Foam Formation in Low Gravity

Francis C. Wessling,* Samuel P. McManus,† John Matthews,‡ and Darayas Patel§
The University of Alabama in Huntsville, Huntsville, Alabama 35899

An apparatus that produced the first polyurethane foam in low gravity has been described. The chemicals were mixed together in an apparatus designed for operation in low gravity. Mixing was by means of stirring the chemicals with an electric motor and propellor in a mixing chamber. The apparatus was flown on consort 1, the first low-gravity materials payload launched by a commercial rocket launch team. The sounding rocket flight produced over 7 min of low gravity during which a polyurethane spheroidal foam of approximately 2300 cm^3 was formed. Photographs of the formation of the foam during the flight show the development of the spheroidal form. This begins as a small sphere and grows to approximately a 17-cm-diam spheroid. The apparatus will be flown again on subsequent low-gravity flights.

Introduction

On March 29, 1989, the first commercial rocket large enough to require a Department of Transportation launch license lifted off from its launch rail in the New Mexico desert at White Sands Missile Range. The payload, called consort 1, contained six experimental apparati, which housed a total of 149 experiments. The payload compartment was approximately 3.5-m long, 0.44 m in diam and 290 Kg in mass. Based on accelerometer data, approximately 7 min of low gravity was obtained on the sounding rocket.[1]

One of the experimental devices was designed to mix chemicals and to form a polyurethane foam, the first polymeric foam to be made in low gravity. Foams have a variety of uses[2,3] including thermal insulation, structural and decorative uses in vehicles (e.g., the bumper and dashboard of automobiles), packing material, sound proofing and many other applications. Annual usage of polyurethane foams is over 600 million lb worldwide.[4] In addition to potential uses as an insulating material, space applications proposed include uses for micrometeroid barriers[5] and structural material for lightweight structures in space. Also, understanding the mechanisms of foam formation may have large economic impacts in Earth applications if it leads to improved strength or better thermal insulation values. Being able to create foams in the space environment may lead to building structures in space, such as habitats on the moon, re-entry vehicles, or large structures. Consequently, a program to make foams in space was begun at the Consortium for Materials Development in Space, a NASA center for the commercial development of space located at the University of Alabama in Huntsville.

Metal foams of aluminum metal using argon gas as the blowing agent were made on Spar I[6] and Spar II[7] rocket flights, and a copper foam using carbon monoxide as the blowing agent was made on Spar X.[8] Other experiments have been done on metal forms[9] in low gravity. However, the authors have been unable to find any literature on the effects of processing polymeric foams in low gravity. The only literature on organic bubbles seems to be related to the formation of films and bubbles from soap solutions on Skylab.[10]

The preceding cited experiments gave no indications about whether a polyurethane foam could be made in low gravity. Consequently, an apparatus was built, and an experiment was performed in order to study how the lack of gravity affected polyurethane foam production. The experiment was to study the efficacy of the mixing process and whether the chemicals would demix or react properly to form a hard urethane foam. Fluid mixing and ejection mechanisms that allowed the mixture to exit a mixing chamber and not to impinge onto other surfaces were to be tested. The foam setting time, the final shape of the foamed material, and the ability of the foam to withstand re-entry and landing loads were to be determined.

Experimental Apparatus

The polyurethane foam formulated for consort 1 was a standard, two-part mixture including a solution of sucrose-based polyol, catalyst, surfactant, and fluorocarbon blowing agent in one chamber and an oligomeric diisocyanate in another chamber. The diisocyanate was incompatible with the polyol and the catalyst; hence, the components had to be stored apart until reaction was desired. The following proportions were used: 1) polyol: Voranol 360© (Dow©), 100 g, 2) catalyst: DABCO 33LV© (Air Products©) 2.0 g, 3) surfactant: DC 193© (Dow Corning©) 1.5 g, 4) blowing agent: Genetron 11© (Allied©) 3.4–3.6 g, and 5) diisocyanate: PAPI-94© (Dow©) 92.5 grams.

The materials from the two chambers would be mixed shortly before the beginning of the low-gravity period. The resultant mixture would then be driven through an exit funnel. Chlorofluorocarbon would begin to come out of the solution at the cream time, which would occur 28–37 s after mixing. Within 10 s of the cream time, the material would begin to expand. A 10-to-20-fold volume increase would be achieved 180–200 s after the initial mixing. The foam would reach its final state after 120–180 s of additional cure. A successful experiment would depend on each stage of the process (total of 300–360 s) occurring under a low-gravity environment. The re-

---

Received May 22, 1989; revision received Nov. 13, 1989. Copyright © 1990 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

*Professor, Department of Mechanical Engineering. Associate Director, Consortium for Materials Development in Space. Member AIAA.

†Professor, Department of Chemistry.

‡Postdoctoral Fellow.

§Graduate Student.

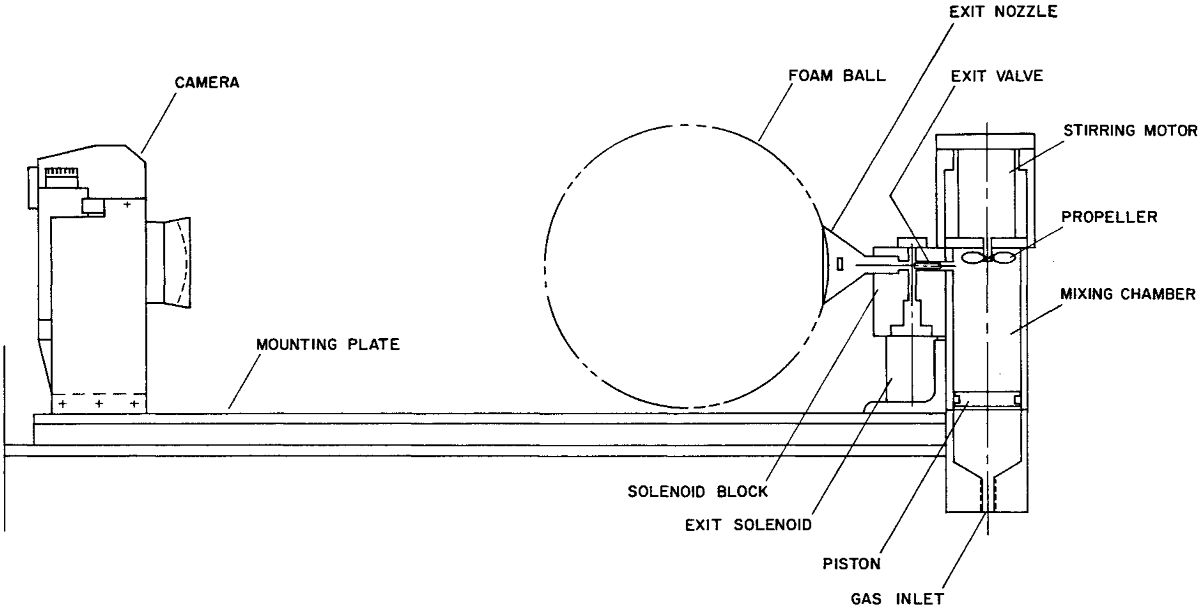

Fig. 1 Mixing apparatus layout.

sultant foam would then be rigid enough to withstand re-entry loads and to impact decelerations of over 245 m/s^2.

The polyol mixture is hydrophillic, and the diisocyanate is hydrophobic. In order to get through dispersal of the diisocyanate into the polyol solution, rapid mixing procedures are necessary. For example, in the laboratory a uniform foam with small cells requires stirring at rates in excess of 2500 rpm for 15 s with a motor-driven, propeller-type stirrer.

Pouring two liquids together into an open laboratory beaker is a simple process. Air in the beaker is displaced by the liquids. Entrapping of air into the resultant mixture usually is of no consequence and often is desired with high-speed stirring. Any excess bubbles are dispelled from the mixture by gravity-created hydrostatic forces when stirring ceases. Gravity helps by keeping the liquid in the lower part of the beaker and near the stirrer. However, in the presence of gaseous components, stirring in low gravity is not as straightforward if one wishes to mix two or more liquids. For example, let us consider injecting the two liquids into an air-filled mixing chamber that contains a propeller. Unlike stirring on Earth, in microgravity, the liquid would be thrown away from the propeller with no force to cause it to return. Eventually, the propeller would spin in the air with no liquid being stirred. Alternatively, an air evacuated mixing chamber of the same volume as the liquid to be stirred would be required. We decided to approach the alternative configuration by storing the propeller in the polyol solution in a chamber that expanded by moving a piston to accommodate the entire mixture (see Fig. 1). To prevent premixing, the isocyanate cylinder (not shown) was covered with an aluminum foil cap that served as a burst valve at operating pressure. Upon activation, the isocyanate was injected into the polyol solution by gas pressure moving a piston, and stirring commenced. The resultant mixture of polyol solution and isocyanate was stirred for 20 s and then ejected from the mixing chamber by a gas-driven, movable piston in the mixing chamber. A small, inconsequential amount of liquid remained in the mixing chamber because of the propeller. The piston moved away from the propeller to alleviate any pressure buildup due to expansion of the foam remaining inside.

A stirring motor had to be selected that would be small enough to fit into the allotted space on the rocket, rugged enough to withstand the rigors of launch and re-entry on a sounding rocket, and powerful enough to stir the viscous liquids adequately. We planned to power the motor with the power source on the rocket, a 28-V battery. Approximately half a dozen different types and brands of 28-V motors were tried. Several of them were adequate for making only one or two batches of foam, although the manufacturer's specifications indicated they would deliver a high rate of spinning and the necessary torque. Typically, the armature windings either melted or shorted out to the armature. The motors would sometimes leak and become contaminated with foam solution, which would generally dissolve the armature insulation. Finally, a motor was found which stirred the mixture adequately. This required adding an additional battery to the rocket because the motor required 16 amps at 8.4 V to stir the two liquids. The other batteries in the rocket were not available to supply this power. The final experimental apparatus showing the stirring motor, an exit funnel, and mirrors appeared as in Fig. 2. Operation of the experiment was controlled by an onboard computer that properly sequenced the events of injection of the isocyanate into the polyol solution, stirring of the polyol solution and the isocyanate, ejection of the mixture, and photographing of the mixture as it exited the funnel on the outlet of the mixing chamber. Mirrors allowed the sides and back of the funnel and foam to be photographed. Figure 3 showed the flight apparatus. A thermistor in front of the funnel can be seen. This allowed measurement of the reaction temperature close to the funnel exit.

An exit funnel was designed with two factors in mind. First, it was needed in order to dissipate the momentum and kinetic energy of the stream. The ideal flow out of the funnel would

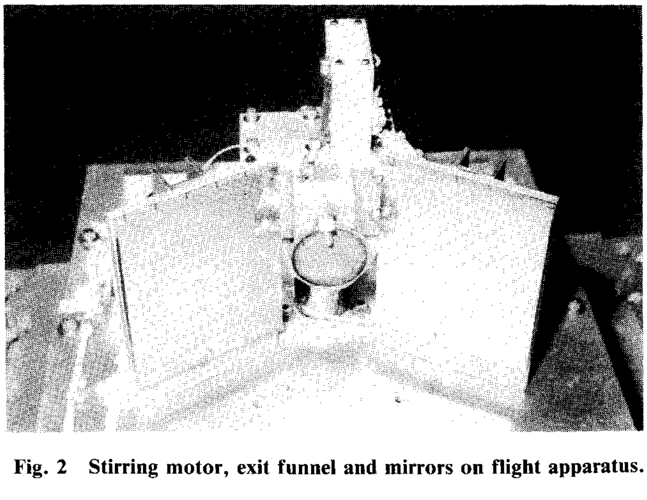

Fig. 2 Stirring motor, exit funnel and mirrors on flight apparatus.

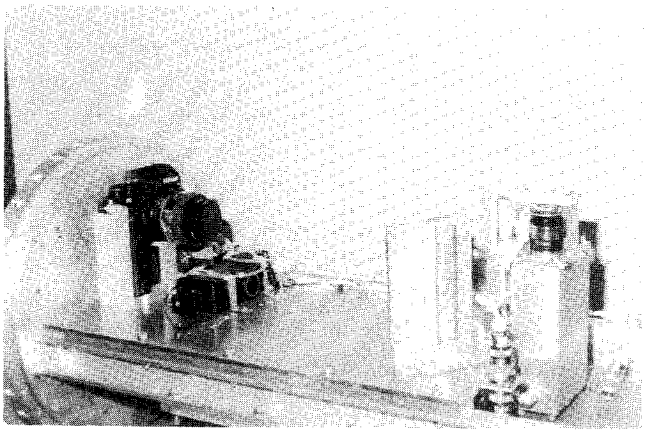

Fig. 3 Active mixing apparatus used for flight.

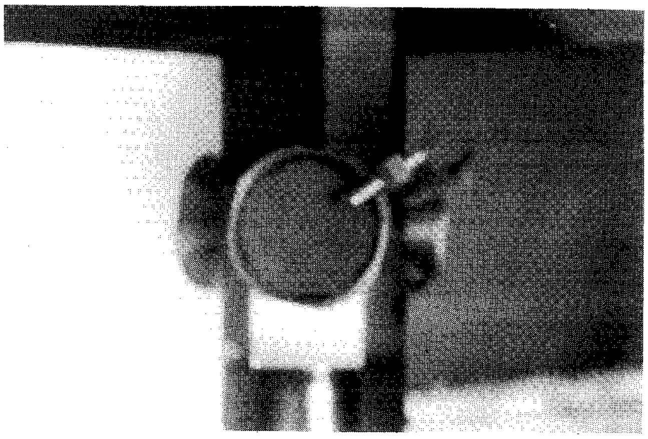

Fig. 5 Empty foam exit funnel seen during flight.

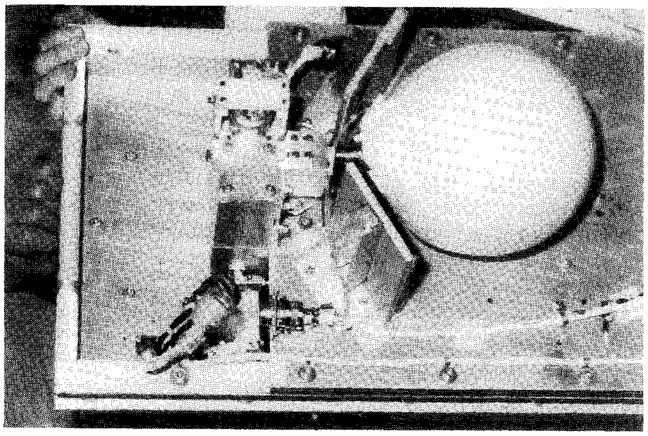

Fig. 4 Polyurethane foam immediately after rocket flight.

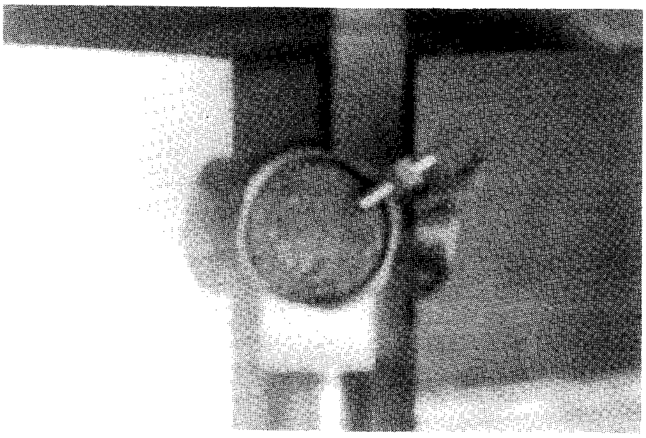

Fig. 6 Foam solution oozing through the screen on the face of funnel.

have a small velocity component normal to the face of the funnel. Thus, when operated on Earth, the foam mixture would flow slowly through a fine mesh screen on the funnel face and then follow the attraction of gravity. Second, the funnel was designed to provide a surface for foam formation in low gravity. A screen on the end of the funnel would provide the surface. The funnel design worked properly in lab tests when low gas pressures were used in the gas tank. Unfortunately, the isocyanate piston would often stick at the lower gas pressures. Tests showed that the isocyanate provided too little lubrication between the o-ring and the wall of the cylinder, thus, causing a large friction force. Lubricating the cylinder wall with silicon grease allowed the piston to move with approximately two atmospheres of gas pressure in the tank. More than 11 atmospheres were required to move the isocyanate piston without lubricant. Unfortunately, silicon grease could not be used for fear of contaminating the chemical reaction with subsequent formation of poor-quality foams. A single gas source supplied the gas to mix the components and to expel the foam mixture from its mixing chamber. A flight rated pressure regulator was not available in time to modify the pressure supplied to the mixing chamber piston before flight. A pressure of approximately 10 atm in the GN_2 tank was necessary to cause complete ejection of the isocyanate into the polyol chamber. The foam mixture was found to exit the mixing chamber at high speed with sufficient momentum to cause the mixture to spray the camera lens placed directly opposite the orifice. This would have resulted in a ruined camera lens and no pictures of the foam processing in low gravity. Additionally, the foam likely would have sprayed all over the rocket interior and ruined any chance of getting a single sample. Thus, an additional orifice was added to create a large flow restriction between the exit from the foam mixing chamber and the funnel.

Results

The apparatus operated as designed during the rocket flight and primary objectives were met as evidenced by the formation of a spherical ball of foam which remained attached to the screen of the funnel (see Fig. 4). This photograph was taken immediately after recovery of the rocket, and the foam that was made appeared well mixed and hard. This demonstrated that the mixing and reaction would occur in low gravity. According to the experiment time line, the isocyanate as injected into the polyol solution and was stirred 19 s before the expected beginning of low gravity. Stirring continued for 11 additional s during which time the foam mixture was ejected through the exit funnel and into a cavity on the rocket. The enclosed sequence of photographs gives a time lapsed record of events at 5-second intervals. The camera viewed the funnel straight on. A mirror on each side of the funnel allowed the back and sides of the funnel to be seen as well as the front; this was evident in the photographs. Some of the pictures are out of focus because of the limited depth of field of the camera. The first low-gravity photograph (see Fig. 5) shows the funnel before the foam mixture begins to exit. The next photograph (see Fig. 6) shows the foam mixture just beginning to exit through the screen on the face of the funnel. Five s later (see Fig. 7), a spherically shaped mass of foam mixture has covered the screen of the funnel obstructing the screen from view. Presumably, surface tension effects predominate to yield an expected spheroidal shape. Photographs at subsequent 5-s intervals (see Figs. 8–12) show the foam mixture going through its cream stage and expansion until the foam ball fills almost the entire field of view. Figure 4 displays the resultant polyurethane foam ball after its return to Earth; the ball is still attached to its funnel on the flight apparatus. Its diameter was approximately 17 cm.

A change in color of the foam mixture occurred between 35 and 40 s after mixing was begun and was indicative that the mixture has completed creaming. This was apparent on the color photographs but was not distinguishable on the black and white prints of this paper. This occurred within the expected range of time for this mixture. Also, the photographs show that the material begins to expand within 10 s of the cream time, just like samples processed on Earth. Thus, as expected, the cream time and the expansion time do not appear to be significantly affected by low gravity.

The fluid ejection mechanism worked well. The mixture exited the funnel nicely and attached itself to the screen as planned. The momentum and kinetic energy dissipating techniques allowed the mixture to ooze out without spattering. No evidence of spattering was found when the apparatus was inspected after flight. A nicely shaped spherical form resulted as can be seen on the photographs. This spheroidal form hardened during low gravity with enough structural integrity to appear undeformed by re-entry stresses. The sounding rocket flight provided sufficient time for hardening to occur.

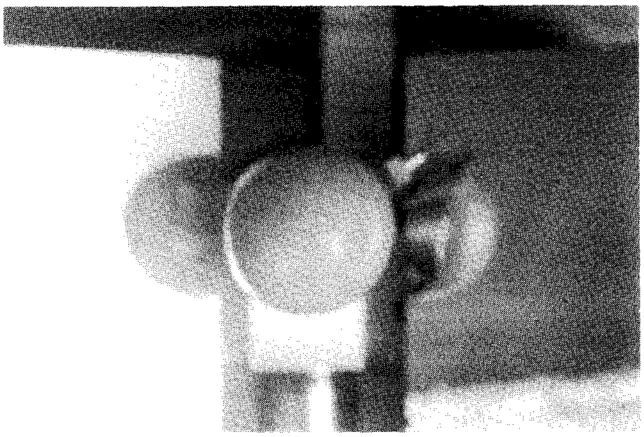

Fig. 7 Small spheroidal solution before cream time.

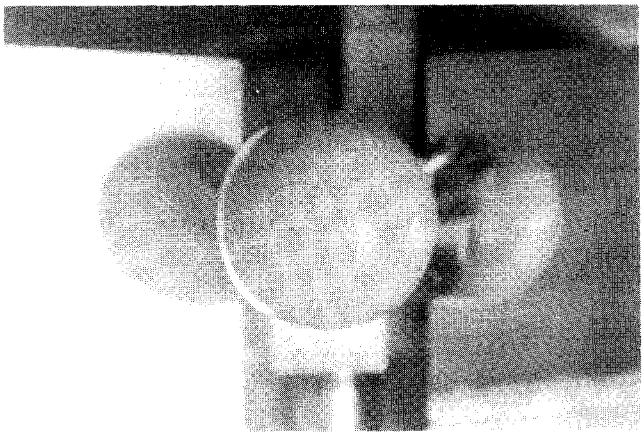

Fig. 8 Mixture begins to cream and expand.

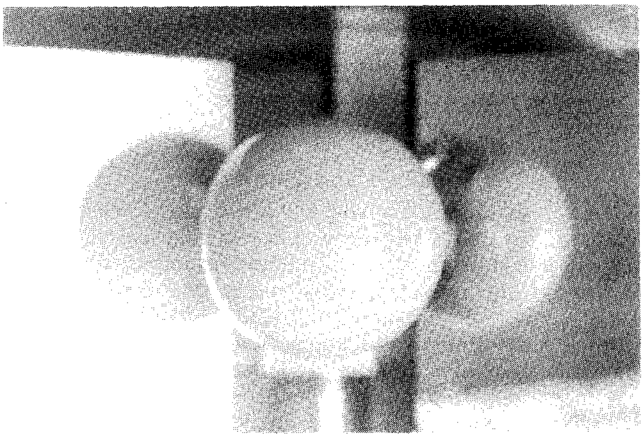

Fig. 9 Polyurethane foam continues expanding in a spherical shape in low gravity.

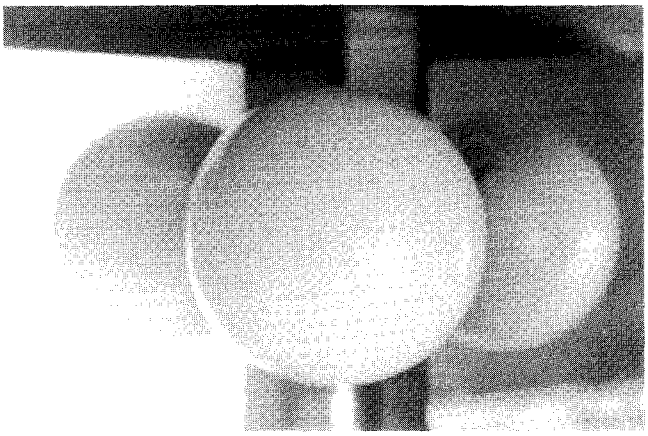

Fig. 10 Expansion continues in low gravity.

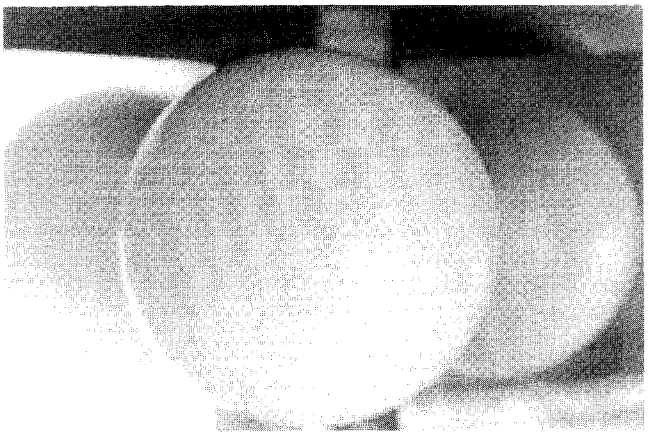

Fig. 11 Bubbles are visible on foam ball surface.

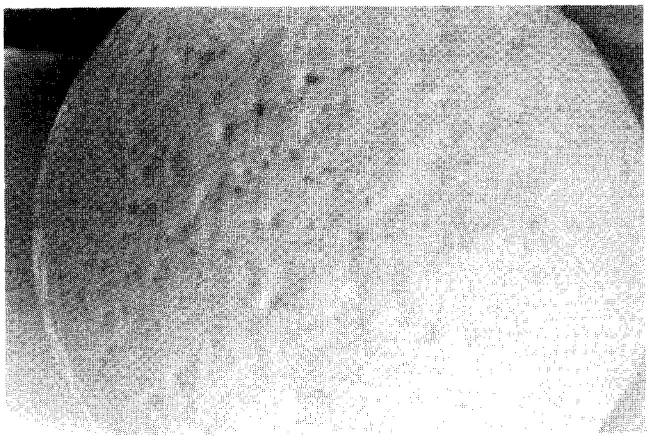

Fig. 12 Bubbles enlarge and break through the surface.

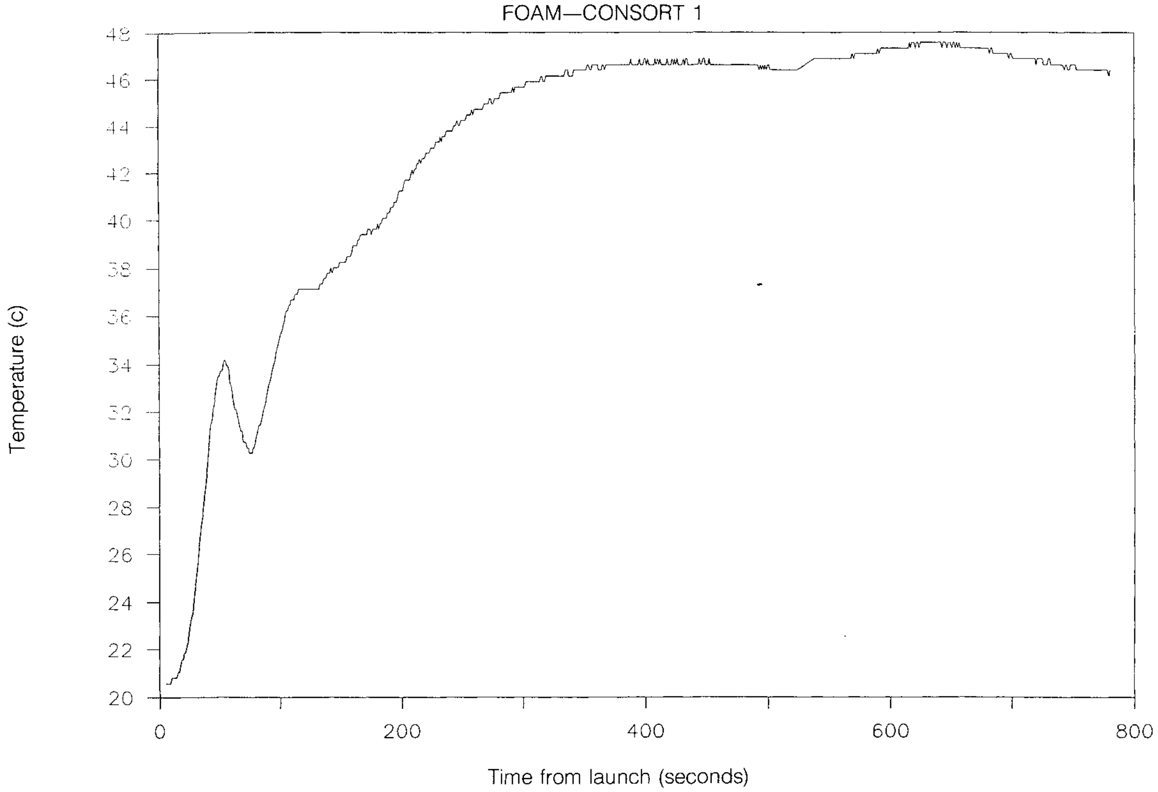

Fig. 13 Temperature of foam thermistor.

Figure 13 displays the temperature recorded by the thermistor placed in front of the funnel. This thermistor recorded the temperature effects of the air in the rocket as well as radiant temperature of its surroundings. The indicated temperature varied from approximately 20° C to 48° C during the course of the flight. There was an initial heatup to 34° C during the ascent stage, reaching a local maximum at 54 s, the time of nose-tip ejection. This temperature then dropped to 30.2° C immediately after entering the low gravity period at 72 s. A local minimum occurred at 76 s, just 2 s before the foam made its appearance on the funnel screen. Then the indicated temperature sharply rose as the exiting foam enveloped the thermistor. This indicated that the mixture temperature was warmer than the surroundings, which is expected when one considers the work of stirring that was done on the mixture. (Temperatures recorded inside other experiments did not display this behavior. One of them, a demixing of immiscible polymers experiment, changed only 1 deg throughout the launch remaining close[8] to 20° C the entire flight.) The rise in temperature of the mixture was expected because the heat of reaction of the reactants normally causes a temperature rise.

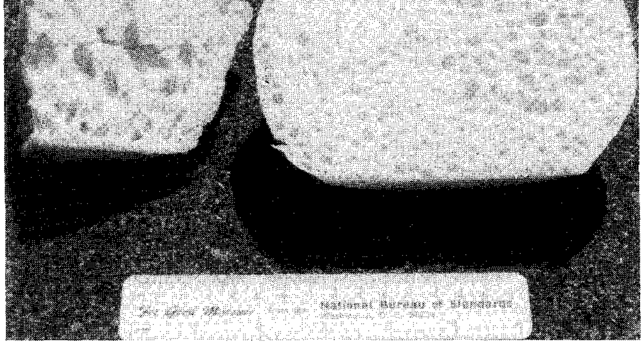

Fig. 14 Foam made in space is on the right; that made on Earth is on the left.

The temperature of the thermistor indicated that the blowing agent of the foam was above its saturation temperature when the foam mixture exited the funnel. The experiment section of the rocket was pressurized to 1 atm of air in the interior. Consequently, the blowing agent had approximately 6° C of superheat when it exited the funnel.

A cross section of the foam formed in space is shown on the right side of Fig. 14, and a cross section of a foam formed on Earth in the same apparatus can be seen on the left side of the figure. The foam samples are both well mixed. The number of pores is not as significant as their shape. The number and size vary throughout the samples. The reason for the large bubbles is a current topic of investigation in our laboratories. The variable sizes of the pores have not allowed obtaining samples of uniform consistency that are necessary for testing of mechanical and thermal properties. Of particular interest here is that the cells of the foam made in space tended to be spherical in shape. Those formed on Earth tended to be elongated. The entire foam mass was spherical when formed in space and shaped like a large pancake when formed on Earth without a container and in the shape of its container otherwise.

Summary and Conclusions

An apparatus for the mixing and formation of polyurethane foam has been built and flown on a sounding rocket. The apparatus has successfully produced the first polyurethane foam in low gravity, producing a volume of approximately 2300 cm^3. A series of photographs showed the development of a polyurethane spheroidal foam as it progressed through its mixing, cream, expansion, and hardening steps. The photographs showed the dominance of surface tension in determining shape. The foam appears generally well mixed and of uniform chemical consistency, but the cells are variable in size. The quality of the foam does not appear to be the same as industrial quality foam. However, this is not inherently due to processing in low gravity but due to possible shortcomings in the processing equipment.

The foam processing performed during the consort 1 flight demonstrated the ability to make polyurethane foam in low gravity. The stirring motor appeared adequate for proper mixing of the ingredients. A gas-driven piston injected the isocyanate into the polyol at the onset of stirring as designed. A second piston served to allow the mixing chamber to expand, and the same piston also expelled the mixture from the mixing chamber when it was moved by the gas pressure. The diffusing funnel properly dissipated the kinetic energy and momentum of the ejecting foam. Thus, the foam spread out onto the screen covering the funnel and formed a spherical-shaped attachment on the screen. Creaming of the mixture seemed to be unaffected by low gravity and occurred within the same time frame as Earth-based samples. The expansion of the foam seemed similar to that which occurs on Earth except that Earth's gravity causes the mixture to spread out like a pancake instead of allowing it to assume a spherical shape. The spherical shape hardened and survived the loads on re-entry.

The exact cause for the various size pores seen on the foam samples made with the apparatus has not yet been determined but may be due to the blowing agent being superheated when stirred. Studies of the foaming process using the apparatus in the laboratory are continuing with the intent of obtaining foams with small bubbles dispersed throughout. The apparatus used on consort 1 worked as designed, and an improved apparatus will be used on future rocket flights.

Acknowledgments

The authors recognize the contribution of Deborah J. Weiker of the Chemical Sciences Division of Hercules, Inc., in Wilmington, Delaware who suggested the chemical formulation for the experiment. The work was sponsored in part by funds from the NASA Office of Commercial Programs under Grant NAGW-812, which established the Consortium for Materials Development in Space at the University of Alabama in Huntsville.

References

[1] Wessling, F. C., and Maybee, G. W., "Consort 1 Sounding Rocket Flight," *Journal of Spacecraft and Rockets,* Vol. 26, No. 5, 1989, pp. 343–351.

[2] Saunders, J. H., and Frisch, K. C., "Polyurethanes: Chemistry and Technology, Part 1, Chemistry, Wiley-Interscience, New York, 1962, pp. 261–343.

[3] Bruins, P. F., ed., *Polyurethane Technology,* Wiley-Interscience, New York, 1969, pp. 67–77.

[4] Crosby, K. A., *Predicasts Base Book,* Predicasts, Cleveland, OH, 1988, pg. 446.

[5] Reynolds, B. W., "Effects of Hypervelocity Particle Impacts on Composite Materials for Expandable Structures Applications," Goodyear Aircraft Corp., Dayton, OH, Rept. No. GER-10663, 1962.

Paul F. Mizera
Associate Editor