2.0 JETLINER CRASH

This section describes the basis for the selection of a large commercial jetliner used in evaluating the crash on to a spent fuel dry cask storage facility and transportation casks, for determining the vulnerability. Section 3.0 describes the method and results of the structure evaluation.

The world-wide family of large commercial jetliners can be classified either as single-aisle or double-aisle commercial passenger jetliners. This classification system recognizes in general terms the relative size (cross-section) of the fuselage and hence the jetliner. In some sense this also categorizes the jetliner by the mass associated with the jetliner. Another and most obvious means of jetliner classification is by the manufacturer, and the specific model of the jetliner.

World-wide the population of jetliner in the class of large commercial jetliners is dominated by the models manufactured by the Boeing Company. Classifying the Boeing aircraft into the single-aisle and double-aisle categories results in the following lists of aircraft in each category for those models with a significant number currently in operation.

Single-aisle: Boeing 717, 727, 737 and 757 models (maximum take-off weight 110,000 to 273,000 lbs.)

Double-aisle: Boeing 747, 767 and 777 models (maximum take-off weight 395,000 to 910,000 lbs.)

2.1 PLANE SELECTION

The [redacted] was selected as the study model. The following are the reasons for selecting the [redacted] in the study: Ex 2

The recent 9/11/01 events in which large commercial passenger jetliner were commandeered and flight controls taken over by individuals who directed the jetliner into civilian targets and military targets were executed using the Boeing 757 and 767 class jetliner. These models represented one jetliner model from each of the above classes. It should be noted that these two Boeing models share identical flight control systems so that a pilot for one can also easily pilot the other jetliner. The Boeing 757, with a reputation of being the cheapest jetliner for airlines to operate, is the work horse of airlines worldwide.

Previous analytical work had been performed by Sandia, that had included an analytical representation of a [redacted] model jetliner suitable for use with structural analysis computer software is based on information sources that do not include the Boeing Company, but rely on other sources to obtain physical information that could be used to develop an analytical model. The staff contacted other national laboratories, the armed services, and other government agencies in search of analytic models of jetliners. The [redacted] model at Sandia was the only one available. Ex 2

Because of the need for expedient commencement of the vulnerability studies, the NRC staff decision was made to use the [redacted] jetliner as the crash jetliner. A contract has been established by Sandia with the Boeing Company, to confirm the adequacy of the jetliner analytical model being used and for NRC's intended purpose. Ex 2

Ex 2 portions

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Although there are larger and heavier jetliner than the [redacted] the staff decided that the expedient approach to began the vulnerability assessments for the spent fuel transportation and dry spent fuel storage casks was to use the existing work that had been completed in the creation of an analytical model of an jetliner as the beginning basis. Effort would then be made to improve the analytical model characteristics so as to more closely represent an actual jetliner. Furthermore, this study is not intended to be a bounding analysis but representative of typical of the jetliner used during the events of 11 September 2001. The [redacted] currently being analyzed represents the [redacted] Ex 2

2.2 ANALYTICAL MODEL OF PLANE

Ex 2

The initial finite-element model of the [redacted] jetliner was developed by reviewing information available in the open literature. Such information includes the physical dimensions, materials, and the mass of the various elements of the jetliner. A model for analytical simulations of crash scenarios must have the capability of allowing the study of the global response as well as the localized response, to identify the most vulnerable behavior of the cask being studied. Based on the available information, Sandia has developed the finite element model that incorporates this geometry, the mass of the jetliner along with a stiffness of the jetliner structure. It has been used at Sandia extensively for many of the current vulnerability studies being conducted at Sandia. However, several important aspects of truly representative modeling, such as the mass distribution of elements within the jetliner structure, accurate location and geometry of the hard or resistant components, still need to be verified and perhaps refined.

In order to verify and improve this current finite element model of the [redacted] an effort is underway with the Boeing Company to examine the current state of the Sandia jetliner model. However, based on the contract provisions, the information to be provided by the Boeing Company will not be specific to a particular model/type of jetliner, rather the information will be for a typical [redacted] This current effort in working with Boeing may result in a new analytical model for the [redacted] jetliner being used in the assessments. Such a model is expected to have additional mass and have a different mass distribution within the model structure. Additionally, it is expected that the stiffness of the model structure may change as a result of more detailed knowledge relative to the connection rigidity between various elements important to the vulnerability assessment such as between the wing and the fuselage and the landing gear assembly and the airframe. Sandia intends to rerun the jetliner crash calculations using the new model of the jetliner developed as a result of the process. The results of these computer simulations may enable the staff to address the vulnerability of the casks from jetliner impact on a generic basis. If such is not the case, other jetliner may need to be studied based on other threat information or management decisions. Ex 2

Ex 2 portion

Draft Section 3.0 Structural Evaluation
Mahendra J. Shah, 11/7/2002

Section 3.0 STRUCTURAL EVALUATION

This section describes structural consequences of a large commercial jetliner crashing onto a spent fuel dry cask storage facility, as well as onto a transportation cask. Effects of the crash on the jetliner fuel tanks, and resulting potential for a fire are described in section 4 (Thermal Evaluation) of this paper. Based on the assessment of structural designs and capabilities of the existing certified cask designs, four dry storage cask systems (out of the seven), and two transportation cask systems (out of sixteen), have been selected for structural vulnerability evaluation. The current large commercial jetliner selected for the evaluation is a [redacted] Section 2.0 of this report describes reasons for selecting the [redacted] for the evaluation.

Ex 2

The four storage casks selected for structural vulnerability evaluation are the free-standing casks HI-STORM 100, NUHOMS 32P, TN-68 and VSC-24. The transportation cask selected for this vulnerability evaluation is the NAC-UMS, rail-mounted cask. These casks were selected based on engineering judgement, including the consideration of the type of construction materials (steel, lead, concrete, etc.), thickness of materials, the number of casks in operation and planned for future operations, the spent fuel content, and radioactivity.

SCENARIOS OF A JETLINER CRASH

Scenarios of a jetliner crash for evaluation of the dry cask storage and transportation systems include such parameters as the crash angle and the maximum speed of the jetliner at the time of the crash. The crash angle and the maximum speed of the jetliner crash were selected based on the probabilities that the pilot of a jetliner may be able to hit the targets of sizes similar to a dry cask storage facility and the transportation vehicle. Evaluation was performed for a range of crash angles varying from xxxxx degrees to xxxxx degrees with the horizontal, and with the maximum speed of the jetliner of xxxxx, to determine the cask damage. The maximum speed of the jetliner was selected based on [redacted]

Ex 2

3.1 STRUCTURAL EVALUATION

3.1.1 STORAGE CASK

The jetliner crash analyses described in this section is for the HI-STORM 100 certified cask design (10 CFR Part), that could typically be used at an Independent Spent Fuel Storage Installation. Other dry cask storage systems, mentioned earlier in this section, have not been evaluated at the current time. The HI-STORM 100 system has a number of casks on a reinforced concrete pad on a foundation, spaced approximately 15 to 18 feet in a square or a rectangular patten. A jetliner crash would, therefore, potentially affect a number of casks during a single event. Some casks would be impacted by the jetliner fuselage and the landing gears, while the other casks would be impacted by the wings and engines and the landing gears. Since the shear strength of wings connections to the fuselage is not significant (based on the DOE-Sandia's experience), the wings would immediately separate from the fuselage during the crash. Consequently, a fuselage impacting a single cask is the governing event for the cask vulnerability study. The staff, therefore, analyzed the structural response of a single cask for a

Ex 2 portions

jetliner crash, and the subsequent interaction of the impacted cask on adjacent casks. Modeling a jetliner crashing onto a series of casks would be highly computer time intensive, and result in significant delays in obtaining results.

The HI-STORM 100 cask includes a concrete overpack (approx. 27 inches thick with a 0.75 inches thick exterior steel shell and a 1.25 inches thick interior shell, and a 4 inches thick bolted steel lid). The MPC, a steel welded canister, is stored inside the overpack, and contains the fuel basket for storing spent fuel, thus providing the containment or a sealed boundary for the spent fuel. The overpack has four vent openings, two at the bottom and two at the top, to allow natural air circulation and cool the MPC. The cask has an outside diameter of 132.5 inches and a height of approx. 231 inches. The total weight of the fully loaded storage cask is approximately 360,000 lbs. Evaluation of the HI-STORM cask for a jetliner crash is performed analytically using a computer code, CTH, for the global responses, and the computer code, PRONTO, for the cask-to-cask interaction. Effects of the rigid components of the jetliner, such as the landing gears and the engines on the cask, are also determined using the PRONTO code.

The jetliner crash on the cask was evaluated using two analyses cases using the CTH code, one for a low coefficient of friction between the cask and the concrete pad, yielding the maximum cask sliding velocity, and the other for a high coefficient of friction between the cask and the pad, yielding the maximum angular velocity of the impacted cask, rotating about the corner. For determining the maximum sliding velocity, the jetliner was assumed to impact a single free-standing vertical cask [redacted] For determining the maximum cask angular velocity, the jetliner was assumed to impact the cask [redacted] The mass and stiffness distribution of the jetliner structure were modeled using the information available in the public arena, and validated by the Boeing Company for the NRC needs. Ex 2

The CTH code simulates numerically the highly dynamic event of a short duration (impact), such as a jetliner crashing on to a dry cask storage system. A system of differential equations, established through the application of the principles of conservation mass, momentum and energy, are solved in an Eulerian (spatial) description of the cask and the jetliner. Since the impact phenomenon involves material strains significantly beyond the yield strength of the material and into the plastic behavior, the normally used Lagrangian finite-element method with the mesh deforming with the loads, is not suitable. The Eulerian description defines the mesh spatially and remains fixed with the material flowing from one cell of the mesh to another. The PRONTO code is a finite-element code, which solves differential equations in a time-domain using a Lagrangian description of the mesh.

Results of the CTH analyses include the maximum cask sliding and angular velocities. Using these values as initial conditions, the PRONTO code was used to analyze the cask impact on adjacent casks, and determine the vulnerability, defined as a breach of the multi-purpose canister (MPC) containing the spent fuel.

Local penetration effects of the rigid components, such as the landing gear, and the engine components, on a cask are determined using the PRONTO computer code. The landing gear is represented as a hollow cylinder, approximately [redacted] and weighing approximately [redacted] Analyses are performed for the landing gear impacting the cask shell [redacted] The lid Ex 2

Ex 2 portions

[redacted] Effects of the engine impact on a cask are evaluated using the Riera method (Reference 3.4.1), for a flexible component impacting a rigid target, for a [redacted] Ex 2

RESULTS OF THE EVALUATION

The maximum cask sliding velocity of the HI-STORM 100 storage cask was determined to be approximately xxxx m/sec or xxxxx mph, while the maximum angular velocity at the time of impact on an adjacent cask was xxxx rad/sec. Local cask damage due to the jetliner impact [redacted] Analyses performed using the PRONTO computer code for cask-to-cask impacts at these velocities indicate that the casks, [redacted] Ex 2

Results of the local penetration analyses, due to rigid components impacting the cask shell and the lid. show that the casks, [redacted] Ex 2

AREAS OF UNCERTAINTY

The analyses performed in these studies were realistic, in that realistic material properties (e.g., mean values) and realistic analytic methods (state-of-the-art structural computer codes) were used. Recognizing that the analytic methods and material properties have associated uncertainties, the staff attempted to assess the potential implications of those uncertainties.

The Following are the major areas of uncertainty in the analysis for a large commercial jetliner crash on to an ISFSI.

A. Jetliner Analytical Model: The jetliner model used in the CTH analyses is based on the information available in the public arena, and may not be completely accurate, or sufficiently representative for this study.. This may affect the results to some extent. The information used for the engines for the PRONTO analysis is based on test data, and is representative. The information for the landing gear used for the PRONTO analysis is based on the available public information, and thus may not be completely accurate. The modeling information for the jetliner is planned to be confirmed by the jetliner manufacturer Boeing. If the changes to the jetliner model are required as a result of the Boeing review, reevaluation of the analyses and results will need to be performed.

B. Material Properties: Since the materials impacted by the jetliner crash undergoes very large strains and changes into the behavior similar to a liquid state, the equation of state relating the density and pressure are required to be used in the CTH code. The information presently used in the CTH analyses for concrete material properties are based on test data for concrete strength greater than the concrete strength of the cask. However, the uncertainty associated with the concrete material properties is not expected to affect the results significantly because the equation of state for the concrete strength of 4000 psi is expected to be similar to the concrete strength of 5000 psi, used in the analyses.

C. Analytical uncertainty: Uncertainty in analytical results exist due to a need to define the physical phenomenon in mathematical equations using conservation of mass, momentum and energy, and in the process of solving the equations in finite space and time. The

Ex 2 portions

amount of uncertainty associated with this process is not significant because the CTH and PRONTO codes have been verified for process applications. However, use of the codes for an event with a large flexible object at high speed crashing into a heavy free-standing object is being done for the first time.

CONCLUSIONS

Based on the analyses performed to date for a large commercial jetliner crash on to a typical dry cask Independent Spent Fuel Storage Installation, it is concluded that the jetliner crash would [redacted]. The major reason for the [redacted] is the fact that the cask is free-standing, and moves upon the jetliner impact, thereby absorbing the energy as the kinetic energy, and not as the strain energy due to local damage. In addition, the steel canister is protected by approximately 27 inches thick concrete cylinder confined by steel shells. Ex 2

3.1.2 TRANSPORTATION CASK

The Transportation cask NAC/UMS is designed to be transported on rail. The cask is cylindrical and has a metal overpack with a dual-purpose metal canister used for transporting spent fuel. The overpack consists of a 2 inches thick interior steel shell, 2.75 inches thick chemical copper Lead, a 2.75 inches thick exterior steel shell, and approx. 5 inches thick neutron shield. The cask has an outside diameter of approx. 93 inches, and a height of approximately 209 inches without impact limiters. The fully loaded cask weighs approximately 255,000 lbs.

A jetliner crash in a [redacted] on the NAC/UMS cask during the transportation, would cause the cask to separate from the rail platform because the tie-down system is designed to resist 5 times the weight of the cask, while the impact forces are estimated to be greater than [redacted] the weight of the cask. Therefore, the behavior of the cask due to a jetliner crash would be similar to the storage cask, which has been analyzed for the jetliner crash. Assuming that the energy transferred to the cask during the crash is linearly proportional to the area of the cask impact, the maximum sliding lateral velocity of the NAC/UMS cask can be computed from the computed velocity of the HI-STORM cask. The maximum sliding velocity is computed as xxxx m/sec or xxxx mph. Assuming that the cask also has a longitudinal velocity same as the traveling rail speed of xx mph, the vectorial addition of the speeds would yield the maximum cask sliding velocity of xxxx mph. Ex 2

The cask traveling at the maximum sliding velocity is assumed to impact realistic targets, similar to soils or concrete targets used in NUREG/CR-6672, section 5.2. Based on this evaluation, it is concluded that the NAC/UMS cask MPC could withstand an impact on a real target of a velocity of xxxx mph without being breached, which is greater than the predicted maximum sliding velocity of the cask due to a jetliner crash. Therefore, it is concluded that the NAC/UMS cask would maintain the structural integrity during a jetliner crash.

3.2 REWORK REQUIRED

The structural evaluation discussed in Section 3.1 will require re-evaluation as described below:

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Ex2

A. Review the( )mathematical model, used in the CTH analyses, with the Boeing Company, to verify the accuracy of the model.

B. Re-perform the CTH analyses for the full duration of the impact, and re-evaluate the casks for the increased maximum cask sliding and angular velocity.

C. Re-perform the CTH analyses for a jetliner speed consistent with the PRONTO analyses.

D. Re-perform the PRONTO analyses using a revised model incorporating the mass and stiffness of the MPC and the fuel basket.

E. Address the uncertainty in material properties, including the effects of the environmental temperatures on the jetliner metal, and storage/transportation casks materials (steel, concrete, etc.).

3.3 ADDITIONAL WORK TO BE COMPLETED

To address the vulnerability of the spent fuel casks in storage and transportation to a large commercial jetliner crash, the following additional work is required to be completed.

A. Evaluate a jetliner crash on other types of storage cask systems (NUHOMS 32P, TN-68, VSC-24).

B. Evaluate effects of the rigid components of a jetliner onto the NAC/UMS rail cask.

3.4 REFERENCES

3.4.1 Riera, Jorge D., On the Stress Analysis of Structures Subjected to Aircraft Impact Forces, Nuclear Engineering and Design, 8 (1968), 415-426, North Holland Publishing Company, Amsterdam

White Paper
Chapter 4 - Consequences

The structural evaluations performed to date have demonstrated that the crash of a large airplane into a storage or transportation cask would [redacted] In the event that [redacted], a summary of how the consequence evaluation would be conducted is being provided.

Ex 2

To adequately evaluate the amount of radioactive material that could be released from a damaged cask, the following information is necessary:

1. The radioactive inventory in the undamaged cask.
2. The number of fuel rods and/or assemblies that are damaged from the event.
3. The fraction of radioactive material that escapes from the damaged rods.
4. Quantity of radioactive material, including particle size distribution, that is release from the cask.
5. Meteorological information.

NUREG/CR-6672, "Reexamination of Spent Fuel Shipment Risk Estimates," provides a information on the mechanisms relating to the release of radioactive material from failed fuel rods as a result of a transportation accident.

To determine the radioactive inventory of the undamaged cask, the computer codes SAS2H, ORIGEN-S, or ORIGEN-ARP may be used. These codes use information such as the assembly array size, fuel burn-up, initial enrichment, number of assemblies in the cask to determine the source term of the fuel. Additionally, the amount of CRUD that has accumulated on the fuel rods, must also be included as part of the source term.

The amount of damage to the cask and the fuel will be determined by the computer codes used in the structural evaluations. [redacted]

The transport of radioactive material from the damaged fuel rods to the cask interior may be determined using the MELCOR computer code. MELCOR is a general-purpose simulation code originally created to analyze severe accidents if light water reactors. MELCOR addresses fluid flow and heat transfer, fuel heat up, fission product release, and aerosol behavior. MELCOR's versatility allows it to be used for a myriad of other scenarios, including spent fuel storage and transportation casks. MELCOR can model fluid flow (e.g. gases and liquids) through compartments, fission product transport as a result of the fluid flows, condensation and evaporation of fission product vapors and deposition of particles onto compartment surfaces.

The output from the MELCOR code will be used in the MACCS2 consequence code to determine ground contamination levels, radiation doses, and health effects from the

Portions Ex2

radioactive material released from a damaged storage cask. MACCS2 can also be used to estimate the economic consequences from the event. MACCS2 uses a simple Gaussian plume model to estimate the downwind transport of airborne particles.

The output from the MELCOR code can also be used as input for RADTRAN 5, which is a transportation accident consequence code. The main limitation with RADTRAN is that it assumes all releases are cold and therefor has not plume rise. RADTRAN can also estimate economic consequences from a damaged cask.