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TESTING OF HIGH PRESSURE HYDROGEN COMPOSITE TANKS

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Abstract

The goals of this project were (a) to provide data to manufacturers, regulatory agencies and the public that are beyond the scope of certification tests to help in demonstrating the viability of onboard compressed gas hydrogen storage, and (b) to provide quantitative information on tank failure and hydrogen release that can be used in the development of improved materials and environmental models. The project consisted of two phases. The first phase focused on tank properties, while the second phase characterized the properties of the ignited hydrogen plume venting from a high-pressure tank. Our results in the first phase indicate that the energy for penetration and a critical flaw size can be quantitatively determined for a specific tank design. The second phase results show that under realistic penetration conditions, ignition of the gas does not produce severe shock wave or temperature conditions to the surrounding environment. Furthermore, the polymer liners in Type IV tanks reduced release rates in some cases.

Introduction

The certification of lightweight composite-based high-pressure tanks for use in onboard hydrogen storage applications generally follows tests and procedures developed for compressed natural gas vessels [1],[2], [3], [4]. These tests generally consider the long-term integrity of the vessels (e.g., cycling fatigue, abrasion) and environmental factors, such as corrosion. Such testing is a necessary condition for the tanks to be accepted by end users and are generally performed by the tank manufacturer. However, there are additional data to be gained from catastrophic testing of high-pressure tanks that can increase our knowledge of the properties of composite tanks. A greater understanding of the failure modes and the properties of hydrogen gas plumes vented from high pressure tanks could aid in enhancing the acceptance of hydrogen for vehicular use as well as increasing the confidence of regulatory agencies, manufacturers and the public in the use of high pressure tanks as hydrogen storage devices. Furthermore, this additional information could be applied to extending current models to fully understand failure mechanisms beyond a uniform burst test condition. This project was aimed at these issues, with the intention of providing experimental data not generally obtained during the certification procedure.

Briefly, the goals of this project can be summarized as follows:

(a) to provide data to manufacturers, regulatory agencies and the public that are beyond the scope of certification tests to help in demonstrating the viability of onboard compressed gas hydrogen storage, and

(b) to provide quantitative information on tank failure and hydrogen release that can be used in the development of improved materials and environmental models.

Initially, our plans were to conduct a comparative study between hydrogen and other fuels, such as gasoline, natural gas, and propane. The data were to be documented and distributed both in written form and in video/film through a collaborative effort with the H2000 project. The project was to be reviewed and approved by an oversight committee of experts coming from both industry and federal agencies. However, the program plan was significantly modified from the original plan in response to criticisms from the reviewers in the FY00 Hydrogen Program Review, using input from the oversight committee members as well as other consultants. The scope of the project was also greatly reduced and focused specifically on quantitative tank penetration tests.

The final project, now completed, consisted of two phases. In Phase I, tests were aimed at generating data on the properties of the tank containing high-pressure gas. The energy required to penetrate the filament-wound composite vessel was determined and examined with current modeling predictions on composite vessels. Phase II of the project addressed the effects of a hydrogen release from a high-pressure tank and the impact of an ignition of the escaping gas plume. The results of Phase I demonstrated that there is a critical flaw size for these vessels above which catastrophic failure will occur. The results also showed a linear dependence of penetration energy on the penetrating rod diameter and thus a relationship with the shear strength of the composite vessel lay-up. The results of Phase II show that ignition of a hydrogen gas release from a high-pressure tank, with a credible release rate, is no worse than other fuels, such as gasoline or propane, and may be less damaging to nearby personnel and equipment.

Test Program Description

Composite Pressure Tanks

State-of-the-art composite vessels were manufactured by a commercial vendor for these tests. They were purchased commercially through a competitive bidding process and certified for use at 34.5 MPa (5000 psi) hydrogen. The polymeric-lined, graphite/glass-reinforced epoxy vessels (Type IV) were tested by the manufacturer to 96 MPa without visible damage. The internal volume is 24 liters with an outside diameter of 23 cm and a total outside length of 35 cm. When filled to 34.5 MPa, they have a storage density of 5-wt.% hydrogen. These vessels are compatible for both hydrogen and natural gas containment. A photograph of the general features of the cylinder is shown in Figure 1. Vessel features include a steel (4340 HSLA) single collar with an attached valve. An integrated pressure relief device is generally used, but was not included for these tests. A small number of similarly constructed vessels (Type IV) were purchased from another vendor. However, the modified test matrix did not include these vessels.

Figure 1. Photograph showing general features of the tests cylinders.

The structural lay-up consisted of a 5 mm thick fiberglass composite outer wrap over an 8 mm thick graphite fiber inner wrap. The liner was a 7 mm thick high-density polymeric liner (Note: these thickness values are approximate). A high strength, low alloy steel collar at one end of the cylinder joined the liner material to the cylinder valve. A schematic of the cylinder lay-up is shown in Figure 2.

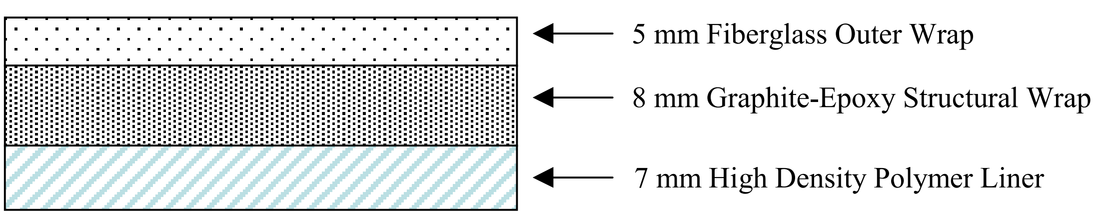

Figure 2. Schematic of composite lay-up.

Test Procedure

Only penetration tests were made in the modified test matrix and two different test sites were used. In Phase I, tests were conducted at a drop tower facility which allowed better video diagnostic capability. However, a large cylindrical shield was employed to protect adjacent buildings and personnel from the potential debris. All Phase I tests were made on tanks filled with nitrogen. In Phase II, a remote facility was used to allow measurements on the hydrogen plume ignition. Overall views of the sites are shown in Figure 3a and 3b. A continuous spark igniter system was used to assure ignition during the hydrogen tests. This simply consisted of a high-performance vehicular spark plug transformer supplying high voltage to spark plug wires positioned at the edge of the expected release plume. More details are given later in this report.

Figure 3a showing drop tower used for nitrogen tests (Tests 1-9)

Figure 3b showing remote cable site used for the hydrogen tests (Tests 10-14)

Extensive diagnostics were employed at both sites. Standard speed (30 fps) videos were used to record the overall test area and to observe close-in to the penetrator impact region on the tank. High-speed video (1000 fps) and film (4000-5000 fps) were used to examine the details of the penetration, tank response and gas release. The internal gas pressure was also recorded throughout the test procedure to determine the gas release rate. Additionally, during Phase II tests, an infrared camera was employed to record the temperature profiles of the ignited gas plumes and pressure transducers were positioned near the target area to determine pressure wave propagation. Post-test examination of the tanks was also conducted, particularly in the fracture regions, to yield information on the failure characteristics of the materials used in the fabrication of the vessels.

In each of the tests, a blunt, cylindrical, weighted rod was dropped onto a rigidly mounted tank. The rod was cable-guided to strike approximately in the center of the cylindrical portion of the tanks. Three different rod diameters were used: 12.7, 25 and 50 mm. The energy of the rod was controlled by adjusting the height and the weight of the rod assembly. Accurate determinations of the impact energy and the energy loss in penetrating the tank could be made directly through velocity measurements taken from the high-speed film and video recordings. A total of 14 tests were conducted, 9 in Phase I and 5 in Phase II. An overall summary of the test conditions is given in Table I.

Table I: Test parameters and observations from the Phase I and Phase II testing

Test #	Rod Dia. (cm)	Cylinder Pressure [MPa]	Drop Height [m]	Rod Weight [kg]	Rod Velocity [m/s]	Rod Energy [kJ]	Remarks
Nitrogen Tests							
1	5.08	24.8	12.1	18.14	13.7	1.7	No visible damage No gas release
2	5.08	24.8	15.2	18.14	18.0	2.9	No visible damage No gas release
3	5.08	24.8	28.0	18.14	22.25	4.52	Visible surface damage No gas release
4	5.08	24.8	26.8	49.0	20.7	10.58	Penetration Gas Release Gas release in 0.2 sec.
5	5.08	34.5	26.8	49.0	20.7	10.58	Penetration **Tank Failure**
6	5.08	34.5	15.2	49.0	16.8	6.92	Penetration **Tank Failure**
7	2.54	34.5	15.2	49.0	16.8	6.92	Penetration Gas Release Gas release in 0.2 sec.
8	1.27	34.5	30.5	12.3	22.9	3.2	Penetration Gas Release Blocked
9	1.27	34.5	30.5	12.3	22.9	3.2	2" Longer spike Penetration Gas Release Blocked
Hydrogen Tests							
10	1.27	34.5	30.5	12.2	22.9	3.2	Penetration Gas release w/ignition Partially blocked Gas release in 6 sec.
11	1.27	24.8	30.5	12.2	22.9	3.2	Penetration Gas release w/ignition Partially blocked Gas release in 60 sec.
12	1.27	34.5	30.48	12.2	22.9	3.2	Penetration Gas Release, no ignition Partially Blocked Daylight Test
13	2.54	34.5	34.4	12.2	24.4	4.3	Penetration Gas release w/ignition Release rate <1 sec
14	1.27	24.8	30.5	12.2	22.9	3.2	Penetration Gas Release w/ignition Blocked

Phase I Results and Discussion

Energy required for penetration

There is little information available in the literature on penetration energies, or on scaling effects for the diameter, wall thickness, etc., in composite tanks. Consequently, we based our initial penetrator energy value on a bullet penetration test conducted by the tank manufacturer. Based on their information, a 50-caliber, 163-grain (10.6 gm) bullet with a muzzle velocity of 850 m/s will penetrate both sides of the tank. The kinetic energy of the bullet is calculated at 3.6 kJ. Hence, an upper estimate of the energy required to penetrate one wall is about 1.8 kJ. Since the bullet had velocity after exiting the second wall, the actual energy imparted to the tank was somewhat lower. We chose this value as a starting point to determine the minimum energy for penetration. However, our initial test was conducted with a larger diameter rod, 50 mm, or approximately 4-5 times greater than the bullet.

The first three tests, summarized in Table I, were conducted on the same tank since the first two drops did not induce any visible surface damage to the tank. The tank was rotated between tests to change the impact point on the surface. In the third test, conducted at an initial energy of 4.5 kJ, the tank surface was damaged, but not penetrated. The initial energy was more than doubled in Test 4, using a new tank, and the penetrator rod easily penetrated the tank at an energy just over 10 kJ. Measurements on a frame-by-frame basis from the high-speed photometrics determined that the 50 mm rod required an energy of 6 kJ to penetrate one side of the tank. The first four tests were conducted with a nitrogen fill pressure of 24.8 MPa (3600 psi). Test 5 was conducted at a higher fill pressure, 34.5 MPa (5000 psi), and with an initial energy just above 10 kJ. For Test 6 the penetration energy was decreased to approximately 7 kJ with all other test parameters similar to Test 5. This test verified the energy value for penetration. Variations in penetration energy for the different fill pressures were within the experimental uncertainty of the measurements.

Additional tests were then conducted with different diameter rods and the penetration energy determined as a function of rod diameter. These results are plotted in Figure 4. One can see that the energy is a linear function of diameter that suggests shear strength dependence as shown in the following equation:

$$\text{Penetration energy} = E_p = \tau \pi d t \delta x$$

Where τ is the shear strength of the composite, d is the diameter of the rod, t is the shell thickness and δx is the distance required to shear the lay-up. Thus, the effective shear area is defined by the circumference of the penetrating rod and the wall thickness over which the rod acts. Examination of the tank penetration shows a cylindrical hole of nearly the same diameter as the rod that is consistent with the above interpretation. Further, high-speed video observations during one of the tests showed an intact disc of the tank shell being ejected from the penetrated region, nearly the same diameter as the rod, again, consistent with the above interpretation.

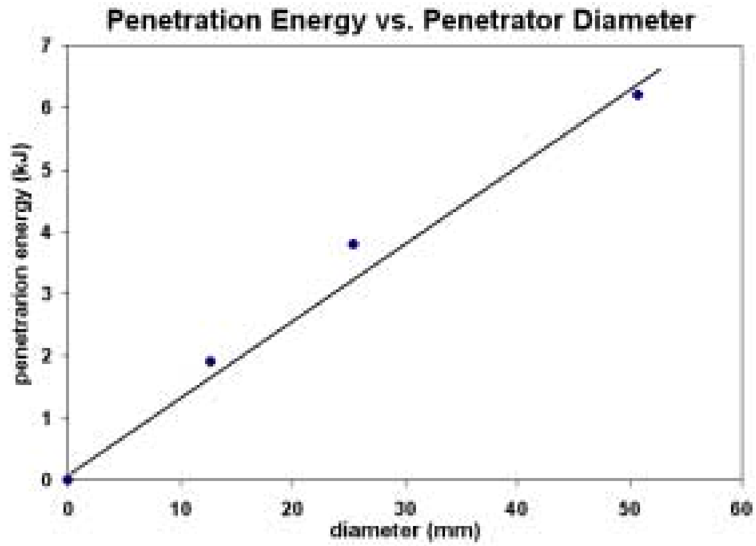

Figure 4. A plot of the measured penetration energy as a function of rod diameter.

Critical penetration size

Overall, the tanks exhibited very robust behavior and, as reported above, required significant energies to penetrate the vessel walls. Furthermore, the penetration is relatively benign and exhibits little collateral damage; that is, (a) the puncture size is of the order of the penetrating rod, (b) the puncture does not grow significantly beyond the rod dimensions, (c) there is little fragmentation produced and, (d) the gas is vented out the hole with the tank remaining intact. The release rate of the gas from the puncture can be dramatically reduced by partial sealing of the exit hole by the organic liner. This will be further discussed later in this report.

There are limitations to any container design, however, and our tests purposely extended beyond credible accident scenarios to determine the limits in the current pressure vessels. We determined that there is a critical penetration size above which the tanks will not contain the design pressure and the tanks will fail catastrophically. Referring to Table I, Tests 4, 5, 6 and 7 span the test conditions over which the tank will fail or not fail. It was found that at a fill pressure of 34.5 MPa, a 50 mm diameter penetration (Test 5) resulted in a circumferential tank failure initiating at the edge of the hole. Test 6 was a repetition of Test 5 to verify that the observed failure was not unique to the particular tank used in the test. This pressure and rod diameter was the only condition found to produce a tank failure. All other rod diameter-fill pressure conditions resulted simply in venting of the fill gas with no further structural failure. A simple calculation of the stress induced in the region of the vessel based on penetration size indicates a shear strength range for the fiber wrap to be 150 - 200 MPa.

Phase II Results and Discussion

The previous tests were conducted using nitrogen as the fill gas to avoid ignition issues and focused on the properties of the high-pressure composite tanks. During the second phase, tests were conducted using hydrogen as the fill gas and were aimed at examining the characteristics of ignited gas plumes vented from punctured high-pressure tanks. Two additional diagnostics, as well as those employed in Phase I, were included for these tests. First of all, an infrared (IR) camera operating at 30 fps was used to observe flame evolution within the gas plume. The camera was temperature-calibrated to provide an approximate temperature gradient within the gas plume. Secondly, pressure transducers were placed at different distances from the tank penetration point to quantify the pressure pulse induced in the surrounding region by ignition of the venting gas. In all, five additional penetration tests were conducted during this phase of the program, with all but one test made with a 12.7 mm diameter rod. Gas ignition was assured through a set of 10 continuous spark igniters placed on a line 15° from vertical from the rod impact point, spaced at 10 cm intervals and at 90° positions around the hole. These positions attempted to provide a spark source at the edge of the gas plume where the hydrogen/air mixture was within the ignition range for hydrogen. The authors are indebted to Michael Swain and Matthew Swain of the University of Miami for sharing their insight and experience in positioning the igniters.

Infrared observations

Figure 5 shows a false color infrared image of the ignited gas plume 133 ms after puncture and ignition during Test 10. In this test, the tank was filled with hydrogen to 34.5 MPa and a 12.7 mm diameter rod was used. The hole in the outer composite wrap was measured after the test and found to be about 25% larger than the rod diameter. The color variation in the figure corresponds to temperature gradients (as indicated on the color bar at the bottom of the figure). This image is one of a series of images that show the evolution of the gas plume with time and was chosen to show the maximum temperature reached during the test. The peak temperature of about 1100°C was reached when the ignition center had risen to almost 6 meters above the test platform. Note that the plume has expanded to almost 3 meters width at this height, consistent with a half angle of 15° assumed in placing the igniters. After 300 ms, the maximum temperature in the plume had dropped to about 800°C. This example was typical of all of the tests and shows that the very high buoyancy of hydrogen rapidly elevates the flame front away from the surrounding area. These results are consistent with those of Swain et. al. [5], [6], [7], [8], in which a continuous gas source was used to form an ignited hydrogen plume. The present results show that with rapid depressurization of a punctured tank, the gas plume both decreases and rises with time. More extensive IR images are shown in the final report of this project to be published.

Pressure impulse measurements

As mentioned previously, pressure transducers were placed at different distances from the pressure vessel to obtain information on the magnitude of the pressure pulse near ground level induced by ignition of the escaping gas. Since the transducers had a limited pressure range, 3 transducers were used in each test, placed at 0.75, 1.5, and 3 meters from the point of impact.

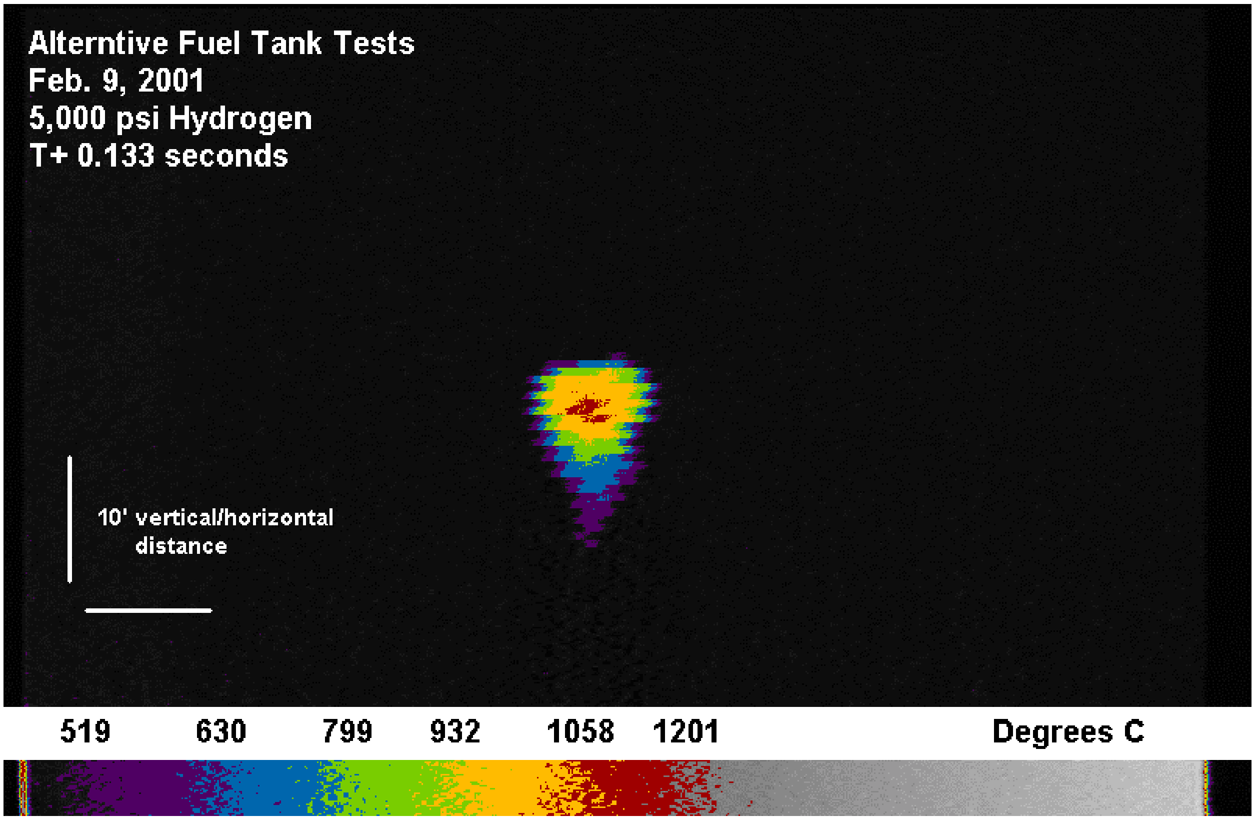

Figure 5. A false color infrared image of an ignited gas plume 133 ms after puncture and ignition of the hydrogen-filled vessel. This image shows the maximum temperature reached during the event. The color bar at the bottom gives the corresponding temperatures and colors.

The transducers were approximately 1 meter off the ground. Figure 6 is a plot of a transducer output approximately 1.5 meters from the ignition source during Test 10 (12.7 mm rod, 34.5 MPa fill pressure). The peak pressure of 0.01 MPa (1.4 psi) above ambient was of very short duration and coincided with ignition of the gas. There is a slight under-pressure developed about 100 ms later that is expected from a pressure wave where the high pressure pulse sweeps air away from the immediate region of the event. At 3 meters from the point of ignition, the peak pulse pressure was only 0.001 MPa (0.14 psi), consistent with a spherical ($1/r^2$) drop-off in pressure with distance. Overall, this is a relatively modest pulse that, we believe, would not lead to serious injuries or damage. As discussed in the next section, Test 10 produced a clean venting of the gas and a relatively large hole for the gas to be vented. We believe that this size of hole, which is larger than typical tubing diameters used in plumbing high pressure tanks, is a reasonable maximum credible failure for a tank of this design. Hence, the present results suggest that the risks associated with storing high-pressure hydrogen are no greater, and perhaps less than, other fuels, such as gasoline or propane.

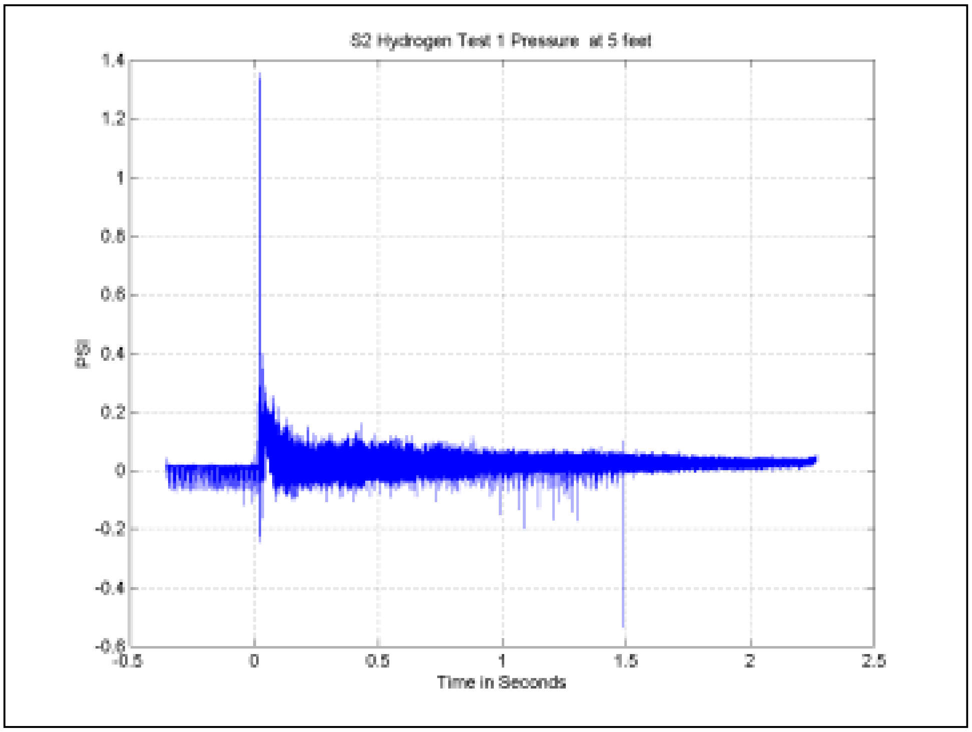

Figure 6. A plot of the overpressure induced by ignition of the venting gas during Test 10 at a distance of 1.5 meters from the tank.

Following the tests, the pressure vessels were disassembled and photographed in order to gain additional information on the test results. This was particularly important with the 12.7 mm diameter penetrator tests because of rod bounce, liner resealing and their effect on the gas venting behavior. The tank pressure as a function of time following rod penetration for Tests 10, 11 and 12 is plotted in Figure 7. Photographs of the tank liners in the region of the punctures are also included in the figure. One can see from the plot that in Test 10 the gas pressure rapidly and smoothly decreased, with the tank emptying after about 5 seconds. In contrast, the gas venting in the other two tests was discontinuous. The discontinuities are related to the rod and polymer liner interaction. It was observed on the video data that after penetration, the rod was always pushed out of the puncture hole by the internal gas pressure, climbed to about a third of the drop height, then fell back to the same region of the tank. The characteristic time for this to occur was about 2.6 seconds in all cases. However, the rod did not always produce the same result when striking the tank on the second time. In Test 10, the photograph of the liner shows that the rod fell a short distance from the original hole (the black circular region), but did not penetrate the liner (the white circular region). In Tests 11 and 12, the gas vented more slowly than in Test 10 and one can see the reason for this in the associated photographs of the liners. In Test 11, the liner was cut open, but a hole was not punched out. Since the puncture was smaller in area, the release of gas was much slower than in the previous test. Interestingly, when the rod fell back, it re-entered the same hole and effectively sealed the tank, preventing further gas release even at an internal pressure of over 14 MPa. Test 12, with a lower fill pressure (24.8 MPa) showed different behavior from the previous two tests. In this case, gas release was extremely slow after the first penetration, consistent with the small liner cut shown in the photograph. When the rod fell the second time, however, the liner hole was opened somewhat further and the gas release rate increased. These tests, we believe, are a further indication that the tank design is robust and the liner characteristics mitigate some of the potential impact of tank penetrations.

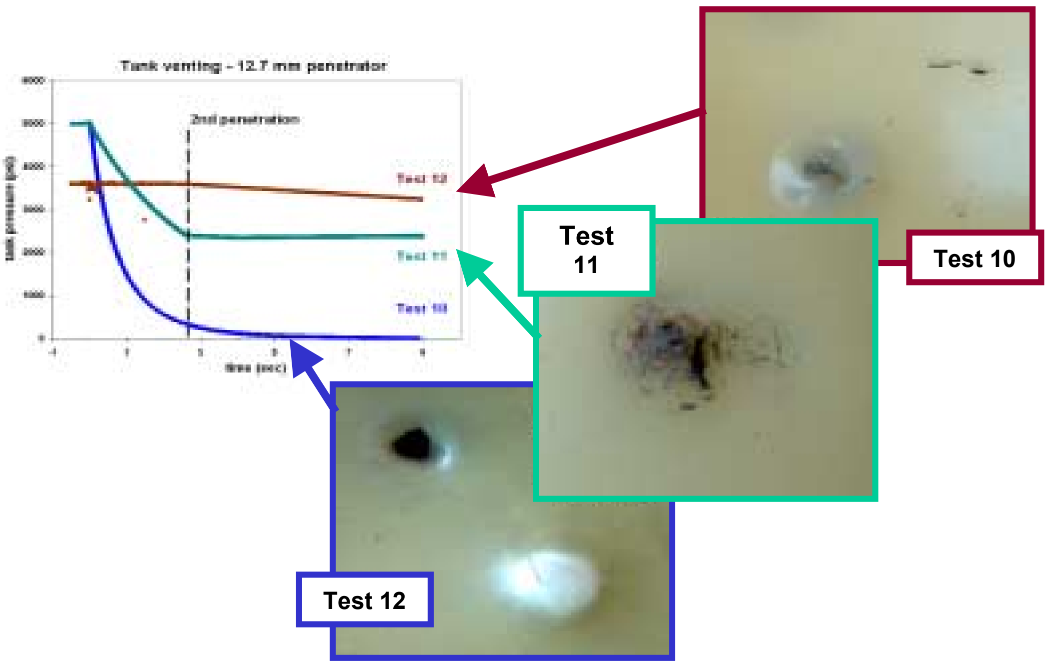

Figure 7. A composite of the measured cylinder pressures during Tests 10-12 with photographs of the corresponding liners obtained after the tests.

Summary

The results of the Phase I measurements suggest that (a) there is a pressure-dependent critical flaw size for composite tanks and, (b) there is a shear energy per unit length required to penetrate the composite wrap and liner that can be quantitatively determined. The values of these parameters are dependent on the specific tank materials and wrap design. The results also suggest that such measurements could be of value in developing composite tank models and in extrapolating tank response beyond the limited range of certification tests.

There are at least three independent modeling efforts that could utilize the data generated in Phase II of this project. First of all, the tank penetration and response results could be used to develop better, more detailed models of material behavior and failure characteristics for Type IV pressure vessels. Secondly, the measured blow-down rates can be compared to predictions based on classical models of supersonic flow through ideal orifices in order to more closely couple such calculations to real-life conditions. Thirdly, the flame propagation measurements can provide useful information for modeling hydrogen burn conditions resulting from high-pressure gas venting into the atmosphere.

One additional result generated by the tests is the overpressure produced by the shock wave of venting and burning. This information should be of value to regulatory agencies, insurance companies, etc.

The objectives of this project were to determine the response of high-pressure hydrogen vessels to extreme conditions, quantify the results and document them for public awareness. It is hoped that the results will aid in fostering acceptance of hydrogen as an alternative to hydrocarbon fuels.

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