Erosion of Polyurethane Insulation

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Panels of NOPCO BX 250 A-2 spray-on polyurethane foam insulation, coated with a Chem Seal ultraviolet radiation barrier protected against yellowing by a Dynatherm coating, were flown on X-15 aircraft in 1967 and 1968 to determine erosion rates. This paper presents curves of erosion rate and environment. The spray foam was replaced in the most severe aerodynamic heating and shear environment on the S-II stage sidewall.

Introduction

THE Saturn S-II stage was the liquid-hydrogen-fueled second stage of the Saturn V launch vehicle, used in the Apollo lunar program. Insulation was required to limit the heat leak to the liquid hydrogen fuel to limit boiloff during ground holds and to prevent gaseous hydrogen from entering the fuel pumps at the S-II engines' ignition. External insulation was chosen since the aluminum alloy tank wall (which was also the vehicle external wall) was stronger at cryogenic temperatures. During the early flights of S-II stages, a helium-purged insulation, consisting of a bonded-on honeycomb core, filled with foam, and with a sealed cover sheet, was used. Following these development flights, a coated light weight spray-on foam insulation was developed. This latter insulation did not require the extensive ground support system for helium purge and leak detection used with the earlier insulation system. The overall test program for development of the spray foam insulation has previously been summarized.[1]

This paper describes a portion of the flight test program conducted to demonstrate that sufficient insulation would survive the S-II launch environment to ensure supply of hydrogen in only the liquid state to the S-II engines' feed pumps. Erosion rates for the test environment are presented in this paper. Additional information on—and test data from—the flight test program, and the ground test studies of spray-foam erosion, have previously been presented.[2]

Material Characteristics and Test Requirements

The spray-on foam insulation and coating used on the S-II-8 and subsequent stages was selected as a result of an extensive research and test program.[1] The NOPCO BX-250 A-2 spray-foam polyurethane insulation materials were supplied by the NOPCO division of the Diamond Shamrock Chemical Co. The thermophysical properties of the foam (as used on the S-II stage and the test panels of this report) are heat capacity - 0.3BTU/lb°F; density - 2 lb/ft^3, emissivity - 0.8. The thermal conductivity (BTU/ft sec°R) was 0.361×10^{-5} at 360 and 600°R, 0.590×10^{-5} at 760°R, and 1.98×10^{-5} at 1460°R. The spray foam was protected against ultraviolet radiation by three layers of Chem Seal 3547 (supplied by the Chem Seal Corporation) modified with FR-2 (supplied by the Stauffer Chemical Company). This ultraviolet barrier was covered with one coat of V-455 vinyl (Dynatherm) (supplied by the Dynatherm Corporation) to maintain a white coat (since Chem Seal yellowed with age). The total thickness of the four layers of coating was approximately 0.015 in.

The selected spray foam had been subjected in wind tunnels to aerodynamic shear stress environments (at near-room temperatures) greater than predicted for the S-II launch environment, without apparent erosion.[2] The foam and coatings had also been tested[1] in radiant heat facilities (without aerodynamic shear stress). The Chem Seal coating had melted and ran at 250°F. The foam cell walls had begun to burst at about 250°F.

For the reasons presented in the Introduction it was considered important to learn whether (and how much) foam would be lost during launch, under conditions of combined aerodynamic heating, aerodynamic shear, and reduction in ambient pressure. A literature survey of the capabilities of existing ground-based facilities in 1967 did not reveal any which could simulate these time-varying conditions from the time when the foam surface temperature would reach 250°F to the time of S-II stage ignition. It was noted, however, that a significant portion of this trajectory was within the operating envelope of the X-15 aircraft. A program was therefore established for testing spray foam insulation on the X-15 aircraft, on a noninterference basis with the aircraft's primary test program.

X-15 Flight Test Program

Spray foam insulation test panels were installed on X-15 research aircraft for flights 3-65-96 and 3-65-97 in 1967, and flights 1-75-133 and 1-76-134 in 1968. For various reasons[2] little useful information was obtained from the first three test flights.

Flight 1-76-134: Test Panels

Four test panels were installed on the speed brakes of the X-15-1 aircraft for Flight Test 1-76-134. Two of the test panels are shown on Fig. 1, as installed. The area aft of the lower panels is open, the area aft of the upper panels contains another experiment. Details of the upper right test panel and its instrumentation are shown on Fig. 2. (Details of the other test panels have been previously presented.[2]) The foam was sprayed on the aluminum panel using techniques similar to those used for spraying the S-II stage. The spray foam "skin" was cut away, and the contour established using similar tools to those for the S-II stage insulation, and the coatings were applied in a similar manner to those on S-II stage insulation coatings. Nevertheless, there probably was some variation in foam cell size and foam density from panel to panel, as well as from panel to stage.

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Index categories: Material Ablation; Thermal Modeling and Experimental Thermal Simulation.

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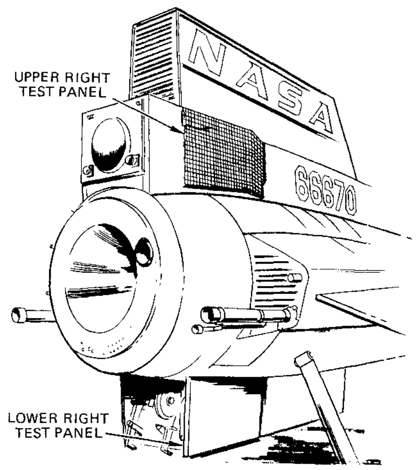

Fig. 1 Test panel installation for Flight 1-76-134 (right quarter view).

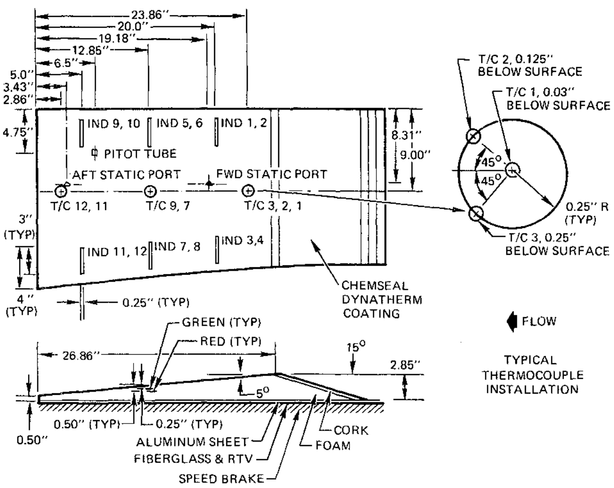

Fig. 2 Upper right test panel.

The upper test panels were contoured so that the aft surface was parallel to the vertical plane of symmetry when the speed brake was opened to 13 degrees during the powered portion of the X-15 flight. Since the cork of 8 lb/ft^3 density used on the compression surfaces of the upper test panel on flight 1-75-133 had been lost, with resulting heavy loss of foam on the test panel, the compression surfaces of the upper test panels on flight 1-76-134 were protected by cork of 30 lb/ft^3 density. The lower speed brake test panels had 0.6 in. thick spray foam. Stability considerations prevented use of thicker panels on the lower speed brakes.

Colored plastic indicators were inserted into the spray foam (see Fig. 2). They were to be used, in conjunction with wing tip pod mounted motion picture cameras and an optical system, to reveal when foam erosion had reached the insertion depths.

As a secondary system to reveal foam erosion, thermocouple beads were buried in the foam at various depths, as shown in Fig. 2. The thermocouples were made from 24 gage (0.02 in. diameter) Chromel and Alumel wires, with a bead diameter of approximately 0.058 in. The nominal locations of the thermocouple beads are shown in Fig. 2. The thermocouple beads were connected through lead wires, signal conditioning equipment, and a commutator to one channel of a recording oscillograph in the X-15 aircraft.

The upper right test panel was also instrumented, with static orifices, and with a pitot rake with top tube instrumented. The active pitot port was 4.5 in. above the backplate. Other tube depths were 2.5 and 3.5 in. above the plate.

Flight 1-76-134: Test Data

Motion picture coverage of the upper and lower test panels was obtained during the portion of flight beginning with the drop of the X-15 aircraft from the B-52 aircraft. The salient events seen on the film have previously been discussed.[2] Unexpectedly, there was no indication of the plastic indicator color on the film. It is possible that the sealant holding the indicators in place melted, and the indicators were sucked out of the panel by the lower pressure at the side of the panel, out of sight of the cameras, where early erosion occurred.

Examination of the test panels after the flight showed that heavy erosion occurred after the completion of the inflight motion picture coverage (approximately 83 sec after X-15 launch for the lower test panels, 229 sec after launch for the upper test panel). The cork of 30 lb/ft^3 density survived the boost and entry environment. The thermocouple wire insulation became porous and expanded, probably due to heat. Some of the coating and foam from the upper test panel was deposited on the fuselage and on the experiment housing behind the speed brake, as well as in the hollow between the speed brakes. The difference in the environment on the upper and lower speed brake test panels was very evident; on the lower panels practically no foam remained.

Two examples of thermocouple bead temperature histories are presented in Fig. 3. Eighteen more have previously been presented.[2] For the upper test panels,[2] the temperatures of thermocouple beads located just below the surface of the spray foam rise to the 235-265°F level at 80 sec after launch. This is the maximum value prior to the opening of the speed brakes to 36°, when very much higher temperatures occur. Thermocouples further below the surface indicate lower temperature levels, as expected, during the boost phase of X-15 flight. The lower test panel thermocouple beads just below the surface of the foam and nominally 0.125 in. below the foam surface indicate peak temperatures of the order of 1000°F by 80 sec after launch. This is taken as indication that the thermocouple beads have become exposed to the hot boundary-layer gases, due to foam erosion.

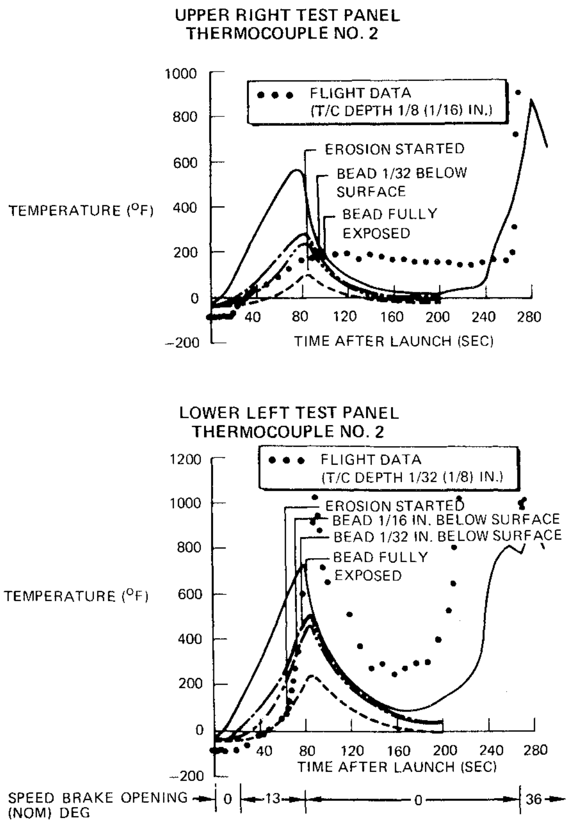

Fig. 3 Temperature history.

Pitot tube pressures and static port pressures were also obtained during the X-15 flight ascent phase. In addition to these measurements made with test panel instrumentation, the angle of attack in pitch and sideslip was obtained from the recording of the servoposition of the movable ball nose (Q-ball) of the X-15 aircraft. The ball is positioned to null pressure differences due to angles of attack and sideslip.

The velocity and altitude-time histories for the flight were determined from radar data obtained from several sites. The variation of atmospheric temperature and pressure, up to 110,000 ft, was obtained from a balloon launch prior to flight. Above 110,000 ft, the U.S. Standard 1962 atmosphere[5] was used for the analysis. Winds at altitude were neglected as components of velocity.

Flight 1-76-134: Analysis

The determination of erosion is made by comparing predictions of foam surface temperature and of thermocouple bead temperature for various bead depths, with measured thermocouple bead temperatures. The predictions utilize an aerodynamic and structural heat transfer program.[3] Required inputs to the program include atmospheric data, trajectory parameters, local flow parameters, thermophysical properties, and structural thermal models. The sources of these inputs will be discussed. The atmospheric data and trajectory data used were obtained as described in the previous portion of this paper and have been presented.[2]

The local flow properties, local pressure, and local Mach number were determined using methodology[4] developed by the (then) Los Angeles Division of North American Aviation, Inc. The predicted local pressures at the static ports, and the predicted local Mach number at the ports, were compared with the measured static pressures and with the Mach number obtained using measured static and measured pitot tube pressures. The agreement was reasonable.[2]

Using the experimental and predicted values of local flow parameters, together with a thermo-structural model of the foam, predicted variations of aerodynamic shear on the foam surface, and foam surface temperature were obtained using the computer program.[3] The agreement between the curves obtained from predicted and experimental values of local pressure and local Mach number is considered satisfactory (Fig. 4).

The thermophysical properties of the spray foam used were presented in a previous section. Appropriate values are used for the Chromel-Alumel bead, individual thermocouple wires, and wire insulation. The foam coating was neglected in this analysis.

Complex structural thermal networks were developed, including the thermocouple bead,thermocouple wire, wire insulation, and the spray foam insulation. The physical model and thermal network for a surface thermocouple bead and for a bead 0.25 in. below the surface, were presented previously.[2] Individual models were used for each bead depth below the foam surface. The thermocouple beads are of the same order of magnitude as the foam cell. Thus, the bead will have contact with the cell wall over only a portion of the bead surface. The foam will be in poor contact with the small diameter thermocouple wire below the bead, since the bead was pushed through a hole pierced in the foam by a wire or thin rod. These poor contacts are represented in the model by thermal gaps. The expansion of the wire insulation at elevated temperature, and the contact gaps between the foam and thermocouple wire insulation are also accounted for in the thermal model. The models were adjusted to assure balanced thermal flow and used the best material property values available. The values of the parameters, such as areas of contact, were adjusted to provide the best agreement between predicted values of thermocouple bead temperatures (prior to start of erosion) and measured values, using a consistent set of parameters, for all the thermocouple locations.

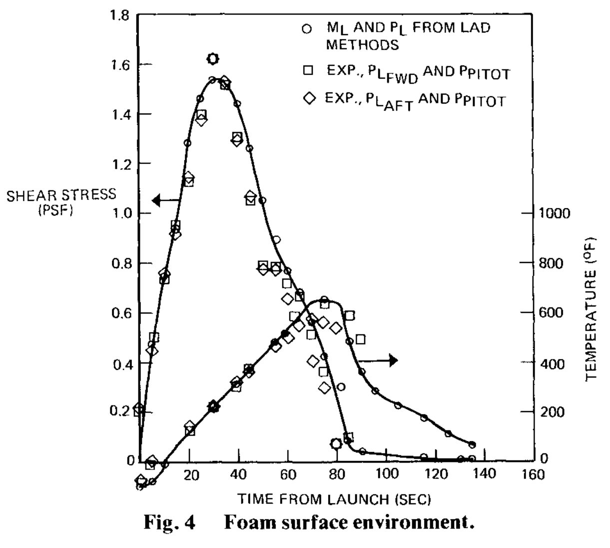

Fig. 4 Foam surface environment.

In Fig. 3, in addition to the flight data of thermocouple bead temperatures as a function of time, the predicted foam surface temperatures and thermocouple bead temperatures for beads at the nominal and lesser depths, are shown as a function of time from launch. The solid line in Fig. 3 presents the prediction for the foam surface temperature. The dashed-double-dotted, dashed-single-dotted, and dashed lines present predictions of temperatures of thermocouple beads at 1/32, 1/16, and 1/8-in. below the foam surface. The predictions were made using the non-receding structural model, input properties, and computer program just described. The predicted initial temperature values at launch (time zero) were obtained for equilibrium conditions for the structural-thermal models, using the environment at launch, and assuming the aluminum plate under the foam was at the ambient temperature for the launch altitude. As can be seen from Fig. 3, there is a difference between absolute level of thermocouple bead temperature and prediction at launch.

The temperature history of Fig. 3 (and those previously presented)[2] are interpreted in the following manner to obtain values for erosion. The start of erosion is taken as the time when the shape of the curve for the flight test values of bead temperature diverges from the shape of the predicted temperature value for the same bead depth. The bead is assumed to be exposed to the boundary layer no later than the time when the flight data for temperature becomes greater than the predicted foam surface temperature for that time from launch. The time when flight data temperature value becomes greater than the predicted value at some intermediate depth is taken as the latest time at which erosion had progressed so that the bead was now at that intermediate depth. These events are also indicated on Fig. 3. The erosion depths and times, obtained in this fashion from Fig. 3 and the previously reported data,[2] are plotted on Fig. 5 for the upper speed brakes and Fig. 6 for the lower speed brakes.

The solid curve in Fig. 5 represents the earliest-time-limit boundary for erosion of given depth of foam from the upper test panels on Flight 1-76-134. The numbers in squares identify data from thermocouples of that designation on the upper right panel. Numbers in circles are for upper left panel thermocouple data.[2] The temperature history[2] for thermocouple 2 on the upper right test panel indicated that initially it was probably at or near 0.067 in. below the foam surface, rather than at a depth of 0.125 in. (Subsequent X-rays of foam test panels instrumented in a similar manner revealed differences between actual and nominal thermocouple depths for several thermocouples.) If the nominal value of 0.125 in. were used, the earliest-time-limit boundary would be represented by the broken line curve of Fig. 5. Based on these curves (Fig. 5) erosion on the upper test panels begins at 83 sec after launch. The initial erosion rate is 0.007 in./sec based on the solid line

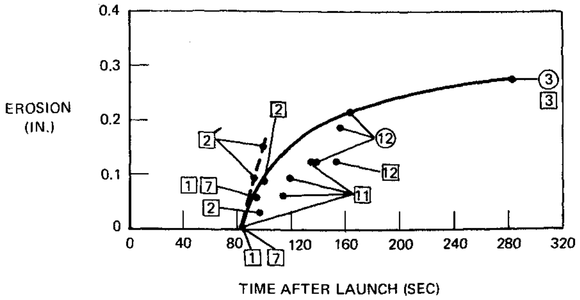

Fig. 5 Upper test panel erosion history.

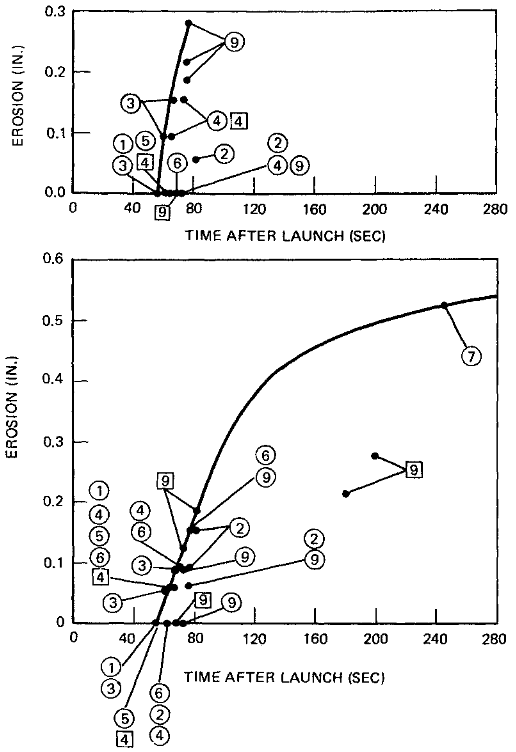

Fig. 6 Lower test panel erosion history.

for consistent trends. The broken-line curve shows a rate of 0.009 in./sec for nominal initial depth data.

Since a large number of thermocouples on the lower test panels produced temperature variations which did not agree with predicted trends, two sets of curves are presented in Fig. 6. For the lower curve where the initial depths were chosen to be consistent with predicted temperature curves, erosion would begin at 56 sec after launch,and progress at a rate of 0.009 in./sec (earliest-time curve), although data from thermocouple 3 could be interpreted as yielding an erosion rate of 0.015 in./sec. The curve beyond 80 sec utilized trends from the upper speed brake erosion rate. Data after 160 sec should be given less credence than data before 160 sec flight time.[2] If the nominal depths were used, the initial erosion rate would be 0.023 in./sec, as shown on the upper curve of Fig. 6. Numbers in squares present data from thermocouples on the lower right test panel; in circles from thermocouples on the lower left panel.

Results

The significance of the results to the S-II program is as follows. The shear stress-foam surface temperature time history curves[2] for the upper test panel and for a single protuberance influenced region of S-II stage spray foam were roughly comparable. Using even the 0.009 in./sec erosion rate, from 110 to 160 sec after liftoff only 0.45 in. of foam would be lost by S-II engine start at 160 sec. after liftoff. This was considered acceptable. The surface environment (shear stress-temperature time history) for the lower speed brake panel was less severe than for the maximum multiple protuberance influenced region of the S-II stage.

If the erosion rate for nominal depth were used, the insulation on the tank in these regions would be lost before S-II stage engine ignition. This was not acceptable, so in these regions, the spray-on foam was replaced with foam-filled honeycomb core protected with bonded-on cork of 30 lb/ft^3 density.

Conclusions

Care must be used in using even a series of ground facility tests at specific points along the trajectory to determine erosion rates, since there is some evidence that prior history of the foam may affect erosion rates. Erosion continued after the surface temperature and aerodynamic shear were lower than the conditions at which erosion began.

A combined heating and aerodynamic shear environment must be used in testing spray-on foam insulation, and similar materials, to determine erosion when the proposed usage would expose the foam to such an environment. Even extreme environments, imposed singly, may not represent the true environment.

The use of thermocouples in an insulation requires great care to determine the actual position of the junction, to understand the rapid drop from surface temperature expected where the junction is "just below the surface," and for analysis to model properly the thermocouple in the insulation. The conductance through thermocouple and lead wire insulation, the conduction through the wires, and the "contact resistance" must be determined for the specific installation. In addition, a receding surface aerodynamic and structural heating digital computation program would be very useful, even though the erosion rates were not known in advance.

References

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