Exelon Generation Company, LLC
1400 Opus Place
Downers Grove, IL 60515-5701

www.exeloncorp.com

Exelon Nuclear

10 CFR 72.7

RS-01-025

February 16, 2001

U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D.C. 20555-0001

Dresden Nuclear Power Station, Units 1 and 2
Facility Operating License Nos. DPR-2 and DPR-19
NRC Docket Nos. 50-10, 50-237, and 72-37

Subject: Request for Additional Information for the HI-STORM 100 Cask System Exemption Request

References:

(1) Letter from R. M. Krich (Exelon Generation Company, LLC) to US NRC, "Request for Exemption from 10 CFR 72.212, 'Conditions of general license issued under 10 CFR 72.210,' and 10 CFR 72.214, 'List of approved spent fuel storage casks,' Regarding the Conditions of Use for the HI-STORM 100 Cask System and for the HI-STAR 100 Cask System," dated January 11, 2001

(2) Letter from R. M. Krich (Exelon Generation Company, LLC) to US NRC, "Request for Exemption from 10 CFR 72.212, 'Conditions of General license issued under 10 CFR 72.210,' and 10 CFR 72.214, 'List of approved spent fuel storage casks,' Regarding the Conditions of Use for the HI-STORM 100 Cask System," dated January 11, 2001

(3) Letter from C. P. Jackson (US NRC) to R. M. Krich (Exelon Generation Company, LLC), "Dresden Independent Spent Fuel Storage Exemption Requests," dated January 29, 2001

In the Reference 1 and Reference 2 letters, in accordance with 10 CFR 72.7, "Specific exemptions," we requested NRC approval of a temporary exemption from the requirements of 10 CFR 72.212, "Conditions of general license issued under 10 CFR 72.210," and 10 CFR 72.214, "List of approved spent fuel storage casks," for the HI-STORM 100 cask system produced by Holtec International, Inc. (i.e., Holtec).

In the Reference 3 letter, we were requested to provide additional information related to the HI-STORM 100 exemption request. The additional information is provided in the enclosure to this letter.

NM1SS01 Public

If you have any questions about this letter, please contact K. M. Root at (630) 663-7292.

Respectfully,

R. M. Krich
Director - Licensing
Mid-West Regional Operating Group

Enclosure - Additional Information Related to the HI-STORM 100 Cask System Exemption Request

ENCLOSURE

Additional Information Related to the HI-STORM 100 Cask System Exemption Request

References:

(1) Letter from R. M. Krich (Exelon Generation Company, LLC) to US NRC, "Request for Exemption from 10 CFR 72.212, 'Conditions of general license issued under 10 CFR 72.210,' and 10 CFR 72.214, 'List of approved spent fuel storage casks,' Regarding the Conditions of Use for the HI-STORM 100 Cask System and for the HI-STAR 100 Cask System," dated January 11, 2001

(2) Letter from R. M. Krich (Exelon Generation Company, LLC) to US NRC, "Request for Exemption from 10 CFR 72.212, 'Conditions of General license issued under 10 CFR 72.210,' and 10 CFR 72.214, 'List of approved spent fuel storage casks,' Regarding the Conditions of Use for the HI-STORM 100 Cask System," dated January 11, 2001

(3) Letter from C. P. Jackson (US NRC) to R. M. Krich (Exelon Generation Company, LLC), "Dresden Independent Spent Fuel Storage Exemption Requests," dated January 29, 2001

(4) Holtec International, Inc. letter, "USNRC Docket No. 72-1014; HI-STORM 100 Certificate of Compliance 1014; HI-STORM 100 License Amendment Request 1014-1, Revision 1, Supplement 1," dated October 6, 2000

In the Reference 1 and Reference 2 letters, in accordance with 10 CFR 72.7, "Specific exemptions," we requested NRC approval of a temporary exemption from the requirements of 10 CFR 72.212, "Conditions of general license issued under 10 CFR 72.210," and 10 CFR 72.214, "List of approved spent fuel storage casks," for the HI-STORM 100 cask system produced by Holtec International, Inc. (i.e., Holtec).

In the Reference 3 letter, we were requested to provide additional information related to the HI-STORM 100 exemption request. The additional information is provided below.

<u>CASK PAD PARAMETERS</u>

We were requested to provide the revised impact analysis with the new cask pad parameters showing acceptable results for the design events (i.e., the design basis drop and tip-over events). The revised impact analysis, which was previously provided in the Reference 4 letter, is provided in the attachment to this enclosure.

Certificate of Compliance (CoC) No. 1014, Appendix B, "Approved Contents and Design Features for the HI-STORM 100 Cask System," Design Features 3.4, "Site-Specific Parameters and Analyses," specifies, in part, the requirements for the strength of the concrete storage pads upon which the HI-STORM 100 casks will be placed. In the

Reference 4 letter and in the revised impact analysis, these requirements are referred to as "Parameter Set A."

As discussed in Reference 1 and in the revised impact analysis, a second set of requirements for the strength of the concrete storage pads has been developed by Holtec that includes a thinner concrete pad, a higher concrete compressive strength, and a less stiff subgrade. In the Reference 4 letter and in the revised impact analysis, these requirements are referred to as "Parameter Set B."

In lieu of the concrete strength requirements currently specified in Design Features Item 3.4.6.b (i.e., Parameter Set A), we are proposing to use Parameter Set B. A comparison of the concrete strength requirements currently specified in Design Features Item 3.4.6.b, the Parameter Set B limits, and the Dresden Nuclear Power Station (DNPS), Unit 1 concrete storage pads parameters is provided below.

Cask Storage Pads and Foundation Characteristics	HI-STORM CoC 1014, Design Features 3.4.6.b (and HI-STORM Final Safety Analysis Report (FSAR), Proposed Rev. 1 (Ref. 4), Parameter Set A)	HI-STORM FSAR, Proposed Rev. 1, Parameter Set B (Ref. 4)	DNPS, Unit 1 Cask Storage Pads
Concrete Thickness (inches)	≤ 36	≤ 28	24
Concrete Compressive Strength (psi at 28 days)	≤ 4,200	≤ 6,000	5020 (worst case)
Reinforcement Top and Bottom (ksi)	60	60	60
Soil Effective Modulus of Elasticity (psi)	≤ 28,000	≤ 16,000	13,000

For the HI-STORM 100 cask system, the concrete storage pads must be designed such that all design basis drop and non-mechanistic tip-over events on the pads result in a HI-STORM cask deceleration of ≤ 45 g at the top of the fuel basket. Using the same methodology previously approved by the NRC for the HI-STORM cask system, we have determined that all sections of the installed DNPS concrete pads are bounded by the revised impact analysis, i.e., by the Parameter Set B design parameters. The Parameter Set B design parameters limit cask deceleration values for design basis drop and non-mechanistic tip-over events to ≤ 45 g at the top of the fuel basket such that no structural failure of the cask system will occur after a postulated design basis drop or non-mechanistic tip-over event. The maximum cask deceleration value at the top of the fuel basket for the design basis drop event is 41.53 g for the Parameter Set B design parameters. The maximum cask deceleration value at the top of the fuel basket for the design basis non-mechanistic tip-over event is 39.91 g for the Parameter Set B design parameters.

SPENT FUEL STORAGE CASK HEAT REMOVAL SYSTEM

In the Reference 2 letter, we identified an issue regarding the potential for the Limiting Condition for Operation (LCO) 3.1.2, "SFSC Heat Removal System," in CoC No. 1014, Appendix A, "Technical Specifications for the HI-STORM 100 Cask System," to not be met as a result of the DNPS design basis flooding accident. However, we are pursuing a means by which blockage of the cask inlet ducts would not result in the Spent Fuel Storage Cask (SFSC) Heat Removal System being inoperable for longer than the Completion Times of LCO 3.1.2 in the event of a design basis flooding accident at DNPS. Therefore, since the Completion Times of LCO 3.1.2 can be met in the event of a design basis flooding accident at DNPS, we are withdrawing this element of the previously submitted exemption request.

FUEL ASSEMBLY CHARACTERISTICS

We were requested to provide the following additional information regarding the Boiling Water Reactor (BWR) fuel assembly characteristics for those fuel assembly parameter limits specified in the Reference 2 letter.

- An explanation with a basis for why the revised fuel characteristics are within the bounds of the analysis performed for the currently approved fuel characteristics,
- For the fuel characteristics that are not bounded by the existing analysis used for the currently approved fuel, confirm that the revised analysis was performed using a previously NRC reviewed and approved methodology,
- For the fuel characteristics that are not bounded by the existing analysis used for the currently approved fuel, specify the revised analysis result and demonstrate all applicable acceptance criteria are met.

Table 2.1-3, "BWR Fuel Assembly Characteristics," in CoC No. 1014, Appendix B, specifies, in part, the fuel assembly parameters for fuel assembly array/classes 6x6A, 6x6B, and 8x8A.

Increased Maximum Design Initial Uranium Mass

Some of the DNPS, Unit 1 fuel assemblies have design initial uranium masses slightly above the specified limit (i.e., ≤ 108 kg/assembly), including the tolerance allowed by Table 2.1-3 Note 3, for the fuel assembly array/classes 6x6A and 6x6B.

In lieu of the maximum design initial uranium mass currently specified in Table 2.1-3, we are proposing to use a maximum design initial uranium mass of ≤ 110 kg/assembly including the tolerance allowed by Table 2.1-3 Note 3, which will envelop these DNPS, Unit 1 fuel assemblies. The following provides the basis for why this proposed revision to the maximum design initial uranium mass is within the bounds of the analysis performed for the currently approved fuel assembly characteristics.

- Structural Evaluation

  Increasing the limit for the design initial uranium mass to ≤ 110 kg/assembly does not increase the weight of the contents or the cask. Therefore, the proposed change does not affect the existing structural evaluation.

- Thermal Evaluation

  Increasing the limit for the design initial uranium mass to ≤ 110 kg/assembly does not increase the decay heat load or change the heat transfer characteristics of the cask. Therefore, the proposed change to the maximum design initial uranium mass is bounded by the existing thermal analysis for previously approved contents.

- Shielding Evaluation

  The limit for the design initial uranium mass was increased to a value slightly less than the value used in the existing shielding analysis. Therefore, no further evaluation is required since a greater value has already been analyzed and found acceptable.

- Criticality Evaluation

  The uranium mass limits in the CoC are determined from the shielding analysis, and are specified as bounding values for groups of fuel classes (e.g. all Babcock & Wilcox 15x15 fuel assemblies). The criticality analyses are based on an independent bounding assumption of a fuel stack density of 96.0% of the theoretical fuel density of 10.96 g/cm^3. The fuel stack density is approximately equal to 98% of the pellet density. Therefore, while the pellet density of some fuels might be slightly greater than 96% of theoretical, the actual stack density will be less. For some fuel classes, this density assumption results in a uranium mass for the criticality analyses that is below the value shown in the CoC. However, this only indicates the conservatism of the shielding analysis for these classes. The criticality analyses are still valid and bounding for all classes, due to the fuel stack density assumption stated above, which is valid for current and future fuel assemblies.

- Confinement Evaluation

  Increasing the initial uranium mass does not increase the confinement source terms or change the design and operation of the confinement system. Therefore, the contents and the content limits are bounded by the confinement analysis for previously approved contents.

Revised Fuel Assembly Parameter Limits

Some of the DNPS, Unit 1 fuel assemblies do not meet the current limits for fuel rod clad inner diameter (ID), fuel pellet diameter, fuel rod pitch, active fuel length, number of fuel rod locations, number of water rods, and water rod thickness specified in Table 2.1-3.

In lieu of the fuel assembly parameter limits currently specified in Table 2.1-3, we are proposing to use the following limits, which will envelop the characteristics of those DNPS, Unit 1 fuel assemblies.

Fuel assembly array/class 6x6A fuel rod clad ID ≤ 0.5105 inches
Fuel assembly array/class 6x6A fuel pellet diameter ≤ 0.4980 inches
Fuel assembly array/classes 6x6A and 6x6B fuel rod pitch ≤ 0.710 inches
Fuel assembly array/classes 6x6A, 6x6B, and 8x8A active fuel length ≤ 120 inches
Fuel assembly array/classes 6x6A and 6x6B number of fuel rod locations "35 or 36"
Fuel assembly array/class 8x8A number of fuel rod locations "63 or 64"
Fuel assembly array/classes 6x6A, 6x6B, and 8x8A number of water rods "1 or 0"
Fuel assembly array/classes 6x6A, 6x6B, and 8x8A water rod thickness ≥ 0 inches

The following provides the basis for why this proposed revision to the fuel assembly parameter limits is within the bounds of the analyses performed for the currently approved fuel assembly characteristics.

- Structural Evaluation

  The proposed changes to the fuel assembly parameter limits do not increase the weight of the contents or the cask. Therefore, the proposed changes do not affect the existing structural evaluation.

- Thermal Evaluation

  The proposed changes to the fuel assembly parameter limits do not increase the decay heat load or change the heat transfer characteristics of the cask. Therefore, the proposed changes to the fuel assembly parameter limits are bounded by the existing thermal analyses for previously approved contents, with the exception noted below.

  Increasing the fuel rod clad ID resulted in a thinner cladding for the fuel assembly array/class 6x6A, which required a revision to the thermal analysis for this array/class. The revised thermal analysis for the fuel assembly array/class 6x6A was performed using a previously NRC reviewed and approved methodology. The bounding fuel cladding stress for the fuel assembly array/class 6x6A "thin clad" (i.e., fuel assembly array/class 6x6A with the thinner cladding) increased from 65.3 MPa to 94.1 MPa, resulting in a decrease in the peak cladding temperature limits as shown below.

Cooling Time (years)	6x6A Peak Clad Temperature Limit (°C)	6x6A "Thin Clad" Peak Clad Temperature Limit (°C)
5	394.4	383.7
6	379.2	370.9
7	354.8	347.7
10	348.8	342.1
15	342.1	334.9

Therefore, these revised peak cladding temperature limits for the fuel assembly array/class 6x6A remain above the peak cladding temperatures calculated for the fuel assemblies in long term storage, and therefore are acceptable.

- Shielding Evaluation

  The source term is dependent upon the uranium mass. The allowable mass loadings for the specified burnup and cooling times are not being changed as a result of these changes. Therefore, the proposed changes do not affect the shielding analysis and further evaluation is not required.

- Criticality Evaluation

  For the criticality evaluation, the fuel assemblies are grouped into assembly array/classes. For each assembly array/class, a theoretical bounding assembly is defined. Criticality calculations were performed to account for the modified dimensions for the bounding assembly in each array/class using the same methodology previously approved by the NRC for the HI-STORM cask system. The maximum k_{eff} for each of the affected array/classes only changed slightly because of the changes in the fuel assembly characteristics. Specifically, the maximum k_{eff} for the 6x6A array/class increased from 0.7602 to 0.7888. The maximum k_{eff} for the 6x6B array/class increased from 0.7611 to 0.7824. The maximum k_{eff} for the 8x8A array/class increased from 0.7685 to 0.7697. Revised results show that the revised fuel assembly parameter limits do not change the bounding fuel assembly array/class for the BWR assemblies (i.e., fuel assembly array/class 10x10A, which has a k_{eff} value of 0.9448). The value for the maximum k_{eff} for each of the affected array/classes meets the k_{eff} of 0.95 acceptance criteria.

- Confinement Evaluation

  The proposed changes do not increase the confinement source terms or change the design and operation of the confinement system. Therefore, the contents and the content limits are bounded by the confinement analysis for previously approved contents.

ATTACHMENT

HI-STORM 100 Deceleration Under Postulated Vertical Drop and Tip-over Event

ATTACHMENT

HI-STORM DECELERATION UNDER POSTULATED VERTICAL DROP EVENT AND TIPOVER EVENT

A.1 INTRODUCTION

Handling accidents with a HI-STORM overpack containing a loaded MPC are credible events (HI-STORM 100 FSAR Section 2.2.3). The stress analyses carried out in Chapter 3 of the HI-STORM 100 Final Safety Analysis Report (FSAR) assume that the inertial loading on the load bearing members of the MPC, fuel basket, and the overpack due to a handling accident are limited by the HI-STORM 100 FSAR Table 3.1.2 decelerations. The maximum deceleration experienced by a structural component is the product of the rigid body deceleration sustained by the structure and the dynamic load factor (DLF) applicable to that structural component. The dynamic load factor (DLF) is a function of the contact impulse and the structural characteristics of the component. A solution for dynamic load factors is provided in HI-STORM 100 FSAR Appendix 3.X.

The rigid body deceleration is a strong function of the load-deformation characteristics of the impact interface, weight of the cask, and the drop height or angle of free rotation. For the HI-STORM 100 System, the weight of the structure and its surface compliance characteristics are known. However, the contact stiffness of the ISFSI pad (and other surfaces over which the HI-STORM 100 may be carried during its movement to the ISFSI) is site-dependent. The contact resistance of the collision interface, which is composed of the HI-STORM 100 and the impacted surface compliance, therefore, is not known a priori for a specific site. Analyses for the rigid body decelerations are, therefore, presented here using a reference ISFSI pad (which is the pad used in a recent Lawrence Livermore National Laboratory report and is the same reference pad used in the HI-STAR 100 TSAR). The finite element model (grid size, extent of model, soil properties, etc.) follows the LLNL report.

An in-depth investigation by the Lawrence Livermore Laboratory (LLNL) into the mechanics of impact between a cask-like impactor on a reinforced concrete slab founded on a soil-like subgrade has identified three key parameters, namely, the thickness of the concrete slab, t_p, compressive strength of the concrete f_c' and equivalent Young's Modulus of the subgrade E. These three parameters are key variables in establishing the stiffness of the pad under impact scenarios. The LLNL reference pad parameters, which we hereafter denote as Set A, provide one set of values of t_p, f_c' , and E that are found to satisfy the deceleration criteria applicable to the HI-STORM 100 cask. Another set of parameters, referred to as Set B herein, is also shown to satisfy the g-load limit requirements. In fact, an infinite number of combinations of t_p, f_c' , and E can be compiled that would meet the g-load limit qualification. However, in addition to satisfying the g-limit criterion, the pad must be demonstrated to possess sufficient flexural and shear stiffness to meet the ACI 318 strength limits under factored load combinations. The minimum strength requirement to comply with

ACI 318 provisions places a restriction on the lower bound values of t_p, f_c' , and E that must be met in an ISFSI pad design.

The focus, however, is to quantify the peak decelerations that would be experienced by a loaded HI-STORM 100 cask under the postulated impact scenarios for the two pad designs defined by parameter Sets A and B, respectively. The information presented also serves to further authenticate the veracity of the Holtec DYNA3D model described in the 1997 benchmark report [A.4.]

A.2 Purpose

The purpose is to demonstrate that the rigid body deceleration experienced by the HI-STORM 100 System during a handling accident or non-mechanistic tip-over are below the design basis deceleration of 45g's (HI-STORM 100 FSAR Table 3.1.2). Two accidental drop scenarios of a loaded HI-STORM 100 cask on the ISFSI pad are considered. They are:

i. Tipover: A loaded HI-STORM 100 is assumed to undergo a non-mechanistic tipover event and impacting the ISFSI pad with an incipient impact angular velocity, which is readily calculated from elementary dynamics.

ii. End drop: The loaded HI-STORM 100 is assumed to drop from a specified height h, with its longitudinal axis in the vertical orientation, such that its bottom plate impacts the ISFSI pad.

It is shown in HI-STORM 100 FSAR Appendix 3.X that dynamic load factors are a function of the predominate natural frequency of vibration of the component for a given input load pulse shape. Dynamic load factors are applied, as necessary, to the results of specific component analyses performed using the loading from the design basis rigid body decelerations. Therefore, it is desired to demonstrate that the rigid body deceleration experienced in each of the drop scenarios is below the HI-STORM 100 45g design basis.

A.3 Background and Methodology

In 1997 Lawrence Livermore National Laboratory (LLNL) published the experimentally obtained results of the so-called fourth series billet tests [A.1] together with a companion report [A.2] documenting a numerical solution that simulated the drop test results with reasonable accuracy. Subsequently, USNRC personnel published a paper [A.3] affirming the NRC's endorsement of the LLNL methodology. The LLNL simulation used modeling and simulation algorithms contained within the commercial computer code DYNA3D [A.6].

The LLNL cask drop model is not completely set forth in the above-mentioned LLNL reports. Using the essential information provided by the LLNL [A.2] report, however, Holtec is able to develop a finite element model for implementation on LS-DYNA3D [A.5] which is fully consistent with LLNL's (including the use of the Butterworth filter for discerning rigid body deceleration from "noisy" impact data). The details of the LS-DYNA3D dynamic model, henceforth referred to as the Holtec model, are contained in the proprietary benchmark report [A.4] wherein it is shown that the peak deceleration in *every* case of billet drop analyzed by LLNL is replicated within a small tolerance by the Holtec model. The case of the so-called "generic" cask, for which LLNL provided predicted response under side drop and tipover events, is also bounded by the Holtec model. In summary, the benchmarking effort documented in [A.4] is in full compliance with the guidance of the Commission [A.3].

Having developed and benchmarked an LLNL-consistent cask impact model, a very similar model is developed and used to prognosticate the HI-STORM drop scenarios. The reference elasto-plastic-damage characteristics of the target concrete continuum used by LLNL, and used in the HI-STAR 100 TSAR are replicated herein. The HI-STORM 100 target model is identical in all aspects to the reference pad approved for the HI-STAR 100 TSAR.

In the tipover scenario the cask surface structure must be sufficiently pliable to cushion the impact and limit the rigid body deceleration. The angular velocity at the contact time is readily calculated using planar rigid body dynamics and is used as an initial condition in the LS-DYNA3D simulation.

The end drop event produces a circular impact patch equal to the diameter of the overpack baseplate. The elasto-plastic-damage characteristics of the concrete target and the drop height determine the maximum deceleration. A maximum allowable height "h" is determined to limit the deceleration to a value below the design basis.

A description of the work effort and a summary of the results are presented in the following sections. In all cases, the reported decelerations are below the design basis of 45g's at the top of the MPC fuel basket.

A.4 Assumptions and Input Data

A.4.1 Assumptions

The assumptions used to create the model are completely described in Reference [A.4] and are shown there to be consistent with the LLNL simulation. There are key aspects, however, that are restated here:

The maximum deceleration experienced by the cask during a collision event is a direct function of the structural rigidity (or conversely, compliance) of the impact surface. The compliance of the ISFSI pad is quite obviously dependent on the thickness of the pad, t_p, the compressive strength of the concrete, f_c' and stiffness of the sub-grade (expressed by its effective Young's modulus, E). The structural rigidity of the ISFSI pad will increase if any of the three above-mentioned parameters (t_p, f_c' or E) is increased. For the reference pad, the governing parameters (i.e., t_p, f_c' and E) are assumed to be identical to the pad defined by LLNL [A.2], which is also the same as the pad utilized in the benchmark report [A.4]. We refer to the LLNL ISFSI pad parameters as Set A. (Table A.1).

As can be seen from Table A.1, the nominal compressive strength f_c' in Set A is limited to 4200 psi. However, experience has shown that ISFSI owners have considerable practical difficulty in limiting the 28 day strength of poured concrete to 4200 psi, chiefly because a principal element of progress in reinforced concrete materials technology has been in realizing ever increasing concrete nominal strength. Inasmuch as a key objective of the ISFSI pad is to limit its structural rigidity (and not f_c' per se), and limiting f_c' to 4200 psi may be problematic in certain cases, an alternative set of reference pad parameters is defined (Set B in Table A.1), which permits a higher value of f_c' but much smaller values of pad thickness, t_p and sub-grade Young's modulus, E.

The ISFSI owner has the option of constructing the pad to comply with the limits of Set A or Set B without performing site-specific cask impact analyses. It is recognized that, for a specific ISFSI site, the reinforced concrete, as well as the underlying engineered fill properties, may be different at different locations on the pad or may be uniform, but non-compliant with either Set A or Set B. In that case, the site-specific conditions must be performed to demonstrate compliance with the design limits of the HI-STORM system (e.g., maximum rigid body g-load less than 45 g's). The essential data which define the pad (Set A and Set B) used to qualify the HI-STORM 100 are provided in Table A.1.

The HI-STORM 100 steel structural elements (outer shell, inner shell, radial plates, lid, etc.), are fabricated from SA-516 Grade 70. The steel is described as a bi-linear elastic-plastic material with limited strain failure by five material parameters (E, S_y, S_u, ϵ_u, and ν). The numerical values used in the finite element model are shown in Table A.2. The concrete located inside of the overpack for this dynamic analysis is defined to be identical with the concrete pad. This is conservative since the concrete assumed in the reference pad is reinforced. Therefore, the strength of the concrete inside the HI-STORM 100 absorbs less energy if it is also assumed to be reinforced.

A.4.2 Input Data

Table A.1 characterizes the properties of the full-scale reference target pad used in the analysis of the full size HI-STORM 100 System. The principal strength parameters that define the stiffness of the pad, namely, t_p, E and f_c′ are input in the manner described in [A.2] and [A.4].

Table A.2 contains the material description parameters for the steel types; SA-516-70 used in the numerical investigation.

Table A.3 details the geometry of the HI-STORM 100 used in the drop simulations. This data is taken from applicable HI-STORM 100 drawings.

A.5 Finite Element Model

The finite-element model of the Holtec HI-STORM 100 overpack (baseplate, shells, radial plates, lid, concrete, etc.), concrete pad and a portion of the subgrade soil is constructed using the pre-processor integrated with the LS-DYNA3D software [A.5]. The deformation field for all postulated drop events (the end-drop and the tipover) exhibits symmetry with the vertical plane passing through the cask diameter and the concrete pad length. Using this symmetry condition of the deformation field only a half finite-element model is constructed. The finite-element model is organized into nineteen independent parts (the baseplate components, the outer shell, the inner shell, the radial plates, the channels, the lid components, the basket steel plates, the basket fuel zone, the concrete pad and the soil). The final model contains 30351 nodes, 24288 solid type finite-elements, 1531 shell type finite-elements, seven (7) materials, ten (10) properties and twenty-four (24) interfaces. The finite-element model used for the tipover-drop event is depicted in HI-STORM 100 FSAR Figures 3.A.1 through 3.A.4. Figures 3.A.5 through 3.A.8 show the end-drop finite-element model.

The soil grid, shown in HI-STORM 100 FSAR Figure 3.A.9, is a rectangular prism (800 inches long, 375 inches wide and 470 inches deep), is constructed from 13294 solid type finite-elements. The material defining this part is an elastic isotropic material. The central portion of the soil (400 inches long, 150 inches wide and 170 inches deep) where the stress concentration is expected to appear is discretized with a finer mesh.

The concrete pad is 320 inches long, 100 inches wide and is 36 inches thick. This part contains 8208 solid finite-elements. A uniform sized finite-element mesh, shown in HI-STORM 100 FSAR Figure 3.A.10, is used to model the concrete pad. The concrete behavior is described using a special constitutive law and yielding surface (MAT_PSEUDO_TENSOR) contained within LS-DYNA3D. The geometry, the material properties, and the material behavior are identical to the LLNL reference pad (Material 16 IIB).

The half portion of the steel cylindrical overpack contains 1531 shell finite-elements. The steel material description (SA-516-70) is realized using a bi-linear elasto-plastic constitutive model (MAT_PIECEWISE_LINEAR_PLASTICITY). HI-STORM 100 FSAR Figure 3.A.11 depicts details of the steel components of the cask finite-element mesh, with the exception of the inner shell, channels and lid components, which are shown in HI-STORM 100 FSAR Figures 3.A.12 and 3.A.13. The concrete filled between the inner and the outer shells, and contained in the baseplate and lid components is modeled using 1664 solid finite-elements and is depicted in HI-STORM 100 FSAR Figure 3.A.14. The concrete material is defined identical to the pad concrete.

The MPC and the contained fuel are modeled in two parts that represent the lid and baseplate, and the fuel area. An elastic material is used for both parts. The finite-element mesh pertinent to the MPC contains 1122 solid finite-elements and is shown in HI-STORM 100 FSAR Figure 3.A.15. The mass density is appropriate to match a representative weight of 356,521 lb. that is approximately mid-way between the upper and lower weight estimates for a loaded HI-STORM 100.

The total weight used in the analysis is approximately 2,000 lb. lighter than the HI-STORM 100 containing the lightest weight MPC.

Analysis of a single mass impacting a spring with a given initial velocity shows that both the maximum deceleration "a_M" of the mass and the time duration of contact with the spring "t_c" are related to the dropped weight "w" and drop height "h" as follows:

$$a_M \sim \frac{\sqrt{h}}{\sqrt{w}}; t_c \sim \sqrt{w}$$

Therefore, the most conservatism is introduced into the results by using the minimum weight. It is emphasized that the finite element model described in the foregoing is identical in its approach to the "Holtec model" described in the benchmark report [A.4]. Gaps between the MPC and the overpack are included in the model.

A.6 Impact Velocity

a. Linear Velocity: Vertical Drops

For the vertical drop event, the impact velocity, v, is readily calculated from the Newtonian formula:

$$v = \sqrt{(2gh)}$$

where

g = acceleration due to gravity
h = free-fall height

b. Angular Velocity: Tip-Over

The tipover event is an artificial construct wherein the HI-STORM 100 overpack is assumed to be perched on its edge with its C.G. directly over the pivot point A (HI-STORM 100 FSAR Figure 3.A.16). In this orientation, the overpack begins its downward rotation with zero initial velocity. Towards the end of the tip-over, the overpack is horizontal with its downward velocity ranging from zero at the pivot point (point A) to a maximum at the farthest point of impact (point E in HI-STORM 100 FSAR Figure 3.A.17). The angular velocity at the instant of impact defines the downward velocity distribution along the contact line.

In the following, an explicit expression for calculating the angular velocity of the cask at the instant when it impacts on the ISFSI pad is derived. Referring to HI-STORM 100 FSAR Figure 3.A.16, let r be the length AC where C is the cask centroid. Therefore,

$$r = \left(\frac{d^2}{4} + h^2\right)^{1/2}$$

The mass moment of inertia of the HI-STORM 100 System, considered as a rigid body, can be written about an axis through point A, as

$$I_A = I_c + \frac{W}{g} r^2$$

where I_c is the mass moment of inertia about a parallel axis through the cask centroid C and W is the weight of the cask (W = Mg).

Let $\theta_1(t)$ be the rotation angle between a vertical line and the line AC. The equation of motion for rotation of the cask around point A, during the time interval prior to contact with the ISFSI pad, is

$$I_A \frac{d^2 \theta_1}{dt^2} = Mgr \sin \theta_1$$

This equation can be rewritten in the form

$$\frac{I_A}{2}\frac{d\,(\dot{\theta}_1)^2}{d\,\theta_1} = \text{Mgr}\sin\theta_1$$

which can be integrated over the limits $\theta_1 = 0$ to $\theta_1 = \theta_{2f}$ (See HI-STORM 100 FSAR Figure 3.A.17).

The final angular velocity θ_1 at the time instant just prior to contact with the ISFSI pad is given by the expression

$$\dot{\theta}_1(t_B) = \sqrt{\frac{2\,\text{Mgr}}{I_A}(1-\cos\theta_{2f})}$$

where, from HI-STORM 100 FSAR Figure 3.A.17

$$\theta_{2f} = \cos^{-1}\left(\frac{d}{2\,r_1}\right)$$

This equation establishes the initial conditions for the final phase of the tip-over analysis; namely, the portion of the motion when the cask is decelerated by the resistive force at the ISFSI pad interface.

Using the data germane to HI-STORM 100 (Table A.3), and the above equations, the angular velocity of impact is calculated as 1.49 rad/sec.

A.7 Results

A.7.1 Set A Pad Parameters

It has been previously demonstrated in the benchmark report [A.4] that bounding rigid body decelerations are achieved if the cask is assumed to be rigid with only the target (ISFSI pad) considered as an energy absorbing media. Therefore, for the determination of the bounding decelerations reported herein, the HI-STORM storage overpack was conservatively made rigid except for the radial channels that position the MPC inside of the overpack. The MPC material behavior was characterized in the identical manner used in the Livermore Laboratory analysis as was the target ISFSI pad and underlying soil. The LS-DYNA3D time-history results are processed using the Butterworth filter (in conformance with the LLNL methodology) to establish the rigid body motion time-history of the cask. The material points on the cask where the acceleration displacement and velocity are computed for each of the drop scenarios are shown in HI-STORM 100 FSAR Figure 3.A.18.

Node 82533 (Channel A1), which is located at the center of the outer surface of the baseplate, serves as the reference point for end-drop scenarios.

Node 84392 (Channel A2), which is located at the center of the cask top lid outer surface, serves as the reference point for the tipover scenario with the pivot point indicated as Point 0 in HI-STORM 100 FSAR Figure 3.A.18.

The final results are shown in Table A.4.

i. Tipover:

The time-histories of the impact force, the displacement and velocity time-histories of Channel A2, and the average vertical deceleration of the overpack lid top plate have been determined for this event [A.7].

The deceleration at the top of the fuel basket is obtained by ratioing the average deceleration of the overpack lid top plate. The maximum filtered deceleration at the top of the fuel basket is 42.85g's, which is below the design basis limit.

ii. End Drop:

The drop height h = 11" is considered in the numerical analysis. This is considered as an acceptable maximum carry height for the HI-STORM 100 System if lifted above a surface with design values of t_p, f_c', *and E equal to those presented in Table A.1 for Parameter Set "A"*. The maximum filtered deceleration at the top of the fuel basket is 43.98g's, which is below the design basis limit.

The computer code utilized in this analysis is LS-DYNA3D [A.5] validated under Holtec's QA system. Table A.4 summarizes the key results from all impact simulations for the Set A parameters discussed in the foregoing.

The filter frequencies (to remove unwanted high-frequency contributions) for the Holtec cask analyses analyzed in this TSAR is the same as used for the corresponding problem analyzed in [A.2] and [A.4]. To verify the Butterworth filter parameters (350 Hz cutoff frequency, etc.) used in processing the numerical data, a Fourier power decomposition was generated.

A.7.2 Set B Parameters

As stated previously, Set B parameters produce a much more compliant pad than the LLNL reference pad (Set A). This fact is borne out by the tipover and end analyses performed on the pad defined by the Set B parameters. Table A.4 provides the filtered results for the two impact scenarios. In every case, the peak decelerations corresponding to Set B parameters are less than those for Set A (also provided in Table A.4).

Impact force and acceleration time history curves for Set B have the same general shape as those for Set A and are contained in the calculation package [A.7]. All significant results are summarized in Table A.4.

A.8 Computer Codes and Archival Information

The input and output files created to perform the analyses reported herein are archived in Holtec International calculation package [A.7].

A. 9 Conclusion

The DYNA3D analysis of HI-STORM 100 reported herein leads to the following conclusion:

a. If a loaded HI-STORM undergoes a free fall for a height of 11 inches in a vertical orientation on to a reference pad defined by Table A.1, the maximum rigid body deceleration is less than 45g's for both Set A and Set B pad parameters.

b. If a loaded HI-STORM 100 overpack pivots about its bottom edge and tips over on to a reference pad defined by Table A.1, then the maximum rigid body deceleration of the cask centerline at the plane of the top of the MPC fuel basket cellular region is less than 45g's for both Set A and Set B parameters..

Table A.4 provides key results for all drop cases studied herein for both pad parameter sets (A and B). If the pad designer maintains each of the three significant parameters (t_p, f_c', and E) below the limit for the specific set selected (Set A or Set B), then the stiffness of the pad at any ISFSI site will be lower and the computed decelerations at the ISFSI site will also be lower. Furthermore, it is recognized that a refinement of the cask dynamic model will accrue further reduction in the computed peak deceleration. For example, incorporation of the *structural* flexibility in the MPC enclosure vessel, fuel *basket*, etc., would lead to additional reductions in the computed values of the peak deceleration. These refinements, however, add to the computational complexity. Because g-limits are met without the above-mentioned and other refinements in the cask dynamic model, the simplified dynamic model described herein was retained to reduce the overall computational effort.

A.10 References

[A.1] Witte, M., et al., "Evaluation of Low-Velocity Impacts Tests of Solid Steel Billet onto Concrete Pads.", Lawrence Livermore National Laboratory, UCRL-ID-126274, Livermore, California, March 1997.

[A.2] Witte, M., et al., "Evaluation of Low-Velocity Impacts Tests of Solid Steel Billet onto Concrete Pads, and Application to Generic ISFSI Storage Cask for Tipover and Side Drop.", Lawrence Livermore National Laboratory, UCRL-ID-126295, Livermore, California, March 1997.

[A.3] Tang, D.T., Raddatz, M.G., and Sturz, F.C., "NRC Staff Technical Approach for Spent Fuel Cask Drop and Tipover Accident Analysis", SFPO, USNRC (1997).

[A.4] Simulescu, I., "Benchmarking of the Holtec LS-DYNA3D Model for Cask Drop Events", Holtec Report HI-971779, September 1997.

[A.5] LS-DYNA3D, Version 936-03, Livermore Software Technology Corporation, September 1996.

[A.6] Whirley, R.G., "DYNA3D, A Nonlinear, Explicit, Three-Dimensional Finite element Code for Solid and Structural Mechanics - User Manual.", Lawrence Livermore National Laboratory, UCRL-MA-107254, Revision 1, 1993.

[A.7] Zhai, J. "Analysis of the Loaded HI-STORM 100 System Under Drop and Tip-Over Scenarios", Holtec Report HI-2002474, July 2000.

Table A.1: Essential Variables to Characterize the ISFSI Pad (Set A and Set B)

Item	Parameter Set A	Parameter Set B
Thickness of concrete, (inches)	36	28
Nominal compressive strength of concrete at 28 days, (psi)	4,200	6,000
Max. modulus of elasticity of the subgrade (psi)	28,000	16,000

Notes: 1. The concrete Young's Modulus is derived from the American Concrete Institute recommended formula $57{,}000\sqrt{f}$ where f is the nominal compressive strength of the concrete (psi).

2. The effective modulus of elasticity of the subgrade will be measured by the classical "plate test" or other appropriate means before pouring of the concrete to construct the ISFSI pad.

3. The pad thickness, concrete compressive strength, and the subgrade soil effective modulus are the upper bound values to ensure that the deceleration limits under the postulated events set forth in HI-STORM 100 FSAR Table 3.1.2 are satisfied.

Table A.2: Essential Steel Material Properties for HI-STORM 100 Overpack

Steel Type	Parameter	Value
SA-516-70 at T = 350 deg. F	E	2.800E + 07
	S_y	3.315E+04 psi
	S_u	7.000E+04 psi
	ϵ_u	0.21
	ν	0.30

Note that the properties of the steel components, except for the radial channels used to position the MPC, do not affect the results reported herein since the HI-STORM 100 is eventually assumed to behave as a rigid body (by internal constraint equations automatically computed by DYNA3D upon issue of a "make rigid" command). In HI-STORM 100 FSAR Section 3.4, however, stress and strain results for an additional tip-over analysis, performed using the actual material behavior ascribed to the storage overpack, are presented for the sole purpose of demonstrating ready retrievability of the MPC after the tip-over.

Table A.3: Key Input Data in Drop Analyses

Overpack weight	267,664 lb
Radial Concrete weight	163,673 lb
Length of the cask	231.25 inches
Diameter of the bottom plate	132.50 inches
Inside diameter of the cask shell	72.50 inches
Outside diameter of the cask shells	132.50 inches
MPC weight (including fuel)	88,857 lb
MPC height	190.5 inches
MPC diameter	68.375 inches
MPC bottom plate thickness	2.5 inches
MPC top plate thickness	9.5 inches

Table A.4: Filtered Results for Drop and Tip-Over Scenarios for HI-STORM 100†

Drop Event	Max. Displacement (inch)		Impact Velocity (in/sec)	Max. Deceleration†† at the Top of the (g's) Basket		Duration of Deceleration Pulse (msec)	
	Set A	Set B		Set A	Set B	Set A	Set B
End Drop for 11 inches	0.65	0.81	92.2	43.98	41.53	3.3	3.0
Non-Mechanistic Tip-over	4.25	5.61	304.03	42.85	39.91	2.3	2.0

† The passband frequency of the Butterworth filter is 350 Hz.

†† The distance of the top of the fuel basket is 206" from the pivot point. The distance of the top of the cask is 231.25" from the pivot point. Therefore, all displacements, velocities, and accelerations at the top of the fuel basket are 89.08% of those at the cask top (206"/231.25").