thermomechanical failure during the flight.

Foreign literature does not mention borrowing Soviet experience of the problem of the thermal protection of missiles. The book [13], which claims to be trustworthy, there was a brief mention of attempts to use oak wood for thermal protection of Soviet and Chinese (?) ballistic missiles. The book made the reader think that the Americans discovered ablating thermal protection on their own.

Thus, for first re-entry vehicle warheads Mk I, Mk II of intermediate-range ballistic missiles Thor and Atlas B/C ordered by the US Airforce, General Electric chose a 545 kg accumulating copper thermal protection. The developers of the Polaris missile ordered by the US Navy used beryllium for thermal protection of its re-entry vehicle. After successful tests, copper in the thermal protection of the Mk II missile was replaced by beryllium.

The developers of the Jupiter military missile family went the other way. In collaboration with Vitro Corporation, they fitted re-entry vehicle of the Jupiter with ablating TPC. It should be noted that this was not a “miraculous moment of clarity,” but a result of serious and comprehensive experiments. In 1956-1959, Americans considered the possibility of using polymer composite materials comprised of
Refrasil® heat-resistant quartz glass fibers, Fiberfrax® aluminum oxide fibers, asbestos, and grade 91LD phenol-formaldehyde resin. Among TPC variants Teflon® and organic fabrics like Nylon® with phenol-formaldehyde resin was studied [25-32].

During flight tests on Cape Canaveral on August 8, 1957, the re-entry vehicle of the Jupiter missile rose to the altitude of 965 km (600 miles) and traveled 1930 km (1200 miles), thus proving the efficiency of using ablating TPC [13]. We should note that this test took place a year after the successful test of the Soviet M5RD missile.

General Electric used ablating TPC based on Nylon® fabric and phenol formaldehyde resin for the Mk III re-entry vehicles of the Thor, Jupiter, Atlas D missiles. The AVCO Company used ablating TPC for the Mk IV re-entry vehicle of the ICBM Atlas E/F and Mk 5 re-entry vehicle for early designs of the Minuteman-I ICBM. After a few years, the largest warhead Mk2 (length 3.05 m, mass 3.7 t) with a 9 Mt thermonuclear charge W-53 was installed on the Titan II (LGM-25C) missile with the 15 000 km range. The first tests of the prototype of this charge took place in 1958. Its thermal protection was also made from composite material based on Nylon® and phenol formaldehyde resin. The re-entry vehicle combined a semi-spherical tip with a 12.5° half-angle cone.

2.3. Development of the method of ablating thermal protection

The logic of the development of strategic offensive arms had led to the creation of compact small re-entry vehicles capable of penetrating the defenses of a potential enemy having air- and space-based missile interceptors. As time passed, multiple independently targetable re-entry vehicles (MIRV) were developed. As far as the shape was concerned, the re-entry vehicles had turned into long pointed cones. Such shape corresponded to the objective of minimizing time spent in the upper layers of the atmosphere to avoid being intercepted by the enemy and reduce the influence of winds on the target impacting accuracy.

The fundamental novelty of the approach to missile thermal protection was in using new materials - carbon fibers and carbon-carbon composite materials having high specific strength and stiffness, endurance to high-speed, high-temperature, chemically active and eroding streams. For instance, the Mk 12 re-entry vehicle designed by the General Electric for the Minuteman III missile deployed in 1970 had three separate conical warheads. The AVCO Company participated in developing the Mk 21 re-entry vehicle for the Peacekeeper (MX) ICBM and a similar Mk 5 re-entry vehicle for the submarine-launched ballistic missile Trident D-5. The Mk 21 re-entry vehicle had a pointed shape with a tip of stitched carbon fabric with a conical body made out of carbon fiber on the epoxy resin with additional ablating carbon-phenol TPC [33].

For the years past, different polymer composite materials were used in ablating TPC: glass fiber reinforced plastics (density 1800-2200 kg/m³), asboplastics (1400-1900 kg/m³), organic fiber reinforced plastics (1200-1450 kg/m³) and carbon fiber reinforced plastics (1500-1650 kg/m³). The protected surface area ranged from fractions of a square meter re-entry vehicle to several square meters (descent modules). The coating mass divided by the unit surface (surface density) was in 10…40 kg/m². Evidently, such surface density is absolutely unacceptable for spacecrafts with a large surface area that can be hundreds of square meters.

Although the problem of thermal protection was widely covered by scientific literature [34-39], many parts of this multi-disciplinary area still need additional research [40-45].

3. Conclusion

1. In the middle of the 1950s, the problem of overcoming the “thermal barrier” related to the high-speed motion of re-entry vehicles of ballistic missiles in the atmosphere was solved by the USSR, and then by other countries. The key decision to overcome this problem was to use ablating coatings from polymer composite materials. Later, similar thermal protection was used on manned and unmanned spacecrafts descending in the atmospheres of the Earth and planets of the Solar system.

2. Thermal protection coatings made of polymer composite materials have high structural and manufacturing efficiency, but they have several significant drawbacks. They are disposable, and they
have a high enough density (1200-2200 kg/m\(^3\)). Thus, the surface density of TPCs is in the range of 10-40 kg/m\(^2\), which is completely unacceptable for spacecrafts with a large surface area. This feature of ablative thermal protection created the demand to create reusable TPCs for large-sized spacecrafts making regular flights at high speed in the atmosphere.

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