Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
SAND2016-8508C
PATRAM 2016

September 18-23, 2016, Kobe, Japan

Paper No. 2054

Explicit Transient Dynamic Finite Element Analyses Supporting the Certification of ENSA's ENUN 24P Spent Nuclear Fuel Transportation Package

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Abstract

Equipos Nucleares, S.A. (ENSA) has contracted with Sandia National Laboratories (SNL) to design the impact limiters for the ENUN 24P pressurized water reactor (PWR) spent nuclear fuel transportation package. A new analysis methodology, based on a previously developed methodology utilized in the certification of the ENSA ENUN 32P package, was employed to assess the performance of the impact limiters for the ENUN 24P package. Benchmarking of the revised methodology was completed utilizing data from the 1/3 scale ENUN 32P drop tests performed at SNL in 2010. Using the new methodology, a total of 83 analyses were performed in support of the certification of the ENUN 24P package, demonstrating its compliance with applicable regulations.

Introduction

The ENUN 24P is a package intended for the storage and transportation of pressurized water reactor (PWR) spent nuclear fuel assemblies. U.S. Federal and international regulations [1-3] stipulate safety performance requirements applicable to the ENUN 24P package. These regulations require that a spent nuclear fuel package be robust enough to limit the amount of hazardous material that might be released to the environment when the cask assembly is subjected to a variety of normal conditions of transport (NCT) and hypothetical accident condition (HAC) scenarios. The most severe NCT and HAC scenarios with respect to the design of the cask and impact limiters are the 0.3 m and 9.0 m drop cases, respectively.

SNL has worked previously with ENSA on the design of the impact limiters for the ENSA ENUN 32P and ENUN 52B packages [4-7]. For the ENUN 32P design, finite element analysis (FEA) were performed in conjunction with 1/3 scale drop tests [8] to demonstrate the design adequacy of the

ENUN 32P. In contrast, the establishment of the ENUN 24P package's performance for certification has been accomplished through a purely modeling and simulation approach [9-11]. To demonstrate that the methodology employed for the ENUN 24P is conservative, and appropriate for analyses supporting the design certification, the methodology has been benchmarked against the previously performed 1/3 scale ENUN 32P drop testing data.

ENUN 24P Cask Description

The ENUN 24P spent nuclear fuel transportation package is comprised of a metallic cylindrical cask (with neutron shielding), two impact limiters, and contents which include up to 24 PWR fuel assemblies secured in a basket (Figure 1). The package has a total length of about 7.9 m, outer diameter of about 3.3 m, and a fully loaded mass of approximately 120,000 kg. The cask makes use of countersunk trunnions located on opposite sides of the cask body.

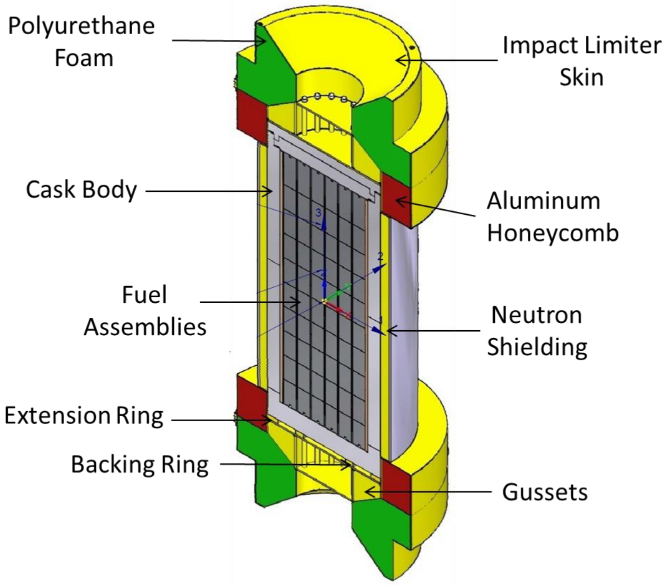


Figure 1 ENUN 24P Major Components.

Impact limiters protect the cask during drop and impact events. Each is comprised of a thin stainless steel shell that encloses a ring of aluminum honeycomb and a volume of polyurethane foam. Both impact limiters have an outer diameter of about 3.3 m and overall length of about 1.9 m. The mass of each impact limiter is about 7000 kg. The impact limiter skin is comprised of both 6.0 mm and 25.0 mm thick plates of carbon or stainless steel. Each impact limiter has 16 carbon steel gusset plates that provide structural rigidity to the impact limiter skin in the vicinity of the attachment bolts and that provide structural support to the ring of aluminum honeycomb material. The aluminum honeycomb energy absorbing material is Trussgrid and the polyurethane foam is Last-A-Foam.

Certification Methodology

The methodology employed for the ENUN 24P package certification analyses was designed to conservatively assess the response of the package when subjected to the range of potential NCT and

HAC drop or impact scenarios. For each impact scenario, two model configurations (designated as either stiff/strong or soft/weak) were considered. These model configurations were selected to represent possible (although potentially unlikely) configurations of the package that will produce bounding response quantities.

The stiff/strong model is configured so that the response of the impact limiters will be at the upper limits of their possible range in stiffness and strength, thus producing the highest cask accelerations and impact limiter attachment bolt stresses. The soft/weak model is configured so that the response of the impact limiters will be at the lower limits of their possible range in stiffness and strength, thus producing the largest amounts of crush in the impact limiters. The configuration (stiff/strong or soft/weak) determines several characteristics of the model, specifically package component temperatures, impact limiter aluminum honeycomb and polyurethane foam strength adjustment factors, and bond configuration between the honeycomb and foam, between the foam and shell, and between the honeycomb and shell.

Two temperature cases are considered, “cold” and “hot”. For the cold temperature case all components of the package are assumed to be at -40 °C. For the hot case, the package components are at temperatures consistent with the regulatory worst case hot conditions (including internal heat generation). Because higher material temperatures are associated with lower material stiffnesses and strengths, the hot temperature case is associated with the soft/weak model configuration, and the cold temperature case with the stiff/strong model configuration.

The crush strength adjustment parameters used for the aluminum honeycomb and polyurethane foam for each case are based on data obtained from the material suppliers or test data acquired by ENSA. For the stiff/strong configuration, the properties used in the model are consistent with each material’s highest plausible crush strength. In contrast, for the soft/weak configuration, the properties used are consistent with each material’s lowest plausible crush strength. The strength adjustment is achieved in the model by applying strength modification factors to the volumetric hardening curves for each material.

In each impact limiter, a bond exists between the foam and honeycomb, between the foam and shell, and between the honeycomb and shell. Because the integrity of each of these bonds is not known (especially over time), two bond configurations are considered in the model, fully bonded and completely unbonded. The stiff/strong model configuration assumes fully bonded, whereas the soft/weak model configuration assumes completely unbonded.

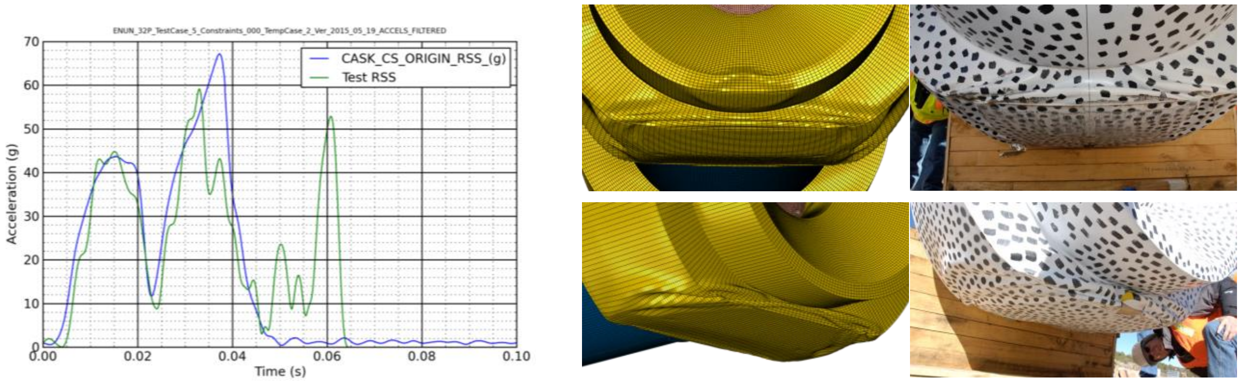
The foam material is anisotropic. The material’s response depends on whether the material is crushed perpendicular to the foam rise direction, or parallel to the foam rise direction. An isotropic material model is used to represent the foam material’s response, but for impact angles of 0 degrees (side-on) up to 45 degrees (corner), perpendicular-to-rise parameters are used because the foam material is largely compacted (crushed) in that direction and for impact angles of 45 degrees (corner) up to 90 degrees (end-on), parallel-to-rise parameters are used because the foam material is largely compacted (crushed) in that direction.

Benchmarking of Methodology

Data obtained from the 1/3 scale ENUN 32P package drop tests was utilized to benchmark the methodology. The ENUN 32P package is sufficiently similar in design (identical materials and similar design concept) to provide a useful dataset against which to benchmark the methodology. The drop tests were performed in November of 2010 at SNL and used a 1/3 scale ENUN 32P cask assembly [8]. In the tests, the package was dropped from two heights (a 0.3 m NCT drop and five 9.0 m HAC drops), at four different angles of impact (0° side-on, 90° end-on, 10° slap-down, and 71° center-of-gravity-over-corner), and with the package components at two different temperatures (cold, about -29 °C, and hot, about 100 °C). Table 1 summarizes the characteristics and pertinent package response metrics for each test.

A finite element model representing the 1/3 scale ENUN 32P test article was created using the same approach and input parameters utilized in the ENUN 24P model [10, 11]. A series of analyses representing the test case scenarios were performed using this model following the upper and lower bound (stiff/strong and soft/weak) methodology described above. A comparison was then made between the test measured and simulation produced response metrics of interest. Table 1 summarizes and compares the critical response metrics from both the tests and analyses. Note, in the table "T" designates a test and "A" designates an analysis, similar tests and analyses are grouped together, and quantities highlighted in yellow represent the critical package response quantity comparisons of interest. Figure 2 illustrates a typical model result.

For the analysis model/methodology to be conservative, the model response for the quantities highlighted in Table 1 need to be greater than the corresponding response observed in the test. For all possible comparisons, the model/methodology is conservative, over predicting the cask center-of-gravity acceleration by at least 8.1% and over predicting the amount of crush by at least 18.8%. Based on these findings, it was concluded that the analysis model/methodology is generally conservative.



(a) Cask C.G. Acceleration Time-Histories

(b) Impact Limiter Deformations

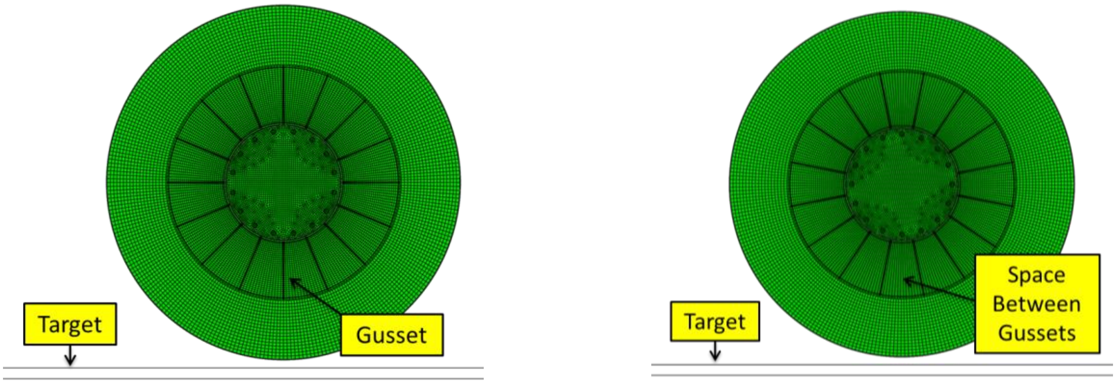
Figure 2 A4-Soft/Weak Analysis Results Comparison vs. T5 (Hot) Test Data.

Table 1 Comparison of Finite Element Analysis Results with Drop Test Data.

Analysis Case or Test ID	Drop Height (m)	Orientation	Assembly Mass (kg)	Assembly Temp. (°C)	Cask C.G. Accel. (g)	Crush Lid End (mm)	Crush Body End (mm)
A1 Stiff/Strong	0.3	Side-On 0°	5024.2	-28.9	**52.1** (+70.0%)	10.6	9.5
T1			5116.5	-30.3	**30.6**	9.0	7.0
-			-	-	-	**No Data**	**No Data**
A1 Soft/Weak			5024.2	100.0	31.9	**16.3** (N/A)	**16.1** (N/A)
A2 Stiff/Strong	9.0	Side-On 0°	5024.2	-28.9	**171.4** (+28.9%)	84.1	81.6
T2			5116.5	-30.2	**133.0**	110.0	58.0
-			-	-	-	**No Data**	**No Data**
A2 Soft/Weak			5024.2	100.0	102.7	**136.1** (N/A)	**134.1** (N/A)
A3 Stiff/Strong	9.0	End-On 90° Lid End Trailing	5024.2	-38.4	**119.1** (+20.9%)	88.4	0.0
T3			5154.5	-38.4	**98.5**	117.0	0.0
-			-	-	-	**No Data**	**No Data**
A3 Soft/Weak			5024.2	100.0	68.8	**205.5** (N/A)	**0.0** (N/A)
A4 Stiff/Strong	9.0	Slap-Down 10° Lid End Trailing	5024.2	-34.2	**94.6** (+8.1%)	79.9	46.7
T4			5127.3	-34.2	**87.5**	108.0	75.0
T5			5127.3	103.0	59.2	**112.0**	**59.0**
A4 Soft/Weak			5024.2	103.0	67.2	**133.0** (+18.8%)	**98.9** (+67.8%)
A5 Stiff/Strong	9.0	C.G. Over Corner 71° Lid End Trailing	5024.2	-28.9	**97.8** (N/A)	204.1	0.0
-			-	-	**No Data**	-	-
T6			5127.3	96.1	75.3	**252.0**	**0.0**
A5 Soft/Weak			5024.2	96.1	65.0	**350.5** (+39.1%)	**0.0** (N/A)

Certification Analyses

A total of 83 analyses were performed using the commercially available finite element analysis software Abaqus/Explicit [12] in support of the ENUN 24P certification. The set of analyses chosen is intended to investigate the range of potential NCT/HAC drop/impact scenarios sufficiently, so as to identify all controlling worst case accident scenarios. Impact angles ranging from -90° (end-on impact with lid end of cask leading) to +90° (end-on impact with lid end of cask trailing) were investigated. For each impact angle considered, rotation angles of 0° and 11.25° were investigated (Figure 3). For each impact angle and rotation angle combination, several cases (1 and 3; 2 and 4; or 1, 2, 3, and 4) were considered. Cases 1 and 2 designate a soft/weak model configuration, and cases 3 and 4 designate a stiff/strong model configuration. Cases 1 and 3 make use of perpendicular-to-rise foam material properties, whereas cases 2 and 4 make use of parallel–to-rise properties.



(a) Rotation Angle = 0°, Gusset Aligned with Target.

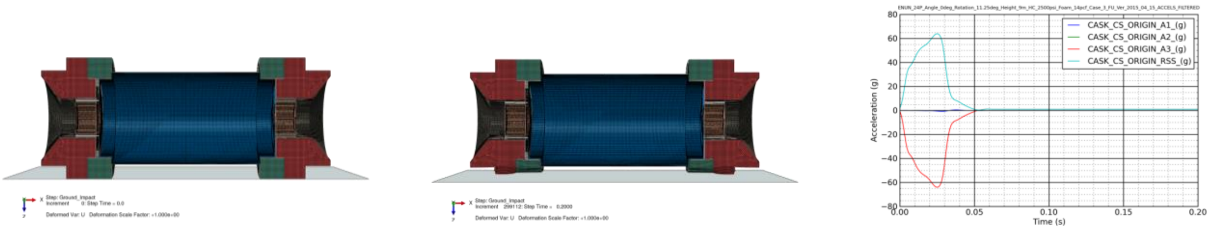
(b) Rotation Angle = 11.25°
Space Between Gussets Aligned with Target.

Figure 3 Rotation Angles.

Table 2 summarizes results from the most critical cases considered (yellow highlighting) as well as from scenarios typically considered in package certification analyses (blue highlighting). For each of the critical scenarios, the critical metric is indicated by red highlighting. The table includes cask center-of-gravity acceleration and cask end accelerations (each filtered with a 100 Hz low-pass Butterworth filter), amount of clearance maintained between the cask and target surface, and maximum impact limiter attachment bolt stress. Figure 4 shows the resulting package deformation and critical metric time histories for each of the critical cases. The 1/3 scale ENUN 32P testing and additional cask analyses have demonstrated that if the cask center-of-gravity acceleration is kept below 65.0 g and the cask lid end accelerations are kept below 100 g, the containment function of the cask will not be compromised. All cases considered were below these limits.

Table 2 Certification Analyses Results Summary.

Run #	Case Number	Hot/Cold	Foam Properties Para./Perp.	Drop Height	Impact Angle	Rotation Angle	Max RSS Accel. Cask CG	Max RSS Accel Cask Ends	Minimum Clearance to Target	Max Bolt Stress		
				m	deg.	deg.	g	g	mm	Pa	Ratio to Yield	Ratio to Ult.
1	3	Cold	Perp.	0.3	0	0	19.4	19.5	364.94	2.6708E+08	0.77	0.30
4	3	Cold	Perp.	9	0	11.25	64.0	64.6	166.87	2.8867E+08	0.84	0.33
38	1	Hot	Perp.	9	0	0	42.4	43.2	49.74	2.8194E+08	0.82	0.32
32	1	Hot	Perp.	9	-4	11.25	33.0	66.4	22.32	2.9245E+08	0.85	0.33
25	3	Cold	Perp.	9	-8	11.25	37.2	91.5	156.06	3.4800E+08	1.01	0.39
68	3	Cold	Perp.	9	10	0	34.2	97.7	163.01	3.4671E+08	1.00	0.39
65	3	Cold	Perp.	9	12	0	32.1	97.7	167.44	3.4608E+08	1.00	0.39
45	1	Hot	Perp.	9	45	0	21.2	32.3	409.94	3.4666E+08	1.00	0.39
48	4	Cold	Para.	9	45	0	24.5	39.3	638.38	2.6030E+08	0.75	0.30
55	2	Hot	Para.	9	72	0	25.3	26.9	620.09	2.5618E+08	0.74	0.29
57	4	Cold	Para.	9	72	11.25	34.0	35.3	876.04	2.6825E+08	0.78	0.30
10	2	Hot	Para.	9	90	0	21.4	21.4	969.18	2.4849E+08	0.72	0.28
11	4	Cold	Para.	9	90	0	39.5	39.5	1229.96	2.5666E+08	0.74	0.29

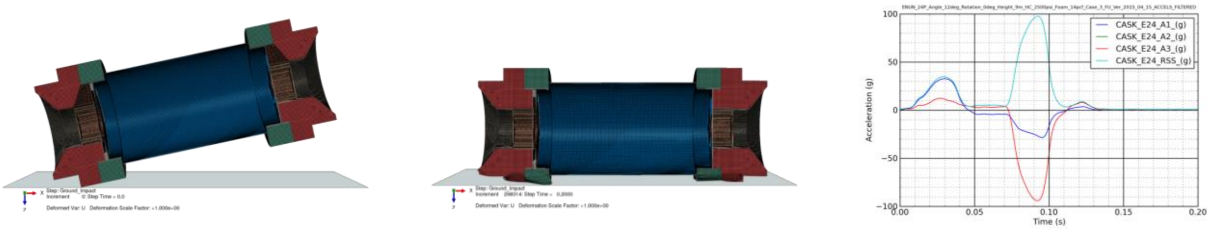


Time = 0 ms

Time = 200 ms

Cask C.G. Accelerations

(a) Run #4 – Maximum Cask Center-of-Gravity Acceleration Case

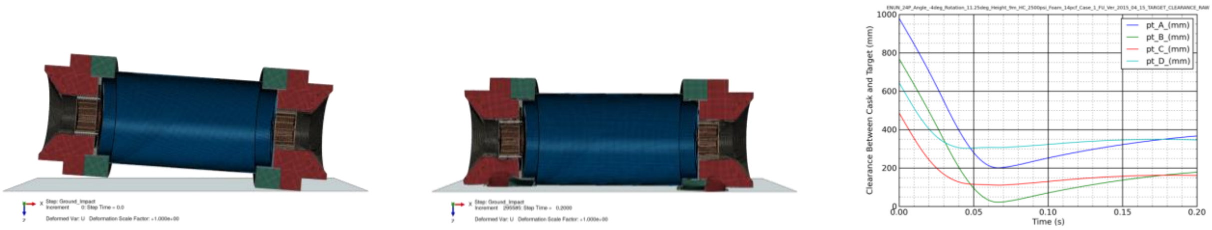


Time = 0 ms

Time = 200 ms

Cask End Accelerations

(b) Run #65 – Maximum Cask End Acceleration Case

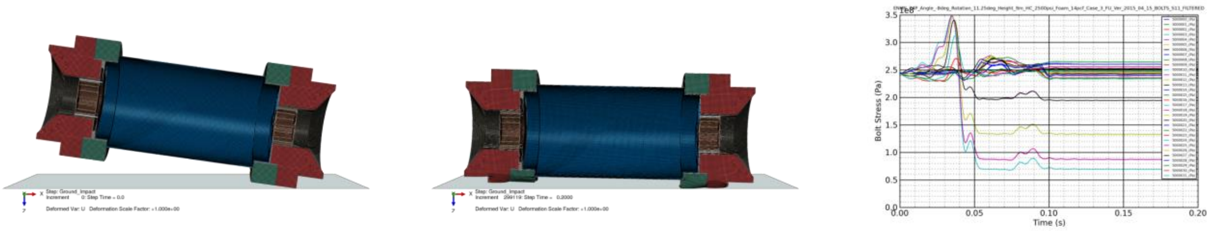


Time = 0 ms

Time = 200 ms

Cask-to-Target Clearance

(c) Run #32 – Minimum Cask-to-Target Clearance Case



Time = 0 ms

Time = 200 ms

Attachment Bolt Stresses

(d) Run #25 – Maximum Attachment Bolt Stress Case

Figure 4 Critical Analysis Case Results.

Summary and Conclusions

Benchmarking of the methodology employed in the certification analyses of the ENUN 24P spent nuclear fuel package against test data obtained during the 1/3 scale drop testing of the ENUN 32P showed the model/methodology to be conservative. Using the benchmarked modeling methodology, a total of 83 certification analyses were performed for the ENUN 24P. Results from the analyses performed indicate that the ENUN 24P impact limiters and attachment bolts meet all of the requirements specified by ENSA for their performance with respect to the 9 m HAC drop scenarios outlined in the U.S. Federal and international regulations.

Acknowledgments

The authors would like to acknowledge Equipos Nucleares, S.A. (ENSA), the sponsors of this work, and specifically David Garrido Quevedo in his role as ENSA program manager.

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