SAND2019-15256R

30 cm Drop Tests

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technologie

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December 20, 2019
M3SF-19SN010202022
SAND2019-XXXX

SUMMARY

The data from the multi-modal transportation test conducted in 2017 demonstrated that the inputs from the shock events during all transport modes (truck, rail, and ship) were amplified from the cask to the spent commercial nuclear fuel surrogate assemblies. These data do not support common assumption that the cask content experiences the same accelerations as the cask itself. This was one of the motivations for conducting 30 cm drop tests.

The goal of the 30 cm drop test is to measure accelerations and strains on the surrogate spent nuclear fuel assembly and to determine whether the fuel rods can maintain their integrity inside a transportation cask when dropped from a height of 30 cm. The 30 cm drop is the remaining NRC normal conditions of transportation regulatory requirement (10 CFR 71.71) for which there are no data on the actual surrogate fuel. Because the full-scale cask and impact limiters were not available (and their cost was prohibitive), it was proposed to achieve this goal by conducting three separate tests. This report describes the first two tests – the 30 cm drop test of the 1/3 scale cask (conducted in December 2018) and the 30 cm drop of the full-scale dummy assembly (conducted in June 2019). The dummy assembly represents the mass of a real spent nuclear fuel assembly. The third test (to be conducted in the spring of 2020) will be the 30 cm drop of the full-scale surrogate assembly. The surrogate assembly represents a real full-scale assembly in physical, material, and mechanical characteristics, as well as in mass.

30 cm Drop Test of 1/3 Scale Cask

The purpose of this test was to obtain acceleration data on the 1/3 scale cask and on the 1/3 scale dummy assemblies. The acceleration pulses on the 1/3 scale dummy assemblies provide the input for the 30 cm drop of the full-scale dummy assembly.

The hardware for this test was provided by ENSA. The dummy assemblies were steel blocks with the same mass as the fuel assemblies, but very different from the fuel assembly structurally. The test was conducted at the BAM facility in Berlin (Germany) in December 2018.

Four locations on the exterior of the cask were instrumented with accelerometers. Eleven dummy assemblies were instrumented on the lid end and 7 on the back end of the cask. One location on the basket (lid end of the cask) was instrumented as well. The instrumentation was done by the SNL team. The BAM staff performed the data acquisition.

Two horizontal drop test configurations were used. In the first configuration, the cask was in its normal position. In the second configuration, the cask was rotated 45 degrees counter clockwise when looking at the lid end about its longitudinal axis.

The accelerations on the cask, dummy assemblies, and basket were analysed. The major conclusions were:

- The peak accelerations on the dummy assemblies vary significantly depending on the location within the cask with the maximum accelerations being ~2.4 times higher than the minimum.
- As expected, the transfer function showed amplification of accelerations from the cask to the assemblies.

To calculate the expected accelerations on the full-scale dummy assembly the maximum accelerations on the 1/3 scale dummy assemblies (on lid end and back end) were decreased and the time was increased proportionally to the scale (factor of 3). This represents the major input into the second test, a 30 cm drop of the full-scale dummy assembly.

30 cm Drop Test of Full-Scale Dummy Assembly

The goal of this test was to find the condition under which the observed acceleration pulses would be similar to the expected acceleration pulses derived from the 1/3 scale cask drop test. Achieving this condition means that the effect of the cask and the impact limiters are adequately represented.

The full-scale dummy assembly is the enlarged by 3 times equivalent of the 1/3 scale dummy assembly. It was manufactured by ENSA using the same materials, scaled dimensions, and manufacturing processes as the 1/3 scale dummy assemblies.

The full-scale dummy assembly was dropped in a full-scale 17x17 PWR metal matrix composite (MMC) basket tube. A basket tube was purchased from ENSA to mimic the boundary conditions the dummy assemblies experienced during the 30 cm drop of 1/3 scale cask.

The full-scale dummy assembly was instrumented with tri-axial accelerometers on the top and bottom ends to obtain the acceleration data comparable with the 1/3 scale drop test. The basket tube was instrumented with two tri-axial accelerometers on the upper surface.

Felt pads were used as a shock absorbing material to mimic the behaviour of the impact limiters and the cask in the 1/3 scale cask drop test. Four pads were attached to the lower surface of the basket tube.

The drop test was conducted in June 2019 at the SNL drop tower (Albuquerque, NM). Four drop tests were performed to get the desired acceleration pulses. After each test the pulse amplitudes, durations, and shapes were examined and the felt dimension were adjusted. The adjustments consisted of reducing the pad area (length) and increasing its thickness.

The felt configuration used in the last drop represents the major input into the third test, a 30 cm drop of the full-scale surrogate assembly.

30 cm Drop Test of Full-Scale Surrogate Assembly

The 30 cm drop tests of the full-scale dummy assembly allowed shock absorbing felt pads to be designed to adequately represent the effect of the cask and the impact limiters. This design will be used in the 30 cm drop of the full-scale surrogate assembly. The assembly will be instrumented with multiple accelerometers and strain gauges to obtain acceleration and strain data at different locations on the rods. These data will help to determine whether or not the fuel rods can maintain their integrity inside a cask when dropped from a height of 30 cm. The test will be conducted in the spring of 2020 and documented in a separate report.

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ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

The authors would like to thank Ned Larson from DOE NE for his programmatic leadership. Thanks also go to BAM and ENSA for their contributions of time, expertise, and hardware for this series of tests.

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REVISION HISTORY

Revision	Date	Description of Revision
0	12/20/19	Initial Issue

ACRONYMS

ADR	Acuerdo Europeo sobre Transporte Internacional de Mercancias Peligrosas por Carretera
BAM	Bundesanstalt for Materialforschung und -prufung
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
DAQ	Data Acquisition
DOE	US Department of Energy
ENSA	Equipos Nucleares, S.A., S.M.E.
FFT	Fast Fourier Transform
FCRD	Fuel Cycle Research and Development
IAEA	International Atomic Energy Agency
MMC	Metal Matrix Composite
MMTT	Multi-Modal Transportation Test
NCT	Normal Conditions of Transport
NRC	Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PSD	Power Spectra Density
PWR	Pressurized Water Reactor
SNL	Sandia National Laboratories
SRS	Shock Response Spectra
TTCI	Transportation Technology Center, Inc.

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SPENT FUEL AND WASTE DISPOSITION
30 CM DROP TESTS

1. INTRODUCTION

The 30 cm drop tests were a follow-on to the 2017 Spanish/US/Korean Multi-Modal Transportation Test (MMTT) that obtained strain and acceleration data during Normal Conditions of Transport (NCT) on surrogate fuel within the ENUN 32P dual purpose rail cask. The goal of the MMTT was to validate the hypothesis that spent nuclear fuel can withstand the shocks and vibrations from NCT. Data were collected during actual heavy-haul truck transport through Spain, small ship from Spain to Belgium, large ship from Belgium to the USA, and rail transportation from Baltimore to Pueblo (Colorado). The detailed report is available at [1]. The summary of the results can be found in [2-8]. A short video documenting the major test events is available on YouTube [9].

Note that the common assumption is that the cask content experiences the same accelerations as the cask itself. The data from the MMTT demonstrated that the inputs from the shock events were amplified from the cask to the surrogate assemblies. This is demonstrated in Figure 1-1 using cask-to-surrogate assembly transfer functions. The transfer function is the relationship between accelerometers on the cask and on the fuel assemblies. The transfer functions are shown for the maximum shock event during rail and heavy-haul transport and for the single bump test conducted at the Transportation Technology Center, Inc. (TTCI) test facility in Pueblo (Colorado). The single bump test was the one with highest accelerations compared to other TTCI tests, except coupling. One representative transfer function between two accelerometers is shown for each case. The peak around 40 Hz is related to the surrogate assembly natural frequency. The transfer function is around 4 at frequencies above 40 Hz and around 1.5 at frequencies below 20 Hz.

The amplification from the cask-to-surrogate assemblies observed in the MMTT was one of the motivations for conducting the 30 cm drop test. The purpose of the test was to measure accelerations and strains on the surrogate fuel assembly and to determine whether the fuel rods can maintain their integrity inside a cask when dropped from a height of 30 cm.

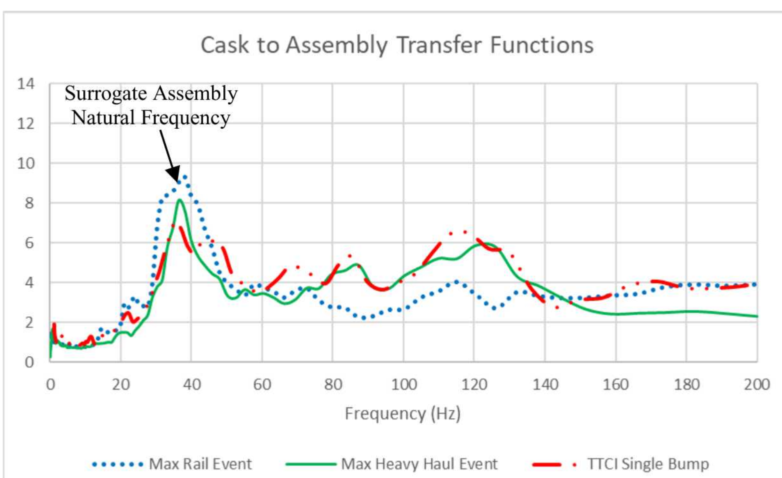


Figure 1-1. Cask to Surrogate Assembly Transfer Functions.

The 30 cm drop is the remaining NRC normal conditions of transportation regulatory requirement (10 CFR 71.71) for which there are no data on the actual surrogate fuel. While obtaining data on the actual fuel is not a direct requirement, it provides definitive information which aids in quantifying the risk of fuel breakage resulting from a cask drop from a height of 30 cm or less. Obtaining these data is not a direct requirement, but it allows for the following:

- Completing the NCT mechanical testing environment
- Better understanding the potential implications of handling incidents
- Quantifying the risk of fuel breakage under the 30 cm drop conditions
- Defining the transfer function from the cask to the fuel for more severe impacts

Ideally, the 30 cm drop test would be conducted with the full-scale cask containing surrogate assemblies. However, the cost of a full-scale cask and impact limiters make this test impractical. At the same time, the 1/3 scale cask with impact limiters and dummy assemblies was available at nominal cost. The decision was made to perform the 30 cm drop tests with the 1/3 scale cask first and then follow with the 30 cm drop tests with the full-scale dummy and surrogate assemblies. This would allow for obtaining the accelerations and strains on the full-scale surrogate fuel assembly in the 3 consecutive steps shown in Figure 1-2.

Step 1 is a 30 cm drop test of the 1/3 scale cask. The goal of this test is to obtain acceleration data on the cask and on the 1/3 scale dummy assemblies. The acceleration pulse on the 1/3 scale dummy assemblies can be converted to the expected acceleration pulse of the full-scale dummy assembly.

Step 2 is a 30 cm drop of the full-scale dummy assembly. The goal of this test is to find the condition under which the observed acceleration pulse would be similar to the expected acceleration pulse derived from Step 1. Achieving this condition means that the effect of the cask and the impact limiters are adequately represented. This step is required because the accelerations on the 1/3 scale dummy assembly are only applicable to the full-scale dummy assembly which is structurally very different from the full-scale surrogate assembly. This involves a series of 30 cm drop tests using different shock absorbing conditions in order to select the shock absorbing material that best mimics the cask and impact limiters.

Step 3 is a 30 cm drop of the surrogate assembly. The goal of this test is to obtain the accelerations and strains at multiple locations on the full-scale surrogate fuel assembly. This test will be conducted using the shock conditions derived in Step 2.

Section 2 describes the 30 cm drop of the 1/3 scale cask (Step 1) in Figure 1-2. Section 3 describes the 30 cm drop of the full-scale dummy assembly (Step 2 in Figure 1-2). The 30 cm drop test of the full-scale dummy assembly will take place in the spring of 2020 and will be documented in a separate report.

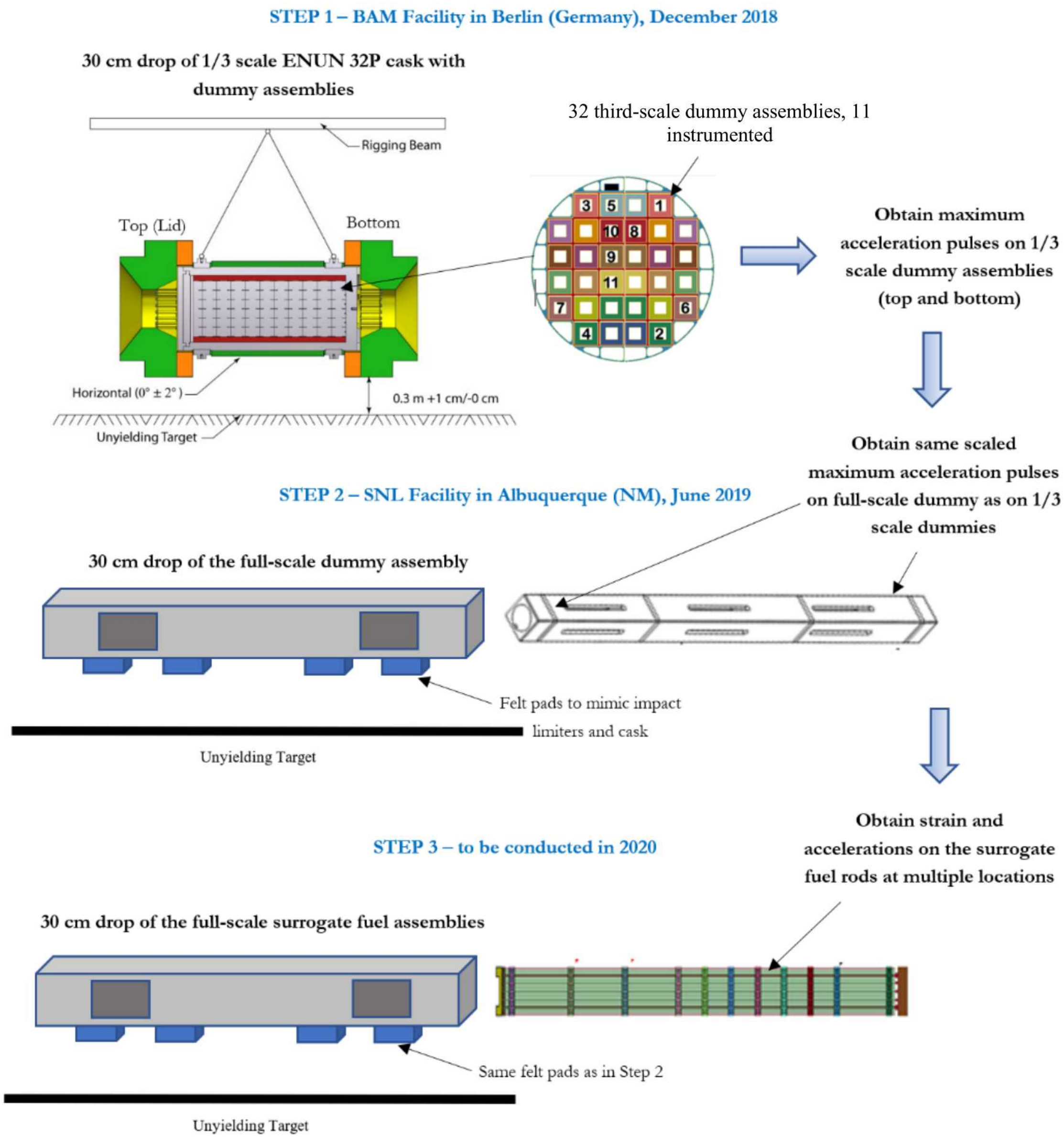


Figure 1-2. Steps to Obtain Accelerations and Strains on the Full-Scale Surrogate Assembly.

2. 30 CM DROP OF 1/3 SCALE CASK

The 30 cm drop tests of 1/3 scale cask (Step 1 in Figure 1-2) were conducted by the Sandia National Laboratories (SNL) team in collaboration with Pacific Northwest National Laboratory (PNNL), Bundesanstalt für Materialforschung und -prüfung (BAM) (Germany), and Equipos Nucleares, S.A., S.M.E. (ENSA) (Spain). The tests took place in December 2018 at the BAM facility in Berlin (Germany). The test plan is documented in [12].

The 1/3-scale ENSA ENUN-32P cask was the scaled model of the same cask used in the multi-mode transportation test. The model included scaled impact limiters, cask body, and basket. The model did not include scaled fuel assemblies, but mass mock-ups of the fuel (referred to as dummy assemblies).

Note that a series of structural impact tests were performed on the same 1/3 scale model by SNL for ENSA in 2010 at the SNL facility in Albuquerque, NM [10]. The purpose of those tests was to confirm that the impact limiters would remain attached to the cask and limit the acceleration transmitted to the cask to values below those used in analyzing the impact limiters under normal transport conditions and hypothetical accident conditions, as well as to demonstrate the package will meet its other functions as defined in IAEA TS-R-1, ADR, and 10CFR71, such as package containment, retrievability of the fuel assemblies and geometric control. The instrumentation in this test was on the outside of the cask. The data collected in 2010 for the 30 cm drop test provided useful information on what accelerations to expect on the cask. The data comparison is presented in Section 2.8.3.

2.1 Introduction

As discussed in Section 1, the purpose of the test was to measure the accelerations on the 1/3 scale cask and dummy assemblies. Note that strains were not measured in the 1/3-scale drop test because the 1/3 scale dummy assemblies are structurally very different from the actual (surrogate) fuel assembly used in the multimodal transportation tests. Strains will be measured in the full-scale surrogate assembly drop tests at SNL in the spring of 2020.

For exact geometric scale models, there is a clear relationship between scale model results and full-scale results. Accelerations in the scale model are higher by the inverse of the scale factor. Stresses and strains are the same in the scale model and prototype (full-scale cask). Time is shorter by the scale factor. This means that strain rates are higher in the scale model.

The study in [11] offers a comparison of experimental results from drop testing of a spent fuel package design using a full-scale prototype model and a reduced-scale model. The decelerations and velocities measured in a 9.3 m vertical drop test [11] are replicated in Figure 2-1. The most significant differences between the full-scale and reduced-scale models (yellow region) are associated with the secondary impact of the contents against the cask lid.

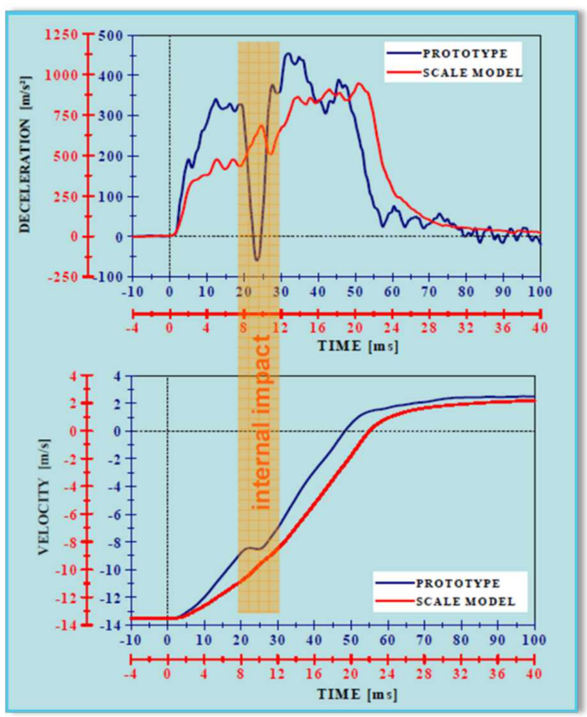


Figure 2-1. Decelerations and Velocities Measured in 9.3 m Vertical Drop Test from [11].

There always will be differences between the full-scale and reduced-scale models because the acceleration field cannot be scaled. The compressed time in the reduced-scale model means that timing of secondary impacts is incorrect. The larger the physical gaps between hardware in the model, the more significant this difference is. Also, the impact limiter material grain size is not scaled.

Table 2-1 reproduced from [11] summarizes the rigid body impact response of the scaled model. The maximum and average deceleration of the reduced-scale model is 17% different from the full-scale model. The differences in the 30 cm horizontal drop are expected to be significantly smaller than in the 9.3 m vertical drop.

Table 2-1. Rigid Body Impact Response of the Scaled Model from [11].

Rigid body impact response of the scaled model	
■ Maximum translation ↑+9% ■ Impact duration ↑+24% ■ Maximum and average deceleration ↓-17%	The scaled model tends to represent the impact of the prototype model as softer

2.2 Test Hardware

The 1/3 scale cask and associated hardware was provided by ENSA, a Spanish government-owned company. ENSA is a multisystem supplier of nuclear components and has proprietary designs for metal containers with double purpose (storage and transport) for Boiling Water Reactor (BWR) and Pressurized Water Reactors (PWR) fuel. ENSA's participation in this project was in line with its policy of continuous improvement and technological innovation. ENSA provided the 1/3 scale cask system at no charge and only recovered the costs associated with the manufacturing of the lid specifically designed for this test and project management.

Figure 2-2 shows the solid model (top) and the photo (bottom) of the 1/3 scale ENSA ENUN-32P cask with the impact limiters.

The cask dimensions and weight are:

- Length (with impact limiters): 2,763 mm
- Diameter (with impact limiters): 1,267 mm
- Weight (loaded cask + impact limiters): ~5,077 Kg

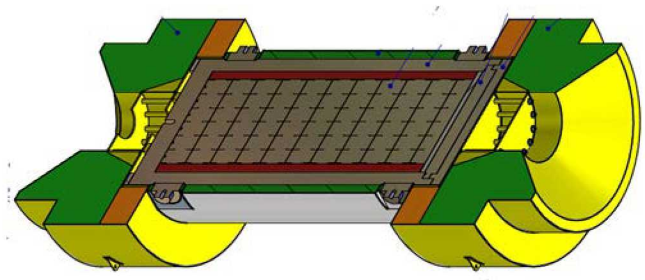


Figure 2-2. Solid Model (top) and Photo (bottom) of the 1/3 Scale ENSA ENUN-32 Cask with Impact Limiters.

Thirty two dummy assemblies to represent the 1/3-scale mass of the fuel were provided by ENSA along with the cask. The solid model of the dummy assembly and its photo while being pulled from the cask are shown in Figure 2-3.

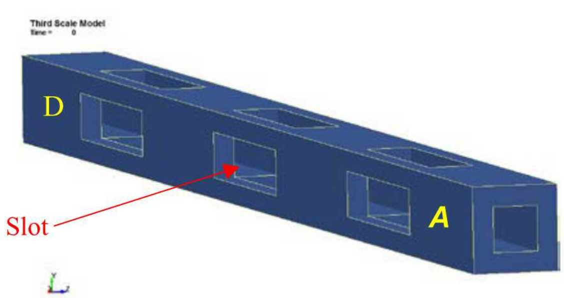


Figure 2-3. Solid Model (left) and Photo (right) of the 1/3 Scale Dummy Assembly.

The original lids (external and internal) of the 1/3 scale ENSA cask were not used in the test. Instead, a special lid was manufactured by ENSA. This lid had the same weight and center of gravity as the two original lids and had two 5 cm holes for the instrumentation cables. Figure 2-4 shows the solid model (left) and a photo (right) of the special lid.

Figure 2-4. Solid Model (left) and Photo (right) of the Special Lid for 1/3 Scale Cask.

Due to the high cost of new impact limiters, it was decided to re-use the impact limiters from the 2010 series of tests. ENSA identified two suitable used impact limiters. Figure 2-5 shows damaged bottom impact limiter. This impact limiter was converted to an upper one. Another bottom impact limiter (Figure 2-6) with similar damage was used on the bottom.

Figure 2-5. Damaged Bottom Impact Limiter that was Modified for Use as a Top Impact Limiter.

Figure 2-6. Damaged Bottom Impact Limiter.

2.3 Instrumentation

The cask with the impact limiters, modified lid, dummy assemblies, and handling tools, was transported from the ENSA facility in Santander (Spain) to the BAM indoor test facility in Berlin in November 2018. Figure 2-7 shows the cask packaging on the right and its arrival to the BAM facility on the left.

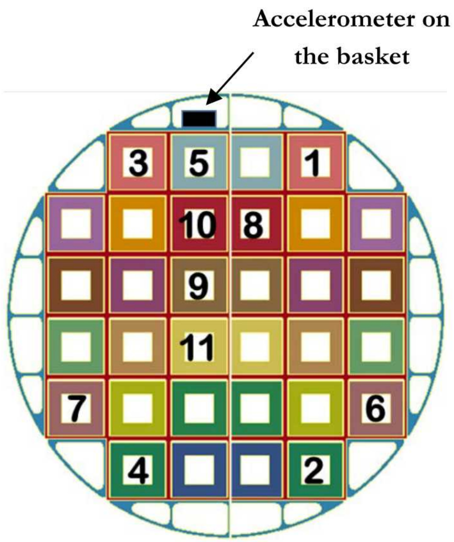
The instrumentation was performed by SNL in November-December 2018. The accelerometers were placed on the assemblies, basket, and on the external surface of the cask. The following sections discuss the details of the instrumentation.

Figure 2-7. BAM Indoor Facility (left) and Cask Packaging (right).

2.3.1 Dummy Assembly and Basket Instrumentation

The dummy assembly instrumentation recommendations were based on LS-DYNA model results of a 30 cm drop of the 1/3 scale ENSA cask [13]. There are four semi-rigid zones on the dummy assembly that are enclosed on four sides. They are much stiffer than the sections that have slots cut in them (Figure 2-3). Modeling predicted that the simulated assembly response would be dominated by rigid body motion (not much deflection) despite the slots. The modeling results demonstrated that the gross motion of each zone was very similar, with some variation. Slightly different accelerometer signals would be expected in each zone, but difference in response would likely be high-frequency and short duration. The recommend accelerometer locations were roughly at the center of mass of the upper (A) and bottom (D) zones (Figure 2-3) to minimize potential noise from the edges.

It was proposed to instrument eleven dummy assemblies and one location on the basket as shown in Figure 2-8.



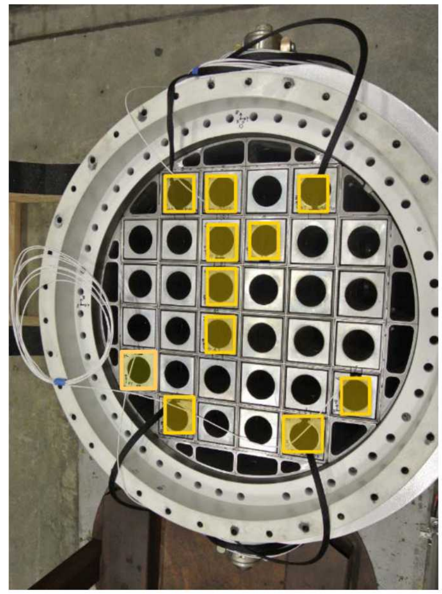


Figure 2-8. Accelerometer Locations on the Dummy Assemblies and Basket.

The rational for selecting eleven assemblies is provided below.

- Locations 1, 2, 3, and 4 were selected because they represented high and low peak accelerations on two sides of the symmetry plane. The non-symmetrical behavior (if any) can thus be identified.
- Locations 5, 6, and 7 were selected because they match instrumented fuel assembly locations in the multi-modal transportation test.
- Locations 8 and 9 were selected to cover all interesting fuel assembly locations identified through modeling.
- Locations 10 and 11 were selected to complete a partial column for cross-comparison and time delay. Average to temporarily bounding response is expected at these locations based on modeling.

The A (top) end of the dummy assemblies was instrumented with a total of 19 channels:

- Locations 1, 2, 3, and 4: triaxial accelerometer at each location.
- Locations 5, 6, and 7: uniaxial accelerometer at each location.
- Locations 8 and 9: uniaxial accelerometer at each location.
- Location 10 and 11: uniaxial accelerometer at each location.

The D (bottom) end of the dummy assemblies was instrumented with a total of 15 channels:

- Locations 1, 2, 3, and 4: triaxial accelerometer at each location.
- Locations 5, 6, and 7: uniaxial accelerometer at each location.

The total number of channels on the dummy assemblies was 34: 19 channels on the A end and 15 channels on the D end. The uniaxial accelerometers were in the vertical orientation. It was expected that triaxial accelerometers on any dummy assembly would show negligible acceleration in axial and lateral directions, except for locations 2 and 4. These locations might have higher than average lateral acceleration. Figure 2-9 shows dummy assemblies from location 4, 5, 7, and 9 (left) and tri-axial accelerometer block (right).

Figure 2-9. Dummy Assemblies from Location 4, 5, 7, and 9 (left) and Tri-Axial Accelerometer Block (right)

The accelerometer location on the basket (Figure 2-8) was selected to correspond with the top accelerometer location in the multi-modal transportation test. The bottom location was not accessible. One triaxial accelerometer was installed.

Table 2-2 provides a summary of instrumentation for the dummy assemblies and the basket.

Table 2-2. Dummy Assembly and Basket Instrumentation Summary.

Channel	Gauge ID	Model Number	Location	Position	Cask Position	Measurement Direction
13	A1AX	7265A	Assembly 1	A	Top (Lid)	+X
14	A1AY	7265A	Assembly 1	A	Top (Lid)	+Y
15	A1AZ	7265A	Assembly 1	A	Top (Lid)	+Z
16	A1DX	7265A	Assembly 1	D	Bottom	+X
17	A1DY	7265A	Assembly 1	D	Bottom	+Y
18	A1DZ	7265A	Assembly 1	D	Bottom	+Z
19	A2AX	7265A	Assembly 2	A	Top (Lid)	+X
20	A2AY	7265A	Assembly 2	A	Top (Lid)	+Y
21	A2AZ	7265A	Assembly 2	A	Top (Lid)	+Z
22	A2DX	7265A	Assembly 2	D	Bottom	+X
23	A2DY	7265A	Assembly 2	D	Bottom	+Y
24	A2DZ	7265A	Assembly 2	D	Bottom	+Z
25	A3AX	7265A	Assembly 3	A	Top (Lid)	+X
26	A3AY	7265A	Assembly 3	A	Top (Lid)	+Y
27	A3AZ	7265A	Assembly 3	A	Top (Lid)	+Z
28	A3DX	7265A	Assembly 3	D	Bottom	+X
29	A3DY	7265A	Assembly 3	D	Bottom	+Y
30	A3DZ	7265A	Assembly 3	D	Bottom	+Z
31	A4AX	7265A	Assembly 4	A	Top (Lid)	+X
32	A4AY	7265A	Assembly 4	A	Top (Lid)	+Y
33	A4AZ	7265A	Assembly 4	A	Top (Lid)	+Z
34	A4DX	727-2K	Assembly 4	D	Bottom	+X
35	A4DY	727-2K	Assembly 4	D	Bottom	+Y
36	A4DZ	727-2K	Assembly 4	D	Bottom	+Z
37	A5AZ	727-2K	Assembly 5	A	Top (Lid)	+Z
38	A5DZ	727-2K	Assembly 5	D	Bottom	+Z
39	A6AZ	727-2K	Assembly 6	A	Top (Lid)	+Z
40	A6DZ	727-2K	Assembly 6	D	Bottom	+Z
41	A7AZ	727-2K	Assembly 7	A	Top (Lid)	+Z
42	A7DZ	727-2K	Assembly 7	D	Bottom	+Z
43	A8AZ	727-2K	Assembly 8	A	Top (Lid)	+Z
44	A9AZ	727-2K	Assembly 9	A	Top (Lid)	+Z
45	A10AZ	727-2K	Assembly 10	A	Top (Lid)	+Z
46	A11AZ	727-2K	Assembly 11	A	Top (Lid)	+Z
47	A12X	727-2K	Basket	A	Top (Lid)	+X
48	A12Y	727-2K	Basket	A	Top (Lid)	+Y
49	A12Z	727-2K	Basket	A	Top (Lid)	+Z

2.3.2 Cask Instrumentation

The four locations of the accelerometers on the cask (Figure 2-10) were the same as in 2010 series of tests at SNL. Tri-axial accelerometers were installed in each location. In total, there were 4 triaxial accelerometers. Table 2-3 provides the summary of instrumentation for the cask.

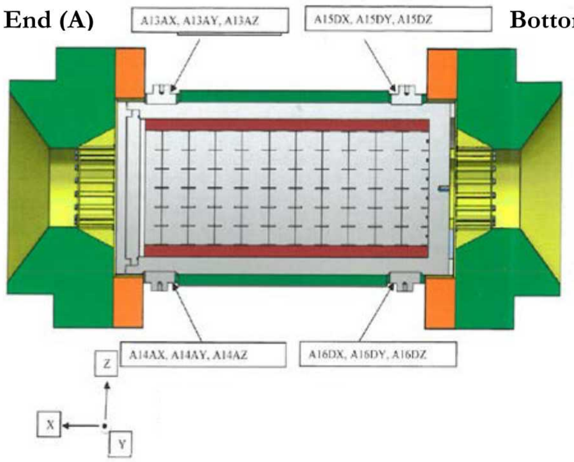


Figure 2-10. Accelerometer Locations on the Cask.

Table 2-3. Cask Instrumentation Summary.

Channel	Gauge ID	Model Number	Location	Position	Cask Position	Measurement Direction
1	A13X	7270A-20K	Cask Body	0˚	Top (Lid)	+X
2	A13Y	7270A-20K	Cask Body	0˚	Top (Lid)	+Y
3	A13Z	7270A-20K	Cask Body	0˚	Top (Lid)	+Z
4	A14X	7270A-20K	Cask Body	180˚	Top (Lid)	+X
5	A14Y	7270A-20K	Cask Body	180˚	Top (Lid)	+Y
6	A14Z	7270A-20K	Cask Body	180˚	Top (Lid)	-Z
7	A15X	7270A-20K	Cask Body	0˚	Bottom	+X
8	A15Y	7270A-20K	Cask Body	0˚	Bottom	+Y
9	A15Z	7270A-20K	Cask Body	0˚	Bottom	+Z
10	A16X	7270A-20K	Cask Body	180˚	Bottom	+X
11	A16Y	7270A-20K	Cask Body	180˚	Bottom	+Y
12	A16Z	7270A-20K	Cask Body	180˚	Bottom	-Z

Note. The sign convention for the accelerometer measurements will be a right-hand rule with the longitudinal (x) along the cask toward direction of the lid, lateral (y) positive to the left when facing the bottom in a direction toward the lid, and the vertical (z) positive upwards.

2.3.3 Sensors

Three different Endevco Corporation accelerometer models were used in the 30 cm drop test:

- 7270A-20K (acceleration up to 20,000 g)
- 727-2K (acceleration up to 2,000 g)
- 7265A (acceleration up to 100 g)

The accelerometers are shown in Figure 2-11. Tables 2-2 and 2-3 describe which model was assign to a specific channel.

Figure 2-11. Accelerometer Models Used in 30 cm Drop Test.

The choice of the accelerometers was based on their availability, their use in the Multi-Modal Transportation Test, and their size. The model 727 was used on the assemblies and basket in the multi-mode transportation test. The model 7265A was used on the cask in the Multi-Mode Transportation Test. The model 7270A was used on the cask in the 2010 series of tests at SNL. The locations of the accelerometers are provided in Table 2-2.

There are holes in the 1/3 scale ENSA cask lid that were used to install the wire leads for the accelerometers. The model 7270A is too big to be used inside the cask. The models used inside the cask (727 and 7265A) are from a family of very low mass (6 gram), piezoresistive accelerometers designed for applications requiring high sensitivity, good low frequency response, and minimum mass loading.

The cables connected to the accelerometers located on the dummy assemblies and on the basket were pulled outside through two holes in the lid as shown in Figure 2-10 (bottom).

2.3.4 Instrumentation Setup

The diagram in Figure 2-12 shows the instrumentation setup for the dummy assemblies, basket, and cask.

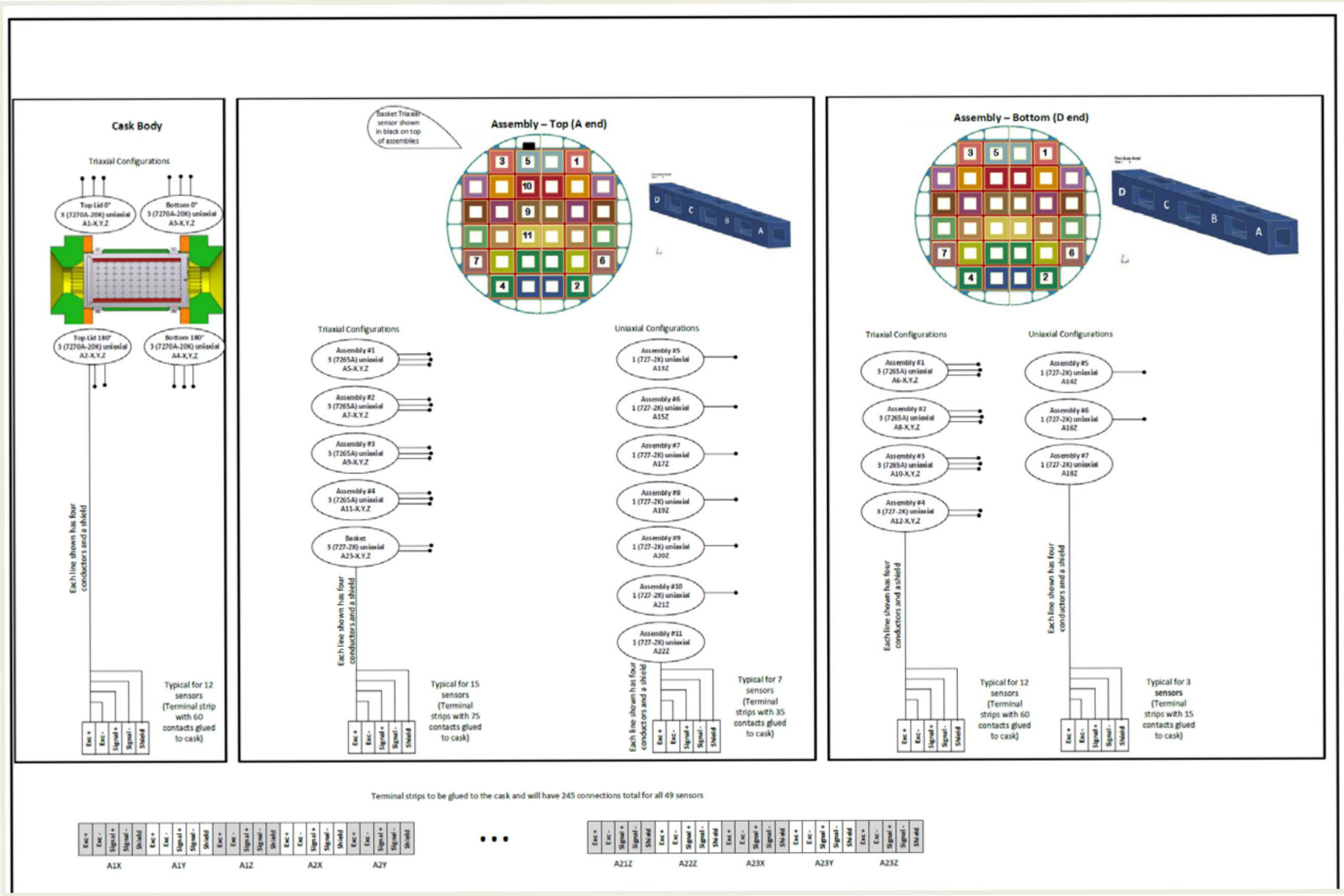


Figure 2-12. Instrumentation Setup.

2.4 Test Configuration

Two horizontal drop test configurations were used. These configurations are shown in Figure 2-13. In the first configuration, the cask was in its normal transport position. In the second configuration, the cask was rotated 45 degrees counter clockwise when looking at the lid end about its longitudinal axis.

The purpose of the 45 degrees rotation test was to quantify the potential variation of dummy assembly impact response due to a change in basket orientation. The dummy assemblies within the cask were expected to witness higher acceleration pulses than the cask body (Section 1). Loads transmitted to the dummy assemblies are transmitted through the basket structure. Rotating the basket orientation in the second test changes the contact area between the basket and the simulated dummy assemblies, and it changes the load path through the basket structure. This secondary test was meant to provide the data to determine if there was a significant difference in dummy assembly loading due to basket orientation.

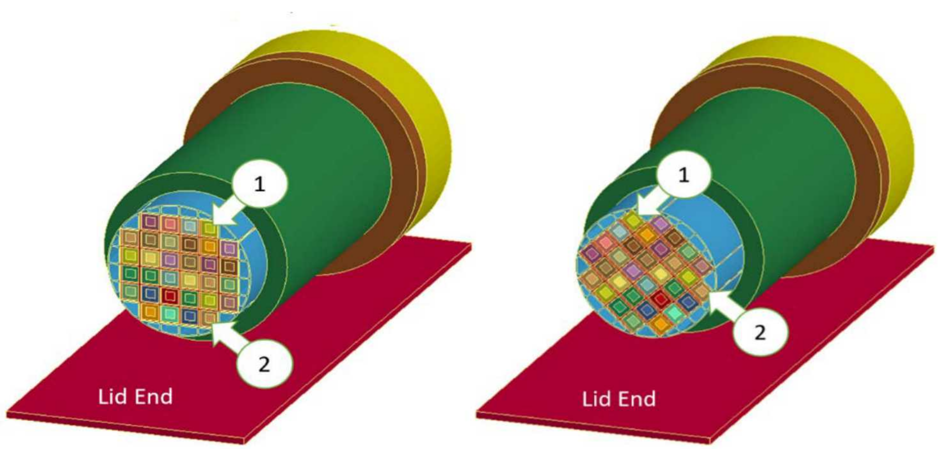


Figure 2-13. Drop Test Configurations.

The impact limiter configurations in the two drop tests are shown in Figure 2-14.

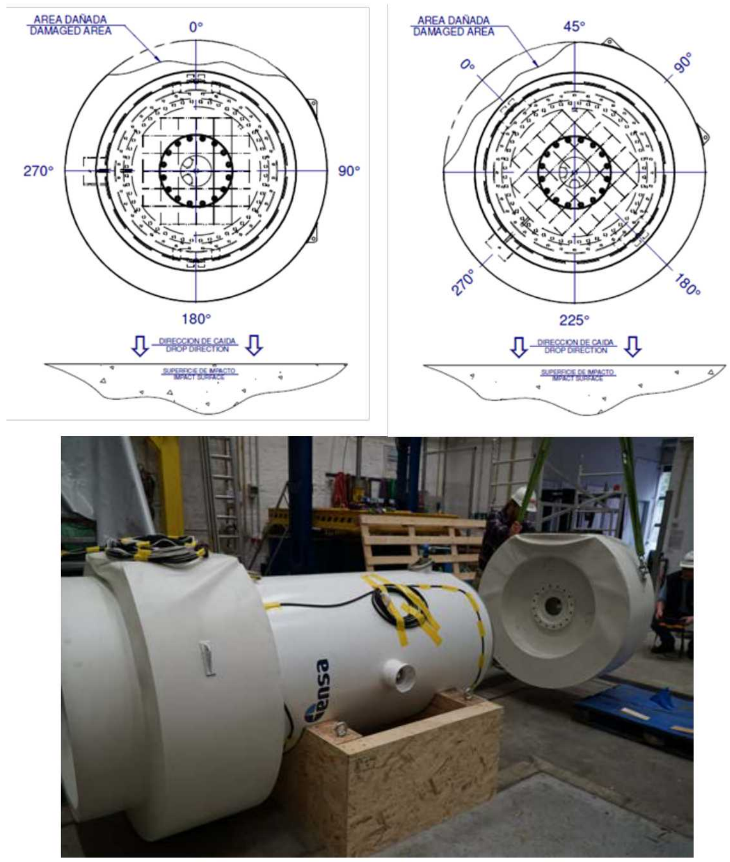


Figure 2-14. Impact Limiter Configurations in Two Drop Tests.

2.5 Rigging

The rigging for the first drop test is shown in Figure 2-15. The trunnions located on the top of the cask were used. The rigging for the second drop test is shown in Figure 2-16. The cask body is rotated and the trunnions cannot be used. In this case the slings were placed around the cask body.

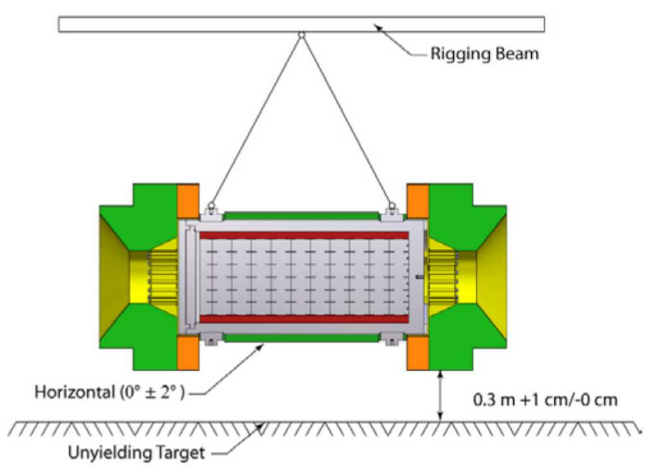


Figure 2-15. Rigging Used in the First Drop Test.

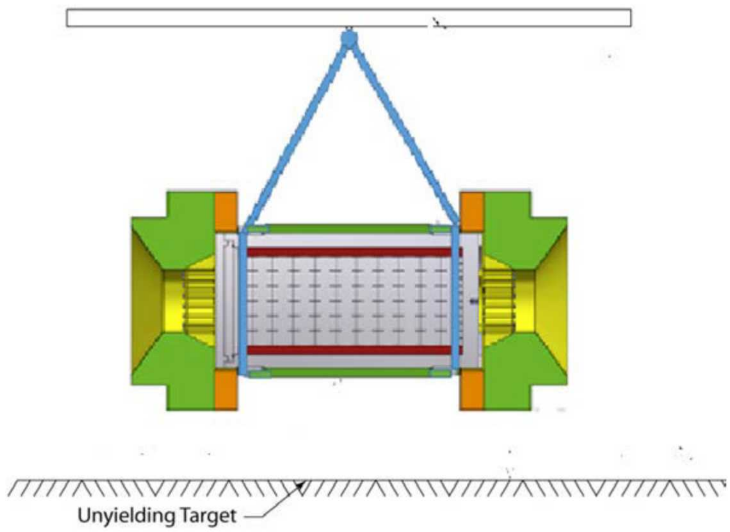


Figure 2-16. Rigging Used in the Second Drop Test.

2.6 Cask Handling and Preparations for Test

Three pieces of equipment were essential for safe handling of the cask during the preparation for the test. The first one was the wooden cradle specifically manufactured by ENSA for this test. The cradle is shown in Figure 2-17. The cask was in the cradle while waiting for handling operations.

Figure 2-17. Wooden Cradle Used in Handling.

The second piece of equipment was needed to safely rotate the cask. After the cask was moved into the BAM indoor facility, it had to be placed in the vertical position. Pulling the dummy assemblies from the cask for installing the instrumentation and then placing them back is practically impossible when the cask is in a horizontal position. To handle the cask the fixture manufactured at SNL for the 2010 series was used. The fixture was shipped to BAM. It is shown in Figure 2-18.

Figure 2-18. Fixture Used to Rotate the Cask during Handling.

The impact limiters were removed prior to placing the cask in the fixture. After the cask was rotated into the vertical position, it was placed on the pad. The dummy assemblies were then pulled out and instrumented. After the instrumented assemblies were inserted in the cask, it was placed in the fixture and rotated into horizontal position. The cask was next moved out of the fixture and the impact limiters were installed.

The third piece of equipment needed for safe handling was the gripper (Figure 2-19) used to handle the dummy assemblies. The gripper was provided by ENSA.

Figure 2-19. Handling Dummy Assembly with the Gripper.

2.7 Data Acquisition and Test Setup

The tests were conducted at the BAM indoor facility on December 11 (first drop) and December 12 (second drop) of 2018. The target was a reinforced concrete block with a mass of 280,000 kg and with dimensions of 6 m x 6 m x 3 m. The impact pad was a steel plate of 18,700 kg (4 m x 2 m x 0.3 m) embedded and fixed onto the concrete block.

A BAM data acquisition (DAQ) system was used (Figure 2-20). The BAM DAQ is designed to record decelerations and strains during the extremely short period of the impact event. The sampling rate was 200,000 Hz. The data acquisition was performed by BAM staff. The test setup before the first drop on December 11, 2018 is shown in Figure 2-21.

Figure 2-20. BAM Data Acquisition System Setup for the Test.

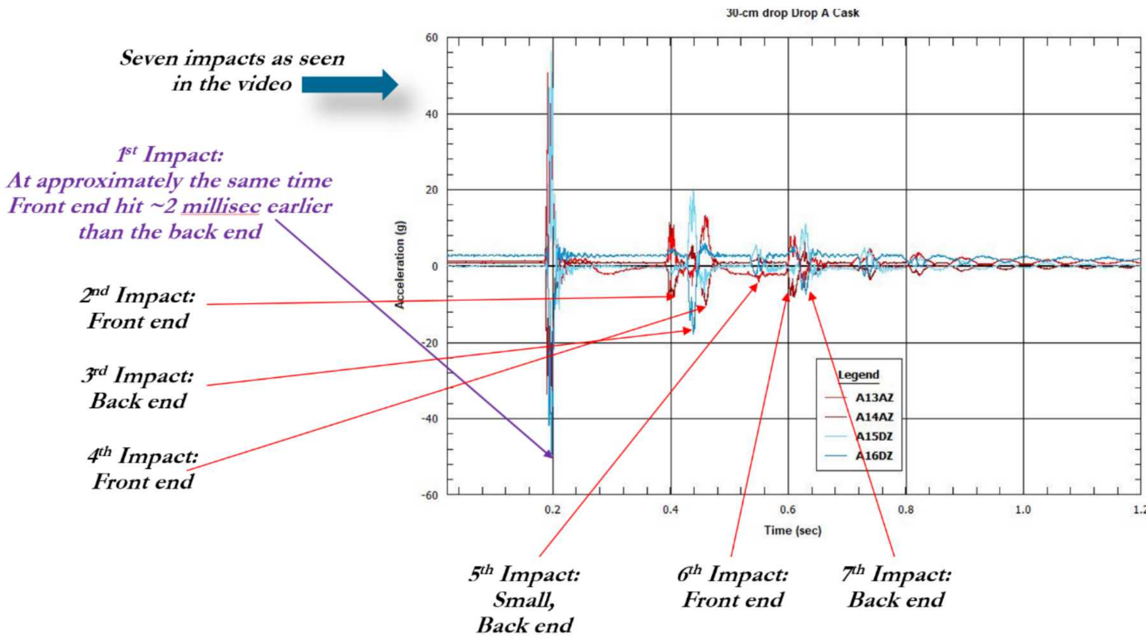
Figure 2-21. Test Setup before the First Drop (December 11, 2018).

2.8 Data Analysis

Data were collected at 200,000 Hz. Section 2.8.1 describes an analysis of the first drop performed on December 11, 2018 referred to as drop A. Section 2.8.2 describes an analysis of the second drop performed on December 12, 2018 referred to as drop B. Section 2.8.3 provides comparison between the data collected in the 2010 series of tests and the 2018 tests. Section 2.8.4 describes the input from the 1/3 scale test into the full-scale dummy assembly drop test. The time histories of the individual accelerometers are provided in Appendix A.

2.8.1 Drop A

Fast camera video and acceleration time histories of Drop A showed that the cask bounced 7 times. It can be clearly seen in Figure 2-22. In this figure the front end of the cask is shown in red and the back end is shown in blue. The first impact has the greatest accelerations. The front end of the cask hit the target slightly before the back end.



Note: front end is shown in red, back end is shown in blue.

Figure 2-22. Cask Acceleration Time Histories during Drop A.

Figure 2-23 shows the acceleration Power Spectra Density (PSD) for the dummy assemblies. The signal strength is insignificant above 1,000 Hz and is not shown. The rigid body response is within the frequency band 0-300 Hz. There is a strong signal within the 800-1,100 Hz. This signal is related to the assembly chattering inside the basket tube. The chattering is not observed when the cask is rotated 45 degrees in Drop B (Figure 2-24) because the assembly movement in this position is restricted.

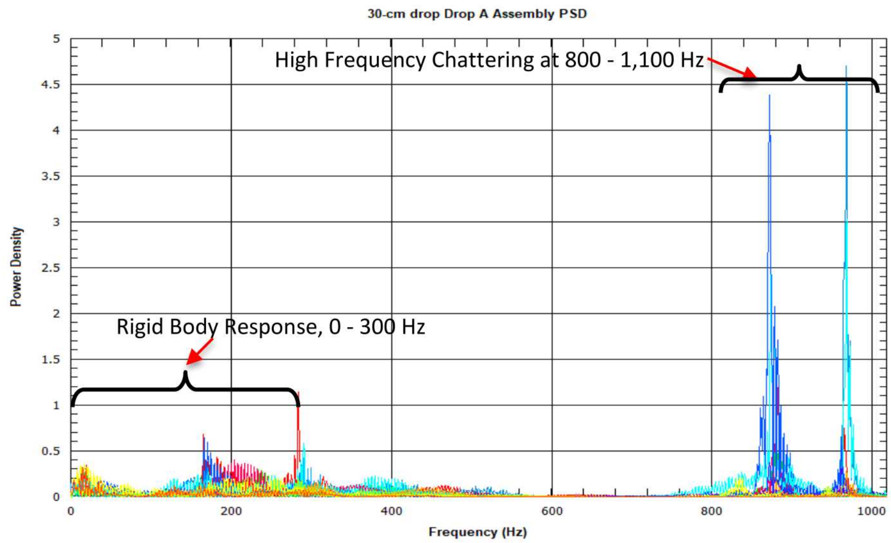


Figure 2-23: Acceleration PSD for Dummy Assemblies in Drop A.

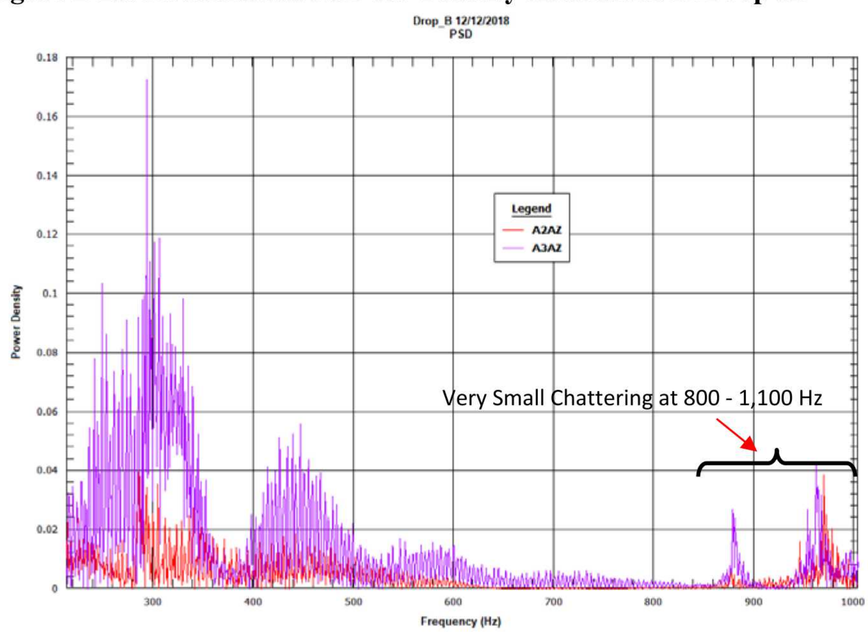


Figure 2-24. Dummy Assembly Acceleration PSD for Dummy Assemblies in Drop B.

Figure 2-25 shows acceleration SRS in X, Y, and Z direction for accelerometers 1DX, 1DY, and 1DZ in Drop A. The high peak in Y direction around 1,000 Hz indicates that the high frequency assembly chattering inside the basket tube occurred in the lateral direction.

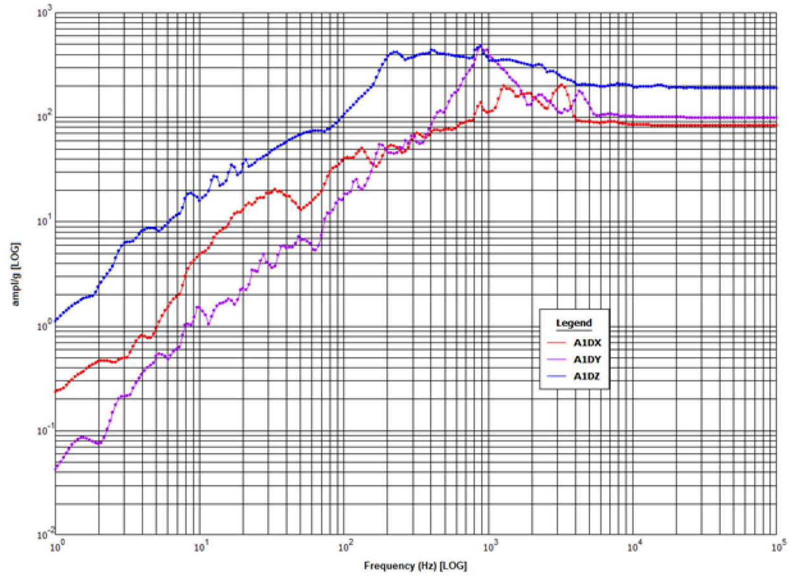


Figure 2-25. Dummy Assembly Acceleration SRS in X, Y, and Z direction (accelerometers 1DX, 1DY, and 1DZ) in Drop A.

The accelerometers that experienced chatter at 870 Hz were A4DZ, A2DZ. There was a small response from A3DZ. At 970 Hz, it was A2AZ and A2DZ. These accelerometers are on the dummy assemblies located next to the cask wall.

Figure 2-26 (left) shows cask acceleration FFT for a broad frequency band and Figure 2-26 (right) shows cask acceleration FFT for the frequency band up to 300 Hz. There is virtually no signal above 300 Hz. Consequently, it is appropriate to use a lowpass Infinite Impulse Response (IIR) filter to 300 Hz.

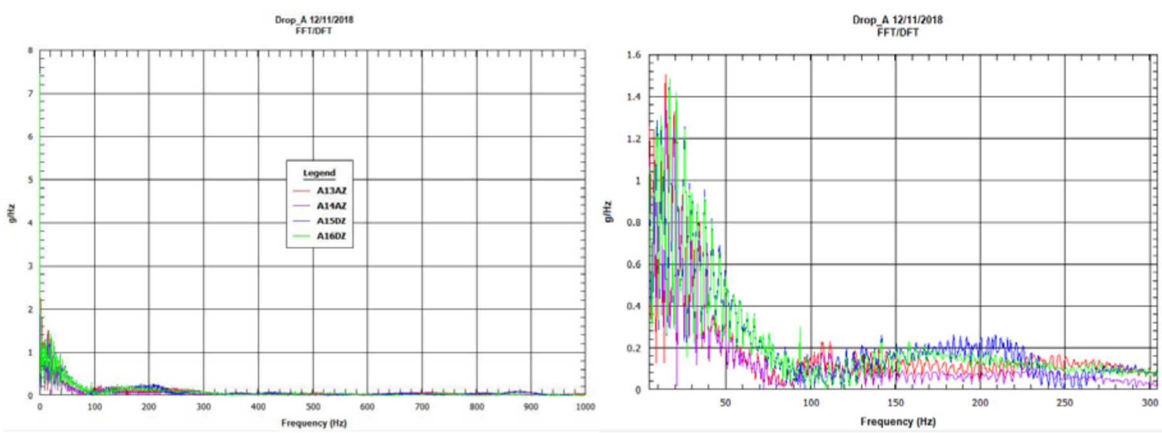


Figure 2-26. Cask Acceleration FFT in Drop A (first impact).

To analyze the system response outside rigid-body frequency band, Table 2-4 compares maximum data recorded with unfiltered data, with a lowpass IIR filter to 500 Hz, and with a lowpass IIR filter to 300 Hz. Accelerometer A5DZ experienced both greatest assembly acceleration and greatest overall system acceleration. Accelerometer A15DZ on the back-end of the cask experienced greatest cask acceleration.

Table 2-4: Maximum Accelerations of Unfiltered and Filtered Data in Drop A.

Filter	Maximum Assembly Acceleration (g)	Accelerometer ID	Maximum Overall System Acceleration (g)	Accelerometer ID	Maximum Cask Acceleration (g)	Accelerometer ID
Unfiltered	379.4	A4DZ	738.9	A12AZ	71.6	A13AZ
Lowpass 300 Hz	167.6	A5DZ	167.6	A5DZ	49.7	A15DZ
Lowpass 500 Hz	259.1	A5DZ	259.1	A5DZ	47.8	A15DZ

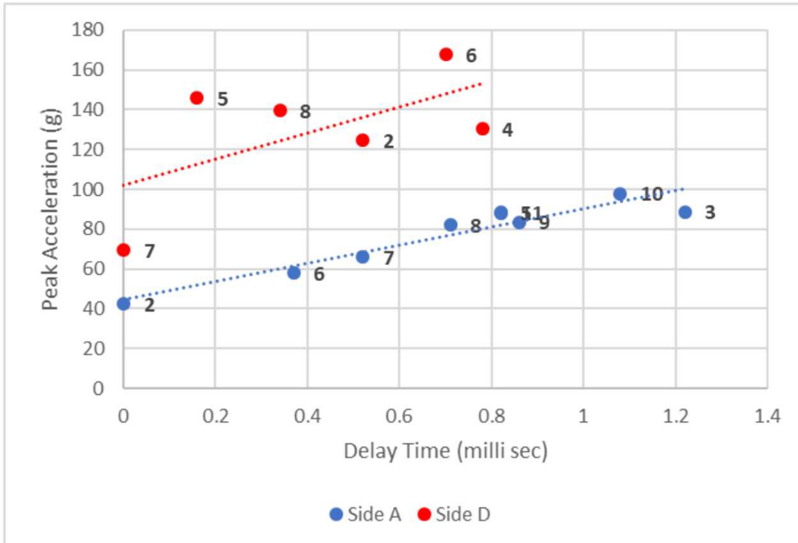
Table 2-5 summarizes the assembly acceleration data for drop A. Side A, which was at the front end of the cask, experienced maximum acceleration in A10AZ. Side D, on the bottom end of the cask, experienced maximum acceleration in A5DZ. Note that accelerometer A1AZ was disconnected during the test.

Figure 2-27 shows peak accelerations versus the delay times (Table 2-5). On both sides, the larger is the delay time, the higher is the peak acceleration.

Table 2-5: Maximum Vertical Accelerations on Dummy Assemblies Filtered to 300 Hz, Drop A.

DROP A	Side A (top)			Side D (bottom)		
Assembly	Max Acceleration (Filtered to 300 Hz)	Time of Max (sec)	Delta T with earliest peak (millisecond)	Max Acceleration (Filtered to 300 Hz)	Time of Max (sec)	Delta T with earliest peak (millisecond)
1	N/A	N/A	N/A	124.61*	0.1958	0.52
2	42.38*	0.1916	0	100.98*	0.1999	4.59
3	88.69*	0.1928	1.22	130.41*	0.196	0.78
4	65.07*	0.1999	8.31	145.8	0.1954	0.16
5	88.34	0.1924	0.82	167.63	0.196	0.7
6	57.95	0.192	0.37	69.48	0.1953	0
7	66.04	0.1921	0.52	139.42	0.1956	0.34
8	81.96	0.1923	0.71			
9	83.48	0.1925	0.86			
10	97.81	0.1927	1.08			
11	88.08	0.1924	0.82			

* These data might have been affected by the accelerometer cutoff limits (Figure 2-37 and related discussion).



Note: the data labels refer to the assembly IDs in Table 2-5.

Figure 2-27. Peak Assembly Accelerations versus Delay Time, Drop A.

To visualize the recorded responses from the different accelerometers during drop A the following color mappings were created, with numbers representing accelerometer ID's and color representing maximum recorded acceleration filtered to 300 Hz. Figure 2-28 shows side A, with a time history during the first impact for the maximum acceleration seen in A10AZ, and the minimum acceleration seen in A2AZ.

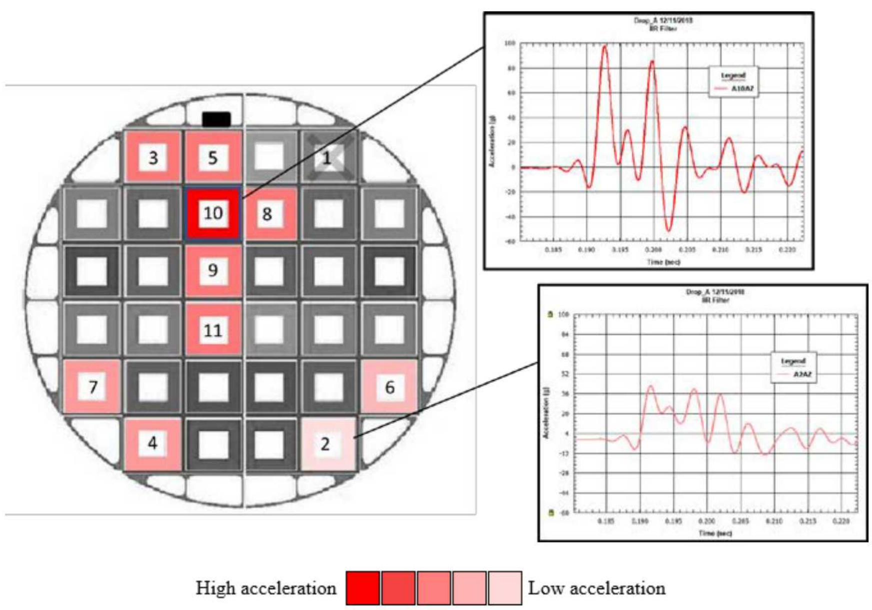


Figure 2-28. Maximum Accelerations on Assembly Front End (Side A) in Drop A.

A similar color mapping for side D is shown in Figure 2-29 with time histories during the first impact of the maximum acceleration recorded in A5DZ, as well as the minimum acceleration recorded in A6DZ.

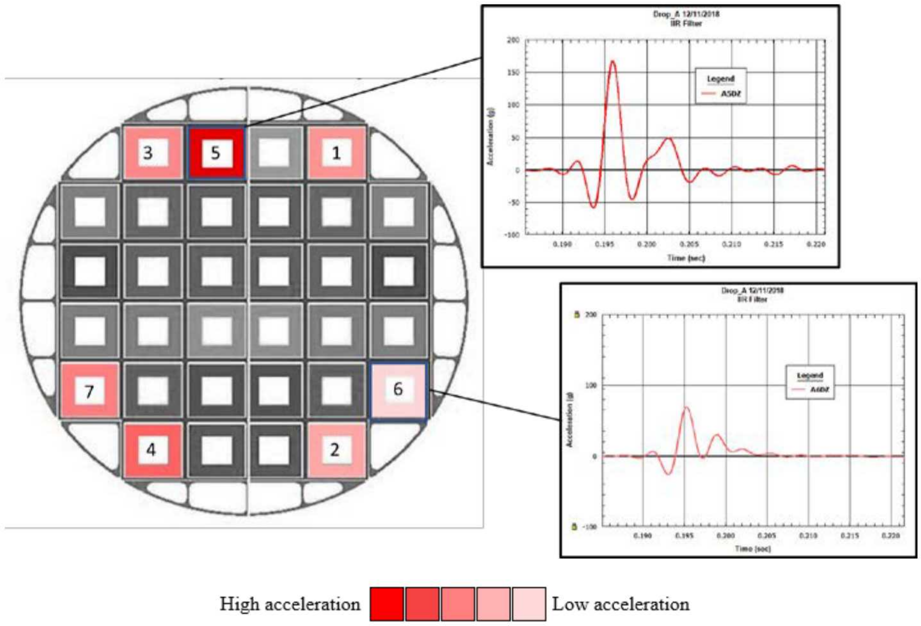


Figure 2-29. Maximum Accelerations on Assembly Back End (Side D) in Drop A.

Figure 2-30 shows the averaged values of maximum accelerations from side A and side D during the first impact filtered to 300 Hz. The maximum of the averaged value is 98.7 g, and the minimum is -23.8 g.

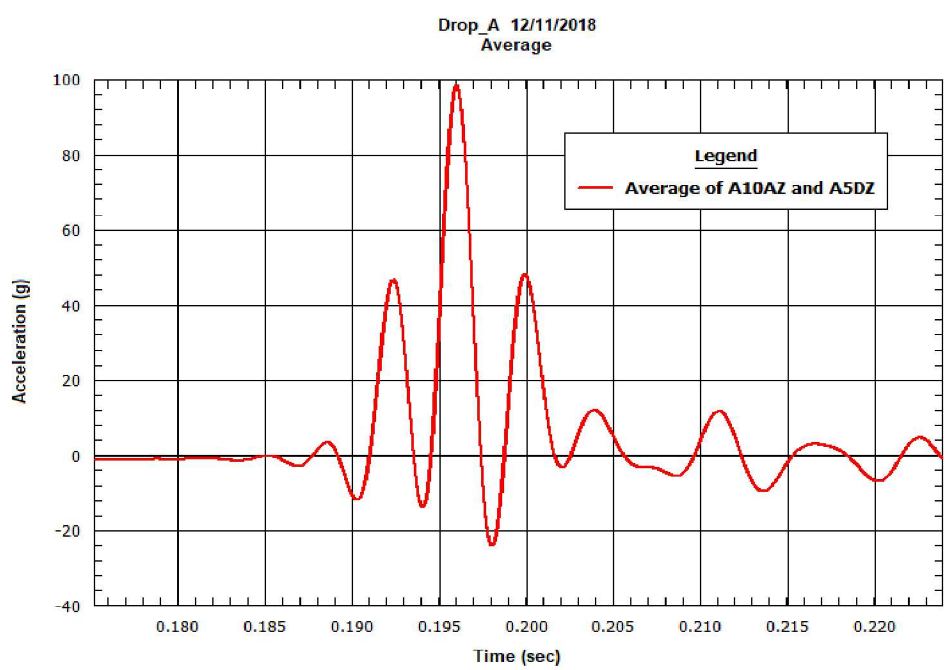


Figure 2-30. Average of Maximum Assembly Accelerations on Front and Back Ends, Drop A.

Figures 2-31 and 2-32 show the individual time histories of vertical accelerations filtered to 300 Hz on both sides of the assemblies.

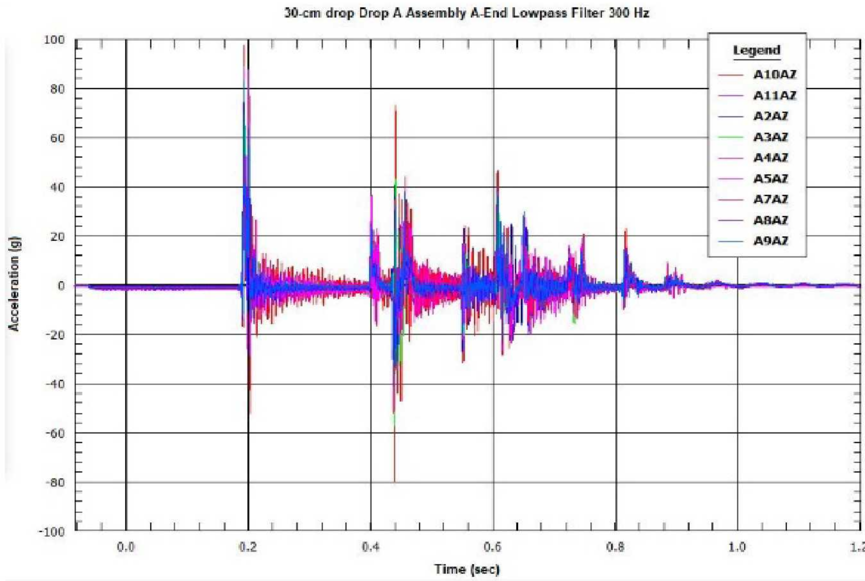


Figure 2-31. Acceleration Time Histories on the Assembly Front (Side A) in Drop A.

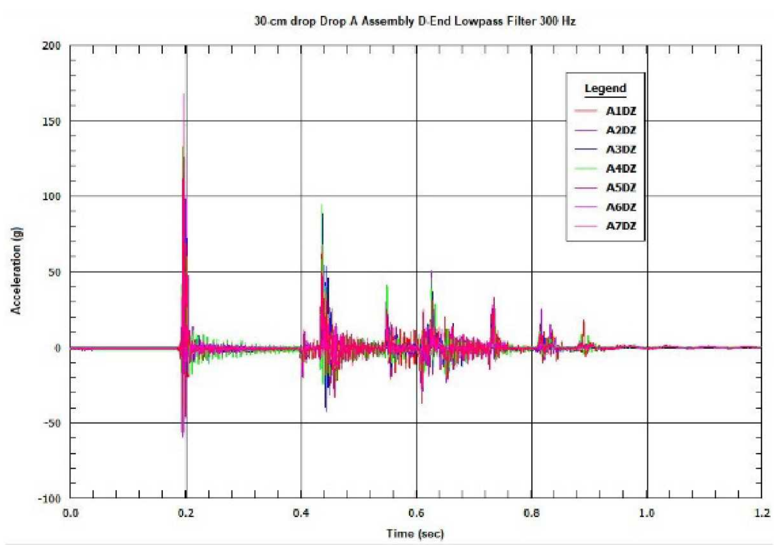


Figure 2-32. Acceleration Time Histories on the Assembly Back End (Side D) in Drop A.

Figures 2-33 and 2-34 show the individual time histories of vertical accelerations filtered to 300 Hz on both sides of the cask and on the front side of the basket.

The maximum acceleration on the cask front was 41.84g in A13AZ at 0.190585 seconds. The maximum acceleration on the basket front (A12AZ) was 55.94g at 0.19176 seconds. In the back end of the cask the maximum acceleration recorded was 49.67g in A15DZ at 0.198065 seconds.

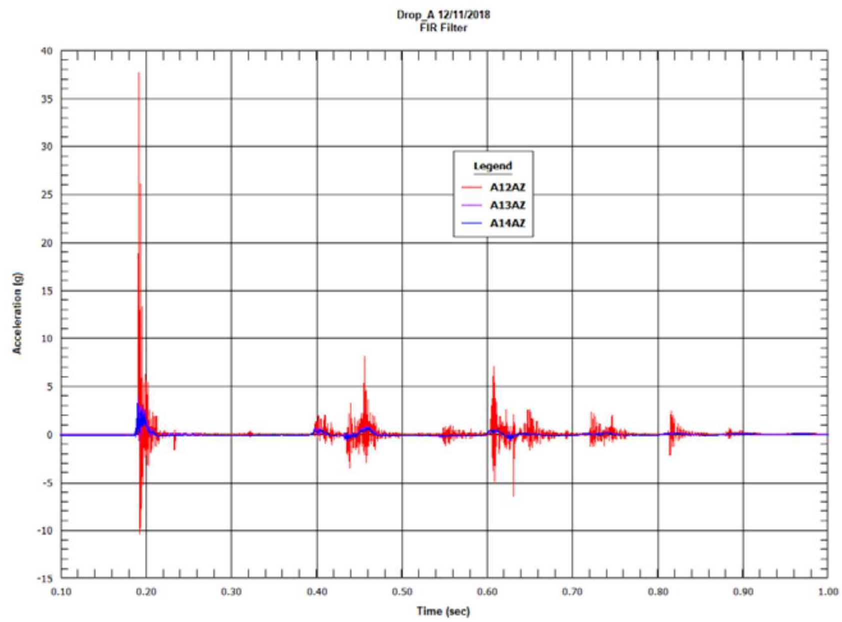


Figure 2-33. Acceleration Time Histories on the Cask and Basket Front End (Side A) in Drop A.

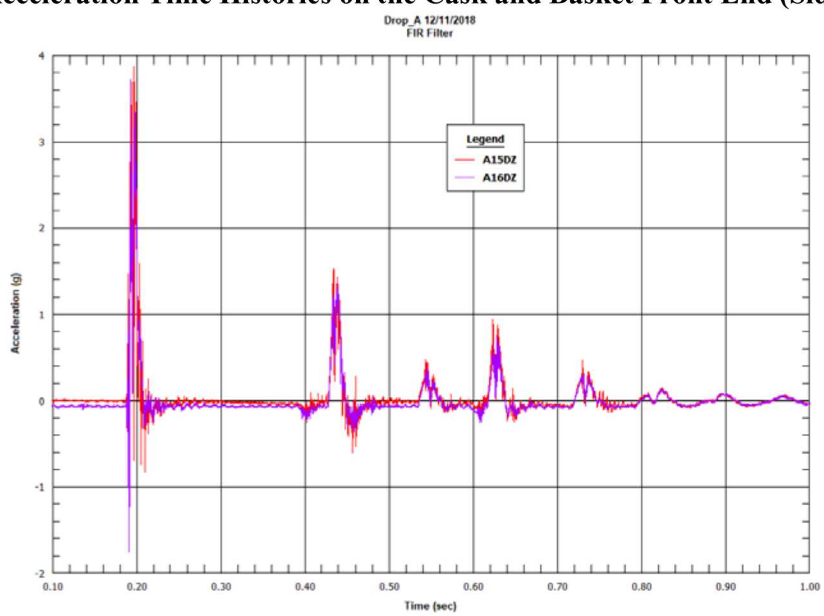


Figure 2-34. Acceleration Time Histories on the Cask Back End (Side D) in Drop A.

Not all accelerometers were able to record the full response during the 30 cm drop test because the model 7265A is limited to 100g +/- 50 g. Only a limited number of accelerometers of a more sensitive model 727 were available and model 7270A is too big to fit inside the cask. This impacted the accelerometers on A1, A2, A3 assemblies (on both side A and side D), along with accelerometers on assembly A4 on side A. Figure 2-35 shows time histories of these accelerometers during drop A.

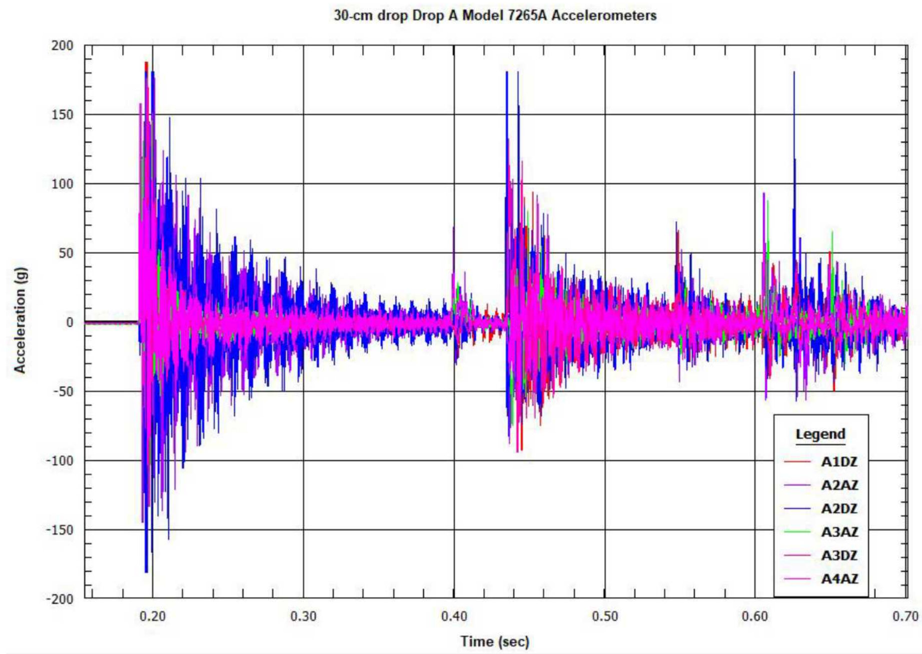


Figure 2-35. Time Histories Impacted by the Accelerometer Cutoff Limits during Drop A.

Figures 2-36 through 2-38 provide a closeup of the unfiltered time histories. The plateau at the maximum and minimum values are evident from these figures.

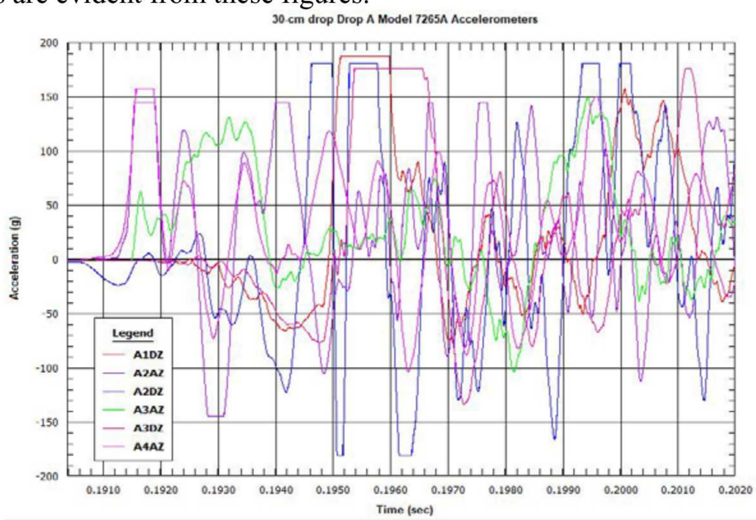


Figure 2-36. Unfiltered Time Histories during First Impact (accelerometers A1, A2, A3 and A4), Drop A.

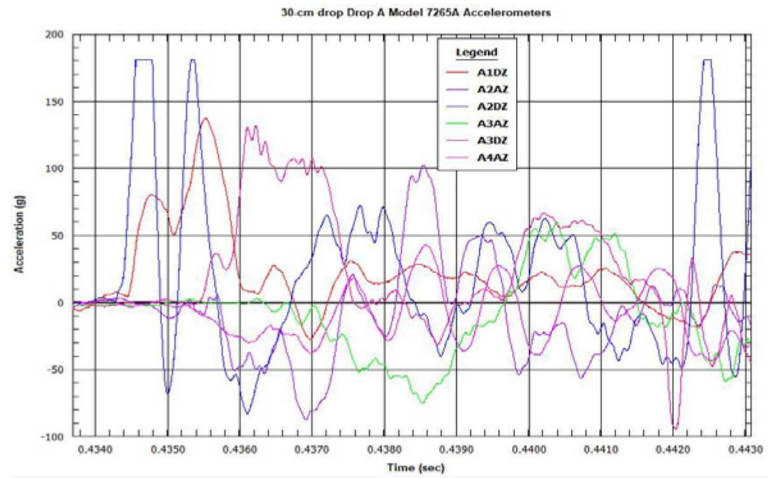


Figure 2-37. Unfiltered Time Histories during Second Impact (accelerometers A1, A2, A3 and A4), Drop A.

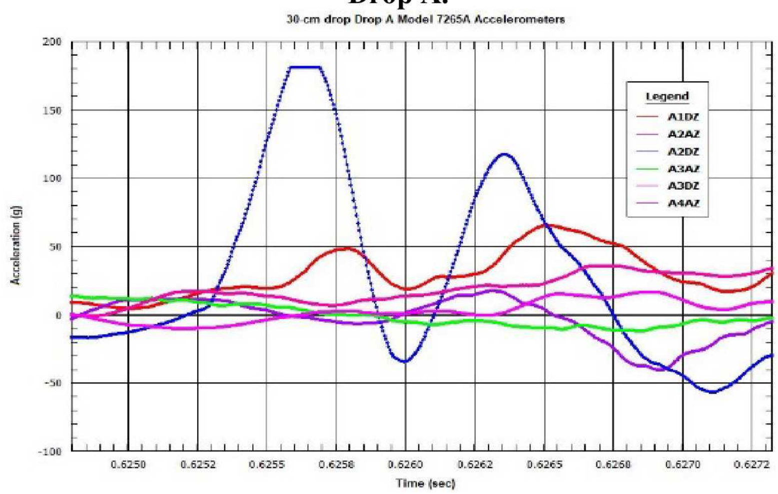


Figure 2-38: Unfiltered Time Histories during Third Impact (accelerometers A1, A2, A3 and A4), Drop A.

Cask orientation during drop A was analyzed as well, for both lateral and longitudinal symmetry during first impact. To determine lateral symmetry the three plots shown in Figure 2-39 were created using accelerometers on opposing ends of the cask. A6DZ/A7DZ, A1DZ/A3DZ, and A2DZ/A4DZ all confirm that the right side hit slightly before the left side with a difference of ~0.4 milliseconds.

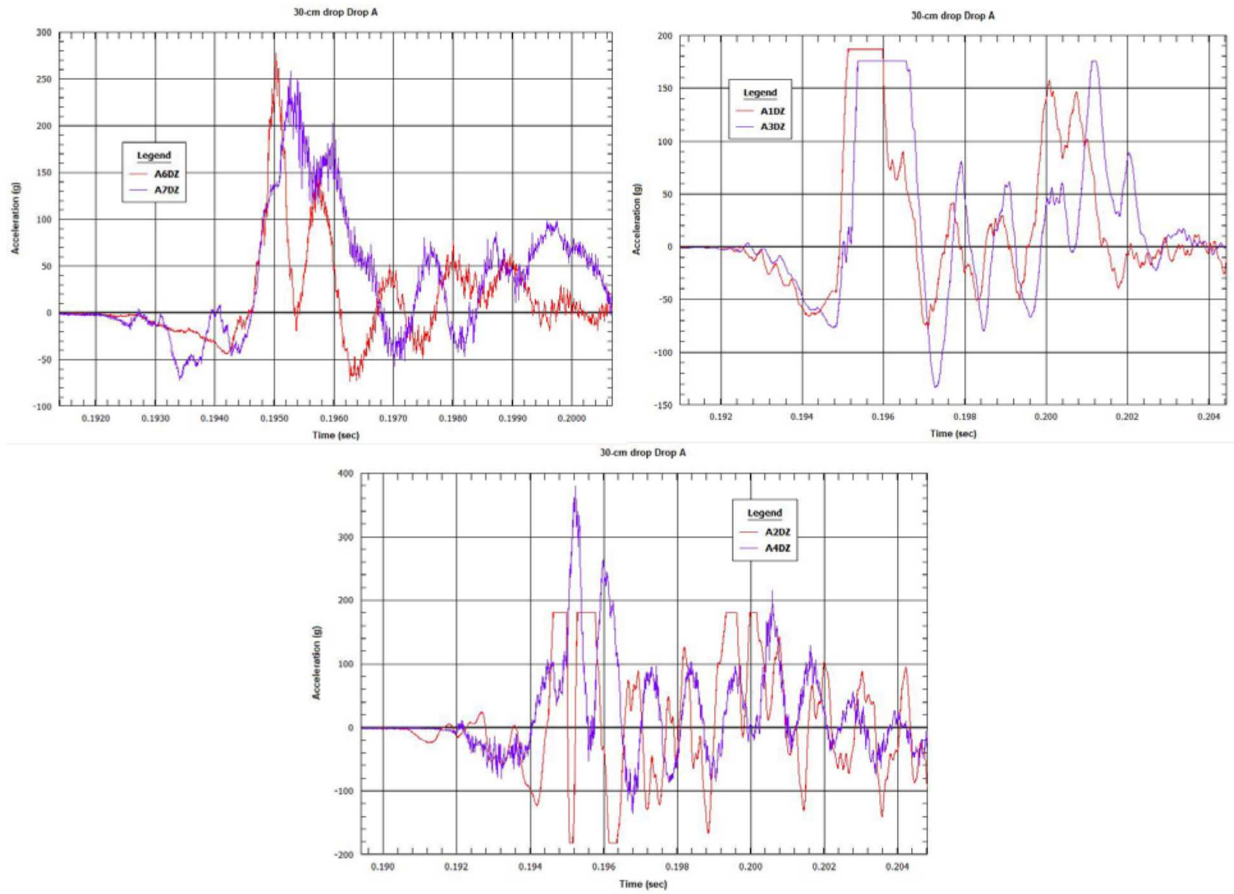


Figure 2-39. Accelerations on the Assemblies on the Left and Right Side of the Cask during First Impact, Drop A.

To illustrate this lateral asymmetry Figure 2-40 shows an exaggerated representation of the cask position during first impact.

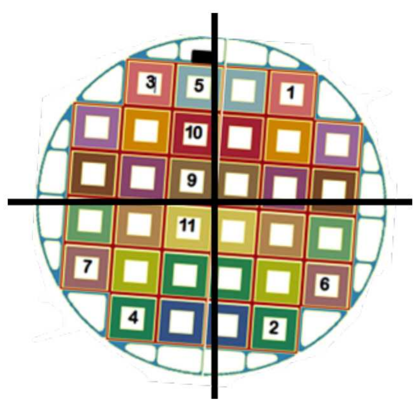


Figure 2-40. Exaggerated Lateral Orientation during First Impact, Drop A.

Longitudinal symmetry of the cask during first impact was compared using A14AZ/A16DZ and A13AZ/A15DZ on opposing ends of the cask (Figure 2-41). These data show that the front end (side A) of the cask hit approximately 2 milliseconds before the back end (side D) of the cask. This is also recorded in the high speed camera video of the test.

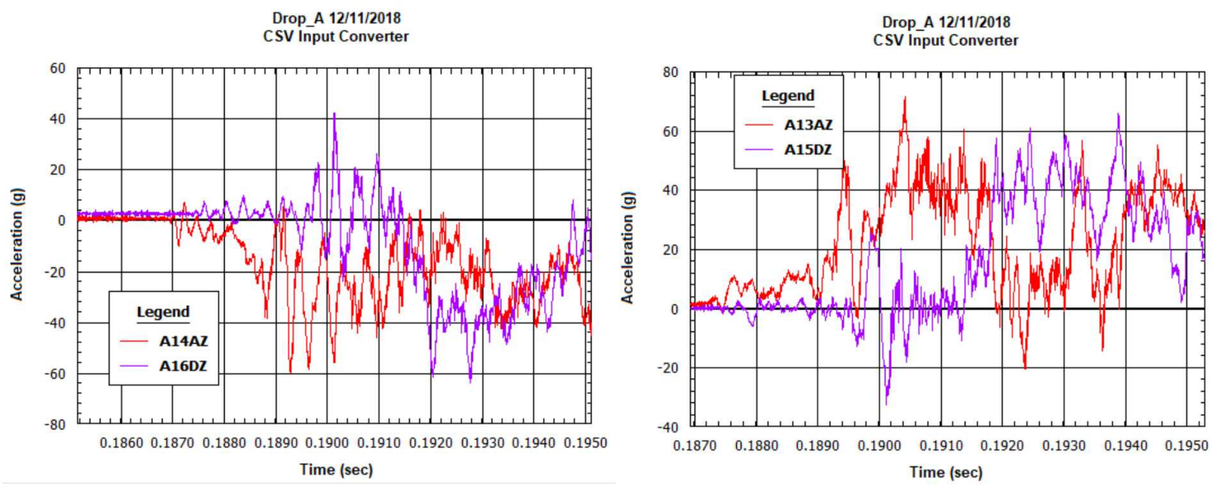


Figure 2-41. Accelerations on the Front and Back Ends of the Cask during First Impact, Drop A.

To illustrate the longitudinal asymmetry Figure 2-42 shows an exaggerated representation of the cask's longitudinal orientation during first impact.

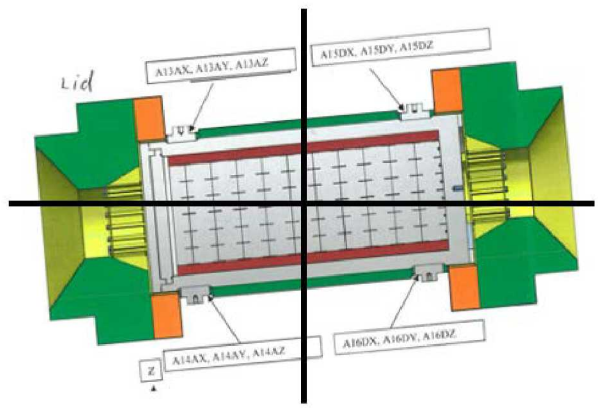


Figure 2-42. Exaggerated Representation of Longitudinal Orientation during First Impact, Drop A.

Time delay through the cask in the vertical direction is demonstrated in Figure 2-43. Shown on the left of this figure are the time histories of the accelerometers A10AZ and A11AZ located on the same column of instrumented assemblies (shown on the right of Figure 2-43). The peak in A11AZ was at 0.192375 seconds and the peak in A10AZ was at 0.193235 seconds, which is 0.86 milliseconds later.

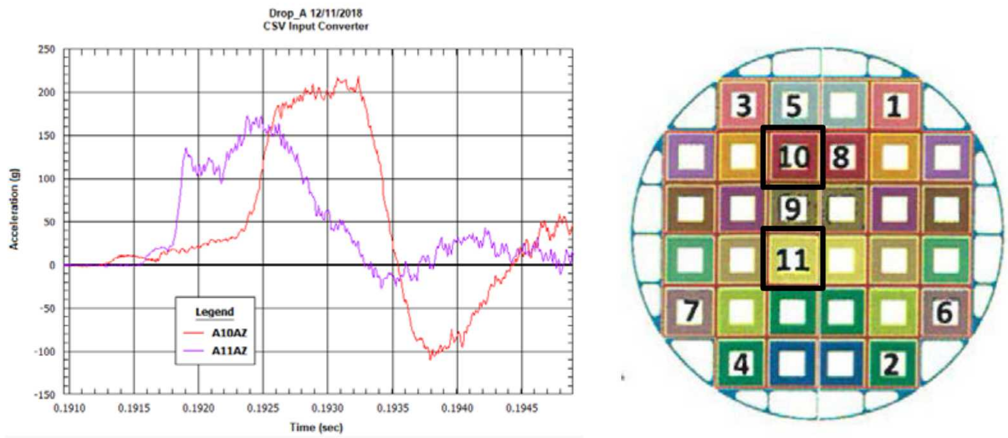


Figure 2-43. Time Histories of Accelerometers (left) in Location 10 and 11 (right) on the Front End, Drop A.

The transfer functions from the cask to the dummy assemblies on A (dummy assembly location 10) and D (dummy assembly location 5) sides are shown in Figure 2-44. As previously discussed, these locations experienced the highest accelerations. The transfer function was calculated by dividing the dummy assembly acceleration SRS by the cask acceleration SRS. The transfer functions on A and D sides are very similar, especially within the frequency band of a primary interest (0-300 Hz). As expected, the accelerations are amplified from the cask to the dummy assemblies.

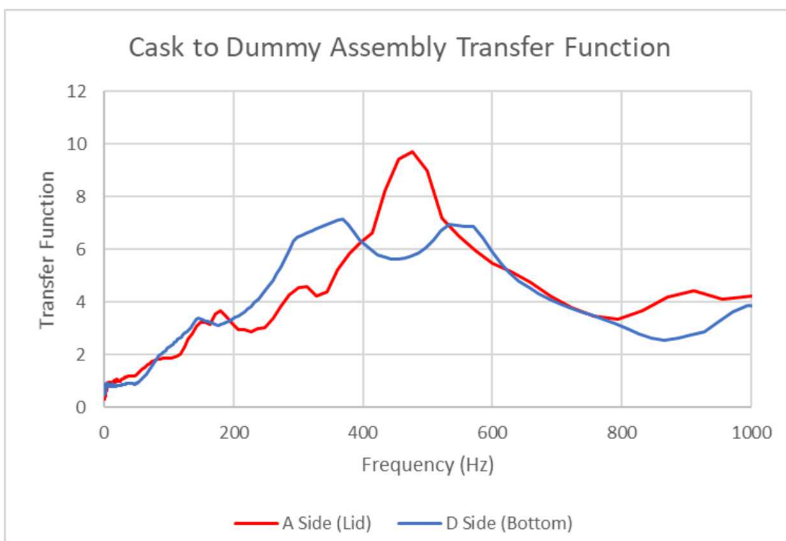


Figure 2-44. Transfer Functions from the Cask to Dummy Assemblies, Drop A.

The transfer function for assembly 5 side D was added to Figure 1-1 in Section 1 and is shown in Figure 2-45. In the high band frequencies, the differences between the full-scale surrogate assembly and 1/3 scale dummy assemblies are due to the surrogate assemblies chattering inside the basket tube. Within the 0-200 frequency band the transfer functions are similar, except the peak around 45 Hz related to the surrogate assembly natural frequency.

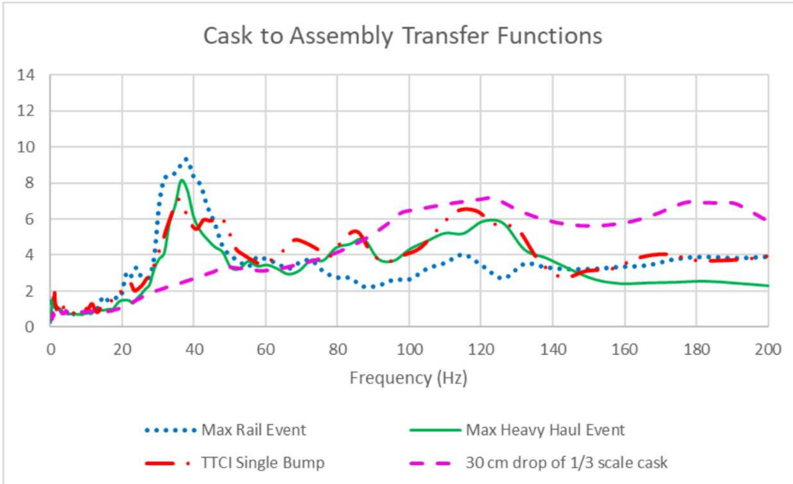


Figure 2-45: Cask to Assembly Transfer Functions in 30 cm Drop Test and Multi Modal Transportation Test.

2.8.2 Drop B

High speed camera video and acceleration time histories of Drop B showed that the cask bounced 5 times. It can be clearly seen in Figure 2-46. The front end of the cask is shown in red and the back end is shown in blue. The first impact has the greatest acceleration, and the front end hit slightly before the back end by approximately 3 milliseconds. Note that in drop B the cask was rotated 45^0 along with the accelerometers. Consequently, the accelerometer coordinate system rotated 45^0 as well. Since the accelerometers are no longer aligned with the velocity vector, for comparison with Drop A, the accelerations from Drop B should be divided by the sine of the rotation angle (0.707). Figure 2-47 compares the accelerations time histories for A3AZ and A3AY divided by 0.707. The time histories are very similar. The following discussion considers the adjusted for rotational angle accelerations on accelerometers in Z direction.

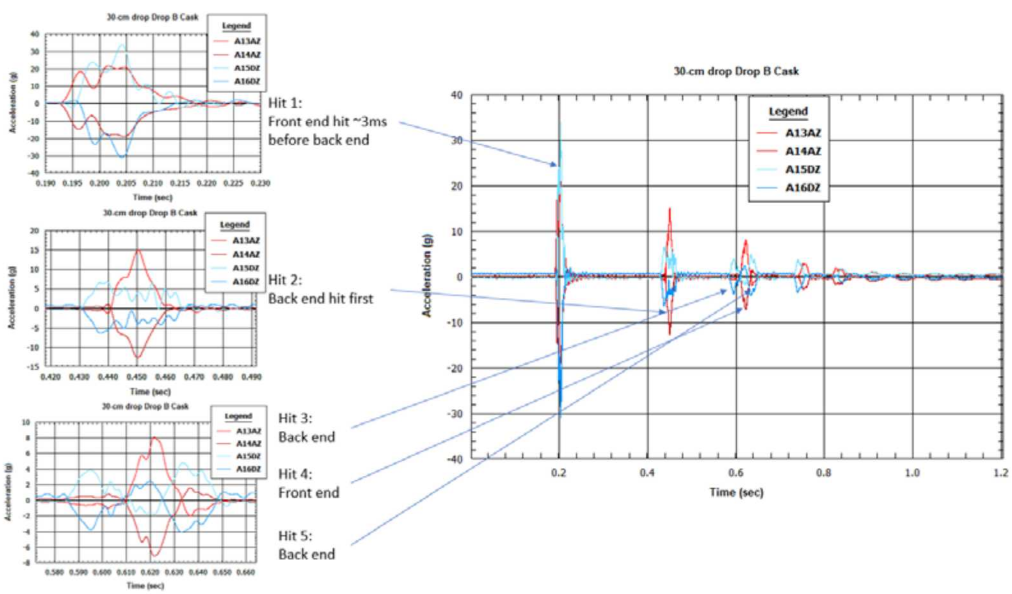


Figure 2-46. Cask Acceleration Time Histories during Drop B.

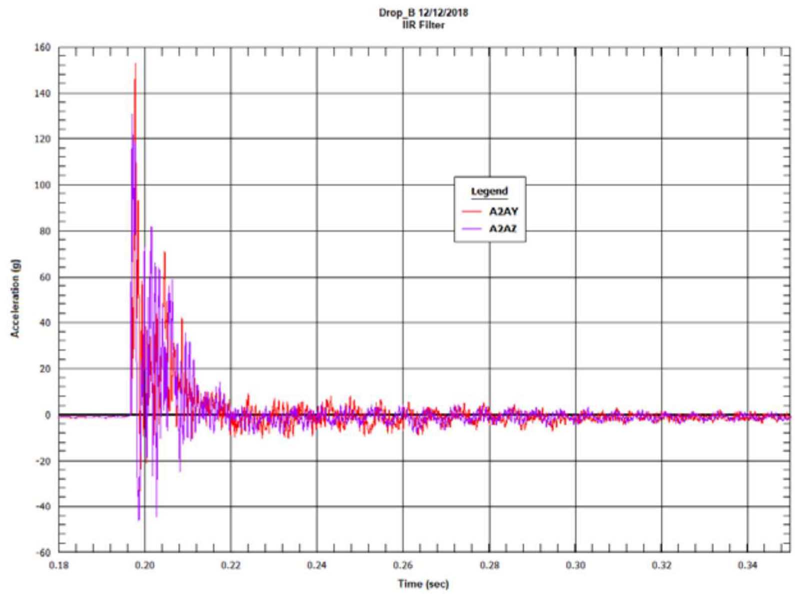


Figure 2-47. Cask Acceleration Time Histories during Drop B.

Table 2-6 compares maximum accelerations on the assemblies and cask recorded during drop B with data unfiltered, with a lowpass filter to 500 Hz, and with a lowpass IIR filter to 300 Hz. Accelerometer A3DZ experienced both greatest assembly acceleration and greatest overall system acceleration. A3DZ is located next to A5DZ which recorded the highest acceleration in Drop A. Accelerometer A15DZ on the back-end of the cask experienced the greatest cask acceleration, the same as in Drop A.

Table 2-6. Maximum Accelerations of Unfiltered and Filtered Data in Drop B.

Filter	Maximum Assembly Acceleration (g)	Accelerometer ID	Maximum Overall System Acceleration (g)	Accelerometer ID	Maximum Cask Acceleration (g)	Accelerometer ID
Unfiltered	447.4	A2DZ	447.4	A2DZ	86.0	A13AZ
Lowpass 300 Hz	171.2	A3DZ	171.2	A3DZ	43.5	A15DZ
Lowpass 500 Hz	231.4	A3DZ	231.4	A3DZ	43.0	A15DZ

Table 2-7 summarizes the assembly acceleration data for drop B. Side A experienced maximum acceleration in A3AZ. Side D experienced maximum acceleration in A3DZ as well. Note that accelerometer A1AZ was disconnected during the test.

Table 2-7: Maximum Accelerations on Dummy Assemblies Filtered to 300 Hz, Drop B.

DROP B	Side A (top)			Side D (bottom)		
Assembly ID	Max Acceleration (Filtered to 300 Hz)	Time of Max (sec)	Delta T with earliest peak (millisecond)	Max Acceleration (Filtered to 300 Hz)	Time of Max (sec)	Delta T with earliest peak (millisecond)
1	N/A*	N/A*	N/A*	156.1	0.201705	1.015
2	58.6	0.197275	0.045	132.1	0.200845	0.155
3	104.0	0.200175	2.945	188.1	0.20304	2.35
4	78.8	0.199065	1.835	101.1	0.20389	3.2
5	85.3	0.19922	1.99	169.3	0.20272	2.03
6	55.0	0.19723	0	60.5	0.20069	0
7	58.6	0.20764	10.41	95.5	0.202465	1.775
8	92.0	0.19901	1.78			
9	91.6	0.19902	1.79			
10	93.1	0.199195	1.965			
11	89.8	0.198935	1.705			

Figure 2-48 compares maximum Z-axis accelerations on the dummy assemblies filtered to 300 Hz during the first impact in Drop A and Drop B. The maximum accelerations and their spatial distributions are very similar in both drops. Slightly higher accelerations in Drop B might have been be partially related to the cumulative effects due to second drop.

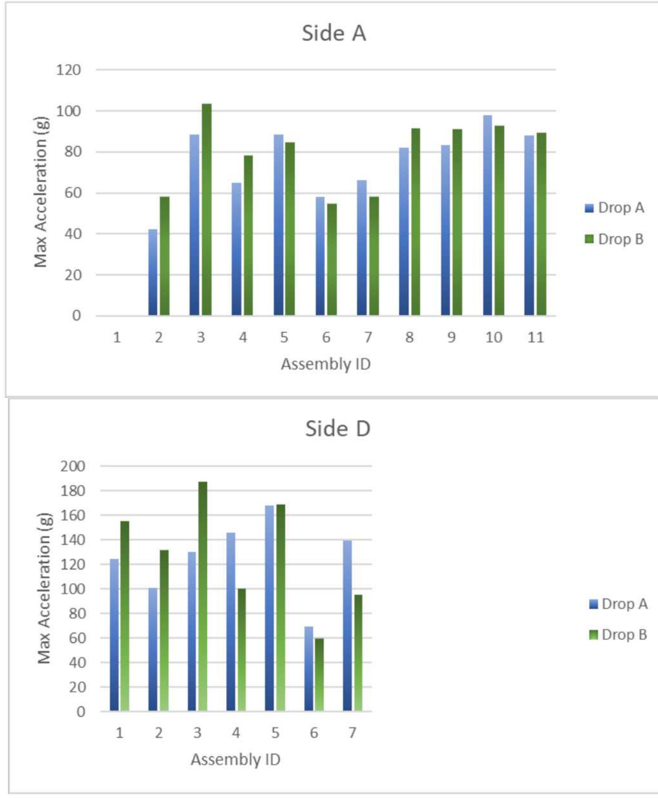


Figure 2-48. Maximum Assembly Accelerations in Drop A and Drop B.

Color mappings to visualize the recorded response from different accelerometers were also created for drop B, again with numbers representing accelerometer ID's and color representing maximum recorded acceleration filtered to 300 Hz (not adjusted for rotational angle). Figure 2-49 shows side A, with a time history during the first impact for the maximum acceleration in A3AZ, and the minimum acceleration in A6AZ.

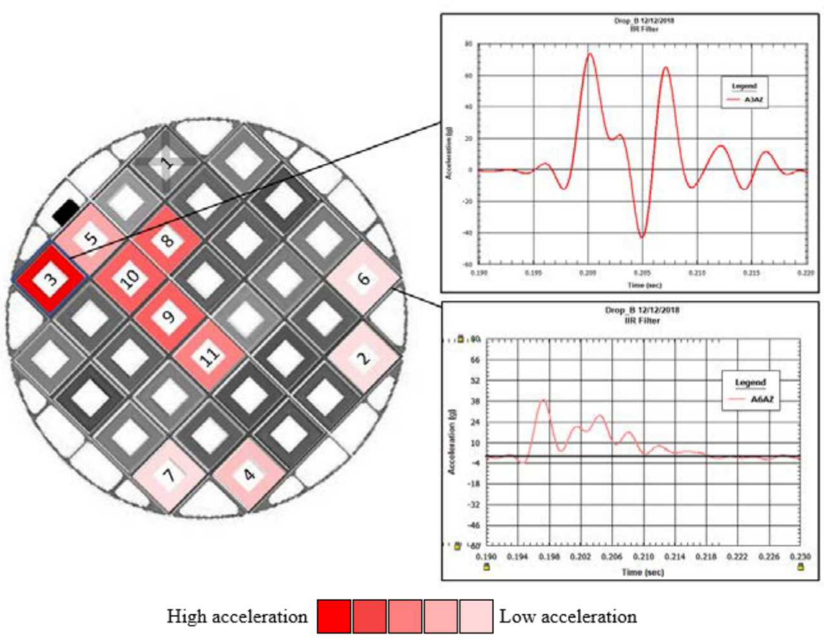


Figure 2-49. Maximum Accelerations on Assembly Front End (Side A) in Drop B.

Similarly, Figure 2-50 shows a color mapping during the first impact for side D; the bottom of the cask. Maximum acceleration was recorded in A3DZ, and minimum recorded acceleration in A6DZ.

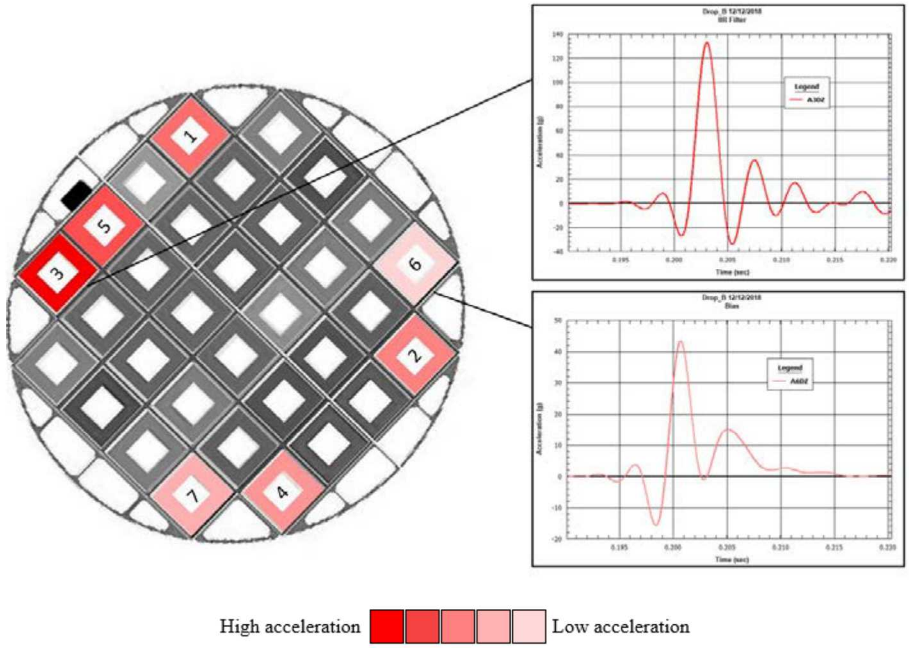


Figure 2-50. Maximum Accelerations on Assembly Back End (Side D) in Drop B.

Figure 2-51 shows averaged maximum acceleration response of the dummy assemblies from side A and side D (not adjusted for rotational angle). The maximum acceleration is 78.15 g, and the minimum acceleration is -34.77 g. During Drop A, the maximum averaged value was higher (98.7 g) and the absolute of the minimum was lower (-23.8 g). The shape of the averaged maximum in Drop B is similar to Drop A (Figure 2-30).

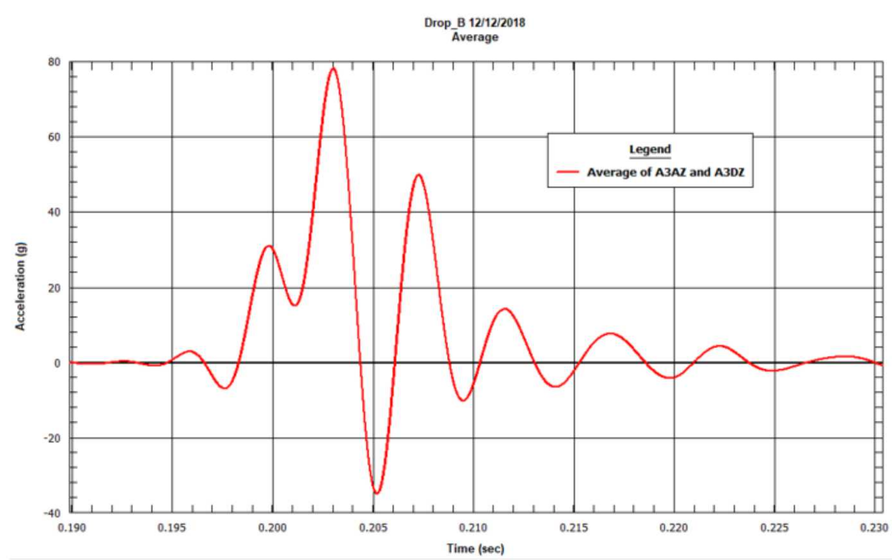


Figure 2-51. Average of Maximum Assembly Accelerations on Front and Back Ends, Drop B.

Figures 2-52 and 2-53 show the individual time histories of Z-direction accelerations filtered to 300 Hz on both sides of the assemblies (not adjusted for rotational angle).

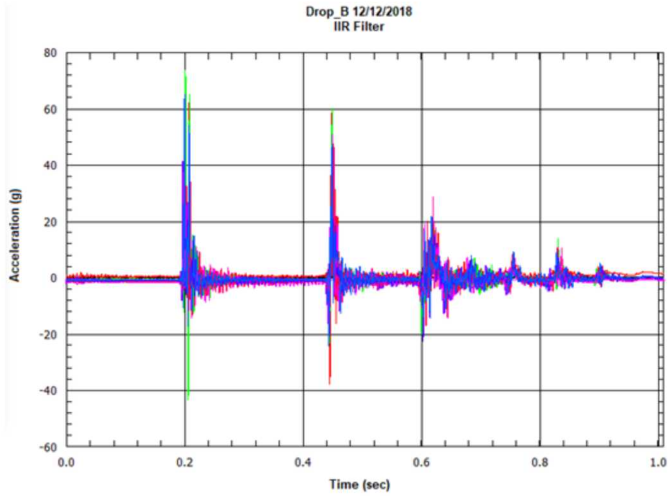


Figure 2-52. Acceleration Time Histories on the Assembly Front (Side A) in Drop B.

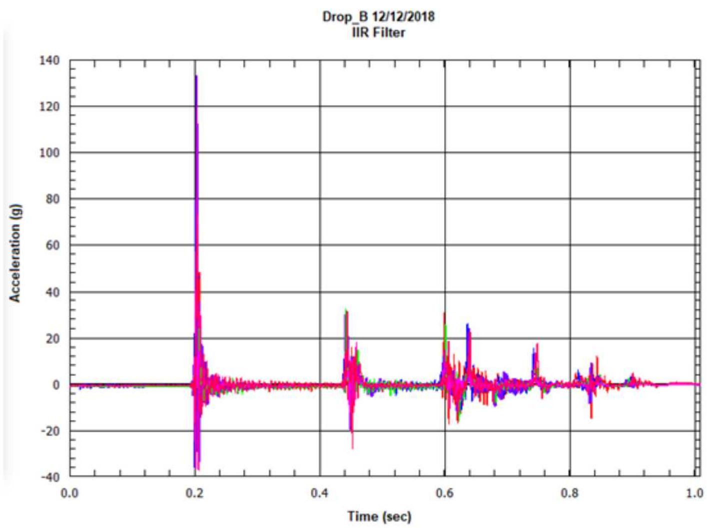


Figure 2-53: Acceleration Time Histories on the Assembly Back (Side A) in Drop B.

Z-direction accelerations on the front end of the cask and basket are plotted in Figure 2-54. The maximum acceleration on the cask was 21.88g in A13AZ at 0.201625 seconds. The maximum acceleration on the basket (A12AZ) was 48.36g at 0.20647 seconds.

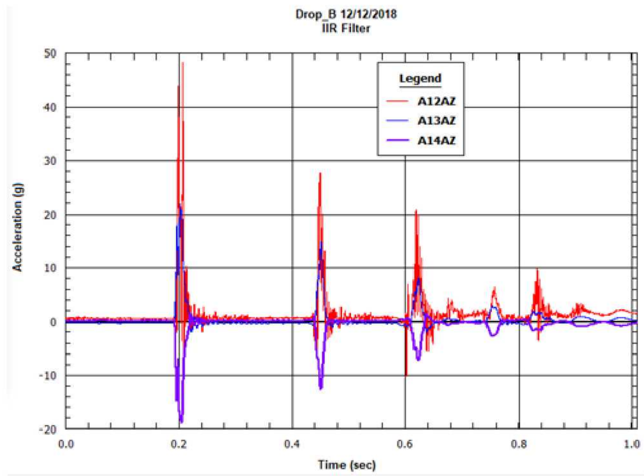


Figure 2-54. Acceleration Time Histories on the Cask and Basket Front End (Side A) in Drop B.

On side D of the cask (Figure 2-55) the cask acceleration (not adjusted for rotational angle) reached an absolute maximum acceleration of 33.8 g in A15DZ at time 0.204165 seconds.

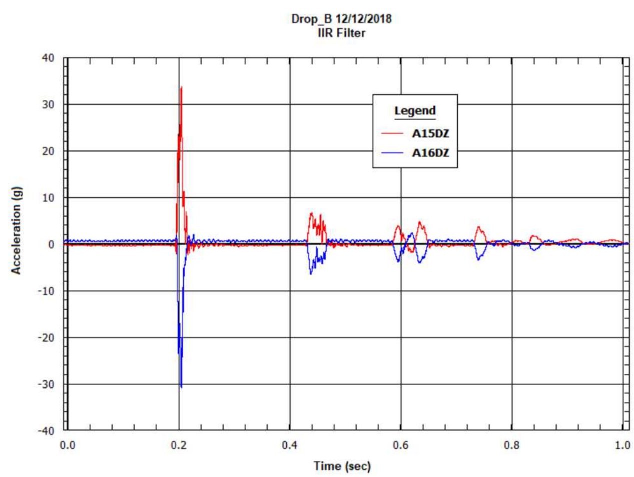


Figure 2-55. Acceleration Time Histories on the Cask Back End (Side D) in Drop B.

Cask orientation during drop B was also analyzed for lateral symmetry during first impact. The accelerometer pairs A4/A7 on the front and back end and A6/A3 on the back end were compared. As evident from Figure 2-56, the right side hit before the left side with a difference of approximately 2 milliseconds. This is also consistent with drop A.

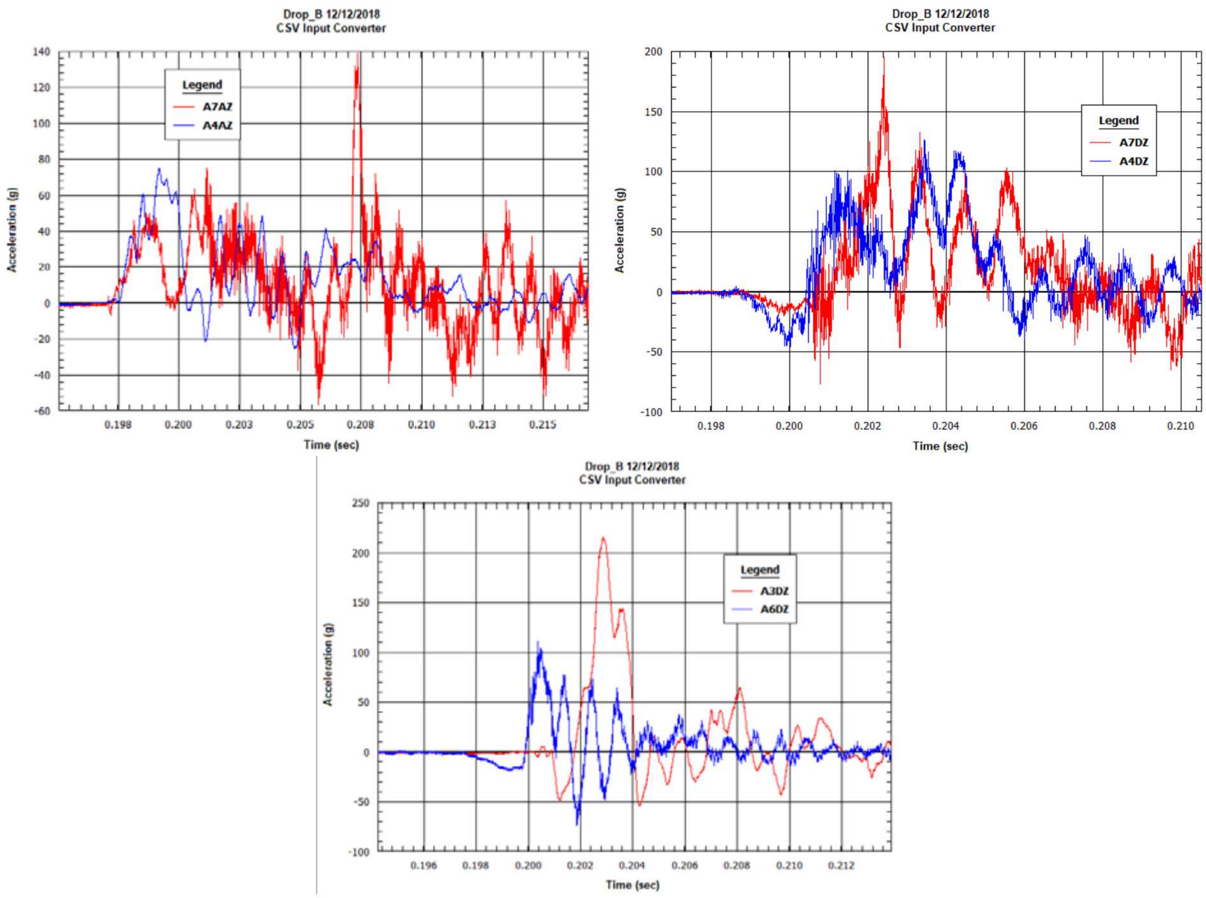


Figure 2-56. Accelerations on the Assemblies on the Left and Right Side of the Cask during First Impact, Drop B.

Figure 2-57 illustrates an exaggerated view of the orientation of the cask during first impact during Drop B. Blue grid lines indicate intended orientation of the 45-degree drop, while black grid lines suggest the actual orientation during first impact.

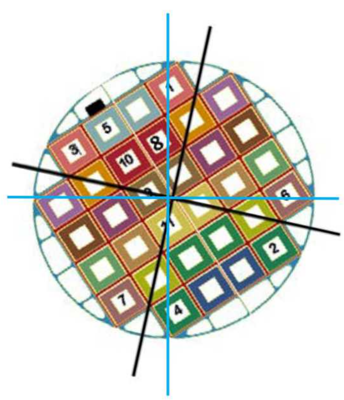


Figure 2-57. Exaggerated Lateral Orientation during First Impact, Drop B.

Figure 2-58 compares cask to dummy assembly transfer function during Drop A and Drop B. The responses through a large frequency band are similar in both shape and magnitude. The slightly higher transfer function in Drop B might be related to the cumulative effects in Drop B that was the second drop.

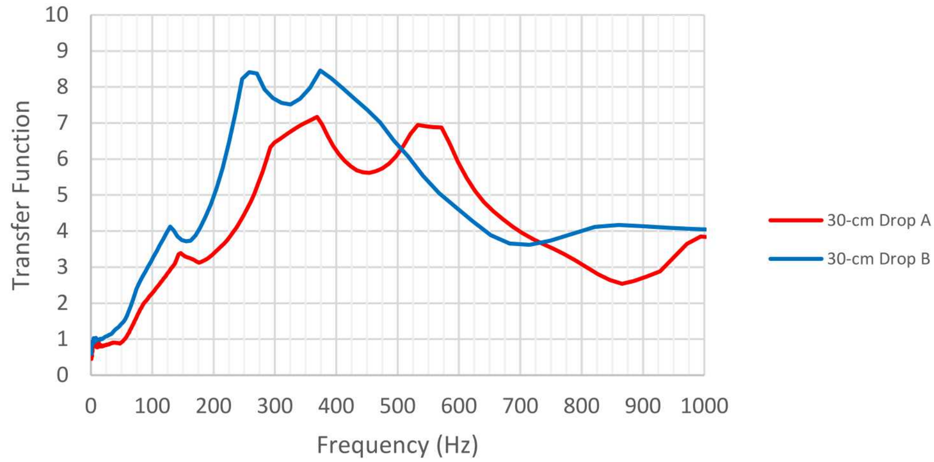


Figure 2-58. Cask to Dummy Assembly Transfer Function during Drop A and Drop B.

2.8.3 Comparison of the Accelerations on the 1/3 Scale Cask in 2010 and 2018 Tests

As was previously discussed, in the 2010 series of tests the instrumentation was only on the outside of the cask. Accelerometers A1-Y and A2-Y were on the top side of the cask recording vertical acceleration. A3-Y and A4-Y were recording vertical acceleration on the bottom side of the cask. Figure 2-59 shows the filtered to 300 Hz accelerations during the first impact on the 1/3 scale cask in the 2010 test and Figure 2-60 shows the corresponding accelerations on the same 1/3 scale cask in the 2018 test (Drop A).

The accelerations on the cask observed in 2010 are very similar to the ones observed in 2018 with the maximum acceleration of 55 g in 2010 and 50 g in 2018. The duration of the first impact pulses were the same (30 millisecond).

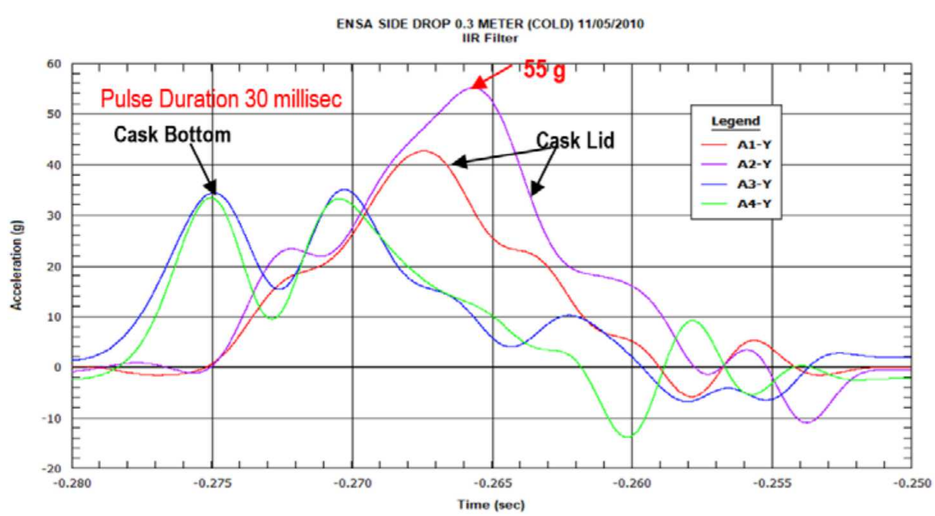


Figure 2-59: 2010 Test: Cask Acceleration Time History During First Impact.

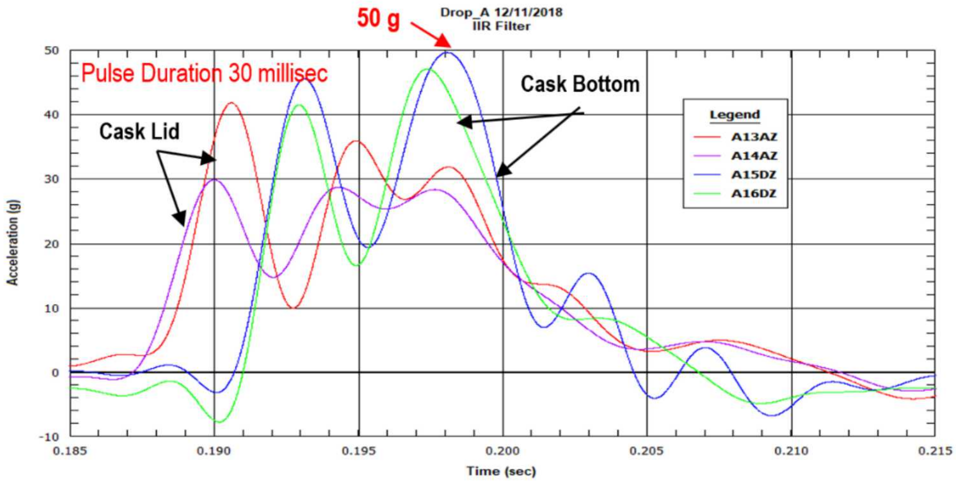


Figure 2-60. 2018 Test: Cask Acceleration Time History During First Impact.

Figure 2-61 compares averaged across four locations (two on the back and two on the lid ends) accelerations on the cask in 2010 and 2018 tests filtered to 300 Hz. Some differences exist because the horizontal drop is never truly horizontal. In 2010, the cask first hit the target with its bottom side and in 2018 it hit the target with its lid side. Also, the impact limiters used in the 2018 tests were not new and may have had slightly different stiffness.

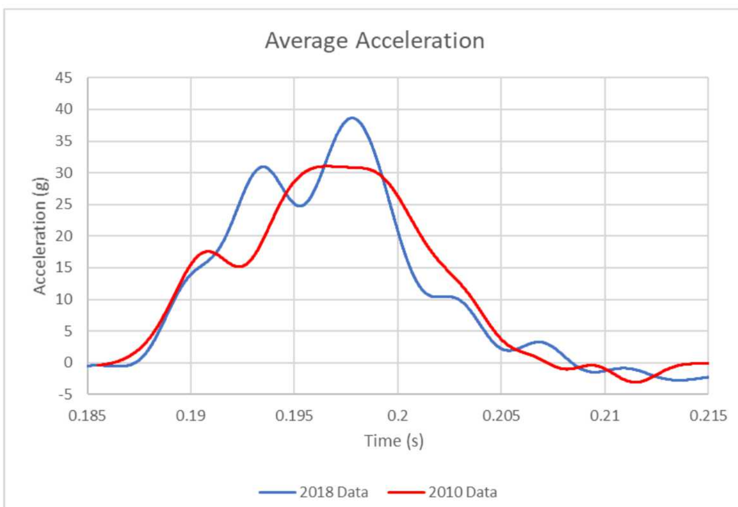


Figure 2-61: Averaged Cask Acceleration Time Histories in 2010 and 2018 Tests.

2.8.4 Inputs into the Full-Scale Assembly drop tests

The maximum accelerations on side A and D of the dummy assemblies in the 1/3 scale cask drop test and the expected accelerations on the full-scale dummy assembly (side A and D) in the 30 cm drop test are shown in Figure 2-62. To calculate the expected accelerations, the maximum accelerations on the 1/3 scale dummy assemblies were decreased and the time was increased proportionally to the scale (factor of 3).

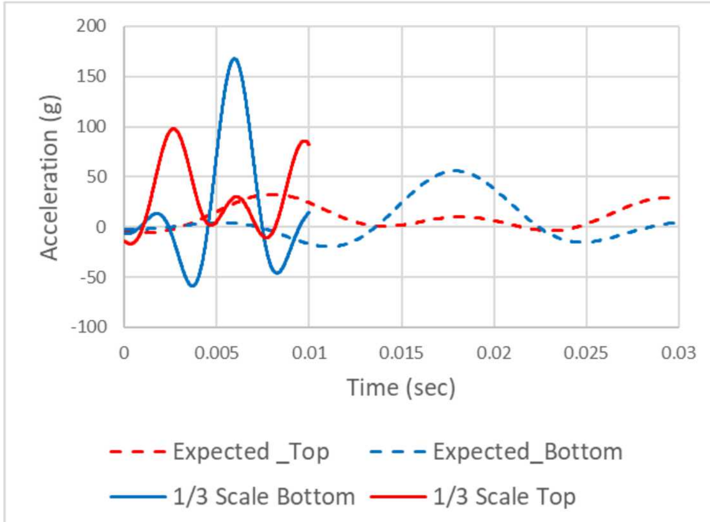


Figure 2-62. 1/3 Scaled Dummy Assembly Acceleration and Projected Full-Scale Dummy Assembly Accelerations in 30 cm Drop.

3. FULL-SCALE DUMMY ASSEMBLY 30 CM DROP TEST

The 30 cm drop test of the full-scale dummy assembly is Step 2 depicted in Figure 1-2. As discussed in Section 1, the goal of this test was to find the condition under which the observed acceleration pulse would be similar to the expected acceleration pulses derived from Step 1. Achieving this condition means that the effect of the cask and the impact limiters are adequately represented. The test plan is provided in [14].

Section 2.8.4 describes how the expected acceleration pulses on the full-scale dummy assembly were calculated. The expected pulses are shown in Figure 2-62.

The dummy assembly was dropped in the actual basket tube. The details on the dummy assembly and basket tube are provided in Section 3.1. The instrumentation of the dummy assembly, basket tube and target surface is discussed in Section 3.2. The handling is described in Section 3.3.

Felt was used as a shock absorber in the drop tests. Four drop tests were performed to achieve a good agreement between the observed and expected acceleration pulse. Section 3.4 provides the details of the tests.

3.1 Test Hardware

3.1.1 Full-Scale Dummy Assembly

The full-scale dummy assembly is the enlarged by 3 times equivalent of the 1/3 scale dummy assembly. It was manufactured by ENSA using the same materials and manufacturing processes as the 1/3 scale assemblies.

The dummy assembly was made of a machined carbon steel rod (S335J2 / ST-52). Its weight was 700 kg. Figure 3-1 shows the drawing of the full-scale dummy assembly on the left and a photo of the manufactured dummy assembly on the right.

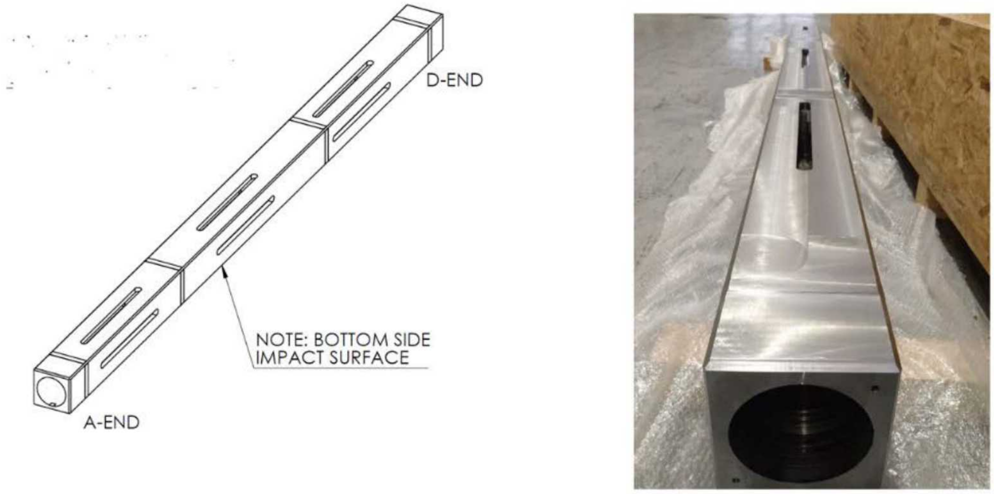


Figure 3-1. Drawing (left) and Photo (right) of the Full-Scale Dummy Assembly.

The dummy assembly has two flats machined into its inner bore (one on each end) to accommodate a triaxial accelerometer block.

3.1.2 Basket Tube

A full-scale 17x17 PWR metal matrix composite (MMC) basket tube was purchased from ENSA to mimic the boundary conditions the assembly experienced during the 30 cm drop of the 1/3 scale cask. The basket tubes in the 1/3 scale cask test were the scaled equivalent of this basket tube. The same basket tubes were in the full-scale ENUN 32P cask used during the multi-modal transportation test.

Two windows were cut on one side of the basket tube as shown in Figure 3-2. These windows will be used to record the behavior of the surrogate assembly rods during the 30 cm drop test (Step 3) with high-speed video cameras.

Figure 3-2. 17x17 PWR Assembly Basket Tube.

3.2 Instrumentation

The full-scale dummy assembly was instrumented with tri-axial accelerometers in the openings on the top and bottom ends to obtain acceleration data comparable with the 1/3 scale drop test. Three strain gauges were placed near the cutouts to measure bending strain in the longitudinal direction in the cutout regions. The dummy assembly instrumentation is shown in Figure 3.3.

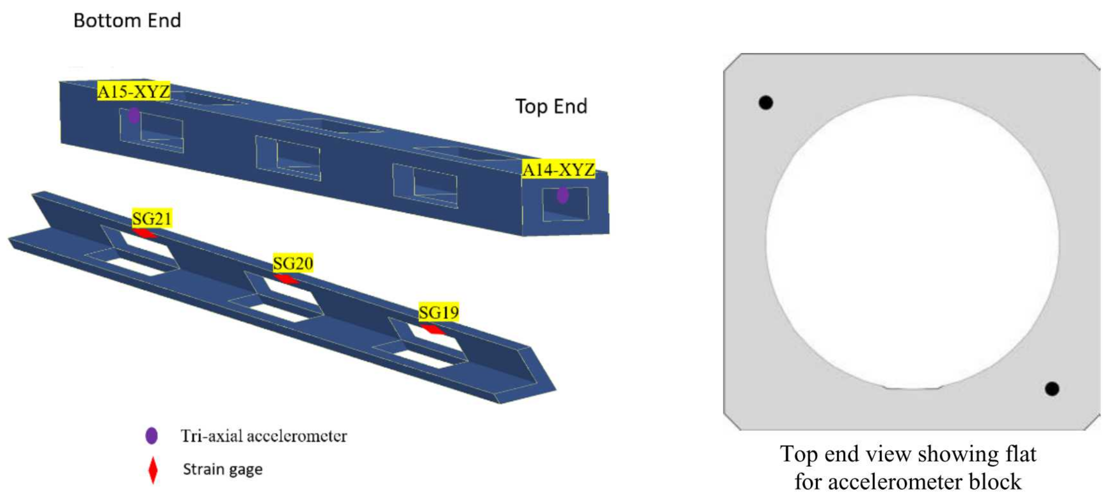


Figure 3-3. Full-Scale Dummy Assembly Instrumentation.

The leads from the gauges on the lower end of the dummy assembly were pulled down the length of the inner bore and exit at the top end.

The basket tube was instrumented with two tri-axial accelerometers on the top face as shown in Figure 3-4. Two uniaxial accelerometers were placed on the target.

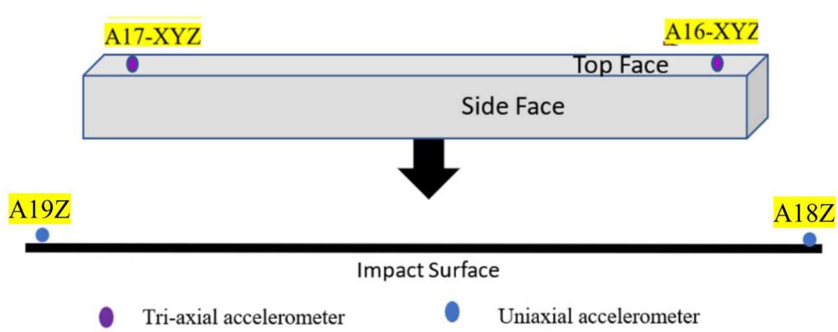


Figure 3-4. Full-Scale Basket Tube and Target Surface Instrumentation.

The same accelerometer models as in the 30 cm drop of the 1/3 scale cask were used. The accelerometer locations and nomenclature are summarized in Table 3-1.

The strain gauges were type CEA-03-062UW-350. The strain gauge locations and nomenclature are summarized in Table 3-2.

Table 3-1. Accelerometer Locations and Nomenclature.

Channel	Gauge ID	Model Number	Location	Assembly Location	Angular Location	Measurement Direction
48	A14X	727-2K-10-120	Dummy-Top	Dummy	0°	X
49	A14Y	727-2K-10-120	Dummy-Top	Dummy	0°	Y
50	A14Z	727-2K-10-120	Dummy-Top	Dummy	0°	Z
51	A15X	727-2K-10-120	Dummy-bottom	Dummy	0°	X
52	A15Y	727-2K-10-120	Dummy-bottom	Dummy	0°	Y
53	A15Z	727-2K-10-120	Dummy-bottom	Dummy	0°	Z
54	A16X	7270A-20K	Basket-tube-top	Basket	0°	X
55	A16Y	7270A-20K	Basket-tube-top	Basket	0°	Y
56	A16Z	7270A-20K	Basket-tube-top	Basket	0°	Z
57	A17X	7270A-20K	Basket-tube-bot	Basket	0°	X
58	A17Y	7270A-20K	Basket-tube-bot	Basket	0°	Y
59	A17Z	7270A-20K	Basket-tube-bot	Basket	0°	Z
60	A18Z	7265A	Impact-sur-top	Impact Surface	0°	Z
61	A19Z	7265A	Impact-sur-bot	Impact Surface	0°	Z

Table 3-2. Strain Gauge Locations and Nomenclature.

Channel	Micro-Measurement Part-number	Strain Gage Designation	Assembly Location	Angular Location	Cask Assembly
28	CEA03-062UW-350	SG19-0	Bottom	0°	Dummy
29	CEA03-062UW-350	SG20-0	Middle	0°	Dummy
30	CEA03-062UW-350	SG21-0	Top	0°	Dummy

3.3 Handling

The instrumented dummy assembly had to be inserted into the basket tube, transported to the SNL drop tower facility, and placed on the target for preparations for the tests. Figure 3-5 shows how it was inserted into the basket tube.

Lifting the basket tube with the dummy assembly inside required a special approach. The basket tube is made of MMC, which consists of a matrix of ‘pure’ aluminum material (very soft) with boron carbide insertions in it (extremely hard). This made it very difficult to machine or grind the basket tube - neither drilling holes or welding was possible. To handle the basket tube, a steel plate was manufactured and attached to the basket tube by steel clamps (Figure 3-6). Two hoist rings were installed in the steel plate to allow for lifting and handling.

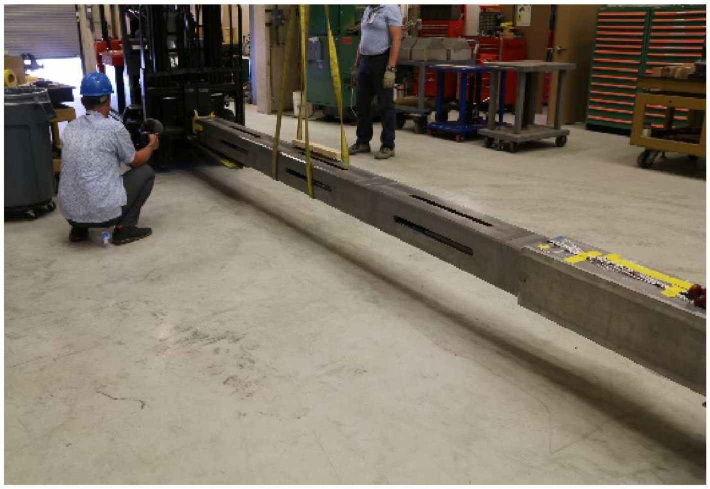


Figure 3-5. The Instrumented Dummy Assembly Being Inserted into the Basket Tube.

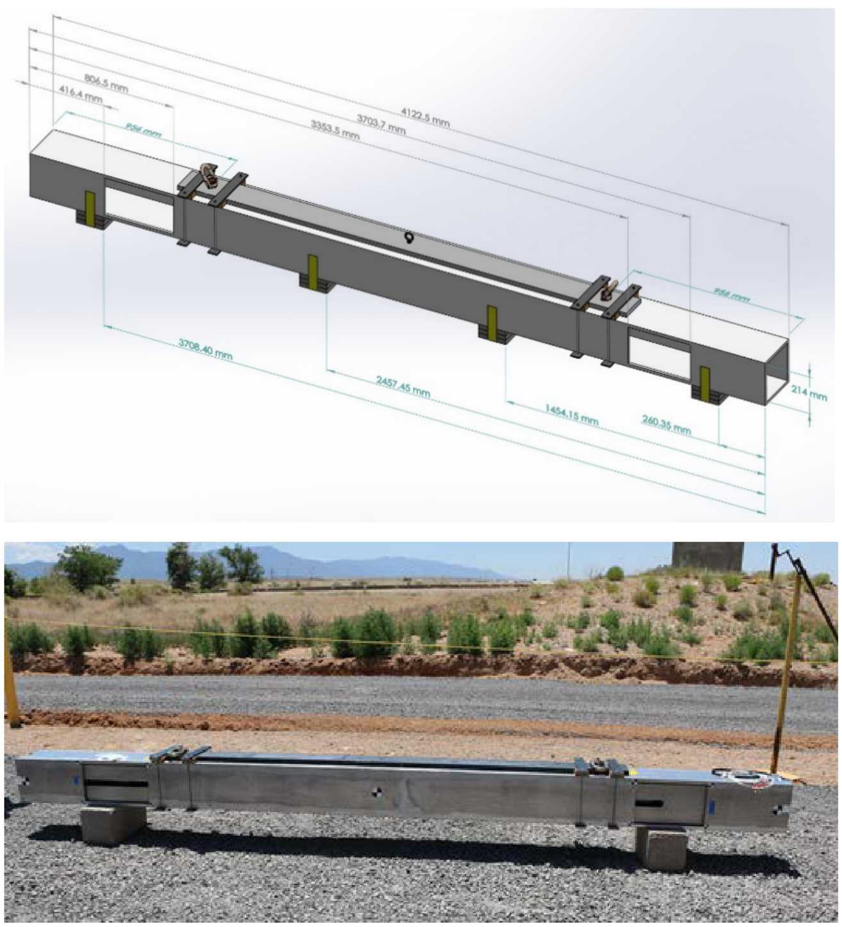


Figure 3-6. Approach to Basket Tube Handling.

The basket tube with the dummy assembly was transported to the drop tower facility by a forklift as shown in Figure 3-7. It was then placed on the target as shown in Figure 3-8.

Figure 3-7. Transporting Basket Tube to the Drop Tower Facility.

Figure 3-8. Placing the Basket Tube on the Target Surface.

3.4 Conducting Drop Tests

Felt pads were used as a shock absorbing material to mimic the behavior of the impact limiters and the cask in the 1/3 scale cask drop test. Four pads were attached to the bottom face of the basket tube. Figure 3-9 shows the setup of the first drop test and the location of the felt pads.

An SNL portable data acquisition system was used to record the instrumentation data. The data were collected at a frequency of 51,200 Hz.

Four drop tests were performed to get the desired acceleration pulse. After each test the pulse amplitude, duration, and shape were examined and the felt dimensions were adjusted. The felt pad dimensions are provided in Table 3-3. The felt pad locations were the same in all the tests. Figure 3-10 shows the felt pad configuration in Test 4.

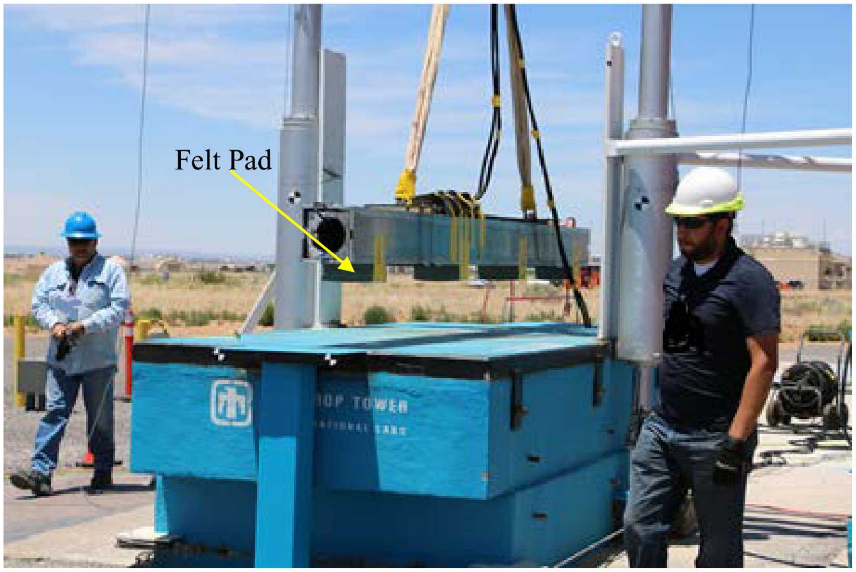


Figure 3-9. First Drop Test Setup.

Table 3-3. Felt pad dimensions in different drop tests.

Drop Test	Pad Dimensions (in)		
	Width	Length	Thickness
Test 1	10	12	1
Test 2	10	9	2
Test 3	10	6	2
Test 4	10	6	3

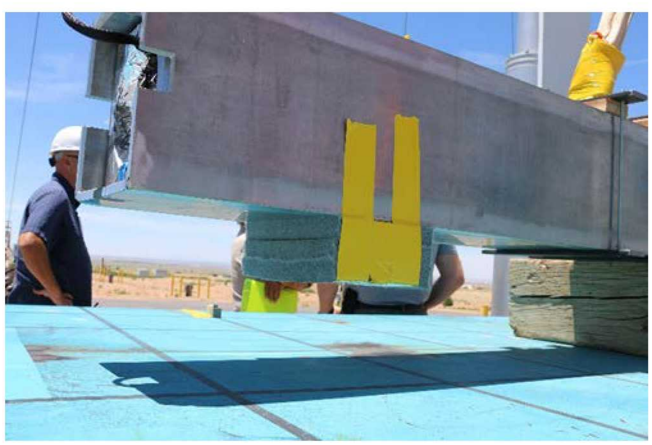


Figure 3-10. Felt Pad Configuration in Test 4.

3.5 Data Analysis

3.5.1 Acceleration Pulse Comparison

The acceleration time histories on the dummy assembly in four tests are shown in Figure 3-11.

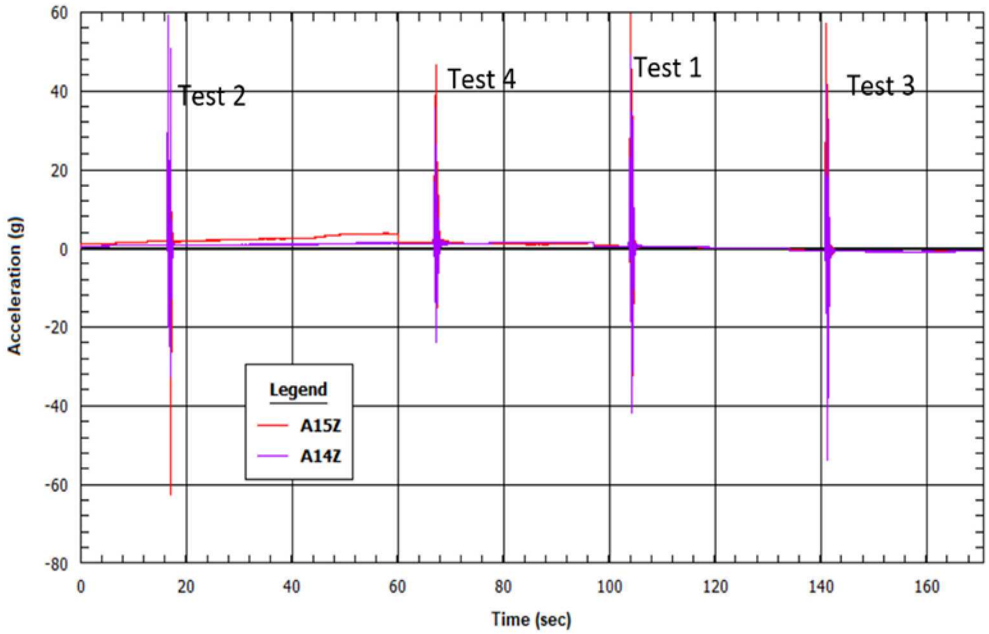


Figure 3-11. Acceleration Time Histories on the Dummy Assembly in Four Tests.

In Figure 3-12 the acceleration pulses registered by A14Z in the different tests were plotted using the adjusted time to provide a better comparison of the corresponding time histories. The data in this figure were filtered to 300 Hz. The pulse peak amplitudes decrease and their durations increase from Test 1 to Test 4 reflecting the changes in felt pad configuration.

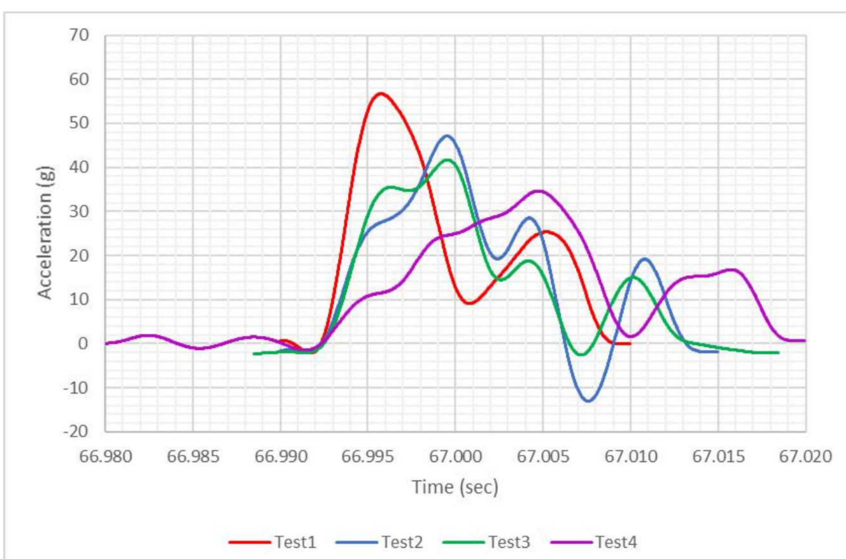


Figure 3-12. Comparison of the Impact Pulses in Four Drop Tests (accelerometer A14Z).

Figure 3-13 shows acceleration SRS (accelerometer A14Z) for the four tests. The responses are very similar within the low band frequency (up to 30 Hz). The major differences in responses are within the frequency band 40 Hz to 300 Hz. The expected peak accelerations decrease from Test 1 to Test 4. The responses are similar in Test 2 and 3 in which felt configuration was not significantly different.

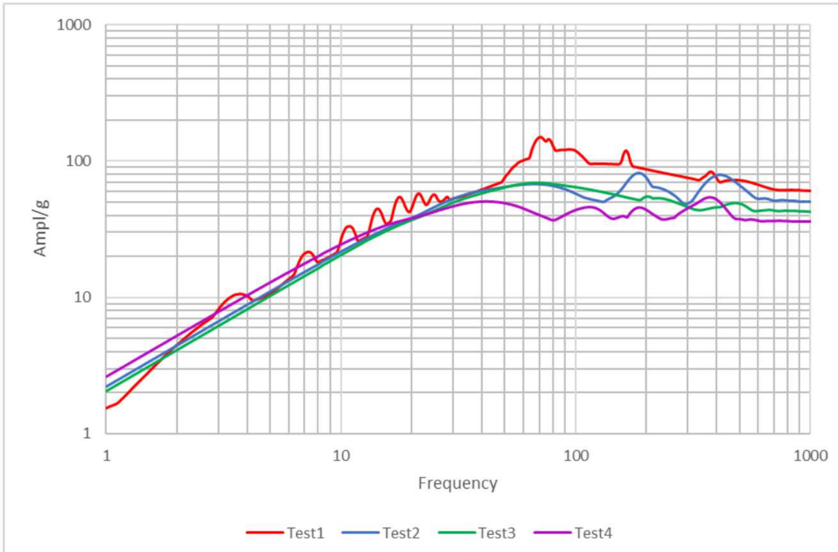


Figure 3-13. Acceleration SRS for Four Tests (accelerometer A14Z).

Figure 3-14 compares scaled acceleration pulses observed on the 1/3 scale dummy assembly to the acceleration pulses observed in Test 4. The full-scale acceleration pulses are in good agreement with the scaled 1/3 scale acceleration pulses. Note that the full-scale assembly drop was virtually horizontal and the accelerations on the top and bottom end of the dummy assembly are very similar. In the 1/3 scale cask drop, the cask lid (top) end hit the target first. This resulted in the different timing of the peak maximum acceleration that can't be reproduced with a strictly horizontal drop.

It was concluded that shock absorbing felt pad configuration in Test 4 adequately represents the effect of the cask and the impact limiters. This configuration will be used in the 30 cm drop of the full-scale surrogate assembly.

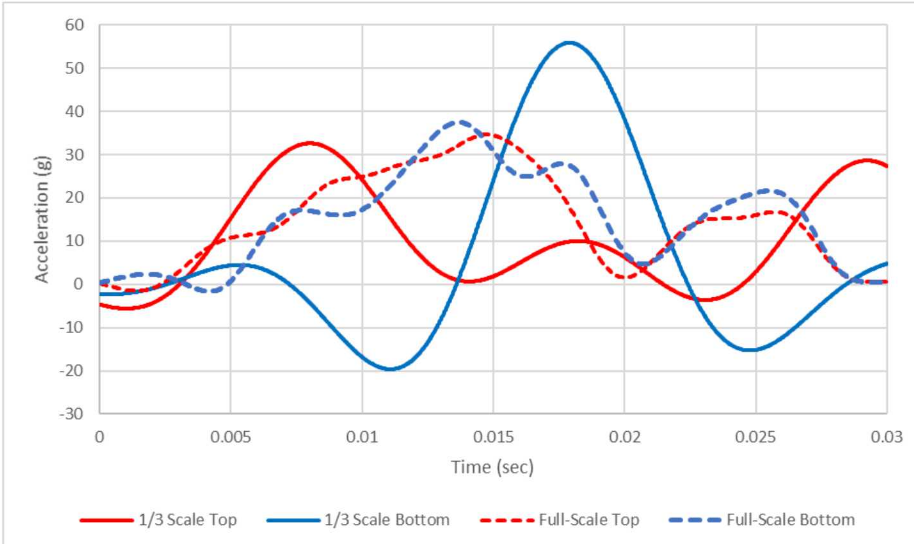


Figure 3-14. Scaled Acceleration Pulses on 1/3 Scale Dummy Assembly Compared to Test 4 Acceleration Pulses.

3.5.2 Comparison between 1/3 Scale and Full-Scale Dummy Assembly Responses

A comparison between the 1/3 scale and full-scale assembly response is needed to confirm that the full-scale dummy assembly and the basket are adequate representation of the 1/3 scale ones. This provides additional justification for using 1/3 scale results as an input into the full-scale tests.

Figure 3-15 compares the basket and dummy assembly acceleration SRS in 1/3 scale (scaled) and full-scale tests (Test 4). The responses are very similar up to 100 Hz. The 1/3 scale dummy differs at higher frequency. As was previously discussed, the dummy assemblies chattered inside the basket tube in the 1/3 scale tests. This effect contributed to the observed high frequency response which does not occur when there is only one full-scale assembly.

Figure 3-15 demonstrates that the responses of the basket and dummy assembly in the 1/3 scale test have the same trend as in the full-scale test. In both tests, the basket and dummy assembly behave similarly up to 100 Hz. The accelerations are attenuated from the basket to the dummy assembly for frequencies greater than 100 Hz.

Figure 3-16 shows the acceleration FFT in 1/3 scale test (scaled) for accelerometer 10AZ located on the front end of the dummy assembly. Figure 3-17 shows the acceleration FFT in the full-scale test (Test 4) for accelerometer 14Z located on the front end of the dummy assembly. The signal strength peaks are very similar in the 1/3 scale and full-scale test. The highest strength is in the frequency band below 100 Hz. There is little signal above 200 Hz. The high frequency peaks are higher in the 1/3 scale test as expected due to chattering. Consequently, reproducing dummy assembly behavior within the 1-100 Hz band is especially important.

Figure 3-18 shows the strain FFT in full-scale Test 4. The strain FFT mimics the acceleration FFT in Figure 3-17. The strain responses to high frequency accelerations are very small. The strain signal is insignificant at frequencies greater than 200 Hz.

Based on these comparisons, it can be concluded that the full-scale dummy assembly adequately reproduces the behavior of the 1/3 scale dummy assembly, especially in the 40 Hz region where the full-scale surrogate assembly has its resonant frequency.

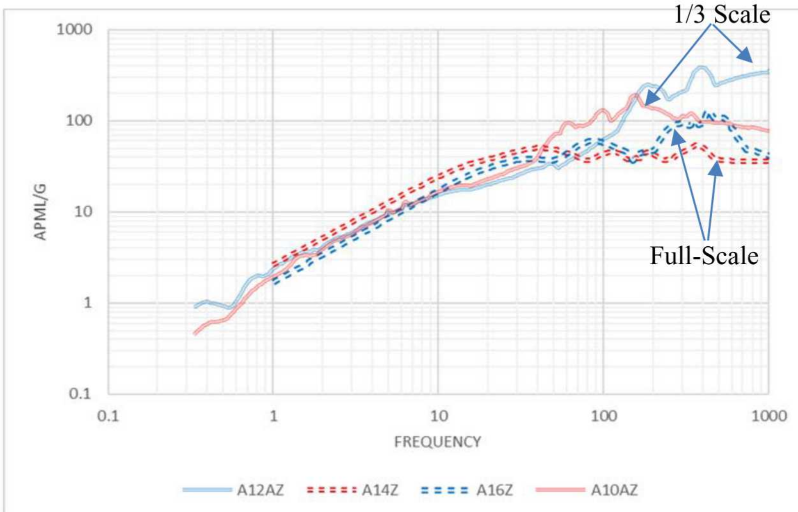


Figure 3-15. Basket and Dummy Assembly Acceleration SRS in 1/3 Scale and Full-Scale Tests.

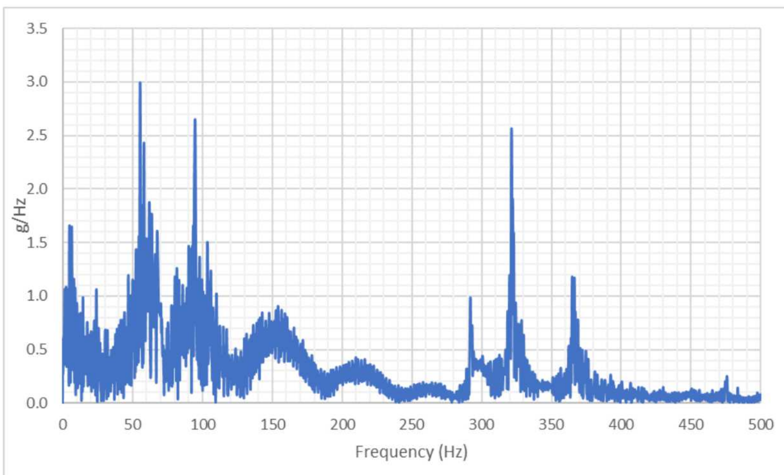


Figure 3-16. Acceleration FFT in 1/3 Scale Test (accelerometer 10AZ).

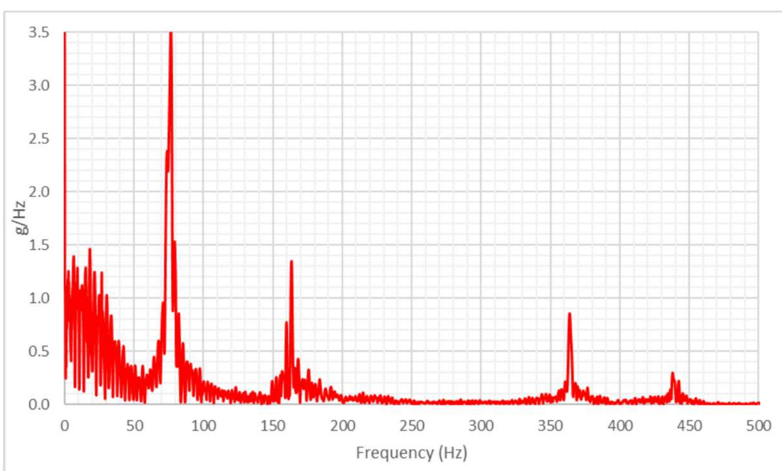


Figure 3-17. Acceleration FFT in Full-Scale Test (accelerometer 14Z).

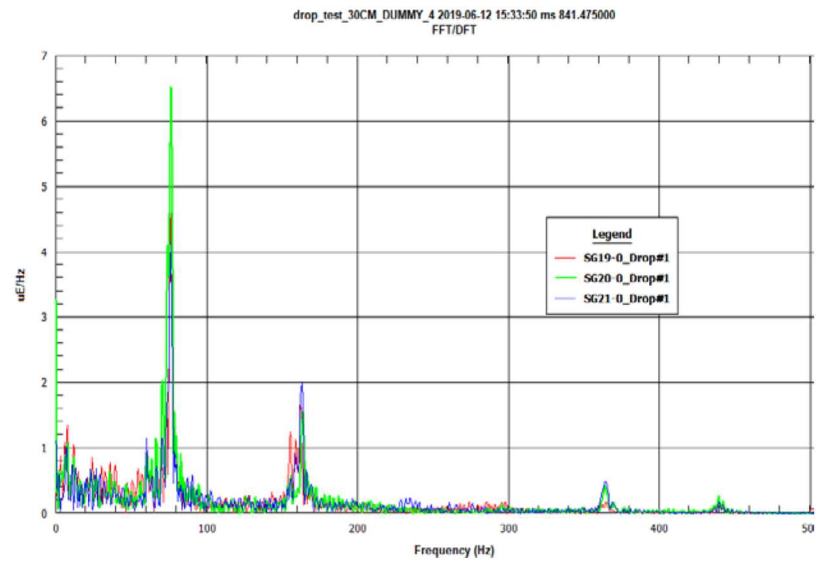


Figure 3-18. Strain FFT in Full-Scale Test.

4. SUMMARY

The goal of the 30 cm drop test is to measure accelerations and strains on the surrogate fuel assembly and to determine whether the fuel rods can maintain their integrity inside a cask when dropped from a height of 30 cm. Because the full-scale cask and impact limiters were not available (and their cost was prohibitive), it was proposed to achieve this goal by conducting three separate tests. This report describes the first two tests – the 30 cm drop test of 1/3 scale cask (conducted in December 2018) and the 30 cm drop of the full-scale dummy assembly (conducted in June 2019). The third test (to be conducted in spring 2020) will be the 30 cm drop of the full-scale surrogate assembly that will produce comparable g-forces to those measured in Test 2. The results of the first two tests were published in [15] and [16].

4.1 30 cm Drop of 1/3 Scale Cask

The hardware for this test was provided by ENSA. The 1/3-scale cask included scaled impact limiters, basket, modified (to allow for internal instrumentation) lid, and 32 dummy assemblies. The dummy assemblies were hollow steel blocks with the same mass as the fuel assemblies, but very different from the fuel assemblies structurally. The test was conducted at the BAM facility in Berlin (Germany) in December 2018. The BAM staff performed data acquisition. The sampling rate was 200,000 Hz.

The purpose of this test was to obtain acceleration data on the 1/3 scale cask and on the 1/3 scale dummy assemblies. The acceleration pulses on the 1/3 scale dummy assemblies provide the input for the 30 cm drop of the full-scale dummy assembly.

Four locations (top and bottom on the lid end and top and bottom on the base end) on the exterior of the cask were instrumented. Eleven dummy assemblies were instrumented on the lid end (side A) and 7 on the base end (side D). One location on the lid end of the basket was instrumented as well. The instrumentation was done by the SNL team.

Two horizontal drop test configurations were used. In the first configuration, the cask was in its normal transport position. In the second configuration, the cask was rotated 45 degrees counter clockwise when looking at the lid end about its longitudinal axis.

The accelerations on the cask, dummy assemblies, and basket were analyzed. The following conclusions were made based on this analysis.

- The accelerations on the cask show virtually no signal above 300 Hz.
- The accelerations on the dummy assemblies show strong signal within the frequency band up to 300 Hz. However, there is an additional high frequency response within the 800-1,100 Hz frequency band. This signal was interpreted as the assembly chattering inside the basket tube because the high frequency response was not observed when the cask was rotated 45 degrees and the assembly movement in this position was restricted. The high peak in lateral direction around 1,000 Hz indicates that the assembly chattering inside the basket tube occurred in the lateral direction.
- Analysis of the acceleration signal using FFT suggested that the accelerations on the cask and on the dummy assemblies can be filtered using a 300 Hz lowpass filter.
- Comparison of the accelerations at the different locations demonstrated that the horizontal drop was not exactly horizontal. The right side of the cask (when looking at the lid) hit slightly before the left side with a difference of ~0.4 milliseconds. The lid end of the cask hit approximately 2 milliseconds before the base end of the cask. This resulted in two acceleration peaks during the first impact with the higher accelerations associated with the second (later) peak. The peak accelerations on the cask and the dummy assemblies are higher on the base end.
- The maximum accelerations on the dummy assemblies vary significantly depending on the location within the cask with the maximum accelerations being ~2.4 times higher than the minimum. Generally, the later the acceleration pulse reaches a specific location inside the cask, the higher the peak acceleration. The locations closer to the top were the ones with the highest accelerations on both ends (A and D).
- Figure 4-1 compares minimum and maximum accelerations on the dummy assemblies, cask, and basket. The minimum accelerations on the dummy assemblies are slightly higher than the minimum accelerations on the cask. The maximum accelerations on the dummy assemblies are significantly higher than the maximum accelerations on the cask and on the basket.
- As expected, the transfer function shows amplification from the cask to the assemblies. The transfer functions on A and D sides are very similar, especially within the frequency band of a primary interest (0-300 Hz).

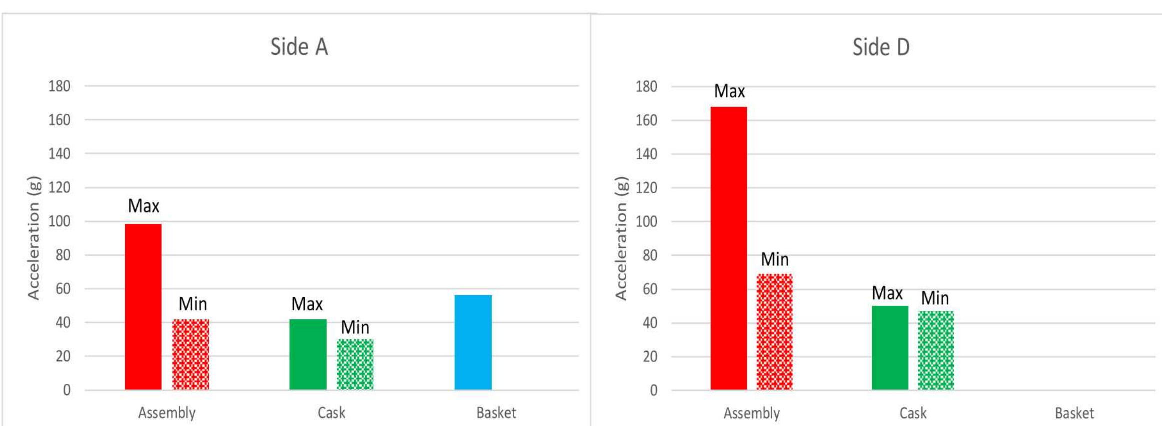


Figure 4-1. Maximum Accelerations on the Assembly, Cask, and Basket, 1/3 Scale Cask Drop A.

In 2010 a series of tests were conducted at SNL with the same 1/3 scale cask. The instrumentation was only on the outside of the cask. The accelerations on the cask observed in 2010 were very similar to the ones observed in 2018 with the maximum acceleration of 55 g in 2010 and 50 g in 2018. The duration of the first impact pulses were the same (30 millisecond).

To calculate the expected accelerations on the full-scale dummy assembly the maximum accelerations on the 1/3 scale dummy assemblies (on side A and side D) were decreased and the time was increased proportionally to the scale (factor of 3). This represents the major input into the second test, a 30 cm drop of the full-scale dummy assembly.

4.2 30 cm Drop of Full-Scale Dummy Assembly

The full-scale dummy assembly is the enlarged by 3 times equivalent of the 1/3 scale dummy assembly. It was manufactured by ENSA using the same materials, scaled dimensions, and manufacturing processes as the 1/3 scale dummy assemblies.

The full-scale dummy assembly was dropped in the full-scale 17x17 PWR MMC basket tube. A basket tube was purchased from ENSA to mimic the boundary conditions the dummy assemblies experienced during the 30 cm drop of 1/3 scale cask.

The full-scale dummy assembly was instrumented with tri-axial accelerometers on the top and bottom ends to obtain the acceleration data comparable with the 1/3 scale drop test. The basket tube was instrumented with two tri-axial accelerometers on the top face.

Felt pads were used as a shock absorbing material to mimic the behavior of the impact limiters and the cask in the 1/3 scale cask drop test. Four pads were attached to the bottom face of the basket tube.

The drop test was conducted in June 2019 at the SNL drop tower (Albuquerque, NM). A SNL portable data acquisition system was used to acquire the data. The data collection frequency was 51,200 Hz.

The goal of this test was to find the condition under which the observed acceleration pulses would be similar to the expected acceleration pulses derived from the 1/3 scale cask drop test. Achieving this condition means that the effect of the cask and the impact limiters are adequately represented.

Four drop tests were performed to get the desired acceleration pulses. After each test the pulse amplitudes, durations, and shapes were examined and the felt dimension were adjusted. The adjustments consisted of reducing the pad area (length) and increasing its thickness.

In the fourth drop test the full-scale acceleration pulses were in good agreement with the expected ones. Note that the full-scale assembly drop was virtually horizontal and the accelerations on the top and bottom ends of the dummy assembly were very similar and occurred practically at the same time. In the 1/3 scale cask drop, the cask lid (top) end hit the target first. This resulted in the different timing of the peak accelerations on the top and bottom ends of the assemblies that can't be reproduced with a strictly horizontal drop.

Additional data analysis was done to demonstrate that the full-scale dummy assembly adequately reproduces the behavior of the 1/3 scale dummy assembly. The analysis compared the acceleration SRS, basket to dummy assembly transfer function, and signal strength (FFT) in 1/3 scale (scaled) and full-scale tests (Test 4). The following conclusions were made.

- The basket and dummy assembly acceleration responses were very similar up to 100 Hz.
- The basket to dummy assembly transfer functions have the same trends and are very similar up to 100 Hz.
- The signal strength peaks are very similar with the highest strength in the frequency band below 100 Hz.

- The full-scale dummy assembly adequately reproduces the behavior of the 1/3 scale dummy assembly.

The felt configuration used in the last drop represents the major input into the third test, a 30 cm drop of the full-scale surrogate assembly.

4.3 30 cm Drop of Full-Scale Surrogate Assembly

The 30 cm drop tests of the full-scale dummy assembly allowed shock absorbing felt pads to be designed to adequately represent the effect of the cask and the impact limiters. This design will be used in the 30 cm drop of the full-scale surrogate assembly. The assembly will be instrumented with multiple accelerometers and strain gauges to obtain acceleration and strain data at different locations on the rods. The behavior of the surrogate fuel rods, as seen in two windows in the basket tube, will also be recorded during the drop using high-speed video cameras.

These data will help to determine whether or not the fuel rods can maintain their integrity inside a cask when dropped from a height of 30 cm. The test will be conducted in the spring of 2020 and documented in a separate report.

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Appendix A

1/3 Scale Cask Drop Tests

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A-1 Individual Accelerometer Responses

Appendix A-1 contains time history data during both Drop A and Drop B of the 30-cm drop test of 1/3 scale cask. Data are filtered using a lowpass filter at 300 Hz. Starting with the exterior of the cask and moving inward to the individual assembly accelerometers, Figure A-1 and Figure A-2 show response in longitudinal, lateral, and vertical directions of the cask. Figure A-3 shows response from the basket accelerometer A12. Figure A-4 though Figure A-14 illustrate individual assembly response.

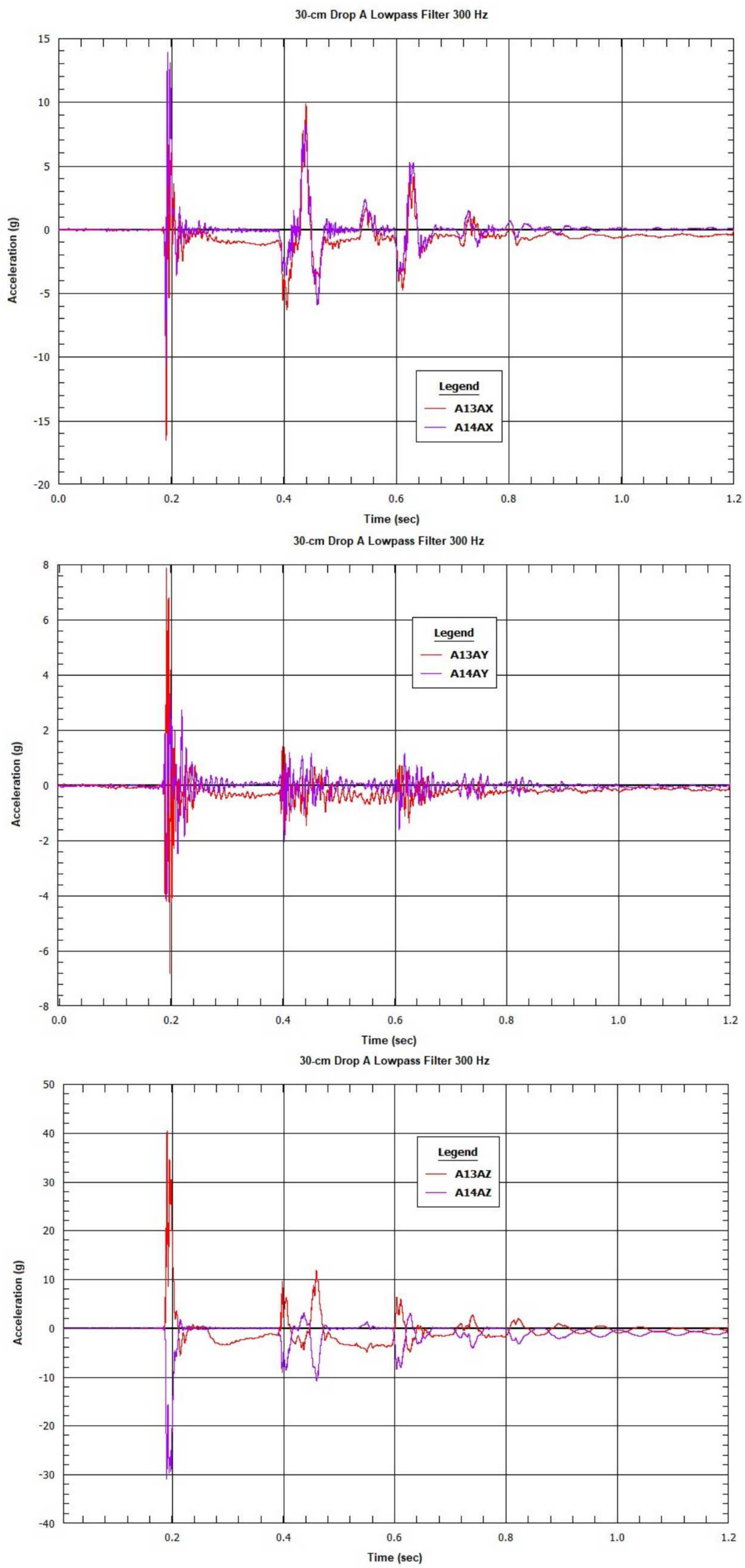


Figure A-1: Drop A - Left Side (A-end) Cask: A13/A14.

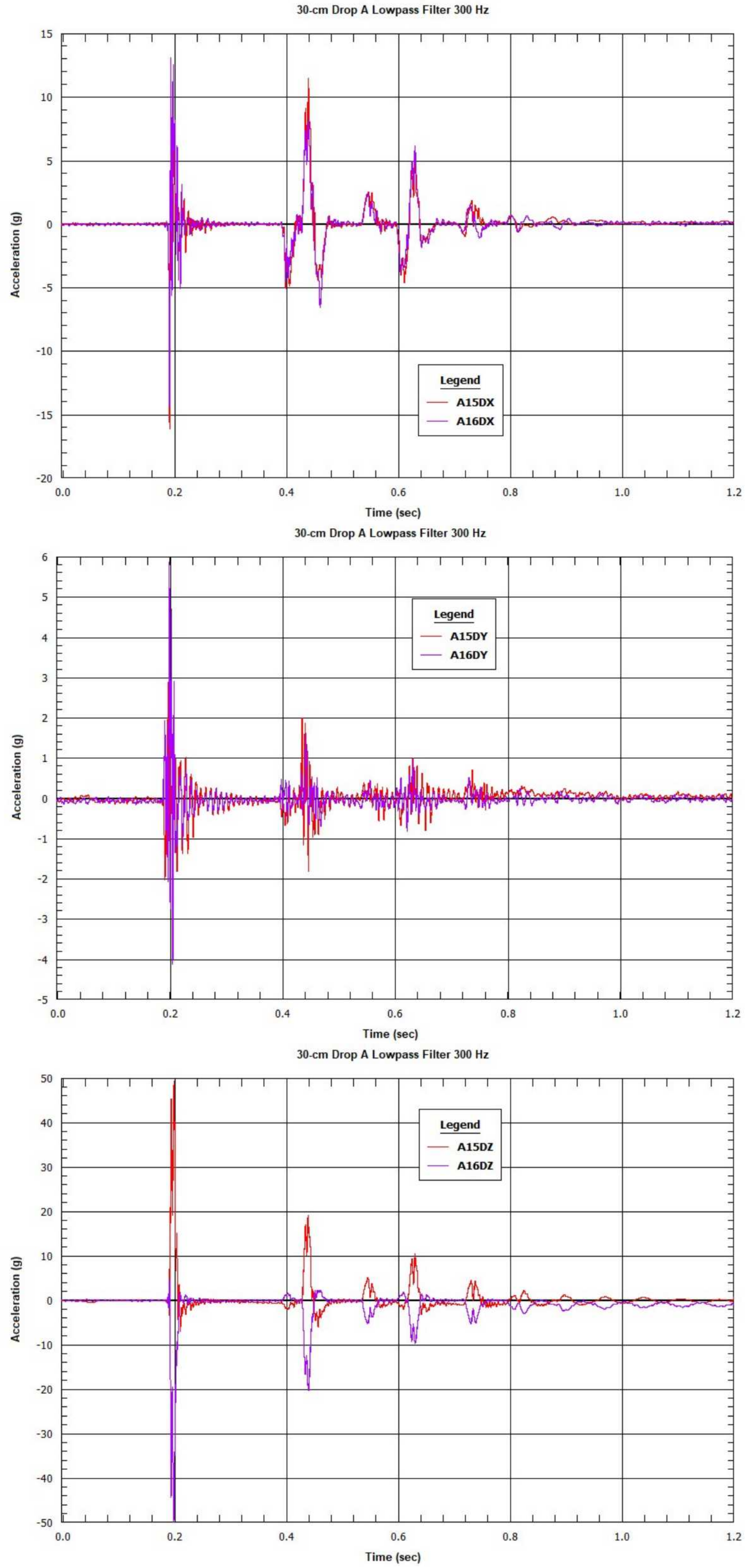


Figure A-2: Drop A - Right Side (D-end) Cask: A15/A16.

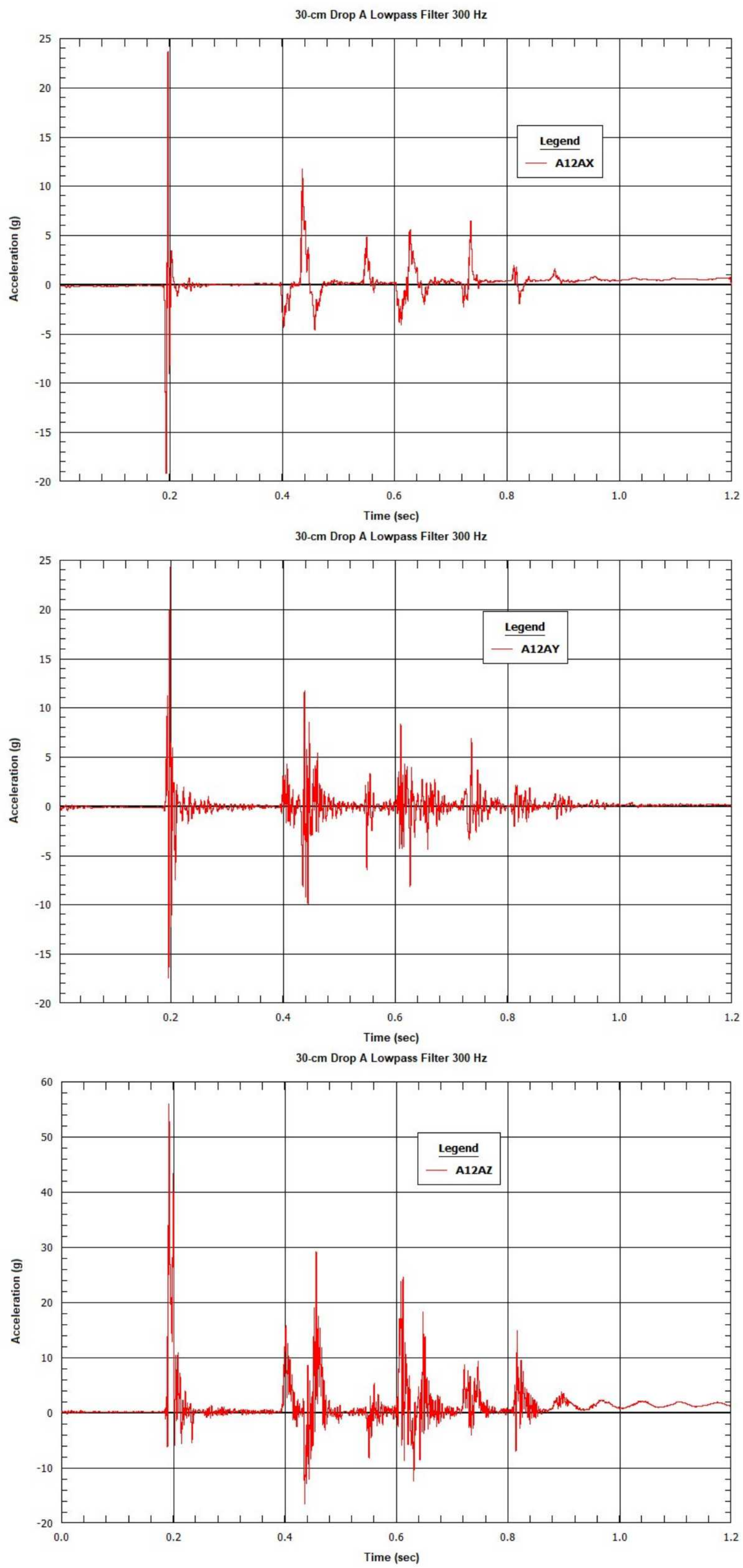
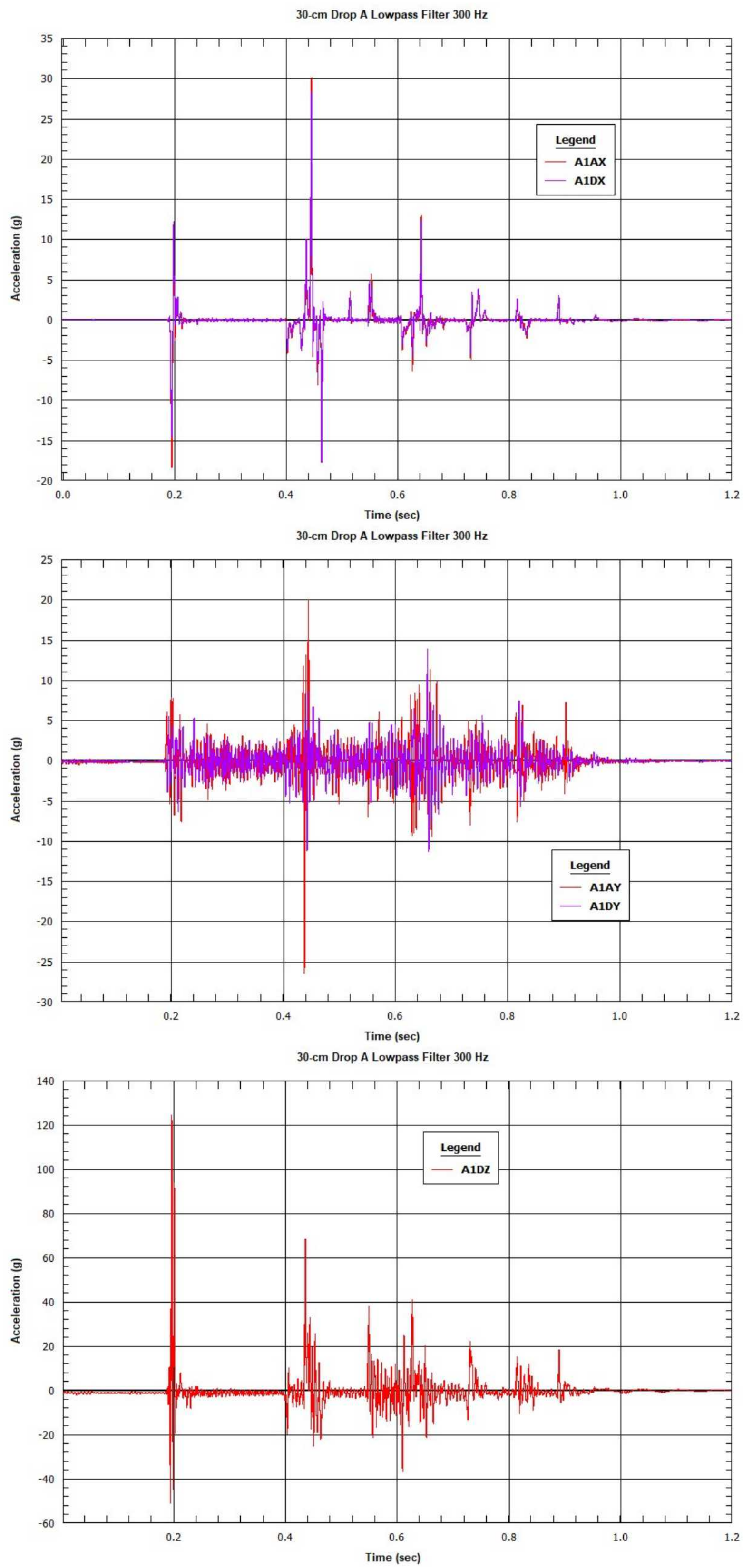


Figure A-3: Drop A - Basket A12.



**Note: Assembly accelerometer A1AZ disconnected.

Figure A-4: Drop A - Assembly accelerometer A1.

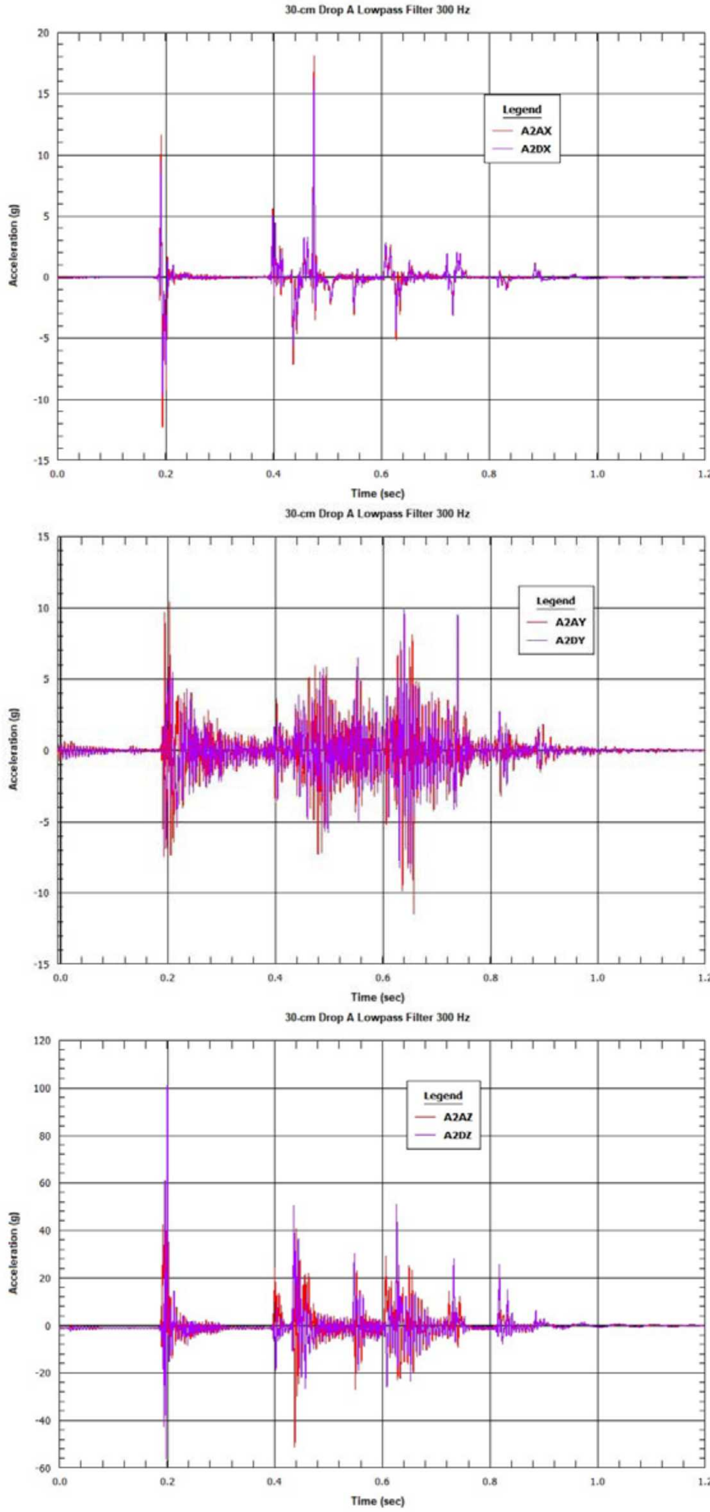


Figure A-5: Drop A - Assembly accelerometer A2

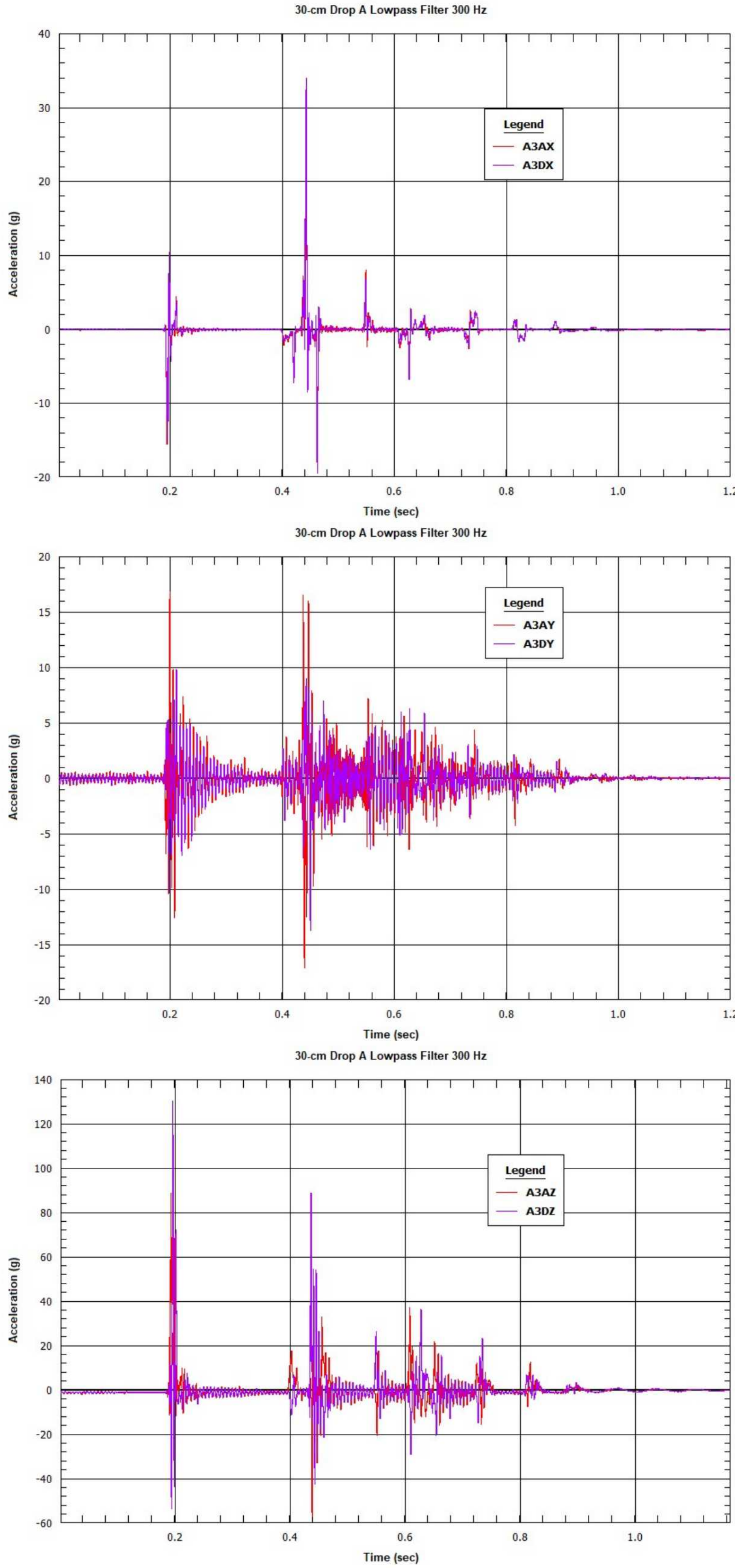


Figure A-6: Drop A - Assembly accelerometer A3

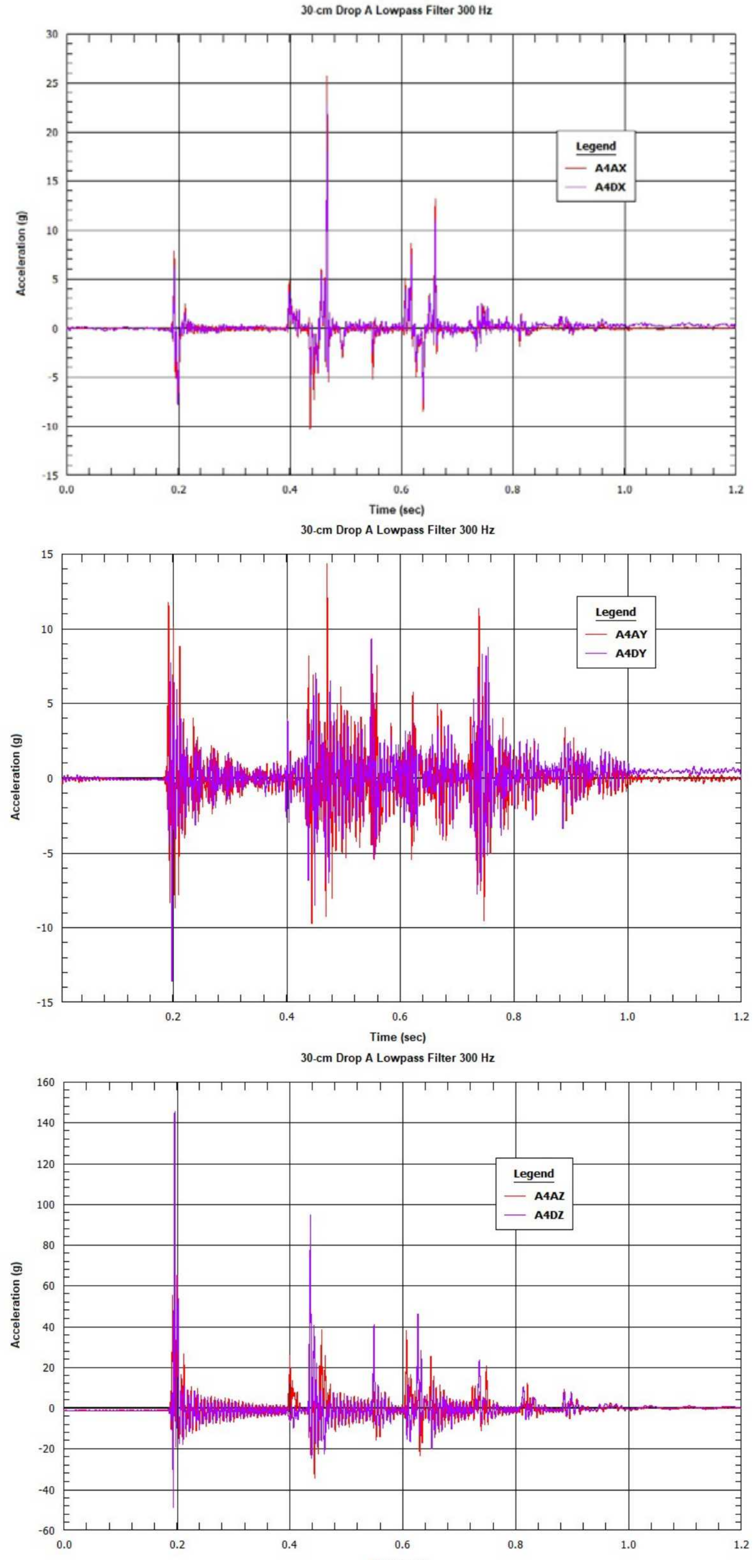


Figure A-7: Drop A - Assembly accelerometer A4

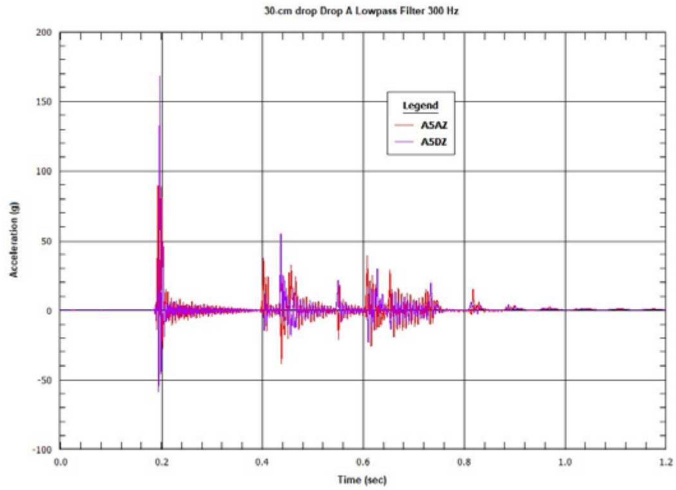


Figure A-8: Drop A - Assembly accelerometer A5

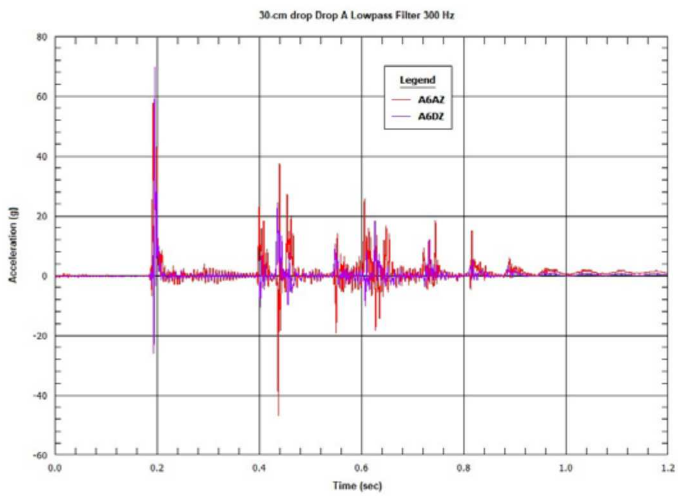


Figure A-9: Drop A – Assembly accelerometer A6

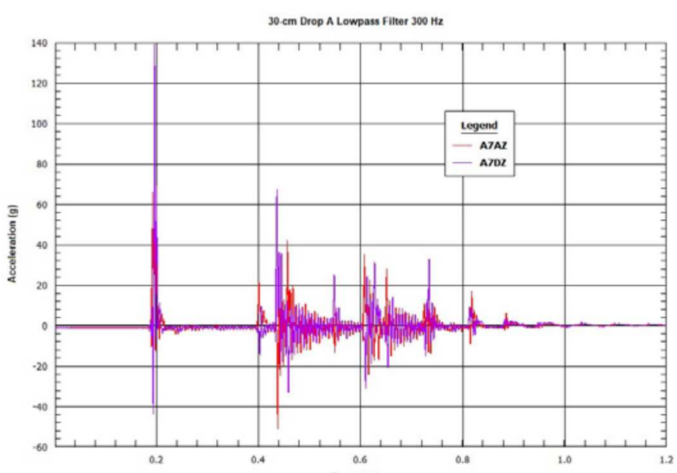


Figure A-10: Drop A - Assembly accelerometer A7

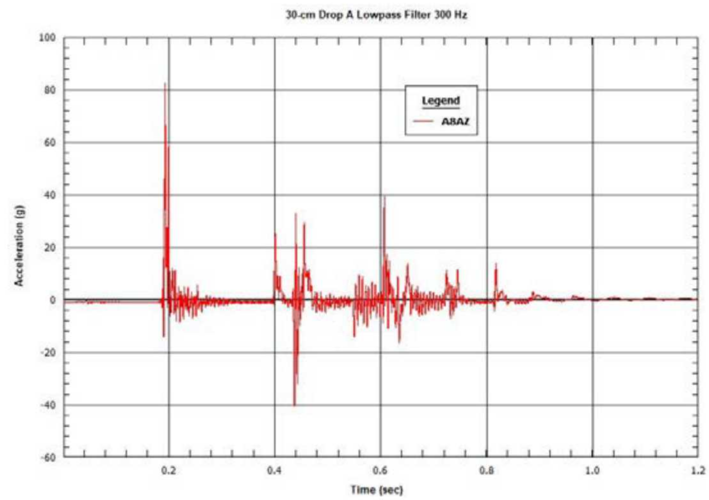


Figure A-11: Drop A – Assembly accelerometer A8

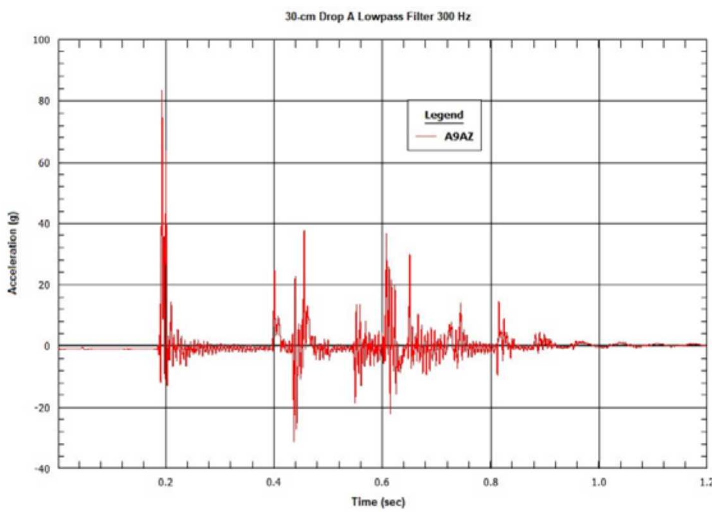


Figure A-12: Drop A - Assembly accelerometer A9

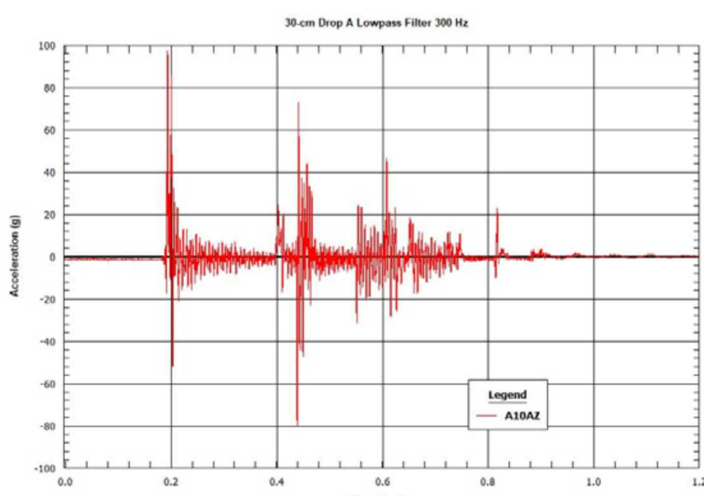


Figure A-13: Drop A - Assembly accelerometer A10

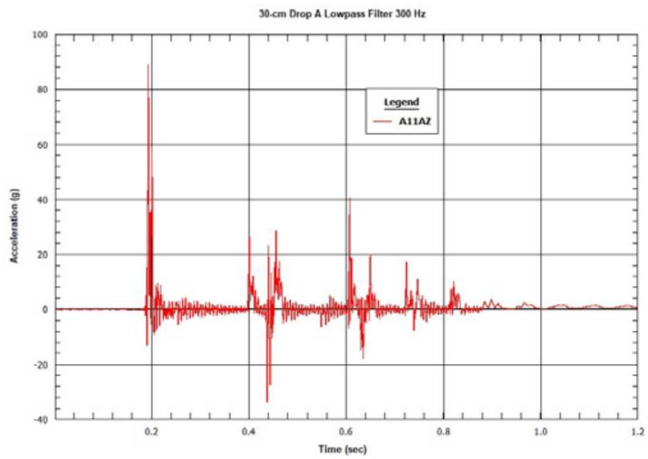


Figure A-14: Drop A - Assembly accelerometer A11

Figure A-15 shows a comparison between assembly accelerometer responses during Drop A. Each figure shows the longitudinal, lateral, and vertical response during initial impact from accelerometer A3 on side A and accelerometer A4 on side D. As expected, vertical acceleration is the highest, with maximum acceleration on the back end, which was consistent for Drop A.

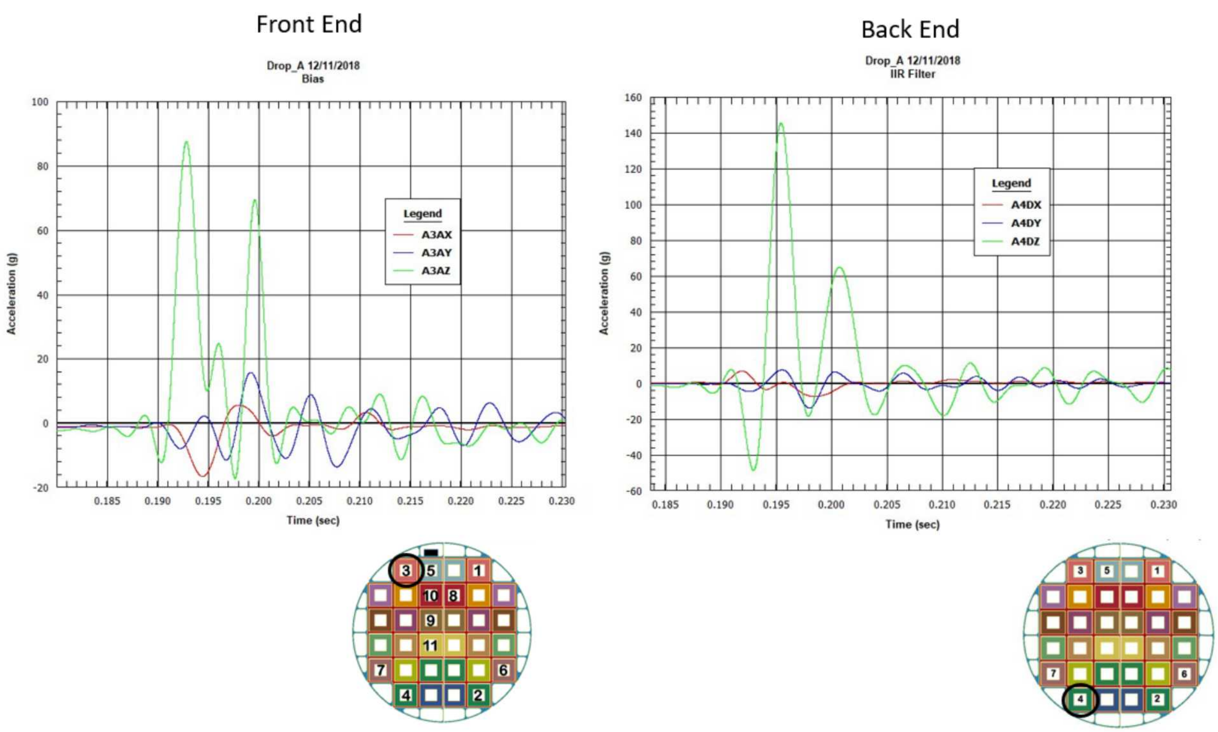


Figure A-15: Drop A - Assembly front and back End

Figure A-16 shows response in the longitudinal, lateral, and vertical direction for the front end of the top of the cask and the back end of the top of the cask. As expected, vertical acceleration is the highest. The front end hit first on initial impact, causing the back end to experience higher acceleration due to being "slammed" down.

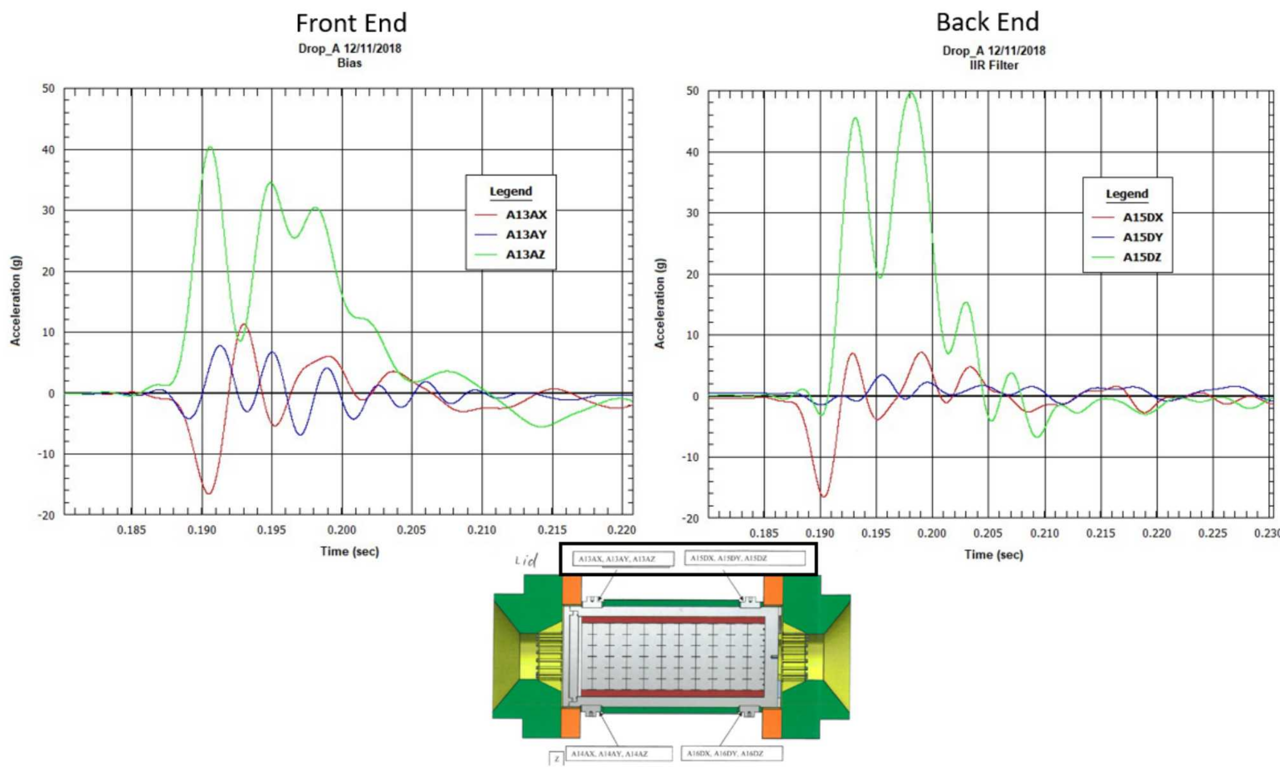


Figure A-16: Drop A - Cask Front End and Back End

The figures below show the Drop B data filtered to 300 Hz. Starting with the exterior of the cask and moving inward to the individual assembly accelerometers, Figure A-17 and Figure A-18 show response in longitudinal, lateral, and vertical directions of the cask. Figure A-19 shows response from the basket accelerometer A12. Figure A-20 through Figure A-30 illustrate individual assembly response.

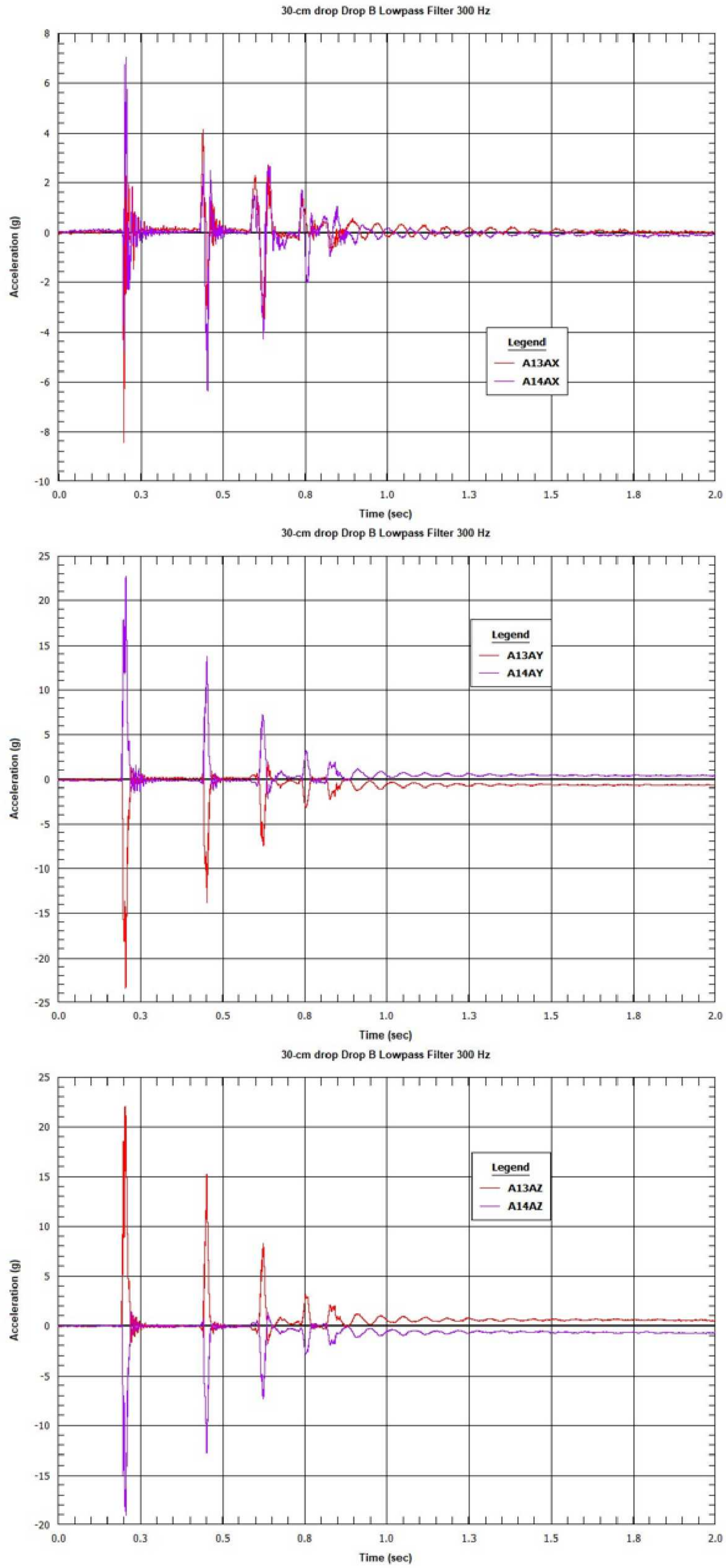


Figure A-17: Drop B – Side A cask accelerometer A13/A14

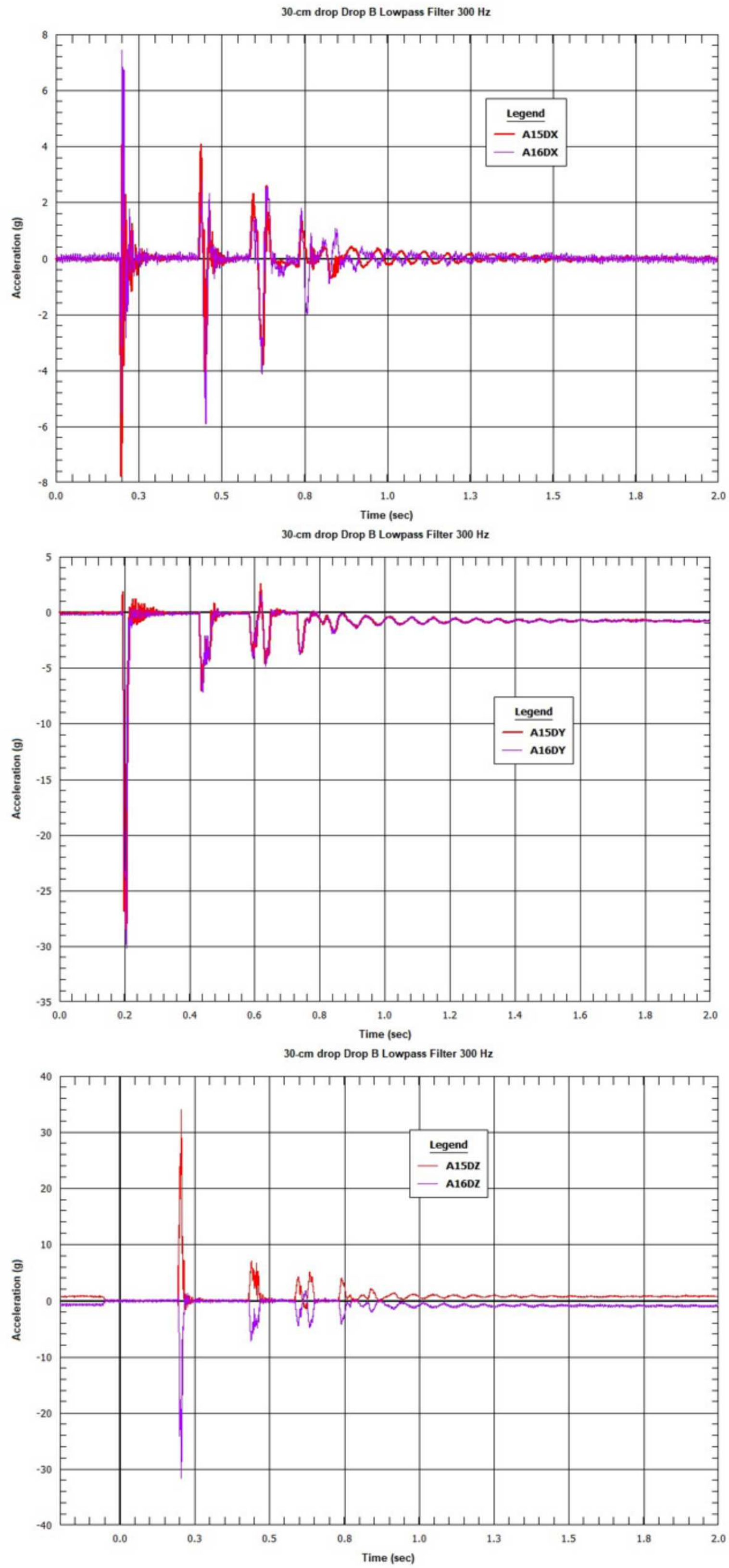


Figure A-18: Drop B - Side D cask accelerometer A15/A16

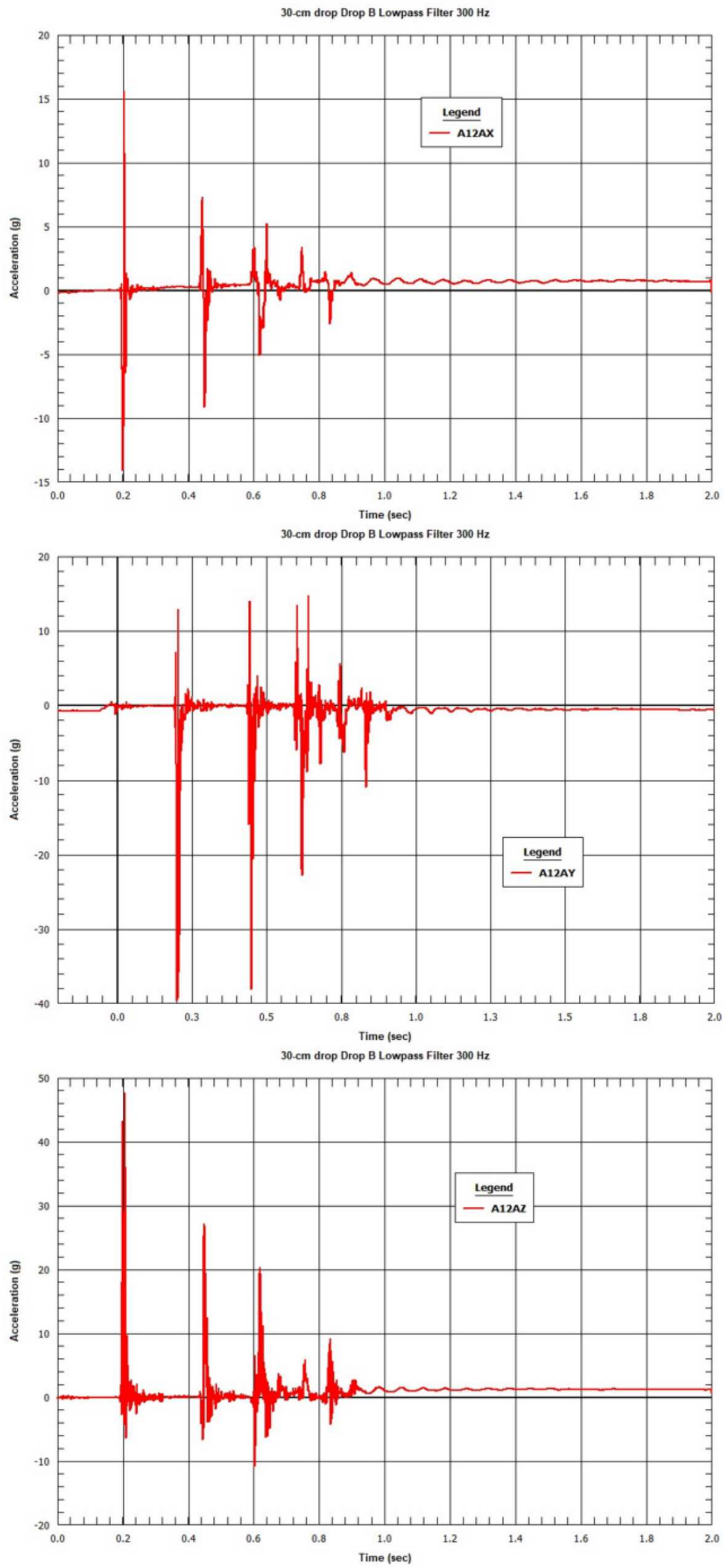
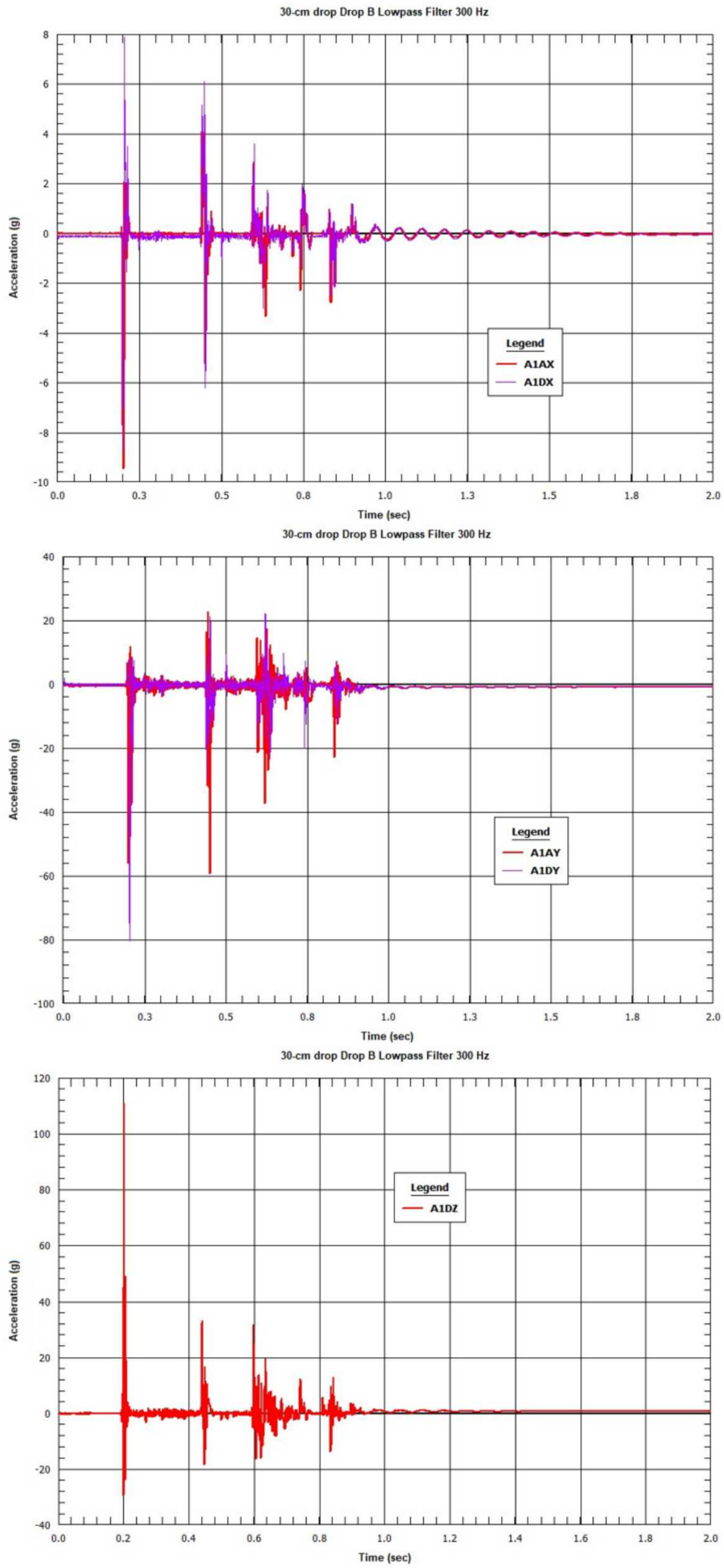


Figure A-19: Drop B – Basket accelerometer A12



**Note: Accelerometer A1AZ disconnected.

Figure A-20: Drop B – Assembly accelerometer A1

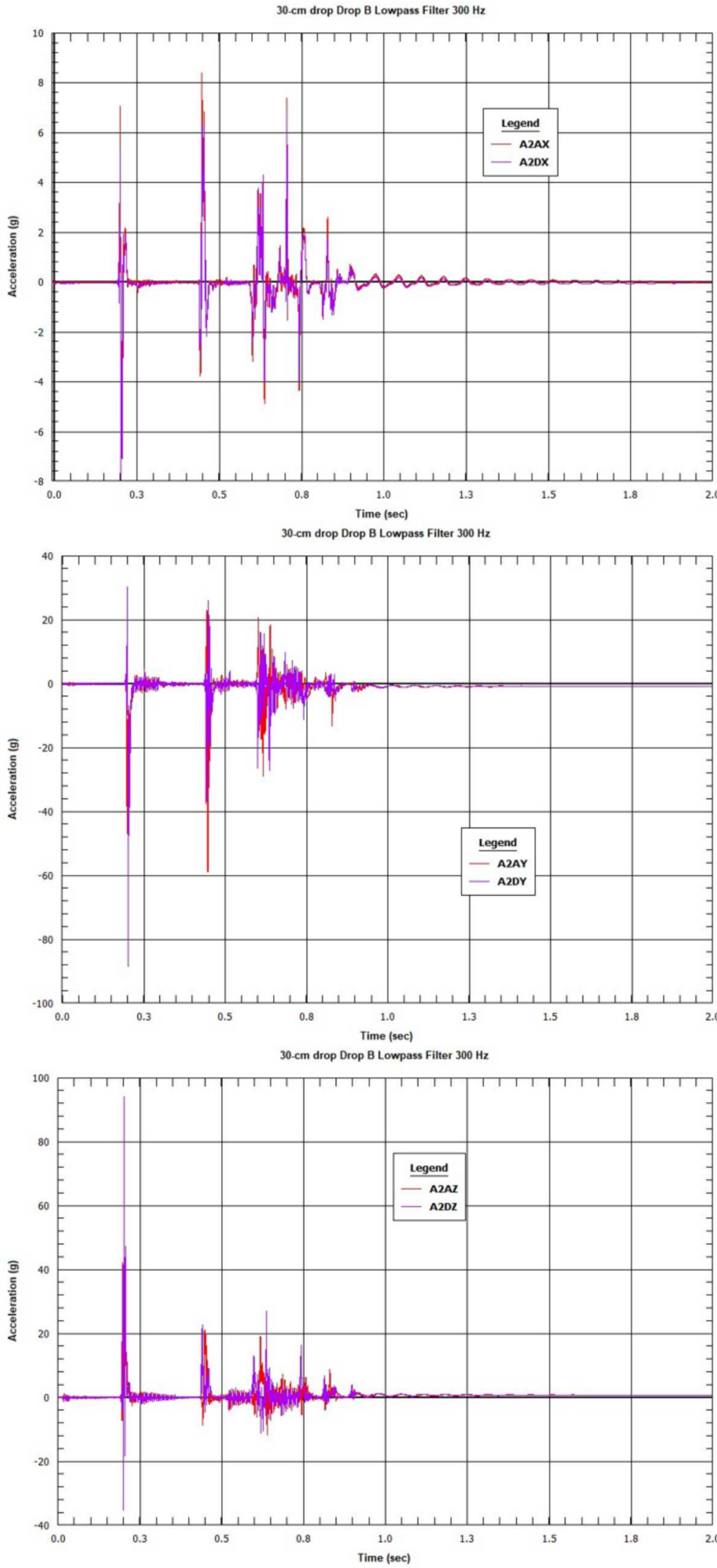


Figure A-21: Drop B – Assembly accelerometer A2

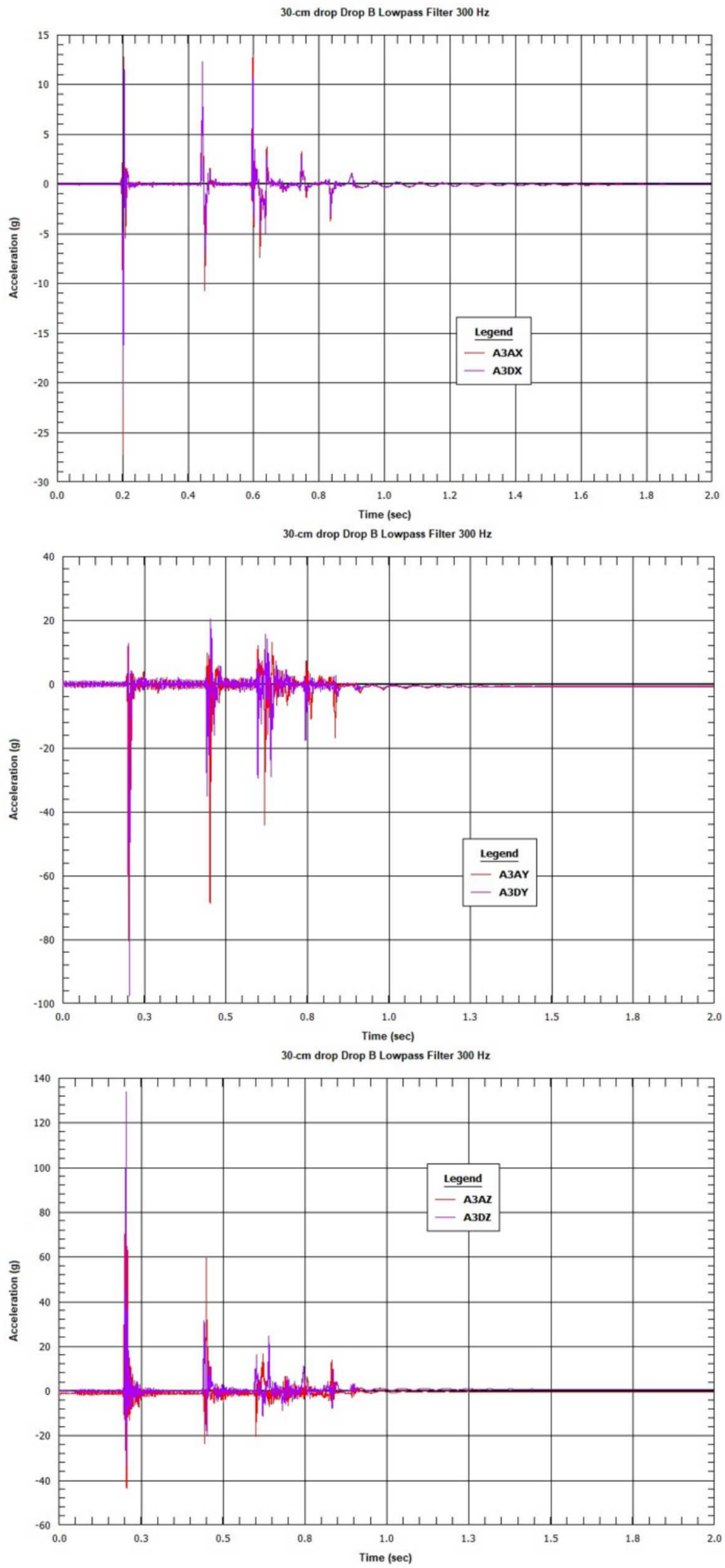


Figure A-22: Drop B – Assembly accelerometer A3

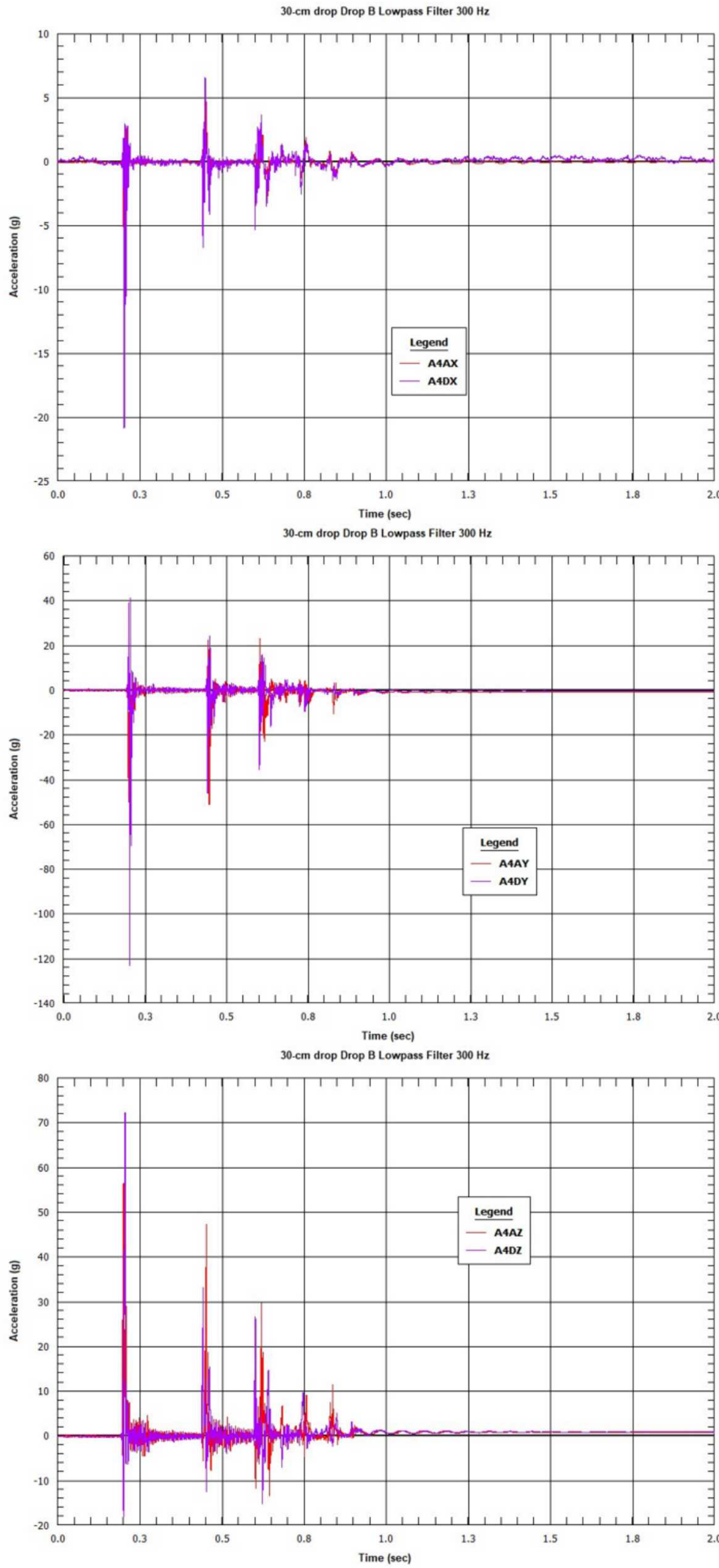


Figure A-23: Drop B – Assembly accelerometer A4

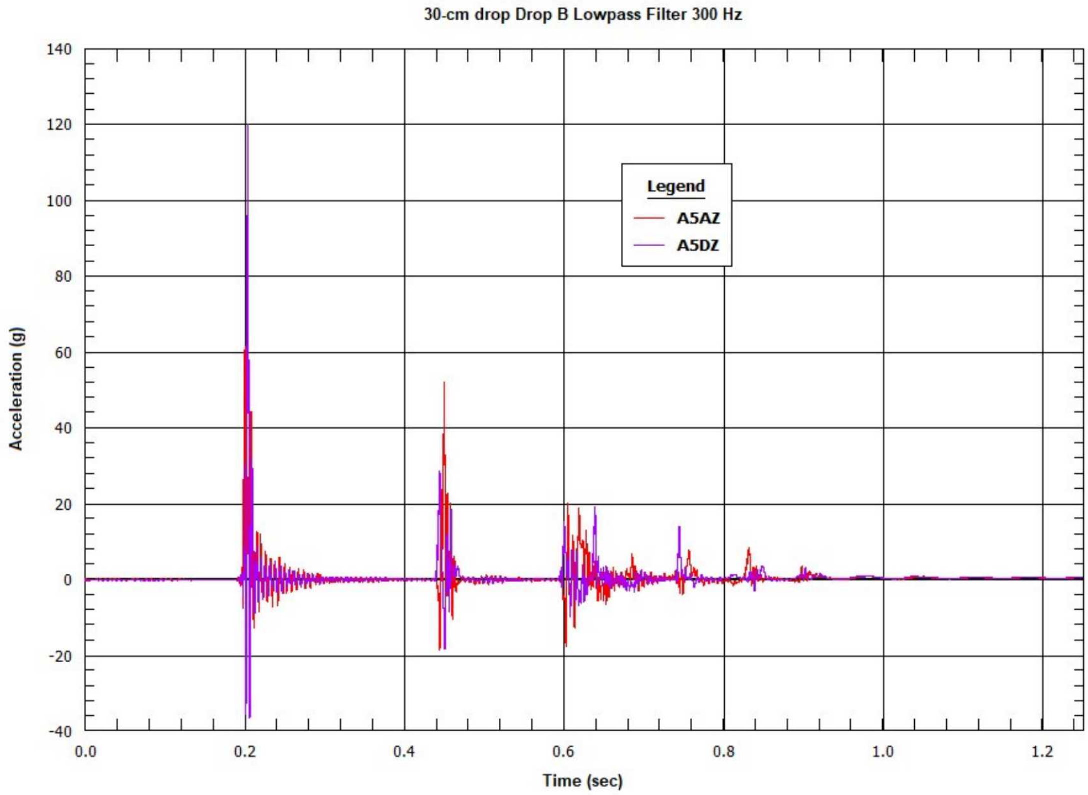


Figure A-24: Drop B - Assembly accelerometer A5

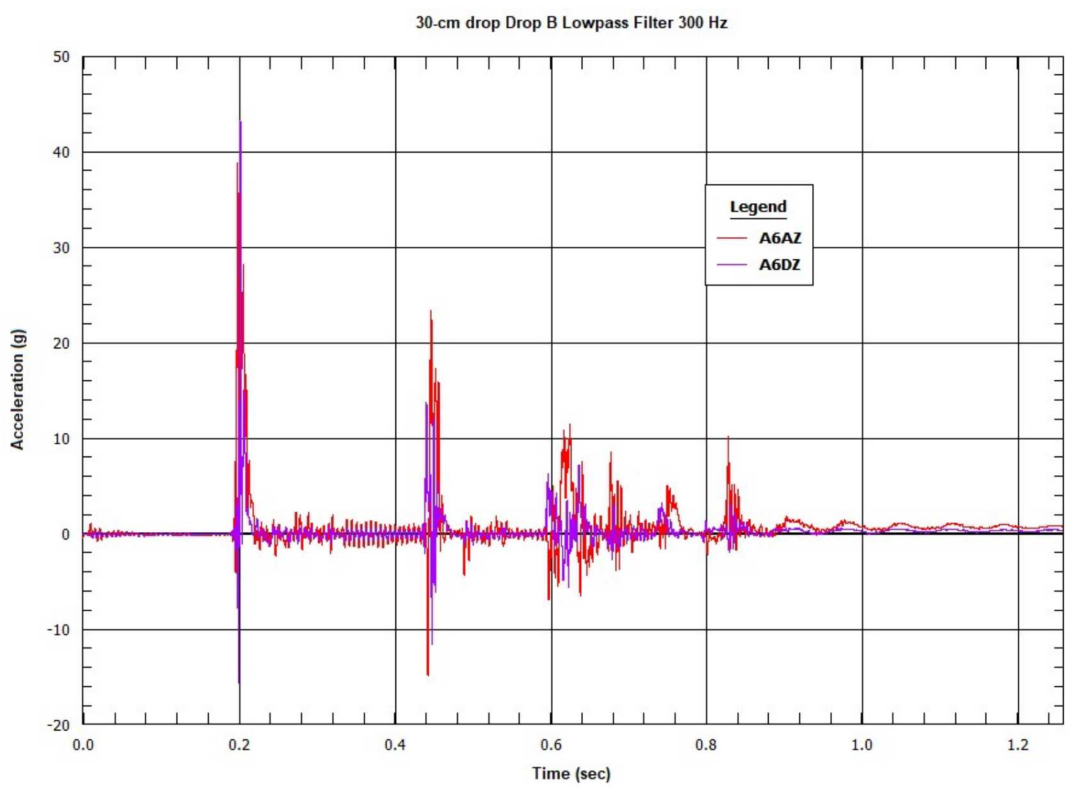


Figure A-25: Drop B – Assembly accelerometer A6

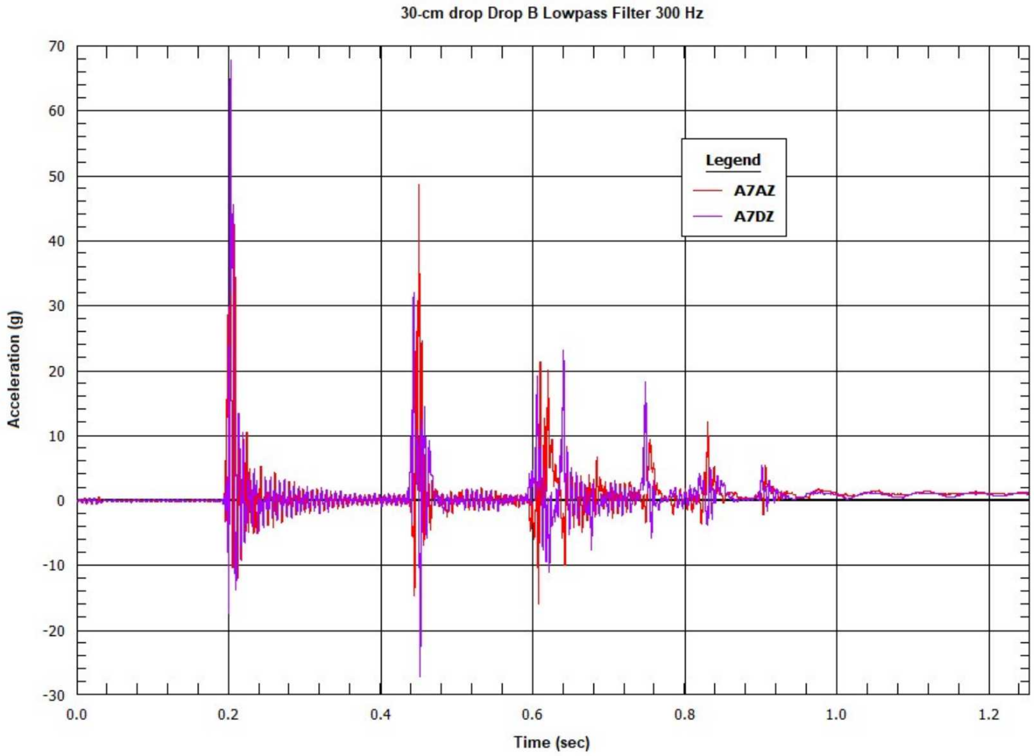


Figure A-26: Drop B - Assembly accelerometer A7

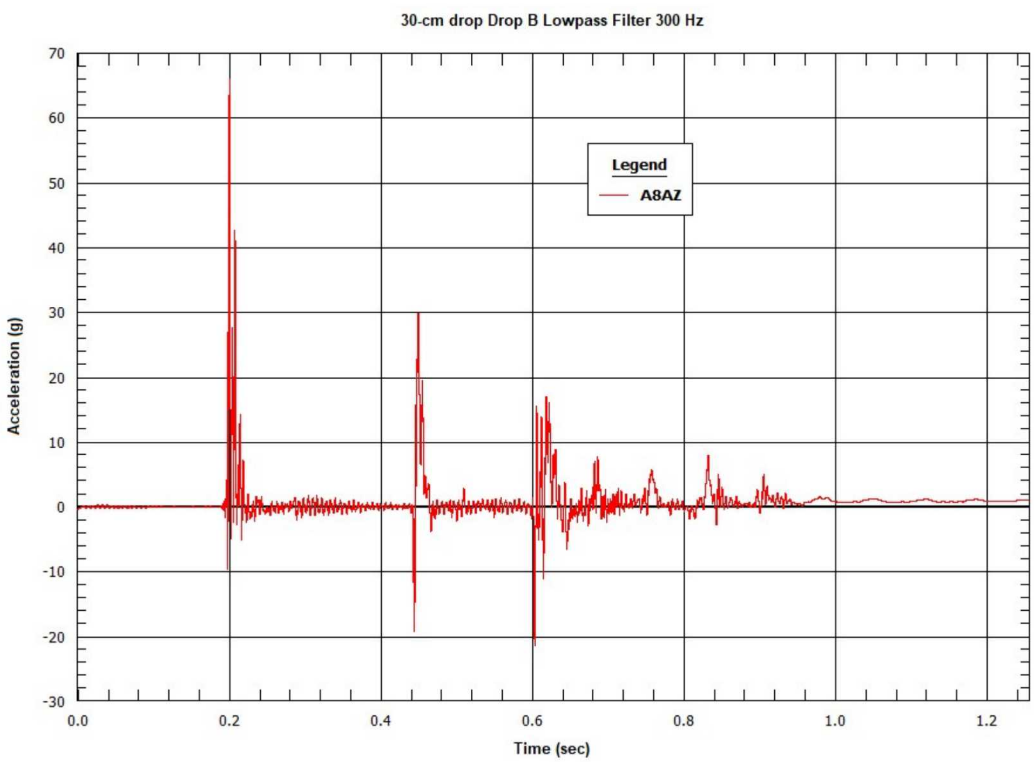


Figure A-27: Drop B – Assembly accelerometer A8

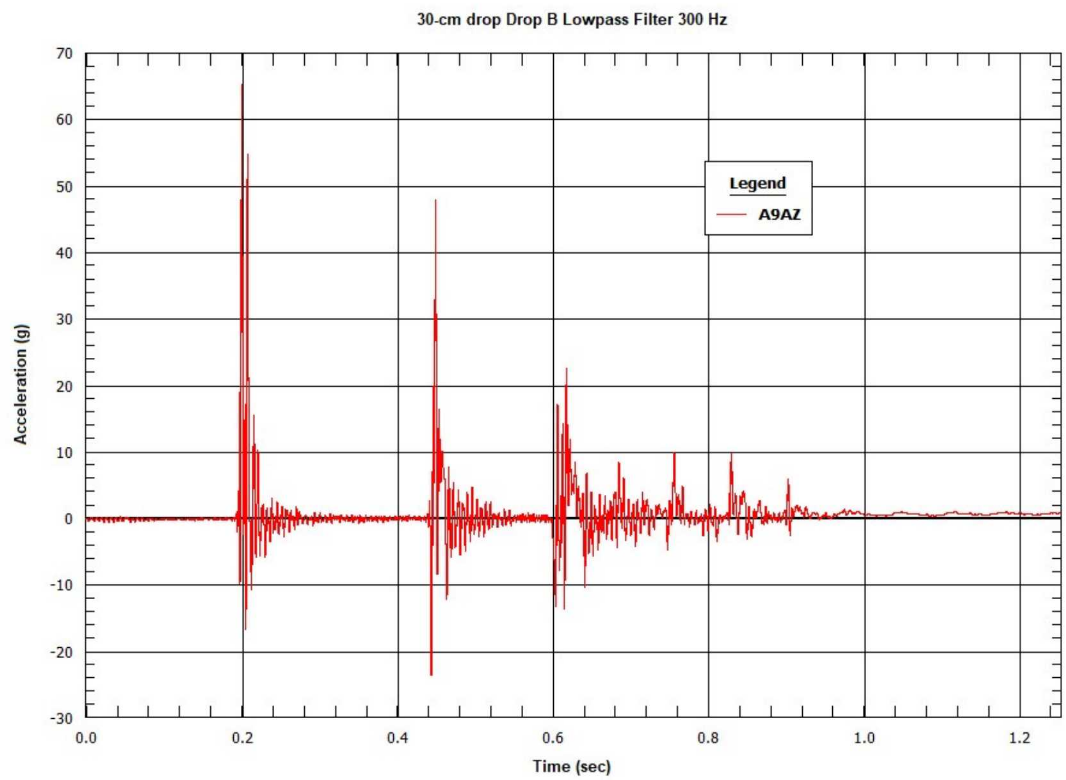


Figure A-28: Drop B - Assembly accelerometer A9

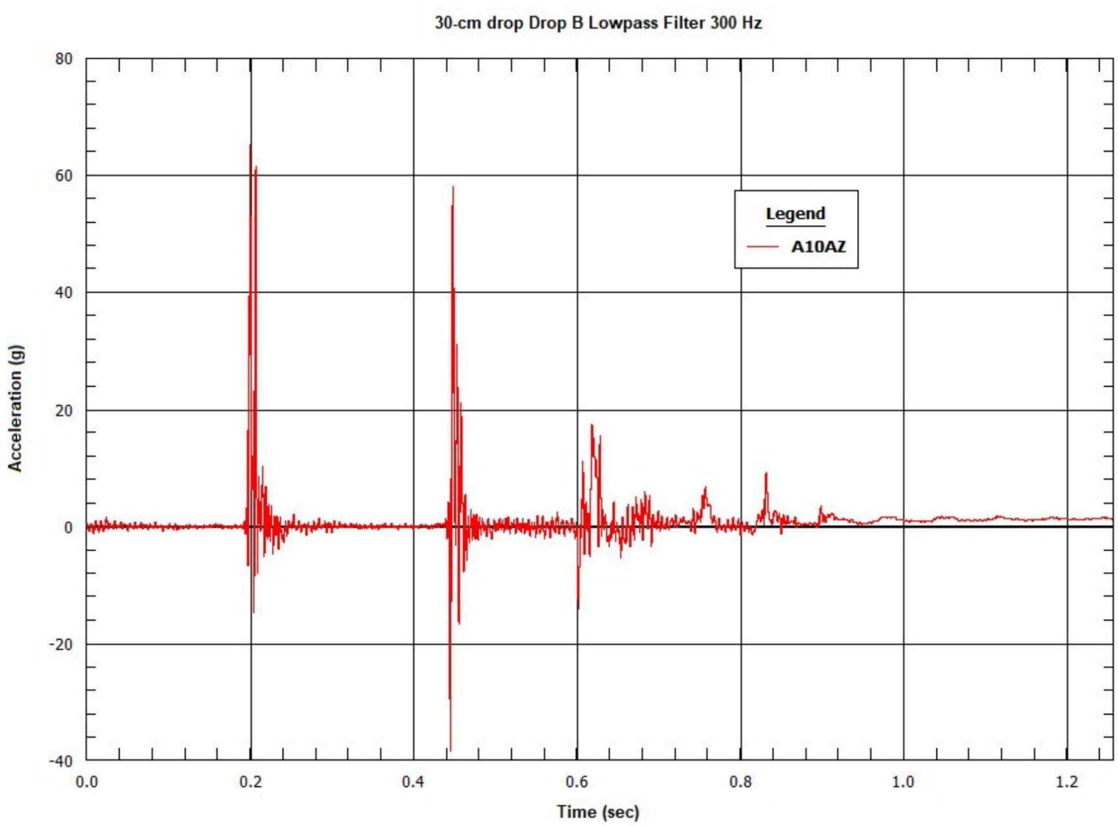


Figure A-29: Drop B – Assembly accelerometer A10

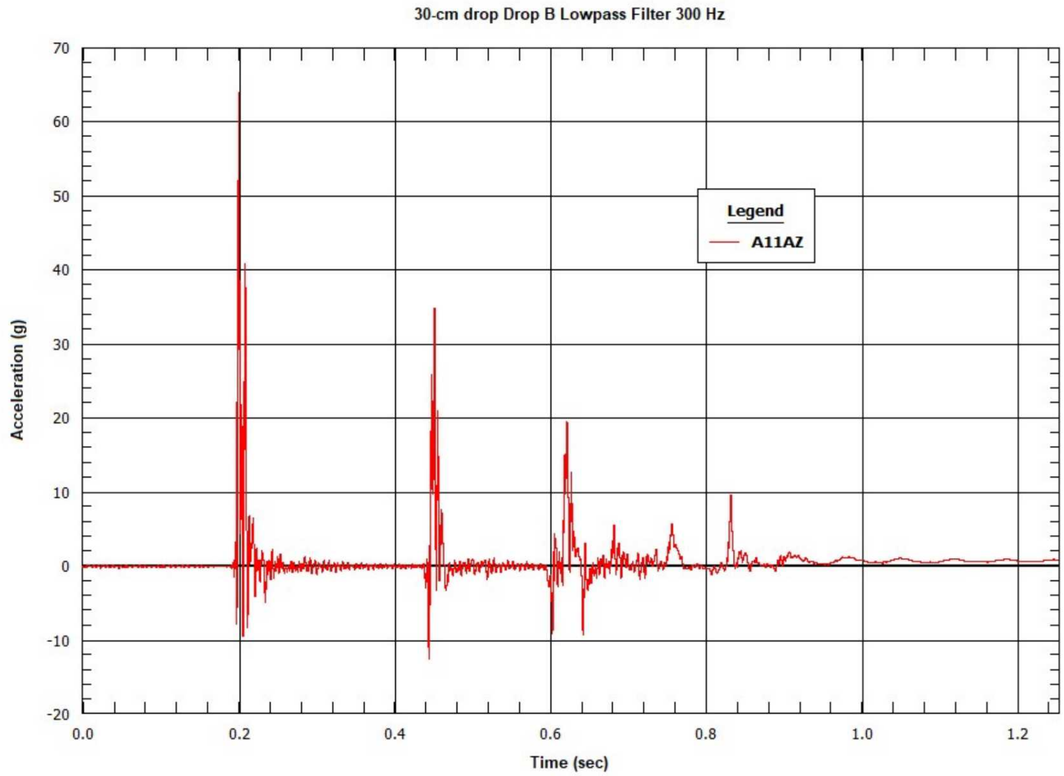


Figure A-30: Drop B – Assembly accelerometer A11