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RESEARCH RESULTS

FRA OFFICE OF RESEARCH, DEVELOPMENT & TECHNOLOGY

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FULL-SCALE SHELL IMPACT TEST OF A DOT-113C120W9 TANK CAR FILLED WITH LIQUID NITROGEN

SUMMARY

On May 14, 2022, the Federal Railroad Administration (FRA) conducted a full-scale shell impact test (Test 13) of a DOT-113C120W9 (also identified as DOT-113) specification tank car at the Transportation Technology Center (TTC) in Pueblo, CO. This test was the final impact test in a planned series of four. A DOT-113 is a double-walled tank car (i.e., tank-within-a-tank) designed to transport authorized cryogenic liquids by rail. The tested tank car was purpose-built for this test to meet the specifications for a DOT-113C120W9 tank car. The tank car had a volume of approximately 34,500 gallons. During the test, a ~297,000-pound ram car equipped with a 12-inch by 12-inch impactor struck the outer shell of the tank car at its mid-height and longitudinally offset 10.8 feet towards the A-end. The researchers intended the offset impact location to be consistent with the impact location in the previous side impact test of a legacy DOT-113 tank car (Test 10). Figure 1 shows the tank car in its pre-test position against the impact wall at the TTC.

Figure 1. Pre-impact DOT-113 (Snapshot from Drone Camera)

This test used cryogenic liquid nitrogen (LN2) as a stand-in for the cryogenic materials typically transported in a DOT-113. The researchers filled the tank car to approximately 97 percent by volume with LN2. The remaining 3 percent volume contained pressurized gaseous nitrogen (GN2). The temperatures and pressures in both the LN2 and GN2 fluctuated prior to the test. The outage pressure was 21 psig immediately prior to the test. The researchers targeted a test speed of 22.0 ± 0.5 mph, intending to puncture both the outer and inner tanks. The measured impact speed was 22.1 mph. This speed and ram mass corresponds to 4.8 million foot-pounds of impact kinetic energy.

At the time of puncture, the impact developed a maximum force of approximately 1.7 million pounds, and the impactor indented the tank car to a depth of approximately 60 inches. The tank car absorbed 4.3 million foot-pounds of energy prior to puncture. After puncturing the inner tank, the impactor continued moving at a speed of 7 mph before coming to rest with the head of the impactor lodged inside the inner tank. Figure 2 shows the state of the DOT-113 tank car following the shell impact test.

Figure 2. Post-impact DOT-113C120W9

BACKGROUND

FRA established a program to evaluate the puncture resistance of various tank car designs. This program supports examining strategies to reduce the potential for release of hazardous materials from tank cars involved in derailments. FRA seeks to develop standardized test and simulation methodologies for quantifying the puncture resistance of tank car designs. This program has previously tested on DOT-105, DOT-111, DOT-112, DOT-117, and DOT-113 specification tank cars under similar shell impact conditions. Researchers performed companion finite element (FE) analysis prior to each test. The test results are used to both validate the pre-test model and improve future FE models. A well validated FE model can then be used to investigate other impact conditions and hazardous materials.

In the DOT-113 test series, Test 10 used a "legacy" DOT-113C120W tank car filled with water and resulted in puncture of both the outer and inner tanks [1]. Test 11 used a purpose-built DOT-113 tank car surrogate filled with water and did not result in puncture [2]. Test 12 used a purpose-built DOT-113 tank car surrogate filled with LN2 and did not result in puncture [3]. Test 13 used a newly constructed DOT-113C120W9 tank car filled with LN2 and resulted in puncture of both the outer and inner tanks. Table 1 summarizes the DOT-113 test series.

Table 1. DOT-113 Shell Impact Test Series

Test #	Test Article	Lading	Impact Speed	Puncture
10	Legacy DOT-113C120W	Water	16.7 mph	Yes
11	Surrogate DOT-113	Water	17.3 mph	No
12	Surrogate DOT-113	LN2	18.3 mph	No
13	New DOT-113C120W9	LN2	22.1 mph	Yes

OBJECTIVES

Test 13 planned to impact the DOT-113 tank car under similar conditions to Test 12, except using a full-size functional tank car instead of a shorter length surrogate tank car. The DOT-113 tank car used in Test 13 had an outer shell made from 9/16- TC128 Grade B carbon steel (TC128) in the normalized condition. The Test 13 inner shell was made from 0.296-inch Type 304 (T304) stainless steel. The objective of Test 13 was to puncture the stainless-steel inner tank in a cryogenic condition, typical of service.

METHODS

The Test 13 DOT-113 tank car consisted of an outer carbon steel shell and an inner stainless-steel shell with similar compositions, thicknesses, and diameters to the Test 11 and 12 surrogates. However, unlike the DOT-113 surrogates, the DOT-113 tank car was manufactured with protective valve housing, couplers, brake rigging, and other safety equipment specific to DOT-113 tank cars. Table 2 summarizes key parameters for Tests 12 and 13.

Table 2. Summary of Tank Car Parameters in Recent Tests

Parameter	Test 12	Test 13
Commodity in Tank	LN2	LN2
Nominal Tank Capacity (water, gallons)	17,900	34,500
Outage Volume in Test	~9%	~3%
Outage Pressure (psig)	30	21
Outer Shell Thickness (inches)	0.608	0.5625
Outer Shell Material (Carbon Steel)	TC128 (normalized)	TC128 (normalized)
Inner Shell Thickness (inches)	0.25	0.296
Inner Shell Material (Stainless Steel)	T304	T304
Insulation Between Tanks	MLI and Vacuum	MLI and Vacuum

Both the moving ram car and the stationary tank car were instrumented. The acceleration, force, velocity, and displacement of the ram car were derived from accelerometers positioned on structural members of the ram car. Speed sensors on the ram car recorded its speed just prior to impact. Laser displacement transducers on the impact wall were positioned in-line with laser displacement transducers on the ram car to measure the external compression of the tank car at its vertical center. Researchers instrumented the tank car with pressure transducers and temperature sensors inside the inner tank using three passthroughs, similar to small manways. At each passthrough, researchers installed one combination temperature-pressure sensor near the top of the passthrough, one thermocouple near the vertical center of the outage, and one thermocouple near the vertical center of the liquid. Researchers installed one combination temperature-pressure sensor in piping leading to the pressure relief valve (PRV). Researchers instrumented the exterior of the tank car with string potentiometers to measure its overall motion. Researchers recorded the impact using conventional-speed and high-speed cameras on the ground and drone-mounted conventional-speed and infrared cameras in the air. Table 3 summarizes the instrumentation.

Table 3. Summary of Instrumentation

Type of Instrumentation	Channel Count
Accelerometers	11
Speed Sensors	2
Pressure Transducers	4
String Potentiometers	4
Laser Disp. Transducers	15
Thermocouples	6
Temperature Probes	3
Total Data Channels	**45**

Even though this was the second shell impact test using LN2, there were uncertainties with the pressures, temperatures, outage volume, and fracture behavior of cryogenic stainless steel prior to the test. Researchers used the post-test finite element analysis (FEA) model of the Test 12 surrogate as a starting point for the pre-test FEA model of the Test 13 tank car. Researchers determined a range of impact speeds that could puncture the tank car by varying the temperature and outage volume in a model sensitivity study. Figure 3 shows a schematic of the Test 13 FE model. Researchers modeled the inner and outer tanks using shell elements with elastic-plastic material properties except in the impact zone. Researchers modeled the impact zones of both the inner and outer tanks using solid elements with elastic-plastic and ductile failure material properties. This combination of shell and solid element types allowed puncture of the tank car to be modeled while reducing the model's run-time.

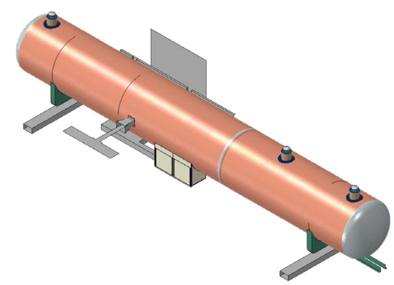

Figure 3. DOT-113 FE Model

Initially, researchers modeled the tanks' material properties based on measurements made on Test 11's TC128 and T304 steels. Researchers later characterized TC128 steel from the Test 13 DOT-113 at room temperature and quasi-static strain rate. Researchers tested T304 stainless steel from the Test 13 DOT-113 at cryogenic temperatures and elevated strain rates, as those conditions were expected to affect the puncture outcome with LN2. The pre-test DOT-113 FE model was updated with material definitions based on the results from ASTM E8/E8M tensile tests. The pre-test models estimated that puncture was possible, but not certain, between 20 and 23 mph. This range was larger than the range seen in prior tests with water because of the previously mentioned uncertainties with the pressures, temperatures, outage volume, and fracture behavior of cryogenic stainless steel.

RESULTS

Figure 4 shows a comparison between the force- and absorbed energy-displacement responses measured in Tests 10 and 13. The results are calculated by averaging the longitudinal accelerometers on the ram car. A CFC-60 filter has been used on these results in accordance with SAE J211-1. Test 10 used an impact speed of 16.7 mph and Test 13 used an impact speed of 22.1 mph. The 4.3 million ft-lbf of energy absorbed in Test 13 corresponds to an initial speed of 20.8 mph, indicating the actual impact speed of 22.1 mph slightly exceeded the minimum speed needed to cause puncture.

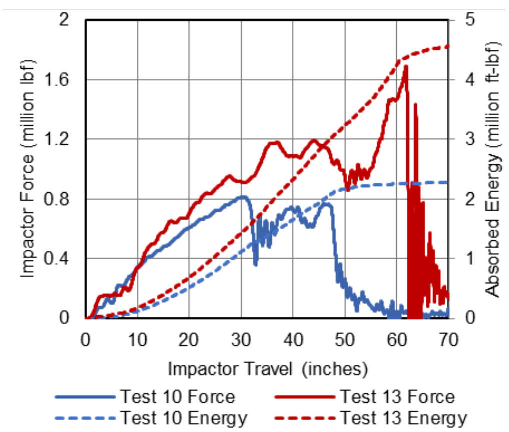

Figure 4. Force- and Energy-displacement Results from Tests 10 and 13 (CFC-60)

The new DOT-113 tank car (Test 13) achieved approximately double the peak force and double the absorbed energy compared to the legacy DOT-113C120W tank car (Test 10). While the initial conditions were not identical, preliminary results indicate a substantial improvement in puncture resistance.

CONCLUSIONS

On May 14, 2022, FRA conducted a full-scale impact test of a newly constructed DOT-113 tank car filled ~97 percent with LN2. The impact occurred at 22.1 mph with a 297,000-pound ram car equipped with a 12-inch by 12-inch impactor. The impact had a kinetic energy of approximately 4.8 million foot-pounds and resulted in puncture of both the outer shell and inner shells.

FUTURE ACTION

Researchers will review test data, photos and videos, and compare them with the behaviors from the FE model for validation. Researchers will update the pre-test FE model to reflect the actual impact conditions (i.e., temperature, pressure, and speed). Researchers will validate the pre-test FE model against the test results and use the validated FE model to investigate the puncture resistance of the DOT-113 tank car under actual service conditions with LNG.

REFERENCES

1. Federal Railroad Administration, "Full-Scale Shell Impact Test of a DOT-113 Tank Car," Research Results No. RR 20-03, February 2020.
2. Federal Railroad Administration, "Full-Scale Shell Impact Test of a DOT-113 Tank Car Surrogate," Research Results No. RR 20-11, July 2020.
3. Federal Railroad Administration, "Full-Scale Shell Impact Test of DOT-113 Tank Car Surrogate Using Liquid Nitrogen," Research Results No. RR 21-22. October 2021.

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