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Aircraft Impact Test on the HI-STAR 180 Dual Purpose Cask

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Abstract

Holtec International developed a dual purpose (storage and transport) spent fuel cask, HI-STAR 180, for use in Switzerland. After initial licensing by the USNRC, the cask is being licensed in Switzerland by the Swiss Regulatory Authority ENSI. The storage regulations in Switzerland require consideration of an aircraft impact, which is defined in the regulation as a force-time history. The requirement was satisfied through a two-phase 1:3.78 scale physical test program carried out at the US Army Aberdeen Proving Grounds (APG) in Maryland, USA.

The first phase of the program consisted of devising and benchmarking a synthetic missile that would emulate the specified force-time curve in a reasonably bounding manner. This phase resulted in a successful design of a missile by testing it against a roller mounted “rigid” wall. The evaluation of the impact from the synthetic missile demonstrated that the missile comfortably bounds the impulse of the aircraft crash event.

In the second phase of this program, a heavily instrumented test cask was impacted by the calibrated missile accelerated along the rail by a rocket-propelled sled. The missile successfully hit the test cask at the most vulnerable location identified in advance through numeric simulations. The impact was bounding in terms of missile weight, velocity, impact force and duration.

The test was confirmed to be successful by the measurements during and after the impact with the following conclusions:

- The post-impact helium leak test showed the leak rate to be three orders of magnitude less than the permissible value.
- The axial stresses in the enclosure lid bolts remained in the elastic range.
- There is no measurable permanent ovalization of the cask's flange.
- Numerical predication using LS-DYNA reasonably matches the measured data of key safety-related cask responses.

The aircraft crash physical test program conclusively demonstrates that the HI-STAR 180 cask can withstand the postulated aircraft crash event with ample margin. In a broader sense, the comparison of the test data with the LS-DYNA simulation of the test indicates the ability of LS-DYNA to predict the consequence of an aircraft strike on a metal cask.

Introduction

The HI-STAR 180 is a dual purpose (storage and transportation) cask for spent nuclear fuel developed by Holtec International. It has been designed for storage in accordance with Swiss regulations and in alignment with IAEA requirements for a type B(U)F transport cask. HI-STAR 180 was licensed by the U.S. NRC in 2009 under 10 CFR 71 to transport high burn-up PWR UO_2 and MOX fuel (Docket Number 71-9325). The cask is designed for up to 37 PWR fuel assemblies, a maximum burnup of 66000 MWd/mtU, a minimum of 3 years cooling time, and a maximum heat load of 32 kW. The HI-STAR 180 is slated to be initially used to store fuel at the Beznau Nuclear Plant in Switzerland, in the plant's on-site storage building, and for off-site transport at a later date. Upon the Swiss regulator's formal release, the first batch of HI-STARs will be built at the Holtec Manufacturing Division (HMD) in Pittsburgh, PA. For a depiction of the cask see Figure 1 below.

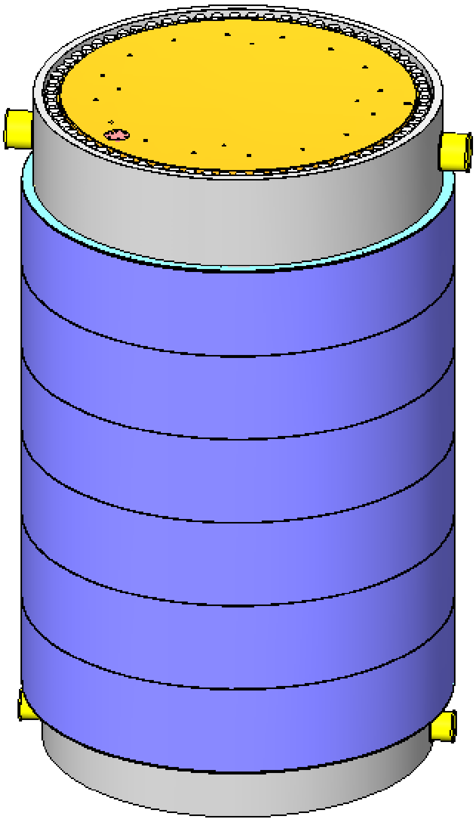

Figure 1 HI-STAR 180 Dual Purpose Cask

A cask containment integrity test program has been carried out to qualify the cask for a postulated aircraft impact event specified in the relevant Swiss regulations [1]. The specific objective of the test program was to verify, by physical testing, that the cask, arrayed vertically in the Interim Storage Building and equipped with an Aircraft Crash Cover (ACC), will remain leak-tight in the wake of an impact from an aircraft. Additionally, pre- and post-test computational simulations of the test were performed, using LS-DYNA [2], to inform the optimal test conditions, and to validate the computational tools. Physical testing was carried out on a scaled embodiment of the HI-STAR 180 cask using a rigorous geometric sizing protocol with a scaling ratio of 1:3.78, with the impulse delivered as specified by the Swiss storage regulatory guide [1], and using a defined post-impact permissible helium leak rate (PHLR).

The program was conducted in two phases

- Phase 1: Devising and qualifying the missile
- Phase 2: Performing the cask impact with the missile from Phase 1

Overall, both the physical and the numerical simulation of the aircraft impact on the HI-STAR 180 cask shows that the impact is ably withstood by the cask and the ACC.

Test Criteria

With respect to the regulatory requirements, the goal of the test program was to satisfy the following acceptance criteria:

- The closure lid bolts will not be permanently stretched by the impact causing a condition of a significant incipient leak rate increase. The post-impact leakage rate measurement shall be smaller than the permissible value.
- The containment boundary of the cask will remain structurally intact, free of any significant gross plastic deformation that adversely affects the fuel retrievablility.

With respect to the numerical simulations the goal was as follows:

- Determine whether the numerical simulations using LS-DYNA reasonably matches the measured key safety related cask-responses, such as acceleration and stress magnitudes.

Phase 1: Missile Development

The first phase of the program focused on the design and qualification of a missile that emulates the regulator’s specified force-time curve in a reasonably bounding manner. This phase consisted of the following steps.

An initial missile design was developed based on a series of LS-DYNA simulations for a rigid wall impact of the missile. The missile was manufactured and a rigid wall impact test was performed at the

US Army Aberdeen Proving Ground. The impact force time history between the missile and the wall was obtained by tracking the acceleration time history of the impacted rigid wall that moves on four supporting rollers on a rigid steel table fixed to the ground. The low friction coefficient (<0.05) of the rollers minimizes the friction force so that the impact force is essentially equal to the acceleration of the rigid wall times the mass of the wall. Two accelerometers were attached to each of the two side surfaces of the wall. The displacement of the wall during the impact was monitored by hi-speed cameras and a linear transducer; the latter directly measured the movement of the rigid wall rear surface relative to the supporting table.

The data obtained from the initial rigid wall impact test indicated that the required impact force-time-history was not met. However, it provided the necessary information for a design adjustment, as well as adjustments to the LS-DYNA model of the missile.

The revised missile design was then used in the second rigid wall impact test, which verified the missile design is successful. The measured impact force time history reasonably matched and bounded the target time history that accounts for various effects of the scale test condition. Therefore, it was concluded that the improved missile design satisfies the regulatory requirement, ensuring a conservative HI-STAR 180 aircraft crash scale test under the same missile impact condition. Moreover, the revised LS-DYNA missile model was able to simulate the rigid wall test by reasonably reproducing the impact force time history and rigid wall responses. A validated numeric missile model is therefore available to simulate the HI-STAR 180 aircraft crash accident scale test.

Figure 2 shows a picture of the missile, as taken during the test.

Phase 2: Missile Impact on Cask

At the beginning of the second phase of this program, the location of the impact on the cask that would maximize the propensity for leakage was the key area of investigation. After a number of impact simulations using LS-DYNA, the most critical angle and location of impact were identified to be the 75% partial horizontal impact at the top of the cask as it resulted in the maximum Von Mises stress in the inner closure lid bolts. However, for satisfying the aircraft impact area requirement and for conservatism, the full horizontal impact (i.e., the top of the missile flush with the top of the ACC) was considered by the test program. In order to envelope the maximum Von Mises stress in the inner lid bolts determined for the 75% partial impact case, an impact velocity higher than that specified by the regulation was used. Thus the velocity of the incident missile was increased from 215 m/s to 230 m/s and the impact missile was made flush with the top of the ACC (full area impact) in the scale model test. This change conservatively resulted in an increase in the impact energy applied to the test cask compared to the regulations.

The HI-STAR 180 scale model aircraft crash test was carried out at the APG L Field in 2013. The heavily instrumented test cask, initially staged on a rigid steel platform, was symmetrically impacted by the calibrated missile accelerated along the rail by a rocket-propelled sled. The missile successfully hit the target point on the test cask, which took off from the platform and landed in the cask catch box as expected. Figure 3 shows the missile and the cask just prior to the missile impact. Figure 4 shows the situation directly after the test, with the cask in the catch box. The first step in validating the test was to ensure that the impact was indeed bounding. As the data in Table 1 confirms, both the velocity of impact and the mass of the missile are greater than the specified minimum for the test. In particular, the total kinetic energy delivered to the target by virtue of the increased incident velocity alone is 60% greater than the regulatory prescribed value and 40% greater than the missile qualification rigid wall impact test value. Furthermore, as reported in Table 1, this increased kinetic energy was delivered to the prototype cask in 20.2 millisecond compared to the target duration of 18.5 milliseconds, a 9% increase. Thus it concluded that the impulse input to the prototype was substantially larger than that required by Swiss regulations.

Table 1: Key Data for the Simulated Aircraft Crash Test

Parameter	Minimum Required	Actual Value in the Test
Weight of the missile, kg	481	490
Incident velocity at impact, m/s	230	273
Duration of impulse, ms	18.5	20.2

The built-in conservatisms of the test program described above considerably increased the risk of potential loss of sealing function in the bolted joint and the overall stress levels in the test cask, which further bolster the safety conclusions drawn by the test program.

The measured data from the aircraft crash scale model test and the corresponding LS-DYNA simulation provide the following significant information:

a. The post-impact helium leak test showed the leak rate to be a factor of 1000 less than the target value.
b. The axial stress in the enclosure lid bolts remained in the elastic range just as predicted by the LS-DYNA simulation, and the LS-DYNA predicted bolt stress bounds the measured stress obtained from the test. The length of the bolts measured after the impact showed no sign of stretching.

c. Based on measured leakage rate it is concluded that the seal did not undergo any significant unloading (zero contact force at the “land” of the gasket joint), whereas the LS-DYNA solution indicated a transient, albeit small, unloading of the “land”. This difference speaks to the conservatism built into the LS-DYNA solution.
d. The LS-DYNA prediction of the cask kinematic response to the missile impact conservatively bounds and reasonably matches the measured data of the cask peak accelerations.
e. There is no measurable permanent ovalization of the cask’s flange although local indentations and scratches at the interface between the ACC and the top flange occurred.
f. Stresses of the cask containment boundary main body remained in the elastic range at all times, and the LS-DYNA predicted stresses bound the measured stresses obtained from the aircraft crash test.
g. There was no damage to the cask that would impact shielding effectiveness.
h. Inspection of the gap between the flange and the primary lid measured at the locations of direct impact and 180 degree across showed that the lid did not move laterally with respect to the flange at all. This means that the bolts are not subject to any post-impact bending action that would occur if the lid were to slide.

Conclusions

The above results, considered in light of the conservatism in the missile design and the large margin in the kinetic energy delivered during the test, provide the assurance that the HI-STAR 180 cask would withstand the postulated aircraft crash event specified by the regulations with ample safety margin. In a broader sense, the comparison of the test data with the LS-DYNA simulation of the test demonstrates the ability of LS-DYNA to predict the consequence of an aircraft strike on a metal cask’s containment boundary performance. The LS-DYNA simulation approach can therefore be used as an alternative to the physical test for Holtec’s metal casks with similar lid joint geometry under a hypothetical aircraft crash event to predict the behavior of containment boundary lid bolts for leak tightness evaluation and for predicting the overall cask body kinematic responses.

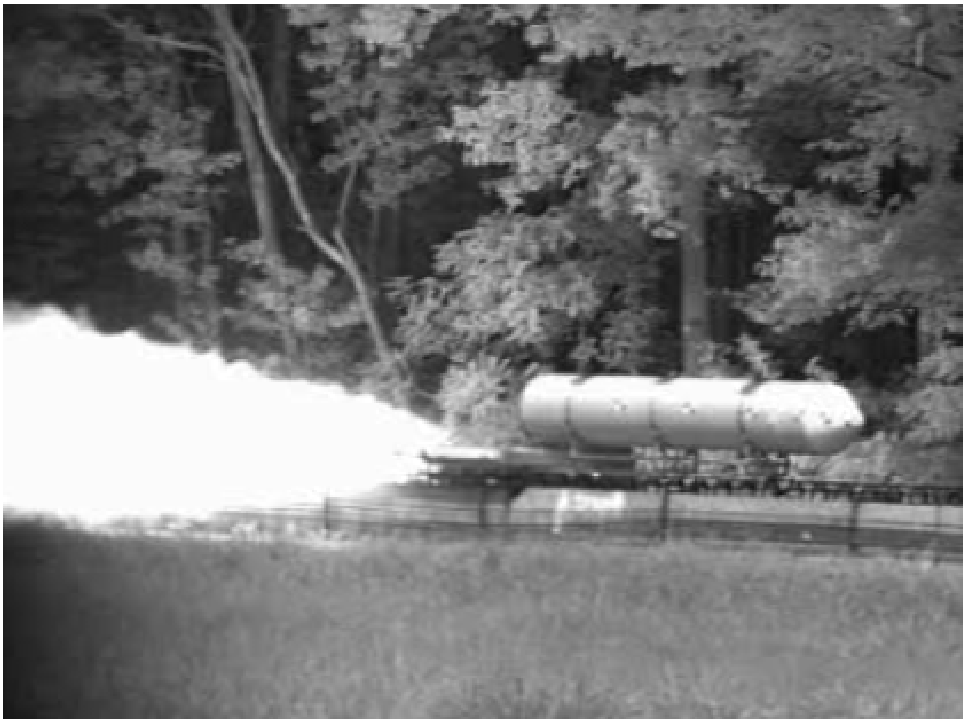

Figure 2 Missile Carried by the Rocket Propelled Sled

Figure 3 Missile just before Impact on Cask

Figure 4 Cask in the catch box after Impact: Good Alignment of the Final Location of the Impacted Cask with the Rail Due to a Symmetric Impact by the Missile

References

[1] HSK-R-102/e, Regulatory Guide for Swiss Nuclear Installations, “Design Criteria for the Protection of Safety Equipment in Nuclear Power Stations against the Consequences of Airplane Crash”, January 1993

[2] LS-DYNA, Version 971 R5.0, Livermore Software Technology