1.0 INTRODUCTION

Following the September 11, 2001, terrorist events at the World Trade Center (WTC) in New York City and at the Pentagon in Virginia, the U.S. Government issued a nationwide alert for the potential of additional terrorist acts within the United States. The NRC Chairman tasked NRC staff to perform top to bottom review of all NRC Licensed activities and evaluate those activities against threats that may exceed the design basis threat (Reference 1). Due to the Chairmans memo, and in response to Congressional inquiries (Reference 2), the U.S. Nuclear Regulatory Commission initiated a vulnerability study at Sandia National Laboratories (SNL) to assess the consequences of a terrorist event on the transportation and storage of spent nuclear fuel, similar in magnitude to the WTC and Pentagon.

2.0 JETLINER

The Spent Fuel Project Office (SFPO) selected a large commercial jetliner similar to those used in the attacks on September 11, 2001, to evaluate the effects of its impact crash into a spent fuel storage facility and transportation package. 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. Generally, this also categorizes the jetliner by the mass associated with the jetliner. Other 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. Define series if it is importent

> Single-aisle: Boeing 717, 727, 737 and 757 models (maximum take-off weight ranges from 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 was selected as the jetliner for the evaluation. The attacks of September 11, 2001, in which large commercial passenger jetliner were commandeered and flight controls taken over by individuals who directed the jetliner into civilian 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. These two Boeing models share identical flight control systems so that a pilot can easily operate both jetliners with no additional training. The Boeing 757, with a reputation of being the most economical jetliner for airlines to operate, is the work horse of airlines worldwide.

Previous analytical work performed by SNL, included an analytical representation of a model jetliner suitable for use with structural analysis computer codes. The previous models are based on information taken from other sources, outside the Boeing Company to obtain the physical information used to develop the analytical model. The staff contacted other national laboratories, the armed services, and other government agencies in search of analytic models of jetliners. At the time, the [redacted] model at SNL was the only one available. Ex2

Because of the need for expediency in performing the vulnerability studies, the staff decided to use the [redacted] jetliner model at SNL. Additionally, at the urging of the NRC, a contract was established between SNL and the Boeing Company, to confirm the adequacy of the SNL jetliner analytical model used and for vulnerability study. Ex2

Although there are jetliners larger and heavier than the [redacted] most expedient approach to assess vulnerability of spent fuel transportation packages and storage facility was to use the existing models as the basis for the study. SNL staff would put future efforts into improving the characteristics of the analytical model to more accurately represent the [redacted] jetliner. Furthermore, this study is not intended to be a bounding analysis but representative of the typical jetliner used during the events of September 11, 2001. The [redacted] model currently being analyzed represents the [redacted] involved in the WTC and pentagon events and therefore represents a realistic jetliner for the study effort. Ex2

Are [redacted] harder to get and/or fly?? Ex2

2.2 JETLINER ANALYTICAL MODEL

The initial finite-element model of the [redacted] jetliner was developed by reviewing information available in the open literature. Such information includes the general 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 impact scenarios that yield the largest consequences. Based on the available information, SNL developed the finite element model that incorporates the available geometry, mass and stiffness of the jetliner structure. It has been used at SNL extensively for many of the current vulnerability studies being conducted. 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. Ex1

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 may result in a much improved 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 connections between the wing and fuselage and the landing gear assembly and airframe. SNL intends to rerun the jetliner crash calculations using the improved model of the jetliner developed as a result of this 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 Ex2

Ex 2 portions

be studied based on other threat information or management decisions. *{why would we need to redo the calcs?}*

3.0 STRUCTURAL EVALUATION

The structural response of a large commercial jetliner crashing onto a spent fuel storage facility or transportation package depends on the cask design, impact speed and angle. Based on initial assessments of the structural design and capability of the existing NRC-certified cask designs, four dry storage cask systems (out of the seven), and two transportation packages (out of sixteen), were selected for the structural vulnerability evaluation.

The four storage designs selected are the free-standing casks HI-STORM 100, NUHOMS 32P, TN-68 and VSC-24. The transportation package selected is the NAC UMS, rail 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 future operations, spent fuel contents, and source term.

CRASH SCENARIOS

Crash scenarios include such parameters as the impact angle and jetliner speed. The impact angle and the speed of the jetliner 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 package. Evaluations were performed for a range of crash angles varying from xxxxx degrees to xxxxx degrees above the horizontal, and with the maximum speed of the The maximum speed of the jetliner was selected based on the available information

Ex 2

3.1 STORAGE CASK Evaluation

The jetliner crash analyses described in this section are for the HI-STORM 100 cask system. The other dry cask storage systems, mentioned earlier, 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, engines and the landing gears. Since the shear strength of wing connections to the fuselage is not significant (based on the SNL experience with previous evaluations), the wings would immediately separate from the fuselage. *{Do we agree with this??}* Consequently, a fuselage impacting a single cask is the governing event for the cask vulnerability study. The SNL analyzed the structural response of a single cask for a jetliner crash, and the subsequent interaction of the impacted cask on both adjacent casks and the concrete pad. Modeling a jetliner crashing onto a series of casks would be very computer intensive, expensive and result in significant delays in obtaining results.

The HI-STORM 100 cask includes a concrete overpack comprised of approximately 27 inches of concrete with a 0.75-inch thick exterior steel shell and a 1.25-inch thick interior shell, and a 4-inch thick bolted steel lid. The steel-welded MultiPurpose Canister (MPC) is stored inside the overpack, and contains the fuel and basket. The MPC provides containment for the spent fuel. The overpack has four vented openings, two at the bottom and two at the top, to allow natural

Ex 2 portions

air circulation and cool the MPC. The cask has an outside diameter of 132.5 inches and a height of 231 inches. The total weight of the fully loaded storage cask is approximately 360,000 lbs. Evaluation of the HI-STORM 100 cask for a jetliner crash is performed analytically using the CTH (reference 3) computer code for the global responses, and the PRONTO (reference 4) computer code for the cask-to-cask (local) 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 and cask impact was evaluated using two different analyses using the CTH code, one with 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. To determine the maximum sliding velocity the jetliner impact was normal against a single free-standing vertical cask with the nose of the jetliner at the mid-point *{is this possible}* of the cask height. To determine the maximum cask angular velocity, the jetliner impacted impacted the cask with the nose of the jetliner at the on the cask to maximize the cask angular velocity, rotating about the bottom corner. Ex2

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. *{Do we need more here?}*

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 the concrete pad. The local analyses looked for breach of the MPC. The criteria for a breach of the MPC is ....

Additional 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 and 24 inches long and weighing approximately .ed for the landing gear impacting the cask shell , The lid portion of the cask system is evaluated for the landing gear impacting at Effects of the engine impact on a cask are evaluated using the Riera method (Reference 5), for a flexible component impacting a rigid target, for a Ex2

RESULTS OF THE EVALUATION

The maximum cask sliding velocity of the HI-STORM 100 storage cask was determined to be approximately 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 Ex2

Portions Ex2

Analyses performed using the PRONTO computer code for cask-to-cask impacts at these velocities indicate that the casks,

Ex 2

Results of the local penetration analyses, due to rigid components impacting the cask shell and the lid, show that the casks,

Ex 2

{What about cask slapdown on the pad?}

AREAS OF UNCERTAINTY

The analyses performed in these studies were realistic, in that realistic material properties (e.g., mean values) analytic methods (state-of-the-art structural computer codes) and impact parameters 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 major areas of uncertainty in the analysis need to be further defined for the vulnerability study

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. *{is this repetitive? Can it come out??}* 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 HI-STORM 100 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. *{Can this be quantified a little bit, such as the strenghth only differs by X psi, etc}*

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

Ex 2 portions

the process of solving the equations in finite space and time. The amount of uncertainty associated with this process is not significant because the CTH and PRONTO codes have been verified for process applications *{meaning?? What are process applications?}*. However, use of the codes for an event with a large flexible *{flexible? Should this be a different adjective?}* 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 typical NUHOMS 100 dry cask storage facility, SNL staff have concluded that the jetliner crash(.

)The major reason the MPC remains intact is the cask is free-standing, and moves upon impact, transferring the planes kinetic energy into the cask kinetic energy, instead of into strain energy causing local damage. In addition, the steel MPC is protected by approximately 27 inches of concrete and two steel shells surrounding the concrete. Ex 2

3.2 TRANSPORTATION CASK

The Model No. NAC UMS transportation package 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-inch thick inner steel shell, 2.75-inch thick lead, a 2.75-inch thick outer steel shell, and a 5-inch thick ceramic neutron shield. The cask has an outside diameter of 93 inches, and a height of 209 inches without impact limiters. The fully loaded cask weighs approximately 255,000 lbs.

A jetliner crash in a( ) on the NAC UMS cask during the transportation, would cause the cask to separate from the railcar. The tie-down system is only designed to resist 5 times the weight of the package, while the impact forces from a jetliner crash are estimated to be greater than( ) the weight of the package. Therefore, the behavior of the package during a jetliner crash would be similar to a storage cask. Ex 2

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 . *{what is the velocity? Need to fill this in or get rid of this information.}* Assuming that the casks longitudinal velocity is the same as the traveling rail speed of xx mph, the vectorial addition of the velocity would yield the maximum cask sliding velocity of xxxx mph. *{what is the velocity? Need to fill this in or get rid of this information.}*

The package 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 MPC could withstand an impact on a real target of a velocity of xxxx mph. *{what is the velocity? Need to fill this in or get rid of this information.}* 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 package would maintain the structural integrity and containment during a jetliner crash.

Ex 2 portions

4.0 Thermal

Thermal

5.0 Consequences

The structural and thermal evaluations performed to date have demonstrated that the crash of a large double-aisle jetliner into a the HI-STORM 100 storage cask or NAC UMS transportation package would Therefore In the event that future evaluations do a summary of how the consequence evaluation would be conducted is provided. Ex. 2

To adequately evaluate the amount of radioactive material that could be released from a damaged MPC, 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," (reference 6) provides 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 *the computer codes* SAS2H (reference 7), ORIGEN-S (reference 8), or ORIGEN-ARP (reference 9) 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. Ex 2

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

The transport of radioactive material from the damaged fuel rods to the cask interior (exterior??) will be determined using the MELCOR computer code. MELCOR is a general-purpose simulation code originally created to analyze severe accidents from 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 casks and transportation packages. The MELCOR model can include 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 (Reference 10) consequence code to determine ground contamination levels, radiation doses, and health effects from the spent fuel released from a damaged storage cask. MACCS2 can also be used to estimate the

Ex 2 portions

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 (reference 11), which is a transportation accident consequence code. The main limitation with RADTRAN is that it assumes all releases are cold and therefore does not include a plume rise model. RADTRAN can also estimate economic consequences from a damaged cask. {what about determine ground contamination levels, radiation doses, and health effects as well?}

6.0 Future Work

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

A. Review the mathematical model, used in the CTH analyses, with the Boeing Company, to verify the accuracy of the model. Ex 2

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. The code calculations were terminated prior to reaching an asymptote for both the maximum sliding velocity and angular velocity for the HI-STORM 100 storage cask.

C. Re-perform the CTH analyses for a jetliner velocity consistent with the PRONTO analyses. The jetliner velocity used in the CTH calculations was used in the PRONTO calculations. Ex 2

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.).

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 impacting the NAC UMS rail cask.

{Are we satisfied with the information provided above for the global analysis of the NAC UMS such that no computer calculations needs to be performed?}

The NRC staff anticipates that all calculations and the final report will be completed by the end of January 2003.

7.0 References

Ex 2 portions

1 Meserve memo to staff dated Sept XX, 2001.

2 Letter, Meserve to Markey Dated October 16, 2001.

3 CTH

4 PRONTO

5 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

6 NUREG/CR-6672

7. SAS2H

8. ORIGEN-S

9. ORIGEN-ARP

10. MACCS2

11. RADTRAN 5