RADOME THERMAL DESIGN

Theoretical and experimental work was done to obtain an efficient thermal design of a radome for a Mach 4 missile. Theoretical studies showed that for both pointed and blunted Von Karman-shaped radomes, maximum tensile thermal stresses were nearly identical. Therefore, because of its lower aerodynamic drag the pointed radome was favored. Experimental verification that the pointed radome could withstand the flight stresses was obtained in full-scale free-jet tests.

R. P. Suess and L. B. Weckesser

for a Mach 4 Missile

The evolution of a radome design for a given missile may follow a devious path. Choice of material and thickness of wall are controlled primarily by electrical requirements, while definition of shape is influenced by aerodynamic and packaging-space demands. After a preliminary radome design has then been determined from these factors, a thermal and stress analysis must be performed to determine its ability to withstand the most severe flight environments expected. If these results suggest potential structural failures (an example of a radome structural failure occurring during a wind-tunnel test is shown in Fig. 1), the design must be reviewed and modified until a high degree of confidence in its structural adequacy is achieved.

Pyroceram as a proven missile-radome material merited attention in the design study for a new Mach 4 missile. *Pyroceram,* a product the house-wife has become familiar with in recent years under the trade name of Corningware,* is essentially a material that has been converted from its original glassy state into a crystalline ceramic by the use of heat treatment. Although this material has good thermal and electrical properties, a Mach 4 environment is more severe than any it had previously encountered. A thorough temperature and stress analysis had, therefore, to be made to insure that the radome could withstand the flight thermal stresses.

Definition of Critical Thermal Environment

Before temperature and stress analyses were performed it was necessary to choose the one missile trajectory that would be thermally most severe.

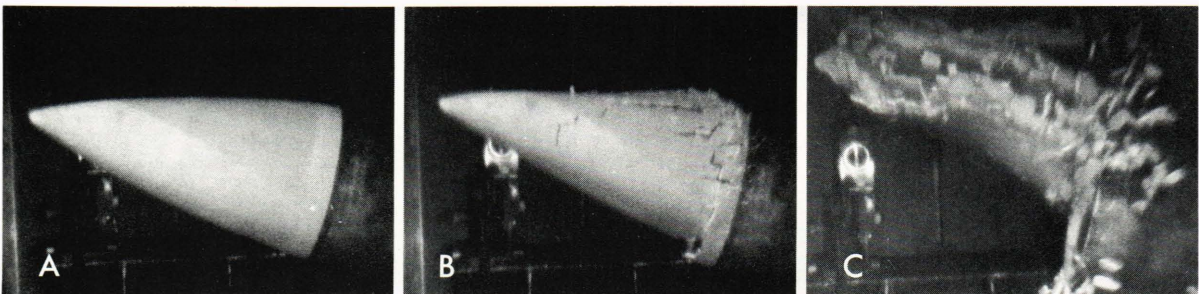* Registered trademark of Corning Glass Works, Inc.

Fig. 1—Photographic sequence of a test-radome structural failure, showing the Pyroceram radome (A) before the start of the failure, (B) 0.003 sec after the start of the failure, and (C) 0.006 sec after the start of the failure. (Printed by permission of the Daingerfield Division, General Dynamics/Pomona.)

Since this could not be done by inspection, a trajectory analysis was made in which 21 representative trajectories, both ballistic and line-of-sight, were considered. Each of these trajectories was used to generate aerodynamic heating on several dummy geometries, each of various thicknesses.

The trajectory chosen as the one that would generate maximum radome thermal stress was the one giving the highest rate of heat input, that is, generating the steepest temperature-time slope. Two interesting results arose from the trajectory analysis:

1. The line-of-sight trajectories gave higher heating rates than the ballistic trajectories, and it was noted that the launch angle did not influence the heating rate significantly.

2. When different radome wall thicknesses were investigated, the same trajectory was found to be thermally most severe for all .

Figure 2 presents the Mach number and altitude history of the trajectory found thermally most severe. Note that the maximum Mach number of this trajectory is considerably below the design number (4.0) of the study. The trajectory analysis revealed that those trajectories that achieved Mach 4.0 were not critical from a radome thermal-stress viewpoint.
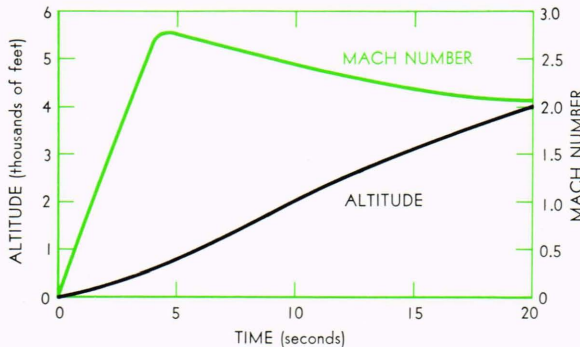

Fig. 2—Trajectory used to obtain the maximum radome thermal stress.
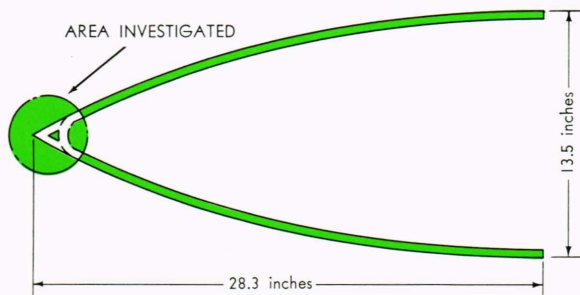

Fig. 3—Sketch of the radome cross-section, showing both the pointed and blunted nose areas.
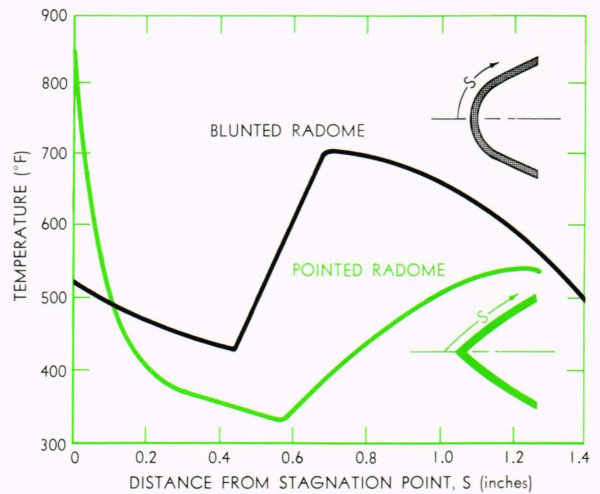

Fig. 4—Outside surface temperatures of the pointed and blunted radomes at a flight time of 5 sec.

Radome Temperature and Stress Analysis

The Von-Karman radome shape (discussed in Ref. 1) and the radome thickness were dictated by other than thermal considerations. The latter did, however, initiate an effort to determine if slightly blunting the radome would result in a reduction of thermal stresses. Since the maximum stress capability of Pyroceram had never been firmly established, and the new environment was more severe than any previously encountered, it was feared that the material would be pushed to near the limit of its thermal stress capability. Any means of reducing the thermal stresses was, therefore, felt worthy of examination. Figure 3 is a sketch of the two radomes analyzed, one a standard Von-Karman shape and the other a Von-Karman blunted with a 1.35-in. radius. Only the extreme forward portion of each radome was analyzed since experience had shown that this was the region of maximum thermal stress.

Two-dimensional temperature analyses of both radomes were performed by means of an IBM 7094 computer program. The program is quite general in nature and can handle complicated three-dimensional geometric configurations involving heat transfer by radiation, conduction, and convection. The theoretical method used for computing aerodynamic heating makes use of the Colburn equation,[2] as modified by Seban and

[1] T. Von Karman, "The Problem of Resistance in Compressible Fluids," Guggenheim Aeronautical Library, California Institute of Technology, Publication No. 75, 1936.

[2] A. P. Colburn, "A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction," *Trans. Am. Inst. Chem. Engr.*, **29**, 1933, 174–210.
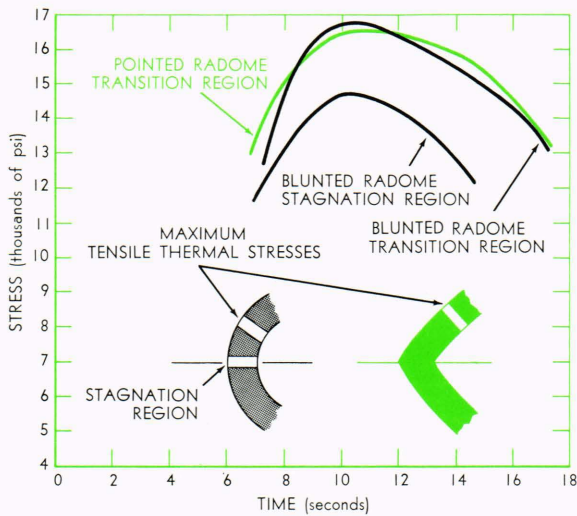
Fig. 5—Tensile thermal stress histories of the pointed and blunted radomes.

Doughty,[3] combined with the reference enthalpy method presented by Eckert.[4] In addition to convective heat transfer, a forward finite difference method is used to handle the differential equation of heat conduction, and the radiation is computed by means of the Stefan-Boltzmann law.

Because radome-shaped bodies do not lend themselves to exact theoretical stress solutions, they must be analyzed assuming the stresses can be approximated by cylindrical or spherical shell theory. In these radome stress analyses, spherical theory was chosen since it yields more conservative (higher) numbers than does cylindrical theory. The stresses were hand-computed using the temperature distributions generated from the heat transfer program described above.

Analyses on both the pointed and blunted radomes produced temperature variations over the surface such as those shown in Fig. 4. It is obvious from this figure that a sharp rise in temperature occurs at the transition point from laminar to turbulent flow on the shell portion of each radome. On both radomes the transition Reynolds number was assumed to be 1.5×10^6. On the pointed radome the maximum temperature (855°F) occurs at the stagnation point, as would be expected. However, on the blunted radome the maximum temperature (705°F) occurs not at the stagnation point but at the transition point. Figure 4 was used as an aid to locate the points of maximum stress since these points can be expected to occur at loca-

tions where the highest heat input has generated the highest temperatures early in flight.

Because the maximum temperature on the blunted radome occurred at the transition point, we expected that the maximum stress would also occur at that point. Figure 5 shows this to be true. The maximum stresses at the transition and stagnation points are 16,850 psi and 14,800 psi, respectively. These values are tensile stresses on the inside surface, which are the most critical because of the relatively low tensile strength of ceramics.

Figure 4 shows that the maximum temperature on the shell portion (i.e., away from the stagnation point) of the pointed radome occurred at the transition point. Consequently, the maximum stress on the shell portion also occurred at that point. This stress was computed and is compared with the maximum stress on the blunted radome in Fig. 5. As can be seen, the stresses are nearly identical. The conclusion to be drawn from this figure is that on the shell portion of the pointed radome the *tensile* stresses are no more severe than those on the blunted radome. In this area little value is gained by blunting the radome, and the drag penalty caused by blunting cannot be justified.

Fig. 6—Stagnation point temperature histories of the pointed and blunted radomes.

[3] R. A. Seban and D. L. Doughty, "Heat Transfer to Turbulent Boundary Layers with Variable Free Stream Velocity," *Trans. ASME,* **78**, Jan. 1956, 217–223.
[4] E. R. G. Eckert, "Survey on Heat Transfer at High Speeds," WADC Technical Report 54–70, April 1954.

However, by reference to Fig. 6, it would seem that a substantial *thermal* stress advantage could be gained at the stagnation point by blunting the radome. This impression is given by the fact that the blunted radome reaches a maximum stagnation-point temperature of only 635°F in 7.5 sec, while the pointed radome reaches 855°F in just 5 sec. At this time there is an extreme temperature gradient along the centerline of the pointed radome. Though large, this gradient generates on the outside surface compressive thermal stresses that are far less critical than are tensile thermal stresses. However, the passing of time would see a progressive decrease of compressive thermal stresses on the outside surface and a build-up of tensile stresses on the inside surface. It should be evident that the discussion of the pointed-radome stagnation-point region has thus far been confined to temperature results. The reason for this is that, because of the geometry of the area, no theoretical method, exact or approximate, is known by which to calculate the thermal stresses in the immediate region of the stagnation point.

Preliminary Experimental Compressive Stress Evaluation

In order to obtain an indication of whether the pointed radome could withstand the high compressive stresses at the stagnation point, a test was set up to determine what thermal environment would be necessary to cause a compressive stress failure at the point. Figure 7 is a schematic of the test apparatus used for this purpose. Small samples of
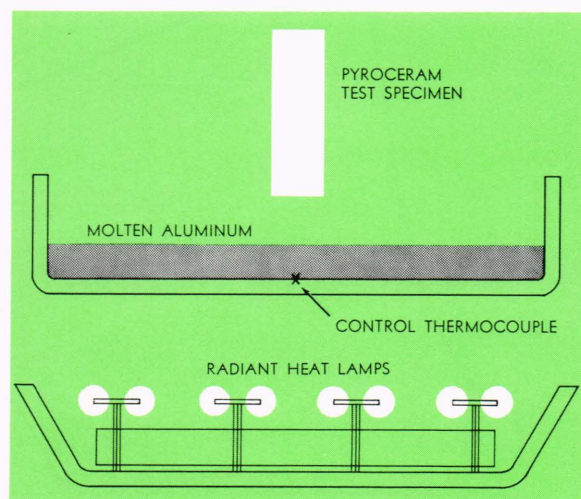
Fig. 7—Sketch showing the test arrangement used in the compressive thermal-stress evaluation of Pyroceram.

Pyroceram measuring 0.25 × 0.125 × 3.0 in. were plunged into a molten aluminum bath and placed in contact with the bottom of the container which had been heated to the desired temperature. The sole purpose of the molten aluminum was to wet the surface of the samples and increase the thermal conductivity between the bottom of the container and the sample. After each test the specimens were examined under a 120-power microscope. No failure was noted at 1100°F or in subsequent tests at 2000°F.

In an effort to find what was needed to generate a compressive thermal stress failure, an oxyacetylene torch was applied to the surface of a sample. The torch generated temperatures high enough locally to soften the material—that is, approximately 2500°F. Cracking was noted after the test, indicating that a compressive thermal stress failure had occurred. There was some concern that the observed crack had occurred during the rapid cool-down of the sample after the test. This was disproved when the test was repeated on another sample that was slowly cooled after the test and on which a similar failure was noted. The conditions causing this failure were obviously far more severe than those expected in Mach 4 flight. For this reason a preliminary conclusion was drawn that no compressive thermal stress problem would exist with a pointed radome at Mach 4.

As a result of the theoretical and preliminary experimental work just described, the conclusion was reached that a pointed Pyroceram radome would be satisfactory for a Mach 4 missile. Because of the complexity and the resulting uncertainty of the theoretical analyses, it was decided to verify the conclusion by testing several radomes at the Ordnance Aerophysics Laboratory (OAL), Daingerfield, Texas.

Full-Scale Wind-Tunnel Tests

The first experiments at OAL showed that the radomes could withstand comfortably the maximum flight tensile thermal stresses that they might face (17,000 psi). Next it was decided to test three radomes to the limit of the facility in order to attempt to cause tensile thermal stress failures.

The testing procedure employed for the Pyroceram radomes was as follows. The radomes were held below the airstream until the tunnel conditions had stabilized as much as possible (this required 4 to 6 sec). The radomes were then injected into the airstream (injection time 0.5 sec) and remained there for 14 sec, which was 1 sec after the computed time of peak thermal stress. The radomes were then withdrawn from the airstream. Just prior to a run the radomes were cooled to an
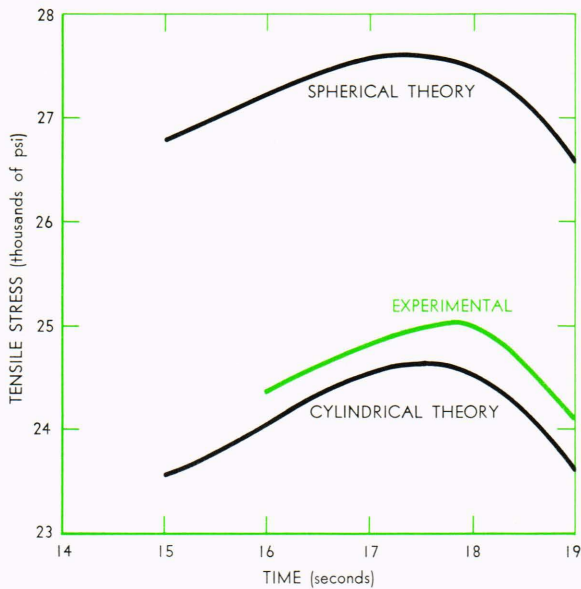
Fig. 8—Tensile thermal stresses measured during wind-tunnel test No. 1 compared with those computed using spherical and cylindrical theory.

initial temperature of $+50°F$ or $-10°F$, depending on the stress level sought. This was accomplished with a CO_2 spray inside the radomes. In order to hold the radomes at these reduced temperatures, each was wrapped in an asbestos cloth that would blow off upon injection into the airstream. The radomes were tested at Mach 2.44, a total pressure of 215 psi, and an average total temperature of approximately $1350°F$.

On two of the three tests, good strain-gauge data were obtained; the results are shown in Figs. 8 and 9. The tunnel flow conditions were essentially the same for both runs. The difference noted in maximum stress between the two runs is due to the difference in initial temperatures.

Comparison of Wind-Tunnel Data with Theory

Because the radomes were instrumented with strain gauges, there was an opportunity to compare measured stresses with those theoretically computed. In order to make this comparison, theoretical predictions were made, using the heat transfer computer program previously described. By this time the program had been amended so that it would compute stresses (based on cylindrical or spherical shell theory[5]) in addition to temperatures. The theoretical results shown in Figs. 8 and 9 were generated by this combined program and are for

[5] S. Timoshenko and J. N. Goodier, *Theory of Elasticity* (2nd ed.), McGraw-Hill Book Co., Inc., New York, 1951.

a location approximately two inches behind the stagnation point.

The experimental data from the first test are shown in Fig. 8, compared with theoretical predictions based on cylindrical and spherical shell theory. Maximum stresses agree within 2% if cylindrical theory is used for the comparison, and within 10% if spherical theory is used. In addition, the shape of the experimental and theoretical curves is quite similar. The agreement is excellent, particularly since the analysis began with only the wind-tunnel pressure and temperature-time histories and Mach number as inputs. The comparison from the second test is shown in Fig. 9. Theoretical and experimental maximum stresses once again compare favorably (2% or 11%, depending upon whether cylindrical or spherical theory is used). However, the shapes of the theoretical curves differ from the experimental, for reasons not known. As mentioned previously, the test conditions were essentially the same as those of the first test, with the exception of the initial radome temperature. The difference noted in maximum stress is attributed to the change in initial temperature.

Considering the large number of variables involved in the theoretical predictions, and the uncertainties in the instrumentation, the comparison of theoretical and experimental stresses is good. Thus, the adequacy of the theoretical method has been demonstrated for use in radome thermal design.
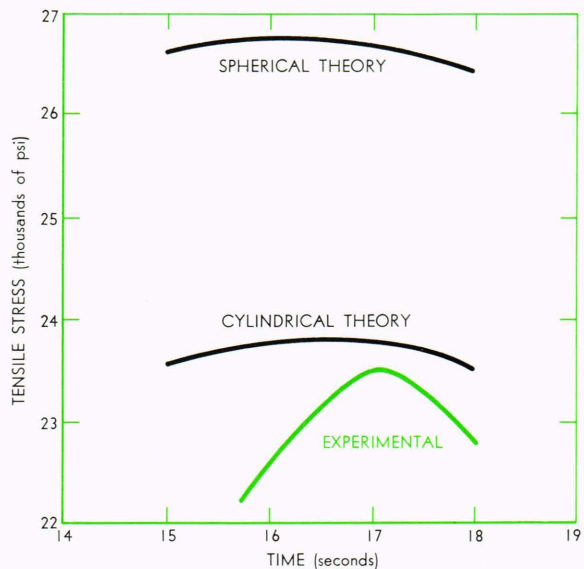

Fig. 9—Tensile thermal stresses measured during wind-tunnel test No. 2 compared with those computed using spherical and cylindrical theory.

Conclusions

The thermal design study for a Pyroceram radome for a Mach 4 missile was successfully conducted. Investigation of the effect on thermal stress of blunting the radome disclosed that little or no reduction in maximum tensile thermal stress may be expected with a 1.35-in.-radius nose. Thus, one cannot automatically assume that the increased drag caused by blunting is justified by the reduction in thermal stress.

Preliminary laboratory tests and later wind-tunnel tests showed that the large compressive stress at the point of the radome would not cause any structural problem. Finally, correlation of strain-gauge measurements made during wind tunnel tests demonstrated that both the theoretical method used to predict temperature gradients and the cylindrical theory used to determine thermal stresses give acceptable results for use in radome thermal design.

a scientist and his hobby

the TECHNOLOGY of WINE-MAKING

G. H. Mowbray

Wine has been called many things since the first known reference to it in Middle Eastern writings dating from 2100 B. C. To Aeschylus it was "the mirror of the heart"; to Shakespeare, "a good familiar creature"; and to William Gilbert, "a panacea for ev'ry conceivable ill."

Others have expressed their feelings less kindly, if no less poetically. Milton spoke of "the sweet poison of misuséd wine"; Pope, of "inflaming wine, pernicious to mankind"; while in Proverbs we are warned that "it biteth like an adder and stingeth like a serpent." No matter which of these positions one espouses—and all of them have merit on occasion —officially, wine is the fermented juice of the grape used as a beverage, or so says the Oxford Dictionary.[1] Federal description, however, is a little more verbose, defining grape wine as "wine produced by the normal alcoholic fermentation of the juice of sound, ripe grapes (in-

The author in his vineyard keeps a close watch on the growth and health of highly prized imported vines.

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[1] *Oxford Universal Dictionary on Historical Principles*, 3rd ed. (rev.), Clarendon Press, London, 1955.