Low-Cost Conformable Storage to Maximize Vehicle Range

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Introduction

Liquefied petroleum gas (LPG) and compressed natural gas (CNG) are currently the leading fuel contenders for converting vehicles from gasoline and diesel to alternative fuels. Two factors that inhibit conversion are additional vehicle costs and reduced range compared to gasoline. In overcoming these barriers, a key element of the alternative fuel system becomes the storage tank for these pressurized fuels. Using cylindrical pressure vessels is the conventional approach, but they do not package well in the available vehicle volume. Thiokol Corporation has developed and is now producing a conformable (non-cylindrical) aluminum storage system for LPG vans. This system increases fuel storage in a given rectangular envelope. The goal of this project was to develop the technology for a lower cost conformable tank made of injection-molded plastic.

Much of the cost of the aluminum conformable tank is in the fabrication because several weld seams are required. The injection-molding process has the potential to greatly reduce the fabrication costs. The whole tank could be molded to the final form in one piece, or a few molded parts could be assembled with a rapid thermoplastic welding process.

In designing an injection-molded tank, material selection becomes a major issue—a wide variety of materials is available. The requirements of a pressurized fuel tank on a vehicle necessitate the proper combination of material properties. Material selection and tank design must be optimized for maximum internal volume and minimum material use to be competitive with other technologies. The material and the design must also facilitate the injection-molding process.

Prototype tanks must be fabricated to reveal molding problems, prove solutions, and measure results. In production, efficient fabrication will be key to making these tanks cost competitive.

The work accomplished during this project has demonstrated that conformable LPG tanks can be molded with thermoplastics. However, to achieve a competitive tank, improvements are needed in the effective material strength. If these improvements can be made, molded plastics should produce a lower cost tank that can store more LPG on a vehicle than conventional cylinders.

Project Information

The U.S. Department of Energy, through the National Renewable Energy Laboratory (NREL), funded Thiokol Corporation to develop technology for using injection molding to produce low-cost conformable pressure tanks for vehicle fuel storage. The period of performance for this project was from March 1995 through December 1997, and this document is the project's final report.

Conformable Storage Concept

Pressurized tanks are typically cylindrical or spherical. These shapes produce membrane loading of the tank wall, which minimizes bending stresses and results in a strong, lightweight tank. When a pressurized tank must fit into a non-cylindrical space, as is usually the case in vehicles, cylindrical tanks waste much of the available space. As shown in Figure 1, a multi-cell tank concept provides more effective use of the available fuel storage volume. The cell geometry is carefully tailored to ensure efficient membrane loading of the cell walls under pressure loads, and

the number of cells is optimized to provide maximum internal volume. Depending on the aspect ratio of the storage envelope, conformable tanks can provide as much as 40% more fuel volume than simple cylinders.

Material Selection and Development

Material Properties

Selection of an injection-molded thermoplastic for a pressurized fuel storage tank is complicated by the large number of available materials, and by how properties can vary depending on processing conditions. Published properties data are available for comparison, but the data may be inconsistent and incomplete. Because some of the key properties needed for pressurized tank design are not usually published, material selections must be made with incomplete data. Our laboratory tests at Thiokol have generated some of the missing data for the more promising materials.

For this application, tensile strength is the most important property. To achieve a competitive tank design, the effective tensile strength should exceed 18,000 pounds per square inch (psi). This strength requirement eliminates many materials, and narrows down the selection to "engineering" thermoplastics, which are typically reinforced with short glass fibers. Because the fibers tend to orient in the direction of molding flow, the strength of these plastics varies according to the direction of that flow—the highest strength is in the direction of flow, and lower strength is transverse to flow. In a pressure tank, where the entire tank is under tensile stress, the strength in the weakest direction will generally control the failure. Unfortunately, the transverse strength is not normally published. In the absence of data, the neat resin strength can be used as an estimate of the transverse strength of a reinforced plastic.

Another important property for automotive tanks is the fracture toughness, typically measured with the notched Izod test (ASTM D256). Tanks must be able to withstand mistreatment, such as pebble impacts and drops. The required toughness will depend on the tank wall thickness; a thicker wall will absorb more impact energy.

Because automotive service can cover a wide temperature range, temperature resistance is also important. The operating temperature may range from a low of -40°F in extreme winter conditions to a high of 180°F in proximity to hot exhaust pipes during summer weather. The best published data related to temperature resistance are the deflection temperatures (ASTM D648), which must be substantially higher than 180°F for our application.

Long-term strength, as measured by the creep rupture test, is key, because LPG tanks must withstand sustained, continuous pressure for long periods of time. The creep rupture test measures the ability of a plastic to carry a sustained load for a long period of time. Thiokol performed high temperature (180°F) creep rupture tests on two materials (AMODEL® A-1115 HS and AMODEL A-1133 HS) to determine the combined effects of sustained loading at high temperature.

Finally, resistance to attack by water, propane, and other chemicals is vital in the automotive environment.

Molded Bar Tests

Most of the available material properties are from injection-molded tensile bars. Tensile properties were measured in the molding direction, providing only the upper limits for material strength. Table 1 is a compilation of data for several candidate materials. The first several lines are from published data sheets, and the Thiokol test results appear at the bottom of the table.

Our tensile test results at 75°F agree well with the manufacturer's data. We also measured strength at 180°F. For most materials, this produced a moderate reduction in strength. One material, which in the initial screening appeared to have adequate strength, was severely weakened at 180°F. The RTP® 2399 X 68911A polyurethane (PU) has a strength of 22,000 psi at 75°F, but only 4400 psi at 180°F. This was one of the higher toughness materials, but the low strength at high temperatures makes it unsuitable for use in a fuel tank.

For a few materials, Forward Technologies measured weld strength for Thiokol using a hot-plate welding process, which is a candidate for tank assembly. Injection-molded tensile bars were cut in half, then welded back together. Weldability is good for the AMODEL® polyphthalamide (PPA) materials. For the 33% glass-reinforced grade, which has a nominal tensile strength of 31.6 ksi, a weld strength of 14.7 ksi was obtained (47% of the original strength). With proper joint design, this would be adequate for tank welding. On the other hand, the Ryton® polyphenylene sulfide (PPS) achieved only 23% of its original strength when welded.

We measured the effects of exposure to LPG and CNG fuels by storing unstrained specimens in fuel for 40 days or longer and then measuring their tensile strength at 180°F. The AMODEL PPA materials showed negligible changes in strength. The Ryton PPS showed about a 9% strength reduction after exposure to LPG, and 15% after CNG exposure. Other samples of these materials were exposed to fuel while under 0.5% strain; none of these showed any visible degradation.

We measured long-term strength by creep rupture tests at 180°F for two materials, and the results are plotted in Figure 2. At a creep time of 10,000 seconds, the AMODEL A-1133 material decreased to 74% of its short-term strength, and AMODEL A-1115 decreased to 80% of its short-term strength.

Tube Burst Tests

Using short tubes under internal pressure, we measured strength transverse to flow direction for several materials—three grades of Vectra® liquid crystal polymer (LCP), three grades of AMODEL PPA, two grades of RTP PPA, and one grade of Ryton PPS. Four samples were tested at 70°F for each material. For the Vectra materials, we also tested samples at 180°F. The tubes were cut from injection-molded cylinders that have constant outer diameter, tapered wall thickness, and a hemispherical dome on one end. Plastic was injected at the center of the dome, resulting in axial flow in the cylinder. We used two variations of molded cylinders. Most of the samples were molded as 2.5 in. diameter by 4 in. long cylinders (see Figure 3). For one material (Vectra A130), the samples were made in a different mold, which was 2.12 in.diameter by 9 in. long. We molded these longer cylinders first, and discovered that they showed significant eccentricity of the core, which resulted in uneven wall thickness and unsymmetrical flow during molding. When we uncovered the asymmetry, we stopped using that mold.We prepared test samples by cutting the cylindrical portion of the molded parts into 4-in. lengths, discarding the

dome. Each sample was tested by clamping it between two plates to seal the ends (see Figure 3), and pressurizing internally with water. O-rings provided a seal between the tube and the plates.

Table 2 shows sample measurements and test results. The strength was calculated as $P*r/t$, where P is the burst pressure, r is the outside radius, and t is the minimum measured wall thickness. Table 3 gives average strengths and their standard deviations, and Figure 4 illustrates the strength distributions.

The Vectra A950 material is formulated for extrusion rather than injection molding. Its unconventional flow characteristics caused it to mold poorly in our cylinders. Most of the parts had prominent knit lines that influenced the failures, resulting in huge variability in measured strength-from 2900 psi to 8400 psi at ambient temperature. In a surprising result from these tests, strength was generally higher at 180°F, averaging 8500 psi.

The Vectra A115 material is reinforced with 15% glass, which results in higher and more consistent strength. At 70°F, the average strength in these tubes was 17,300 psi, which is 62% of the handbook strength of 28,000 psi. The strength dropped to 9200 psi at 180°F.

Vectra A130 is reinforced with 30% glass. According to the published data sheets, this increase in reinforcement has no effect on the tensile strength, which remains at 28,000 psi. However, our tests showed a substantial reduction in the hoop strength of the tubes, to 6,300 psi. This might be partly because of the different molding configuration (the longer, smaller tube with significant eccentricity). Also, this test measures strength transverse to the molding flow, where the glass fiber reinforcement is not effective.

The AMODEL A-1133 HS (PPA with 33% glass), RTP 4005 (PPA with 30% glass), and Ryton R-4XT (PPS with 40% glass) all showed similar strength and variability. AMODEL A-1145 HS (PPA with 45% glass) and RTP 4001 (PPA with 10% glass) had about 25% less strength, but the variability was also much lower. AMODEL A-1115 HS (PPA with 15% glass) had the worst variability, with a coefficient of variation of 60%.

Dissected Tank Tests

We molded one partial subscale tank from RTP 2399 X 68911A (40% glass reinforced PU). Two subscale tanks molded from AMODEL A-1133 HS (33% glass reinforced PPA) were dissected for measurement of the material properties as molded in the conformable tank configuration. We cut samples from the cylinder walls and from the internal webs, then measured strengths in the axial direction (parallel to molding flow) and in the circumferential or transverse direction (perpendicular to molding flow). For the AMODEL tanks, strength was also measured across a major knit line. Because of the curvature in the cylinder, tensile samples were not possible in the circumferential direction, so we used flexure samples instead. We also tested flexure samples in the axial direction for comparison.

Table 4 gives the results of the PU tank dissect tests. Strength in the axial direction in the cylinder reaches 97% of the ideal strength based on molded tensile bars. Strength in the transverse direction in the interior web is only 27% of the ideal strength. The loss of strength at 180°F is excessive, which disqualifies this material as a candidate for the tanks.

Table 5 gives the results of the PPA tank dissect tests. Strength in the axial direction in the cylinder is only 75% of the ideal strength. Strength in the circumferential direction is 34% of the

ideal strength. The strength of the knit line is approximately the same as the circumferential strength. Transverse strength in the web is somewhat higher, at 47% of ideal, possibly because of mixed flow directions in this region.

These dissected tank tests indicate that the effective strengths for reinforced plastics in the conformable tank configuration are only about 25% to 35% of the ideal strength. This is mainly because the anisotropic material properties tend to be oriented in the wrong directions. Good strength is achieved in the axial direction, but the highest stresses are in the circumferential direction, where strengths are very low. This problem might be corrected by designing the mold to fill in the circumferential direction. However, even with careful mold filling design, it is likely that there would be some regions where the flow orientation is poor, or where weld lines form, and failure would simply occur at the weakest location. A better option is to find or develop materials with adequate strength in the weakest direction.

Primary Candidate Materials

The two most promising materials identified are:

- AMODEL AS-1133 HS—a PPA, reinforced with 33% glass. It was selected for excellent strength in the flow direction, moderate strength in the transverse direction, good high-temperature creep strength, excellent chemical resistance, good toughness, and moderate cost. It has the disadvantage of strong anisotropy caused by the glass reinforcement.

- FORTRON® 0214 C1—a PPS, with no reinforcement. It was selected mainly because it was the strongest unreinforced material found. Its isotropic properties make it less sensitive to molding flow. It also has excellent chemical resistance and moderate cost. On the negative side, its toughness is low and mold shrinkage is high.

We used both these materials in the last set of subscale tanks molded.

System Design

Design Requirements

To ensure safety and acceptance, pressurized fuel tanks for vehicles are subject to strict design and verification requirements. Because the requirements for LPG containers are similar to those for CNG, we based our design on the CNG standards. However, some key differences between LPG and CNG do affect the tank requirements. Propane has a much lower vapor pressure than natural gas, and is stored as a liquid, rather than as a compressed gas, at the vapor pressure of the ambient temperature. Thus, the pressure does not vary as the tank is filled or drained, but does vary as the temperature changes, as shown in Figure 5. The service pressure for LPG is substantially lower than that for CNG.

Three levels of suggested requirements for LPG tanks are defined below.

- Design requirements give guidance in the design phase so the tank will meet functional needs and safely withstand service loads and exposure conditions.

- Design verification and qualification tests are a series of specific tests that must be met by developmental tanks prior to going into production. They verify that the design actually meets its goals.

- Production verification is a set of tests that must be passed by each production tank or by tanks selected randomly from production runs. These tests ensure that production is under control, and that production of safe tanks continues.

During tank design, the requirements shown in Table 6 are used to guide the selection of materials, wall thicknesses, and other features of the tank design. They include the design envelopes, applied loads, service life, environmental conditions, and safety requirements.

The table provides two external envelopes. The subscale envelope is for a small tank for preliminary development. This envelope has been used for the tanks molded to date. The full-scale envelope is the Chrysler Ram van tank envelope for which aluminum tanks are currently being produced. This is a potential market for the plastic tanks, and serves as a good point of comparison between aluminum and plastic conformable tanks.

The internal volume of the tank must be maximized because the main rationale behind the conformable tank concept is to pack more fuel into the available space than is possible with cylindrical tanks. Cylindrical steel tanks can provide an internal volume of about 70% of a brick-shaped external envelope, if multiple small cylinders are packed together. To be competitive, the conformable tanks should exceed this 70% volume efficiency.

The service pressure of 250 psig corresponds to the vapor pressure of propane at 118°F. Although the environmental temperature may locally reach 180°F, the fuel temperature is not expected to exceed 118°F. If it does, the peak pressure is controlled by a relief valve that allows venting to cool the fuel.

A design structural safety factor of 4.0 on ultimate strength provides leeway for variation of properties in the injection-molded plastic, and for small defects. In general, the 4.0 factor for ultimate strength will control, rather than the 2.0 factor for yield strength, because the yield strength is close to the ultimate strength for most high-strength plastics.

During a 15-year service life for the tank, the number of pressurization cycles is conservatively estimated at 18,000—more than three cycles per day for 15 years. For LPG tanks, these pressure cycles are driven by temperature changes rather than by filling and emptying.

Design Verification and Qualification Tests

To ensure that the tank design will meet functionality and safety requirements prior to going into production, Table 7 prescribes a rigorous series of tests. These requirements are based on References 1 through 3.

Production Verification

Once the tanks have gone into production, continuing tests are necessary to ensure that the manufacturing process remains under control and continues to produce safe tanks. These tests, based on Reference 1, include proof and leak tests on each individual tank, and cyclic and burst tests on each production lot of tanks, as described in Table 8. A production lot would be the tanks produced from a single lot of plastic during one production shift.

Subscale Tank Design and Analysis

Subscale Design 1

Tank Design. The subscale tank is designed to fit an external envelope of 6 x 10 x 12 in. Two internal structural webs divide it into three chambers. There are four external ports, two in each end of the tank, which open into the side chambers. Six holes in each web allow flow between the chambers. Figure 6 shows the general configuration of the subscale tank.

This tank uses 95.6 in^3, or 5.10 lb, of plastic. It has an internal volume of 479.3 in^3, or 2.07 gal. The volume efficiency is 66.6%, comparing this internal volume to the volume of the 6 x 10 x 12 in. external envelope. This is slightly below the target value of 70% volume efficiency.

The cylinder and web thicknesses were sized for a service pressure of 250 psi, a safety factor of 4.0, and an effective material strength of 16,000 psi. However, detailed analysis (below) shows that a higher effective material strength is actually needed because of stress concentrations.

The external ports are reinforced by threaded metal bosses that are molded into the tanks. The internal holes in the webs are reinforced by flanges, which reduce the stress concentrations around the holes without having to thicken the entire web.

The external contours of the tank are formed by an aluminum injection mold. The internal contours are formed by a core assembly consisting of sand cores supported by steel rods that pass through the external ports of the tank. Spacing between the sand cores is maintained by tubular aluminum inserts, which also form the holes to allow fuel to flow through the webs between cells in the finished tank. The sand cores are formed from silica sand with a water-soluble binder. After injection molding, the steel rods are pulled out and the sand is washed away with water. The aluminum inserts remain in the finished tank.

Sand cores, which provide a lower cost method of molding small numbers of tanks, are planned for use only during tank development. During production, another method will be used to form hollow tanks. One option is a lost-core process that uses meltable metal cores. Another option is to mold a tank in separate parts that can be thermoplastically welded into a complete tank.

Finite Element Analysis. We performed several finite element analyses for the subscale tank design to ensure that it would meet the requirements. The different analyses included different levels of refinement and concentrated on different regions of the tank.

A shell element model of one-eighth of the tank was used to determine stresses in the cylinder and web walls, and to design the flanges that reinforce the web holes. The three planes of symmetry of the tank allow it to be modeled by this one-eighth model, shown in Figure 7.

We used the axisymmetric model in Figure 8 to analyze the region around the port, and to study the interaction between the metal boss and the surrounding plastic. The model shown here includes the redesigned metal boss, which we will discuss later. The axisymmetric analysis included contact elements between the boss and the plastic, and modeled the mold shrinkage of the plastic.

We used the plane strain cross section model in Figure 9 to analyze the junction between the cylinder walls and the interior webs.

The three-dimensional solid model in Figure 10 models a symmetric section of the whole tank, including an accurate representation of the boss. However, it uses rather coarse elements, and does not model fillets and fine details. It accounts for the effects of wall thickness better than the shell model.

Table 9 summarizes analysis input properties. The plastic properties are typical values for a 30% to 40% glass-reinforced PPA. Properties are shown for both aluminum and steel because analyses were done for both the original aluminum boss as well as the later steel boss.

Analysis results are summarized in Table 10. The highest stress shown is 6477 psi (at the operating pressure of 250 psi) in the web in the narrow gap between the flange of the small hole and the web/cylinder junction, based on the three-dimensional solid analysis. The second highest stress is near the same location, in the web/cylinder junction fillet, based on the cross section analysis. The three-dimensional solid analysis did include some higher stresses, but they were very localized and were not expected to cause tank failure.

Based on the finite element analyses, an effective material strength of 25,900 psi would be needed to achieve the required 4.0 safety factor.

Tanks were molded of AMODEL A-1133 HS material. They were then burst tested, tests that will be discussed in more detail later. The average burst pressure was 427 psi, with a standard deviation of 53 psi. Based on the finite element analysis, this indicates a nominal effective strength of 11,000 psi.

Port Sealing

When the first burst test was done (Tank 4), we observed leakage around the molded-in metal bosses. We saw leakage even before pressure was applied. The original design assumed that mold shrinkage of the plastic would cause it to squeeze onto the boss, providing a tight metal to plastic seal. Apparently, however, the plastic does not bond to the metal, and the interface provides a leak path.

Prior to testing the other three tanks, we designed a fitting that threaded into the molded-in bosses, and sealed with an O-ring against the plastic surface around the boss. Figure 11 shows the fitting design, and Figure 12 illustrates how it interfaces with the tank port.

We performed a finite element analysis of the fitting to determine how it would respond to changes in the temperature and pressure of the tank. The plot in Figure 13 shows how much the O-ring gap opens as the tank is cooled. The maximum O-ring gap opening is 0.0012 in. at -40°F. This reduces the O-ring squeeze from 25% to 24%, which is not enough to affect the seal.

This fitting worked well. We observed no leakage in any of the other three tanks, even after 15,000 pressure cycles on Tank 6.

Intermediate Design

Keeping the following constraints and considerations in mind, we designed an intermediate subscale tank design.

- Keep stresses in plastic below 10,000 psi at the design burst pressure of 1000 psi.

- Do not change any outer contours, which are controlled by the existing injection mold. New molds will be required for the internal cores.

- Facilitate manufacture by the metal lost-core process. Provide slope for complete drainage of core material, at least in the two side chambers.

- Assume no bonding between plastic and molded-in bosses. They must be retained by a mechanical lock only, and must be restrained against rotation.

Figure 14 shows the resulting subscale tank. All the walls are thicker to compensate for the lower material strength. The inner contour of the domes allows the side chambers to drain completely through the ports when the tank is vertical. The middle chamber still cannot be drained completely, but this is not vital in a subscale design that is used only for testing.

We reduced the number of holes in the webs and relocated them to reduce unnecessary stress concentrations and improve drainage. The four holes in each web are now located in the corners of the domes, where tensile stresses in the web are reduced by the bending of the dome under pressure. They are located as close as possible to the extremities of the web to allow nearly complete liquid drainage from one chamber to another.

The boss is retained against blowout loads by its flange. An undercut angle on the edge of the flange prevents the boss from being pushed into the tank. It is restrained against rotation by six holes that are filled with plastic.

This tank design uses 171.5 in^3 or 9.14 lb of plastic and contains 403.0 in^3 or 1.74 gal of internal volume. This is 80% more plastic than the original subscale design, an increase that was necessary to accommodate lower material strength. The volume efficiency is reduced from 66.6% to 56.0%, far below the target of 70%. Improvements in the effective plastic strength will be necessary to achieve a competitive design.

We did not build any tanks to this intermediate design.

Subscale Design 2

Tank Design. We prepared the second complete subscale tank design with the goal of reaching a design burst pressure of 1000 psi with the worst expected material properties. The design strength is 7200 psi. This is a lower bound estimate of the strength of AMODEL A-1133 HS, as molded in the tank configuration. Based on the burst tests of subscale tank design 1, there was a 99% probability of the strength being greater than 7200 psi, as illustrated in Figure 15.

In redesigning the subscale tanks, the outer contour was kept the same, so no modifications of the injection mold were required. Because internal contours were changed in order to change the wall thicknesses and internal features, new molds for the sand cores had to be fabricated.

Figure 16 shows tank design 2. Wall thicknesses have increased to 0.57 in. in the cylinder, 0.53 in. in the internal webs, and 0.90 in. in the domes. The tank contains 265 in^3, or approximately 14 lb of plastic. The internal volume is 308 in^3, for a volume efficiency of 43%. The holes through the webs have been relocated and reduced in number to reduce the stress concentrations. This should also improve flow during molding.

Finite Element Analysis. To arrive at this design, we conducted a series of finite element analyses. In these analyses, the cylinder thickness, web thickness, y-joint fillet radius, and web

hole radius and location were adjusted to obtain a balanced design with maximum stresses below 7200 psi at 1000 psi pressure. Table 11 gives the results of each iteration.

These analyses used three-dimensional solid finite elements rather than shell elements, providing accurate results even in the junctions between the internal webs and the outer cylinders and domes. Stress contours at 1000 psi pressure for the final configuration are shown in Figures 17 and 18. The highest predicted stress is 7080 psi, somewhat lower than the target of 7200 psi, so the burst pressure was expected to exceed 1000 psi.

Full-Scale Tank Design

We designed a preliminary full-scale tank with the following constraints:

- Keep stresses in plastic below 10,000 psi at the design burst pressure of 1000 psi.

- Maximize tank volume in an envelope of 14 x 24 x 36 in.

- Facilitate manufacture by the metal lost-core process. Provide slope for complete drainage of core material.

- Assume no bonding between plastic and molded-in bosses. They must be retained by a mechanical lock only, and must be restrained against rotation.

The result is shown in Figure 19. The design includes ports in both ends of all three chambers, providing improved support and alignment for the cores during injection molding, and facilitating complete drainage of the molten core material. After manufacture, the ports are designed to be closed by fittings that thread into the ports and seal with O-rings against the outer face of the plastic, similar to those used for the burst tests on the subscale tanks.

This tank design uses 2495 in^3 or 133 lb of plastic and contains 7301 in^3 or 31.6 gal of internal volume. The volume efficiency is 60%, low compared to the target of 70%, but better than that of the intermediate subscale tank, which was designed with the same criteria.

Cost Model

We developed a cost model, implemented as an Excel spreadsheet, to estimate the relationship between material properties and tank cost, weight, and volume. The cost model includes strength criteria to hold internal pressure as well as toughness criteria to withstand external impact.

Thin wall membrane theory is used to estimate wall thicknesses for the webs, domes, and cylinders to hold the pressure. Transverse direction strength is the important material property for this criterion. For impact, closed form equations are used to approximate the cylinder wall deformation, stress, and strain under a point load, and to estimate the energy absorbed before cracking. This criterion accounts for yielding if the material is ductile. The important material properties for impact are the flow direction strength, modulus, and failure strain.

Using simplified tank geometry, the required wall thicknesses calculated from the strength and impact criteria are translated into material volume and internal volume. By comparing these calculations with the detailed design analyses of the subscale tanks, the calculations have been verified as reasonably accurate.

The primary end results of the cost model are the internal volume, tank weight, and tank cost. The internal volume can be expressed in total gallons, or as a volume efficiency, which is the internal volume divided by the volume of the rectangular external envelope. With the volume, weight, and cost, it is still difficult to rank different tank materials, because a lower cost can compensate for some lost volume or increased weight. An overall grade parameter that combines these three values has been proposed, as volume divided by cost times weight. Thus, more volume, lower cost, or less weight result in a higher overall grade. The units of the overall grade are in^3/\$-lb.

Tables 12 through 14 give cost model calculations for an aluminum tank and for the two primary plastic candidates . These cost models are based on the best estimates of material properties after testing the first subscale tank design. As we will discuss, these properties were not achieved when the thicker second design was fabricated. Table 15 shows the cost model for a "target" material. This represents a hypothetical material custom developed for pressure tanks.

The results are compared in Figure 20. The volume efficiency of the plastic tanks is lower than the aluminum baseline. Because the plastics are not as strong as aluminum, thicker walls are necessary, which displaces some of the fuel volume. Likewise, the weight of the plastic tanks is higher, although the target material would approach the weight of an aluminum tank. The advantage of injection-molded tanks is in the cost, as the figure shows. The plastic tanks approach half the cost of an aluminum tank. With this cost advantage, plastic tanks have the potential of a higher overall grade than aluminum, also shown in Figure 20.

System Fabrication

Subscale Design 1

First Molding Run

Injection molding was done at Hettinga Equipment, in Des Moines, Iowa. In the first molding session, on January 24-25, 1996, we planned to mold with two candidate materials: RTP 2399 x 68911A (PU), and AMODEL A-1133 HS (PPA). However, because of molding problems, we used only the PU material.

A single set of aluminum cores was to be used for the initial molding, to set process parameters. This required cutting the plastic part into several pieces to remove the cores prior to molding the next part. The first part molded with the PU material was overfilled because of a miscalculation of shot size. This resulted in substantial flashing and thicker walls. The part filled completely, with no visible voids. It was much more difficult than expected to cut this tough plastic off of the mandrels. Rather than delaying the rest of the molding while cutting the plastic, we decided to go ahead with the sand cores. Only four sets of sand cores were available, and we planned to mold two with each material.

The first part made on a sand mandrel was only about 80% filled. However, much more serious than the partial filling was the fact that the sand cores were shifted and partially fractured by the injection pressure. As shown in Figure 21, injection was through a single gate at the center of one end of the part. Pressures at that end caused the cores to push toward the opposite end. The

sand cores were supported by bearing against the metal bosses, but the sand in this area fractured, allowing the cores to push over the bosses until they contacted the end of the mold (see Figure 22). The connections between the three core sections were adequate. The three cores moved as a unit, failing only around the bosses.

We made three changes to try to correct the problem for the next injection attempt. The two downstream bosses were machined down to make room for heavy washers between the bosses and the sand cores to better support the cores. The injection gate diameter was increased to allow better flow into the mold. The melt and mold temperatures were increased to reduce viscosity. The shot size was also corrected to obtain complete filling. However, the changes were not sufficient. The cores again fractured at the polar bosses and shifted. The loads were high enough to permanently deform the washers.

For the third sand core assembly, we continued with the PU material. The downstream bosses were again modified, placing a stack of two heavy washers between the boss and the sand. Again, we increased the gate diameter. Runners were cut into the middle core to improve flow of plastic to the far end of the part. One runner was cut down the center of each web, approximately 0.37 in. wide by 0.19 in. deep. The mandrel again fractured and shifted.

With the fourth sand core assembly, we used double washers again, and cut larger runners into the center core. Two runners were cut on each web, approximately 0.5 in. wide by 0.19 in. deep. The end of the middle core was cut off to make an inlet chamber to help plastic reach the runners. As before, the mandrels fractured and shifted. However, with more plastic flow through the webs, the mandrels were also forced outward, which resulted in thick webs and thin outer walls.

This first molding session produced no complete tanks, but one of the partial tanks was dissected to obtain tensile strength samples as discussed earlier.

Molding Process Changes

After the first molding session, we made four changes to produce good parts in the second molding session.

We modified the injection mold to inject simultaneously at both ends of the tank, and added a second gate in the other end of the mold (see Figure 23). We also added a symmetrical runner system to bring plastic simultaneously to both ends of the tank.

We changed the sand binder formulation to provide higher strength at the mold temperature. The original formulation, with a PVA binder, has a strength of about 800 psi at 300°F. The new binder, with a sodium silicate binder, has a strength of about 4800 psi at 300°F.

Because the original core surface was somewhat rough and quite porous, we added a smooth coating to the sand cores to reduce friction and improve plastic flow during injection.

Finally, we changed the boss design to provide better support to the sand cores. The new boss flares out to provide a 1.5 in. diameter bearing surface against the sand (Figure 24). To reduce deformation, the material was changed to steel.

Second Molding Run

These molding process changes resulted in a successful second molding session on March 20-21, 1996. We prepared ten sets of sand cores for this session, and molded tanks from AMODEL A-1133 HS. The changes solved the problem of the sand cores shifting during injection.

Photos of the mold are shown in Figures 25 through 28. Figure 25 shows half the mold, prior to inserting the sand cores. Figure 26 shows the sand cores in the mold. They are supported by steel rods that are held in place by toggle clamps. Figure 27 shows the runner system, which provides balanced flow to the two ends of the mold. Figure 28 shows the molded part just after opening the mold. The weld line where the two flow fronts meet at the middle of the part is visible in this photo.

The first part was incompletely filled. We cut apart the second part to confirm that it filled completely. We used the same molding process parameters on the next seven parts. On the final part, higher injection rates and pressures were used, which produced a slightly smoother finish. Several of the parts had dark streaks, possibly caused by local overheating of the resin during injection. These streaks were most evident on the last part. Most of the parts also have some chalky surface areas on the domes, probably caused by local concentration of glass fibers. A knit line is clearly visible at the midplane, where the two main injection fronts meet. More complicated knit lines are visible on the internal webs, where plastic flows around the web holes and meets on several fronts.

Following molding, the tanks were annealed at 300°F for a minimum of 2 hours at the recommendation of Hettinga Equipment representatives.

After molding, Tanks 1 and 2 were cut up immediately to confirm complete interior filling. Tanks 3 and 7 were dissected for tensile bars, flexure bars, and impact tests. Tanks 4, 8, and 10 were burst tested. Tank 6 was pressure cycled and burst. Tanks 5 and 9 are being used for display.

Subscale Design 2

Starting on May 19, 1997, and finishing on May 22, 21 tanks of subscale design 2 were molded at Hettinga. Fourteen tanks were molded with AMODEL AS-1133 HS, and seven with FORTRON 0214 C1. Table 16 gives the results of the molding, which encountered serious problems in the form of shrinkage cracks, voids, weak molding weld lines, and collapsed aluminum inserts.

The shrinkage cracks are a result of the plastic part being molded around and completely enclosing a rigid core. These cores are made of silica sand with a water-soluble sodium silicate binder. The sand cores are rigid and have low thermal expansion. Because the plastic shrinks significantly after molding, and the cores do not, large stresses built up in the plastic, resulting in cracks in many of the tanks. Shrinkage is accentuated by thicker sections, and did not cause apparent problems in the original tank design. In the first few tanks, the sand was washed out after the tanks had cooled, by immersing the whole tank in water and allowing the cores to soften gradually. In later tanks, the sand was washed out as soon as possible after molding in an attempt to allow the plastic to shrink more freely. Water was injected through a hose to soften and wash out the sand internally without cooling the plastic too rapidly. This process was only partly successful. Some tanks cracked before the sand could be washed out. Others cracked audibly during wash out. Others cracked several hours or more after wash out, although internal cracks

were probably present earlier. Two of the FORTRON tanks that were shipped without cracks were found to have cracks after going through the annealing treatment.

The first tank molded was cut into quarters to check the internal filling. We found several voids near the main weld line, as shown in Figure 29. The largest voids are about 0.45 in. x 0.27 in. in size. After molding a few more tanks, the molders felt that the voids were caused because the runners were freezing off before the mold was completely packed. To allow better flow through the runners, the mold was pulled off of the machine, and the runners and sprues were increased in size. This mold modification was completed before molding Tank 8. It did not completely solve the void problem.

Weak molding weld lines were apparent in many of the parts. Many of the shrinkage cracks occurred along the main weld line. Figure 30 shows an interesting flow pattern at the weld line in one of the FORTRON tanks. This looked like a potential weak spot, but the burst test fracture did not go through this spot. In some of the FORTRON tanks, glossy fracture surfaces were seen along the weld line, indicating a cold weld.

When some of the sand cores were being washed out, we could not get cross flow of water from one side cell to the other. The center cell was apparently sealed. We cut open one of these tanks (number 5), and found that the aluminum inserts that form the holes through the webs had crushed under the injection pressure. This problem was solved first by replacing the aluminum tubes with steel. Later we simply filled the aluminum tubes with loose sand to prevent them from collapsing.

Fabrication Methods

Cup Welding

The shrinkage problems encountered in molding the subscale tanks may have resulted from the part completely enclosing a rigid core. Molding the tank in halves would result in some freedom for axial shrinkage, reducing shrinkage problems. This would also simplify tank fabrication by eliminating the need to mold cores and remove them after molding the tank.

Some type of joining process would be required to assemble the tank halves, producing a hermetic and structural connection. Thermoplastic welding is one option. Initial trials have been done with this process.

Four materials were tested in a welded bottle configuration, as shown in Figure 31. Forward Technology Industries, Inc., made the welds using a hot plate process. The weld is at the thinnest wall section of the bottle, giving it a severe test. In most cases the bottles failed with a longitudinal crack, not along the circumferential weld. Table 17 summarizes the material strengths computed from the measured burst pressures.

Even though the failures did not follow the weld, the welded bottles were generally weaker than the monolithic tubes. For AMODEL A-1133 HS, the welded bottles were substantially weaker, as shown in Figure 32. For RTP 4005, the welded bottles approached the strength of the non-welded tubes, as shown in Figure 33. If welded tank fabrication is found to be the best approach, a change in material would be necessary.

Process Improvement

Our work has shown that the potential strength of the plastics is not being obtained in the molded tanks. Processing modifications that would improve the effective strength of the molded plastics are needed. We discussed this problem with an Amoco material engineer, who suggested that we contact TherMold Partners in Stamford, Connecticut, and investigate its vibrational molding technique.

Vibrational Molding

We held a meeting with representatives of TherMold Partners to investigate its vibrational molding technology, known as RHEOMOLDING^{SM}. This technology has the potential to improve the effective material strength in our conformable tanks, making lighter, more competitive designs feasible. The potential is good enough that feasibility tests should be planned in the future.

Data published by TherMold shows significant strength increases (on the order of 20%) for various unfilled materials with RHEOMOLDING. A dramatic strength increase of 111% was seen for a 45%-glass-fiber-filled PPA molded with a weldline. An improvement in weldline strength is important in the conformable tanks because weldlines are formed as a result of flow around the boss inserts and web holes, as well as at the part midplane caused by injection from both ends. RHEOMOLDING also reduced the variability of strength, especially in samples with a weldline.

To date, TherMold has tested samples only in the direction of flow. Future feasibility tests should start with molding and testing transverse direction lab samples. If these samples show significant improvement in the transverse direction strength, the next step would be to test RHEOMOLDING on the subscale tank. In the laboratory testing phase, a matrix of processing parameters would be run to identify the optimum conditions. Processing parameters include the frequency, amplitude, and duration of vibration. The sample thickness would also be varied to identify scale-up effects. Testing on subscale tanks would then require purchasing a limited license for the RHEOMOLDING technology, and installing the RHEOMOLDING equipment on a molding machine at Hettinga (or another molder).

Experimental Program

Subscale Tank Design 1

Burst and Cyclic Pressure Tests

Four tanks of design 1 were burst tested, and the results are given in Table 18. The average burst pressure for the four tanks was 427 psi. One tank (number 8) burst at a significantly lower pressure than the other three. Because of a data acquisition problem, the exact burst pressure was not recorded for this tank, but based on manual observation of the pressure gage and correlation with a strain gage, the burst pressure was about 350 psi.

Tank 10 was molded with higher injection rates and pressures than the other tanks. Although it had the highest burst pressure at 464 psi, the difference was not large enough to be significant.

Tank 6 went through 15,000 pressure cycles, but still burst at 459 psi, indicating no degradation caused by pressure cycling.

It is not possible to identify for certain where failure initiated in these tanks. However, all four tanks have in common a failure along the junction between the internal web and the outer cylinder walls near the middle of the tank, as shown in Figure 34. This appears to be the most likely failure location. This location agrees with the location of maximum stresses in the finite element analyses. From this fracture, cracks propagate across the web and into the cylinder and dome regions. In this location, the stress at the average burst pressure of 427 psi is 11,000 psi based on finite element analysis. This agrees very well with the circumferential direction strength, 10,700 psi, measured from dissected samples.

Although all these tanks have a prominent mid-length knit line because plastic was injected from both ends, in only one case does a fracture follow this knit line. On Tank 8, a crack runs axially the whole length of the tank on one side cylinder, and takes a lateral jog of about 2 in. along the knit line (see Figure 35). Similar axial cracks on the other tanks pass straight through the knit line. It appears that this knit line is normally not detrimental in these tanks. Indeed, the dissected samples show that the knit line has about the same strength as the transverse to flow direction in the material.

Impact Tests

We performed impact tests on Tanks 3 and 7, which were also the source for the dissect samples. Each tank was first cut in half longitudinally through the middle chamber. One half was reserved intact for impact testing; the other half was cut into lab samples.

Impact tests were done on a drop weight tester with a 0.5 in. diameter hemispherical impacter, instrumented to measure loads and energies. The half tank rested with the cut surface flat on a table, and the impacter struck it on the cylindrical part of the side chamber. Four impacts were made at different locations on each half-tank. Table 19 summarizes the available energy at impact, the energy absorbed by the tank, and observations of damage at the impact site.

The critical impact energy level for the subscale tank is about 5 foot-pounds (ft-lb). If the available impact energy is below 5 ft-lb, no damage is expected. Between 5 and 8 ft-lb, local cracking is likely. Above 8 ft-lb, the tank is likely to be pierced.

The full-scale tank needs to be able to withstand an impact of 22.1 ft-lb, based on Reference 1. The critical value for the subscale tank is well below this, indicating that impact is a significant design constraint. Scaling the tank up to full size will increase the critical value, but it may also be necessary to select a tougher material, possibly at the expense of some tensile strength.

Subscale Tank Design 2

Burst Tests

Burst tests were done for five tanks of subscale design 2: three AMODEL tanks and two FORTRON tanks. Results were given in Table 16.

Burst test results for the AMODEL material were low and variable. In the original subscale tank design, with 0.19 in. thick cylinder walls, the average burst pressure for AMODEL was 427 psi. In the current design, with the wall thickness tripled to 0.57 in., the average burst pressure decreased to just 302 psi. The low burst pressures probably result from internal shrinkage damage. Failure modes were different in all three tanks. Tank 2 burst at 189 psi. It started leaking along the main weld line, but failed with a longitudinal split along one side. Tank 14 failed at 289 psi with a local crack along the main weld. Tank 13 burst at 430 psi, breaking into two halves along the main weld line.

The FORTRON material produced much better results, but still below the 1000 psi target. The two tanks that could be burst tested failed at 643 and 839 psi, for an average of 741 psi. Failure modes were quite consistent. Both tanks fragmented into numerous pieces, with cracks radiating from the intersection between the main weld line and the web/cylinder y-joint (see Figure 36). We found voids in both tanks at this location. Tank 21 (with the higher burst pressure) had a poor weld line in this area, indicated by smooth, glossy internal surfaces (see Figure 37). Tank 20 did not have similar indications of a weak weld. It did have porosity (numerous small voids) in both domes (see Figure 38), although failure did not appear to begin there. One void near the weld line in Tank 21 had a darkened interior, as though it had been burned or contaminated (see Figure 39).

Accomplishments

In Phase I of the Low-Cost Conformable Storage project, we evaluated materials, designed a subscale tank, and fabricated and tested several copies of the tank. Tank burst pressures were lower than planned, and we found that the effective material strength as molded in the tank was much lower than expected. Based on the lower effective material strength, the subscale tank was redesigned, and a similar design was produced for a full-scale tank. It appears that these tanks would not be competitive because of the low volume efficiency and large amount of material required.

In Phase II, we redesigned the subscale tank in an attempt to reach the target burst pressure with conservative material properties. The target burst pressure was not achieved because the thicker walls caused processing problems. Most of the tanks developed obvious shrinkage cracks after molding, and the few tanks that could be burst tested failed at low pressures because of internal damage.

Phase II also encompassed a preliminary investigation of technologies that may help produce a viable tank. Thermoplastic welding was shown to be capable of producing a useful pressure vessel. Research into vibrational molding indicates a potential to improve as-molded material properties, but would need to be further explored with suitable tests.

The project did demonstrate, in one of the tanks, a burst pressure exceeding three times the operating pressure for LPG. It demonstrated the moldability of conformable pressure tanks, and also identified some concerns with the molding process. We developed a successful method to seal the ports, and tested it in a cyclic pressure test.

Based on this work, we now understand the limits of injection-molded plastics for pressure tanks better. Processing flow, weld lines, and shrinkage are important. The strength of reinforced plastics is highly anisotropic. Toughness and impact tolerance are an important design concern.

Temperature sensitivity is significant, as plastics lose strength at high temperatures, and become brittle at low temperatures. Thermoplastics are injected at extremely high pressures, making it necessary to use very strong, rigid cores to form hollow cells. The injection-molding process can be difficult to scale up. Increases in wall thickness create higher shrinkage and increase cycle times by requiring longer cooling. Larger parts also require huge presses to contain the injection pressure.

The Future

Achieving traditional safety factors and light weight in plastic tanks requires an increase in the strength of the material. A likely way to increase the strength is to reinforce the material with fabric. This could be done in a structural reaction injection-molding (SRIM) process, or perhaps as a modification to thermoplastic injection molding. Another option is to pursue the development of higher strength thermoplastics.

Structural Reaction Injection Molding

The SRIM process is used commercially for producing large structural parts. It involves placing a reinforcement preform into a mold, and then injecting a thermoset resin into the mold. The resin has low viscosity and is injected at low pressure, typically less than 100 psi, allowing the use of less expensive mold tooling.

Figure 40 shows a concept for a SRIM conformable tank. This concept starts with rotationally molded liners to form the hollow cavities. Braided fiber reinforcement preforms would be placed over the liners, and the liners would be attached together, then placed into the mold for injection of the resin.

In this concept, the rotationally molded liners provide sealing for the fuel. The braided reinforcement carries most of the load, and the resin keeps the reinforcement in place.

This concept has several advantages. The existing subscale injection mold could be adapted for SRIM molding. The reinforcement provides the strength, reducing the requirements for the plastic. The liners form the cavities and seal the tank, so there are no cores to remove after molding. Tooling cost is relatively low for both rotational molds and SRIM molds, because they operate at low pressure. SRIM is suitable for scaling up to large parts.

One challenge is the joining and sealing of the separate cell liners. The liners need to be connected together with ports that allow fluid flow but are completely sealed. This can probably be done with a thermoplastic welding process.

Higher Strength Thermoplastic Development

Developing higher strength thermoplastics is a more challenging approach, but an important approach, because in the long run, it has the potential to produce the lowest cost tank. It would also have great benefit for many other applications that require higher strength thermoplastics.

Initial target material properties have already been defined and are listed in Table 20. These targets would no doubt be refined as the program progressed.

AEROSPACE & INDUSTRIAL TECHNOLOGIES

This development project would carry a high risk of failure and a relatively high expense. There is no guarantee that sufficient improvements could be made in the material properties. Numerous tanks would have to be molded to confirm progress, because plastics are very sensitive to the molding process.

Fabric-Reinforced Thermoplastic Injection Molding

The injection molder, Hettinga Technologies, has suggested incorporating fabric reinforcement in an injection-molded tank, a concept illustrated in Figure 41. The tank would be molded in halves to reduce shrinkage problems and improve cycle times. Fabric reinforcement preforms would be placed into the mold prior to injection, and the plastic would flow into the reinforcement during injection. The tank halves would be joined by adhesive lap joints or thermoplastic welding. Various joining options are illustrated in Figures 42 through 44.

This approach has some advantages. The reinforcement provides the strength, so the thermoplastic resin could be selected for easy processing, good sealing, chemical resistance, toughness, and low cost. This approach also builds very directly on the injection-molding experience from this project.

There are also some challenges to this approach. It may be difficult to keep the reinforcement in place at the high injection pressures. Joining the tanks halves reliably will be a concern. New molds would probably be required for a development project, because the current mold is designed for monolithic tanks.

Conclusions

This project demonstrated the feasibility of conformable plastic pressure tanks, but also identified several difficulties. Several options are available to develop increased strength, which will make the conformable plastic tanks an attractive option.

References

1. "American National Standard for Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers, "ANSI/AGE NGV2-1992, August 6, 1992.
2. Federal Motor Vehicle Safety Standard (FMVSS) No. 304, Compressed Natural Gas Fuel Container Integrity, September 1994.
3. Supplemental Notice of Proposed Rulemaking (SNPRM), National Highway Traffic Safety Administration (NHTSA), Federal Register Excerpt 59 FR 65299 No. 242, December 19, 1994.

Table 1, Material Properties Data

Chemical Name		Polyphenylene Sulfide	Polyphenylene Sulfide	Polyphenylene Sulfide	Polyphenylene Sulfide
Commercial Name		Ryton R-4XT	RTP 1301	RTP 1305	FORTRON 0205 P4
Manufacturer		Phillips	RTP	RTP	Hoechst Celanese
Filler		Glass Fiber 40%	Glass Fiber 10%	Glass Fiber 30%	None
Special Features		Dimensional stability & good moldability	Flame retardant, heat & chemical resistant	Flame retardant, heat & chemical resistant	high flow, low flash
Processing Temp	°F		610	610	560
Mold Shrinkage, 1/8"	in/in		0.0060	0.0020	0.0120
Mold Shrinkage, 1/4"	in/in				
Melting Point	°F				
Density	lb/ft3	103.0	88.0	99.3	84.3
Tensile Str, Yield	lb/in2		3.7E+3	17.0E+3	12.5E+3
Tensile Str, Break	lb/in2	29.0E+3			12.5E+3
Elongation, Yield	%				
Elongation, Break	%	1.00			4.00
Tensile Modulus	lb/in2		1.0E+6	1.9E+6	
Flexural Str, Yield	lb/in2	41.0E+3	12.0E+3	25.0E+3	21.0E+3
Flexural Modulus	lb/in2	2.0E+6	850.0E+3	1.5E+6	600.0E+3
Compressive Str	lb/in2	34.0E+3	10.0E+3	22.0E+3	
Izod, Notched, R.T.	ft-lb/in	1.70	0.80	1.60	0.50
Linear Thermal Exp	in/in/°F		20.0E-6	14.0E-6	23.0E-6
Continuous Svc Temp	°F				
Defl Temp, 264 psi	°F	500	450	500	221
Defl Temp, 66 psi	°F		500	500	390
Water Absorp, 24 hr	%		0.0200	0.0200	0.0200
Cost	$/lb				4.44
Thiokol Tests:					
Tensile Strngth, 75°F	lb/in2	27.0E+3			
Elongation, 75°F	%	1.40			
Modulus, 75°F	lb/in2	2.30E+6			
Tensile Strngth, 180°F	lb/in2	21.5E+3			
Elongation, 180°F	%	1.52			
Modulus, 180°F	lb/in2	2.21E+6			
Weld Strngth, 75°F	lb/in2	6.2E+3			
Weld % of full strngth	%	23			
Strength at 180°F after LPG	lb/in2	19.5E+3			
Strength at 180°F after CNG	lb/in2	18.3E+3			
Aging in fuels with .5% strain		no damage			
Creep Strngth, 180°F, 10000 sec	lb/in2				
Hoop strength in tubes, 75°F	lb/in2	13.4E+3			
Hoop strength in tubes, 180°F	lb/in2				

Table 1, Material Properties Data (Continued)

Chemical Name		Polyphenylene Sulfide	Polyphenylene Sulfide	Polyphthalamide	Polyphthalamide
Commercial Name		FORTRON 0214 C1	FORTRON 1140 L6	AMODEL A-1115 HS	AMODEL A-1133 HS
Manufacturer		Hoechst Celanese	Hoechst Celanese	Amoco	Amoco
Filler		None	Glass 40%	Glass 15%	Glass 33%
Special Features		Unreinforced, natural color		Heat stabilized, low moisture absorption exc chem resist	Heat stabilized, low moisture absorption exc chem resist
Processing Temp	°F	590	590	605	605
Mold Shrinkage, 1/8"	in/in	0.0120	0.0020	0.0060	0.0020
Mold Shrinkage, 1/4"	in/in				
Melting Point	°F			590	590
Density	lb/ft3	84.3	102.0	78.6	89.3
Tensile Str, Yield	lb/in2	12.5E+3	29.0E+3		
Tensile Str, Break	lb/in2	12.5E+3	29.0E+3	18.6E+3	32.0E+3
Elongation, Yield	%				
Elongation, Break	%	4.00	2.00	2.00	2.50
Tensile Modulus	lb/in2		2.1E+6	1.2E+6	1.9E+3
Flexural Str, Yield	lb/in2	21.0E+3	40.0E+3	24.8E+3	46.0E+3
Flexural Modulus	lb/in2	600.0E+3	2.0E+6	900.0E+3	1.7E+6
Compressive Str	lb/in2			30.0E+3	40.0E+3
Izod, Notched, R.T.	ft-lb/in	0.50	1.90	0.80	2.10
Linear Thermal Exp	in/in/°F	259.0E-6	12.0E-6	19.0E-6	13.0E-6
Continuous Svc Temp	°F			356	365
Defl Temp, 264 psi	°F	221	500	531	545
Defl Temp, 66 psi	°F	390	536	558	567
Water Absorp, 24 hr	%	0.0100	0.0200	0.3000	0.2100
Cost	$/lb	5.65	3.52	2.75	2.75
Thiokol Tests:					
Tensile Strngth, 75°F	lb/in2			17.7E+3	31.6E+3
Elongation, 75°F	%			1.75	2.24
Modulus, 75°F	lb/in2			1.07E+6	1.92E+6
Tensile Strngth, 180°F	lb/in2			16.3E+3	25.9E+3
Elongation, 180°F	%			1.90	2.59
Modulus, 180°F	lb/in2			1.03E+6	1.77E+6
Weld Strngth, 75°F	lb/in2			11.3E+3	14.7E+3
Weld % of full strngth	%			64	47
Strength at 180°F after LPG	lb/in2			16.0E+3	25.2E+3
Strength at 180°F after CNG	lb/in2			16.0E+3	24.9E+3
Aging in fuels with .5% strain				no damage	no damage
Creep Strngth, 180°F, 10000 sec	lb/in2			13.1E+3	19.1E+3
Hoop strength in tubes, 75°F	lb/in2			7.8E+3	14.1E+3
Hoop strength in tubes, 180°F	lb/in2				

Table 1, Material Properties Data (Continued)

Chemical Name		Polyphthalamide	Polyphthalamide	Polyphthalamide	Polyphthalamide
Commercial Name	.	AMODEL AS-1133 HS	AMODEL A-1145 HS	RTP 4001	RTP 4005
Manufacturer		Amoco	Amoco	RTP	RTP
Filler		Glass 33%	Glass 45%	Glass Fiber 10%	Glass Fiber 30%
Special Features		High heat defl temp modulus, strngth, & creep resist;thick walls	Heat stabilized, low moisture absorption exc chem resist	High strength & stiff, Heat defl temp, thermal stability	High strength & stiff, Heat defl temp, thermal stability
Processing Temp	°F	605	605		
Mold Shrinkage, 1/8"	in/in	0.0040	0.0020		
Mold Shrinkage, 1/4"	in/in				
Melting Point	°F	590	590		
Density	lb/ft3	91.1	97.4	79.3	88.7
Tensile Str, Yield	lb/in2			13.5E+3	29.0E+3
Tensile Str, Break	lb/in2	32.0E+3	37.5E+3		
Elongation, Yield	%			1.00	2.00
Elongation, Break	%	2.50	2.60		
Tensile Modulus	lb/in2	1.9E+6	2.5E+3	1.0E+6	1.9E+6
Flexural Str, Yield	lb/in2	46.0E+3	52.6E+3		
Flexural Modulus	lb/in2	1.7E+6	2.0E+6	900.0E+3	1.6E+6
Compressive Str	lb/in2	40.0E+3	45.5E+3		
Izod, Notched, R.T.	ft-lb/in	2.10	2.50	0.60	1.80
Linear Thermal Exp	in/in/°F	13.0E-6	8.0E-6	21.0E-6	13.0E-6
Continuous Svc Temp	°F	365	365		
Defl Temp, 264 psi	°F	545	549	420	530
Defl Temp, 66 psi	°F	567	574		
Water Absorp, 24 hr	%	0.2100	0.1200		
Cost	$/lb	2.85	2.75		
Thiokol Tests:					
Tensile Strngth, 75°F	lb/in2		35.1E+3		
Elongation, 75°F	%		2.53		
Modulus, 75°F	lb/in2		2.23E+6		
Tensile Strngth, 180°F	lb/in2		26.1E+3		
Elongation, 180°F	%		3.23		
Modulus, 180°F	lb/in2		1.89E+6		
Weld Strngth, 75°F	lb/in2		14.5E+3		
Weld % of full strngth	%		41		
Strength at 180°F after LPG	lb/in2		25.6E+3		
Strength at 180°F after CNG	lb/in2		25.4E+3		
Aging in fuels with .5% strain			no damage		
Creep Strngth, 180°F, 10000 sec	lb/in2				
Hoop strength in tubes, 75°F	lb/in2		10.8E+3	11.2E+3	15.2E+3
Hoop strength in tubes, 180°F	lb/in2				

Table 1, Material Properties Data (Continued)

Chemical Name		Polyphthalamide	Polyamide-Nylon 6/6	Polyurethane	Polyester (LCP)
Commercial Name		RTP 4007	RTP 207H	RTP 2399 X 68911 A	Vectra A950
Manufacturer		RTP	RTP	RTP	Hoechst Celanese
Filler		Glass Fiber 40%	Glass Fiber 40%	Glass Fiber 40%	
Special Features		High strength & stiff, Heat defl temp, thermal stability	High impact	High impact, Low water absorption	Not for injection molding
Processing Temp	°F		550	500	545
Mold Shrinkage, 1/8"	in/in	0.0020	0.0010	0.0010	0.0020
Mold Shrinkage, 1/4"	in/in	0.0030	0.0030	0.0020	
Melting Point	°F				536
Density	lb/ft3	95.5	88.0	94.0	
Tensile Str, Yield	lb/in2	30.0E+3	21.0E+3	27.0E+3	24.0E+3
Tensile Str, Break	lb/in2				24.0E+3
Elongation, Yield	%	2.00	3.30	2.40	
Elongation, Break	%				3.00
Tensile Modulus	lb/in2	2.2E+6	1.6E+6	1.8E+6	1.4E+6
Flexural Str, Yield	lb/in2	40.0E+3	32.0E+3	65.0E+3	24.5E+3
Flexural Modulus	lb/in2	2.0E+6	1.2E+6	1.3E+6	1.3E+6
Compressive Str	lb/in2		23.8E+3		
Izod, Notched, R.T.	ft-lb/in	2.00	4.00	8.00	10.00
Linear Thermal Exp	in/in/°F	10.0E-6	9.0E-6		
Continuous Svc Temp	°F				
Defl Temp, 264 psi	°F	535	480	200	356
Defl Temp, 66 psi	°F		495		
Water Absorp, 24 hr	%	0.2000	0.6000	0.0140	0.0000
Cost	$/lb		3.19		
Thiokol Tests:					
Tensile Strngth, 75°F	lb/in2	31.4E+3	23.4E+3	22.1E+3	
Elongation, 75°F	%	2.01	3.12	2.00	
Modulus, 75°F	lb/in2	2.02E+6	1.38E+6	1.40E+6	
Tensile Strngth, 180°F	lb/in2	24.5E+3	14.4E+3	4.4E+3	
Elongation, 180°F	%	2.48	6.61	5.77	
Modulus, 180°F	lb/in2	1.90E+6	620.00E+3	253.00E+3	
Weld Strngth, 75°F	lb/in2				
Weld % of full strngth	%				
Strength at 180°F after LPG	lb/in2				
Strength at 180°F after CNG	lb/in2				
Aging in fuels with .5% strain					
Creep Strngth, 180°F, 10000 sec	lb/in2				
Hoop strength in tubes, 75°F	lb/in2				5.0E+3
Hoop strength in tubes, 180°F	lb/in2				8.5E+3

Table 1, Material Properties Data (Continued)

Chemical Name		Polyester (LCP)	Polyester (LCP)	Polyester (LCP)	Polyester (LCP)
Commercial Name		Vectra A115	Vectra A130	Xydar G-540	Xydar G-930
Manufacturer		Hoechst Celanese	Hoechst Celanese	Amoco	Amoco
Filler		Chop Glass 15%	Chop Glass 30%	Glass	Glass
Special Features		very easy flow		high strength, processability & flame res.	
Processing Temp	°F	520	545	620	
Mold Shrinkage, 1/8"	in/in		0.0010		
Mold Shrinkage, 1/4"	in/in				
Melting Point	°F	536	535	590	610
Density	lb/ft3		99.9	106.0	99.8
Tensile Str, Yield	lb/in2	28.0E+3	30.0E+3		
Tensile Str, Break	lb/in2	28.0E+3	30.0E+3	21.2E+3	19.6E+3
Elongation, Yield	%				
Elongation, Break	%	3.00	2.00	1.50	1.60
Tensile Modulus	lb/in2	1.9E+6	2.4E+6	2.9E+6	2.7E+6
Flexural Str, Yield	lb/in2	30.0E+3	37.0E+3	27.0E+3	25.0E+3
Flexural Modulus	lb/in2	1.6E+6	2.1E+6	2.3E+6	2.0E+6
Compressive Str	lb/in2				
Izod, Notched, R.T.	ft-lb/in	5.50	2.80	8.30	1.80
Linear Thermal Exp	in/in/°F		2.8E-6	7.0E-6	7.0E-6
Continuous Svc Temp	°F				
Defl Temp, 264 psi	°F	417	446	466	520
Defl Temp, 66 psi	°F				
Water Absorp, 24 hr	%	0.0000	0.0100		
Cost	$/lb	11.60	9.00	6.95	7.30
Thiokol Tests:					
Tensile Strngth, 75°F	lb/in2				
Elongation, 75°F	%				
Modulus, 75°F	lb/in2				
Tensile Strngth, 180°F	lb/in2				
Elongation, 180°F	%				
Modulus, 180°F	lb/in2				
Weld Strngth, 75°F	lb/in2				
Weld % of full strngth	%				
Strength at 180°F after LPG	lb/in2				
Strength at 180°F after CNG	lb/in2				
Aging in fuels with .5% strain					
Creep Strngth, 180°F, 10000 sec	lb/in2				
Hoop strength in tubes, 75°F	lb/in2	17.3E+3	6.3E+3		
Hoop strength in tubes, 180°F	lb/in2	9.2E+3	4.6E+3		

Table 1, Material Properties Data (Continued)

Chemical Name		Polycarbonate				
Commercial Name		Makrolon 2605				
Manufacturer		Miles Inc.				
Filler		None				
Special Features		Exc impact str, ductil, dimen stability				
Processing Temp	°F					
Mold Shrinkage, 1/8"	in/in	0.0060				
Mold Shrinkage, 1/4"	in/in					
Melting Point	°F					
Density	lb/ft3	74.9				
Tensile Str, Yield	lb/in2	9.3E+3				
Tensile Str, Break	lb/in2	10.5E+3				
Elongation, Yield	%	6.00				
Elongation, Break	%	120.00				
Tensile Modulus	lb/in2	330.0E+3				
Flexural Str, Yield	lb/in2	12.5E+3				
Flexural Modulus	lb/in2	330.0E+3				
Compressive Str	lb/in2	11.0E+3				
Izod, Notched, R.T.	ft-lb/in	17.00				
Linear Thermal Exp	in/in/°F	39.0E-6				
Continuous Svc Temp	°F					
Defl Temp, 264 psi	°F	268				
Defl Temp, 66 psi	°F	283				
Water Absorp, 24 hr	%	0.1500				
Cost	$/lb					
Thiokol Tests:						
Tensile Strngth, 75°F	lb/in2					
Elongation, 75°F	%					
Modulus, 75°F	lb/in2					
Tensile Strngth, 180°F	lb/in2					
Elongation, 180°F	%					
Modulus, 180°F	lb/in2					
Weld Strngth, 75°F	lb/in2					
Weld % of full strngth	%					
Strength at 180°F after LPG	lb/in2					
Strength at 180°F after CNG	lb/in2					
Aging in fuels with .5% strain						
Creep Strngth, 180°F, 10000 sec	lb/in2					
Hoop strength in tubes, 75°F	lb/in2					
Hoop strength in tubes, 180°F	lb/in2					

Table 2, Tube Burst Data

Commercial Name	Specimen Number	O.D. (in)	Thickness End A Max	End A Min	End B Max	End B Min	Temp. (°F)	Burst Pressure (psi)	Strength (psi)	average & std dev. (psi)
Vectra A950	A950 1	2.50	0.131	0.128	0.210	0.204	70	862.40	8422	5036
Vectra A950	A950 2	2.50	0.131	0.129	0.226	0.205	70	555.99	5388	2494
Vectra A950	A950 3	2.50	0.132	0.126	0.219	0.205	70	342.13	3394	
Vectra A950	A950 4	2.50	0.131	0.123	0.218	0.202	70	289.52	2942	
Vectra A950	A950 5	2.50	0.131	0.127	0.218	0.204	180	995.55	9799	8531
Vectra A950	A950 6	2.50	0.131	0.127	0.218	0.204	180	641.28	6312	1767
Vectra A950	A950 7	2.50	0.131	0.127	0.218	0.204	180	804.35	7917	
Vectra A950	A950 8	2.50	0.131	0.127	0.218	0.204	180	1026.00	10098	
Vectra A115	A115 39	2.50	0.128	0.124	0.215	0.204	70	1726.60	17405	17346
Vectra A115	A115 40	2.50	0.126	0.123	0.214	0.204	70	1727.60	17557	284
Vectra A115	A115 11	2.50	0.127	0.124	0.214	0.204	70	1679.50	16930	
Vectra A115	A115 12	2.50	0.128	0.124	0.214	0.205	70	1735.30	17493	
Vectra A115	A115 41	2.50	0.126	0.123	0.214	0.205	180	934.79	9500	9176
Vectra A115	A115 42	2.50	0.127	0.123	0.214	0.204	180	894.59	9091	247
Vectra A115	A115 9	2.50	0.127	0.124	0.215	0.205	180	912.61	9200	
Vectra A115	A115 10	2.50	0.129	0.124	0.215	0.205	180	884.01	8911	
Vectra A130	A130 2-a	2.12	0.141	0.119	0.179	0.135	70	510.48	4547	6314
Vectra A130	A130 2-b	2.12	0.179	0.136	0.206	0.148	70	928.68	7238	1342
Vectra A130	A130 7-8-a	2.12	0.132	0.123	0.162	0.144	70	696.38	6001	
Vectra A130	A130 7-8-b	2.12	0.166	0.147	0.194	0.162	70	1035.70	7468	
Vectra A130	A130 7-4-a	2.12	0.138	0.122	0.161	0.143	180	500.56	4349	4553
Vectra A130	A130 7-4-b	2.12	0.167	0.147	0.192	0.162	180	673.75	4858	354
Vectra A130	A130 7-10-a	2.12	0.131	0.124	0.161	0.143	180	486.41	4158	
Vectra A130	A130 7-10-b	2.12	0.167	0.146	0.192	0.161	180	667.49	4846	
AMODEL A-1115 HS	1115-1	2.50	0.132	0.123	0.220	0.214	70	611.00	6209	7819
AMODEL A-1115 HS	1115-6	2.50	0.133	0.126	0.221	0.198	70	1331.00	13204	4667
AMODEL A-1115 HS	1115-27	2.50	0.132	0.126	0.223	0.211	70	734.00	7282	
AMODEL A-1115 HS	1115-18	2.50	0.132	0.126	0.223	0.213	70	1129.00	11200	
AMODEL A-1115 HS	1115-15	2.50	0.142	0.128	0.228	0.219	70	123.00	1201	
AMODEL A-1133 HS	1133-32	2.50	0.137	0.127	0.228	0.215	70	1538.00	15138	14095
AMODEL A-1133 HS	1133-24	2.50	0.135	0.128	0.220	0.213	70	1728.00	16875	2523
AMODEL A-1133 HS	1133-26	2.50	0.134	0.127	0.226	0.214	70	1114.00	10965	
AMODEL A-1133 HS	1133-29	2.50	0.134	0.126	0.218	0.213	70	1351.00	13403	
AMODEL A-1145 HS	1145-37	2.50	0.136	0.129	0.221	0.213	70	1329.00	12878	10817
AMODEL A-1145 HS	1145-36	2.50	0.136	0.129	0.220	0.213	70	1147.00	11114	1336
AMODEL A-1145 HS	1145-2	2.50	0.133	0.126	0.222	0.213	70	931.00	9236	
AMODEL A-1145 HS	1145-3	2.50	0.132	0.125	0.221	0.213	70	1044.00	10440	
AMODEL A-1145 HS	1145-4	2.50	0.134	0.126	0.222	0.216	70	1050.00	10417	
RTP 4001	4001-4	2.50	0.131	0.126	0.218	0.210	70	1032.00	10238	11210
RTP 4001	4001-6	2.50	0.131	0.124	0.220	0.210	70	1014.00	10222	1034
RTP 4001	4001-42	2.50	0.135	0.127	0.216	0.208	70	1167.00	11486	
RTP 4001	4001-63	2.50	0.134	0.126	0.219	0.211	70	1149.00	11399	
RTP 4001	4001-64	2.50	0.133	0.127	0.221	0.210	70	1291.00	12707	
RTP 4005	4005-4005	2.50	0.136	0.127	0.218	0.208	70	1372.00	13504	15224
RTP 4005	4005-	2.50	0.133	0.126	0.217	0.204	70	1200.00	11905	2370
RTP 4005	4005-19	2.50	0.135	0.129	0.226	0.216	70	1736.00	16822	
RTP 4005	4005-8	2.50	0.132	0.126	0.219	0.209	70	1704.00	16905	
RTP 4005	4005-3	2.50	0.136	0.129	0.222	0.213	70	1753.00	16986	
Ryton	Ryton 41	2.50	0.136	0.127	0.224	0.214	70	1666.00	16398	13391
Ryton	Ryton 37	2.50	0.120	0.110	0.212	0.200	70	1341.00	15239	2308
Ryton	Ryton 18	2.50	0.136	0.126	0.227	0.213	70	1255.00	12450	
Ryton	Ryton 9	2.50	0.134	0.127	0.225	0.216	70	1121.00	11033	
Ryton	Ryton 3	2.50	0.135	0.128	0.225	0.216	70	1212.00	11836	

Table 3, Tube Burst Summary

Material	70°F			180°F		
	Mean (psi)	Std Dev (psi)	N	Mean (psi)	Std Dev (psi)	N
Vectra A950	5036	2494	4	8531	1767	4
Vectra A115	17346	284	4	9176	247	4
Vectra A130	6314	1342	4	4553	354	4
AMODEL A-1115 HS	7819	4667	5			
AMODEL A-1133 HS	14095	2523	4			
AMODEL A-1145 HS	10817	1336	5			
RTP 4001	11210	1034	5			
RTP 4005	15224	2370	5			
Ryton	13391	2308	5			

Table 4, Tank Dissect, RTP2399 x 68911A Polyurethane, Tensile Bars

	75°F	180°F
Molded Bars	22,100	4,400
Dissected Tank		
Cylinder	21,400	11,500
Inner Web	6,000	2,500

Table 5, Tank Dissect, AMODEL A-1133 HS Polyphthalamide

	75°F		180°F	
	Tensile Strength (psi)	Flexure Strength (psi)	Tensile Strength (psi)	Flexure Strength (psi)
Molded Bars	31,600		25,900	
Dissected Tanks				
Cylinder Axial	23,800	42,300	22,000	41,800
Cylinder Hoop	10,700*	19,000	13,300*	25,300
Knit Line Axial	11,100		11,300	
Knit Line Hoop	11,900*	21,100	11,100*	21,100
Web Transverse	14,700		12,100	

* Estimated from flexure strength

Table 6, Tank Design Requirements

Condition	Requirements	Comments
Tank Design		
External Envelope Subscale Full-Scale	 12" x 10" x 6" 36" x 24" x 14"	
Internal Volume	>70% of external envelope	
Fuel	LPG	
Loading		
Service Pressure	250 psig	Nominal internal pressure
Structural Factor of Safety	4.0 on ultimate 2.0 on yield	Burst test verification
Dynamic Loads	30 mph vehicle crash 20 ft empty tank drop	
Service Life		
Tank Life	15 years	Includes 15,000 cycles to service pressure plus 3,000 to 1.25 x service pressure
Environmental Conditions		
Temperature	-40°F to 180°F	.
Humidity	0% to 100%	
Vehicle, road, and other fluids	Salt spray Engine oil Antifreeze Battery acid Brake fluid Propane and constituents Other chemicals	"Identification of Service Environment of NGV Fuel Cylinders", July 1994, Gas Research Institute
Impact and Abrasion	Rock and gravel impact and scrapes	Pendulum impact and flaw tolerance tests
Safety		
Fire	No fragmentation of tank when subjected to fire or puncture	
Puncture		

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Table 7, Design Verification and Qualification Tests

	Description	Purpose
1.	Burst Test. Three tanks. The tank is filled with water, pressurized to 2.25 times the service pressure, and held for ten seconds. Pressure is then increased to rupture. The pressurization rate is not to exceed 200 psi/second.	Verifies the tank's ability to withstand the pressure of the fuel.
2.	Pressure Cycles. Three tanks. The tank is filled with water and subjected to 13,000 cycles from 10% to 100% of service pressure, followed by 5,000 cycles from 10% to 125% of service pressure. The frequency is not to exceed 10 cycles/minute. The tank is required to experience no leakage.	Verifies the tank's ability to withstand cyclic pressure loads caused by temperature variation over a 15-year service life.
3.	Environmental Cycles. One tank. The tank is filled with a mixture of water, hydrogen sulfide, carbon dioxide, and propane. It is held at 140°F for 30 days. It is then drained at held for 48 hours unpressurized at 140°F and 95% relative humidity. Then, while at 140°F, it is subjected to 5,000 pressure cycles between 10% and 125% of service pressure. Next, it is subjected to 5,000 pressure cycles between 10% and 100% of service pressure at a temperature of -40°F. The tank is required to experience no leakage nor permanent deformation.	Evaluates the tank's resistance to internal corrosion, high humidity, and high and low temperatures.
4.	Salt Spray Test. One tank. The tank is subjected to a salt spray for 240 hours. It is then subjected to 5,000 cycles between 10% and 125% of service pressure at ambient temperature and humidity, followed by 5,000 cycles between 10% and 100% of service pressure at -40°F. The tank is required to experience no leakage nor permanent deformation.	Evaluates the tank's resistance to road salt.
5.	Flaw Tolerance. One tank. A longitudinal flaw is cut near mid-length on the tank, 1.0" long by 0.030" deep. The tank is subjected to 1,500 pressure cycles from 10% to 100% of service pressure. The tank is required to experience no flaw propagation. Pressurize to burst and record burst pressure.	Evaluates the tank's resistance to external abrasion.
6.	Pendulum Impact. One tank. The empty container is struck by an impacter with a kinetic energy of 22.1 ft-lb, at a temperature of 70°F. The impacter is to be in the shape of a pyramid with a square base and four equilateral pyramid sides. The edges and tip are to be rounded with a 0.12" radius. The mass of the impacter is to be 33 lbs. After impact, the tank is subjected to 1,500 cycles from 10% to 100% of service pressure, and is required to experience no leakage.	Evaluates the tank's ability to withstand a sharp external impact, such as a rock strike.
7.	Drop Test. One tank. The empty, unpressurized tank is dropped 10 feet in a horizontal orientation onto a smooth concrete floor. If damage is visible the tank must still withstand 1,500 pressure cycles from 10% to 100% of service pressure without leakage. If no damage is visible the tank must then withstand 5,000 cycles from 10% to 125% of service pressure followed by 13,000 cycles from 10% to 100% of service pressure without leakage.	Evaluates the tank's ability to withstand a blunt external impact.
8.	Bonfire Test. One tank. The tank is filled with LPG and suspended above a fuel fire. The tank is required to vent to zero pressure without rupturing.	Evaluates the tank's ability to safely vent when exposed to fire.
9.	High Temperature Creep. One tank. The tank is filled with water and pressurized to 125% of service pressure at a temperature of 180°F, and held for 200 hours. It is then returned to 70°F and pressurized to 1.5 times service pressure, and held for at least 30 seconds. The tank is drained and pressurized with dry air and inspected for leaks. Then it is refilled with water and subjected to 5,000 cycles from 10% to 125% of service pressure. No leakage nor permanent deformation is allowed.	Evaluates the tank's ability to withstand high temperatures.
10.	Gunfire. One tank. The tank is pressurized to service pressure with air or nitrogen. It is impacted by a 0.30 caliber armor piercing projectile at approximately 2800 feet/second at an angle of approximately 45° to the cylinder wall. The container is required to not fragment.	Evaluates the tank's ability to withstand a puncture without catastrophic failure.
11.	Permeation. One tank. Permeation of propane through the tank wall is measured at service pressure. It must not exceed 0.25 cc per hour per liter of internal volume.	Evaluates the permeability of the tank for fuel.

Table 8, Production Verification Tests

1.	Proof Test. Every production tank will be pressurized to 150% of the service pressure and held for at least 30 seconds. Permanent volume expansion during this test is not to exceed 5% of the total expansion.
2.	Leak Test. Every production tank will be leak tested at service pressure with dry air. Weld seams and other joints will be examined for leakage.
3.	Cyclic Pressure Test. One tank from each lot will be subjected to 5,000 cycles from 10% to 125% of service pressure, at a frequency not to exceed 10 cycles per minute. No leakage nor failure is allowed. The tank is to be destroyed after the test.
4.	Burst Test. One tank from each lot will be subjected to a burst test. This may be the same tank that went through the cyclic pressure test. The tank will be pressurized to 2.25 times the service pressure, held for ten seconds, and then pressurized to failure. The pressurization rate is not to exceed 200 psi/second.

Table 9, Analysis Input Properties

Property	Plastic	Aluminum	Steel
Modulus (psi)	1.9E6	1.0E7	2.9E7
Poisson's ratio	0.41	0.3	0.3
Coeff. of Thermal Exp. (in/in/°F)	3.3E-5	1.3E-5	6.5E-6
Mold shrinkage (in/in)	2.0E-3		

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Table 10, Finite Element Analysis Results, Original Subscale Design

Location	Stress (psi) at Service Pressure of 250 psi
Shell Analysis	
Cylinder	4830
Web	4740
Small hole flange	3720
Large hole flange	3870
Dome	5696
Axisymmetric Analysis	
Around Boss	5325
Cross Section Analysis	
Cylinder	3843
Web	3750
Junction fillet	5765
3-D Solid Analysis	
Cylinder	4515
Mid web	3900
Web between small hole and web/cyl junction	6477
Small hole flange	4874
Large hole flange	4242
Dome	5540

Table 11, Analysis Iterations for Second Subscale Design

Model Name	Cylinder Thickness	Web Thickness	Fillet Radius	Web Hole Radius	Web Hole Y-coord	Web Hole Z coord	Y-joint	Hole inner edge	Hole outer edge
sub2_solid	0.500	0.350	0.300	0.625	1.600	3.800	7920	8940	9220
sub3_solid	0.500	0.450	0.400	0.625	1.500	3.750	7920	8200	7340
sub4_solid	0.500	0.450	0.500	0.625	1.600	3.800	7980	7640	7670
sub5_solid	0.550	0.450	0.500	0.625	1.500	3.750	7050	7620	7550
sub6_solid	0.550	0.500	0.500	0.500	1.600	3.900	7250	7340	6750
sub7_solid	0.570	0.530	0.400	0.500	1.600	3.900	7080	6930	6530

Table 12, Cost Model for Aluminum Tank

		Value	Source or Description
6061 Aluminum			
Full Size Conformable			
		Value	Source or Description
Inputs			
Material Properties			
	Density (lb/in3)	0.1000	
	Mtl Cost ($/lb)	2.60	
	TD Tens Strength (psi)	38000	
	FD Flex Strength (psi)	38000	
	FD Flex Modulus (psi)	10.0E+6	
	FD Fail Strain (in/in)	0.0040	
	Poisson's Ratio	0.30	
Fabrication			
	Fab Cost ($/tank)	1000.00	Estimate
Requirements			
	Burst Pressure (psi)	1000	4 x operating pressure
	Impact (in-lbs)	0	pendulum impact
Design Geometry			
	Conformable?	1	1=conformable, 0=cylinders
	Wh (in)	24.00	Tank Width
	Wv (in)	14.00	Tank Thickness
	L (in)	36.00	Tank Length
	Nh (integer)	3	Number of cells across width
	Nv (integer)	1	Number of cells through thickness
	b/r (ratio)	0.5000	Dome height/radius ratio
	Ch/r (ratio)	0.7143	Cell width/radius, optimize for max inside vol.
Calculations			
	Cv/r (ratio)	--	Cell thickness/radius
	r (in)	7.0000	Cell wall radius
	Ch (in)	5.0000	Cell width
	Cv (in)	--	Cell thickness
	ti (in)	0.0000	thickness of outer wall for ductile impact
	ts (in)	0.1842	thickness of outer wall for strength
	tr (in)	0.1842	thickness of outer wall
	th (in)	--	thickness of horizontal webs
	tv (in)	0.1316	thickness of vertical webs
	tD (in)	0.3684	thickness of domes
	theta h (rad)	--	
	theta v (rad)	1.2056	
	At (in2)	290.90	Total cross section area of tank profile
	Ap (in2)	15.31	Cross section area of walls
	Sd (in2)	775.74	Approximate surface area of domes
	Vd (in3)	1357.54	Approximate volume of domes
	Vt (in3)	9793.70	Total external volume of tank
Outputs			
	Vp (in3)	729.81	Total volume of tank walls and domes
	Vi (in3)	9063.90	Internal volume
	gallons (gal)	39.24	Internal volume
	Veff (%)	74.93%	Volume efficiency
	weight (lbs)	72.98	Empty tank weight
	material cost ($)	189.75	
	total cost ($)	1189.75	
	V/$W (in3/$-lb)	0.10439	Combined Performance

Table 13, Cost Model for AMODEL AS-1133 HS Tank

	Value	Source or Description
AMODEL AS-1133 HS		
Full Size Conformable		
		Inputs
Material Properties		
Density (lb/in3)	0.0528	Amoco
Mtl Cost ($/lb)	2.85	Amoco
TD Tens Strength (psi)	7296	Tank Burst, 99% probability
FD Flex Strength (psi)	46000	Amoco
FD Flex Modulus (psi)	1650000	Amoco
FD Fail Strain (in/in)	0.0250	Amoco
Poisson's Ratio	0.41	Amoco
Fabrication		
Fab Cost ($/tank)	200.00	Estimate
Requirements		
Burst Pressure (psi)	1000	4 x operating pressure
Impact (in-lbs)	265	pendulum impact
Design Geometry		
Conformable?	1	1=conformable, 0=cylinders
Wh (in)	24.00	Tank Width
Wv (in)	14.00	Tank Thickness
L (in)	36.00	Tank Length
Nh (integer)	3	Number of cells across width
Nv (integer)	1	Number of cells through thickness
b/r (ratio)	0.5000	Dome height/radius ratio
Ch/r (ratio)	0.7143	Cell width/radius, optimize for max inside vol.
		Calculations
Cv/r (ratio)	--	Cell thickness/radius
r (in)	7.0000	Cell wall radius
Ch (in)	5.0000	Cell width
Cv (in)	--	Cell thickness
ti (in)	0.2422	thickness of outer wall for brittle impact
ts (in)	0.9594	thickness of outer wall for strength
tr (in)	0.9594	thickness of outer wall
th (in)	--	thickness of horizontal webs
tv (in)	0.6853	thickness of vertical webs
tD (in)	1.9189	thickness of domes
theta h (rad)	--	
theta v (rad)	1.2056	
At (in2)	290.90	Total cross section area of tank profile
Ap (in2)	79.74	Cross section area of walls
Sd (in2)	775.74	Approximate surface area of domes
Vd (in3)	1357.54	Approximate volume of domes
Vt (in3)	9793.70	Total external volume of tank
		Outputs
Vp (in3)	3801.08	Total volume of tank walls and domes
Vi (in3)	5992.63	Internal volume
gallons (gal)	25.94	Internal volume
Veff (%)	49.54%	Volume efficiency
weight (lbs)	200.70	Empty tank weight
material cost ($)	571.99	
total cost ($)	771.99	
V/$W (in3/$-lb)	0.03868	Combined Performance

Table 14, Cost Model for FORTRON 0214 C1 Tank

		Value	Source or Description
		FORTRON 0214 C1 PPS	
		Full Size Conformable	
		Value	Source or Description
		Inputs	
Material Properties			
	Density (lb/in3)	0.0488	Hoechst Celanese
	Mtl Cost ($/lb)	5.65	Hoechst Celanese
	TD Tens Strength (psi)	12500	FD Tensile Strngth, Hoechst
	FD Flex Strength (psi)	21000	Hoechst Celanese
	FD Flex Modulus (psi)	600000	Hoechst Celanese
	FD Fail Strain (in/in)	0.0400	Range .03-.06, Hoechst
	Poisson's Ratio	0.41	Estimate
Fabrication			
	Fab Cost ($/tank)	200.00	Estimate
Requirements			
	Burst Pressure (psi)	1000	4 x operating pressure
	Impact (in-lbs)	265	pendulum impact
Design Geometry			
	Conformable?	1	1=conformable, 0=cylinders
	Wh (in)	24.00	Tank Width
	Wv (in)	14.00	Tank Thickness
	L (in)	36.00	Tank Length
	Nh (integer)	3	Number of cells across width
	Nv (integer)	1	Number of cells through thickness
	b/r (ratio)	0.5000	Dome height/radius ratio
	Ch/r (ratio)	0.7143	Cell width/radius, optimize for max inside vol.
		Calculations	
	Cv/r (ratio)	--	Cell thickness/radius
	r (in)	7.0000	Cell wall radius
	Ch (in)	5.0000	Cell width
	Cv (in)	--	Cell thickness
	ti (in)	0.4443	thickness of outer wall for ductile impact
	ts (in)	0.5600	thickness of outer wall for strength
	tr (in)	0.5600	thickness of outer wall
	th (in)	--	thickness of horizontal webs
	tv (in)	0.4000	thickness of vertical webs
	tD (in)	1.1200	thickness of domes
	theta h (rad)	--	
	theta v (rad)	1.2056	
	At (in2)	290.90	Total cross section area of tank profile
	Ap (in2)	46.54	Cross section area of walls
	Sd (in2)	775.74	Approximate surface area of domes
	Vd (in3)	1357.54	Approximate volume of domes
	Vt (in3)	9793.70	Total external volume of tank
		Outputs	
	Vp (in3)	2218.61	Total volume of tank walls and domes
	Vi (in3)	7575.09	Internal volume
	gallons (gal)	32.79	Internal volume
	Veff (%)	62.62%	Volume efficiency
	weight (lbs)	108.23	Empty tank weight
	material cost ($)	611.52	
	total cost ($)	811.52	
	V/$W (in3/$-lb)	0.08624	Combined Performance

Table 15, Cost Model for Target Material

	Value	Source or Description
Target Material		
Full Size Conformable		
		Inputs
Material Properties		
Density (lb/in3)	0.0500	
Mtl Cost ($/lb)	6.00	
TD Tens Strength (psi)	18000	
FD Flex Strength (psi)	18000	
FD Flex Modulus (psi)	500000	
FD Fail Strain (in/in)	0.0600	
Poisson's Ratio	0.41	
Fabrication		
Fab Cost ($/tank)	200.00	Estimate
Requirements		
Burst Pressure (psi)	1000	4 x operating pressure
Impact (in-lbs)	265	pendulum impact
Design Geometry		
Conformable?	1	1=conformable, 0=cylinders
Wh (in)	24.00	Tank Width
Wv (in)	14.00	Tank Thickness
L (in)	36.00	Tank Length
Nh (integer)	3	Number of cells across width
Nv (integer)	1	Number of cells through thickness
b/r (ratio)	0.5000	Dome height/radius ratio
Ch/r (ratio)	0.7143	Cell width/radius, optimize for max inside vol.
		Calculations
Cv/r (ratio)	--	Cell thickness/radius
r (in)	7.0000	Cell wall radius
Ch (in)	5.0000	Cell width
Cv (in)	--	Cell thickness
ti (in)	0.3328	thickness of outer wall for ductile impact
ts (in)	0.3889	thickness of outer wall for strength
tr (in)	0.3889	thickness of outer wall
th (in)	--	thickness of horizontal webs
tv (in)	0.2778	thickness of vertical webs
tD (in)	0.7778	thickness of domes
theta h (rad)	--	
theta v (rad)	1.2056	
At (in2)	290.90	Total cross section area of tank profile
Ap (in2)	32.32	Cross section area of walls
Sd (in2)	775.74	Approximate surface area of domes
Vd (in3)	1357.54	Approximate volume of domes
Vt (in3)	9793.70	Total external volume of tank
		Outputs
Vp (in3)	1540.70	Total volume of tank walls and domes
Vi (in3)	8253.00	Internal volume
gallons (gal)	35.73	Internal volume
Veff (%)	68.23%	Volume efficiency
weight (lbs)	77.04	Empty tank weight
material cost ($)	462.21	
total cost ($)	662.21	
V/$W (in3/$-lb)	0.16178	Combined Performance

Table 16, Molding Results, Subscale Design 2

Serial Number	Material	Washed	Cracked	Cut	Inserts	Good	Remarks	Burst Pressure (psi)	Failure Mode
1	A	I		Y	A				
2	A	I			A	Y	possible hairline cracks by weld	188	leaked on weld; longitudinal split on side
3	A		Y		A				
4	A		Y		A		opened mold too early		
5	A	I,NCF	Y	Y	A				
6	A		Y		A				
7	A		Y		A				
8	A	H,NCF			A				
9	A	H,NCF	Y		A		fine cracks during wash		
10	A		Y		A				
11	A		Y		S				
12	A		Y		SA				
13	A	H			SA	Y		430	broke in half at weld line
14	A	H			SA	Y		289	cracked and leaked at weld
15	F	H	Y		SA		cracked through dome overnight		
16	F	H	Y		SA		cracked during annealing		
17	F	H	Y		SA				
18	F	H	Y		SA		cracked during annealing		
19	F	H,I	Y		SA				
20	F	H			SA	Y		643	fractured into numerous pieces
21	F	H			SA	Y		839	fractured into numerous pieces

Materials:	A = AMODEL AS-1133 HS
	F = FORTRON
	0214 C1
Washed:	I=immersed
	H=hose, internal wash
	NCF=no cross flow
Inserts:	A=aluminum
	S=steel
	SA=sand filled aluminum

Table 17, Welded Bottle Burst Summary

	70°F		
Material	Mean (psi)	Std Dev (psi)	N
RTP 4001 weld	3083.9	1154.5	10
RTP 4005 weld	13829	755.61	2
AMODEL A-1115 weld	7088.7	475.61	2
AMODEL A-1133 weld	7339	614.69	2

Table 18, Tank Burst Tests, First Subscale Design

Tank Number	Test Date	Burst Pressure	Notes
4	27 March 1996	435 psi	leakage around bosses
8	3 June 1996	≈350 psi	data acquisition problem
10	3 June 1996	464 psi	higher injection rate & pressure
6	7 June 1996	459 psi	cycled 15,000 times, 50-150 psi

Table 19, Impact Test Results

Impact Number	Tank Number	Energy (ft-lb)		Observed Damage
		Impact	Absorbed	
1	3	10.2	5.1	pierced
2	3	5.0		none
3	3	7.5	6.1	none
4	3	8.3	5.1	pierced
5	7	7.2	6.0	surface dent, interior cracks
6	7	7.0	4.9	interior cracks
7	7	6.3	4.3	interior cracks
8	7	5.3	4.3	interior cracks, possible damage from #7

Table 20, Target Properties for Material Development

Property	Current	Target
Strength in weak direction	12 ksi	>18 ksi
Modulus	600 ksi	>500 ksi
Strain	4.0%	>6.0%
Mold Shrinkage	1.2%	<0.5%
Cost/pound	$5.65	<$6.00
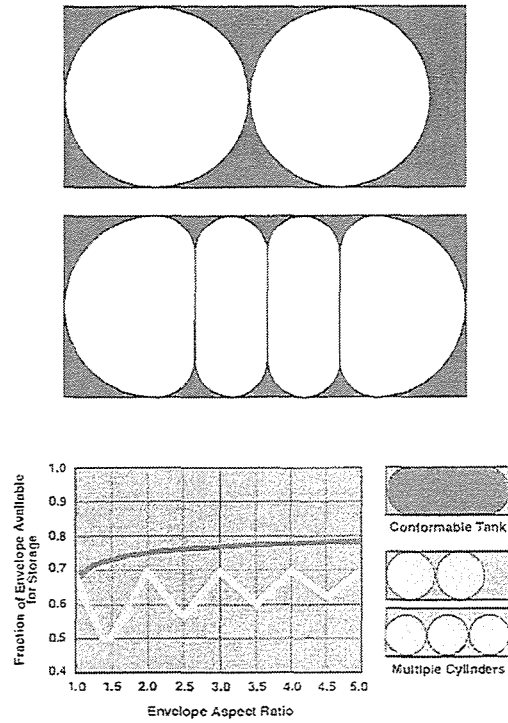
Figure 1, The Conformable Storage Concept

A1133:
stress = 26951 * time^-.03742
R^2 = .864

A1115:
stress = 16824 * time^-.02703
R^2 = .768
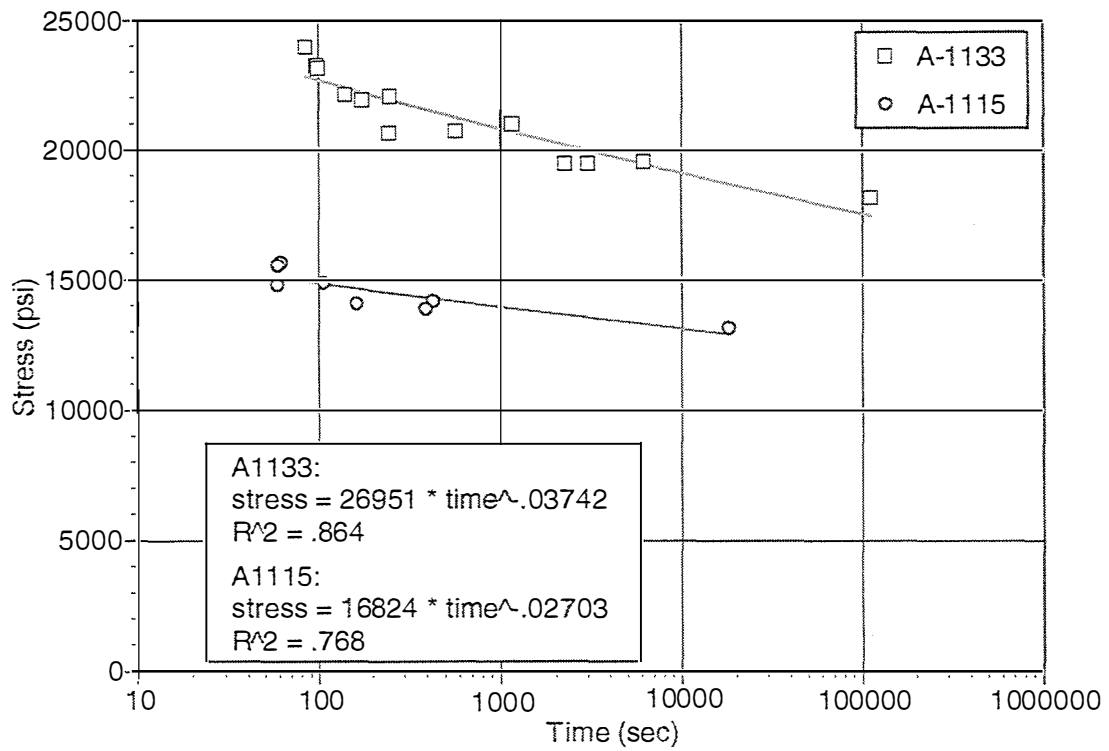
Figure 2, Creep Rupture at 180°F
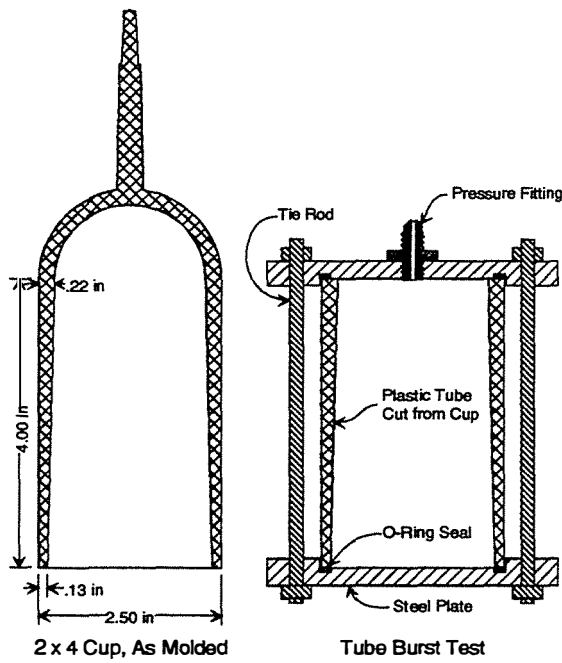
Figure 3, Cup Mold and Tube Burst Test
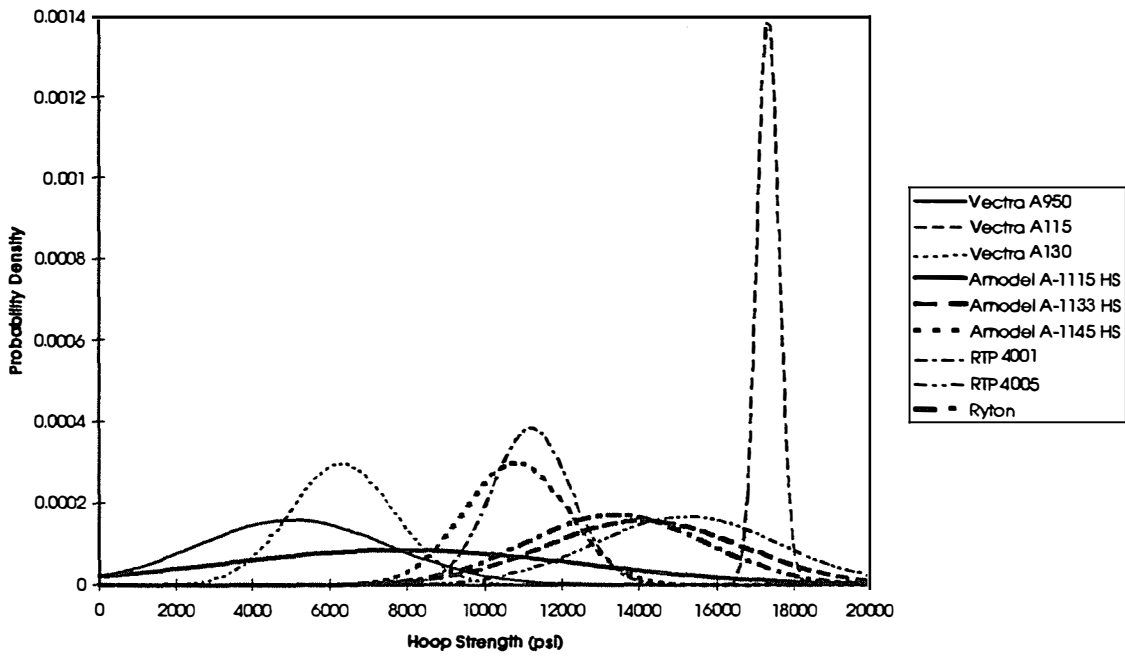
Figure 4, Tube Burst Results

$$f(x) = 0.009043 \cdot x^2 + 0.8643 \cdot x + 20.64$$
$$R^2 = 0.9998$$
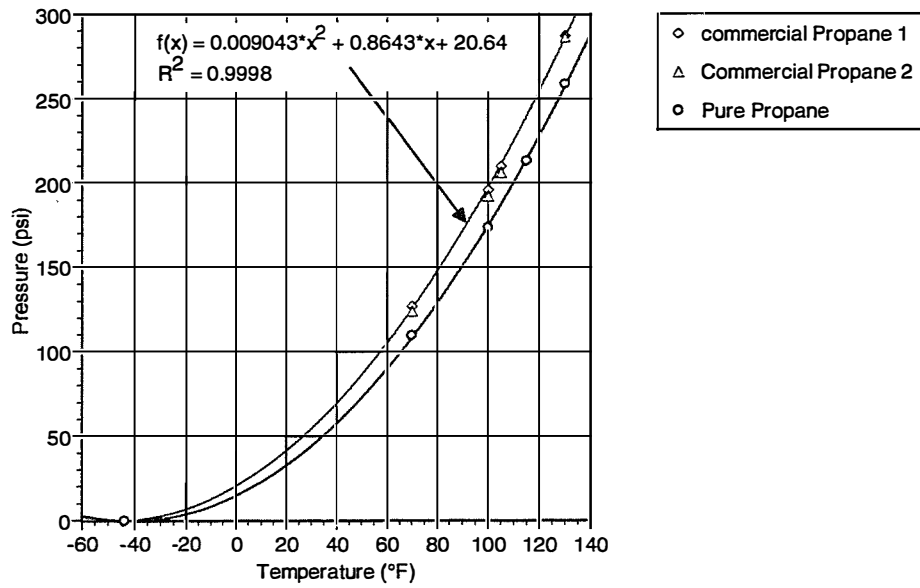
Figure 5, Propane Pressure versus Temperature

Web, 0.125 Thick

Cylinder, 0.19 Thick
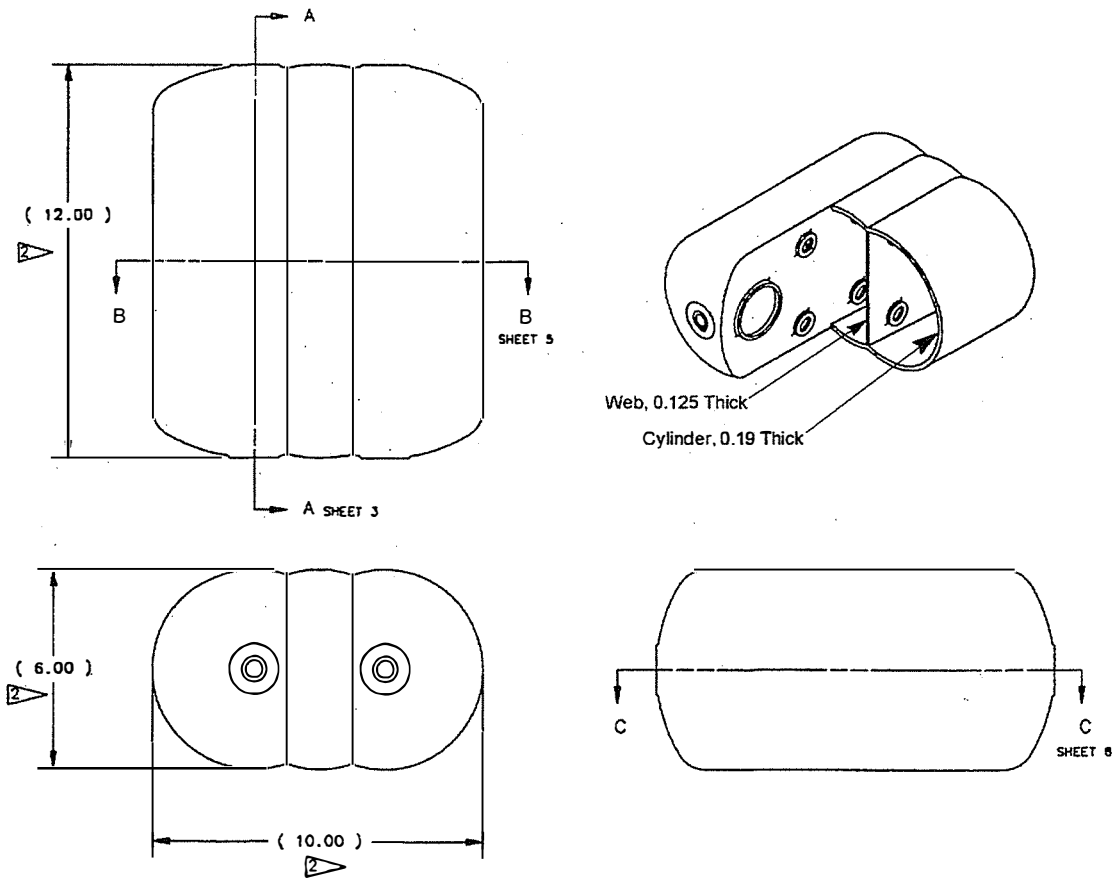
Figure 6, First Subscale Tank Design
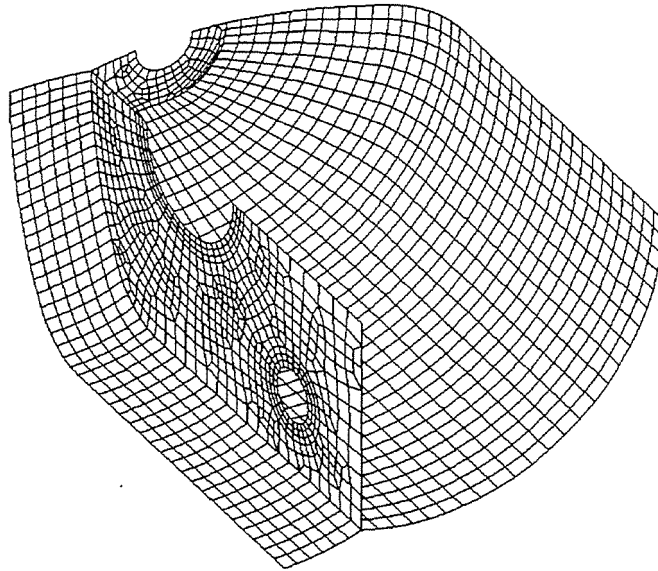
Figure 7, Shell Element Model of First Subscale Tank

R

Z
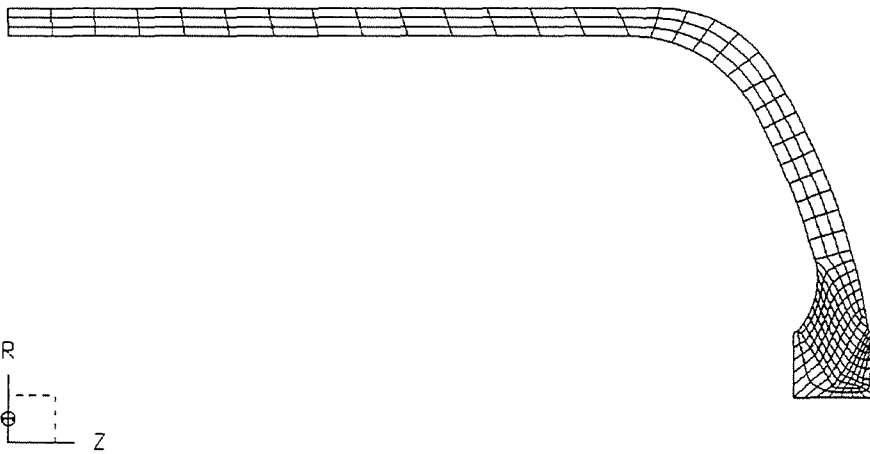
Figure 8, Axisymmetric Model of First Subscale Tank
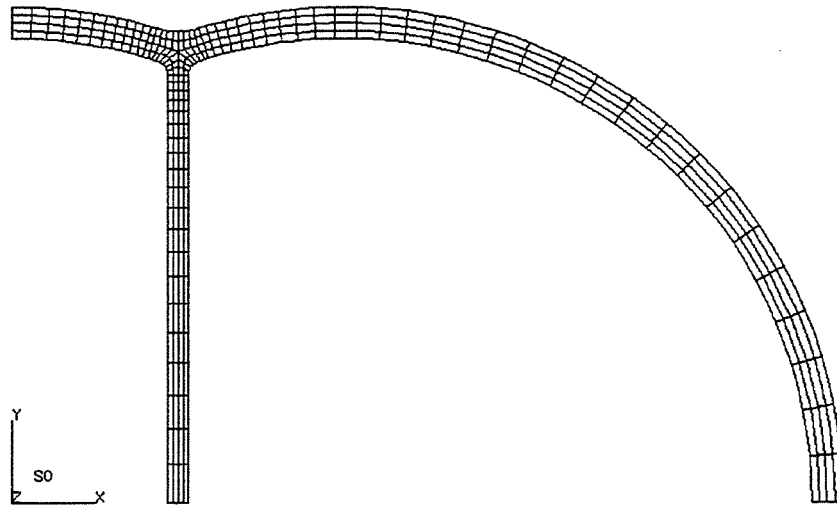
Figure 9, Cross Section Plane Strain Model of First Subscale Tank
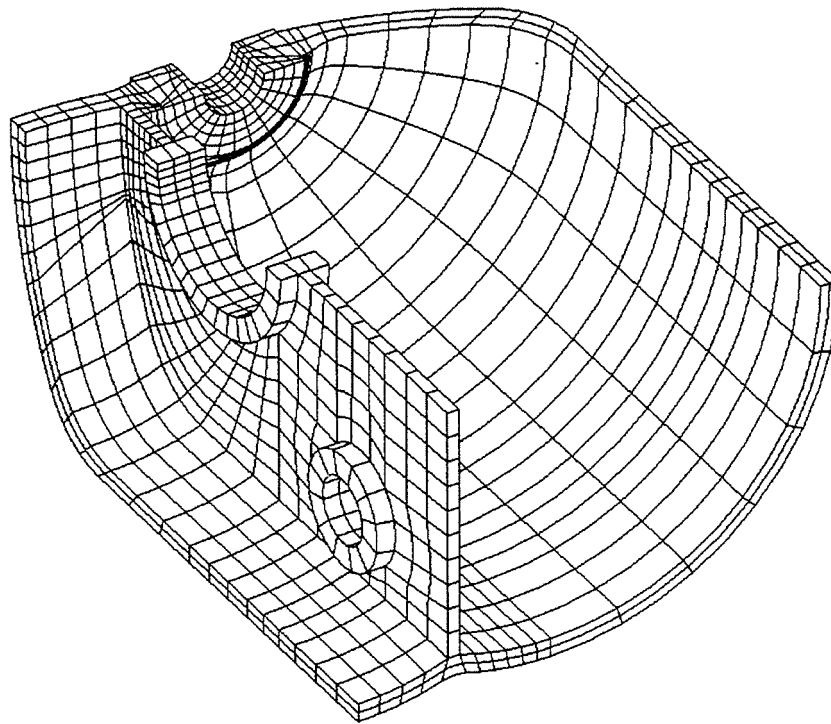
Figure 10, 3-D Solid Element Model of First Subscale Tank

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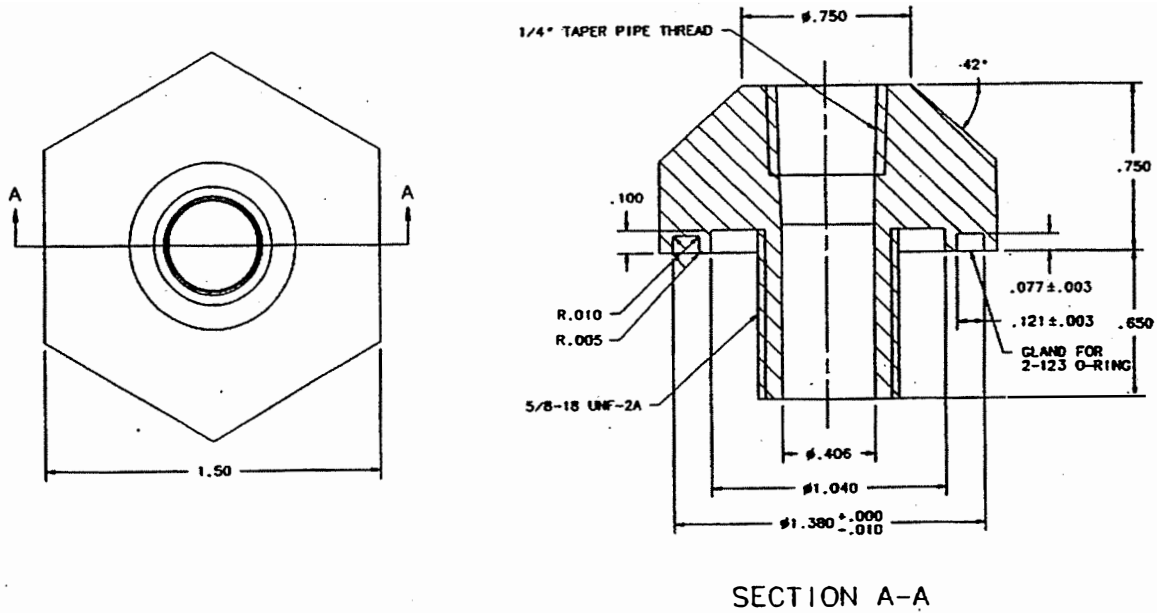
Figure 11, Port Fitting Designed to Eliminate Leakage

Port Fitting

O-Ring

Tank Dome
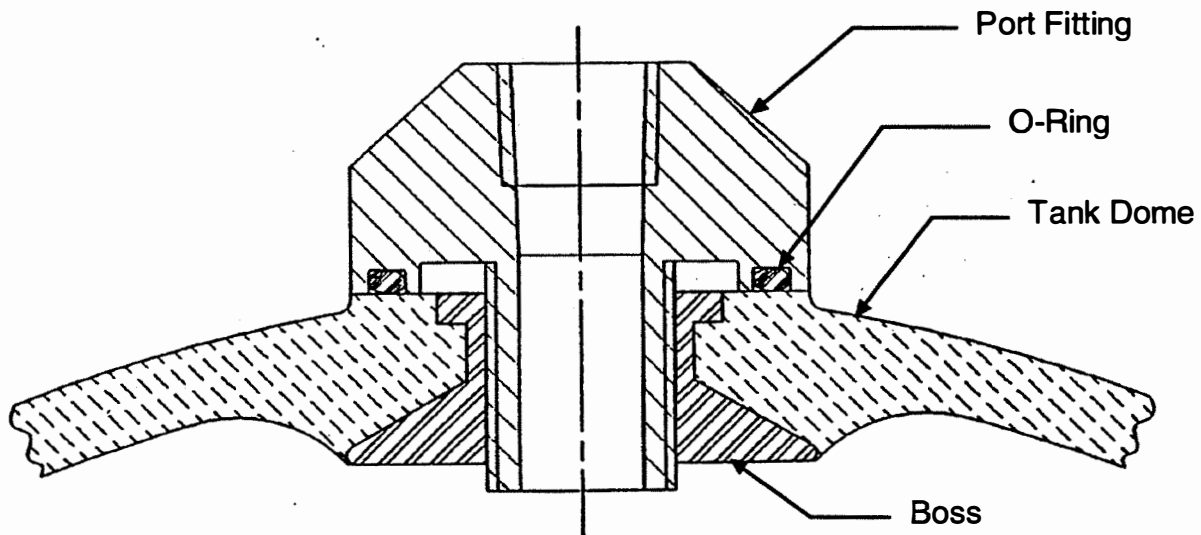
Boss

Figure 12, Port Fitting Seals Against Plastic Face

Boss Shrinkage Analysis
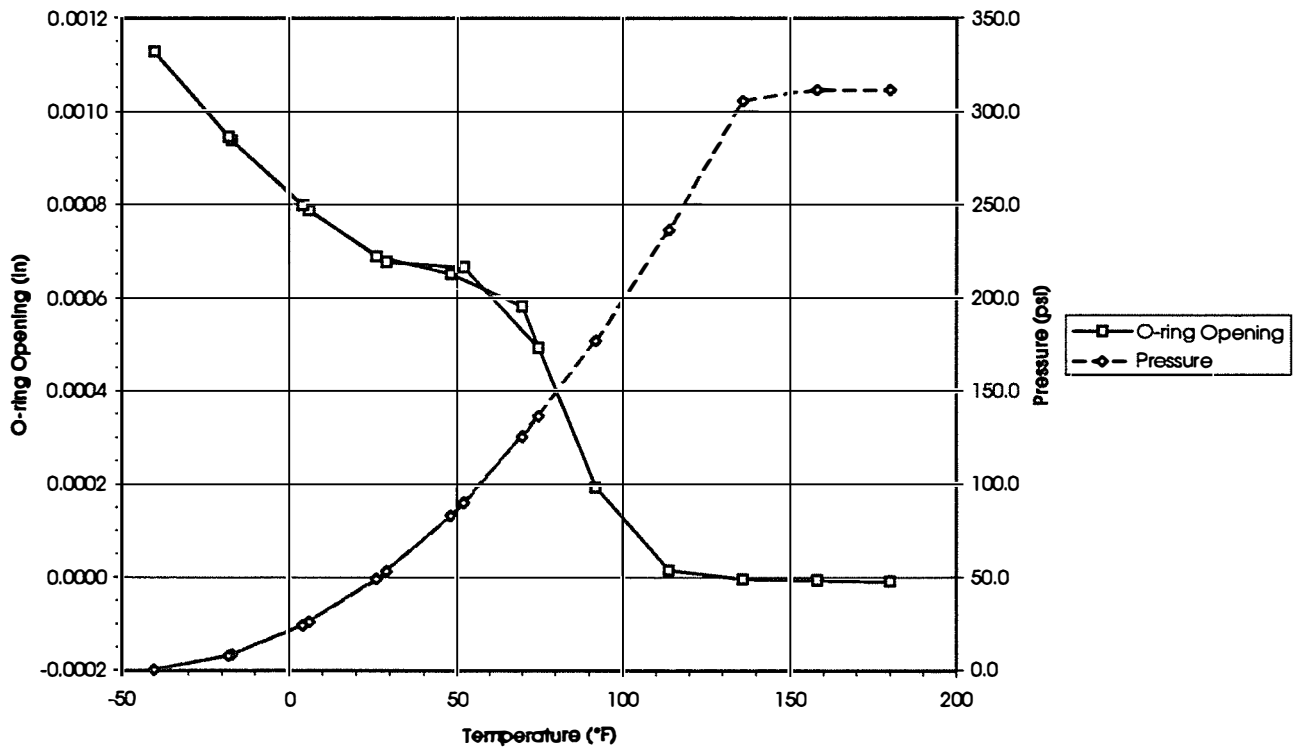
Figure 13, Boss Seal Gap Opening Analysis
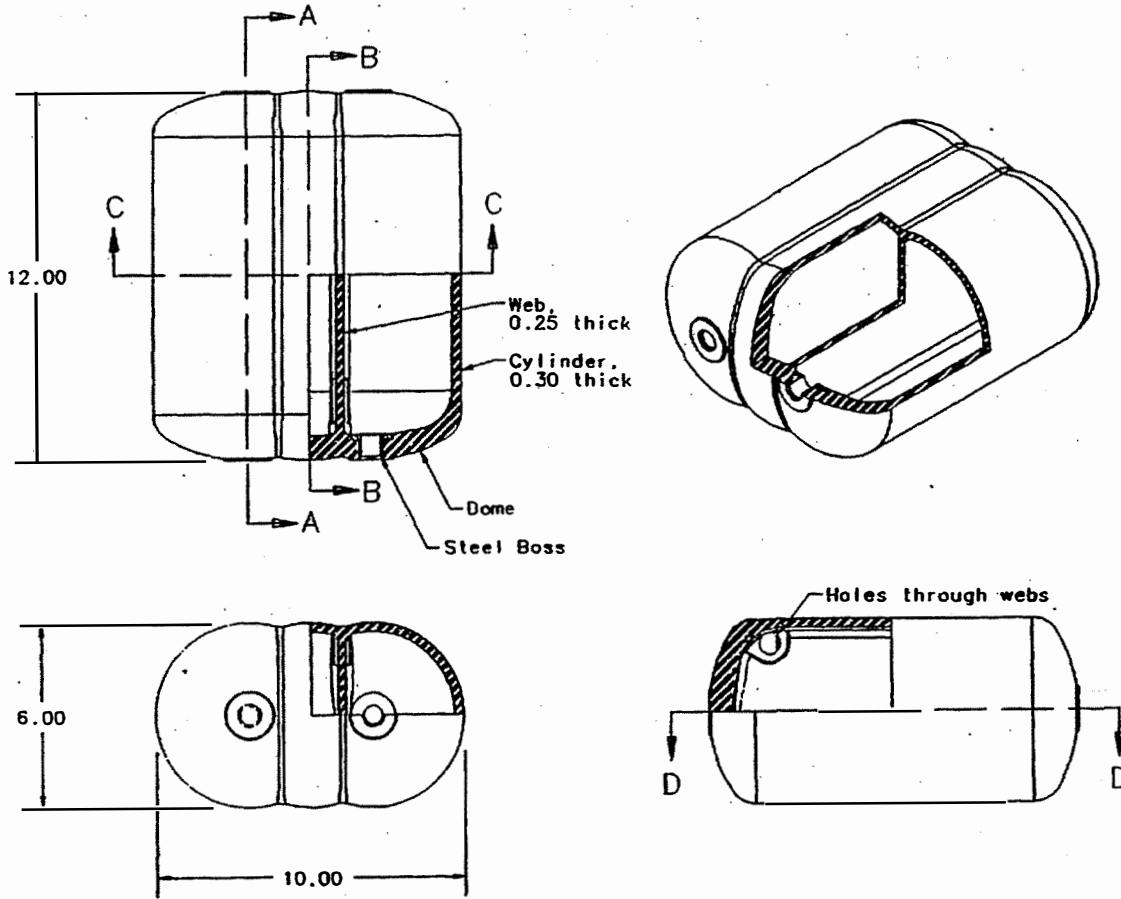
Figure 14, Intermediate Subscale Tank Design
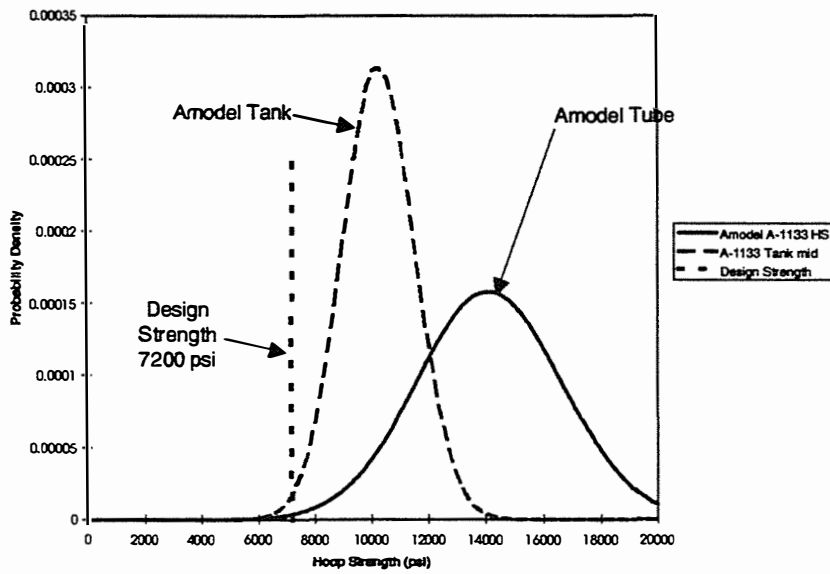
Figure 15, Design Strength for Subscale Tank Design 2
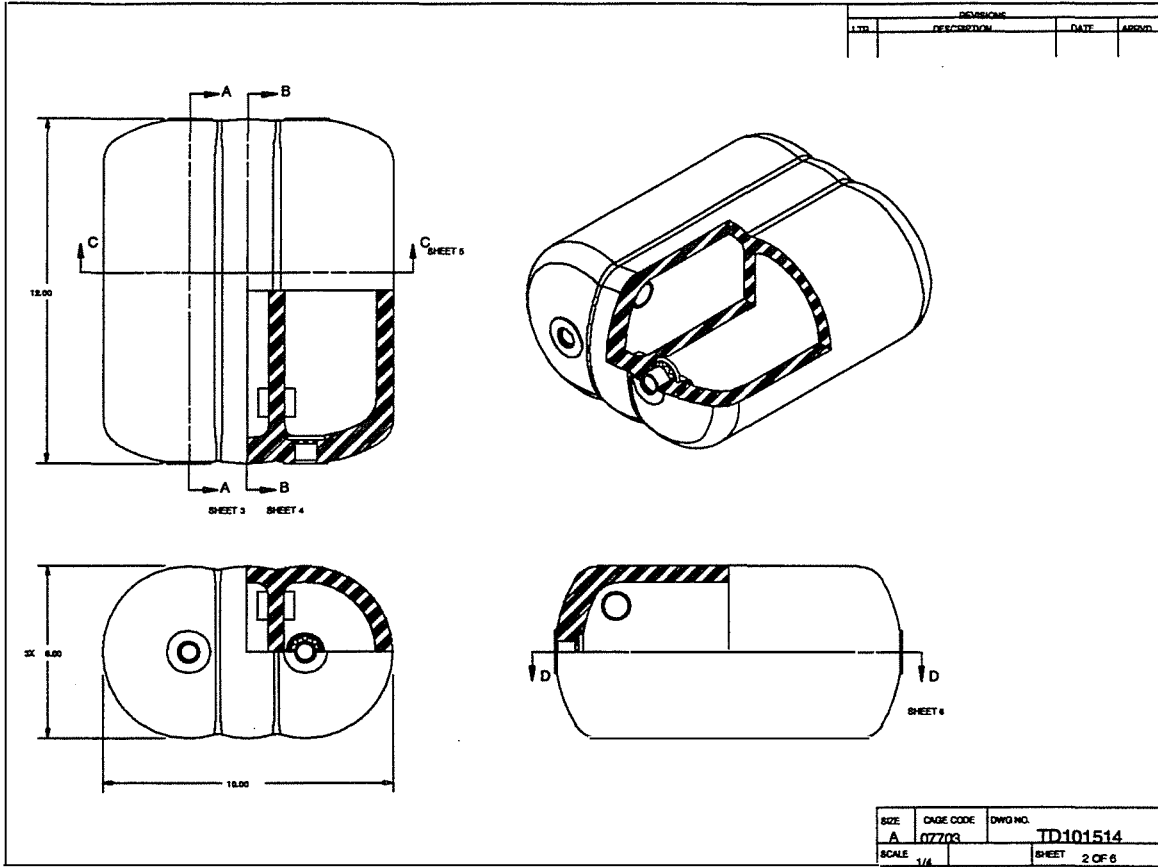
Figure 16, Subscale Tank Design 2
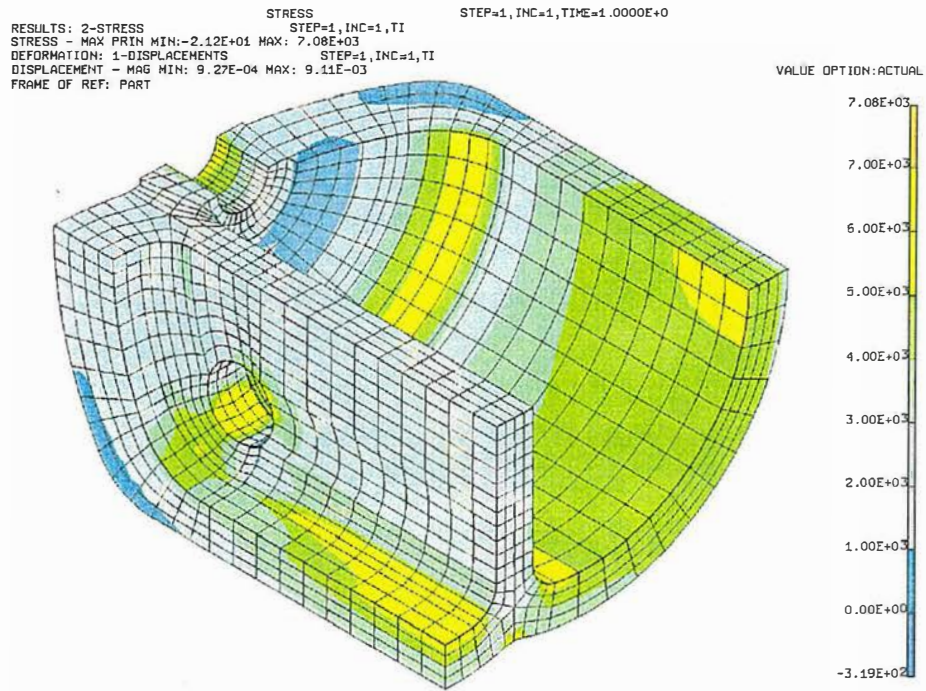
Figure 17, Stress Analysis for Design 2, Inside
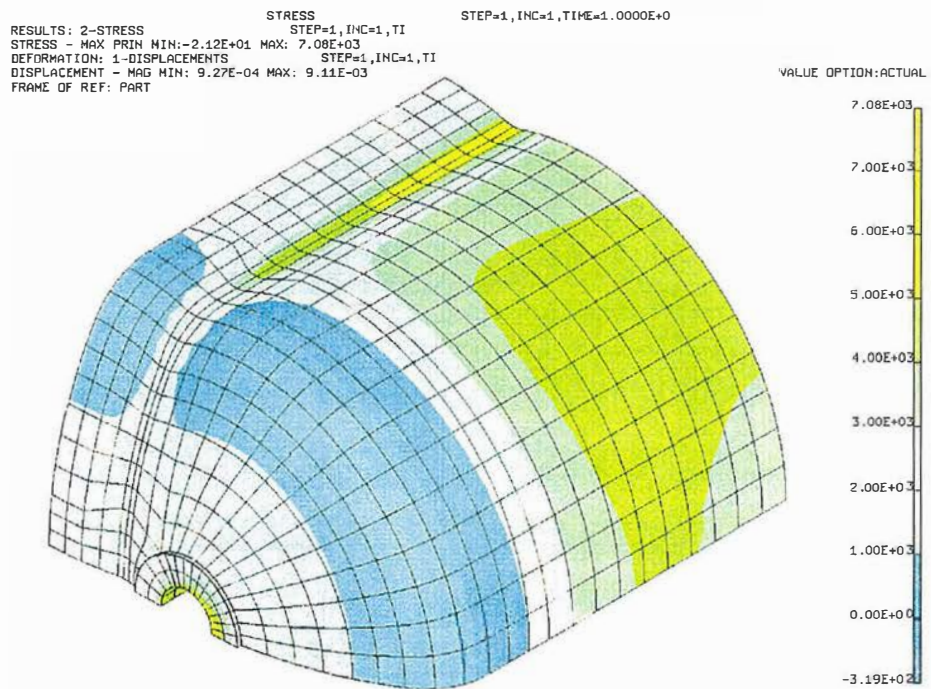
Figure 18, Stress Analysis for Design 2, Outside

A

B   B

36,00

Web.
0.60 thick

Cylinder.
0.69 thick

A

Dome

Steel Boss

14.00

24.00

Holes through webs

C   C
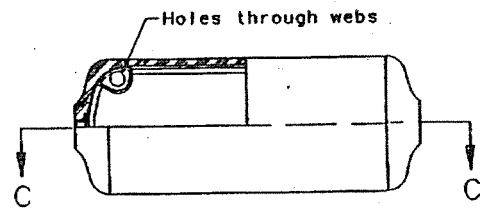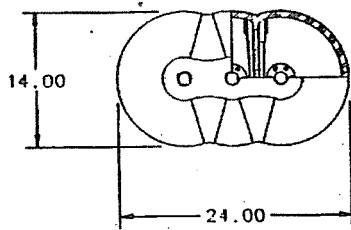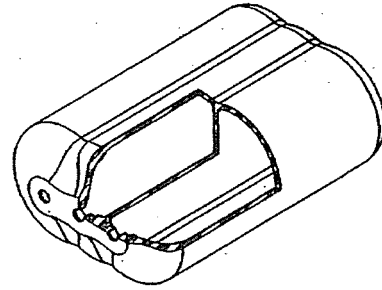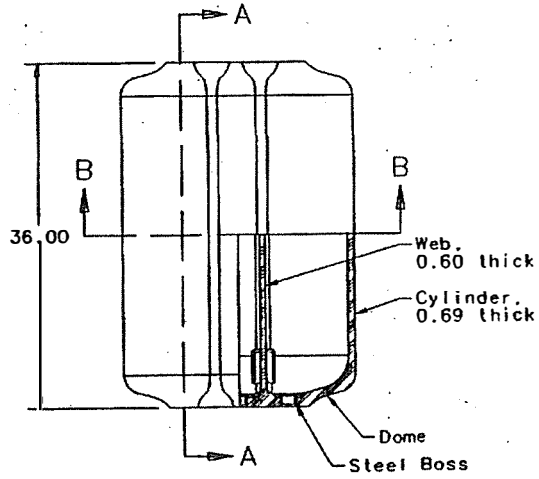
Figure 19, Full Scale Tank Design
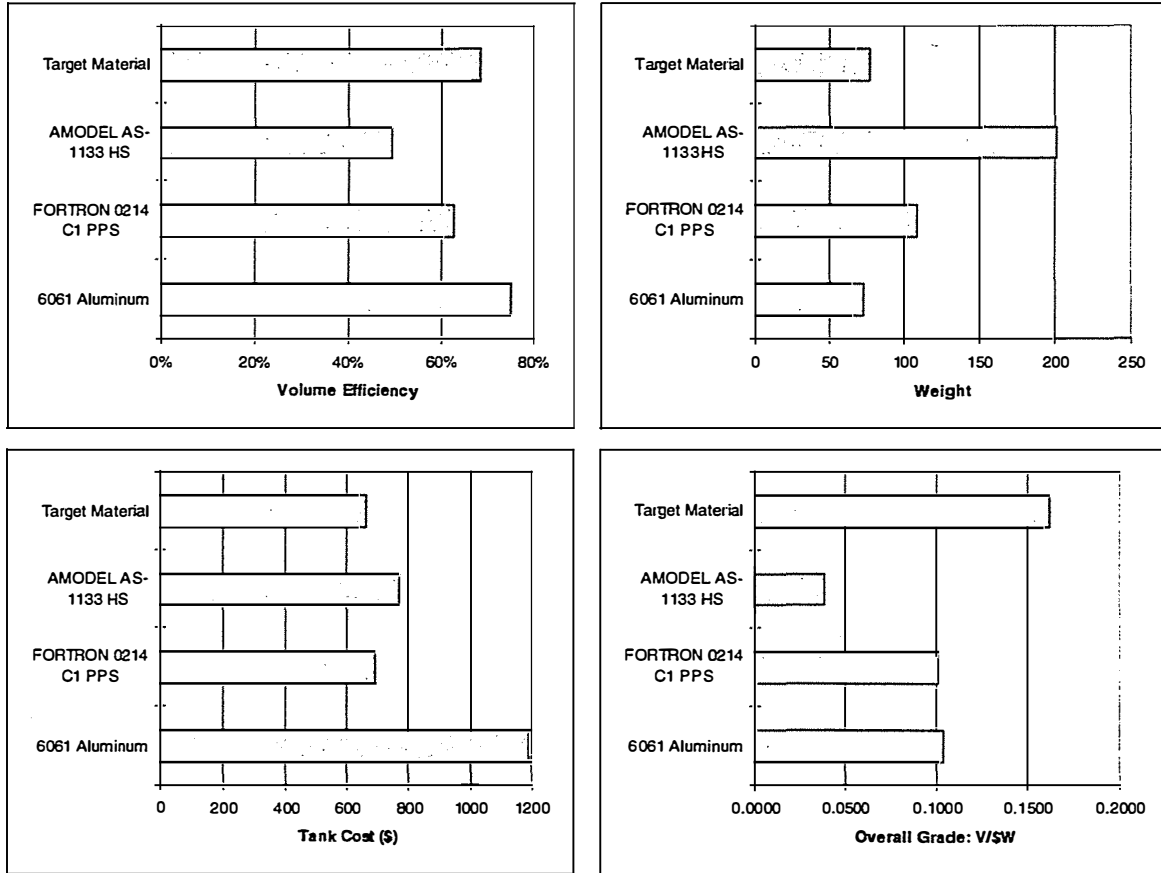
Figure 20, Cost Model Comparisons
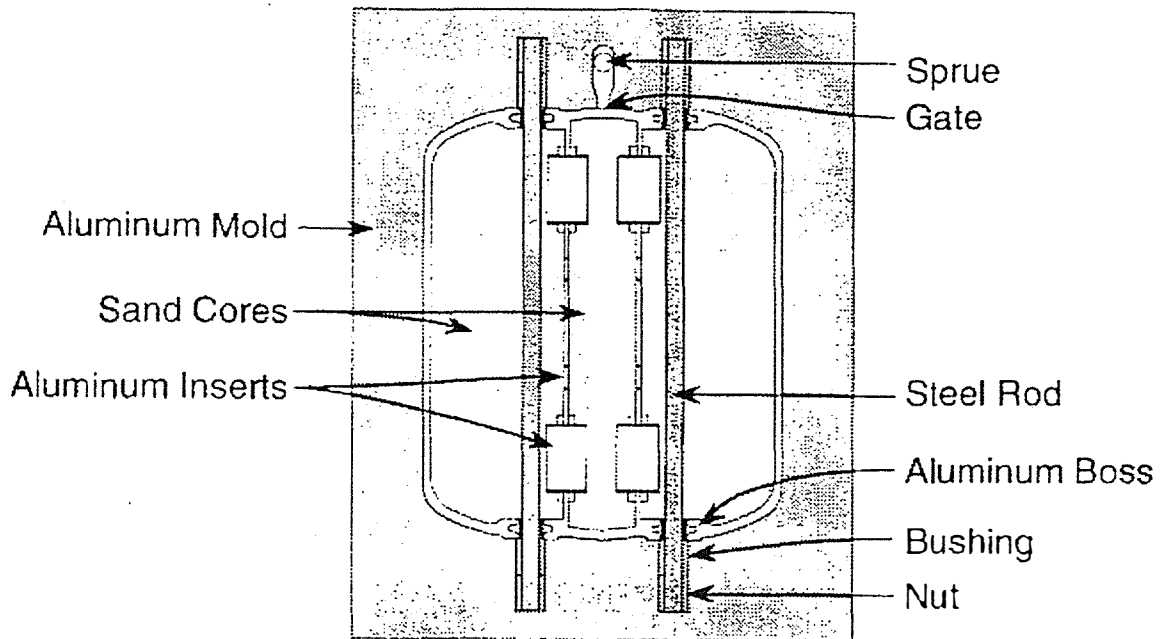
Figure 21, Original Injection Mold

Plastic was injected at top end.

Injection pressure pushed cores downward.

Three core parts moved as a unit, sliding down on rods.

Sand fractured locally where supported by bottom bosses.

Sand cores stopped when they contacted mold at bottom dome.

One dome is thicker than planned.

Cylinder and web thicknesses are correct.

Other dome has zero thickness.
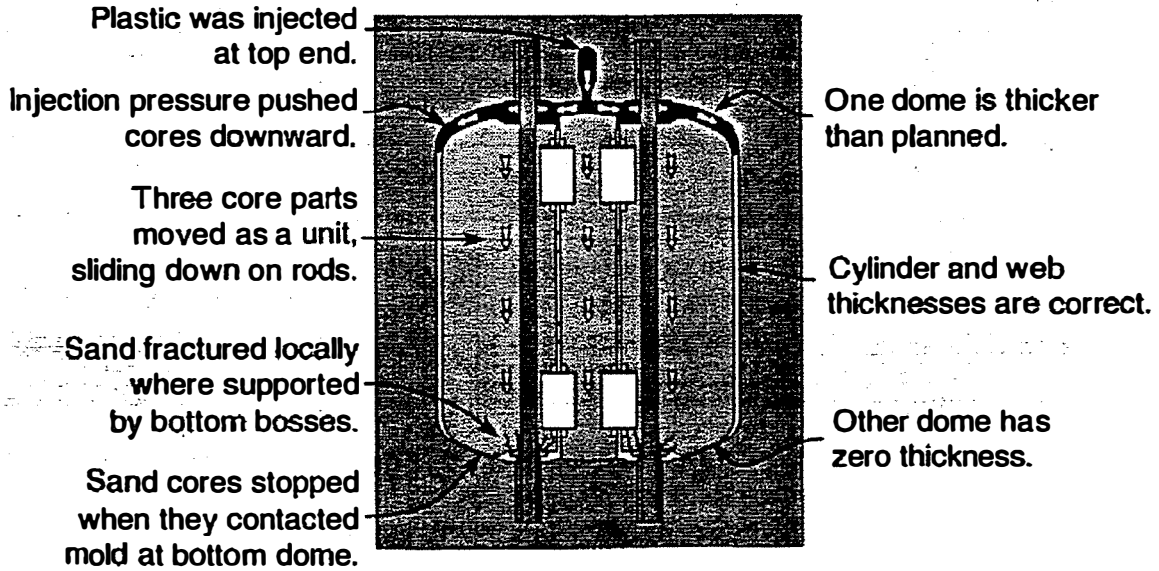
Figure 22, Sand Core Failures

Simultaneous injection at both ends to balance axial loads on sand cores

Different sand binder has higher strength at mold temperatures.

Smooth finish on sand for better flow of plastic

New boss design provides better support to sand cores.
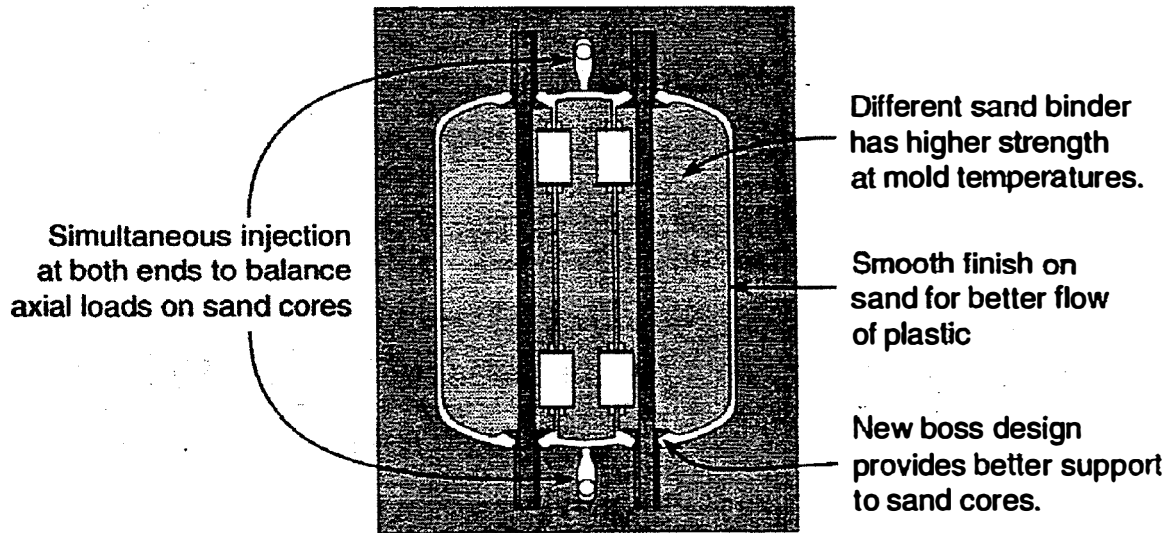
Figure 23, Molding Process Improvements

NOTES:

1. MATERIAL: 4130 STEEL. HEAT TREAT TO 150 Ksi MINIMUM YIELD STRENGTH.

.81

A

.56

30.0°

.10

ø.75

ø1.54

5/8 UNF-2B

R.03

R.03
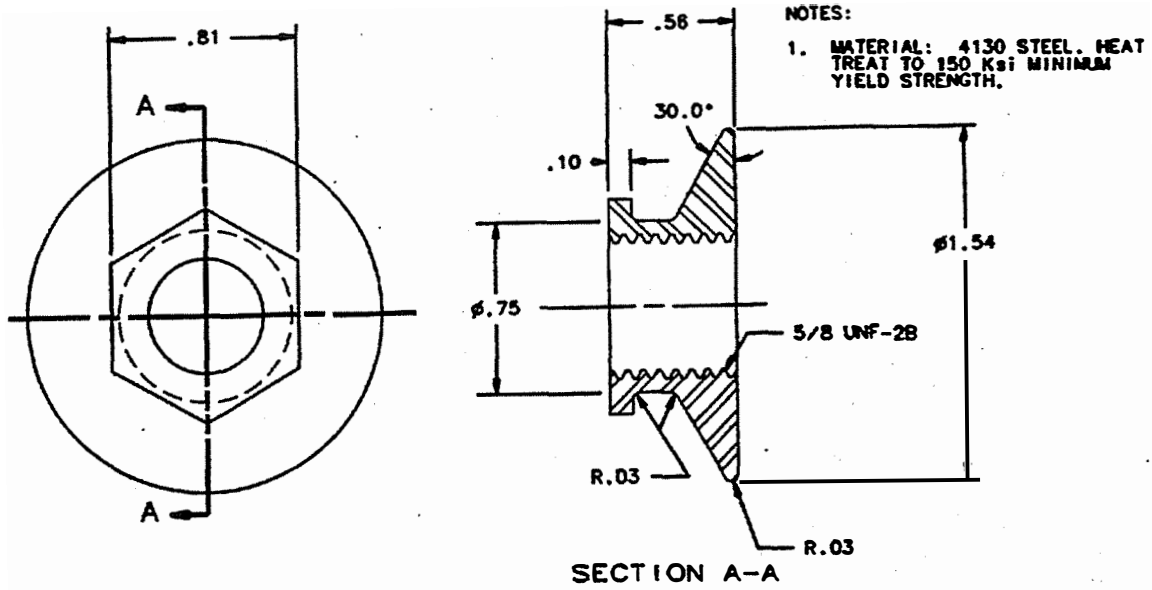
SECTION A-A

Figure 24, Redesigned Boss
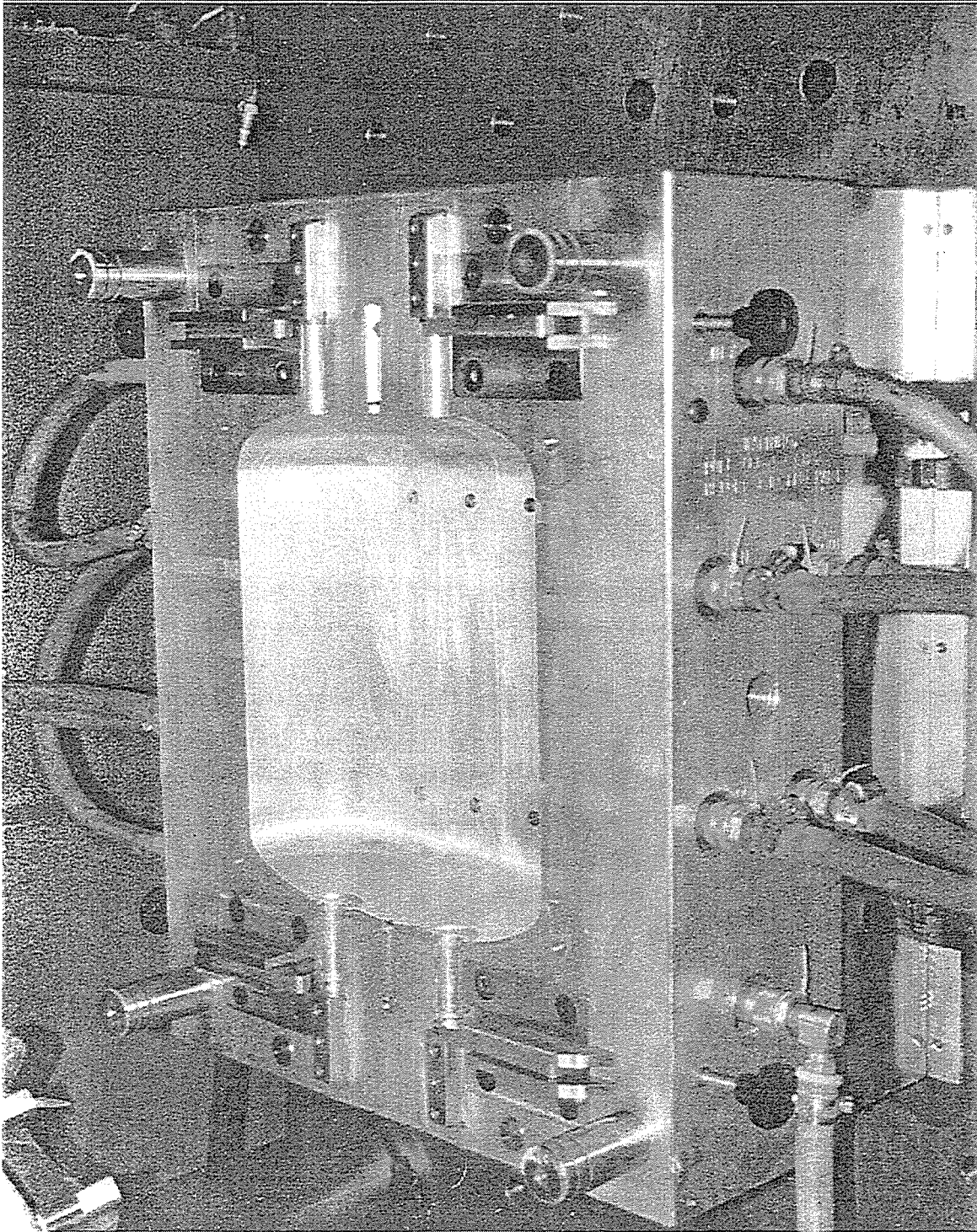
Figure 25, Injection Mold for Subscale Tank
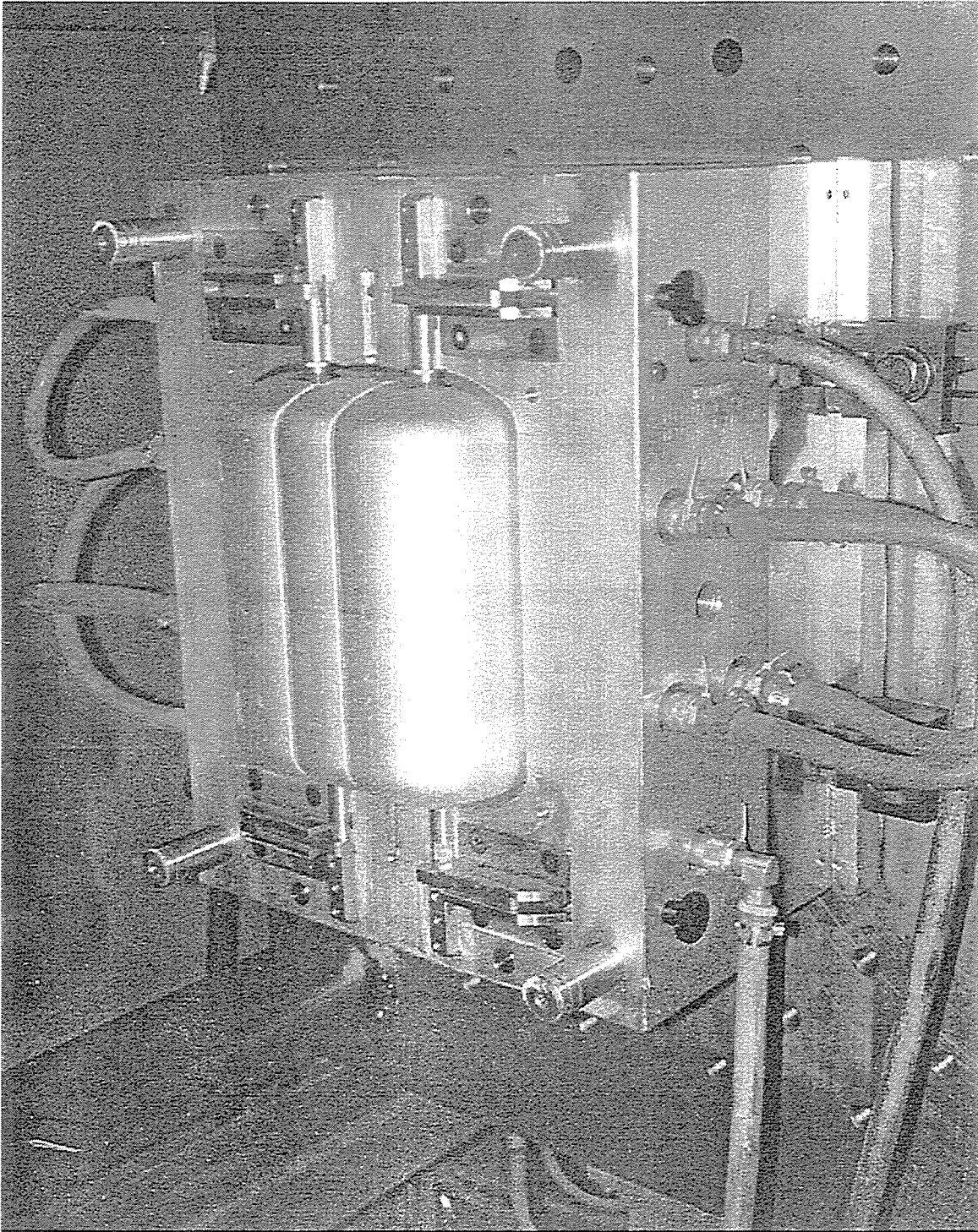
Figure 26. Sand Cores in Injection Mold
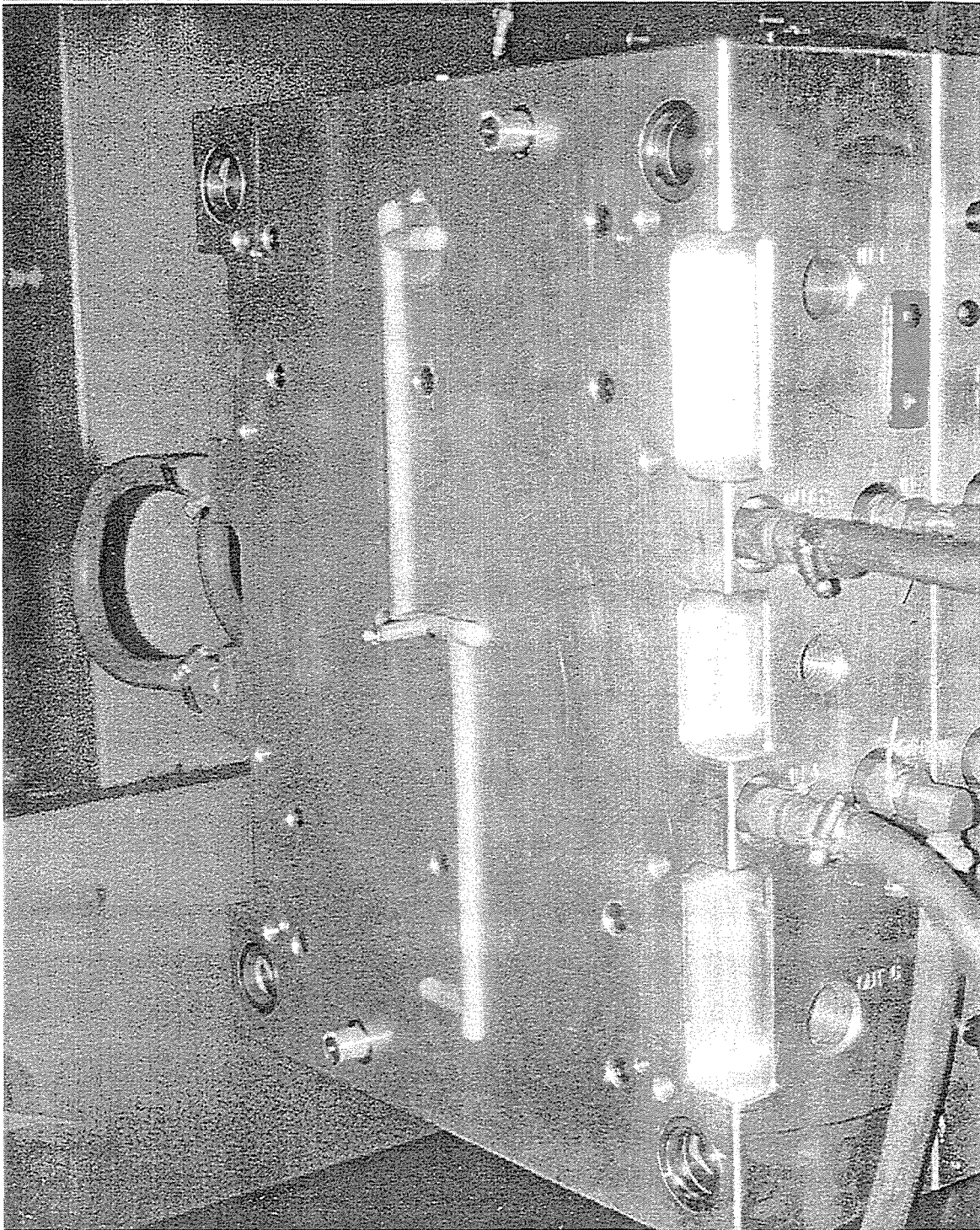
Figure 27, Runner System for Balanced Injection at Both Ends
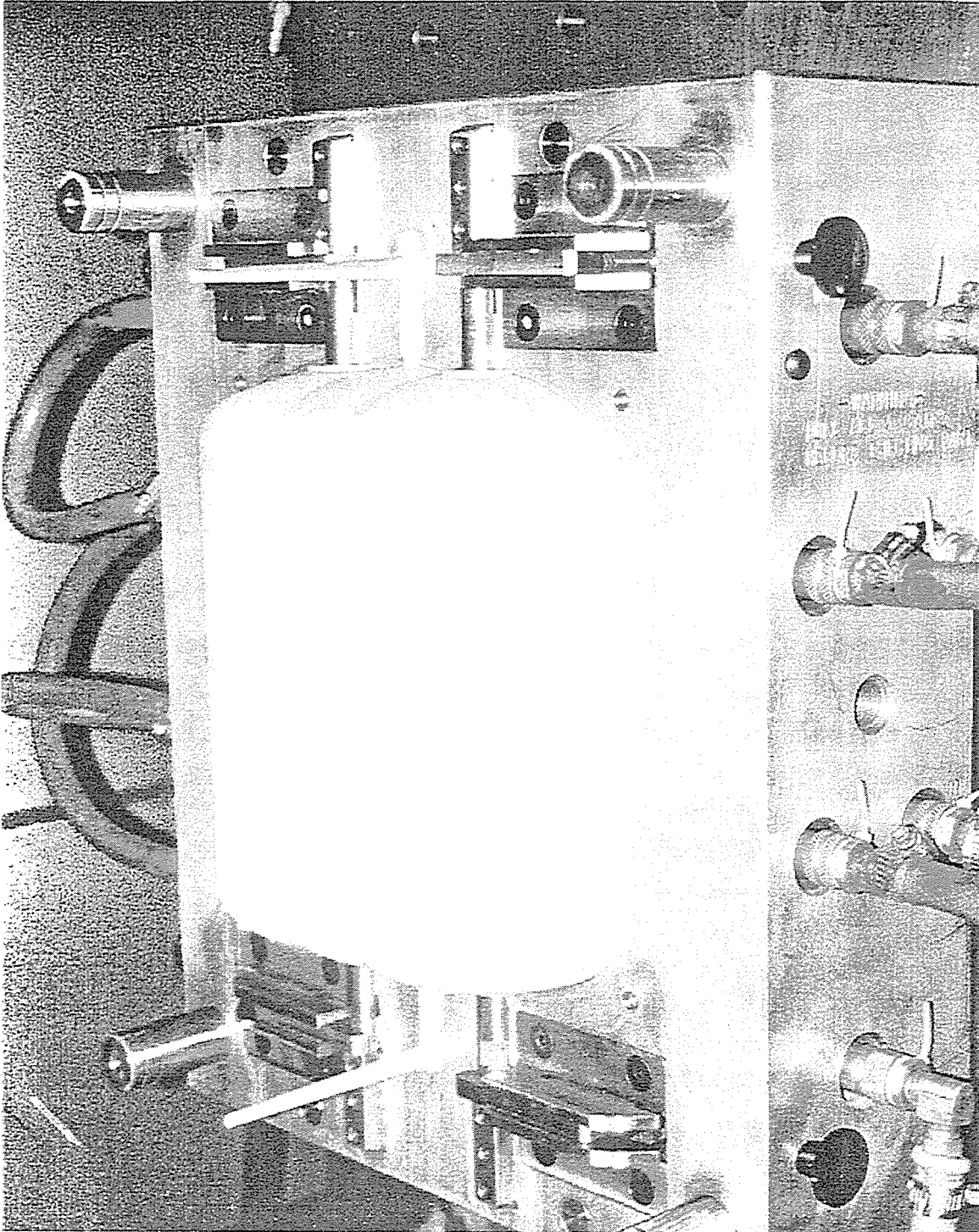
Figure 28, Mold Opened after Molding Part
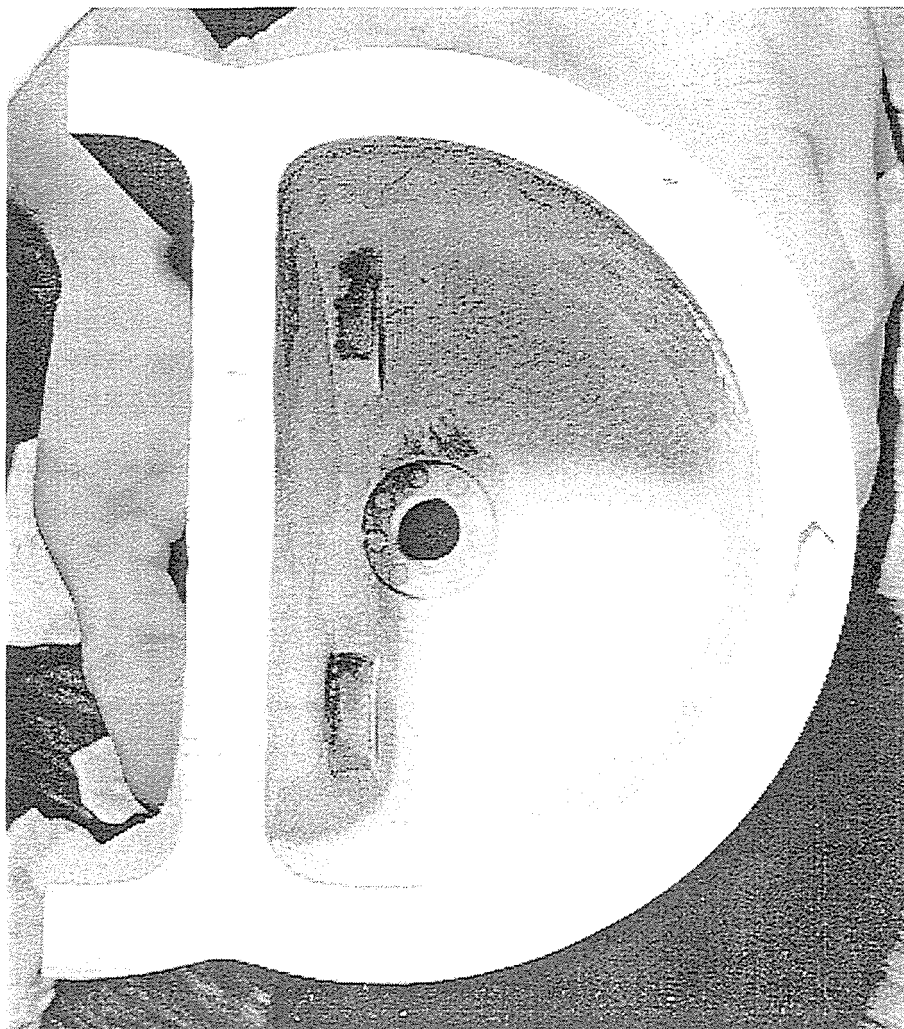
Figure 29, Design 2, Tank #1, Dissected
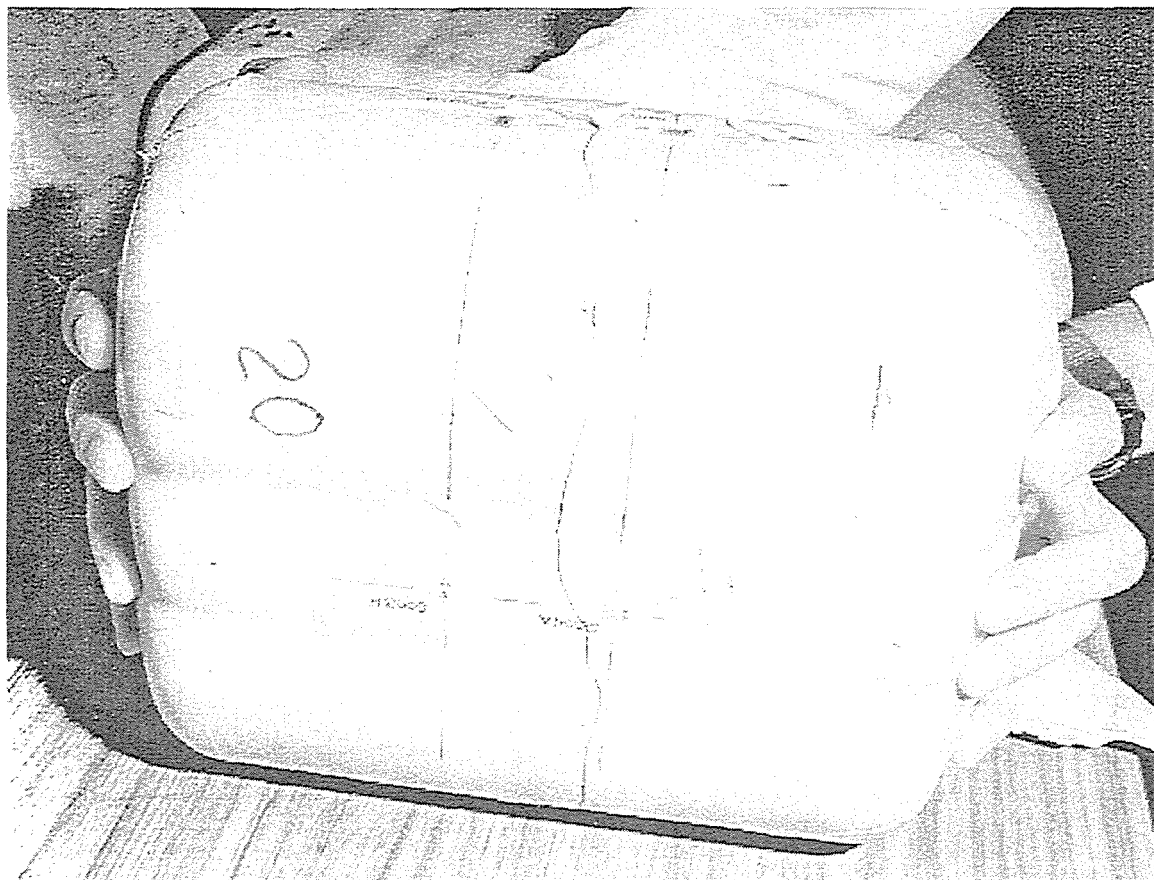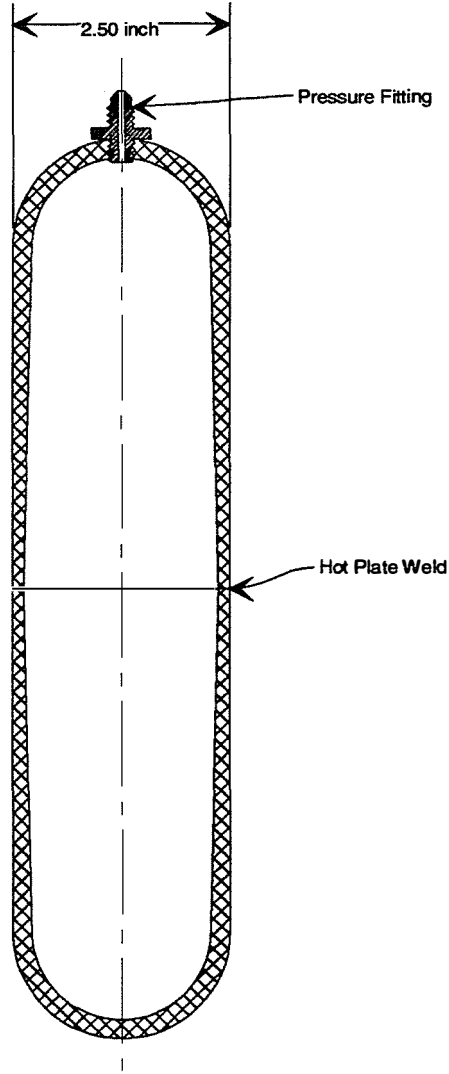
Figure 30, Design 2, Tank #20, After Burst Test

2.50 inch

Pressure Fitting

Hot Plate Weld

Figure 31, Welded Bottle Test

Welded Bottle vs Tube Bursts
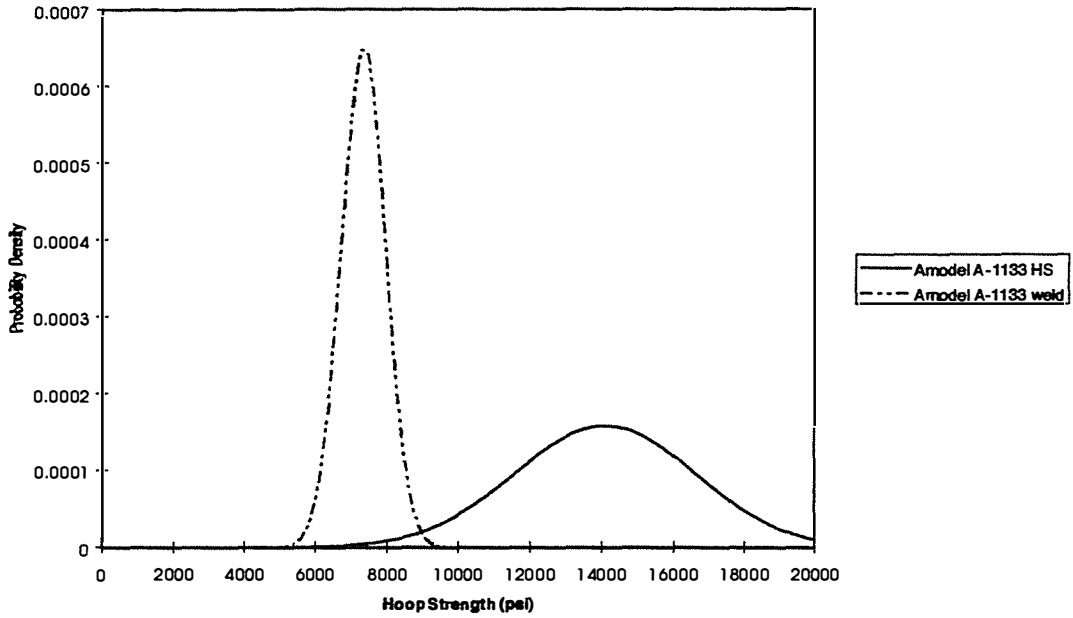
Figure 32, Weld Tests for AMODEL A-1133 HS

Welded Bottle vs Tube Bursts
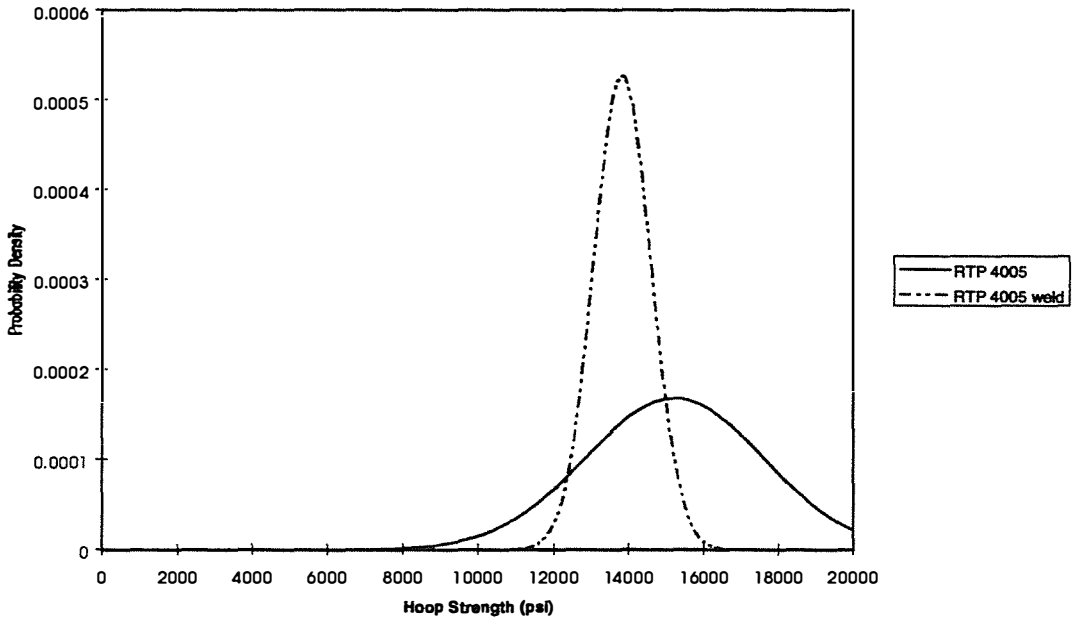
Figure 33, Weld Tests for RTP 4005

Figure 34, Design 1, Tank #10, After Burst Test
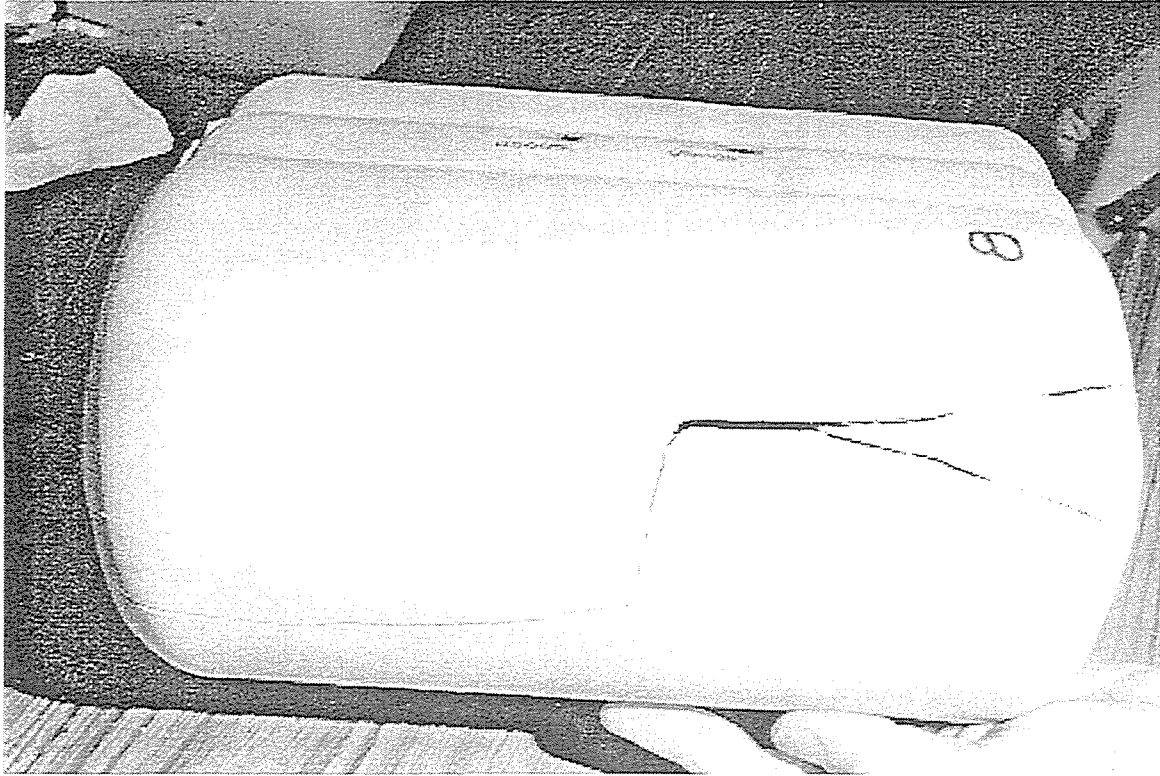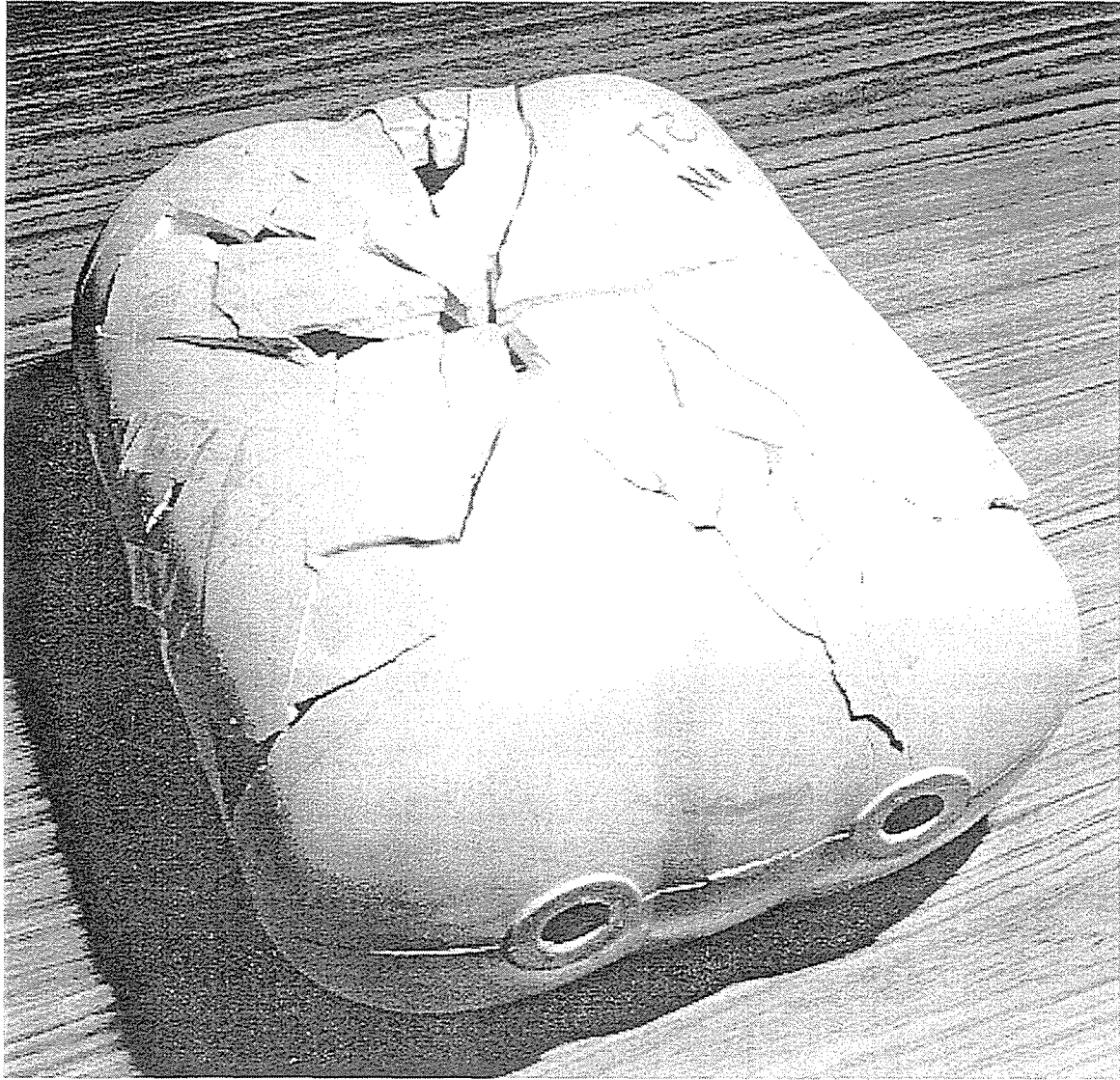
Figure 35, Design 1, Tank #8, After Burst Test

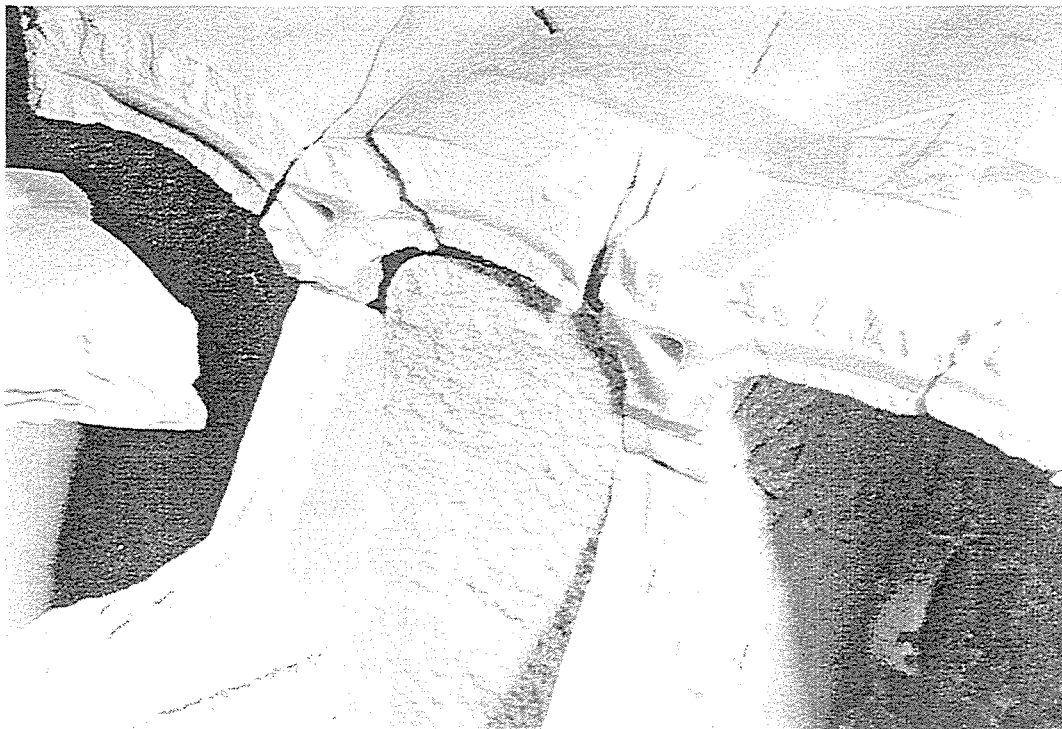Figure 36, Design 2, Tank #21, Reassembled After Burst Test

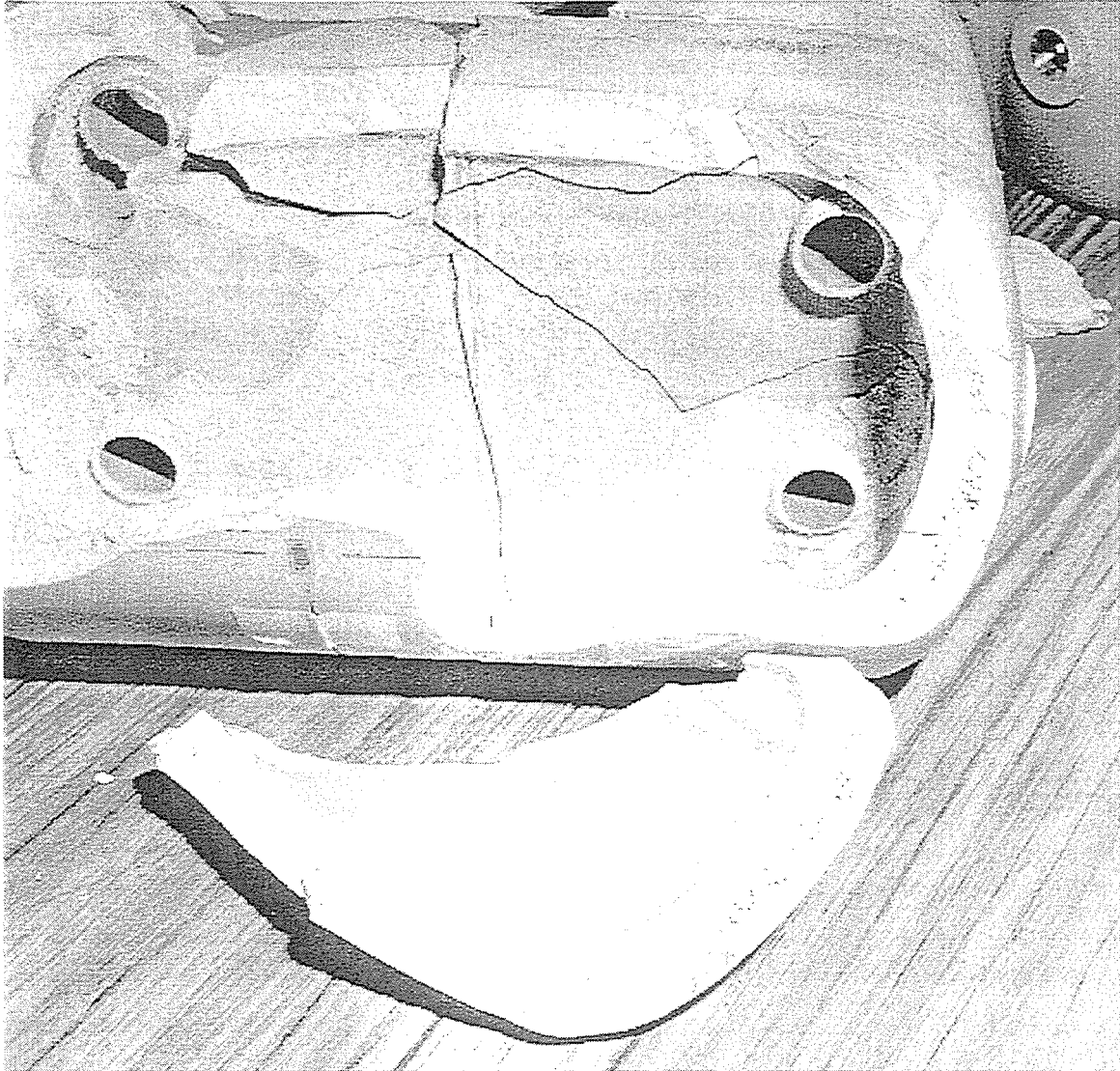Figure 37, Design 2, Tank #21, Weld Line Fracture

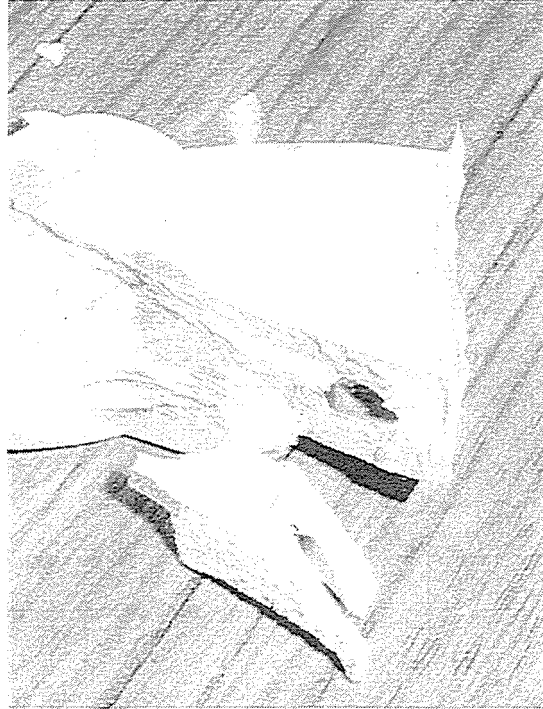Figure 38, Design 2, Tank #20, After Burst Test

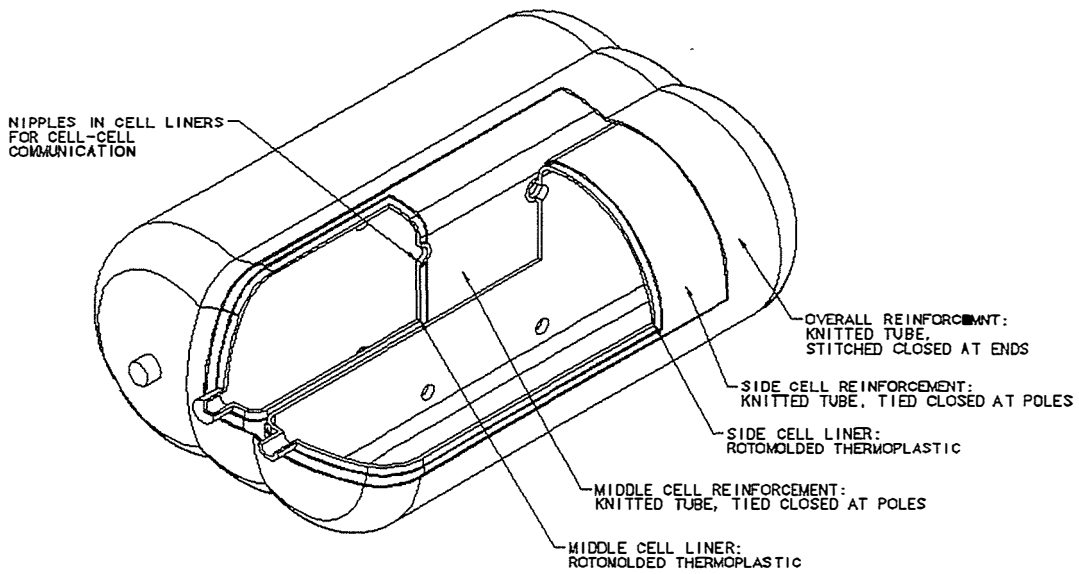**Figure 39, Design 2, Tank #21, Void Near Weld Line**

NIPPLES IN CELL LINERS
FOR CELL-CELL
COMMUNICATION

OVERALL REINFORCEMENT:
KNITTED TUBE,
STITCHED CLOSED AT ENDS

SIDE CELL REINFORCEMENT:
KNITTED TUBE, TIED CLOSED AT POLES

SIDE CELL LINER:
ROTOMOLDED THERMOPLASTIC

MIDDLE CELL REINFORCEMENT:
KNITTED TUBE, TIED CLOSED AT POLES

MIDDLE CELL LINER:
ROTOMOLDED THERMOPLASTIC

Figure 40, Design for SRIM Molding

CORE MOLD

CELL REINFORCEMENT PREFORMS

OVERALL REINFORCEMENT PREFORM

CAVITY MOLD
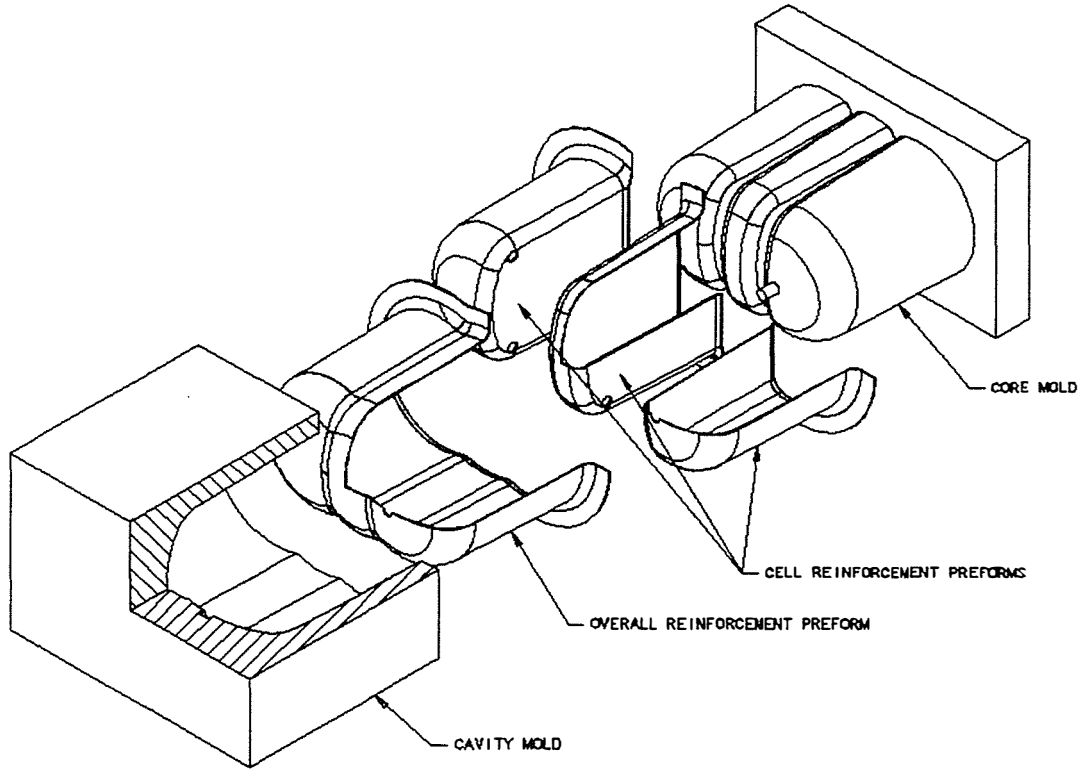
Figure 41, Fabric Reinforced Thermoplastic Injection Molding

INJECTION MOLDED THERMOPLASTIC
WITH EMBEDDED REINFORCEMENT

LAP JOINT FOR ADHESIVE BONDING
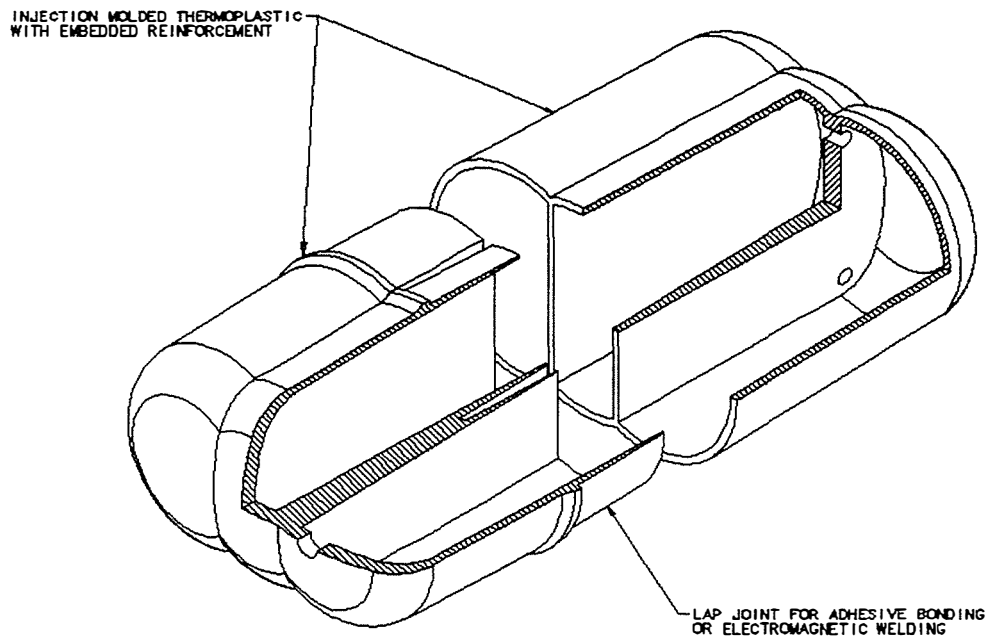OR ELECTROMAGNETIC WELDING

Figure 42, Lap Joint for Joining Tank Halves
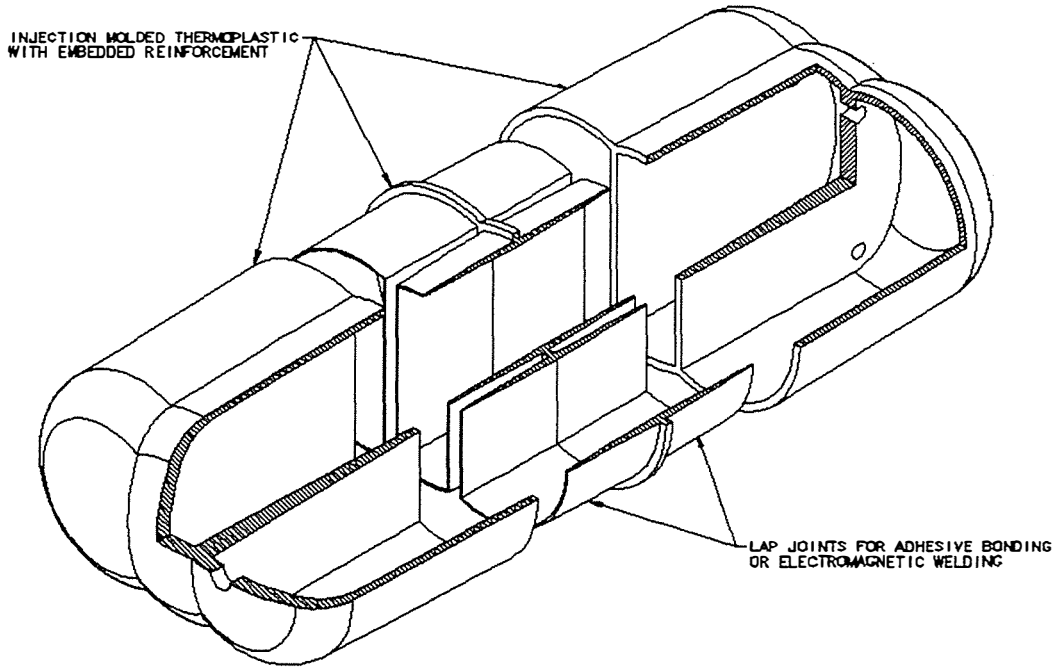
Figure 43, Double Lap Joint for Joining Tank Halves
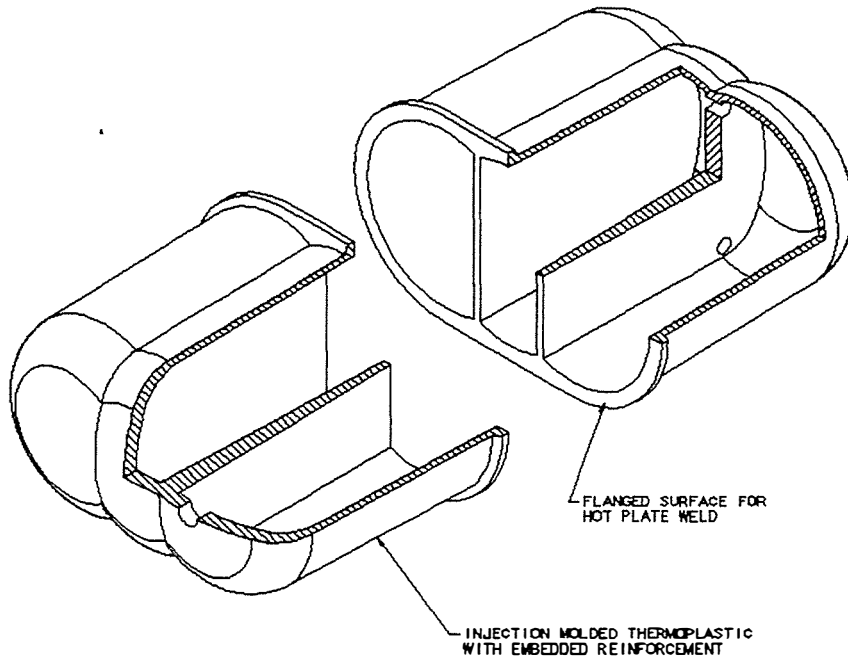
Figure 44, Butt Joint for Joining Tank Halves

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13. ABSTRACT *(Maximum 200 words)* Although liquefied petroleum gas and compressed natural gas are attractive contenders for converting vehicles from gasoline and diesel to alternative fuels, two factors inhibit conversion: additional vehicle costs and reduced range compared to gasoline. In overcoming these barriers, a key element of the alternative fuel system becomes the storage tank for these pressurized fuels. Thiokol Corporation has developed and is now producing a conformable aluminum storage system for liquefied petroleum gas, which increases the fuel storage in a given rectangular envelope. This project's goal was to develop the technology for a similar conformable tank made of injection-molded plastic to decrease costs.

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