PROBABILISTIC RISK ASSESSMENT OF BOLTED DRY SPENT FUEL STORAGE CASKS: REVISITED

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ABSTRACT

EPRI performed a Probabilistic Risk Assessment (PRA) of a bolted dry spent fuel storage cask in December of 2003. The study was performed for a bolted cask at a "generic" pressurized water reactor (PWR) site. A generic site was chosen so that the widest variety of challenges could be considered. The study calculated the annual individual radiological risk and consequence associated with a single cask lifecycle where the lifecycle is divided into three phases: loading, on-site transfer and on-site storage. The study used standard methods of PRA with the following analysis tasks: initiating events, data analysis, human reliability analysis, structural analysis, thermal-hydraulic analysis, accident sequence analysis and consequence analysis. The results of the original study show that risk is extremely low with no calculated early fatalities and a first year risk of latent cancer fatality of 3.5E-11 per year per cask. Subsequent year risk to the general public is even lower; with, again no early fatalities and a cancer risk of 4.2E-12 per cask per year.

In 2004, EPRI revised the spent fuel cask PRA assessment to remove selected conservative assumptions associated with various analysis simplifications. The updated study calculates a first year cancer risk of 5.6E-13 per year per cask with no early fatalities. This corresponds to a 98% reduction in the latent cancer radiological risk. The update study calculates a subsequent year risk is 1.7E-13 per year per cask. This corresponds to a decrease of 96% decrease in the latent cancer radiological risk.

The conclusions of the original study and its subsequent update confirm the extremely low radiological risk to the general public of the dry storage of spent nuclear fuel. In addition, the extremely low radiological risks associated with the dry storage of nuclear fuel indicates a potential for increased risk-informing of regulations associated with the design of spent nuclear fuel casks and facilities as well as the handling of spent nuclear fuel.

INTRODUCTION

EPRI complete the original PRA of a bolted spent fuel cask to assess the radiological risks to the public due to the lifecycle of a dry fuel storage cask. The original study is documented in “Probabilistic Risk Assessment (PRA) of Bolted Storage Casks: Quantification and Analysis Report” [1]. The study was performed to gain insights related to the risks associated with the dry storage of spent nuclear fuel.

The original study as well as the subsequent study [2] is performed on a bolted cask design at a generic PWR site. A bolted cask design [3] as well as a PWR site is chosen to complement on-going work by the U.S. NRC which is performing a similar study for a welded cask at a boiling water reactor (BWR) site. A generic site is chosen as opposed to a particular site so that the widest range of challenges can be addressed.

METHODOLOGY

The original study as well as its revision both used traditional PRA techniques [4] in their development. There are several notable exceptions. First, the cask PRA includes both design basis and beyond design basis events as well as external hazards. In addition, the figure of merit in this study is radiological risk as measured by early fatalities and latent cancer risk. The development of the spent fuel cask PRA is divided into eight tasks. These are:

Initiating Event Analysis. The initiating event analysis determines those events that could present a hazard to the cask and potentially release radionuclides into the environment.

Data Analysis. The data analysis determines the probabilities and frequencies of occurrence of the various hazards, the probabilities associated with the failure of radionuclide barriers and the probability of failure of mitigating systems.

Human Reliability Analysis. The human reliability analysis assesses the probability of various human actions the can impact an accident sequence. These events include those associated with the handling of the spent fuel, handling of the cask and monitoring of the cask.

Structural Analysis. The structural analysis is performed to assess the probability and the mode of the failure of the cask confinement under the conditions postulated in the accident sequences. The conditions postulated in the accident sequence includes both design basis and beyond design basis events.

Thermal Hydraulic Analysis. The thermal hydraulic analysis is performed to assess the probability as well as the mode of the failure of the cask under various thermal hydraulic conditions postulated in the accident sequences.

Accident Sequence Analysis. The accident sequence analysis is performed to both develop and quantify the accident sequences associated with the cask life cycle. The accident sequence analysis uses standard fault tree modeling techniques to produce and quantify the accident sequences.

Consequence Analysis. The consequences analysis determines for each accident sequence to consequence to a member of public located near the site boundary. This distance varies from 100 to 300 meters depending on the accident sequence.

Results Interpretation. The final task of the spent fuel cask PRA is the interpretation of the analysis results.

RESULTS

Original Study Results

The original study results [1][5], sorted by lifecycle phase, are summarized in Table I. As can been seen from the table, the loading risk dominates the risk profile with 80% of the total risk. This phase is followed by the storage phase at 12% and transportation phase at 8%. However, as noted in the original study this conclusion is driven by several significant assumptions.

Table I. Summary of Original Study Results (Sorted by Lifecycle Phase)

Lifecycle Phase	First Year Risk (per cask per year)	Subsequent Year Risk (per cask per year)	Percent of Total Risk (First Year)
Cask Loading Phase	2.8E-11	N/A	80%
Cask Transportation Phase	2.9E-12	N/A	8%
Cask Storage Phase	4.2E-12	4.2E-12	12%
Total of All Phases	3.5E-11	4.2E-12	100%

The top six sequences, in order of contribution, from the original study are provided on Table II.

Table II. Summary of Top Sequences (Original Study)

No.	Sequence	Phase	Frequency	Percent
1	Horizontal Drop	Loading	2.6E-11	73%
2	Refueling Building Structural Failure (seismic event)	Loading	2.5E-12	7%
3	Horizontal Drop	Transfer	2.3E-12	6%
4	Heavy Loads Exceed Structural Limits (high winds and missiles)	Storage	2.1E-12	6%
5	High Temperature and Forces (Aircraft and natural missiles)	Storage	2.0E-12	6%
6	High Temperature Fire (Transporter Fire)	Transfer	6.4E-13	2%

Key Assumptions

While every attempt was made to perform a realistic study of the risks associated with the spent fuel cask life cycle, significant assumptions were required to meet the study goals within the resources available. Significant assumptions were made to bound the analysis, reduce or simplify the analysis, or to facilitate identification or quantification of the accident sequences. Therefore, the original study should not be classified as a best estimate analysis. The analysis is not so conservative as to portray it as conservative. The best description of the analysis is an estimate of the radiological risk within the bounds provided by the assumptions documented in the report. Several assumptions made in the original analysis have a significant impact on the analysis results. These assumptions are:

1. A generic plant was analyzed. The purpose of assuming a generic plant site was to allow reflection of the widest set of challenges to the cask. However, plant specific hazards that are not reflected in the generic evaluation could lead to an underestimation of the total risk while challenges that are included in the analysis that are not present at a specific site can result in an overestimation of the risk.

2. The original cask study assumed that the cask movement to the transporter is comprised of a two-stage process where the cask is lifted twice. Since, the lifting process contributes significantly to the total risk in the original study this assumptions is significant. In practice, several utilities use a single move process.

3. It was assumed that acceleration related events resulted in two fuel pin failures. Since failed fuel pins are the source of the radiological consequence, this assumption directly impacts the estimated risk.

4. The fragility analysis associated with the horizontal drop of the cask within the refueling building has a high epistemic uncertainty. The uncertainty is assigned due to the potential for the cask to impact other equipment within the zone of influence during decent. In practice, many utilities have clear load paths that encompass the zone of influence of the cask and therefore, the epistemic uncertainty could be overstated. The overstatement of the epistemic uncertainty leads to a high-calculated mean value for the failure of the cask confinement when dropped horizontally within the refueling building.

5. Refueling building mitigation is not addressed in the original study. It is likely that the refueling building ventilation systems, designed to mitigate the radionuclide releases from a range of refueling accidents, would significantly reduce the dose and therefore risk to the general public.

6. Weather conditions, and therefore exposure, were optimized for the maximum possible dose to the receptor individual. Therefore, risk was conservatively portrayed.

Revised Study Results

The revision to the spent fuel cask PRA was undertaken to remove or reduce the impacts associated with simplifying assumptions. Specifically, assumptions related to the fragility analysis in horizontal drops, refueling building mitigation and weather conditions were investigated (assumptions 4, 5, and 6). Assumptions 1, 2 and 3 were not modified during the revision to the study. In addition, the opportunity was taken, during the performance of the revision to correct minor omissions and errors in the original report.

The results of the revised study are a reduction of 98% in the first year cancer risk to a value of 5.6E-13 per year per cask with no early fatalities and a reduction of 96% in the subsequent year risk to a value of 1.7E-13 per year per cask.

Table III provides the results of the updated study sort by lifecycle phase. See Table IV for Summary of Top Sequences from the Revised Study.

Table III. Summary of Revised Study Results (Sorted by Lifecycle Phase)

Lifecycle Phase	First Year Risk (per cask per year)	Subsequent Year Risk (per cask per year)	Percent of Total Risk (First Year)
Cask Loading Phase	6.3E-14	N/A	11%
Cask Transportation Phase	3.3E-13	N/A	59%
Cask Storage Phase	1.7E-13	1.7E-13	30%
Total of All Phases	5.6E-13	1.7E-13	100%

Table IV. Summary of Top Sequences (Revised Study)

No.	Sequence	Phase	Frequency	Percent
1	High Temperature Fire of Transporter	Transfer	3.2E-13	58%
2	Heavy Load Exceed Structural Limit (high winds and missiles)	Storage	8.5E-14	15%
3	Cask Failure Due to High Temperature and Forces (aircraft and natural missiles)	Storage	8.3E-14	15%
4	Vertical Cask Drop	Loading	5.8E-14	10%
5	Horizontal Cask Drop	Transfer	5.6E-15	1%
6	Refueling Building Structural Failure (seismic event)	Loading	4.0E-15	0.7%

Results Comparison

As can be observed from a comparison of the total risk of the original and revised study there is a 98% decrease from 3.5E-11 per cask per year in the original study to 5.6E-13 per cask per year for the revised study. This corresponds to a factor of 60 decrease in total frequency of latent cancer deaths. Figure 1 illustrates graphically the differences between the relative lifecycle risk (by lifecycle phase) of the original study and revised study.

It can be observed from Figure 1, that the relative contribution of the loading phase has decreased dramatically from the original study. At the same time the relative contributions of the transfer and storage phases has increased significantly. Much of this change is due to the treatment of assumption number 5. In the original study the refueling building mitigative systems, specific the air handling and filtration systems, were not modeled. In the revised study, a detailed fault tree model was created of the air handling and filtration systems. The result of the additional modeling is a significant reduction in the dose to the general public for those accident sequences that occur during the loading phase inside the refueling building. In addition, assumptions related to release level (i.e., ground level versus elevated) were also modified. This also has an impact on the radiological dose to the general public. Lastly, assumptions related to weather conditions were also changed to more adequately reflect average weather conditions as opposed to worst possible weather conditions (assumption number 6). It should be noted that the treatment of the weather conditions affect not only those sequences that occur during the loading phase but all cask lifecycle sequences.

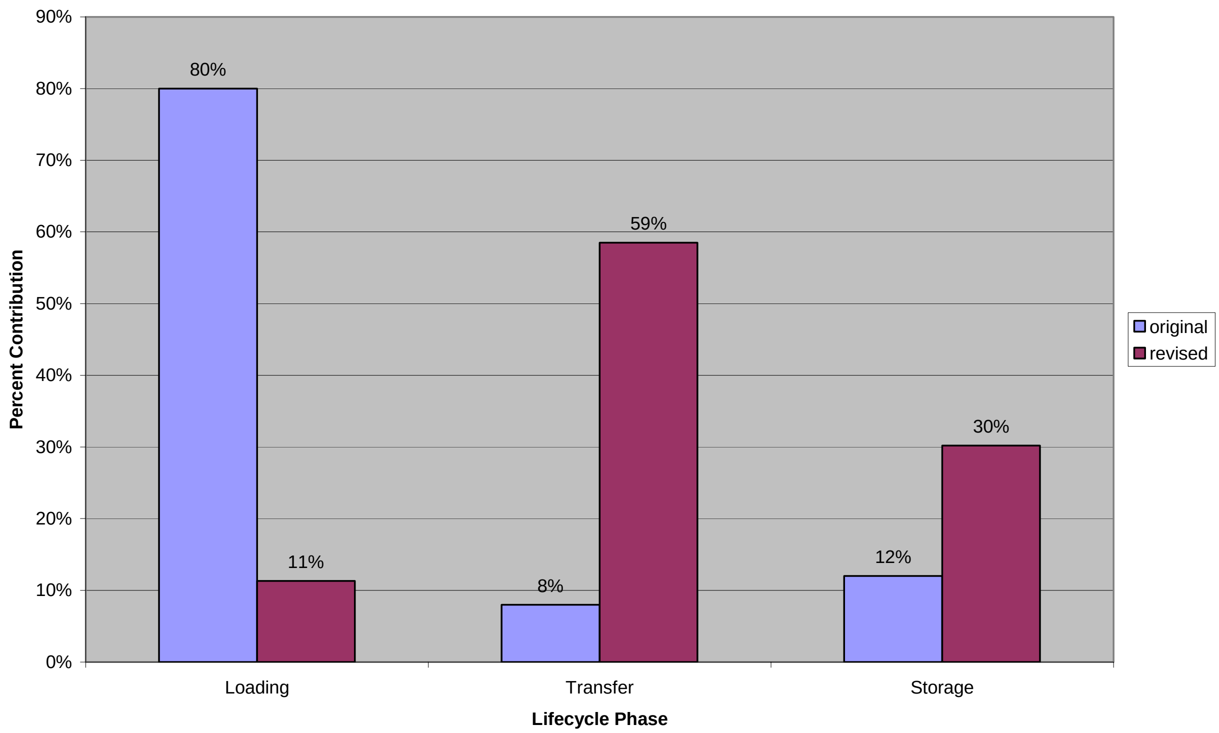

Fig. 1. Comparison of Percent Contributions to Lifecycle Phases

On an absolute basis, the absolute risk drops for all cask lifecycle phases. In the case of the loading phase, the absolute risk drops a factor of 444, with the transfer and storage phases dropping by significantly smaller factors of 8.8 and 24.7, respectively.

The significant change in the relative contributions of the lifecycle phases is also evidenced in the accident sequences. In the original study the top sequence was a horizontal drop of the cask within the refueling building, which contributed 73% to the total risk. This sequence no longer appears within the top six sequences. This is a result of the impact of the adjustment of assumptions 5 and 6 as well as assumption 4 which is the revision of the epistemic uncertainty associated with the horizontal drop of the cask.

The second sequence in the original study is the structural failure of the refueling building due to a seismic event (7%). It is assumed that a cask tip-over occurs in this sequence. As such, the failure of the cask confinement barrier is assigned as a horizontal cask drop event. This sequence is reduced by the reduction in the epistemic uncertainty associated with a horizontal drop of the cask. In the revised cask study, this sequence is sequence number 6 contributing 0.7% to the total risk.

The third sequence in the original study is the horizontal drop of the cask within the refueling building during the cask-loading phase. This sequence contributed 6% to the total risk in the original study. This sequence does not appear in the top six sequences in the revised study as a result of the modifications to assumptions 5 and 6 as well as the consideration of elevated release pathways.

The fourth sequence in the original study is heavy loads exceeding the structural capacity of the cask as a result of high winds and missiles. This sequence contributed 6% in the original study and is sequence number 2 in the revised study contributing 15% to the total risk.

The fifth sequence in the original study is cask failure due to high temperature and forces due to aircraft crashes or natural missiles. This sequence contributed 6% to the total risk in the original study and is represented by sequence number 3 in the revised study contributing 15% to the total risk.

The sixth sequence in the original study is cask failure due to a high temperature transporter fire during transport. This sequence contributed 2% in the original study and is represented by accident sequence number 1 in the revised study contributing 58% to the total risk.

One additional sequence appears in the revised study top six sequences to replace the original accident sequence number 1. This sequence is the horizontal drop of the cask during the transfer phase. This sequence appears as number 5 in the revised study and contributes 1% to the total risk.

CONCLUSIONS

Both the original study and the revised study conclude that the risk to the general public of the lifecycle of a bolted dry fuel storage cask is extremely low. The revised study concludes that the risk of latent cancer fatality is 5.6E-13 per cask per year for the first year and 1.7E-13 per cask per year for subsequent years. Both studies conclude that there are no calculated early fatalities for the general public. These risks are orders of magnitude below other risks found in the nuclear power industry and those encountered by the public in day-to-day activities. The results of the studies demonstrate the ruggedness of the cask to withstand both design basis and beyond design basis events.

While the revised study represents an improvement in the technology used to measure the risk as well as the reduction of several key conservatisms, the application of the probabilistic methods employed to assess health risks of storage casks remains in its infancy (e.g., regulator review of the methods and results of the studies has been performed). While additional research is desirable to ensure all contributors are appropriately reflected in the results, at these low levels of risk, significant allocation of resources is generally not warranted unless there is a commensurate reduction in the regulatory burden associated with the design, handling, or monitoring of dry fuel storage casks.

It is important to note that the result of the cask studies is limited to the calculation of the public health risk. Other risks, such as economic risk and public perception of dry fuel storage are not within the scope of these studies. Such events include drop of the cask without confinement breach and without radiological release as well as other potential economic events. While the frequency of occurrence of these events is relatively low when compared with other risk in the nuclear power industry as well as those encountered by the public in day-to-day activities, they are significantly higher in likelihood than the radiological risk to the general public. The economic and public perception risks are not emphasized in either study, however, the frequency of occurrence of events are calculated in the studies and available to the reader for consideration. In addition, the methods used in the studies to evaluate radiological risk could be applied in the determination of economic or other risks.

REFERENCES

[1] "Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Quantification and Analysis Report", EPRI Technical Report 1002877, December 2003.

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[3] Transnuclear, Inc., "TN32 Final Safety Analysis Report", Revision 1.

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[5] "Probabilistic Risk Assessment (PRA) of Bolted Dry Spent Fuel Storage Cask", ASME ICONE12-49607, 12th International Conference on Nuclear Engineering, April 2004.