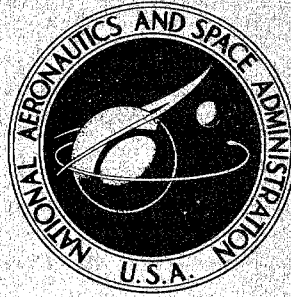


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PANEL FLUTTER STUDIES OF
BOOST-VEHICLE FULL-SCALE
FLIGHT INSULATION PANELS

by Michael L. Nacht and Richard L. Greene

Lewis Research Center

Cleveland, Ohio

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SUMMARY

Two full-scale quarter-segment Centaur flight insulation panels were tested in the Lewis 10- by 10-foot supersonic wind tunnel over a Mach number range of 2.0 to 3.5 at a 0° angle of attack. The test objective was to determine the ability of the panels to resist flutter under conditions simulating the flight environment. Mach number, dynamic pressure, and panel tension were the primary test variables, and liquid nitrogen was employed to produce cryogenic temperatures on the underside of the panels. Analytical comparison of panel characteristics with a conservative flutter criteria which neglected the stiffness of the supporting tank indicated that panel resistance to flutter was questionable. Examination of strain-gage output used to detect panel movement during the tunnel tests revealed that no flutter was experienced by the panels at any of the test conditions.

INTRODUCTION

The cryogenic propellant tanks of launch vehicle upper stages must be protected from aerodynamic heating during the boost phase of flight to prevent excessive boiloff losses. Both internal and external insulation concepts have been utilized successfully. An essential requirement for the external insulation system is that it maintain its structural integrity during the high dynamic pressure and aerodynamic heating phases of the launch trajectory. The basic philosophy regarding external insulation involves a choice between a jettisonable or nonjettisonable system. The feasibility of a lightweight, sealed foam, constrictive wrapped, nonjettisonable system is discussed in reference 1; reference 2 details the results of a wind tunnel investigation of the concept when subjected to an aerodynamic heating environment similar to that which would be encountered during a typical launch trajectory.

A payload penalty results, however, by carrying a nonjettisonable insulation throughout the launch trajectory. The objective of the jettisonable concept is to minimize this

penalty by removing the panels after leaving the sensible atmosphere. This form of insulation may, however, be subject to flutter problems if the insulation panels are not rigidly supported by the tank surface at all flight conditions.

The Centaur stage hydrogen tank utilizes a jettisonable insulation concept wherein four quarter-segment panels are bolted longitudinally to each other in such a manner that tensile forces are created which pull the panels against the tank surface. This tensile force is influenced by the degree of pre-tension created by tightening the bolts and by the internal tank pressure schedule which stretches the tank skin. The aft ends of the panels are fastened to the vehicle on a mounting ring located at the junction of the hydrogen and oxygen tanks. This ring design requires that the panels lift off the tank surface along the aft 16 inches of the panel length, and it is the only point at which the panels are attached to the vehicle. To provide circumferential flexibility and to accommodate electrical wiring, each panel has a longitudinal hollow rib which is also raised above the tank surface.

It is apparent then that two different modes of panel flutter are possible: (1) a gross flutter of an entire panel when static or dynamic load conditions are such that there is inadequate contact between the panel and the fuel tank or (2) a localized flutter of those portions of the panel which are never brought into contact with the tank surface.

Because of the rather complex nature of an analysis of the flutter characteristics of such panels, an experimental investigation was initiated in the Lewis 10- by 10-foot supersonic wind tunnel. Single full-scale quarter-segment panels were tested, thus providing the most accurate simulation of the flight installation consistent with the size limitation of the test facility. Mach number, dynamic pressure, and panel tension were the primary test variables, while the differential pressure across the panel was maintained near zero (the most flutter-prone condition). Strain-gage instrumentation, which was monitored during tunnel testing, was used for panel flutter detection.

SYMBOLS

- D panel bending stiffness, in. -lb
- E panel modulus of elasticity, psi
- I moment of inertia
- l panel length, in.
- M Mach number
- q dynamic pressure, psi
- t panel thickness, in.

w panel width, in.

μ Poisson's ratio, 0.12 for fiberglass skins

Subscripts:

c panel core

i inner skin

o outer skin

s panel skin

∞ free stream

APPARATUS AND PROCEDURE

Figure 1 shows the Centaur insulation panels located on the flight vehicle. Their installation in the 10- by 10-foot supersonic wind tunnel is shown in figure 2. The panel

with the center protuberance, designated as the antenna tunnel panel, was production hardware of the type used on Atlas/Centaur missions. A fairing, mounted upstream of the panel, simulated aerodynamically a portion of the flight vehicle nose fairing. The cylindrically uniform panel was an earlier design of some of the segments of the flight hardware. Both panels were nonhomogeneous in design, being composed of 1.0-inch thick polystyrene-foam filled fiberglass honeycomb sandwiched between 0.015-inch thick fiberglass skins. These skins consisted of several layers of fiberglass cloth coated with an epoxy structural adhesive and sealed with an epoxy-resin surface conditioner. Both panels were 189 inches long by 86.75 inches wide ($l/w = 2.18$).

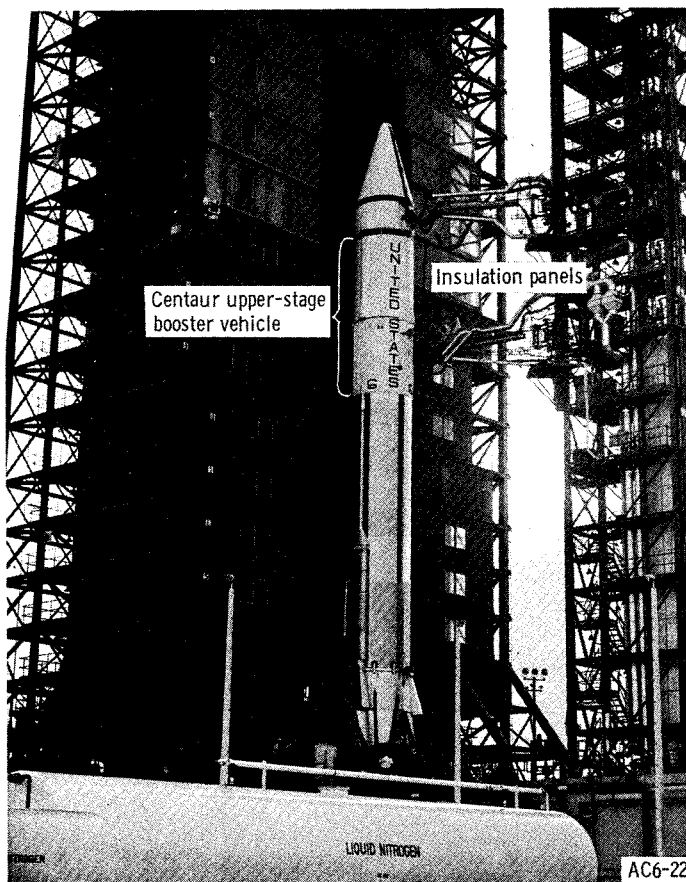
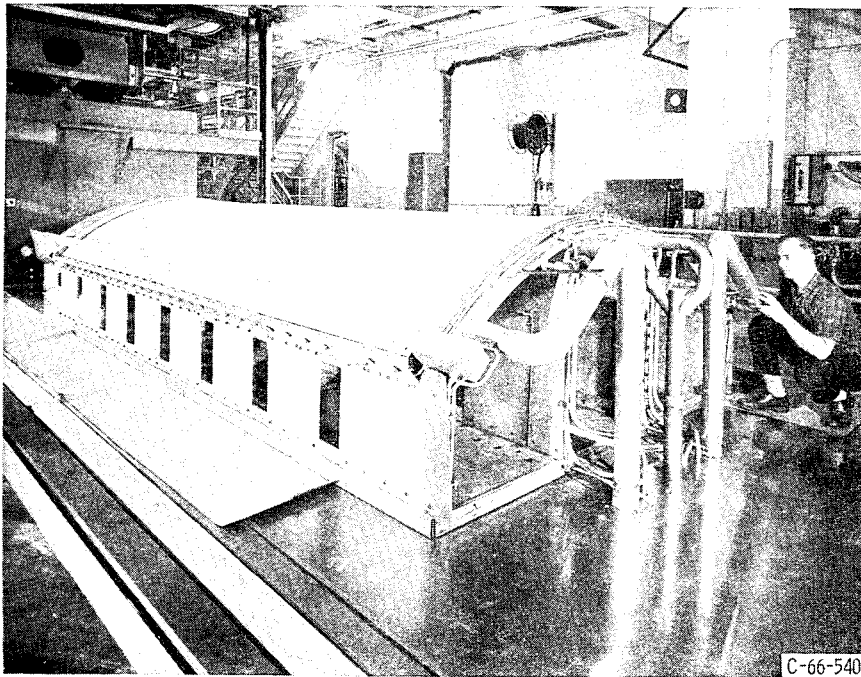


Figure 1. - Insulation panels on Centaur vehicle.



(a) Antenna tunnel panel.



(b) Cylindrically uniform panel.

Figure 2. - Centaur insulation panel installed in 10- by 10-foot supersonic wind tunnel.

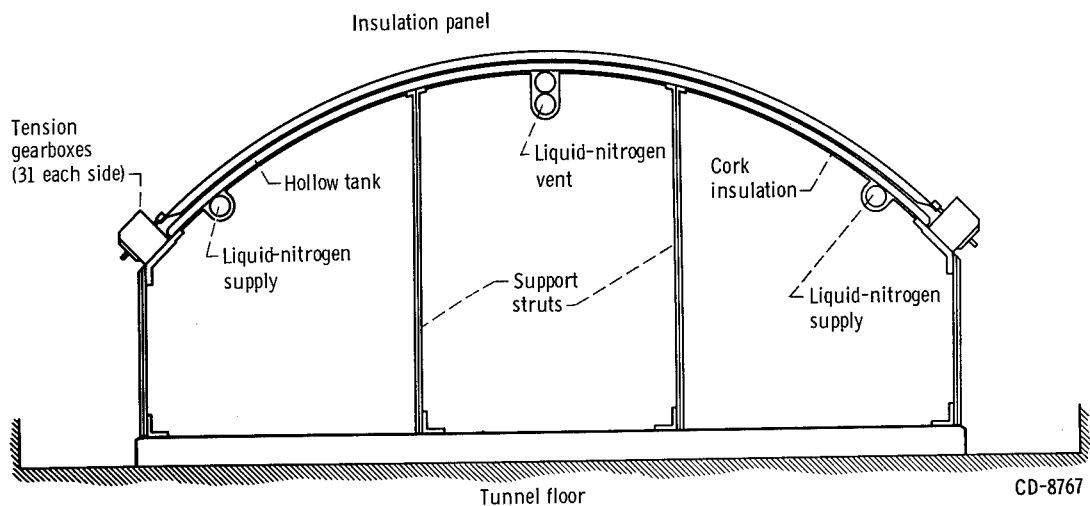


Figure 3. - Cross section of panel-tank fixture mounted on tunnel floor.

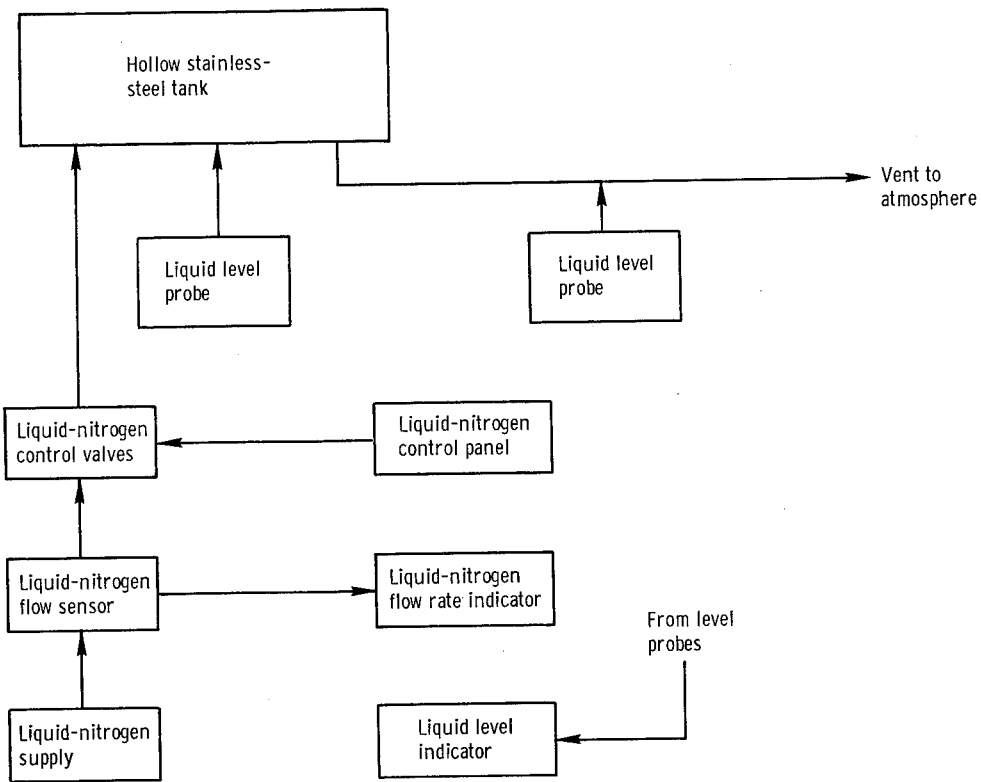
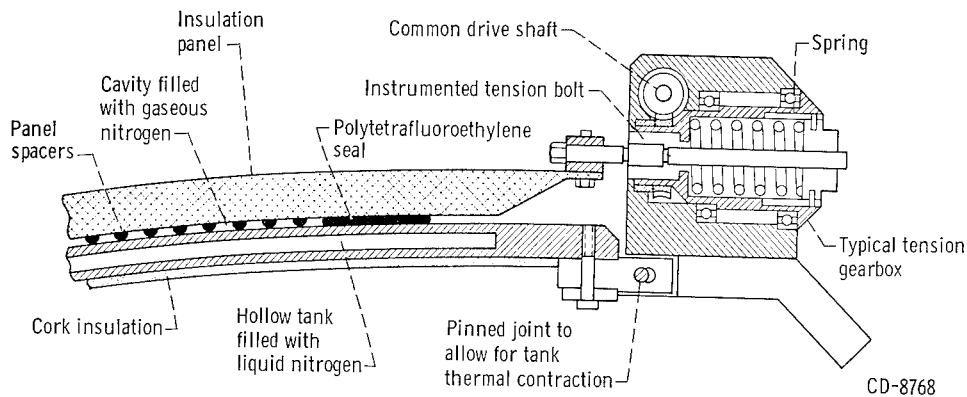
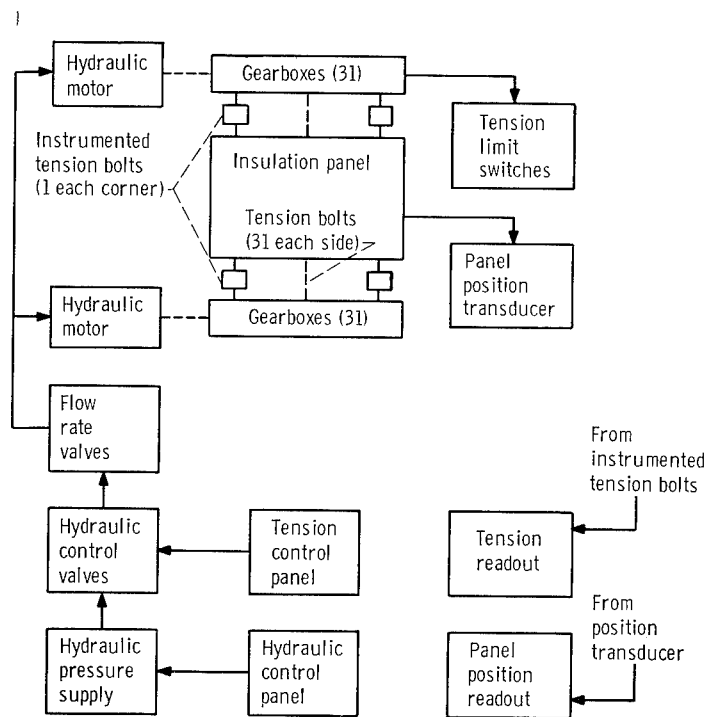


Figure 4. - Diagram of cryogenic supply system.



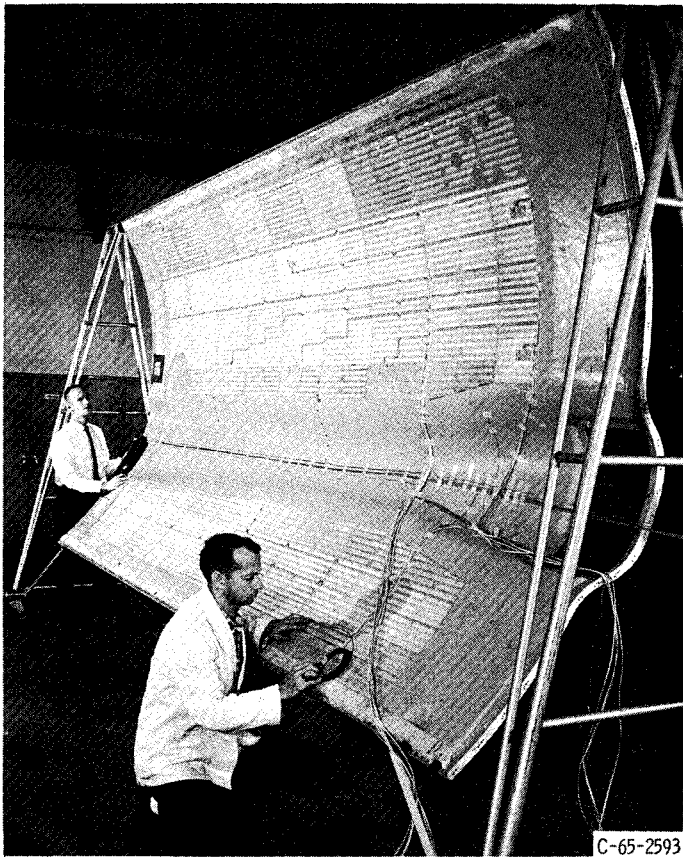
(a) Detail of tension mechanism.



(b) Diagram of tension control and instrumentation.

Figure 5. - Insulation panel tension system.

Each panel was mounted on a hollow tank fixture that was supported above the tunnel floor by a series of struts. The tank, depicted in figure 3, was filled with liquid nitrogen to simulate the flight environment. Although the flight tank skin was thin and flexible, it was pressurized to such high values (in excess of 20 psi) relative to the external air loads that it was effectively a rigid surface. Therefore, to simplify the tunnel fixture design, thick tank walls were utilized to produce the same rigidity. The panel edges were attached to the tank on each side by a series of bolts which engaged individual spring-loaded gearboxes that provided a means of varying the tension in the panel. The spring



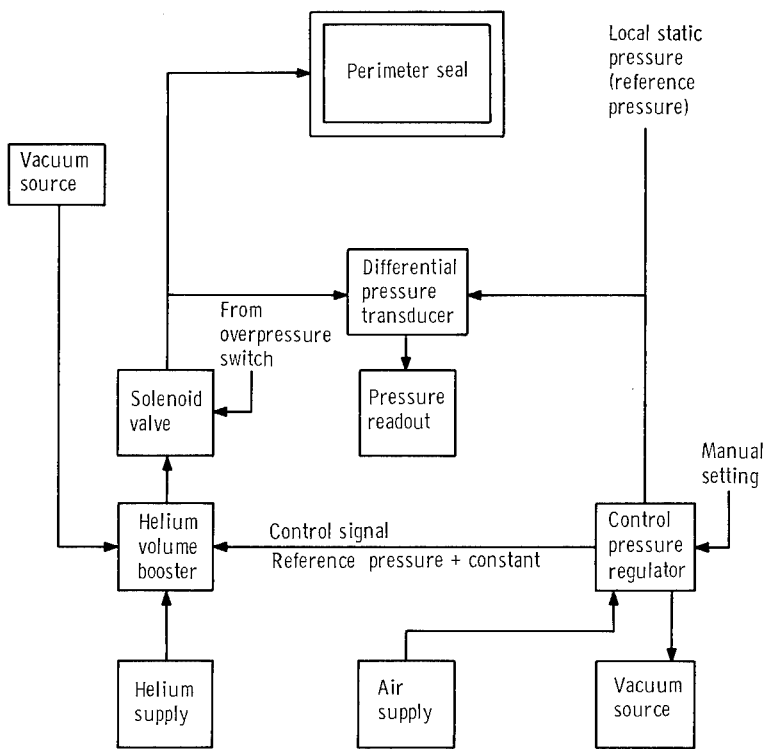
(a) Underside of insulation panel.
Figure 6. - Panel differential pressure system.

characteristics were selected to simulate the constraints exerted on the quarter panel by the other three quarter segments. The aft end of the panel was rigidly attached to the tank while the forward end was unrestrained, thus duplicating the details of panel installation on the flight vehicle. The nose fairing, located upstream of the panel, prevented tunnel flow from impinging on the panel leading edge. To maintain the tank at cryogenic temperatures, a nitrogen control system, illustrated in figure 4, regulated the flow of liquid nitrogen to the tank. Liquid level probes installed in the tank and vent line were monitored to ensure that the tank was filled with liquid nitrogen.

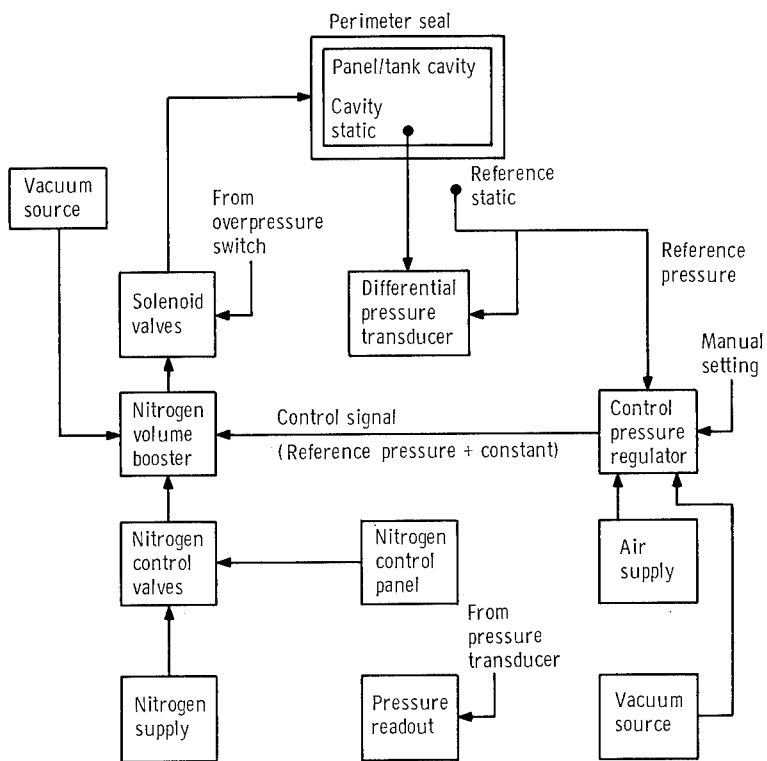
Panel tension, a primary flutter parameter, was provided by a bolt-gearbox arrangement illustrated in figure 5. On each side, the individual

gearboxes were coupled by a common drive shaft to a hydraulic motor. Variation of panel tension was achieved by rotating the drive shafts, which, in turn, increased or decreased the spring load of each bolt attached to the panel. Selection of the desired panel tension required actuation of two bidirectional hydraulic motors. Position transducers attached between the panel and forward gearboxes provided control room indication that the panel remained centered on the tank fixture. Tension-limit switches were used to prevent loading the panel beyond its structural limits. One strain-gage instrumented bolt on each corner of the panel provided a signal for digital readout of panel tension in the control room.

The underside of the insulation panel was fabricated with longitudinal spacers in order to provide a cavity between the panel and tank, as shown in figure 6(a). To prevent the panel from freezing to the cryogenic tank, a dry, gaseous-nitrogen atmosphere was maintained in the cavity. (The spacers were not continuous, thus allowing the gas to flow circumferentially). As cited in reference 3, a zero differential pressure across the panel is the most flutter prone condition. To achieve this condition, the pressure of the



(b) Diagram of helium pressurization apparatus.



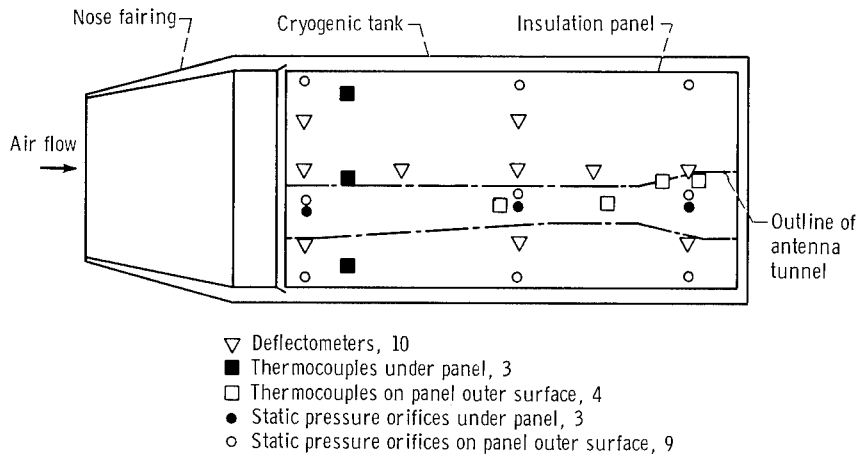
(c) Diagram of gaseous-nitrogen pressurization apparatus.

Figure 6. - Concluded.

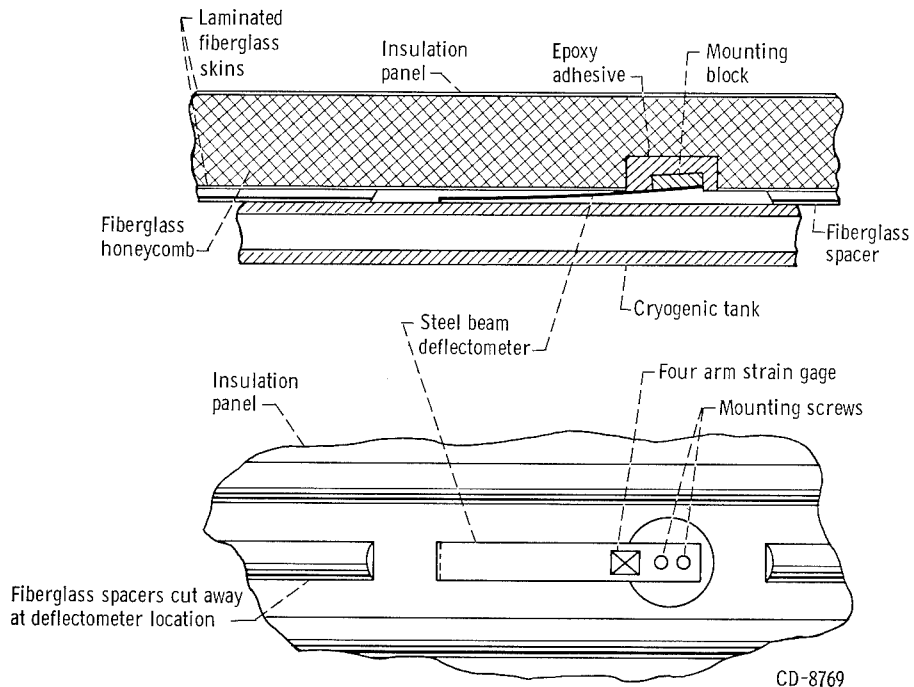
the gaseous nitrogen under the panel was regulated with respect to local static pressure on the panel surface. To pressurize the cavity, an inflatable perimeter seal between the tank and the panel was required. The development of this seal was a formidable task because of the cryogenic temperatures and relative movement between the panel and the tank. The relative movement between the panel and tank was a result of tank thermal contraction and panel elongation during tension. The antenna tunnel panel presented an additional seal problem in that the panel shape was modified as the tension was varied. This resulted in a change in the clearance between the panel and the tank. The seal design that proved most satisfactory was a 6-inch wide, 0.005-inch-thick polytetrafluoroethylene sheet that was folded over, heat sealed, and attached to the panel with retainer strips and screws.

To prevent condensation of the seal pressurizing gas at cryogenic temperature, helium was used to inflate the seal. The helium pressurization system, as shown in figure 6(b), maintained the seal pressure at a constant value above tunnel static pressure. This was accomplished by a pressure referenced air regulator which provided a pneumatic control signal to a helium volume booster. The output of the volume booster, which pressurized the seal, was the sum of the instantaneous tunnel static pressure and a constant provided by a manual setting of the control regulator. A differential pressure transducer provided a signal for digital readout, and safety devices were used to prevent seal overpressurization. Figure 6(c) shows a diagram of the gaseous nitrogen system employed to maintain automatically a differential pressure of near zero across the panel. This pressurization system functioned in the same manner as that used for the seal. Static pressure orifices located above and below the panel were connected to a differential pressure transducer that produced a signal for digital readout. Preset safety switches connected to solenoid valves in the cavity pressurization lines prevented differential pressures from exceeding the structural limits of the insulation panel. Redundancy was employed in the system to avoid panel damage in the event of component failure.

The test apparatus was thoroughly instrumented to provide sufficient system monitoring (fig. 7). Ten strain-gage instrumented beams (deflectometers) were attached to the underside of the panel in those regions supported by the tank surface to record panel movement. In the unsupported regions, photographic observations were used to detect panel motion. Three thermocouples underneath the panel measured the temperature on the tank surface, and the panel outer surface temperature was measured by thermocouples at four locations. To monitor and control differential pressure across the panel, nine static pressure measurements were made on the panel outer surface, and three in the cavity between the panel and the tank. Each deflectometer used for panel flutter movement consisted of a steel beam $3/8$ by 3 inches long, with a four-arm strain gage cemented near one end. The deflectometer was attached to the insulation panel on one end, while the other end rested on the cryogenic tank. Its analog output signal was monitored



(a) Instrumentation location.



(b) Detail of instrumentation for panel flutter measurement.

Figure 7. - Insulation panel instrumentation.

TABLE I. - WIND-TUNNEL TEST CONDITIONS

Average free-stream conditions			Average panel tension, lb/in.	Average panel surface temperature, °F	Tank temperature, °F
Mach number, M_∞	Dynamic pressure, q_∞ , lb/sq ft	Total temperature, °F			
3.5	200	269	95	155	-315
	200	274	70	165	-318
	300	283	100	175	-316
	300	314	70	220	-316
3.0	540	222	100	140	-315
	540	223	70	145	-315
2.5	530	111	115	65	-318
	530	111	70	65	-318
2.0	200	96	135	50	-319
	200	94	100	50	-318
	200	92	70	50	-318
	400	98	135	55	-318
	400	99	100	55	-318
	400	100	70	55	-315
	700	109	135	70	-304
	700	115	100	75	-314
	700	115	70	75	-313

during tunnel testing on an oscillograph recorder and recorded on magnetic tape.

The primary test variables are listed in tabular form in table I. The values shown are for the antenna tunnel panel test, while a similar program was also conducted for the cylindrically uniform panel. Mach number was varied from 2.0 to 3.5 and dynamic pressures from 200 to 700 pounds per square foot. These conditions represented the limitations of the test facility. Average panel tension varied from 70 to 135 pounds per inch, which includes a range extending from the minimum flight pretension to slightly less than the structural limits of the panel. Below the minimum tension value, the panel would have lifted off the tank and loss of seal capability would have resulted. Increase of the tension beyond the upper limit would have violated the structural integrity of the panel. The test procedure was to vary the parameters from the safest condition to the most flutter-prone case. Testing commenced at the highest Mach number, minimum dynamic pressure, and maximum panel tension (representing the safest condition). The differential pressure across the panel was maintained near zero at all test conditions.

RESULTS AND DISCUSSION

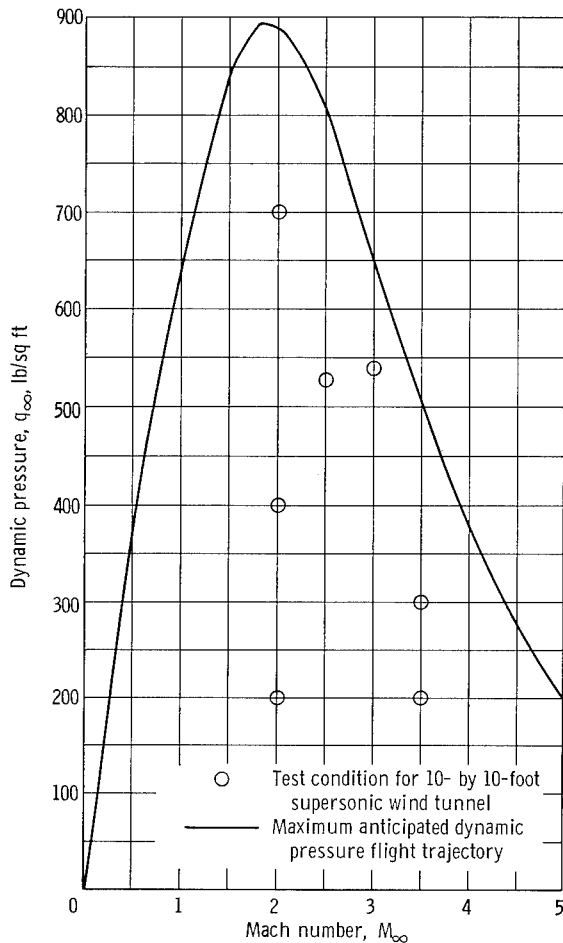


Figure 8. - Dynamic pressure as function of Mach number for maximum anticipated flight trajectory and 10- by 10-foot supersonic wind tunnel test conditions.

Prior to flutter testing the panels, an effort was made to predict the propensity of the panels to flutter with the aid of existing flutter criteria published in the literature. Flight conditions as well as wind-tunnel test conditions were considered in this study. A root sum square upper-limit trajectory curve of dynamic pressure against Mach number reflects the current maximum trajectory presently envisaged for the Atlas/Centaur flight vehicles. Figure 8 presents a comparison of these dynamic pressure values with those experienced by the insulation panels in the wind tunnel. It should be noted that, at $M_\infty = 2.0$ and $q_\infty = 700$ pounds per square foot, the wind-tunnel test condition was 78.5 percent of the flight value, while at $M_\infty = 3.0$ and $q_\infty = 540$ pounds per square foot, it was 83.7 percent.

In the prediction of panel flutter characteristics, considerable experimental effort has revealed that flutter is dependent on several panel physical properties as well as local flow conditions. A frequently referred to non-dimensional flutter parameter for thin metal panels is

$$\left(\sqrt{M^2 - 1} \frac{E}{q} \right)^{1/3} \frac{t}{l} \quad (1)$$

Reference 3 incorporated this parameter in its presentation of a flutter envelope useful in predicting flutter by flat, simply supported metal panels. Extending the use of this parameter to nonhomogeneous sandwich panels, reference 4 concluded that the flutter boundaries of sandwich panels were close in agreement with boundaries for metal panels when compared on the basis of an equivalent panel stiffness. The sandwich panel bending stiffness can be taken into account by replacing thickness t in equation (1) by an effec-

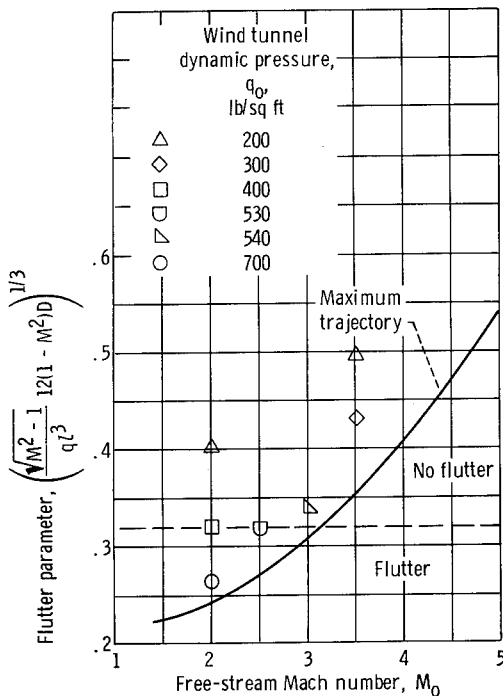


Figure 9. - Predicted flutter characteristics of Centaur insulation panels.

tive thickness t_{eff} , as discussed in reference 3, where

$$t_{\text{eff}} = \left[12(1 - \mu^2) \frac{D}{E} \right]^{1/3} \quad (2)$$

Thus, the panel flutter parameter becomes:

$$\left[\frac{\sqrt{M^2 - 1}}{ql^3} 12(1 - \mu^2)D \right]^{1/3} \quad (3)$$

To include the effect of different panel inner and outer skin temperatures, the panel stiffness for the subject panels can be expressed as

$$D = EI_{\text{equivalent}} = \frac{E_o E_i t_s (t_c + t_s)}{E_o + E_i (1 - \mu^2)} \quad (4)$$

Experimental work done to determine the critical values of the flutter parameter, although fairly comprehensive for flat panels, has been quite limited for curved panels. Reference 5 is one of the few studies which includes an experimental investigation of flutter boundaries for curved panels. The data of reference 5 indicate that panel curvature has a stabilizing effect on flutter. The critical values of the flutter parameter are shown to decrease by 35 percent when curved metal panels are compared with similar flat panels. Although the panels investigated in reference 5 had the same curvature as the Centaur insulation panels, the critical values observed are not applicable to the Centaur case because of significant differences in length-to-width ratios and loading conditions. An additional stiffening effect is produced on the Centaur panels with the longitudinal antenna tunnel protuberance.

Therefore, for a lack of a more applicable panel flutter parameter than that of equation (3), a critical value of 0.32 was assumed. This value is that for a flat panel with the same length to width ratio of 2.18 (from ref. 3) as the curved panels. It is acknowledged that this neglects effects of curvature, and thus is a conservative boundary. In addition, it is only applicable to the gross panel flutter characteristics under static or dynamic loading conditions which permit a panel to lift off the rigid tank surface. Figure 9 shows the flutter parameter plotted as a function of Mach number for all wind-tunnel test conditions and for the maximum anticipated flight trajectory of figure 8. Assumed schedules of core and skin temperature variations were utilized for the trajectory curve, and

measured temperatures were utilized for the wind tunnel test points. The critical value of the flutter parameter, as described above, was used to separate the predicted flutter and no-flutter regions in this figure. The figure indicates that both the test conditions and the anticipated flight conditions fall within the predicted flutter region for the lower Mach numbers.

Examination of the wind-tunnel test data, as obtained from the recorded output of the deflectometers, indicated that neither the cylindrically uniform panel nor the antenna tunnel panel experienced flutter at any of the test conditions. In fact, no significant vibratory motion was recorded during the entire test program.

The localized flutter characteristics of the unsupported portions of the panels which are not in contact with the tank surface (the antenna tunnel and the aft 16-inch section) are even more difficult to analyze because of the irregular shape or edge restraint conditions. However, visual observations and examination of high-speed motion pictures of these portions of the panels did not detect any inclination to be flutter prone.

CONCLUDING REMARKS

The study of panel flutter, although fairly comprehensive for flat panels, has not been thoroughly explored for curved panels. Additionally, investigations with insulation panels introduce unique problems inherent in this testing technique. It was found that dealing with full-scale flight hardware in wind-tunnel testing presented numerous operational problems in terms of installation and instrumentation. Furthermore, duplication of flight environment for the Centaur panels required the incorporation of cryogenic temperatures, a remote-control tensioning system, and a differential pressure control system of substantial complexity. The scarcity of data available to predict adequately the behavior of curved panels under flutter conditions is an additional prencious factor in this subject area. However, information regarding the resistance to flutter of the Centaur panels over the range of flow conditions permitted by the test facility was obtained. It may be concluded that experimentation has verified the lack of a flutter problem for the Centaur insulation panels under the conditions tested.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 28, 1966,
891-05-00-01-22.

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