Hypervelocity Impact of Composite Overwrap Pressure Vessels

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ABSTRACT

There is a limited amount of hypervelocity impact (HVI) data on pressurized composite overwrapped pressure vessels (COPV). In recent years, NASA has performed HVI tests to characterize impact conditions resulting in either leak or burst of the COPVs representative of spacecraft hardware. This paper reports on the results of 40 tests that have been conducted on several types of COPV configurations, pressurized by inert gas to near the vessels rated maximum expected operating pressure (MEOP). These tests were used to better understand COPV response under HVI conditions and develop ballistic limit equations (BLE) related to these tests.

1 INTRODUCTION

There is significant use of composite overwrapped pressure vessels (COPV), like that shown in Fig. 1, by space faring entities, and they are primarily used for mission critical functions like propulsion and life support systems [1]. Despite the popularity of these vessels, there is little published hypervelocity impact (HVI) data on pressurized COPV. The purpose of this work has been to partially fill this void by developing a database of COPV response under HVI conditions for a select group of representative vessels.

To this end, forty tests have been conducted at two different regions of pressurized vessels: hoop to dome transition region (HTDTR) and cylinder as identified in Fig. 1. While there are many shield systems that can be used with an operational COPV, these tests have focused on the performance of the unshielded COPV. These tests have mapped COPV leak and rupture response to impact conditions like the impactor size, speed and material.

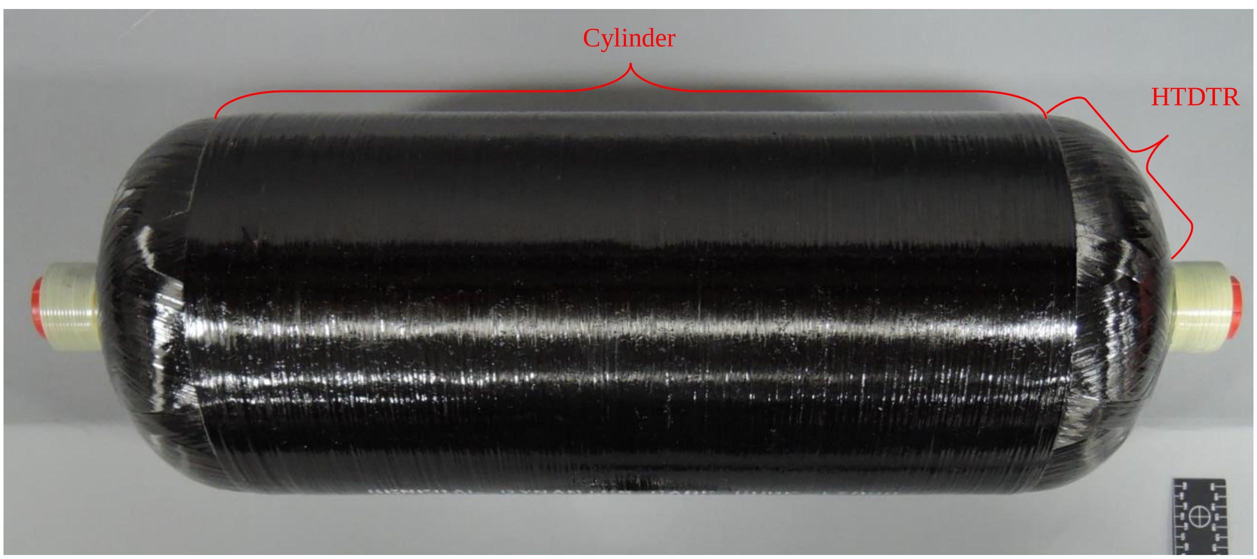

Figure 1 Overall view of a typical COPV considered in this work. The two regions that have been considered, cylinder and HTDTR, are identified with regional indicators.

2 Hypervelocity Impact Tests

Hypervelocity impact tests were performed at the NASA White Sands Test Facility (WSTF) Remote Hypervelocity Test Laboratory (RHTL) on pressurized COPV targets. The 4.3 mm diameter two-stage light-gas launcher mounted on the 25.4 mm diameter launch range and traditional 25.4mm diameter launch range was used in the testing (Fig. 2 and 3) [2].

Figure 2 Overall view of the gun configuration (internal the test facility).

Figure 3 Overall oblique view of the target tank (external to the test facility).

2.1 Target Description

There were five different types of COPV samples made available for this effort, via the WSTF COPV group. A general description of the COPV types are listed below in Table 1. Due to sensitivity of specific information, nominal values are being reported in this table.

Table 1. General COPV Sample Summary

COPV tank type	Overwrap material	Overwrap thickness		Liner material	Liner thickness		MEOP (psi)	Tank volume (CCs)
		HTDTR (cm)	Cylinder (cm)		HTDTR (cm)	Cylinder (cm)		
1	composite	Variable 0.08 – 0.51	0.25	aluminum	Variable 0.32 – 1.27	0.20	4300	11000
2	composite	Variable 0.29 – 0.99	0.64	Inconel	Variable 0.12 – 0.86	0.08	4500	97000
3	composite	Variable 0.29 – 0.99	0.64	Inconel	Variable 0.12 – 0.86	0.08	4900	97000
4*	composite	N/A	Variable 0.33 – 0.37	aluminum	N/A	Variable 0.15 – 0.18	3000	3900
5*	composite	N/A	0.19	aluminum	N/A	Variable 0.16 – 0.23	3000	11000

*denotes HTDTR region not impacted on this COPV sample type.

Each test sample was secured within a test fixture that incorporated a blast mitigation system to minimize damage to internal target tank components and target tank itself. The test fixture shown in Fig. 4 used a polycarbonate multi-layer shield that resided above and beneath the COPV to mitigate target tank damage if rupture was to occur.

Figure 4 Representative of test fixture that would secure COPV tank types 1, 4 and 5 (typical).

The test fixture shown in Fig. 5 and 6 was used for COPV types 2 and 3. These vessels have considerably more volume than the smaller COPVs (1, 4 and 5) and required a more comprehensive blast mitigation system. A Dyneema® mesh was wrapped around the tank and secured using a Dyneema rope that was interwoven through the mesh and at both ends to form a bag like structure. The Dyneema mesh was cut to reveal the desired impact location and allow projectile impact on the COPV without impacting the mesh material. In addition, the COPV was surrounded by a steel and wood structure designed to absorb fragment energy and allow gas flow out of the barrier. This was a frangible barrier and not designed to contain the burst or fragments completely, but to aid in the deceleration of fragments from the COPV, if burst occurred during pressurized HVI testing.

Figure 5 Overall front view of sample secured within the target tank (left) and close-up view of desired impact location with Dyneema mesh window cut (right). Both images taken prior to wood blast mitigation installation.

Figure 6 Overall front oblique view of sample. Image taken with the wood blast mitigation measures in place, the larger gap present between the slats, provides an avenue for the projectile to pass through to the target. Dyneema rope was also employed to bind the wood to the steel structure.

2.2 Test Matrix

The test conditions as shown below in Table 2 were developed by the NASA Johnson Space Center Hypervelocity Impact Technology (HVIT) [3] collaboratively with the WSTF and NASA Engineering and Safety Center (NESC) COPV testing team. Aluminum 2017-T4 (density 2.796 g/cm^3) and stainless steel 440C (density 7.667 g/cm^3) spherical projectiles were used in these tests. All tests were performed at velocities ranging from 4.0 km/s and 7.2 km/s, at a variety of impact angles ranging from 0° to 60°. The HTDTR impact angles were obtained by referencing the cylinder plane to impact location and taking the difference from angle to which a sample is set for a given test.

3 TEST RESULTS

Results and recorded test parameters for all pressurized tests are as listed below in Table 2.

Table 2. Hypervelocity Test Data

Test number / COPV type	Impact location	Projectile type	Projectile diameter (cm)	Projectile mass (g)	Velocity (km/s)	Impact angle (deg)	Test pressure (psi)	Results
HITF16080 / 1	cylinder	Al 2017-T4	0.030	0.00004	7.24	47º	4250	No leak
HITF16081 / 1	cylinder	Al 2017-T4	0.050	0.00018	6.82	47°	4278	No leak
HITF16159 / 1	cylinder	Al 2017-T4	0.100	0.00146	7.41	47°	4234	No leak
HITF16160 / 1	cylinder	Al 2017-T4	0.152	0.00510	7.06	48°	4186	Leak
HITF16161 / 1	cylinder	Al 2017-T4	0.238	0.01975	7.08	45°	4014	Rupture
HITF16162 / 1	cylinder	Al 2017-T4	0.201	0.01191	7.01	45°	4226	Rupture
HITF16163 / 1	HTDTR	Al 2017-T4	0.152	0.00514	7.04	45°	4212	No leak
HITF16164 / 1	HTDTR	Al 2017-T4	0.201	0.01190	7.19	45°	4214	Leak
HITF16165 / 1	cylinder	Al 2017-T4	0.172	0.00741	7.23	45°	4226	Leak
HITF16166 / 1	cylinder	Al 2017-T4	0.151	0.00505	7.24	0°	4075	Leak
HITF16167 / 1	cylinder	Al 2017-T4	0.172	0.00741	7.01	0°	4221	Rupture
HITF16168 / 1	cylinder	Al 2017-T4	0.231	0.01795	7.03	60°	4215	Rupture
HITF16169 / 1	cylinder	Al 2017-T4	0.201	0.01191	7.08	60°	4220	Leak
HITF16170 / 1	cylinder	Al 2017-T4	0.250	0.02290	4.07	45°	4255	Rupture
HITF16171 / 1	cylinder	Al 2017-T4	0.201	0.01194	4.08	45°	4270	No leak
HITF16504 / 1	cylinder	440C SS	0.109	0.00525	7.10	45°	4175	Leak
HITF16505 / 1	cylinder	440C SS	0.129	0.00861	7.10	45°	4162	Rupture
HITF17078 / 2	cylinder	Al 2017-T4	0.271	0.02923	7.19	45°	4413	No leak
HITF17079 / 2	cylinder	Al 2017-T4	0.340	0.05775	7.02	45°	4464	Leak
HITF17080-B / 2	HTDTR	Al 2017-T4	0.172	0.00742	7.01	12°	4449	No leak
HITF17081 / 2	HTDTR	Al 2017-T4	0.201	0.01194	7.12	19°	4460	Leak
HITF17082 / 2	HTDTR	Al 2017-T4	0.299	0.01194	7.12	19°	4444	Leak
HITF17287 / 2	cylinder	Al 2017-T4	0.340	0.05772	6.95	0°	4427	Leak
HITF17552 / 2	cylinder	Al 2017-T4	0.501	0.18404	6.82	0°	4405	Rupture
HITF18412 / 3	HTDTR	440C SS	0.090	0.00288	7.00	19°	4415	Leak
HITF18413 / 3	HTDTR	440C SS	0.100	0.00399	7.00	19°	4419	Leak
HITF18432 / 3	cylinder	440C SS	0.199	0.03153	7.01	45°	4440	Leak
HITF18435 / 3	cylinder	440C SS	0.170	0.01980	6.99	45°	4349	No leak
HITF18438 / 3	cylinder	440C SS	0.189	0.02703	6.97	45°	4425	No leak
HITF18483 / 3	HTDTR	440C SS	0.090	0.00289	7.06	45°	4413	Leak
HITF19001 / 3	HTDTR	440C SS	0.090	0.00288	4.20	19°	4494	No leak
HITF19037 / 3	HTDTR	440C SS	0.109	0.00525	4.16	19°	4403	No leak
HITF19123 / 4	cylinder	Al 2017-T4	0.100	0.00146	6.98	45°	2884	No leak
HITF19124 / 4	cylinder	Al 2017-T4	0.130	0.00322	7.04	45°	2885	Leak

Table 2. Hypervelocity Test Data (continued)								
Test number / COPV type	Impact location	Projectile type	Projectile diameter (cm)	Projectile mass (g)	Velocity (km/s)	Impact angle (deg)	Test pressure (psi)	Results
HITF19125 / 4	cylinder	Al 2017-T4	0.111	0.00202	6.90	45°	2918	No leak
HITF19126 / 5	cylinder	440C SS	0.120	0.00686	7.06	45°	2911	No leak
HITF19127 / 5	cylinder	440C SS	0.090	0.00290	7.04	45°	2893	No leak
HITF19128 / 5	cylinder	440C SS	0.100	0.00399	6.90	45°	2896	No leak
HITF19241 / 5	cylinder	440C SS	0.129	0.00860	7.09	45°	2918	Leak

Figures 7 – 8 show the results of pressurized COPV (Type 3 tank) test HITF18435. This test illustrates a no leak.

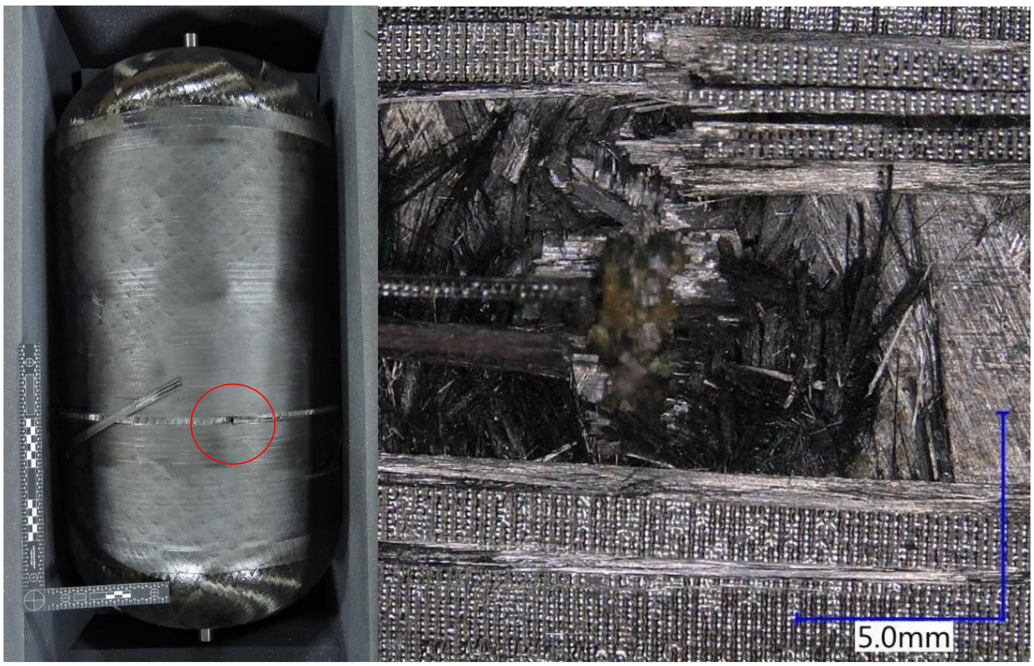

Figure 7 Overall view of entry damage to front of sample (left) and close-up view of entry damage (right / damage located within red circle in adjacent image).

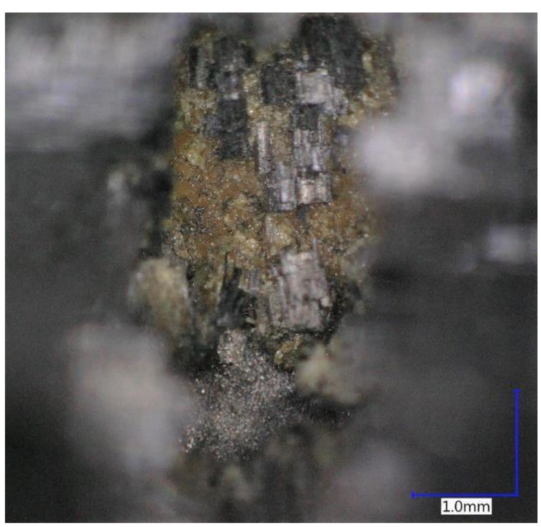

Figure 8 Close-up view of crater bottom.

Figures 9 – 11 show the results of pressurized COPV (Type 2 tank) test HITF17082. This test illustrates that a leak or vent can produce extreme thrust. The COPV stayed intact (no rupture) but the leak caused the tank to pull free from the test fixture, break through the wooden protective shield around the COPV, impact against the target tank (leaving a shallow impression) and landing on top of the debris and remains of the test fixture.

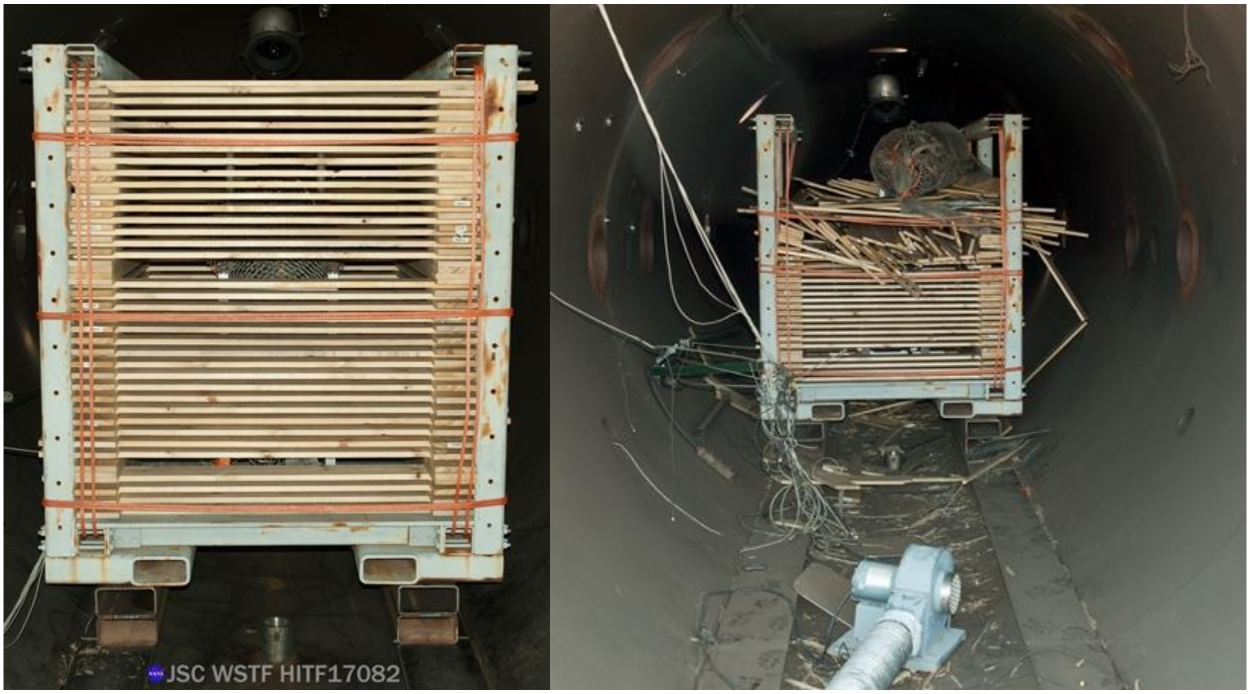

Figure 9 Overall rear view of sample configuration within the target tank pre-test (left) and rear view of damage to sample configuration post-test (HITF17082), with debris scattered all along the target tank floor (right). Both images with wood blast mitigation in place.

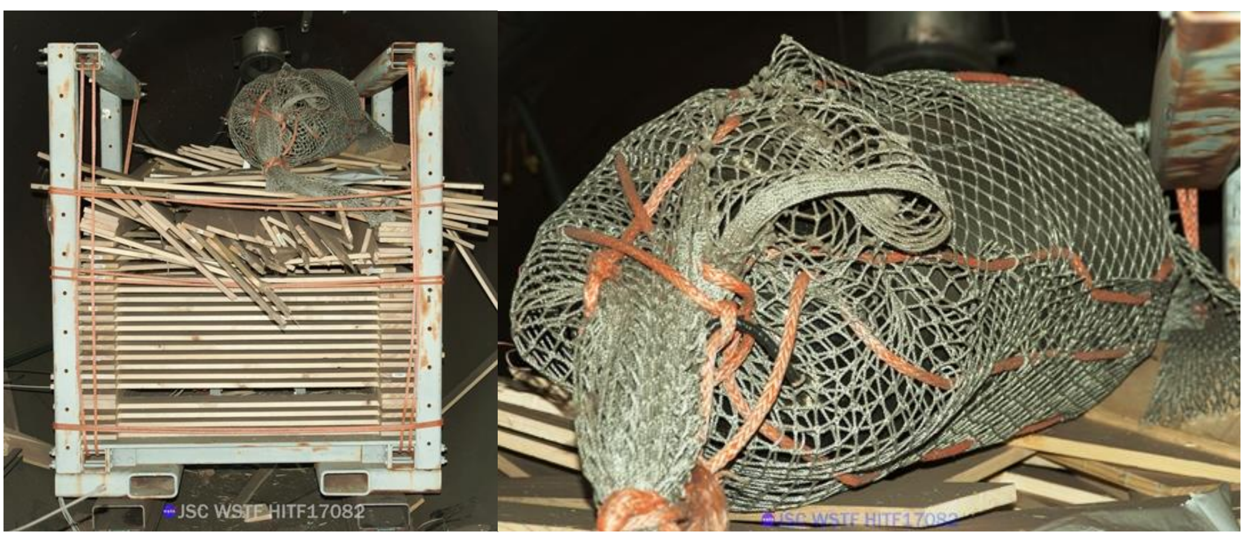

Figure 10 Close-up rear view of damage to sample configuration within the target tank post-test HITF17082 (left) and close-up of sample resting atop of wood blast mitigation (right).

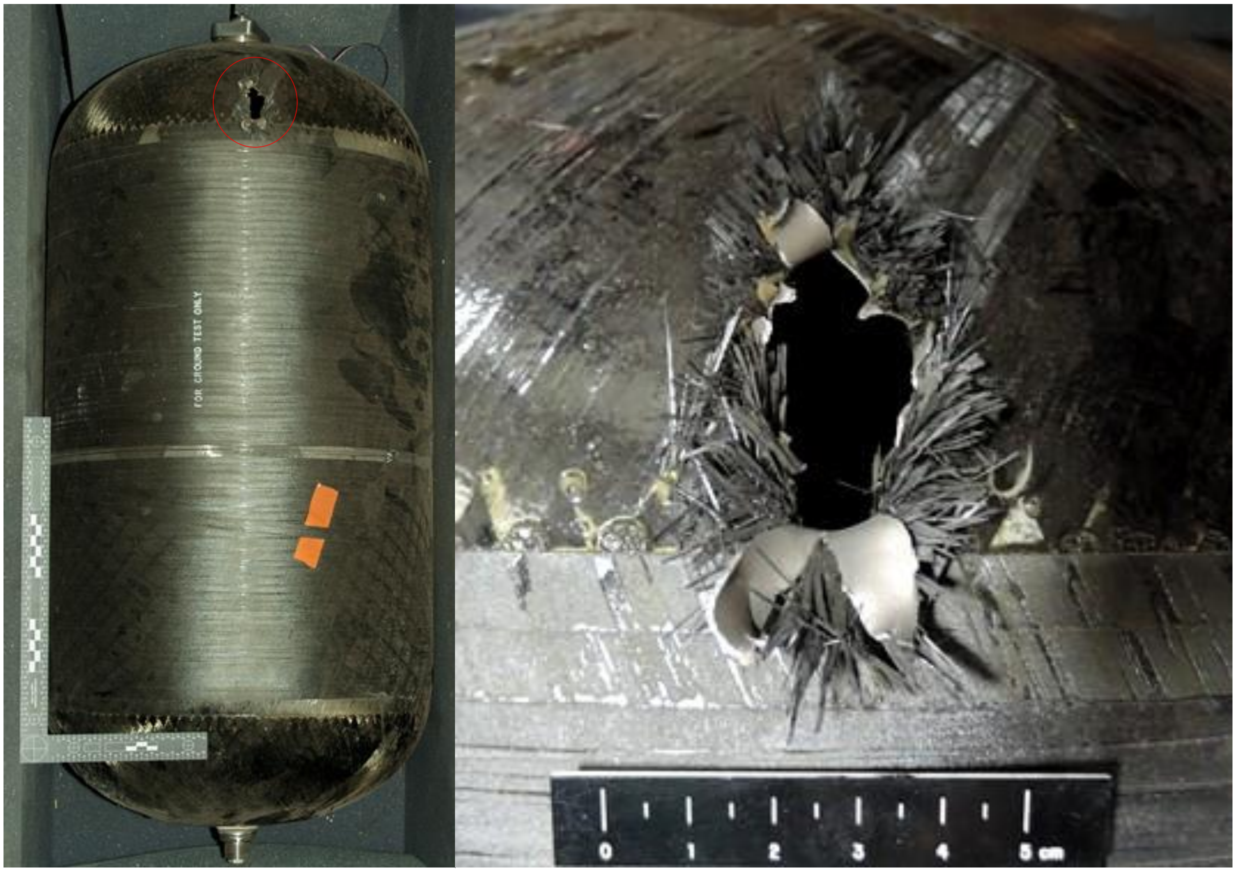

Figure 11 Overall view of damage to COPV tank (left) and overall view of entry damage (right / damage located within red circle in adjacent image) for HITF17082.

Figures 12 – 15 show the results of pressurized COPV (Type 2 tank) test HITF17552. This test illustrates how destructive a ruptured COPV can be.

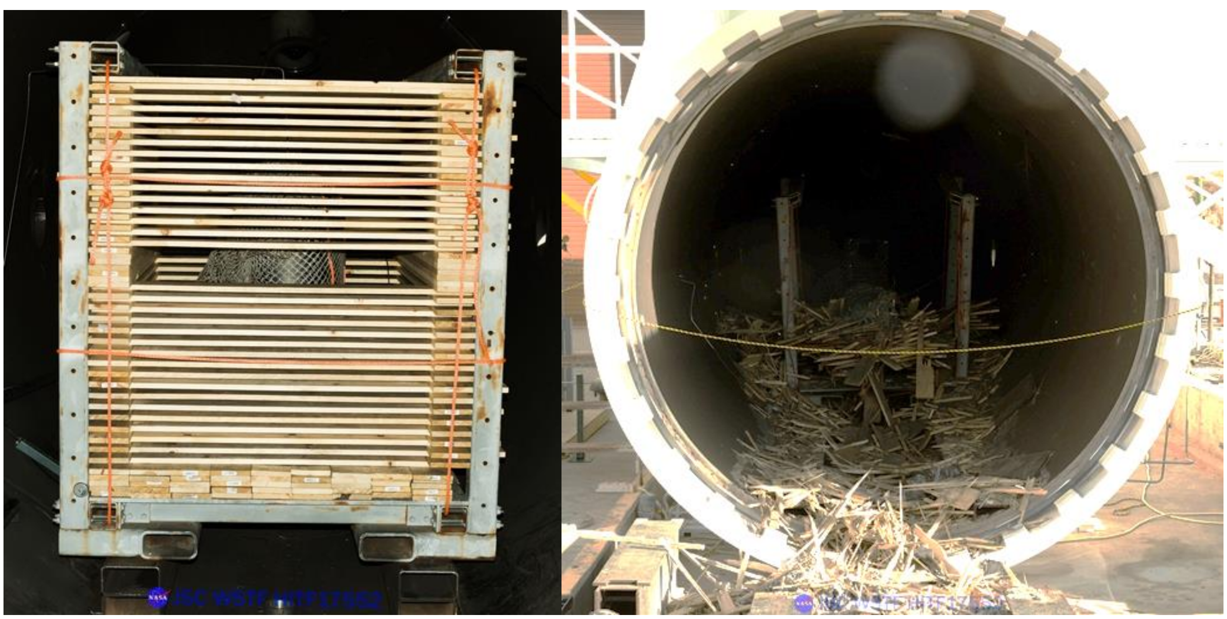

Figure 12 Overall rear view of sample within target tank pre-test (left) and view of damage within the rear of target tank post-test HITF17552 (right).

Figure 13 Overall rear view of damage adjacent to test fixture within target tank (left) and close-up view of damage present within the test fixture as a result of HITF17552 (right).

Figure 14 Close-up rear view of damage to test fixture with 16mm thick steel base plate visible HITF17552.

Figure 15 Overall front view of target within the target tank pre-test (left) and overall view of most significant COPV tank carcass remnants post-test HITF17552 on pad outside of target tank (right).

4 CONCLUSION

This paper describes the results of 40 non-shielded COPV pressurized HVI tests, out of these tests the only ruptures came from impacting the cylinder region of the COPV. These tests show that a COPV can sustain damage to the overwrap and to the liner without venting or rupturing the COPV in this configuration. In addition, a leak or perforation of the liner can produce a significant thrusting event. These tests and future tests will be used to enhance community knowledge of COPV's under HVI conditions.

5 REFERENCES

1. P.B. McLaughlan, S.C. Forth, L.Grimes-Ledesma, Composite Overwrapped Pressure Vessels, A Primer, NASA/SP-2011-573, March 2011.

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