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DYNA-SOAR SKIN PANEL DEVELOPMENT

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INTRODUCTION

Reentry from orbital velocity by glider-type vehicles imposes new and severe requirements for external surfaces. The relatively long heating period coupled with the requirements of maintaining aerodynamic shape at high equilibrium temperatures and minimum weight create major design and development problems. This paper presents certain aspects of the analysis and development testing of external panels for use at temperatures as high as 2,700° F.

The surface panels to be reviewed are shown in the vehicle cross section in figure 1. The cross section and structural arrangement are representative of a reentry, radiation-cooled, glide vehicle. In general, the operating temperature of the upper surface is less than 2,000° F while the lower surface equals or exceeds this number. The only structural purpose of the panels under discussion is to transfer the external airloads to the internal primary load-carrying structure. Thermal gradients through the airframe structure require that the external surfaces absorb thermal deformations, either through flexing or movement of the panel supports or by deformations, such as buckling, of the panel itself.

A typical reentry heat and load environment for the external surfaces is shown in figure 2. The maximum lower surface temperature attained was 2,700° F for panel A, with pressure loadings in the vicinity of 1 to $1\frac{1}{4}$ psi. Panel B, on the upper wing surface, reaches a temperature of 2,000° F. The simultaneous increase of load and temperature during maneuvers is due to increased heating with increased angle of attack. In addition to temperature and aerodynamic loads, such items as airstream erosive effects and stiffness requirements to prevent flutter also influence the panel design.

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SYMBOLS

k	thermal conductivity factor which relates heat flow (Btu/sq ft-hr) to thermal gradient ($^{\circ}$F/in.) in a given material, $\frac{\text{Btu-in.}}{\text{sq ft-hr-}^{\circ}\text{F}}$
ρ	density of material, lb/cu ft
q	air pressure on outer surface of glider, lb/sq ft

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DESIGN APPROACH

With the environment established, a design approach can be formulated as outlined in figure 3. First a basic material is selected suitable for the required operating temperatures. For temperatures up to 2,000° F, the superalloys such as René 41, a nickel-base alloy, are available. These materials may be used with a high degree of structural confidence up to 2,000° F. For temperature in excess of 2,000° F, refractory materials such as the molybdenum alloys or niobium alloys must be considered for external covering if a conventional sheet-metal construction is to be used. In the area of insulation, recent developments of both alumina and zirconia fibers have shown promise of a relatively efficient insulation for use up to 2,900° F.

These material limitations are fundamental in establishing panel configuration. For temperatures to 2,000° F a conventional design utilizing the superalloys is possible. For areas where the temperature exceeds 2,000° F, the use of the superalloys in the panel structure is only possible if an insulating heat shield is used to protect them from the high-temperature airstream. The use of refractory alloys for the primary panel structure is not considered satisfactory at this time.

Surface panel development has been divided into two types - noninsulated panels for use to 2,000° F and insulated panels for use to 2,700° F.

Verification of the structural integrity of the panels employs, in general, the following testing:

- Simulated environment
  - Load and temperature
  - Sonic (with and without heat)
  - Plasma tunnel (erosive and thermal shock)
- Actual environment (free flight)

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NONINSULATED PANELS

For structural temperatures up to 2,000° F, development of the superalloys permits the use of conventional sheet-metal designs for the external surface. In keeping with the design philosophy of minimizing thermally induced stresses, a skin panel has been developed which utilizes a flat skin spot-welded to a corrugation. A typical panel is shown in figure 4. This type of surface panel is currently being evaluated both analytically and experimentally at the Boeing Airplane Company.

The structural environments are being simulated in the laboratory, as practical, as either singularly applied or combined test conditions. Testing has been confined to heat, surface pressure load, sonic excitation, and panel flutter. Three superalloys were used for this panel development program.

Heat and Load Testing

Panels 71 by 22 inches have been fabricated from 0.010-gage sheet metal. The cross sections of the panels are shown in figure 4. Two panels of René 41, two of Hastelloy X and two of Haynes Stellite 25 were tested. One of each pair of panels employed a "Z-edge" design at the corrugation ends, and the other a "creased-edge" design. These edge treatments are illustrated in figure 5.

The test setup of the panel is shown in figure 6. The bank of heat lamps can be seen above the panel. The panel was mounted as the top of a flat box on the test table. Load was applied to the top of the panel by pulling vacuum in the box. A beaded pressure seal was used between the panel edges and the vacuum box. The beading permits unrestrained longitudinal growth of the panel, and flexing of an adjacent unbeaded area permits lateral growth.

Each panel was subjected to 10 heat-load cycles representative of a typical reentry. Maximum loadings of 0.8 psi at 2,000° F were included in the testing. After these environmental tests, the panels were heated to 2,000° F, soaked for 10 minutes, and loaded to failure. The pressure loading was applied in finite steps, with the load held constant for 5 minutes at each step. Deflection to 1/2 inch at the center of the panel was considered the failure point. Test results are summarized in figure 7. All of the Z-edge panels supported a loading of 2 psi for at least 1 minute. The creased-edge panels supported only about 50 percent as much load due to the weakness of the short nonstiffened length just inside the edge of the panel.

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Sonic Testing

Structural verification of these panels by sonic testing is also required. The skin panels of a typical boost-glide vehicle are subjected to rocket-engine and aerodynamic noise during the boost and reentry glide phases of the flight. A maximum overall noise level during launch of 145 decibels is anticipated. During the boost and reentry phases the glider will be exposed to an overall level of 135 decibels due to aerodynamic noise. The maximum temperature at which significant noise levels occur will not exceed 500° F. At this temperature the mechanical properties of the structural materials used are not significantly different from those at room temperature. For this reason sonic testing has been conducted at room temperature.

A series of superalloy panels were sonic tested at the Boeing Airplane Company. These tests were conducted in the Boeing progressive wave sonic test chamber. The sonic generator is the siren type which produces a sinusoidal wave form of a given single frequency and intensity. Panels are mounted in this facility in such a way that sonic waves move parallel to the surface of the panel, thus minimizing the standing wave effect. Pressure levels are adjusted directly from a microphone reading with the panel in place.

Figure 8 shows results of a series of sonic tests for panels of three superalloys (René 41, Hastelloy X, and Haynes Stellite 25). The panels were constructed of an 0.010-gage skin spot-welded to an 0.010-gage corrugation and had the Z edge shown in figure 5. The panels were simply supported on two edges with the distance between supports being 22 inches.

An approach to reducing the scatter in sonic test data is shown in the lower plot. The equivalent static uniform pressure load is calculated (utilizing uniform-load simple-support equations) based on the measured deflection during sonic testing. Time to failure from the upper plot is converted to cycles to failure. This is possible inasmuch as all testing was at a single resonant frequency. The values for equivalent pressure and cycles to failure are then plotted as shown in figure 8 to show relative life of the test panels. This approach essentially corrects for tolerances in measuring sound levels and for the variation in the damping of the panel to the test-jig bolted joint. This joint contributes the major portion of the overall test-installation damping.

In the lower load, high life region, all curves of figure 8 are drawn through test points where no failure occurred. Similar sonic tests were made to evaluate the effect of both the beaded edge and creased edge shown in figure 5.

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Initial failure of the Z-edge panels occurred at the spotwelds and adjacent material connecting the Z-angle to the inner nodes of the corrugations. This was followed by failures in the spotwelds connecting the outer nodes of the corrugation to the doubler and skin. With the edge of the panel in this flexible condition, cracks appeared in the skin, doubler, and corrugation. Initial failure of the beaded- and creased-edge panels occurred at the spotwelds connecting the corrugations to the doubler and skin.

Conclusions from this program were that the Z-edge configuration was superior for all materials, that René 41 panels provided the longest fatigue life, and that all test panels demonstrated the capability of withstanding the noise environment anticipated during the flight of a typical boost-glide vehicle.

Flutter Testing

Flutter characteristics of typical corrugated skin panels have been evaluated in the Langley Unitary Plan wind tunnel. The effects of panel surface heating were investigated during these tests as well as variations in corrugation geometry.

Heating of the panels was investigated to determine the effect of skin buckling on inducing flutter of the panel. In general, it was found that heating the panel enough to cause buckling tends to decrease the response amplitude of the panel and to increase the critical flutter dynamic pressure.

One technique developed to increase the stiffness of the panel was the addition of flat straps attached to the back of the panel as shown in figure 9. The straps were placed normal to the corrugations and spaced 5.1 inches. The straps were terminated at the edges of the panel on the last full corrugation. There was no indication of flutter of the stiffened panel at the test Mach numbers and dynamic pressures. The straps proved to be a simple and lightweight method of increasing the flutter capability of the corrugated panel.

INSULATED PANELS

For the surface areas of a hypersonic boost-glide vehicle where skin temperatures are too high for the superalloys, that is, approximately 2,000° F, insulated panels are required. A typical insulated panel designed to operate in the temperature range from 2,000° F to 2,700° F is shown in figure 10. The panel consists of an airload-carrying, corrugated inner panel of superalloy, a layer of insulation,

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and a hard outer surface for protection of the insulation from high-velocity airstream erosion.

This panel design is such that the erosion shield is secondary structure only. It transmits the local aerodynamic pressures through supporting clips to the superalloy corrugated inner panel. This design arrangement has been adopted due to a lack of a reliable structural material for load beaming in a 2,700° F environment.

Insulation Properties

Several promising insulations with various high-temperature capabilities are compared in figure 11. A measure of insulating efficiency as applied to airframe design is the factor $k\rho$; that is, the product of thermal conductivity times the density of the insulation. For high insulating efficiency, low values of $k\rho$ are desired. The data presented as solid lines are based on test experience at the temperature indicated and represent the current limit of conductivity data. Testing of these insulations at higher temperatures is required to establish the insulating properties which are predicted by the dashed portion of the curves. The dashed curves do not extend beyond the maximum hot wall temperature to which the material is known to have been successfully submitted. It will be noted that there is a serious lack of data above 2,000° F, the temperature range currently of interest. The alumina- and zirconia-fiber insulations have shown promise for satisfactory performance at temperatures in the range from 2,000° F to 3,000° F. The data are based on sea-level atmospheric pressure with the exception of the bottom curve which is included for comparison of altitude effect.

Insulated Panel Testing

Insulated panels incorporating various insulations, erosion shields, attachments, and assembly techniques have been fabricated and thermally tested at the Boeing Airplane Company. These insulated panels have included either a metal or a ceramic erosion shield. Some of the ceramic shields were reinforced by a wire grid.

Testing to date has been limited to a maximum temperature of 2,000° F. However, these tests, coupled with those of higher temperature evaluation of materials, have established the foundation for insulated panel designs to operate up to 2,700° F.

The thermal response of certain types of insulated panels as determined by testing is shown in figure 12. The outer surface of each panel was heated to the test temperature by radiant lamps. After heat flow

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had stabilized, the temperatures were measured at various locations. The lowest curve shows the characteristics of a panel which was partly insulated by the erosion shield. The erosion shield was made from 4- by 6-inch tiles of foamed silicon carbide. The tiles were 1/8 inch thick, and pairs of tile were cemented together for a total thickness of 1/4 inch. The upper curve shows the characteristics of a similar panel with less insulating thickness. These panels survived the test without damage, but the tiles are fragile and several were cracked during fabrication.

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The remaining data points show the characteristics of panels with noninsulating erosion shields. Four different insulations were tested in conjunction with this type of shield. Two insulations were load-carrying types and two were non-load-carrying types.

The non-load-carrying types of insulation included Q-felt (silica fiber) at a density of 3 lb/cu ft and Fiberfrax (aluminum silicate) fibers at a density of 8 lb/cu ft. The load-carrying types included Fiberfrax fibers in a board form at a density of 20 lb/cu ft and a ceramic honeycomb in which cells were filled with Fiberfrax at a density of 8 lb/cu ft.

The erosion shields on the load-carrying type of panels included metal, alumina, and alumina reinforced with wire grid. The alumina shielding broke apart during the test, but the wire-grid reinforcement was able to retain the pieces in place; however, the extensive cracking of alumina indicates a probable failure in reentry environment. All of the metal erosion shields survived the tests.

Five different designs were used for supporting the erosion shield in the test panels:

(1) A load-bearing board type of insulation for compression, and wires at 3-inch intervals for tension loads (A formed sheet-metal part in the center of the panel similar to those shown in figure 10 provided shear transfer.)

(2) Ceramic spacers at 3-inch intervals for compression and shear, and a wire through each spacer for tension.

(3) Studs at 3-inch intervals, reaching through the insulation and carrying all types of load.

(4) Formed sheet-metal parts similar to those shown in figure 10. (The spacing of posts in one test panel was less than that shown so that the posts along each inner panel corrugation were simply 1/2-inch strips of corrugation. In another panel these strips of corrugation were replaced by a continuous sheet of corrugations.)

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(5) Formed metal channels nested in pairs so that a space between the outer flanges supported the edges of erosion-shield panels.

The wire tension members were sewn through the reinforcing grids in the reinforced alumina shield, and through small formed sheet-metal fittings on the metal shield parts. The studs were attached to the metal parts by speed nuts and to the ceramic shield by ceramic cementing of an imbedded head or sheet-metal fitting. The formed sheet-metal parts were attached by either spotwelding or riveting, depending on the similarity of the metals.

All of these supporting schemes survived the tests without failure with the exception of the alumina erosion shields. The continuous corrugated sheet used for the inner support structure was found to be undesirable for two reasons. First, the thermal response was poor due to excessive heat paths which short circuited the insulation. Second, the free thermal growth of the shield was restrained by the relatively cool valleys of the corrugations. Resulting thermal stresses were found to cause cracking of the shield after several reentry heat-plus-load cycles.

CONCLUDING REMARKS

Development to date has shown that the design and fabrication of structurally sound external surface panels for use to 2,700° F on reentry vehicles are possible. For temperatures to 2,000° F, environmental testing of noninsulated panels has established the capability of these structures to survive the reentry environments. For temperatures between 2,000° F and 2,700° F there are still questions to be answered; however, sufficient work has been accomplished to indicate that these questions will be resolved through a normal design-development program.

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SURFACE PANELS IN GLIDER STRUCTURE

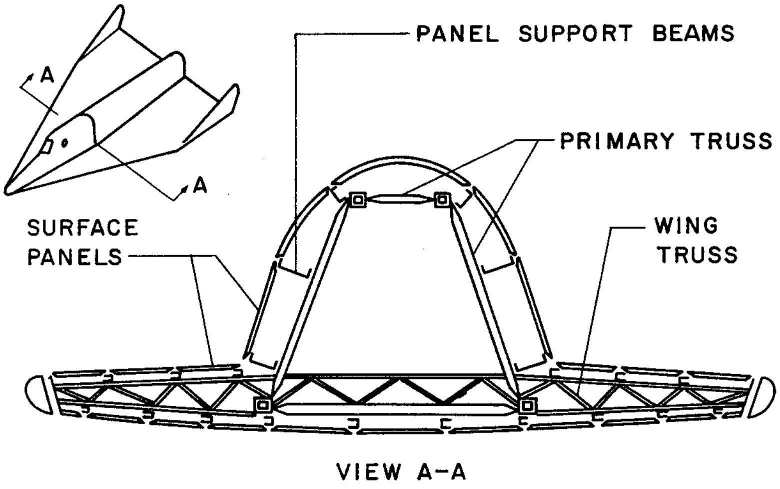

Figure 1

PANEL ENVIRONMENT DURING REENTRY

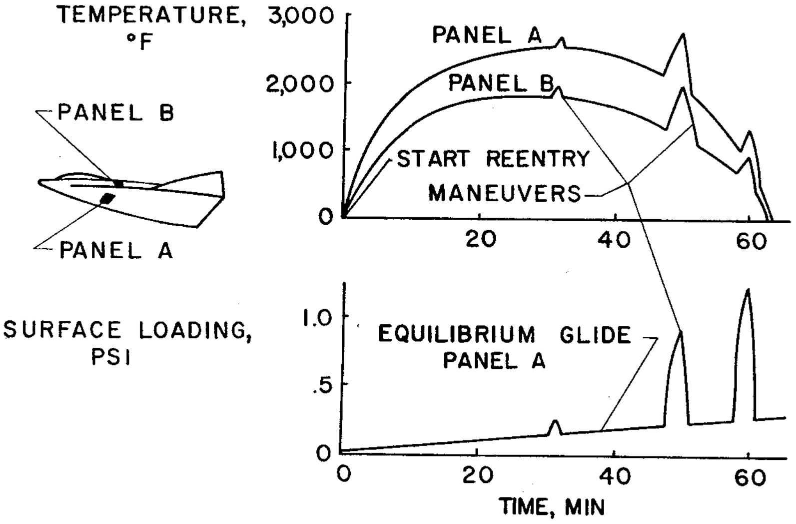

Figure 2

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DESIGN APPROACH

- MATERIAL
  - (1) SUPERALLOYS (2,000 °F MAXIMUM)
  - (2) REFRACTORY ALLOYS (OVER 2000°F)
  - (3) INSULATION (OVER 2,000°F)
  - (4) CERAMICS

- CONFIGURATION
  - (1) NONINSULATED (UP TO 2,000°F)
  - (2) INSULATED (ABOVE 2,000°F)
  - (3) "THERMAL RESTRAINT FREE" SUPPORT

- TEST
  - (1) SIMULATED ENVIRONMENT
  - (2) ACTUAL ENVIRONMENT

Figure 3

NONINSULATED PANEL

(USE LIMITED TO MAXIMUM TEMPERATURE OF 2,000 °F)

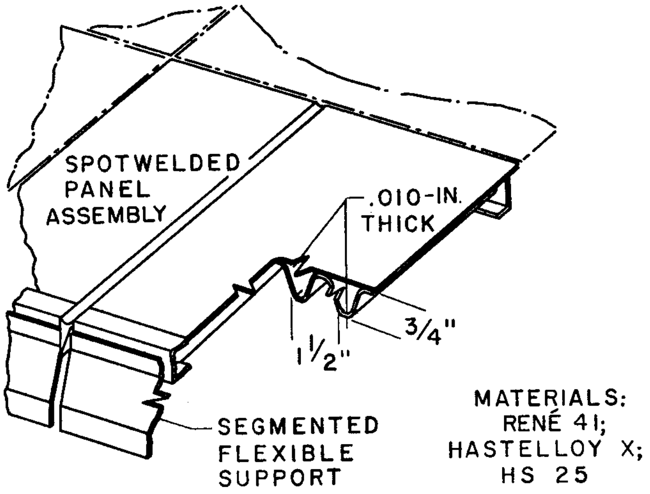

Figure 4

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PANEL-EDGE CONFIGURATION

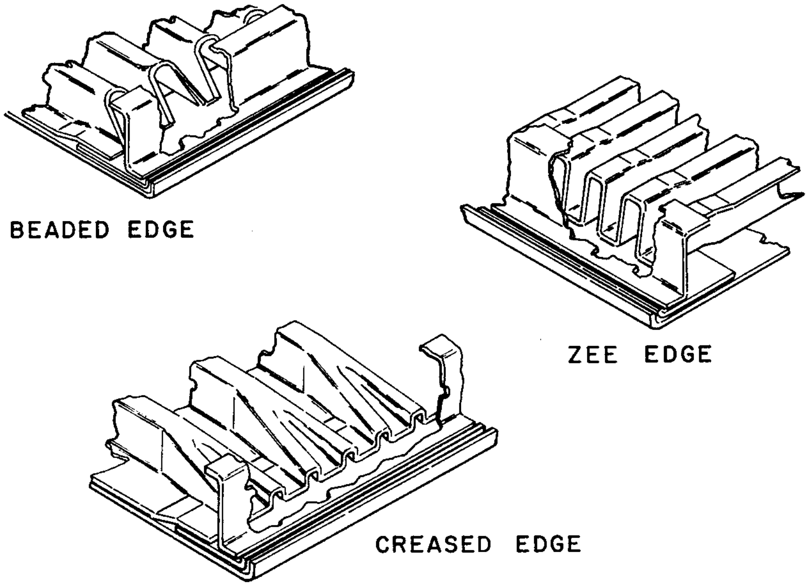

Figure 5

HEAT AND LOAD TEST SETUP

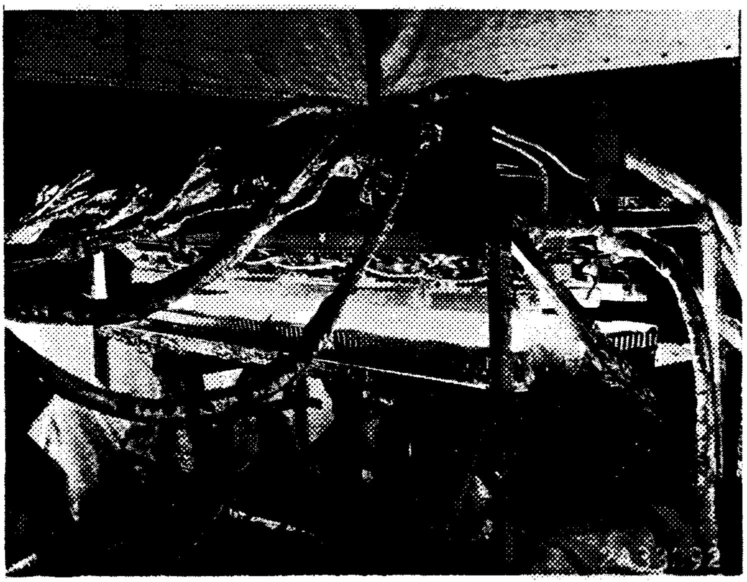

Figure 6

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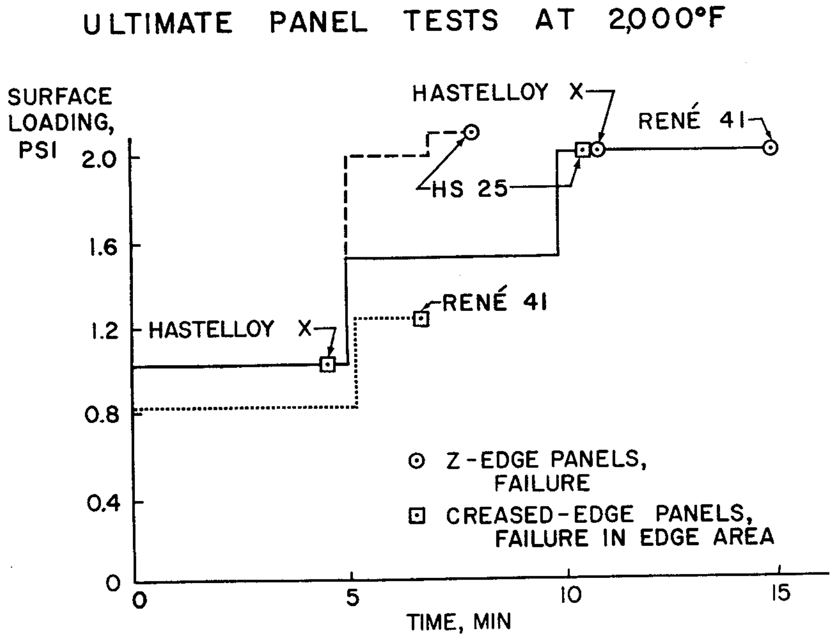

Figure 7

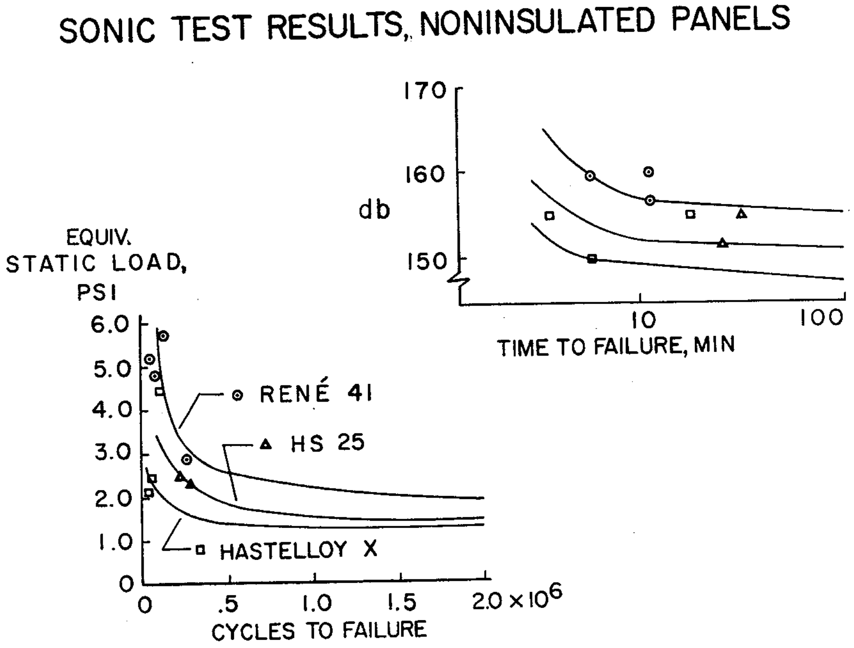

Figure 8

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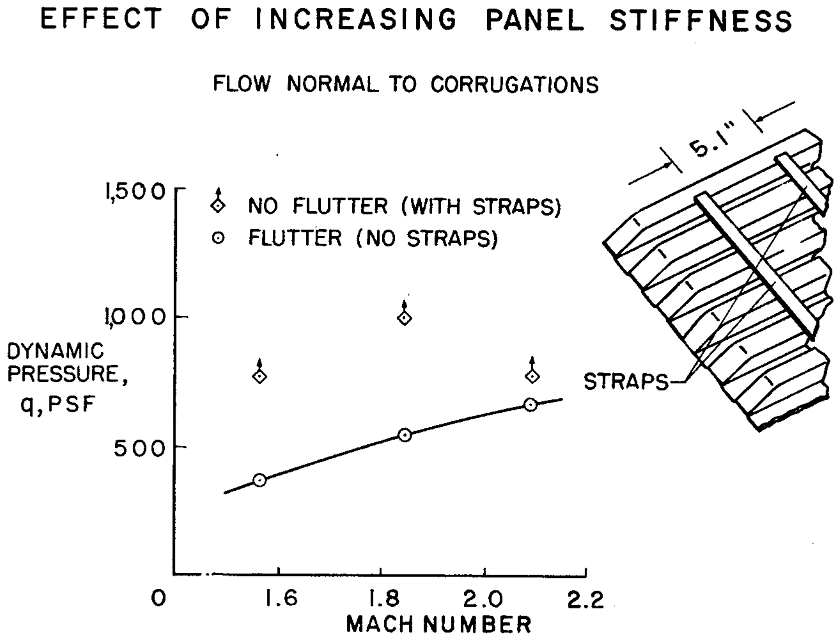
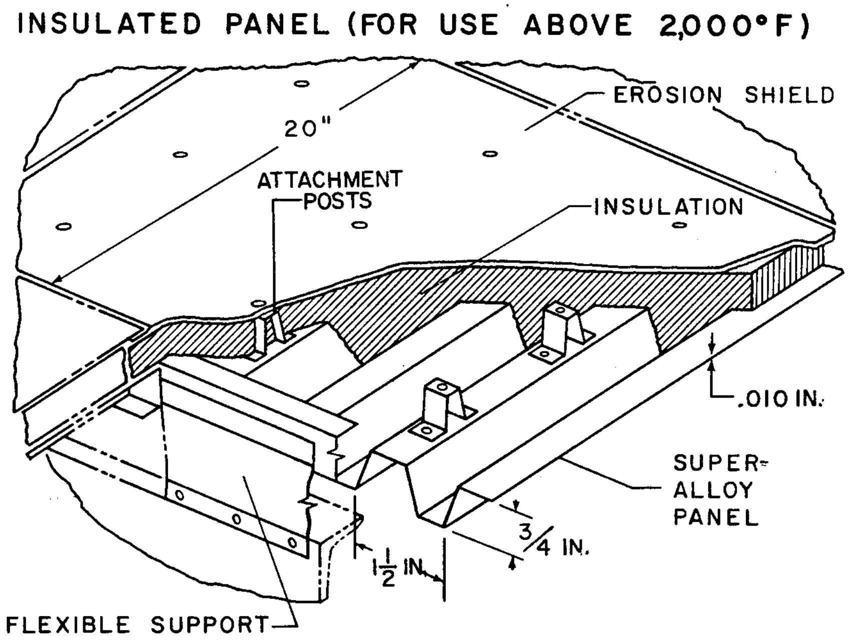


EFFECT OF INCREASING PANEL STIFFNESS

FLOW NORMAL TO CORRUGATIONS

Figure 9



INSULATED PANEL (FOR USE ABOVE 2,000°F)

Figure 10

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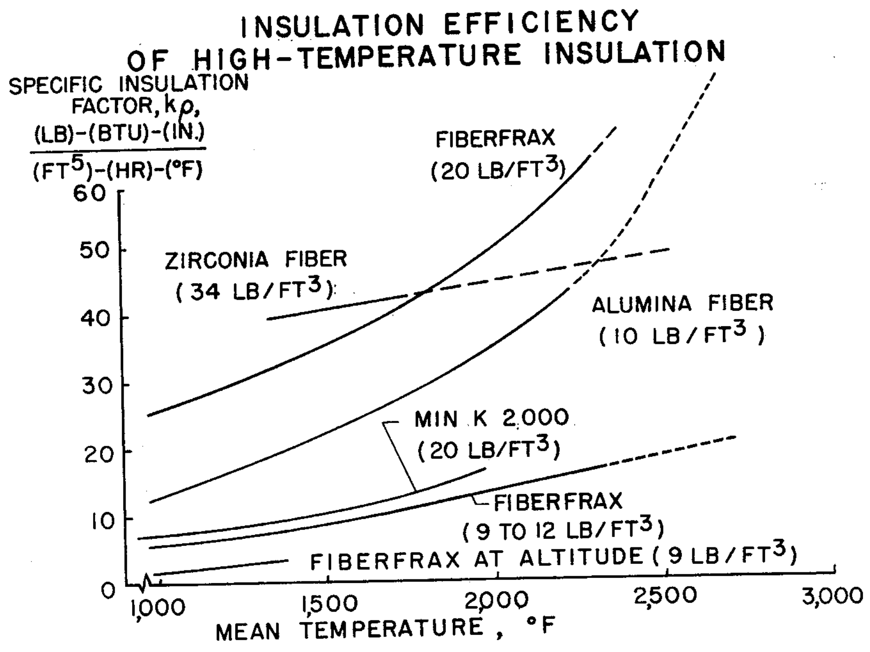

Figure 11

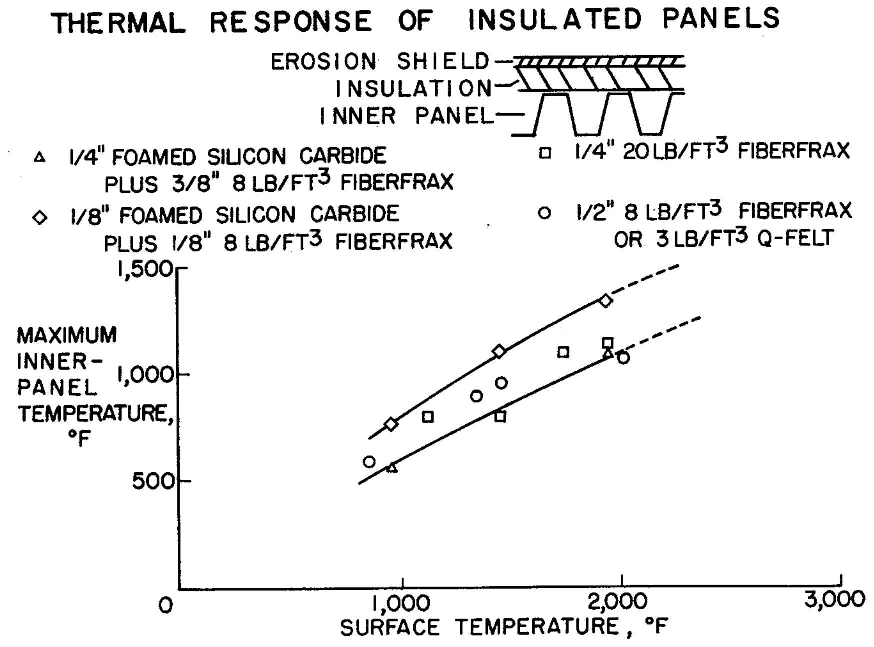

Figure 12

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