

MATERIALS PROBLEMS IN AIRBORNE RADOMES DESIGNED FOR HIGH SPEEDS

by

R. A. Spurr, Senior Staff Chemist

and

G. D. Robertson, Head of Materials Application Section

Plastics Department
Research Laboratories
Hughes Aircraft Company
Culver City, California

I. INTRODUCTION

The task of choosing materials for radomes to be flown at supersonic speeds is a difficult one. Before the design of a radome can be started, it is necessary that the designer have on hand adequate data concerning electrical and mechanical requirements. There is presently no simple line of reasoning by which he can proceed directly from this information to the selection of an appropriate material. The complexity of the problem is indicated by Figure 1. Because of the interrelation of the many factors involved, selection of an adequate material requires a careful balancing of a number of considerations and usually results in compromises in the degree to which each requirement is met. The choice is made more difficult by the lack of data on the performance of most materials under the conditions expected in flight.

It is the purpose of this paper to point out certain lines of inquiry which may be helpful in the selection of materials or in the development of new materials. It will not be possible in the time allotted for this paper to treat the problems involved in a comprehensive manner. Instead, after a brief discussion of some general considerations, a description will be given of experimental work being carried on at Hughes Aircraft Company with the aim of filling gaps in the existing information concerning properties of materials. Much of the work reported deals with the effects of aerodynamic heating, currently one of the important factors in radome design and material selection. Discussion of this topic will point out some of the interrelationships suggested by Figure 1.

II. EFFECTS OF AERODYNAMIC HEATING

A. General Considerations

Stagnation temperatures encountered at different altitudes and velocities are shown in Figure 2A. It should be noted that the temperatures of the boundary layer air and of the radome surface are generally lower than the stagnation temperature, as shown in Figure 2B.¹ The data plotted in Figure 2B are for operation under transient conditions at altitudes from 35,000 to 100,000 feet for an interceptor radome with a surface emissivity of 0.9; the indicated difference between the boundary layer and surface temperatures is due primarily to the loss of energy from the surface by radiation and by conduction through the radome. The bulk of the radome remains at temperatures considerably lower than the surface temperature. For these

reasons design considerations based on stagnation temperature alone are unnecessarily severe.

The important deleterious or potentially deleterious effects caused by heating fall roughly into two categories: reversible and irreversible. Reversible effects include variation of modulus, strength, and dielectric properties with temperature. Irreversible effects can occur in the following ways: 1. organic material in the radome may be oxidized; 2. material may be thermally degraded by nonoxidative processes; 3. absorbed moisture or contained gas may be rapidly expanded with the formation of blisters; 4. stresses set up by temperature gradients may cause delamination or crazing.

Estimation of the effect of temperature for both reversible and irreversible changes must include consideration of the length of time during which the material will be at high temperature. The shortness of some missile flights makes possible the use of materials which would degrade during long exposure to the peak temperatures encountered. For example, one material which loses strength and also begins to depolymerize at relatively low temperatures has been successfully flown under conditions which produce maximum surface temperatures of 525°F and average surface temperatures of about 350°F. The strength of this material, as shown in Figure 3, would not appear to be adequate upon first consideration; however, because of its low thermal conductivity and the short flight times, the temperature of the bulk of this material does not increase appreciably. Consequently, the radome performs satisfactorily.

Tests on radome materials have been carried out at many temperatures and the results are often difficult to compare. It is helpful in ranking materials to have a way of relating the rate r of thermal decomposition at a given temperature T to the rate r_0 which would be obtained at another temperature T_0 . The following equation may be derived from the well-known Arrhenius relation:

$$\frac{r}{r_0} = \exp \left[-\frac{E}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (1)$$

where the rates r and r_0 may be expressed in percent decomposition per unit time, E is the activation energy of the reaction, R is the gas constant, and T and T_0 are absolute temperatures. A rule of thumb is that the quantity E/R is about 30,000°K for the nonoxidative thermal decomposition of many plastic materials.² Expressed more specifically, a rise of 15°F in temperature causes a doubling of reaction rate in the region from 600 to 700°F.

B. Electrical and Mechanical Behavior

Investigations of the characteristics of materials at elevated temperatures have been concerned with evaluation of specific electrical and mechanical factors. Measurements of such electrical properties as dielectric constant and loss tangent at high temperatures are difficult, but progress is being made in obtaining reliable values. Figure 4 shows the reversible increase of dielectric constant with temperature for four fiberglass laminates.

Among the materials shown, the rate of increase is greatest for phenolic and least for silicone; epoxy and TAC-polyester show an intermediate rate. The dielectric constants for silicone and phenolic laminated panels held for various times at high temperatures are compared in Figure 5. The severe heating of the panels indicated on the figure brought about irreversible changes in the material which are reflected in the values of the dielectric constant obtained. The difference between the two types of laminates after exposure to 750°F for two hours can be seen easily (Figure 6*); almost all the resin has been burned from the phenolic panel but the silicone laminate appears to have suffered no permanent damage.

Partly because of the ease with which ultimate flexural strength can be measured, wide use has been made of it as a means for rating materials. A decrease in this quantity with increasing temperature may, like changes in the dielectric constant, be reversible or irreversible in character. It should be noted that room-temperature strength is no criterion of performance at high temperature. Thus a resin which shows extraordinarily high strength at room temperature may be considerably inferior to another resin at 500°F (see Figure 7). Oxidation may be important in the degradation of resins at high temperature. As shown in Figure 8, exposure of samples of phenolic laminates to 500°F for five hours in a nonoxidative environment caused only a slight decrease in room temperature flexural strength; the decrease was marked when oxygen was allowed access to the sample.

The aerodynamic heating which occurs when a missile radome is rapidly accelerated to supersonic speeds produces thermal shock, because the thermal gradients formed may give rise to severe stresses within the radome. Figure 9 shows the temperatures of the outer and inner surfaces of an alumina cone immersed in a bath of molten metal. By adjustment of the bath temperature and the time of immersion, a wide variety of flight conditions may be simulated. Laboratory results have been correlated to some degree with similar results obtained from actual flight tests. Hughes Aircraft Company is conducting a series of such tests from which considerable temperature data have been secured. (See "Temperature Data for the Falcon Radome," by J. H. Beno, R. W. Quint, and E. F. Smith, presented at this Symposium.)

III. NEW EXPERIMENTAL METHODS

Existing plastic materials are not in general suitable for the high-temperature requirements which are expected to be imposed by high-speed aircraft and missiles to be developed in the near future. The course of development of the new materials needed will be guided by investigations of relationships between composition and molecular structure on the one hand and physical and thermomechanical properties on the other. Several studies of these kinds involving the use of recently perfected instrumental methods have been undertaken at Hughes Aircraft Company.

In the study of plastic materials intended for use at high temperatures, infrared and ultraviolet spectrometers have a number of applications. It is possible, for example, to analyze resins of unknown composition, to detect the appearance or disappearance of functional groups as a result of oxidation, and to identify products of thermal degradation. Spectroscopic methods are particularly appropriate for thermosetting resins, whose insolubility in the

common solvents makes them difficult to analyze by ordinary chemical methods.

The usefulness of the X-ray diffractometer is fourfold. First, it provides a means of quantitative analysis of compounds. The principle of the analytical method is shown in Figure 10 in which the intensities of the characteristic scattering peaks of anatase and rutile are related to their abundances in titanium dioxide. Second, X-rays yield information concerning the distribution of intramolecular and intermolecular spacings in a material and serve as a measure of resin cure. In Figure 11 it can be seen that the peak of the scattering curve moves to longer distances with increasing cure time of a phenolic resin. Third, through small-angle X-ray scattering, information concerning molecular chain lengths is obtained. Fourth, X-rays establish degree of crystallinity³ which affects elastic modulus and ultimate tensile strength.

The electron microscope yields structure in greater detail than X-ray scattering. In the electron micrographs of a phenolic resin shown in Figure 12† the spots of high density may be considered as polymerization nuclei of the plastic. These regions probably have higher cohesive strength than the relatively amorphous regions surrounding them. The spots are most readily visible near the edges of sections where they have apparently been left by the tearing action of the microtome blade, which separates them from the weaker matrix in which they are imbedded. In certain specimens polymerization nuclei can be observed in some regions but not in others. Prolonged heating apparently increases the number of the nuclei, as can be seen in Figure 12.*

In the measurement of elastic modulus with the usual physical testing machines, it is difficult to control the temperature of the sample; in addition, there is generally no provision for controlling the atmosphere surrounding the sample. As a result of these considerations an apparatus, shown in Figure 13, has been designed to measure at controlled temperature and atmosphere the natural frequency of the sample in the form of a vibrating reed. Young's modulus is given by the following expression:

$$E = K \rho \frac{L^4}{D^2} f^2 \quad (2)$$

where E is the modulus, ρ is the density of the material, L and D are respectively the free length and the thickness of the reed, and f is the resonance frequency in cycles per second.⁴ If metric units are used throughout, K has the value 38.24. The logarithmic decrement δ , which is a measure of the internal friction of the reed, is given by the equation

$$\delta = \frac{\pi}{\sqrt{3}} \frac{f_2 - f_1}{f} \quad (3)$$

where f_2 and f_1 are the frequencies (just above and below the resonance frequency f) where the amplitude has one-half its maximum value.

IV. CONCLUSION

Much of the research and development activity discussed here has been undertaken only recently. Preliminary results, however, are encouraging, and it is hoped that some of the ideas presented will stimulate work elsewhere. At any one institution only limited contributions can be made to the store of knowledge. If present high interest in the field of radomes continues, further progress will undoubtedly be made in the development of materials for high temperature uses.

REFERENCES

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2. S. L. Madorsky and S. Straus, "Thermal Degradation of Polychlorotrifluoroethylene, Poly- α , β , β Trifluorostyrene, and Poly-p-Xylylene in a Vacuum," Journal of Research of the National Bureau of Standards, Vol. 55, pp. 223-230 (October 1955).
3. S. Krimm and A. V. Tobolsky, "Quantitative X-ray Studies of Order in Amorphous and Crystalline Polymers," Journal of Polymer Science, Vol. 7, p. 57 (1951).
4. L. E. Nielsen, "Some Instruments for Measuring the Dynamic Mechanical Properties of Plastic Materials," ASTM Bulletin No. 165, pp. 48-52 (April 1950).

* Because of the format requirements of this publication, photographs can not be reproduced. Those figures not included here can be obtained by requesting them from the authors. A list of these figures and their captions follows.

Figure 6. Behavior of phenolic and silicone laminates on exposure to 750°F (Photo No. R 38778 - Phenolic, Photo No. R 38779 - Silicone)

Figure 12. Electron micrographs of phenolic resin panels (left) Postcure for 4 hours (right) Postcure for 428 hours (micrographs)

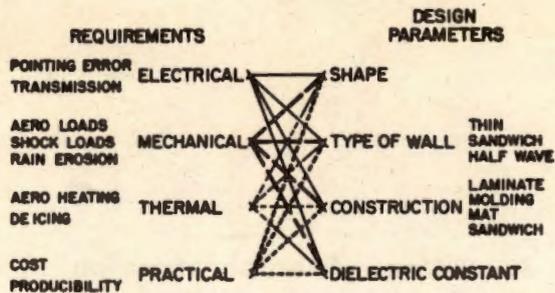


Figure 1. Interrelations of typical requirements and design parameters

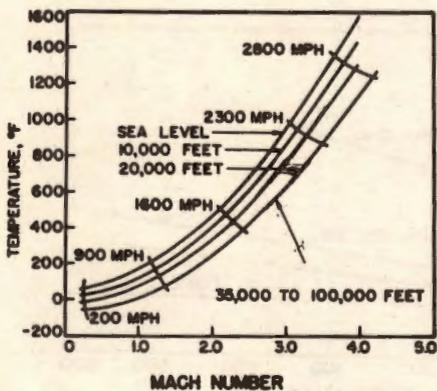
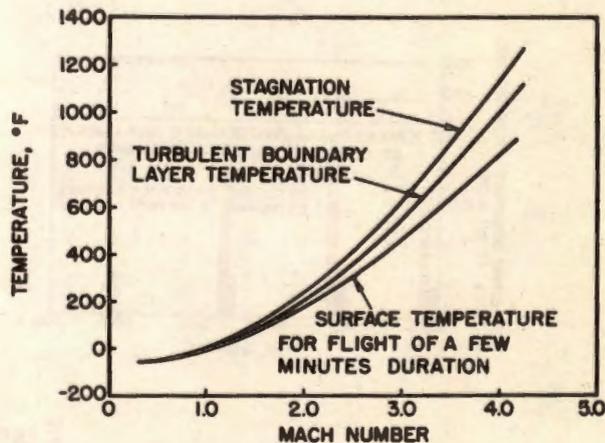


Figure 2A. Stagnation temperature as a function of Mach number for various altitudes

Figure 2B. Transient heating of a typical aircraft radome



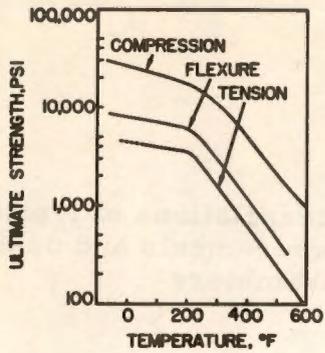


Figure 3. Effect of temperature on the strength of a radome material

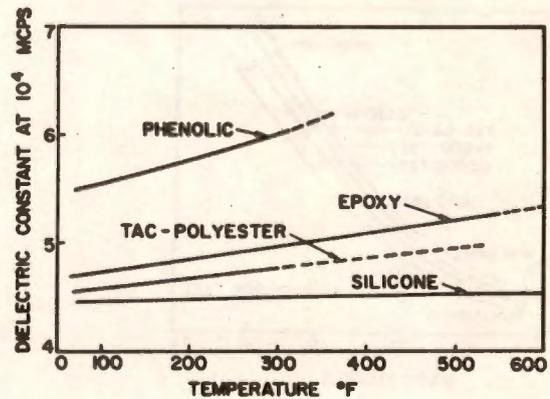


Figure 4. Reversible effect of temperature on the dielectric constants of fiberglass laminates

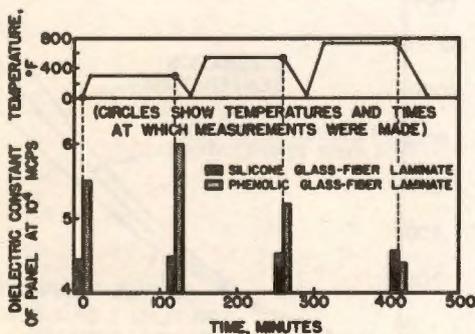


Figure 5. Irreversible effect of temperature on the dielectric constants of fiberglass laminates

Figure 7. Comparison of the strengths of laminates containing various phenolic resins

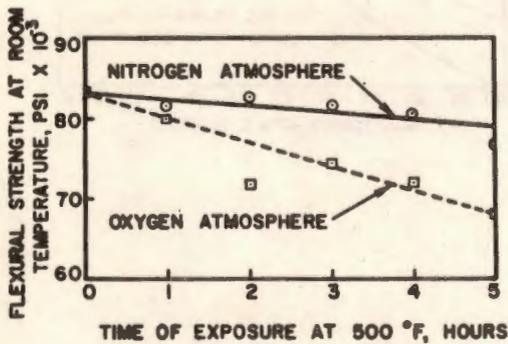
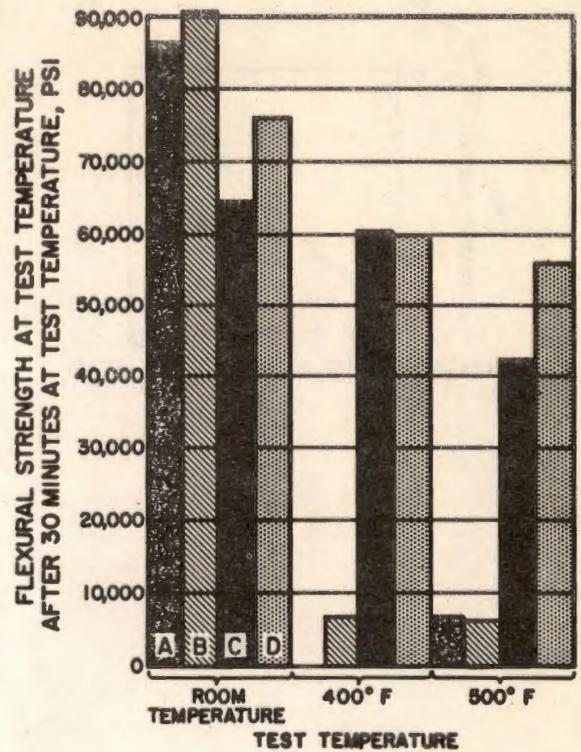


Figure 8. Effect of oxidation on the strength of a phenolic laminate

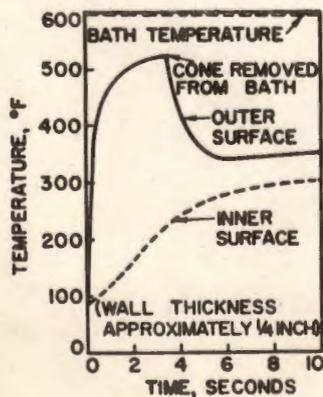


Figure 9. Rapid heating of a ceramic cone

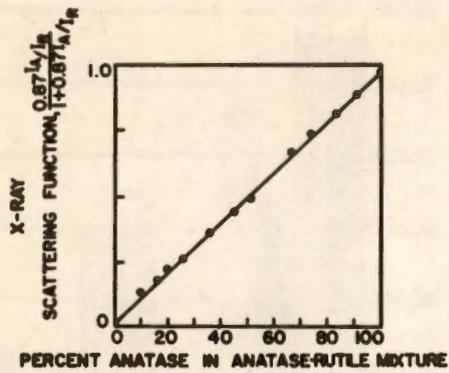


Figure 10. Analysis by X-ray scattering intensities of anatase-rutile mixture

Figure 11. X-ray scattering for a phenolic resin

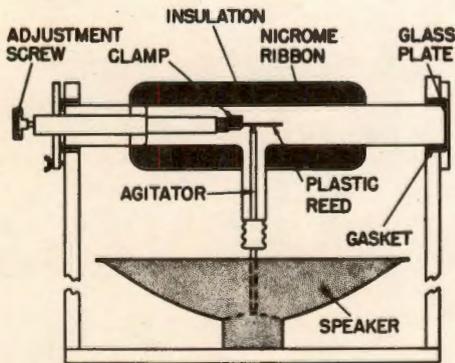
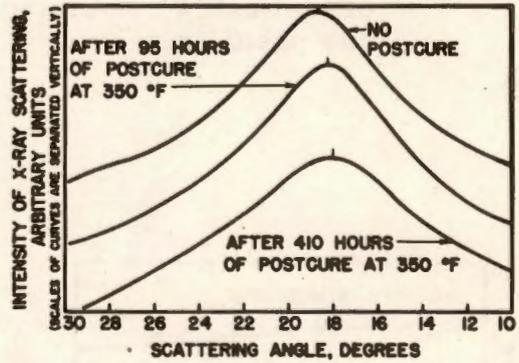


Figure 13. Elastometer