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FLIGHT CAPABILITIES OF HIGH-SPEED-MISSILE RADOME MATERIALS

The flight capabilities of future generation surface-to-air missiles are likely to challenge the mechanical and thermal limitations of present radome materials. New materials are being investigated to meet the demand for improved radome characteristics. The merits of four radome materials undergoing development have been assessed through flight performance modeling in several key areas for comparison with the performance of three current radome materials. The continuing need to improve radome erosion resistance while maintaining or improving electrical transmission qualities has been evident from these assessments.

INTRODUCTION

Advances in propulsion technology have pushed velocity capabilities of missile interceptors well into the hypersonic (>Mach 5) range. Higher missile speeds result in greater aerodynamic heating and faster intercept closure rates; moreover, higher missile altitudes permit less aerodynamic control. Future missile interceptors must consequently operate in a more stressful thermal environment and under more stringent guidance homing requirements. The missile component design most profoundly affected by this combination of conditions is the radome.

The radome is a protective interface between the missile tracking system and the atmosphere. It is aerodynamically efficient and minimally obstructive to radar tracking signals in the radio frequency band. New missile performance capabilities will render conventional radome design standards inadequate. Thus, interest in radome development is being renewed, and radome designers are being challenged to advance the state of the art.

Computer modeling is the primary means of assessing the merit of a particular radome design during its development phase. The Unified Radome Limitations (URLIM) Program[1] is used at APL to model constraints on radome performance, including material limits such as temperature and stress (both thermal and mechanical stress) as well as the aberration of radar signals passing through the radome. All of these limitations, except for mechanical load, are functions of aerodynamic heating. Radar aberration changes as material properties change with temperature, altering the angle between the apparent and true line of sight to a target. This angular deviation, which varies with the look angle between the missile centerline and the antenna, is called boresight error (BSE). Boresight errors frequently necessitate compensation by the guidance computer to ensure homing accuracy.

New radome materials are evaluated by comparing their flight performance with that of current benchmark materials. These comparisons have been made for four radome materials proposed for the next generation of missile interceptors.

DISCUSSION

Radome Materials

Material properties desirable for advanced missile radome designs include high melting temperature, high tensile strength, high fracture toughness, a low coefficient of thermal expansion (CTE), and a low and stable dielectric constant at radio frequencies. High tensile strength and fracture toughness together with a low CTE not only prevent stress failures but also preclude the formation and propagation of cracks resulting from rain and dust impact (erosion environment). A stable dielectric constant, which is temperature-dependent, reduces BSE's caused by aerodynamic heating, and a low dielectric constant allows relaxed manufacturing tolerances for wall thickness. Ceramics come closest to satisfying these requirements. In fact, all but the most exotic radomes undergoing development have a homogeneous ceramic wall.

The most prevalent materials used for existing missile radomes are Pyroceram 9606 made by Corning Glass Works and slip-cast fused silica (SCFS) made by Brunswick and Ceradyne. Other ceramics that have received attention or are being considered for advanced applications include the following:

- Rayceram 8 made by Raytheon
- Nitroxyceram made by Loral Aeronutronic
- Reaction-bonded silicon nitride (RBSN) made by Boeing
- Hot-pressed silicon nitride (HPSN) being developed by GTE, Norton, and Ceradyne
- Celsian being developed by the Naval Surface Warfare Center.

Pyroceram 9606 and Rayceram 8 are cordierites and are composed of magnesia, silica, and alumina. Nitroxyceram and celsian each also have three constituents; nitroxyceram consists of silicon nitride, boron nitride, and silica, whereas celsian is made of barium oxide, alumina, and silica. Slip-cast fused silica is composed of silica and air, but RBSN and HPSN are formed almost entirely of silicon nitride along with small amounts of sintering catalysts.

Each material presents a unique set of advantages and disadvantages for high-speed-missile radome applications. A qualitative comparison of each material with respect to six performance criteria desirable for good radome design is given in Table 1. A rating system from poor to excellent is used in the table. All ratings above poor signify that the material will perform adequately under ideal conditions (no erosion environment or nuclear blast). A rating of fair suggests the material may not be adequate under adverse flight conditions. A good rating means the material will perform satisfactorily during adverse flight conditions, except on rare occasions. Ratings above good imply that the material will perform well even under adverse conditions. Radar performance can be corrected adequately for BSE's when using any of the materials rated good or better.

Current Radome Materials

Pyroceram 9606. Pyroceram 9606 radomes of various shapes are in tactical use on the Phoenix, Sparrow, and Standard missiles. As seen in Table 1, this material has no major weaknesses and is a relatively good candidate for high-speed missile flight. The prime virtue of Pyroceram 9606 is its highly developed manufacturing process. Since a large body of working knowledge exists about Pyroceram 9606, given its widespread use as a radome material, it offers a baseline against which to evaluate new radome materials. The melt limit for each material, except SCFS, is defined herein as the temperature at which a phase change occurs. For Pyroceram 9606, the melt limit is 1622 K, and the room temperature design tensile strength is 155 megapascals (MPa).

Slip-Cast Fused Silica. Slip-cast fused silica radomes are in tactical use on the Patriot missile and are soon to be employed on a new version of the Standard missile. Thus, SCFS, like Pyroceram 9606, has a large technology base and a proven application history. As seen in Table 1, SCFS has two excellent features: its resistance to thermal shock and its radar transmission qualities. These qualities derive from SCFS's stable dielectric constant and extremely low CTE. The two drawbacks for SCFS are low resistance to erosion and low mechanical strength. The mechanical strength limitation can usually be overcome by using thicker radome walls without compromising radar transmission. Slip-cast fused silica has the lowest dielectric constant of all the materials under consideration and thus has less stringent wall tolerances. The melt limit for SCFS was chosen as 1811 K, the temperature at which radar transmission begins to deteriorate as the material softens. The room temperature design tensile strength is 28 MPa.

Rayceram 8. As seen in Table 1, Rayceram 8, like Pyroceram 9606, is a material with consistently good radome characteristics for high-speed flight. It has slightly better temperature and radar transmission characteristics than Pyroceram 9606 but somewhat lower strength. Rayceram 8 has a proven manufacturing technology, which was demonstrated during its investigation for use on the Advanced Medium Range Air-to-Air Missile, but it is not currently used on a tactical missile system. Nevertheless, since all developmental problems connected with Rayceram 8 have been overcome, it is included as a current radome material. The melt limit for Rayceram 8 is 1922 K, and its tensile strength at room temperature is 131 MPa.

Radome Materials in Development

The improvement of erosion resistance has been a principal aim in radome development. Unfortunately, erosion-resistant materials tend to have poor electrical performance. Nevertheless, some ceramics, most containing silicon nitride, have been found that may provide a good compromise between electrical performance and erosion resistance. Some may even exceed the electrical performance and erosion resistance of the cordierites. These ceramics are nitroxyceram, HPSN, RBSN, and celsian.

Manufacturing processes for the materials being developed are in various states of refinement. The physical properties of these materials are continually being adjusted to improve one quality or another. Tensile stress limits for these materials are mostly based on measurements

Table 1. Advantages and disadvantages of seven radome materials.

Performance criteria	SCFS	Celsian	Pyroceram 9606	Rayceram 8	Nitroxyceram	RBSN	HPSN
Maximum temperature	Good	Fair	Fair	Fair	Good	Good	Very good
Thermal shock resistance	Excellent	Fair	Good	Good	Very good	Fair	Very good
Maneuvering capability	Fair	Good	Good	Good	Good	Good	Excellent
Radar transmission	Excellent	Very good	Good	Good	Very good	Good	Good
Rain and dust erosion	Fair	Fair	Good	Good	Very good	Very good	Very good
Ease of manufacture	Very good	N/A	Very good	Good	Fair	Fair	Fair

Note: SCFS = slip-cast fused silica; RBSN = reaction-bonded silicon nitride; HPSN = hot-pressed silicon nitride. Poor = critical limiting factor; Fair = possible limiting factor (adverse flight conditions); Good = not a likely limiting factor; Very good = advantage; Excellent = strong advantage.

made on small samples and, as is typical with ceramics, need to be adjusted (downward) to ensure applicability to a full-scale radome by using statistical analysis to account for size effects.

Nitroxyceram. Table 1 shows nitroxyceram to be a strong contender in all categories except ease of manufacture. Manufacturing problems arise from difficulties inherent in the hot isostatic pressing operation used to shape and densify the radome. Erosion resistance is better than that of any current material, whereas electrical performance surpasses that of all materials except SCFS. Nitroxyceram, furthermore, has high thermal conductivity and a low elastic modulus, which help to reduce thermal stresses below those of most other radome ceramics. The melt limit of nitroxyceram (when nitrogen gas begins to dissociate from the surface) is approximately 1811 K, and its room temperature tensile stress limit is 207 MPa. The first electrical tests of a prototype nitroxyceram radome at elevated temperatures are scheduled for mid-1992.

Hot-Pressed Silicon Nitride. Hot-pressed silicon nitride has excellent mechanical capabilities and erosion resistance as noted in Table 1. The yield stress for HPSN at room temperature is about three times greater than that of any of the previously described ceramics. Its major limitation is a strong dielectric constant dependence on temperature, causing large BSE's at high radome temperatures. Additionally, its high dielectric constant imposes tight wall tolerances. At this time, a full-scale HPSN radome has not been manufactured successfully, but GTE/WESGO has made a very good subscale radome by casting and sintering. As with nitroxyceram, the melt limit of HPSN is 1811 K. Its room temperature design tensile strength is 552 MPa.

Reaction-Bonded Silicon Nitride. The performance of RBSN, as described in Table 1, resembles that of nitroxyceram. The electrical performance and erosion resistance of RBSN are, likewise, superior to the currently used ceramics. Also, its manufacturing process is better developed than is the case for the other silicon nitrides. The melt limit of RBSN is 1811 K, and its room temperature stress limit is 138 MPa.

Celsian. Celsian is the newest of the materials being developed, and its manufacture is currently limited to small coupon samples. As evidenced by the comparisons in Table 1, the development of celsian is being pursued because of its very good radar transmission properties. Improvements are being made to raise its thermal shock and rain erosion capabilities. The melt limit of celsian is 1644 K, and its tensile strength at room temperature is 97 MPa.

Radome Shapes

The ideal radome shape for radar transmission is a hemisphere, but the most aerodynamically efficient cross section for hypersonic flight is a slender body. Existing radome contours represent a compromise between these two extremes. Maximizing radome volume to accommodate more electronic hardware is another goal in radome shape design.

Radome contours are usually cones, ogives, or combinations thereof. The von Kármán is another popular shape because it maximizes the volume-to-drag ratio for a given fineness ratio (length/base diameter). Figure 1 provides examples of conical, tangent ogival (an ogive that is tangent to the missile at its base), and von Kármán shapes. Ogival radome shapes offer greater volume than the von Kármán for a given fineness ratio, specifically to house larger antennas, but sacrifice a small amount of drag performance. Cones with small half-angles (<20°) are used to minimize aerodynamic heating and maximize erosion resistance at the expense of radome volume or drag or both. Sometimes a combination cone–ogive is used. A slender cone is used in the nose region to minimize aerodynamic heating and erosion and is then broadened to an ogive to increase radome volume more efficiently. Blunted tips, typically between 0.5 and 1.0 cm in radius, are used to induce a normal shock in front of the radome, thereby reducing skin friction and surface heating rates.

ANALYTICAL METHODS

Aerodynamic Heating

As previously mentioned, URLIM, the computer model for this analysis, was developed specifically to perform time-dependent heating analyses for radome geometries. To calculate convective heat transfer rates, the URLIM Program first uses inviscid boundary layer edge condi-

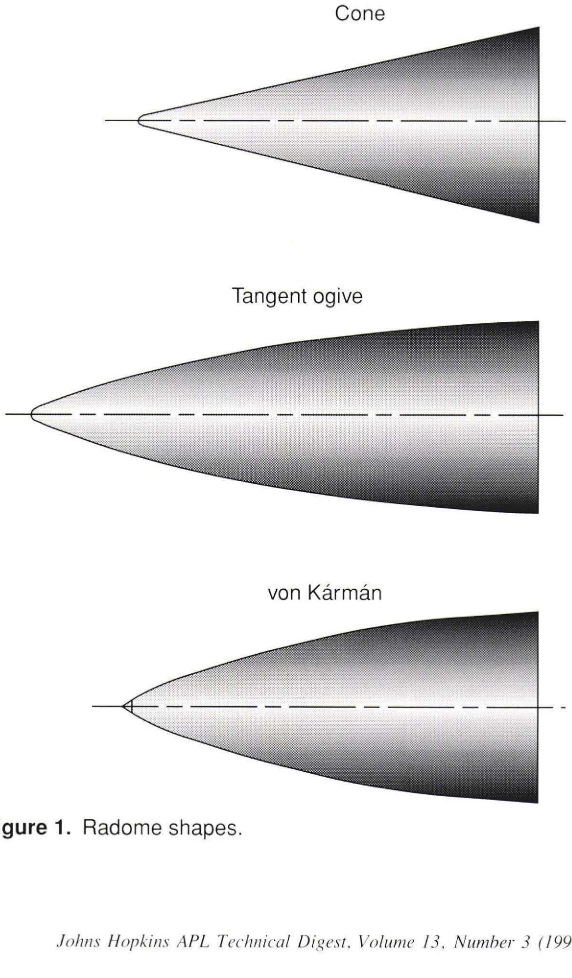

Figure 1. Radome shapes.

tions supplied by another code to calculate skin friction. These edge conditions are dependent on radome geometry, Mach number, altitude, and angle of attack.

Heating correlations are employed to convert the edge conditions into skin friction for laminar and turbulent flows, with an assumed instantaneous transition from one heating correlation to the other. The heating correlations use Eckert's reference enthalpy method[2] to account for compressibility effects and Colburn's Reynolds analogy[3] to convert skin friction into a heat transfer coefficient.

The boundary layer on hypersonic missile radomes changes from laminar to turbulent flow usually within the first 5 s of flight. Choice of a transition Reynolds number, therefore, has minimal impact on peak temperatures and thermal stresses. For this study, boundary layer flow was assumed to be turbulent for the entire flight.

An energy balance that sums convection (as calculated above), conduction, and radiation heat transfer rates is performed at the radome surface. The radome wall contains thermal nodes that are networked together using finite difference theory. Heat transfer is balanced through each node at each time step throughout a missile trajectory, providing temperatures for each node. Given the temperature distribution through the radome wall, thermal stresses are calculated by subdividing the wall into elements and using an analytical solution for a thick-walled cylinder developed by Rivello.[4]

Seeker Performance

Room temperature dielectric constants of ceramics are primarily determined by density and, to a lesser extent, by the types and concentrations of sintering aids and additives. Aerodynamic heating causes the radome dielectric constant to change, thus altering the apparent location of the target and varying BSE. Missile guidance systems are limited by the rate at which this change occurs, which is a function of the change in BSE slope. Generally, it is desirable to have BSE slope changes not greater than 0.010 to 0.020 degree of look angle error per degree of look angle to eliminate the need for guidance compensation.

To optimize electrical transmission, the wall thickness is always tailored to an even multiple of half the radar wavelength in the material according to the following equation:

$$d = \lambda/2\ (\epsilon - \sin^2\phi)^{1/2},$$

where d is the half-wave wall thickness, λ is the free-space radar wavelength, ϵ is the dielectric constant, and ϕ is the angle between the radar beam and a vector normal to the radome wall. As rising radome temperatures increase the material dielectric constant, the electrical thickness of the radome wall will also increase. In effect, these changes shift the centerband transmission frequency of the radome downward, thereby detuning the antenna. X-band radomes are usually designed with half-wave wall thicknesses, whereas radomes designed to transmit at Ka-band generally require full-wave or $^3/_2$-wave walls to maintain their structural integrity.

The URLIM Program calculates the change in BSE slope resulting from wall temperature increases using an empirical equation relating changes in radome material dielectric constant to changes in BSE slope. This method, although crude, is adequate for making relative comparisons among candidate radome materials. Additional factors that influence BSE shifts, such as axial temperature gradients, radome shape, and antenna location and design, must be accounted for to obtain a more accurate estimate of the BSE shifts. These assessments are usually made after a particular radome material has been selected on the basis of its relative performance.

Erosion

The change in BSE induced by rain erosion is manifested by a decrease in radome wall thickness, which tunes the radome wall away from the radar transmission frequency. Significant erosion has only been measured on SCFS walls. On the evidence of test experience, the other radome materials are more likely to fracture before significant erosion occurs. The extent of SCFS wall erosion caused by rain is calculated within the URLIM Program through an empirical model proposed by Balageas.[2] For other ceramics, different empirical estimates of radome survivability are used (off-line from URLIM) based on particle impact studies.

MODEL DEFINITIONS

To evaluate material performance, a radome model is constructed for each material and flown on a thermally stressful trajectory. A von Kármán radome shape is used with a 35° angle of incidence at the nose tip. This angle is relatively steep for new radome designs and results in high aerodynamic heating and material erosion. This shape is nevertheless adequate for making material performance comparisons on a relative basis.

The radome wall is divided longitudinally into five segments, each of which has a thick-walled cylindrical configuration. The centers of each segment are located 2.5, 10.2, 25.4, 40.6, and 55.9 cm from the nose tip along the radome centerline. The radius of each cylinder is equal to the length of a line segment drawn from the outer surface contour (at the midpoint of a longitudinal segment) to the radome centerline normal to the outer surface. Thus, a radome can be visualized as a series of five cylinders with increasing radii butted end to end. One-dimensional heat flow (through the wall) is assumed for each cylinder. Experience has shown axial conduction between cylinders to be negligible. The thermal node and stress element definitions for a typical wall segment are shown in Figure 2.

The flight chosen for this study is 100 s long and peaks at about Mach 6, as shown in Figure 3. This trajectory imposes a harsh flight environment (aerodynamic heating and erosion) for today's materials.

ANALYSIS RESULTS

Temperature

Surface temperature histories for all of the radome materials at an axial distance of 2.5 cm from the tip are presented in Figure 4. Aerodynamic heating induces peak surface temperatures in the range of 65% to 80% of the

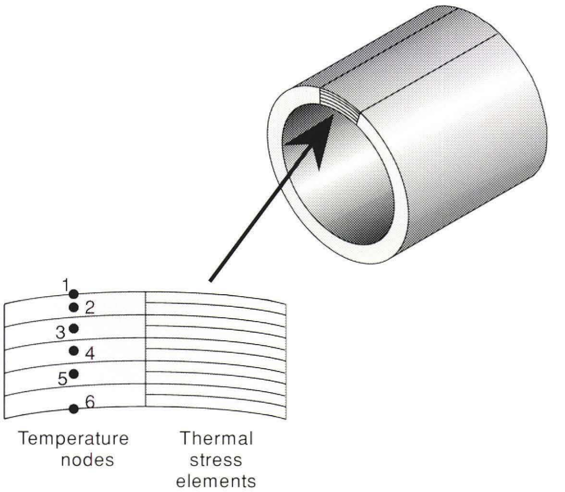

Figure 2. Thermal node and stress element definitions for a typical radome wall segment with each station approximated as a thick-walled cylinder.

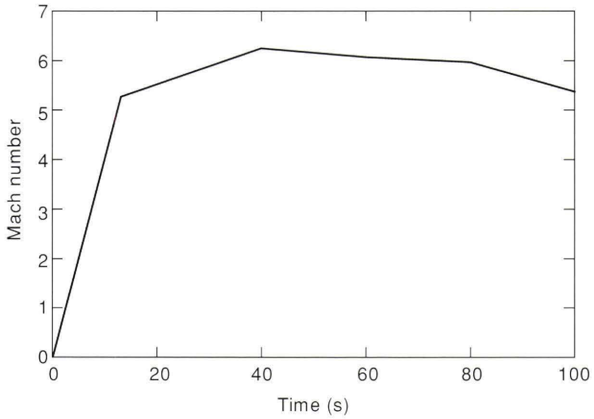

Figure 3. Typical radome flight test Mach number history.

maximum allowable temperature, depending on the material. With at least a 20% margin of safety, aerodynamic heating is not a limiting factor for material temperature during the thermally stressful missile trajectory. Although surface temperatures are nearly equal, the materials with lower thermal conductivity will allow less heat to flow into the wall, resulting in lower average wall temperatures (and less BSE slope change).

Thermal Stress

During aerodynamic heating, thermal stresses are tensile on the inner surface and compressive on the outer surface. Thermal stress histories for all of the radome materials are presented in Figure 5 as a percentage of the maximum design tensile strength. The measurements were again taken at an axial distance of 2.5 cm from the tip. Stresses peak during the boost phase of flight when the maximum through-wall temperature gradient exists. The tensile strength of radome materials will decrease with increasing temperature. At the time of maximum stress, however, the average through-wall temperatures have not risen enough to lower the material strength significantly.

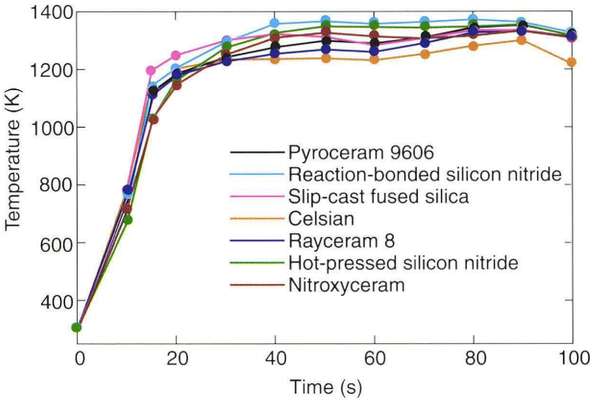

Figure 4. Surface temperature histories for seven radome materials at an axial distance of 2.5 cm from the tip.

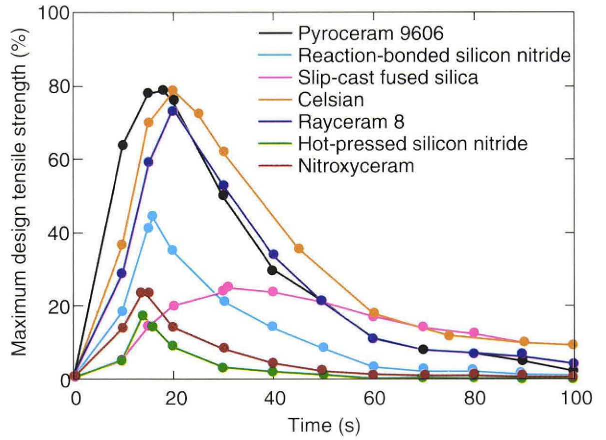

Figure 5. Thermal stress histories for seven radome materials as a percentage of maximum design tensile strength.

Slip-cast fused silica, nitroxyceram, and HPSN clearly have superior thermal stress performance, with 18% to 25% of their thermal stress limits reached. Reaction-bonded silicon nitride reaches 43% of its stress limit and thus demonstrates good thermal stress performance. Thermal stresses in the remaining materials reach 74% to 80% of the material strength limit. For celsian, the 20% margin of safety will be eroded when the tensile strength values are adjusted downward to account for size effects (relating measurements on small coupons to a full-size radome). Thus, celsian currently has a marginal thermal shock capability.

BSE Slope Change

The maximum change in BSE slope as calculated by the URLIM Program can provide a basis for judging the electrical performance of each radome material (the lower the percent change in BSE slope, the better the electrical performance). The maximum percent change in the BSE slope during the flight is shown for each material in Table 2.

Table 2. Maximum percent change in boresight error (BSE) slope during radome flight tests.

Material	BSE slope (maximum % change)
Pyroceram 9606	5.3
SCFS	1.4
Rayceram 8	5.0
Nitroxyceram	3.9
RBSN	5.2
HPSN	5.1
Celsian	3.7

As expected, SCFS has by far the best electrical performance and is least likely to necessitate guidance compensation—a significant advantage over the other materials. Two developmental materials, nitroxyceram and celsian, have significantly better electrical performance than the two cordierites (Pyroceram 9606 and Rayceram 8). Reaction-bonded silicon nitride and HPSN, developed for their erosion resistance, have electrical performance comparable with that of the cordierites.

Erosion Resistance

When missiles fly through rain, significant material erosion can result. Rainfall rates are quantified as follows: light rainfall is less than 4 mm/h, moderate rainfall is greater than 4 mm/h and less than 20 mm/h, and heavy rainfall is greater than 20 mm/h. Light rainfall below 3000 m is used herein as the environment for rain erosion comparisons.

Rain erosion predictions are hard to make owing to the difficulty and expense of simulating an actual rainfield and pushing a radome through it at hypersonic speeds (e.g., the rocket sled test). To reduce costs and increase control of the drop size, single-particle impact tests are typically conducted on small samples at elevated temperatures to assess erosion resistance.

Because of silicon nitride's good hardness and fracture toughness, HPSN and RBSN exhibited excellent erosion resistance in single-particle impact tests.[5-8] The tests showed that these materials will easily survive a light rain environment.

A nitroxyceram radome model (coated with a protective silicon nitride–silicon dioxide layer) has shown susceptibility to cracking through a portion of its wall in the single-particle impact tests,[9] although a radome made of nitroxyceram is expected to survive flight through a light rain environment.

Data from a series of sled tests were used to derive an equation for predicting the structural integrity of Pyroceram 9606 in a rain environment. The equation predicts that Pyroceram 9606 will survive a light rainfield below 3000 m. No erosion data exist on Rayceram 8, but its material properties as well as its molecular structure, which is similar to that of Pyroceram 9606, indicate it will be almost as strong.

The erosion of SCFS has been studied extensively, and an erosion predictor has been incorporated into the URLIM Program. Analysis using this model showed that the SCFS radome will lose up to 7% of its wall thickness during an extended flight through a light rainfield below 3000 m. Depending on the exact amount of material lost and the altitude of the missile, the radome may allow the guidance system to perform acceptably. In some long-duration flights, however, erosion of SCFS will lead to missile failure.

Celsian has demonstrated poor erosion resistance from single-particle impact.[10] The fracture patterns suggest that this material has a predominantly glassy (brittle) substructure and low toughness. Efforts are currently under way to raise the fracture toughness of celsian to enhance its acceptability as a radome material for the future.

The capabilities of most of the materials discussed in this article have not been assessed in a moderate to heavy rainfield. Certainly the silicon nitride–based materials will perform the best, followed by the cordierites, and finally by SCFS and the present version of celsian. A dividing line between the cordierites and silicon nitride materials is anticipated for successful flight through a moderate rainfield.

Nuclear Blast

A missile interceptor should be able to survive a nuclear blast. To assess the ability of each radome material to survive heating from a nuclear blast, a radiative heat flux was added to the aerodynamic heating during the boost phase of flight when thermal stresses are peaking. Many of the materials will reach or exceed their temperature limits, causing a melt layer to form on the outer surface. The attendant effect on electrical transmission is unknown for most of these materials. Also unknown is the effect that material softening may have on the structural integrity of the radome in the presence of aerodynamic forces. A summary of the effects of a nuclear blast on the various materials is presented below.

Material	Nuclear Blast Effects
Pyroceram 9606	Surface melt: degraded performance during blast, unknown performance after blast.
SCFS	Surface melt: degraded performance during blast, electrical recovery after blast.
Rayceram 8	Surface melt: degraded performance during blast, unknown performance after blast.
Nitroxyceram	Material softening: unknown effect.
RBSN	Radome fracture due to excessive thermal stress.
HPSN	Material softening: unknown effect.
Celsian	Radome fracture due to excessive thermal stress.

Maneuvering Stress

The addition of maneuvering stresses resulting from flight dynamics and thermal stresses caused by aerodynamic heating in the radome attachment region can sometimes produce flight-limiting stress levels. Maneuvering stresses are typically in the range of 14 to 21 MPa, regardless of the material. Thermal stresses in the attachment region can be produced by expansion within the radome wall and also by CTE mismatches of the attachment joint design. The radome-missile joint is designed to minimize thermal stresses at material interfaces by matching CTE's within the joint. If one assumes that the joint design imparts no additional thermal stress to the radome wall, the summation of maneuvering stresses and thermal stresses (from free thermal expansion of the radome wall) is not a flight-limiting factor for the materials considered in this article.

CONCLUSIONS

The development of radome materials for hypersonic missile interceptors is a fertile technological field. What was once marginally acceptable material performance is quickly regressing to unacceptable performance as missile velocities increase and intercept altitudes decrease. Slip-cast fused silica demonstrates excellent electrical performance and satisfactory mechanical performance, but SCFS radomes may erode significantly in a rainfield. To improve rain erosion resistance and maintain or improve radome electrical performance, however, are difficult challenges. Nitroxyceram shows promise in both areas, but it requires a difficult and expensive manufacturing process that calls for refinement. The cordierites cannot match SCFS's electrical performance, which places burdens on the radome manufacturer to control wall tolerances and on the missile manufacturer to provide guidance compensation—especially with the more stringent guidance specifications expected in the future. Work is under way to improve the thermal shock capability of RBSN and celsian (and erosion resistance in the case of celsian). Hot-pressed silicon nitride has excellent erosion resistance, but its electrical performance is equal or inferior to that of the cordierites. Nevertheless, the proposed approaches to radome design discussed in this article are advancing the state of the art and will eventually offer viable alternatives to existing concepts.

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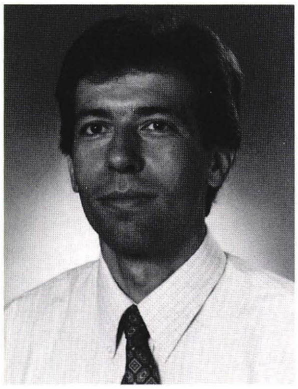

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