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DEVELOPMENT OF TRUSS TYPE DYNA-SOAR GLIDER STRUCTURE

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INTRODUCTION

This paper is concerned with the structural design evolution, construction, and testing of airframe components suitable for a delta-wing, glider-type reentry device. The structural design of a reentry vehicle is influenced by the configuration of the vehicle and the load and thermal input conditions associated with the flight trajectory. During reentry, the typical glide vehicle is capable of using a number of equilibrium glide paths, during which flight is maintained at essentially constant values of W/SC_L. The glide vehicle is also capable of performing high-load-factor maneuvers from the reentry glide path.

For the purposes of this paper, the structural temperature rise due to the thermal energy imparted during reentry is that rise which is associated with a radiation-cooled structure. The basic structural concept considered employs skin panels which transmit the external aerodynamic loads to the primary load-carrying structure. These panels also serve as an exterior protective heat shield such that the primary structure does not reach the temperatures experienced by the outer shell. The primary load-carrying structure is considered to be maintained at temperatures below 2,000° F; therefore, the use of superalloy construction materials is permitted.

The concept of cooling by thermal radiation leads to temperature differences in the various internal structural members. These temperature differences, or gradients, depend on the structural arrangement and the magnitude of the change in exterior skin temperature with time. For example, the temperature gradient between the upper and lower wing surface is greatest during high-load-factor maneuvers at hypersonic speeds. These temperature gradients produce differential changes in the lengths and orientation of the various internal structural components. High stresses can occur in a structural design in which the elongation and rotation of structural elements are restrained. Thermal stresses of this nature can be eliminated from the primary structure by utilizing a statically determinate trusswork employing pinned attachments.

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Static room temperature and hot tests performed on various truss members and joints and on the forward structural section of a full-size vehicle have verified that the truss-type structure has the structural capability required of a typical Dyna-Soar reentry glider. This type of structure can be constructed by using the current state of the art in materials development and manufacturing methods.

SYMBOLS

C_L	lift coefficient
S	reference lifting area of the vehicle, sq ft
W	total weight of the vehicle, lb
$T_0 \ldots T_3$	local structural temperatures, °F

DISCUSSION

Structural Arrangement

The structural arrangement shown in figure 1 is representative of the truss-type structure developed for a typical Dyna-Soar reentry glider. This particular reentry vehicle component is currently being fabricated for structural testing which will duplicate typical reentry environmental conditions. The structure is 10.5 feet long and is a full-size representation of the forward section of the vehicle. René 41, a nickel-base superalloy material, is used throughout the structure with the exception of the lower surface skin panels which are made of HS-25, a cobalt-base superalloy. The body is composed of two main longitudinal trusses joined together with four cross frames. Diagonal bracing between the longerons of the main trusses has the capability of reacting asymmetrical loading conditions. The primary wing structure is made up of wing-spar trusses and leading-edge beams. The wing-spar trusses are perpendicular to the leading edge of the vehicle and are attached to the main body trusses at the lower longerons and vertical body truss members. Air loads are transmitted to this primary truss structure by means of corrugated skin panels. These panels transfer the applied air loads to the leading-edge beams, intercostals, longerons, and keel beam by simple beam action. In order to understand this airframe development more fully, it is necessary to investigate the conditions and basic concepts which affect the structural design.

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Structural Design Conditions

The flight trajectory of a hypersonic glider reentry vehicle is composed of three phases: boost, orbit, and reentry. High wind shear conditions and rapid heating rates can exist during the boost phase. During this phase, the internal primary structure is cool and, consequently, these conditions do not affect the design of most of the structural members. During the orbital phase of the flight, the substructure likewise is cool and loads due to activation of reaction controls are small. It develops that the principal design conditions for the primary structure occur for combinations of temperature and aerodynamic loads during the reentry phase of the trajectory. For approximately 30 minutes after initiation of reentry, the heating rate of the external surfaces is gradual and the overall vehicle structural temperatures tend to approach equilibrium conditions. This phase of the reentry is characterized by high temperatures and relatively low structural loads. Figure 2 shows typical temperatures for the inner surface of the lower skin and lower chord of a wing-spar truss during the final 50 minutes of reentry. Equilibrium temperature conditions are shown for one factor flight and uninsulated skin panels in an area away from leading-edge effects. For this case, the maximum temperature of the internal primary structure is 1,530° F. This condition occurs when the maximum skin temperature is 1,780° F.

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Transient structural temperatures are illustrated for a high-load-factor maneuver condition. The curves show that the internal structural temperatures during this severe maneuver will be somewhat lower than those at maximum equilibrium conditions. However, the aerodynamic loading combined with the temperatures during this type of maneuver can be the designing condition for the primary load-carrying structure.

Structural temperatures experienced during a severe pull-up maneuver are shown in figure 3. Transient temperatures are shown for the inner surface of the lower skin and the lower and upper chords of a wing-spar truss. After initiation of maneuver, the temperatures increase until the maneuver load factor is decreased. With a reduction in flight load factor, the skin temperature decreases rapidly and after a short time lag the internal structural temperatures also peak and decrease. Even though thin materials are used for construction, internal structural heating rates are small immediately after maneuver initiation. For a representative maneuver time of 30 seconds, the transient temperatures of the lower and upper spar chords are 300° F and 330° F below their respective equilibrium temperatures based on a skin temperature of 2,000° F. At this time, the temperature gradient between lower and upper spar chords is approximately 390° F. High-load-factor maneuver conditions of this type, combined with the associated structural-temperature differences, usually constitute the principal design conditions for the primary structure of the vehicle.

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Structural Concept

The effect of temperature gradients between members of a typical truss bay is shown in figure 4. With truss joints in the fixed condition, the changes in member lengths due to differential thermal expansions produce stresses from end moments and shears. If all joints are pinned, there is no resistance to changes in relative member orientation. Bending of the truss members is thereby eliminated and the structure becomes free of this type of thermal stress.

Multiple-bay truss deflection caused by differential temperatures must be considered since this deflection will modify the aerodynamics of the glider. Calculations indicate that multiple-bay truss deflections due to temperature gradients across the truss are not significantly changed by varying the positions of the truss verticals and diagonals. As a result, the design of a truss-type structure is primarily based on optimum weight considerations.

Structural Design and Construction

Air loads are carried by the skin panels in simple beam bending. The method of reacting the loads from these panels is shown in figure 5. Shear forces from the panels result in nearly uniform loads carried in bending by the leading-edge beams, intercostals, longerons, and the keel beam. The end shear forces from these members are reacted at the joints of the wing spars and body trusses. With this arrangement, the primary stresses in the truss elements are due to axial loads.

The weight of structural joints represents a significant portion of the total weight of the structure. When a truss structure is designed for axial forces, pinned connections are heavier than fixed joints. However, the lighter fixed joints introduce moments and shears into the members because of the temperature distributions previously discussed. These additional loads require the truss members to be heavier. In figure 6 the weight of truss-type structure for a typical wing spar with three different conditions of joint fixity is shown. For the fully pinned condition the weight of the joints approaches 30 percent of the total truss weight. Although joint weight decreases in the fully fixed case, the weight of the total structure is approximately 130 percent of an equivalent pinned joint truss. A design where only certain joints are fixed results in the lightest structure. Thermal stresses are present in some of the members in this latter arrangement but they are of small magnitude. The advantage of incorporating some fixed joints becomes apparent at connections between many members in more than one plane.

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A typical wing spar in which this design technique has been utilized is illustrated in figure 7. This wing spar is used on a structure currently being fabricated for test. All truss material is René 41 superalloy. Tubular members have been swaged where there are space limitations on the sizes of connections. Pinned connections are formed by bolting through tabs or fittings which have been fusion welded in tube end slots. Fixed connections are formed by fusion welding the members to fittings or gussets.

A typical joint for the intersection of wing and body truss elements for current test structure is shown in figure 8. Longeron loads are transmitted through a bolted connection. A fitting is used to attach the wing and body truss tubes to the longeron. Wing-spar members are fusion welded to a lug which is bolted to this fitting. A similar arrangement is used for the body cross-frame elements. The bolted connection between the fitting and longeron allows independent rotation of the vertical-diagonal assembly in the main truss plane.

Superalloys were selected for the construction of the primary structure since the temperature environment does not exceed $2,000^{\circ}$ F. Materials evaluated have included M-252, René 41, and HS-25 superalloys. The structural design conditions and the desirable material properties of René 41 at elevated temperatures have led to the selection of this material for the trusswork. René 41 is a precipitation hardenable material. After solution treating at $1,975^{\circ}$ F the material is aged at $1,400^{\circ}$ F for 16 hours. This process increases the strength of René 41 at temperatures below $1,600^{\circ}$ F. Conditions which produce high stresses in the primary structure occur at temperatures below the range where the creep of René 41 becomes significant.

The longeron shown is formed from sheet stock and consists of a close-out plate spot-welded to a hat section. Beads are incorporated in the hat-section design to increase crippling strength.

Swaged-tube manufacture has been developed by starting with a tube size intermediate between the basic section required and the swaged end. Tube ends are swaged by a succession of cold-draw operations with the use of intermediate anneals. With the material in the annealed condition, fluid forming is utilized to increase the basic section to the diameter required. Final treatment of René 41 assemblies consists of solution treatment and aging.

Tests Results

Structural testing conducted by the Boeing Airplane Company has included elevated-temperature tests on structural elements and components

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of various cross sections and materials. A full-scale structural assembly representing an earlier design version of a truss-type structural arrangement has been built and tested to prove this structural concept for a reentry glide vehicle.

Element tests.- Five substructure elements have been life-tested. These elements are shown in figure 9. They represent two designs typical of the glider structure. These components were subjected to a continuous program of 20 minutes at 1,200° F, 20 minutes at 1,400° F, 10 minutes at 1,600° F, and 4 minutes at 1,800° F, with approximately 50 percent of the ultimate compression design load applied at each corresponding temperature level. This program represented the cumulative time at predominant temperatures and stresses for 10 glider reentries. After this program the specimens were tested to failure in compression at 1,800° F.

The materials used for element construction were the superalloys René 41, HS-25, and Hastelloy X. The René 41 specimen was age-hardened after welding.

All the capped-hat sections were constructed with identical sheet gages and weld patterns. The overall length of the hat-section specimens was 43.92 inches with a distance of 40.00 inches between support-bolt center lines. The basic section of square-capped-hat design, 3.0 inches on a side, extended for 12.80 inches at midspan. This section was of 0.040 gage with each side beaded to increase crippling strength.

Swaged tube elements were 16.9 inches long with an overall length of 19.70 inches including end tabs. The distance between support pins was 18.00 inches. The basic section of the tubes was 1.50 inches in diameter with 0.014-inch-thick wall. The section is swaged over a distance of 3.0 inches to 0.50-inch diameter with an 0.027-inch-thick wall. The reduced sections were 0.40 inches long and slotted to receive the end tabs. Stiffener rings of 0.020 gage were fusion plug welded to the specimens at the junction of the basic section and swaged end in order to increase the strength in the transition area.

Because of the lengths and section properties of the specimens, the elements were critical in crippling. Life testing was accomplished for the elements and the failure stresses at 1,800° F are shown as a ratio of the corresponding predicted crippling stresses. The test results compare favorably with analytically predicted strengths for the two structural shapes manufactured from the three basic materials.

A view of the test facility used for these tests is shown in figure 10. The elements were heated by air-cooled high-density radiant heat lamps with ceramic reflectors mounted on aluminum manifolds. Power

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to the lamps was regulated by control thermocouples mounted on the specimens and the use of ignitron controller carts. Load was applied to the specimens by a hydraulically operated test machine. Thermal expansion of the machine during testing was reduced by wrapping all exposed parts in aluminum foil.

Structural-concept model tests.- This test structure was a full-size vehicle forward section approximately 6.5 feet long. Its primary purpose was to verify the structural integrity of the truss-type design concept. In addition, the heat transfer through the structure and the deflections of the model due to heat and load were evaluated throughout the tests. This test specimen was subjected to seven simulated reentry flight trajectories, including maneuvers, which an actual reentry vehicle would encounter. A view of the specimen is illustrated in figure 11.

The test specimen was fabricated from M-252 superalloy sheet stock and, consequently, the design was restricted to parts which could be fabricated in the sheet metal shops. All parts were spot-welded together with the exception of the bolted-member connections. For example, the tube members were constructed of two hat sections spot-welded together. The specimen was built around two fore-and-aft full-depth trusses. The second and fourth verticals from the forward end employed pinned ends whereas the diagonal members were connected by short tabs at the joints. These main trusses were connected by three cross frames. A leading-edge beam was attached to the outboard ends of the cross frames. The exterior skin panels were made of corrugated sheet spot-welded to a flat external skin.

An overall view of this structural-concept model during testing is shown in figure 12. Instrumentation on the concept model consisted of 327 thermocouples, 28 high-temperature strain gages, 12 deflection indicators, and 1 dynamometer-bar load indicator. Thermocouples were installed to measure temperature distributions on the external skin and throughout the joints and members of the trusswork. The test specimen was cantilevered from the reaction jig by extensions of the main trusses. Load was applied by one hydraulic jack acting through a fulcrum beam to an evener system. The evener system was attached at 22 load points on the specimen. All points were at the intersections of main truss members and along the leading-edge beams. Heat was applied to the specimen from radiant heat lamps. The lamps were fixed to a jig which surrounded the specimen. This lamp jig was hinged at the reaction support and counterbalanced to rise with the model as it deflected.

The first test run was a load-only test to check the load distribution and room-temperature deflections of the model. The model was subsequently tested with a maximum lower surface skin temperature of 500° F to check the heating facility and to investigate the effects of moderate temperatures on the specimen. A total of seven simulated

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reentry tests were conducted on this specimen. The first two reentry tests reached maximum lower surface skin temperatures of 1,600° F and 1,800° F. Two other tests reached a maximum temperature of 1,900° F and three tests imposed a maximum of 2,000° F. Test loads simulated one-factor flight conditions and two maneuver conditions to the maximum aerodynamic capability of the vehicle represented. The heating rate of the lower skin surface was maintained at 3° F per second during the maneuver conditions.

The first high-temperature reentry to 1,900° F verified the structural concept. The specimen survived all testing with no damage to the primary structural members. Deflection readings taken during the tests indicated that the specimen behaved elastically. No measurable creep or permanent deformation occurred to the primary structural components. Some minor cracks and spot-welded failures on the skin panels and skin expansion joints occurred. The corrugated sections of the skin panels did not experience damage. The damage to the outer surface skins was apparently the result of the skin-support structure being too rigid and not allowing freedom of movement of the panel corners.

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Numerous data were obtained on heat transfer throughout the structure. Representative of the numerous temperature results were the measurements of temperatures of truss structure attached to the lower surface skin panels. As shown in figure 13, the temperatures and thermal gradients of elements attached directly to the skin are high. These measurements were taken on the lower chord of the main truss. A substantial decrease in member temperatures and thermal gradients is obtained by attaching skins a small distance away from the primary truss elements by means of clip angles. This arrangement was used between the skin panels and cross frames. Current designs of skin panel to truss component attachments utilize this method.

Even though the programed model surface isotherms were difficult to obtain during testing, the variation of skin-panel temperatures along the main truss chords were close to those required. Figure 14 shows the temperatures through the body truss structure for the most critical reentry test. The results show that temperature differences between the lower chord and diagonal members are much higher than those between the diagonal and upper chord members. This high gradient has been decreased in current truss-type structural design by not attaching chord members directly to the skin panels.

The complexity of truss joint structure does not readily lend itself to analytical solution. The maximum temperatures attained near a representative concept model joint are shown in figure 15.

CONCLUDING REMARKS

In conclusion, it can be stated that, although the concept of structural cooling by thermal radiation leads to differential member temperatures, thermal stresses are essentially eliminated in the trusswork by the use of pinned joints. Structural design is improved from the standpoint of weight by employing fixed joints where the truss members will not be adversely affected.

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Fabrication capability has been demonstrated by the manufacture of airframe components using superalloy materials of construction. The testing of these components at their design temperatures has confirmed the analytically predicted strengths.

Testing of a full-size vehicle forward section by repeated heat and load programs simulating reentry trajectories has indicated that pinned-joint structure is not adversely affected by large differences in component temperatures. Temperature data have led to a better understanding of heat transfer between internal structural elements. This information has been utilized to improve the design of current truss-type airframes. These tests have verified that a radiation-cooled primary structure, employing a trusswork design, has the structural capability required for a typical Dyna-Soar reentry glider.

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STRUCTURAL ARRANGEMENT FOR A TYPICAL GLIDE VEHICLE

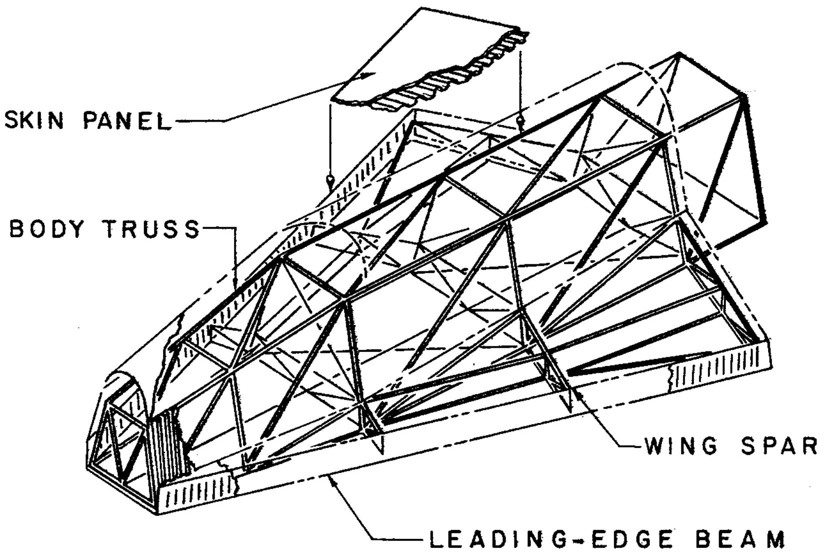

Figure 1

TYPICAL STRUCTURAL TEMPERATURES DURING REENTRY

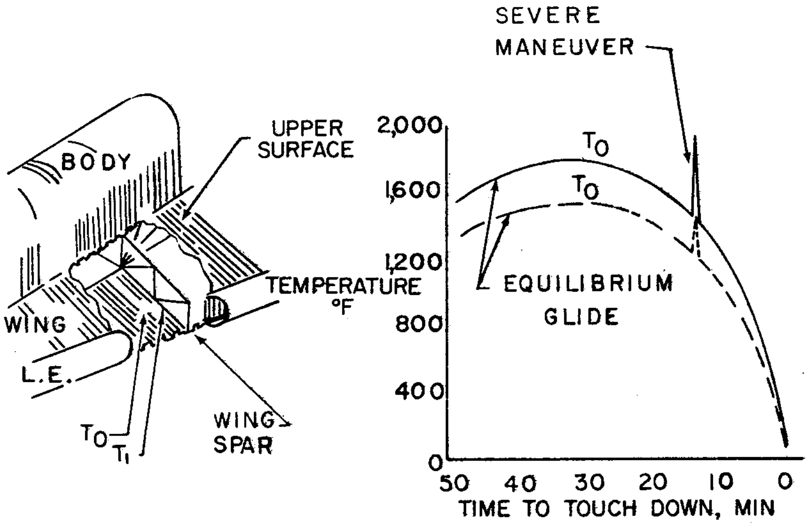

Figure 2

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TYPICAL STRUCTURAL TEMPERATURES DURING SEVERE REENTRY MANEUVER

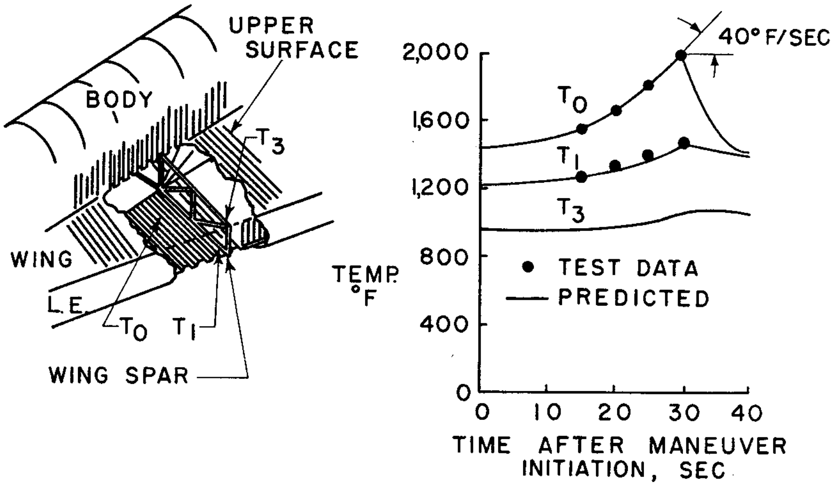

Figure 3

SINGLE-BAY TRUSS DEFLECTION DUE TO DIFFERENCE IN STRUCTURAL TEMPERATURES

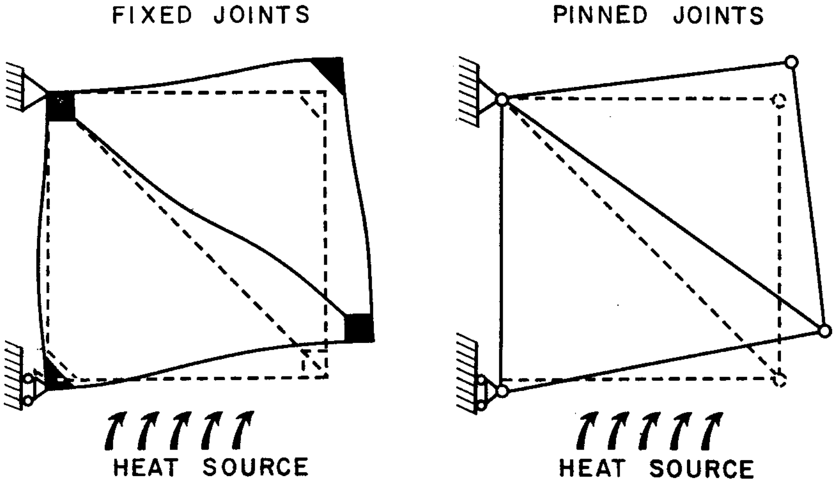

Figure 4

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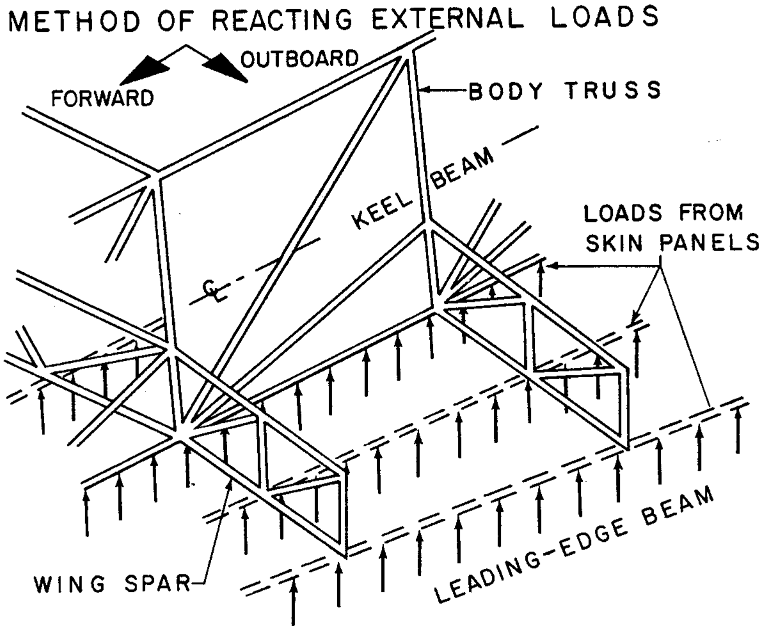

Figure 5

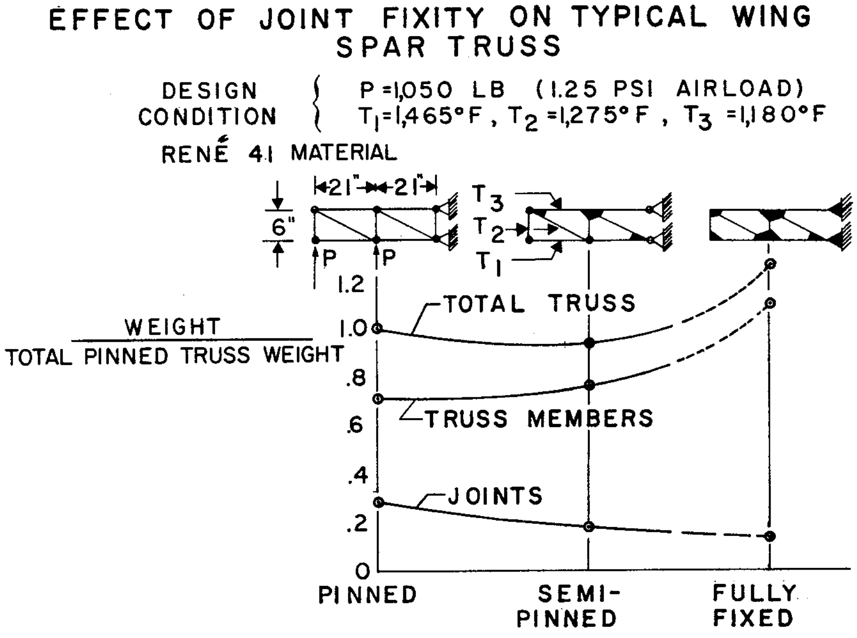

Figure 6

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TYPICAL WING-SPAR DETAIL

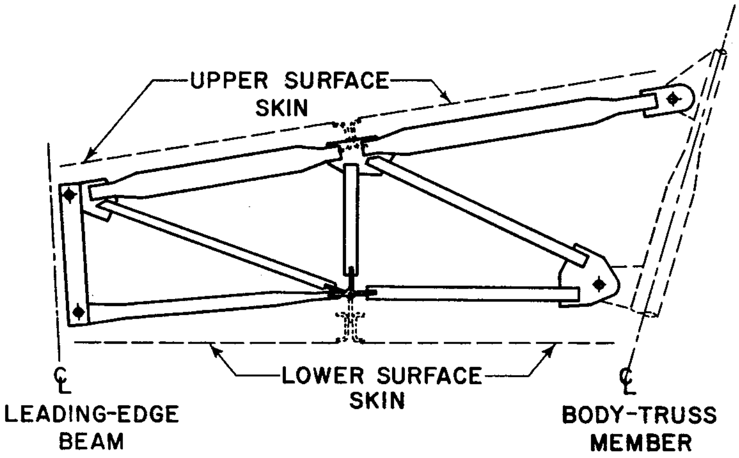

Figure 7

TYPICAL JOINT DETAIL

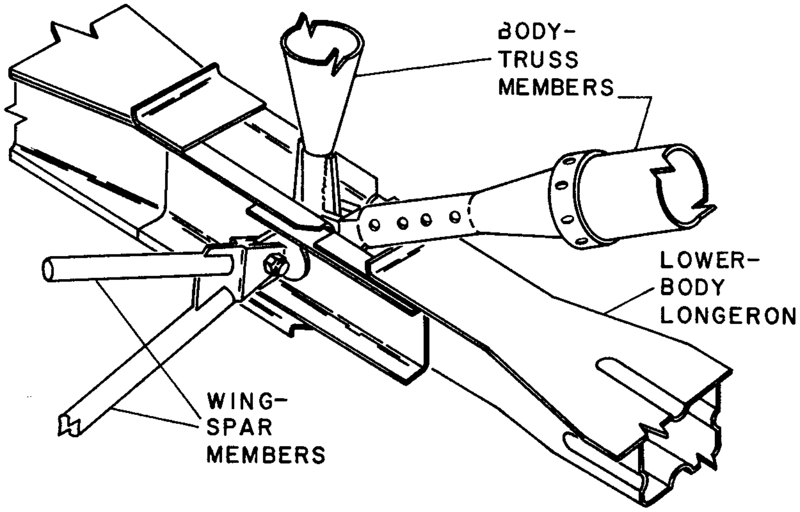

Figure 8

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COMPRESSION CRIPPLING
TESTS OF TRUSS ELEMENTS; 1,800° F TEST TEMPERATURE

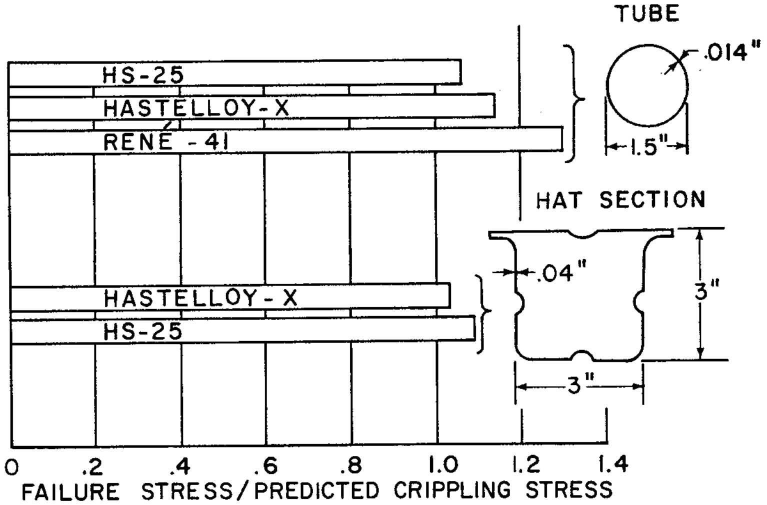

Figure 9

TEST FACILITY FOR COMPRESSION CRIPPLING TESTS OF TRUSS ELEMENTS

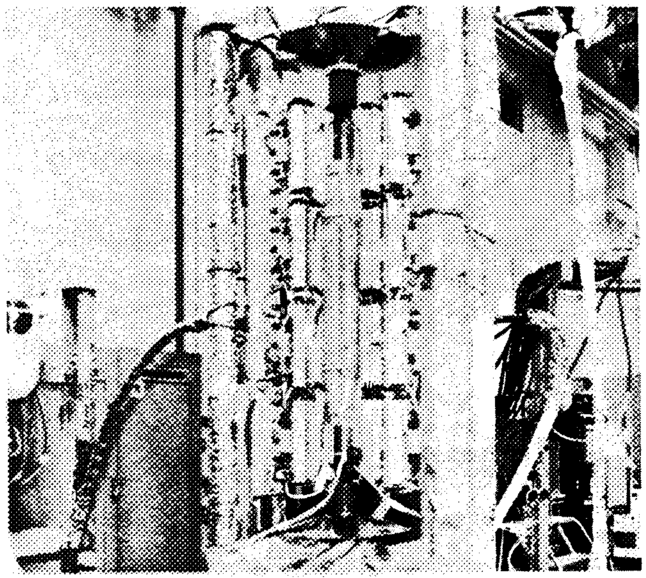

Figure 10

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STRUCTURAL-CONCEPT MODEL

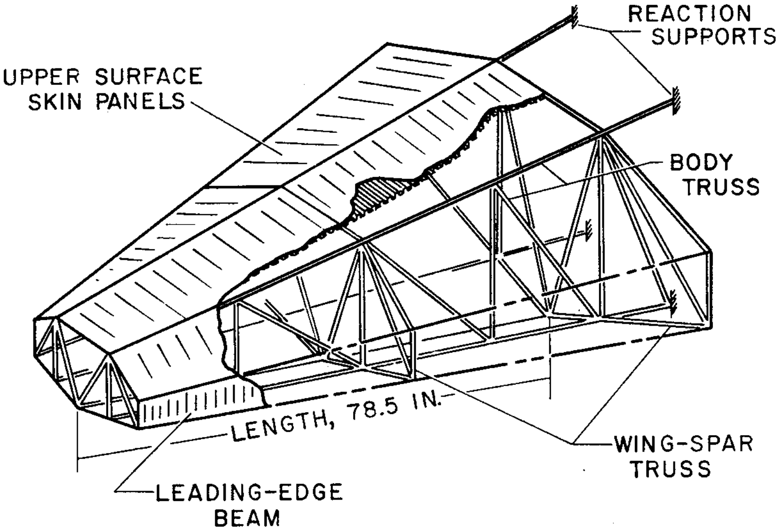

Figure 11

TEST FACILITY FOR STRUCTURAL-CONCEPT MODEL

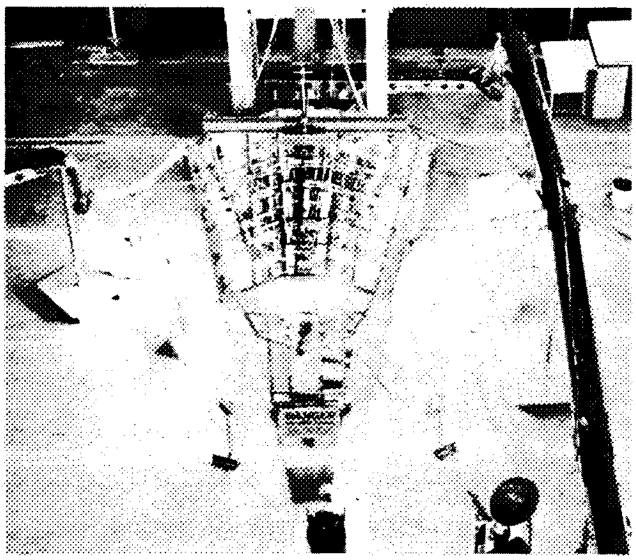

Figure 12

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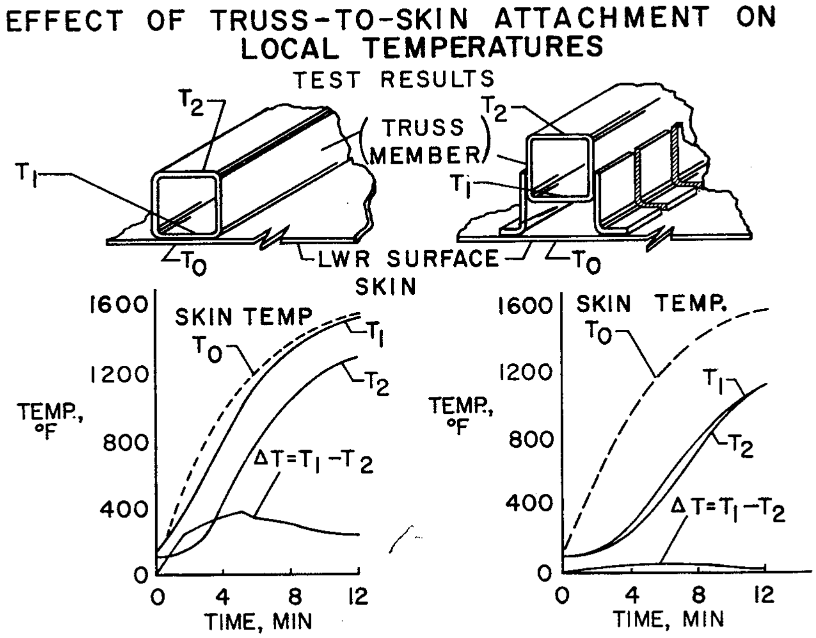

Figure 13

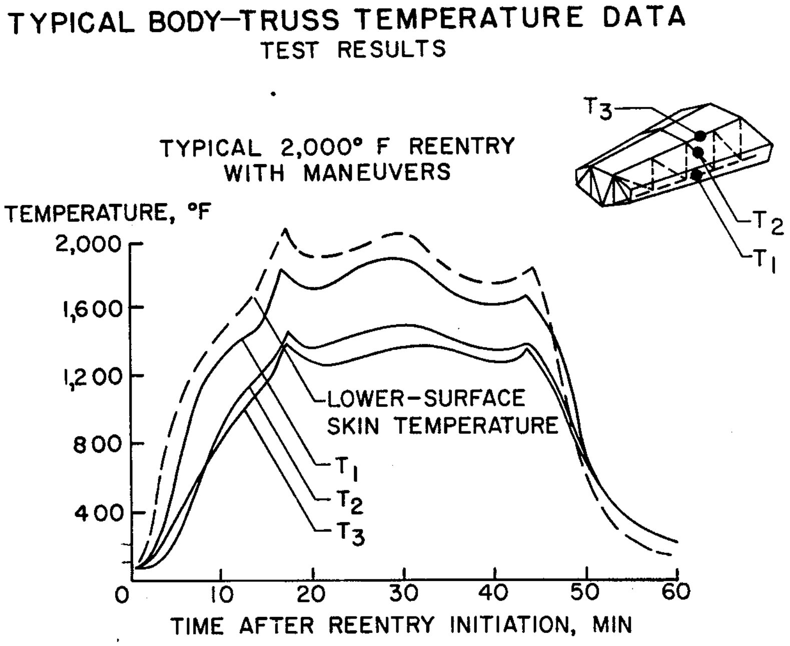

Figure 14

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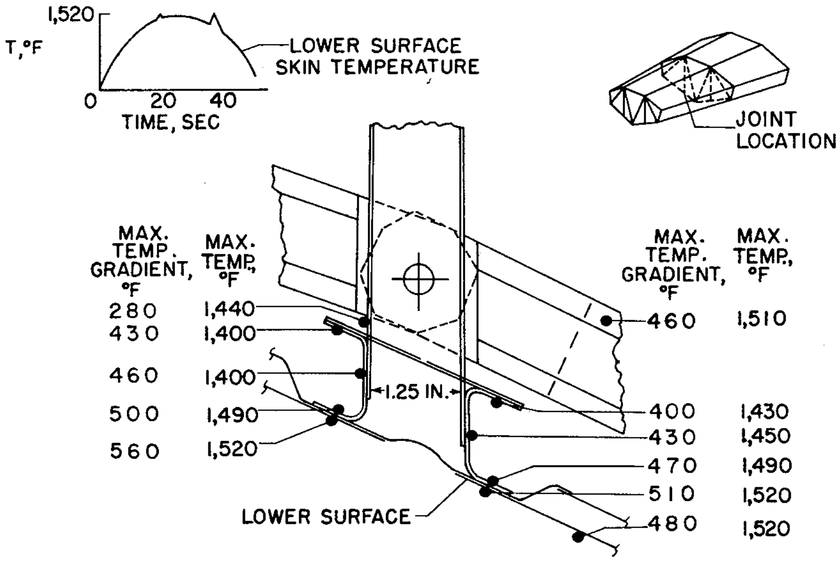

TYPICAL JOINT TEMPERATURES

TEST RESULTS

Figure 15

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