Transportation Safety and Risk Assessment Analysis Plan

The project will use NRC licensed cask designs to perform the transportation risk assessment. The casks to be analyzed are the GA-4 (a steel-DU-steel truck cask with directly loaded fuel), the HI-STAR 100 (an all-steel rail cask with an internal canister), and the NAC-STC (a steel-lead-steel rail cask with directly loaded fuel). In addition, one un-licensed variation will be analyzed, either the NAC-STC or the HI-STAR 100 including a bolted canister. The GA-4 cask and the NAC-STC cask are only licensed to transport PWR fuel. Because of this and since PWR fuel is more prevalent in the spent fuel inventory, only PWR fuel will be considered in this assessment. Prior risk assessments and some recent detailed modeling of fuel assemblies has shown PWR assemblies are more prone to cladding failure than BWR assemblies [1], so the assessment of the response of PWR assemblies will bound that for BWR assemblies. The accident environments of NUREG/CR-6672 will be replicated to allow comparison of results.

Structural Analyses

The structural analysis will be performed using the explicit finite element code PRESTO, developed by Sandia National Laboratories (SNL). All casks will be modeled for closure end, closure corner, and flat side impacts at 30, 60, 90 and 120 mph onto a flat rigid target. These velocities were chosen to enable direct comparisons with the results from NUREG/CR-6672 and because the historical accident record includes impacts at above 90 mph. Impacts into other targets (yielding surfaces) will use the same methodology that was used in NUREG/CR-6672 to determine equivalent impact velocities.

Computational Tools

The analyses required for this work will necessitate the use of an explicit transient dynamic finite element code. Several codes of this type are available at Sandia (LS-DYNA, ABAQUS Explicit, PROTONO, PRESTO) and have been evaluated for this class of problem. While all of the codes are capable of calculating the response of casks to the extreme environments of this study, there are several issues involving the treatment of material failure and contacts that indicate the best code for the task is PRESTO. In regulatory analyses such as those conducted for certification, the issue of material failure is usually not of concern. However, when the analyses are for extra-regulatory events it is necessary to consider material failure and whether it has been achieved. Both PRESTO and PRONTO have an improved (vs. plastic strain or stress) failure model (tearing parameter) that is not available in DYNA or ABAQUS. In addition, PRESTO has an iterative contact algorithm that more accurately calculates the contact stress between adjacent parts. This is especially true when there is a large mismatch in stiffness between the parts, such as between the cask body and its impact limiter.

The results from the PRESTO calculations will be supplied electronically in a form that can be read with commercial post-. This will enable the NRC to utilize the analysis results for other projects as needed.

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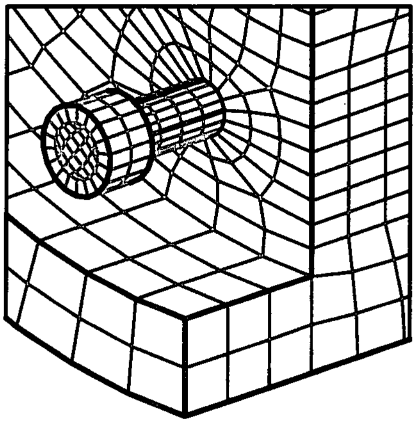
General Modeling Characteristics

In performing the structural analyses, an attempt will be made to strengthen the structural analyses in NUREG/CR-6672. Subtask (1b) of the current statement of work (SOW) directs SNL to develop high fidelity models of the casks, canister (HI-STAR only), respective contents (fuel), and the respective impact limiters. The current models will include more geometric details in the bolt flange area. While the bolted joint in NUREG/CR-6672 contained an extremely short bolt with only one element through the section, the current bolt model will be more detailed, similar to the bolt model shown in the figure below. In addition, proper lid flange geometry and a nominal lid gap will be included. While the lid seal will not be explicitly modeled, the gap between the mating surfaces will be monitored to determine the extent of seal leakage. The inclusion of bolt preload into the model will also be investigated.



Detailed Bolt Model

The cask impact limiter will be explicitly modeled. Details for each cask are described in the sections below. A general feature of these models will be the modeling of the energy absorbing material using the orthotropic crush material model in PRESTO. The structural members will be modeled using shell or possibly hex elements, depending on the thickness of these components. If the design and geometry of the bolted connection permits, the attachment of the impact limiters may be modeled using the spot-weld feature in the code. This feature allows two surfaces to be attached using specified force displacement functions. This will require a separate finite element analyses to determine these functions for each bolted connection. Overall, this will be a more efficient method for modeling bolted connections in less critical areas (away from the closure flange area).

For the analyses of the cask with the canister, the contents (basket and fuel) will be modeled as a homogeneous mass using the orthotropic-crush material model. For the direct loaded casks, the fuel bundles will also be modeled as a homogeneous mass using the orthotropic-crush material model. However, some detail of the basket structure will be included in an effort to gain a better understanding of the diminution of force through the basket.

Areas of Concern

Traditionally, the results from numerical analysis are easiest to defend when they fall into one of two categories. In the first category, the structure is only slightly damaged so that there is high confidence in the survivability and performance of the structure. The second is when severe damage is predicted and there is a high confidence that the structure has failed completely. Between these two extremes, determining the magnitude of the damage and the reduction in the performance requires a more prudent and judicious approach.

In this project, components of the cask (especially the impact limiter) may experience material failure, so the analyses may be between the two extremes. As the speed of the impact is increased, the impact limiters will be severely deformed, the bolts in the closure will stretch and the closure may begin to separate creating a leak in the closure seal. At still higher velocities, the impact limiter attachment bolts and possibly the impact limiters may fail completely. Accurately modeling the deformation and possible failure of these components is critical to accurately predicting the cask response. While the current model described above will contain more geometric details, the accuracy of the calculation for these severe impacts depends highly on the constitutive modeling of the material and the failure criterion used to predict rupture. Frequently, these two criteria are coupled.

Obtaining the required material data for the constitutive models may require additional work. While sufficient data may be available for some of the common materials, such as 304L stainless steel, getting property data (e.g. stress-strain data) for some of the bolt materials or the high strength stainless (XM-19) used throughout the GA-4 cask may require some tensile testing. This will put more pressure on an already tight budget.

Determining material failure is an even more complicated issue. For example, a large part of the Private Fuel Storage (PFS) hearings on the F-16 aircraft impact were devoted to debating the failure criteria for stainless steel, despite the fact that the analytical results were in the first category (very low strains). While several failure theories and criteria exist [2][3][4], specific material data needed to populate these functions are almost nonexistent and obtaining this data for the cask materials will require additional time and testing. It is vital that these analyses have well founded and defendable failure criteria, since the entire consequence analysis is based on the structural response of the cask.

Modeling the impact limiters will also be a very challenging area. The energy absorbing material will be modeled using the orthotropic crush material model in PRESTO. While some data is available, properties for some of the materials may not be readily available (e.g., some wood materials). Also, it is not clear at this point what effect the glues used to assemble component pieces of the impact limiter have on the overall performance of the limiter. In addition, at some finite velocity, the impact limiter may fail catastrophically, such as the splintering of the wood and rupturing of the stainless steel casing. Modeling this type of failure may not be possible with the current Lagrangian model. However, if such events do occur, excessively large loads will be transmitted to the cask body. Similarly, a gross buckling failure of the honeycomb material would also lead to higher loads being transmitter to the cask body. It is not clear whether these concerns can be addressed within the tight scope of this project. Where data shortcomings are identified, Sandia will assess the cost associated with developing the required data. If there is not sufficient funding within the project scope, engineering judgment will be used within the analyses. When this occurs, the assumptions will be provided to NRC for concurrence.

Specific Model Methodology

The following are specific details relevant to each cask analysis:

GA-4

The impact limiter model will include the interior gussets (modeled with shell elements) and the segments of aluminum honeycomb, which will be modeled using an orthotropic crush material model. The adhesive joints may be modeled with a frictional contact although this will not permit tensile forces to develop between the segments. The exterior skin of the impact limiter will be modeled with shell elements. The radial plates in the impact limiter support structure have a series of holes in them. In the finite element model an equivalent solid cross section will be used and modeled with shell elements. The impact limiters will be attached to the cask body via spot-welds at the bolt locations.

The cask body, including both the inner and outer shells and the DU shielding will be modeled with hex elements. The joints between the DU segments will be included. The assumption will be used that the DU segment-to-segment contact and the segment-to-shell contact are frictionless.

The cask closure will be modeled including the tapered gap between the lid and cask body. A detailed model of the closure bolts will be included. The seals will not be explicitly included in the model, but the lid deformations at the seal locations will be tracked and used to determine seal behavior.

The ribs of the fuel support structure will be modeled with shell elements that have equivalent stiffness to the actual plates with holes filled with B4C pellets. A small detailed model of the actual plate structure will be compared with the shell model. The individual fuel assemblies will not be included in the model, but a beam-model of a fuel assembly will be used to obtain smeared stiffness in the axial and transverse directions to be used in the cask model. This beam model will also be used to estimate the number of rod failures that occur by using the smeared fuel assembly accelerations as an input force.

HI-STAR 100

The impact limiter model will include the interior gussets (modeled with shell elements) and the segments of aluminum honeycomb, which will be modeled using an orthotropic crush material model. The exterior skin of the impact limiter will be modeled with shell elements. The impact limiters will be attached to the cask body via spot-welds at the bolt locations. This is very similar to the model used in the PPS protocol report [5].

The cask body will be modeled with hex elements assuming that the multiple layers of SA516 act as a monolith and the inner layer of SA203-E is modeled separately. The contact between these two layers will be modeled as a frictional contact. This is similar to the model that was used for the PPS protocols report.

The cask closure will be modeled including the gap between the lid and cask body. A detailed model of the closure bolts will be included. Bolt preload will be considered. This was not included in the PPS protocol model of the cask.

The canister will be modeled using hex elements for all components. A separate material will be used for the weld region to enable the tracking of stresses within the weld. Residual stresses that result from the welding process will not be included. The basket structure and individual fuel assemblies will not be included in the model. Instead a smeared representation of the contents of the canister will be used. The beam-model of a fuel assembly will be used to obtain smeared stiffness in the axial and transverse directions to be used in the cask model. If there are no failures in the canister, there will be no need to determine the response of the individual fuel assemblies. If there are canister failures (it may be prudent to assume that human error results in some failures even if the analysis does not predict them), it will be assumed that all of the assemblies experience equal accelerations, and the beam model will be used to estimate the number of rod failures that occur by using the smeared fuel assembly accelerations as an input force.

NAC-STC

The impact limiter model will include the interior gussets (modeled with shell elements) and the segments of redwood and balsa wood, which will be modeled using an orthotropic crush material model. The exterior skin of the impact limiter will be modeled with shell elements. The impact limiters will be attached to the cask body via spot-welds at the bolt locations. Sandia performed scale model drop tests of this limiter for NAC International, so the data from these tests is available to validate the impact limiter model.

The cask body, including both the inner and outer shells and the lead shielding will be modeled with hex elements. This will allow a more precise determination of the amount of lead slump than has been made in prior risk assessments. The contact between the lead and the shells will be assumed to be frictionless.

The cask closure will be modeled including the gap between the lid and cask body. A detailed model of the closure bolts will be included. Bolt preload will be considered.

The direct loaded version of this cask will be used. The basket fuel tubes, structural disks, and heat transfer disks will be modeled using shell elements. The tie rods will be modeled using hex elements. The individual fuel assemblies will not be included in the model, but a beam-model of a fuel assembly will be used to obtain smeared stiffness in the axial and transverse directions to be used in the cask model. This beam model will also be used to estimate the number of rod failures that occur by using the smeared fuel assembly accelerations as an input force.

Bolted Canister

Both the HI-STAR 100 and the NAC-STC are certified to transport fuel in welded canisters. A generic bolted canister will be designed and this canister will replace the contents of either of these two casks. The choice of cask to be used will be made after the results for both casks with their certified contents are available. The generic bolted canister will have shell, lid, and basket dimensions similar to the certified welded canister. The only modification will be the replacement of the welded seal with a metallic seal and bolts.

Thermal Analyses

The thermal analyses will be performed using the commercially-available finite element code, MSC PATRAN/Thermal and the Sandia developed fire code, CAFE. All casks will be modeled assuming that neither the body nor the impact limiters are damaged. This addresses the realistically conservative policy by recognizing that a severe mechanical impact immediately followed by a long-term co-located fire is highly unlikely. The initial condition for all fire analyses will be determined from steady-state analysis of the normal conditions of transport conditions defined in 10CFR71.71. The results of these analyses will also be compared with results presented in the SARs. The thermal analyses will use 3D representations of the casks to calculate temperature distributions throughout the cask, including the seal region and the spent fuel region. Approximately 21 transient thermal analyses will be performed. These will include an 800°C, a 1000°C, and a CAFE fire for each cask. 800°C and 1000°C are the two fire environment temperatures that were used in NUREG/CR-6672 and, therefore, will be used again for this work. Regarding fire duration, the 800°C and the 1000°C fires will be 30 minutes and a long (~11 hrs) fully engulfing fire will be simulated using the CAFE fire code with realistically calculated fire temperature distributions. The CAFE calculations will be performed assuming no wind conditions with the cask lying on the ground (only impact limiters touching ground). Cool-down analyses after different fire durations will be performed to capture internal peak temperatures, which, for thermally-massive objects, typically occur after the fire.

The analyses that will be performed for each cask are summarized below:

- one 30-minute, 800°C P/Thermal fire
- one 30-minute, 1000°C P/Thermal fire
- one long (~11 hrs) CAFE fire
- four P/Thermal cool-down analyses starting at different fire durations (1, 2, 3, and 11 hours)

The material properties presented in the SAR will be used in all models. The fuel region will be homogenized for all casks and benchmarked against SAR data. The models will have enough refinement to capture the temperature history at locations of interest, such as the seal and the fuel regions.

Computational tools

Some of the fire scenarios that are being considered for this project will be modeled using a computational fluid dynamics (CFD) code that is coupled with a finite element (FE) analysis code. The preferred coupled analysis codes are CAFE-3D [6, 7, 8] and MSC PATRAN/Thermal [9]. CAFE is a fast-running three-dimensional CFD and radiation heat transfer computer code that includes the dominant physics present in fires and therefore is capable of simulating fires realistically. This code, developed largely at Sandia National Laboratories, has been successfully coupled to commercially available finite element (FE) analysis computer codes. MSC PATRAN/Thermal (P/Thermal) is a commercially-available FE thermal code. CAFE calculates the fire field and provides time- and space-varying boundary condition information to the P/Thermal FE code, which calculates the three-dimensional heat transfer response of the object exposed to the fire modeled by CAFE. These two codes interact throughout the fire simulation, making the coupled CFD-FE analysis tool known as CAFE-P/Thermal.

In addition to CAFE being a fast running fire code, its especial coupling to a FE analysis code allows the user to define and construct detailed FE models of objects that are exposed a fire, which in turn, allows the user to capture the heating of internal components better than what is possible in current commercially-available CFD codes that can simulate fire. In addition, CAFE was designed for the modeling of large fires engulfing large, thermally-massive objects. The results obtained from CAFE runs of experimental fire tests for the benchmarking of the code demonstrate the ability of the code to realistically capture the fire physics. CAFE was designed to be used on workstation computers and does not require the special need of a massive parallel computer.

Commercially-available codes such as Fluent and CFX are capable of modeling a fire. However, these codes typically require very long run time on large computing platforms. These codes are also capable of calculating the heat conduction of objects affected by a fire. However, the solid objects are meshed with the same grid structure that is used for the fluid flow sections of the model, making the modeling of small internal features in the object of interest very difficult or nearly impossible because the computational time steps may become prohibitively small due to the very small fluid flow computational grids. The magnitude of this problem is even grater when simulations of large domains and of tens of minutes are necessary for the proper evaluation of the accident being studied.

Other codes such as NIST's FDS can simulate a fire but are limited to just that, simulate a fire. That is, there is no coupling of a CFD fire and a three-dimensional heat transfer model of the object or objects that are affected by the fire. Because of the lack of this feature, decoupled analyses are often performed in which a fire is modeled with a fire-only modeling tool and boundary conditions are later applied to a FE model of the object of interest. While this is a plausible way of modeling the response of an object engulfed or affected by fire, there is no feedback from the object back to the fire and the effects of a large and relatively cold object on the fire are not captured.

Therefore, it is proposed that the CAFE-P/Thermal CFD-FE analysis tool is used for the computational simulations that are a part of this project. CAFE is a natural choice for the evaluation of realistic severe thermal conditions resulting from an accident involving large and long-duration fires.

Areas of Concern

The selected analyses described above do not encompass all possible considerations for determining thermal response. This section describes some areas the NRC may want to consider, either in addition to or in place of, the proposed analyses described above.

Selection of the realistic fire duration – There are two possibilities being considered at this time. These are:

1. Redo the analyses presented in NUREG/CR-6672 using three-dimensional finite element analysis (including an 11-hour fire) and be more specific about the temperature distribution throughout the cask (especially the seal region and the fuel region), as well as addressing comments identified in the Issues Report (NUREG/CR-6768). This will update and validate the results presented in NUREG/CR-6672 through the use of higher fidelity finite element models.

or,

2. Not perform extremely long duration fire analyses (e.g., 11 hours) and evaluate accident data to determine realistic durations of large co-located fires. This alternative will help eliminate the misuse of thermal analysis results from fires that have extremely low probability of occurrence. However, if the structural analyses that are performed as part of this effort are more aligned with what was done in NUREG/CR-6672 than the thermal work, this will make the two sections different.

For this study option 1 is the better choice because the public has already been sensitized to the fact that long duration fires are a significant threat to packages. These analyses will provide a better quantification of that threat. In the risk assessment part of the project the very low probability of an 11-hour fully-engulfing fire will be stressed. This approach also allows direct comparison with NUREG/CR-6672. Failure to include fires of this duration is likely to result in claims that NRC is trying to hide unfavorable results.

Location of pool relative to the cask – The location of the pool fire can greatly affect the thermal response of the cask. The most unlikely scenario is for the pool fire and the cask to be co-located. The most damaging condition for a co-located fire is when the atmospheric conditions are such that wind does not blow the flames off of the cask. In other words, the fire has to be fully engulfing. Other scenarios in which the pool fire is adjacent to the cask and wind conditions are such that hot flames are blown onto the cask are also very damaging. This scenario also has a low probability of occurrence. Long duration fires do occur, but the probability that they are co-located with a cask or adjacent to the cask with the right wind conditions for the entire duration is vanishingly small. However, the thermal assault to the cask from this type of fire may be of concern either for the risk analyst or the general public. Therefore, in an effort to try to simulate a realistic fire scenario, one has to select a location for the fuel pool and the cask that produces results that are as useful for a risk analyst as those in NUREG/CR-6672. Given the infinite number of possible combinations of fire location, wind direction, and fire duration, this decision can prove to be a very difficult one to make.

Reference

Recommendations

Damaged cask and limiters – If there is a desire for additional analyses with damaged limiters and cask, the damage state of the cask and impact limiters presented in the SAR or those states calculated in the structural section of this project can be used (however, there are multiple damage states depending on the angle of impact). These analyses produce results that are more realistic if a risk analyst is looking at a fire-following-impact scenario. If the NRC desires to include this type of analyses in the NUREG report, schedule and cost of the project could be affected unless a smaller number of analyses of the undamaged casks are performed.

Thermal properties of damaged materials – Safety analysis reports typically include a thorough summary of the thermophysical properties. An additional concern is that often cask manufacturers neglect the impact limiters and neutron shield when performing thermal analyses for certification, so the SAR may not include properties for these components even in an undamaged state. It is also very common that properties for materials in a damaged state are not readily available. This limits the ability to perform proper thermal analysis of damaged components, for example, crushed impact limiters. If damaged state data is not available and accurate modeling of damaged components is desired, an effort to measure material properties in their damaged state is necessary. SNL has done limited work in this area in the past and data for the materials of interest may already be available.

Source Term Analyses

The source term analysis will use the number of failed rods, rod impact energy, and containment hole sizes calculated by the structural analysis and the time of burst rupture (region specific) calculated by the thermal analysis for input. MELCOR models of the HI-STAR 100/NAC-STC (from a compartment code point of view these two casks are very similar except the canister in the HI-STAR will be neglected for the STC) and of the GA-4 will be made to calculate blow-down times and internal deposition. The general method used in the vulnerability analyses will be used to calculate the release fractions. In this analysis, an implicit assumption is that all fuel rods are initially intact.

Risk Analyses

Accident Rates and Event Trees

The accident rates will be updated prior to the risk analysis. The rail accident rates will be compiled from 5 years of rail accident data from the Federal Railroad Administration (FRA) and the past 30 years of Hazardous Materials Incident Reports (HMIR). Contacting the Hazardous Materials/Radioactive Materials Program Specialists from the FRA and the major rail companies will provide specifics for hazardous material accidents. The event trees developed for the PPS will be used.

The truck accident rates will be complied using state-by-state data for the past 5 years for large truck accidents and looking at the past 30 years of the HMIR. A comparison of large truck accidents, hazardous material accidents, and radioactive material accidents will also be investigated to see if adjustments within the truck accident rates should be made. A comparison of the truck accident rates will also be made to the WIPP TRUPACT-II, SGT, and SNF accident/incident rates if adequate data are available.

Records of RAM transportation accidents show that most such accidents do not involve the cargo. However, any accident or incident, however minor, will result in the vehicle sitting immobile at the accident scene for some period of time. SNF casks emit external radiation, and first responders, workers, inspectors, and members of the public could be exposed for the time that the vehicle is immobilized. Therefore, the times involved in accidents in which the vehicle is immobile will be investigated. Such accidents will be used in modeling accidents in which the spent nuclear fuel shipments do not result in a release, but are stopped for a significant period of time.

Routine Shipment Risk Analysis

Impoundments?

Using the selected rail and truck casks, routine exposure to the crew, workers, inspectors, and the public (the affected populations) can be determined using RADTRAN 6.0. The SAR for each of the casks will be used to determine the average gamma/neutron exposure rate. These exposure rates will be used to determine the exposure to the affected populations.

Unit risk factors will not be used in the routine analysis. RADTRAN 6.0 can analyze multiple routes and categorize each route state-by-state and by rural, suburban, and urban population zone. The routes will be selected using WebTRAGIS, a web-based transportation routing analysis and graphic information system computer code which replaced INTERLINE and HIGHWAY, and consideration of the routes selected from state groups. A comparison of some of the NUREG/CR-6672 routes will also be conducted.

A few cases will be selected to compare doses to the Reasonably Maximally Exposed Individual (RMEI) between RADTRAN 6.0 and RISKIND 2.0. The differences will be discussed with respect to the differences in modeling.

Probabilistic Risk Assessment (PRA) will also be conducted for each of the affected populations. Using the Incident-Free Importance Analysis Summary, the input parameters influencing each output will be distributed if necessary. A detailed discussion will be done for each of the parameters distributed.

Accident Risk Analysis

Upon completion of the structural and thermal analysis and the source term estimation, specific scenarios will be selected for analysis. Each of these scenarios will be assigned an accident probability, release fraction, aerosolized fraction, and respirable fraction. These scenarios are only for those accidents which involve release. Vehicle speeds and other accident parameters that could result in these scenarios will be discussed.

If one or more accident scenarios could result in a loss of lead shielding (LOS) for the rail cask (either due to lead slump determined in the impact analyses, or lead melt determined in the thermal analyses), the RADTRAN 6.0 LOS model will be used to determine the dose and dose-risk to the affected population groups. The LOS results will be compared with those done in NUREG/CR-6672.

Unit risk factors will not be used in the accident risk analysis. Routes and route segments will be selected as discussed in the section on routine incident-free transportation.

The RADTRAN 6.0 stop model will be used to estimate the dose and dose risk to the populations of concern for accidents which involve the spent fuel package sitting somewhere for a period of time and result in no release of the package contents.

PRA will also be conducted for each of the affected populations. The input parameters influencing each output will be distributed if necessary. A detailed discussion will be included for each of the distributed parameters. Four different types of accidents will be analyzed using the PRA approach.

1. Accidents which involves a release of the package contents.
2. Accidents that involves a LOS for a rail cask.
3. Accidents that do not involve a LOS or release of the package contents (RADTRAN 6.0 stop model).
4. Accidents that lead to a criticality event (it is expected that the probability of this type of accident is vanishingly small, but explicit demonstration of that fact will be included).

The PRA results will be compared with those done in NUREG/CR-6672.

Accident Consequence Analysis

The consequence analysis will be conducted for each accident scenario. The analysis will be conducted for entire routes as well as selected locations within each of the population zones. The selected locations will not be named, but will provide a general understanding of potential consequences involved within that particular type of population zone.

Unit risk factors will not be used in the accident consequence analysis. Routes and route segments will be selected as discussed in the section on routine incident-free transportation.

PRA will also be conducted for each of the affected populations as discussed in the section on accident risk analysis.

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