U.S. Department of Transportation
Federal Railroad Administration

RESEARCH RESULTS
FRA OFFICE OF RESEARCH, DEVELOPMENT & TECHNOLOGY

RR 21-22 | **October** 2021

FULL-SCALE SHELL IMPACT TEST OF DOT-113 TANK CAR SURROGATE USING LIQUID NITROGEN

SUMMARY

On July 24, 2021, the Federal Railroad Administration (FRA) conducted a full-scale shell impact test (Test 12) of a surrogate DOT-113 specification tank car at the Transportation Technology Center (TTC) in Pueblo, CO. This test was the third DOT-113 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 "surrogate" tank car was purposefully built for this test with the essential features of a DOT-113 and an outer tank of a slightly thicker steel than required by specification. The tested surrogate did not feature all the equipment required of a DOT-113 tank car (e.g., cabinet, couplers, and trucks) and was approximately 35 percent shorter in length. The shell of the outer tank was struck by a ~297,000-pound ram car equipped with a 12-inch by 12-inch impactor at its mid-height and longitudinally offset ~2.5 feet towards the A-end. This offset impact location was intended to be consistent with the impact location in the previous two DOT-113 impact tests (Tests 10 and 11). Figure 1 shows the tank car in its pre-test position against the impact wall at the TTC while using a high-speed video frame.

Figure 1. Pre-impact DOT-113 Surrogate

This test used cryogenic liquid nitrogen (LN2) as a stand-in for the cryogenic materials typically transported in a DOT-113. The tank car was filled to approximately 95 percent by volume with LN2. The remaining 5 percent volume contained pressurized gaseous nitrogen (GN2). The temperatures and pressures in both the LN2 and GN2 fluctuated prior to the test, with the outage at ~30 psig and ~120 K (-244 °F) just prior to impact. The target test speed of 17.7± 0.5 mph was intended to ensure an impact speed greater than or equal to the measured impact speed of 17.3 mph from Test 11. The measured impact speed was 18.3 mph. This speed and ram mass corresponds to approximately 3.3 million foot-pounds of impact kinetic energy.

The surrogate resisted the impact without tearing either the inner or the outer tank. The impactor indented the DOT-113 surrogate to a maximum depth of ~59 inches before stopping and rebounding. The impact developed a maximum force of ~1.2 million pounds. Figure 2 shows the outer shell immediately following rebound of the ram car while using a high-speed video frame.

Figure 2. Post-impact DOT-113 Surrogate

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 other specification tank cars (e.g., DOT-105, DOT-111, DOT-112, DOT-117, and DOT-113) under similar shell impact conditions. A companion finite element analysis (FEA) is performed prior to each test. The test results are used to both validate the pre-test model and improve future finite element (FE) models. A well validated FE model can then be used to investigate other impact conditions and hazardous materials.

Previously, Test 10, using a “legacy” DOT-113 tank car filled with water, resulted in puncture of both the inner and outer tanks [1]. Test 11, using a DOT-113 tank car surrogate filled with water, did not puncture under similar test conditions [2]. Test 12, using a DOT-113 tank car surrogate filled with LN2, did not puncture.

OBJECTIVES

Test 12 planned to impact the DOT-113 surrogate under similar conditions to Test 11, except with cryogenic LN2 used instead of water. The outage volume was adjusted between Tests 11 and 12 based on the allowable filling density for liquefied natural gas (LNG) by rail published in the Pipeline and Hazardous Materials Safety Administration’s (PHMSA) 2020 Final Rule (85 FR 44994). The DOT-113 surrogate used in Test 12 had an outer shell made from 0.608-inch TC128 multi-layer insulation, and a vacuum throughout its annular space. The inner tanks used in both tests were made of 1/4-inch ASTM A240 Type 304 (T304) stainless steel. Test 12’s objective was to examine the change in tank car impact response with the inner tank at a cryogenic temperature, typical of service.

METHODS

The tank car consisted of an outer carbon steel shell and an inner stainless-steel shell with similar thicknesses and diameters to the Test 11 surrogate. The test surrogates were not manufactured with couplers, brake rigging, and other safety equipment specific to DOT-113 tank cars that were not expected to affect the test results. Table 1 summarizes the key parameters for Test 11 and Test 12.

Table 1. Summary of Tank Car Parameters in Recent Tests

Parameter	Test 11	Test 12
Commodity in Tank	Water	LN2
Nominal Tank Capacity (water, gallons)	19,300	17,900
Outage Volume in Test	17.6%	5% (target)
Outage Pressure (psig)	50	~30
Outer Shell Thickness (inches)	9/16	0.608
Outer Shell Material (carbon steel)	TC128 (normalized)	TC128 (normalized)
Inner Shell Thickness (inches)	1/4	1/4
Inner Shell Material (stainless steel)	T304	T304
Insulation Between Tanks	MLI (impact zone only)	MLI and Vacuum

Both the moving ram car and the stationary surrogate were instrumented for this test. 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. The surrogate was instrumented with pressure transducers and temperature sensors in its piping, and thermocouples within the inner tank. Externally, the surrogate was instrumented with string potentiometers to measure its overall motion. The test was recorded using conventional-speed and high-speed cameras on the ground and drone-mounted conventional-speed and infrared cameras in the air. Table 2 summarizes the instrumentation.

Table 2. Summary of Instrumentation

Type of Instrumentation	Channel Count
Accelerometers	11
Speed Sensors	2
Pressure Transducers	5
String Potentiometers	4
Laser Disp. Transducers	15
Thermocouples	5
Temperature Probes	5
Total Data Channels	**47**

Researchers performed the FEA in conjunction with the test. Figure 3 shows a schematic of the FE model. The pressure and temperature responses of the LN2 and GN2 at impact were not known before the test. Three different modeling techniques were employed in the pre-test FEA to attempt to estimate the expected range of behaviors by the fluids. The inner and outer tanks were modeled using shell elements, except in the impact zone, with elastic-plastic material properties. The impact zones of both the inner and outer tanks were modeled using solid elements, with elastic-plastic and ductile failure material properties defined. This combination of shell and solid element types allowed the puncture of the tank car to be modeled while reducing the model's run-time.

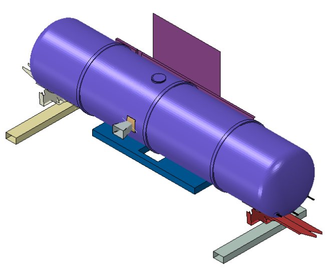

Figure 3. DOT-113 Surrogate FE Model

The tanks' material properties were modeled based on measurements made on Test 11's TC128 and T304 steels. The pre-test FE model used material models based on the results of ASTM E8/E8M tensile tests. The TC128 steel was characterized at room temperature and quasi-static strain rate. The T304 stainless steel was tested at cryogenic temperatures and elevated strain rates, as those conditions were expected to affect the puncture outcome in Test 12. The pre-test models estimated that puncture was possible, but not certain, between 16.5 and 19.5 mph. This range was larger than the range seen in prior tests, owing to uncertainty in the pressures, temperatures, and fluid behaviors inside the tank car at the time the models were run.

RESULTS

The impact occurred at 18.3 mph and resulted in the ram car coming to a stop and rebounding without puncturing either tank. Figure 4 shows the force-displacement and energy-displacement results from the test. The force results are calculated by the average of three longitudinal accelerometers on the ram car multiplied by the mass of the ram car. A CFC-60 filter has been used on these results in accordance with the Society of Automotive Engineers (SAE) J211-1.

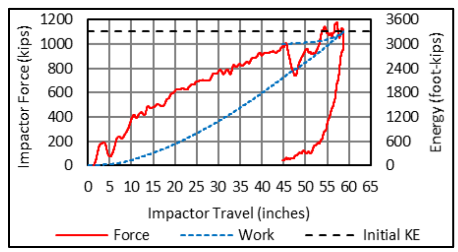

Figure 4. Test Force-displacement and Energy-displacement Results at 18.3 mph (CFC-60)

Figure 5 shows a comparison between the force-displacement responses measured in Test 10, Test 11, and Test 12. Test 10 used a "legacy" DOT-113 tank car [1], had an impact speed of 16.7 mph, and resulted in puncture of both the inner and outer tanks. Test 11 used a "modern" DOT-113 surrogate with a thicker outer tank made from a better steel, had an impact speed of 17.3 mph, and did not result in puncture of either tank. Test 12 used a similar "modern" DOT-113 surrogate with a slightly thicker outer tank, had an impact speed of 18.3 mph, and did not result in puncture of either tank.

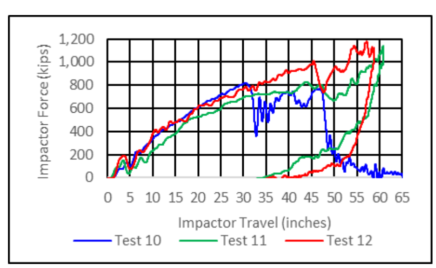

Figure 5. Force-displacement Results from Tests 10, 11, and 12 (CFC-60)

CONCLUSIONS

FRA conducted a full-scale impact test of a surrogate DOT-113 test article partially filled with LN2 on July 24, 2021. The impact occurred at 18.3 mph with a 297,000-pound ram car having a kinetic energy of approximately 3.3 million foot-pounds. The ram car was equipped with a 12-inch by 12-inch impactor. The DOT-113 surrogate resisted the impact without puncture of either the inner or outer tank.

FUTURE ACTION

The test data, photos, and videos will be reviewed and compared with the behaviors from the FEA model for validation. The pre-test FE model will be updated to reflect the actual impact conditions (e.g., temperature, pressure, and speed). Additional material testing on both tanks from Test 12 will be performed to improve the material behaviors in the model. Any improvements made in the DOT-113 surrogate post-test FE model will be incorporated into the pre-test model of the next planned DOT-113 test (Test 13). Table 3 summarizes the planned DOT-113 test series.

Table 3. Planned DOT-113 Test Series

Test #	Test Date	Test Article	Lading
Test 10	November 2019	Legacy DOT113	Water
Test 11	June 2020	Surrogate DOT-113	Water
Test 12	July 2021	Surrogate DOT-113	LN2
Test 13	TBD 2022	New DOT-113	LN2

REFERENCES

[1] Federal Railroad Administration, "Side Impact Test and Analyses of a Legacy DOT-113 Tank Car," Technical Report No. DOT/FRA/ORD-21/28, Washington, DC: U.S. Department of Transportation, September 2021.

[2] Federal Railroad Administration, "Full-Scale Shell Impact Test of a DOT-113 Tank Car Surrogate," Research Results No. RR 20-11, Washington, DC: U.S. Department of Transportation, July 2020.

ACKNOWLEDGEMENTS

The Volpe National Transportation Systems Center performed analysis, test planning, and reporting. Transportation Technology Center, Inc performed test planning, instrumentation setup, data collection, test execution, and reporting.

CONTACT

Francisco González, III
Hazardous Materials Program Manager
Federal Railroad Administration
Office of Research, Development and Technology
1200 New Jersey Avenue, SE
Washington, DC 20590
(202) 493-6076
francisco.gonzalez@dot.gov

KEYWORDS

DOT-113, tank cars, impact testing, puncture resistance, hazardous materials, HAZMAT, finite element analysis, model validation

CONTRACT NUMBER

693JJ620F000040