20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 9, Paper 1936

Technical Challenges related to the Spent Nuclear Fuel Dry Cask Storage/Transportation Analysis and Design

Tripathi Bhasker (Bob) P. [a]

[a] United States Nuclear Regulatory Commission, Mail Stop: EBB-3D-02M
Washington, DC 20555-0001, USA
e-mail: ***Bhasker.Tripathi@nrc.gov***

Keywords: Spent Nuclear Fuel, Dry Cask Storage, Storage and Transportation, Technical Challenges.

1 ABSTRACT:

With the introduction of new, and highly sophisticated spent fuel dry cask storage and transportation designs involving three-dimensional non-linear dynamic finite element analyses, using codes such as: ANSYS, LS-DYNA, ABAQUS and others, industry as well as the U. S. Nuclear Regulatory Commission (NRC) is faced with unique technical challenges for which there are few precedents.

Licensees, spent nuclear fuel dry cask storage and transportation vendors, and, in turn, the NRC are managing the potential application of: 1) exotic and un-conventional non-code approved materials; 2) increased mass and fissile material loads; 3) increased number of fuel assemblies for both, boiling water reactor (BWR) and pressurized water reactor (PWR) fuels; 4) burn-up credit; 5) fracture mechanics analytical approach; 6) loading high burn-up fuels; and 7) analysis vs. testing, etc. Addressing these design considerations has created new technical challenges to demonstrate that the integrity of the fuel assemblies is maintained during the storage and/or transportation phase, and to demonstrate compliance with the applicable requirements of Title 10 of the Code of Federal Regulations (10 CFR) Part 72, and 10 CFR Part 71 respectively.

This paper will discuss, in general, these and other issues from an overall perspective. This paper will also elaborate, in detail, some of the issues related to analysis vs. testing, and the merits and pitfalls of full-scale vs. scaled model testing used to demonstrate the structural integrity of the cask and its contents. I will also briefly discuss pre-test and post-test calculations, validation and benchmarking of analyses based on drop tests, test positions, test sequences and other state-of-the-art measurement techniques to measure the decelerations, and other relevant issues.

2 OVERVIEW OF STORAGE AND TRANSPORTATION ISSUES:

Currently there are 51 independent spent fuel storage installations (ISFSIs) across 33 States in the US. This amounts to over about 1,100 loaded storage casks. An ISFSI map is available at www.nrc.gov, (ADAMS # ML083020621). Over the past few years, NRC has experienced a significant increase in the technical complexity of casework in both Part 71 radioactive material transportation and Part 72 spent fuel storage applications. More optimized designs with reduced engineering and safety margins have required a closer more detailed technical review of the applications. Also, we encouraged applicants to “bundle” submittals, rather than separately submit several minor amendments and revisions. In the short run, although it may appear that the number and workload for spent fuel storage submittals has decreased, it is quite the contrary.

The applications now often consist of several “bundled” changes which typically add to the length and complexity of each individual review. In addition, vendors and licensees increased use of 10 CFR Part 72.48 change authority has significantly complicated the technical review of applications. NRC staff review must not only focus on the changes contained in applications requiring review/approval, but NRC must also develop an understanding of the changes implemented by vendors and licensees under the 10 CFR Part 72.48 change authority, and the relationship/impact of the collective set of changes.

Although much of the increasing technical complexity of casework has been evident in the applications related to transport and storage of spent fuel, many of the same technical challenges have been identified in storage and transportation of radioactive materials casework. The following examples provide comparisons between casework a few years ago and present casework, and identify some of the significant technical challenges being addressed by NRC.

A high-level overview of what NRC, as the regulator, sees on the horizon for spent fuel storage in USA, including some possible future "Vision" is presented here.

In the near term – what we are currently facing and what we will/may deal with in the next few years; the kinds of information we are being challenged to make regulatory decisions on and manage; process issues that are being driven by industry trends and licensing actions. The Vision – what we may see in the long-term with respect to regulatory involvement in the future of spent fuel storage. Industry designs are introducing new approaches for tackling technical and other issues, for example: above-ground storage to below-ground storage, the potential of future implementation of transportation aging and disposal (TAD) casks, etc. In the ever changing and increasing unstable domestic and worldwide environments, security considerations are even more important. Environmental considerations have required attention and will continue to do so in certain locales - possibly on an even broader basis. Another thing to consider is, a growing sensitivity to the connection between 10 CFR Part 72 and 10 CFR Part 71, certification. Some other challenging scenarios are: managing the review of design concepts – a cask with design "attributes" versus a cask with specific discrete and defined design elements. Often we ask, "What is it we (the NRC) are approving?" The NRC must look at methods to make the licensing process more efficient and "user-friendly" both for the stakeholders and internally for the NRC staff.

Ten years ago, a large-capacity spent fuel storage and transport cask was designed to hold 24 PWR assemblies. Presently, a large-capacity spent fuel storage and transport cask is designed to hold 32 – 37 PWR assemblies (a 50% capacity increase with no commensurate increase in cask dimensions). Ten years ago, spent fuel storage casks were designed for a thermal load of up to about 20 KW. Presently, spent fuel storage casks are designed to hold approximately 40 KW thermal loading (a 100% increase in thermal loading, with continued reliance on passive heat dissipation). Ten years ago, high burn up fuel considered for storage and transport was limited to a maximum 45 MW days / MTU. Presently, high burn up fuel considered for storage and transport is in the range of up to 70 MW days/MTU (a 50% increase in burn up). Very little research has been performed on higher burn up fuel and cladding during long term storage and how this higher burn up fuel and cladding will behave under the 10 CFR Part 71 transport hypothetical-accident-conditions.

On the theme of new and novel design approaches, the NRC is constantly being challenged in the technical area to review information that pushes the envelope. Some examples are: Higher heat loads that push temperatures to within a few degrees of acceptance criteria, use of new materials – e.g., application of neutron absorber materials for which there is little community experience and long term performance data available, increasing the mass and fissile material loaded into storage containers, increasing the number of fuel assemblies in a cask means less space for thermal mediation – a denser basket, loading higher burn up fuels, taking advantage of burn-up credit, using un-conventional and non-code approved materials, using fracture mechanics approach to demonstrate fuel cladding integrity of high burn up spent fuel. Applicants may have been allowed in the past to store and transport low burn up fuel, however, the same fracture mechanics criteria and approach may not be applicable when it comes to storing and transporting spent fuel that has been categorized as high burn up fuel. There is a limited amount of mechanical properties test data for high burn-up fuel cladding with radial hydrides. Due to the lower stress and hydrogen content expected in low burn-up rods, the mechanical properties of cladding material, such as ZIRCALOY family of fuels, with circumferential hydrides was determined to be acceptable for use when analyzing cladding behaviour from low burn-up rods. However, this is not acceptable for the analysis of high burn-up rods where the stress is much higher and considerable hydride reorientation might occur.

All these challenges are placing greater emphasis on the knowledge base for the WHOLE fuel cycle. Fuel vendors have to consider the back end of the fuel cycle. Not proactively considering the back end of the fuel cycle compounds the technical challenges when it comes time to store the spent fuel. And finally, the growing trend toward analytical modelling. With greater computing power and modelling capabilities, coupled with the rising cost of testing, analytical modelling is becoming ever more the norm. This is challenging the NRC when it comes time to make the safety finding, and approve a design

Other long-term issues that need to be addressed in future:

We need to take note of successes in licensing, and similarly learn from processes that can be improved. We are currently exploring licensing terms, as an outcome from recent license renewal actions the agency has taken for site specific ISFSIs. We are also exploring the nexus between 10 CFR Part 72 and Part 71, and perhaps a means of drawing those two regulations closer together and avoiding the “storage only license.” Applying a more risk informed and performance based approach to licensing is always ripe for application. Ways to help us as the regulator to plan more effectively may include “Letters of Intent”, plainly stated schedules for which the NRC can plan, obtain, and allocate resources for.

What we may see in the long-term with respect to regulatory involvement in the future of spent fuel storage? Will there be a shift toward consolidated storage and or longer-term storage? And if so, NRC will need to be in a position to review such applications. What will be the extent to which fuel retrievability should be considered? A key consideration is the characterization of the fuel at the time of storage. Our evolving national strategy regarding waste management may include the potential for recycling and reprocessing. Where might that leave consideration of interim storage for spent fuel? Are there alternative waste configurations and waste streams for storage? A market where domestic vendors are selling US licensed designs abroad. Where international entities are supplying components for US licensed designs for domestic use and potentially manufactured entirely abroad, to be used domestically. This trend will most likely increase. How will the combining of the storage of spent fuel and transportation will affect the final approval? With a maturing storage program the focus will be ever more on transportation issues and what, when and how the fuel in storage will be transported. These and other issues may shape the way, we as regulators conduct business in the future.

3. INCREASING TECHNICAL COMPLEXITY OF NRC TRANSPORTATION AND STORAGE CASEWORK:

Modeling and Analysis:

The evolving “state of the art” in computational modelling technology supports more refined and exact modelling and prediction of transport package and storage cask performance under routine and accident conditions. These advanced computer-assisted tools are being used by applicants in structural, thermal, shielding, and criticality analyses, and may necessitate their use by NRC in review of these applications. The higher-capacity casks, higher heat loads, increased fissile-material contents, and increased source terms collectively and significantly challenge engineering design margins, which in turn requires more exacting design and commensurate markedly more detailed and exacting NRC technical review. The use of “state of the art” modelling technologies necessitate a significant increase in the NRC information technology equipment and computational modelling software, along with enhanced training and skill of the NRC technical reviewer in use and interpretation of the new modelling technology, tools and results. With the increased fissile-material content of casks and the reduction or changes in neutron-absorbing material in the cask canister, to support the increased number of assemblies, consideration of burn up credit and moderator exclusion requires significant technical analysis and development of information and data to support evolving technical arguments.

New Designs and New Materials of Design:

An underground storage design has presented new structural, civil, thermal, and environmental modelling and review issues not seen in previous reviews. New lighter-weight transfer cask designs to facilitate cask loading and movements for sites with limited crane capacities, raise new shielding, thermal, and structural modelling and review issues not seen in previous reviews. New spent fuel canister designs relying in large part on mechanical rather than welded connections challenge structural reviews in ways not seen in previous reviews. New materials (e.g. METAMIC) of design require extensive review to understand how they perform under structural, thermal and radioactivity challenges, and how they meet NRC performance requirements.

High Burn up Fuel, Increased Number of Fuel Assemblies, Mass and Fissile Material Loads:

From the thermal perspective, new designs for spent fuel storage and transportation casks present NRC with ever increasing challenges. As the decay heat-load capacities increase and cooling time for the spent fuel assemblies decrease for the new designs, thermal margins for the fuel clad and other cask components, including seals, are decreasing. The need for the NRC to thoroughly review and understand the analysis methodologies being submitted for approval of new designs becomes increasingly vital as thermal margins decrease. The models used to analyze the designs being submitted must be more precise and more accurate, and methods must be convincingly validated and benchmarked, in order for the staff to have reasonable assurance that the models are correctly predicting the behavior of the submitted designs. Because of uncertainties associated with materials and specifically with the properties of high burn up fuel, the NRC generally encourages a degree of conservatism in the modelling approach. This degree of conservatism will become more challenging to include in the analysis and design, as the capacities and heat-loads of cask designs increase.

Burn up Credit and Criticality for Transportation Packages:

Burn up is defined as: the amount of energy released from a fuel assembly in a reactor in terms of Megawatt-Days per Metric Ton of initial Uranium (MWD/MTU), which results in an overall reduction of fuel assembly reactivity. Criticality safety analyses for spent nuclear fuel transportation packages have typically been performed with the conservative assumption that the fuel is unburned. This assumption, in general, results in a large margin of sub-criticality, and reduces the number or initial enrichment of spent fuel assemblies that may be transported in a package.

In an effort to make spent fuel transportation packages more efficient, applicants for certificates of compliance under 10 CFR Part 71 have increasingly sought credit for the reduction in reactivity that occurs with spent fuel burn up, or burn up credit, in their criticality safety analyses. The ultimate goal is to have higher capacity for dry storage and transportation, and the ability to transport an entire inventory of commercial spent fuel when needed. NRC's Division of Spent Fuel Storage and Transportation (DSFST) published Interim Staff Guidance 8 (ISG-8), "*Burn up Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks*," in May of 1999, with subsequent revisions in July of 1999 (Revision 1) and September of 2002 (Revision 2). This document provides guidance regarding acceptable approaches to burn up credit criticality analyses for intact spent PWR assemblies in transportation packages. One application for burn up credit has been approved by NRC and three others are under consideration.

The details of the technical basis supporting the recommendations in ISG-8, including that for: 1) the licensing basis limits and model assumptions, 2) acceptable validation techniques for isotopic depletion and criticality codes, 3) the determination of burn up credit loading curves, and 4) the assigned burn up loading value, will be addressed in a technical paper titled, "Realism and Robustness in Criticality Safety for Spent Nuclear Fuel Transportation" at the "Topical Meeting of the ANS Nuclear Criticality Safety Division, 2009". Additionally, the paper will discuss staff considerations for a potential future revision to ISG-8, which may incorporate new data and computational techniques available for isotopic depletion and criticality code validation, as well as potential alternatives to in-pool burn up measurements to prevent assembly misloads.

4 STRUCTURAL ANALYSIS VS. TESTING ISSUES:

Dry cask storage and transportation vendors, as well as ISFSI licensees are increasingly seeking NRC approval by analysis-only when submitting new applications. This has been made possible by the recent advances in computing power. The obvious advantage of using advanced computing to determine structural response is that a vendor or licensee can extract volumes of information from a given analysis that would otherwise not be feasible from physical testing because of instrumentation limitations or cost constraints. The disadvantages of an advanced analytical approach include, but are not limited to material modelling with failure, accurate homogenization of anisotropic materials, component simplification, lack of incorporating initial imperfections, lack of accurate weld modelling, appropriate selection of biaxial or tri-axial material effects, mesh selection and refinement, and rate effects, in addition to user error with respect to the chosen computational modeling software. Given these disadvantages, it is incumbent on the applicant to demonstrate the capability of both the software being used, as well as the associated methodologies, such that they are able to replicate events from a known test case that is representative of the genre of packages they wish to license. This demonstration is the benchmark analysis.

A benchmark analysis can contain several levels of rigor, depending on the goal of a particular application. The levels of rigor in the benchmark analysis are dependent on the degree of instrumentation available for the test. If for example, the selected benchmark test only employs accelerometers on the external surface of the package then the benchmark analysis is sufficient only in determining whether the analysis can replicate rigid-body deceleration, it does not imply, nor is it acceptable to assume, that the applicant has accurately modeled tri-axial bolted joint behaviour. This scenario would require an additional layer of rigor, to include a verified component model of a single bolt under a dynamic tri-axial load that could subsequently be incorporated in the full dynamic model of the package.

International Perspective on the issue of Analysis Versus Testing:

There are certain difficulties and serious limitations of the scaled-model testing. Possible errors must be taken into account when using results of scaled-model tests. Per the International Atomic Energy Agency (IAEA) regulations for spent fuel package response under accident conditions, drop testing with reduced-scale models, as opposed to a full-scale model testing is an acceptable method to meet the regulations. The Federal Institute for Materials Research and Testing (BAM) in Germany has conducted drop tests on spent fuel packages for storage and transport, using both a full-scale prototype and its reduced-scale model, as required, at various height and orientations. See Figure 1 through Figure 3 (Courtesy of BAM - Droste, Bernhard, 2007) below for details. The test results were compared for both the full-scale and reduced-scale 1:2.5 model for responses (Quersetti, Thomas; et. al). Comparison of the analyzed experimental data showed the similarity of the impact response between the scaled and prototype model and concluded that it depends on many influencing phenomena and parameters besides the apparent limitations of the scaling model. It was also found that the effect of the internal impact caused a high temporary loading on the primary lid and its lid bolts, as indicated by the appropriate strain measurements. It was concluded that the effect of the internal impact did not appear adequately, in the scaled-model test, although the original existing gap between cask lid and contents/basket was exactly modelled. Acceleration due to gravity played a decisive role in the relative movement and internal impact. The effects of scaling, influence of manufacturing processes, simulation of basket and radioactive content, questions of similarity between scaled model and full-scale prototype, limited number of drop tests, drop test orientations, temperature effects on impact limiter properties, etc. are addressed in Koch (Koch, Frank; et.. al).

Figure 1. 9-Meter Vertical Drop Cask

Figure 2. 9-Meter Oblique Drop Cask

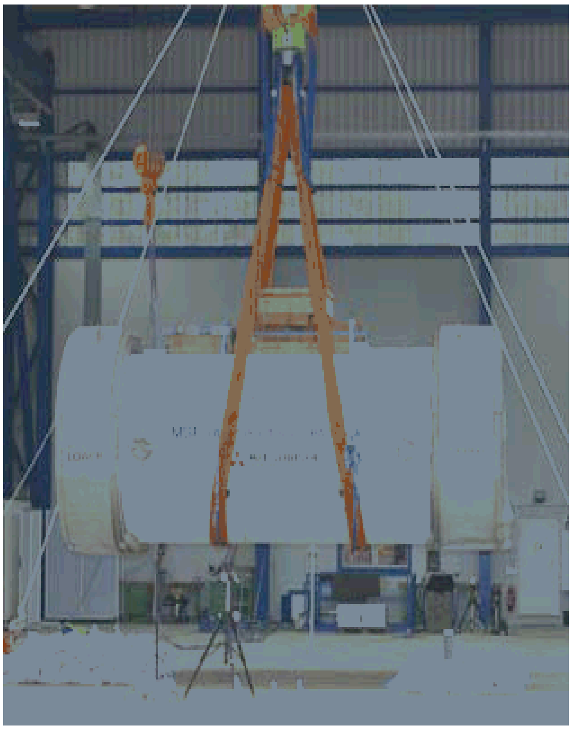

Figure 3. 1-Meter Horizontal Drop - Cask Orientation

Dr. Droste of BAM (Droste, Bernhard 2007) has summarized the entire issue of full-scale and small-scale models very eloquently as follows: …..“Small-scale model drop testing and calculation can be an essential part of mechanical safety assessment. However, for small-scale testing it needs a lot of pre- and post-test calculations that need to be verified based on drop tests. Both full-scale and small-scale testing of package drops need material/component testing and transfer investigations to verify the original package response and its structural analysis. Full-scale package drop testing is more effective for complete package design verification, calculation verification and safety demonstration. However, in case of large spent fuel and casks (e.g. with more than 100 tons) it is nearly impossible to realize a complete drop-test program with one specimen; some dedicated test positions/sequences have also to be accompanied with small-scale model, component, and material tests, as well as by calculations, to cover all worst-case conditions. In this case, also pre- and post-test calculations are necessary. The state-of-the art performance of reduced-scale and full-scale model drop testing needs extensive pre-test analysis, a complete test program with sophisticated measurement techniques and complex analysis, to verify the original package design. A complete safety assessment needs a complex combination of all test methods such as: small-scale, full-scale package testing, component tests, materials tests, and calculations and reasoned arguments to comply with all regulatory and design conditions"…...

NRC Package Performance Study – Current Status and Approach:

The NRC has continued to plan for the package performance study (PPS), in accordance with the Commission direction. Associated with this effort, the NRC has been re-evaluating the timing and scope of the PPS to account for recent developments regarding spent nuclear fuel transportation casks as follows: Perform a demonstration test on a rail transportation cask. Tie the demonstration test schedule to either Department of Energy (DOE)'s placing an order for or NRC's issuance of a certificate of compliance for a transportation, aging, and disposal (TAD) cask. Continue preparatory work for the demonstration test and keep the Commission apprised of its progress. Complete the review and analysis of the BAM drop tests analysis.

The NRC is taking a multi-step approach to accomplish the PPS objectives as follows: The first step will be to validate the NRC and industry practices, and enhance public confidence in the use of computer modelling and scale model tests as a basis for certification of transportation casks. Next, complete full scale and scale model casks drop test analyses, and compare results with the analyses conducted by the BAM on the German and Japanese casks and test data. Report results to the NRC Commission and provide report to the public. The response of the casks during a regulatory drop test and a realistic severe train accident scenario will be compared. NRC will then apply results from the German and Japanese analyses to the TAD casks that are likely to be used to transport nuclear fuel to the proposed long term repository. Independent drop test analyses on two TAD casks that have been certified by the NRC will be performed, and computer simulation of a train-locomotive impact on the German and Japanese casks will be done to compare the results of a similar impact on the two TAD casks. The final step will be to visually demonstrate the performance of a NRC certified spent nuclear fuel transportation cask in a realistically severe accident and to demonstrate NRC's ability to predict such performance by computer modelling. Specifically perform 9 meter (30 feet) regulatory drop test, train-locomotive crash demonstration test, and fire test on the on the selected TAD cask that was previously subjected to a locomotive crash demonstration test.

5 CONCLUSIONS:

What does all this mean? NRC will need to prioritize the issues and challenges. Some are more pressing than others; however, they should not become an impediment to stakeholders, while upholding the fundamental principle of safety. Dependent on the degree of the technical challenge we are encountering, extended review durations will be required. Information submitted for review and approval to support a new approach or concept, takes more time than usual. Obtaining data to make a finding can be challenging and takes time. Facilitating dialogue in an open and public forum can be difficult at times when dealing with new proprietary designs. Interaction with our stakeholders is paramount to a successful outcome. And not just with applicants. Sometimes due to the degree of technical complexity of the application, the best way is open face-to-face dialogue. This, however, may be hampered by distance and the availability of the individuals involved. And as the demands on resource availability have increased, resources must be utilized as efficiently as possible.

In summary, this paper has briefly touched upon a wide variety of issues facing spent nuclear fuel storage and transportation. Some issues are current and we need to resolve them now, and some of the issues are what we envision in future. We also discussed technical challenges that NRC is facing due to: use of the un-conventional non-code materials for the storage and transportation casks, analysis vs. testing for normal, and accident conditions regulatory drop analysis, effects of scale-model vs. full-scale cask for drop analysis, high burn up fuel and problems associated with transporting such fuel, etc., Industry wide a milestone has been reached in US - with over 1100 loaded licensed spent fuel casks at 51 ISFSIs storing over 42,000 fuel assemblies [Store Fuel April 7, 2009]. NRC should use this experience to: Become more effective and efficient. Both the short-term and the long-term Vision regardless of the evolving market environment aim to provide a more stable and predictable regulatory framework. The complexity and number of licensing actions we are foreseeing will challenge existing resources. However in the interest of being more effective and efficient there are initiatives under way to cope with the ever increasing demands.

Acknowledgements: *The author would like to thank E. William (Bill) Brach, Christopher Regan, Jason Piotter, Andrew Barto and Christopher Bajwa for their input in the preparation of this paper. A special thanks to Christopher Regan for a thorough review of the paper.*

6 REFERENCES:

Droste, Bernhard, 2007. Experiences and Perspective of Package Testing Under Hypothetical Accident Conditions". Opening Technical Plenary Session, October 22, 2007. PATRAM 2007, Miami, Florida, USA

Koch, Frank, et.al. Koch Frank; Droste Bernhard; Krietsch Torsten. Consequences of Drop test Parameter Limitations for Subsequent Package Design Safety analysis. Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials, PATRAM 2007, October 2007, Miami, Florida, USA

Quercetti, Thomas, et.al. Quercetti, Thomas; Muller Karsten; Schubert Sven. Comparison of Experimental Results from Drop Testing of a Spent Fuel Package Design Using a Full-scale Prototype Model and a Reduced-scale Model. Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials, PATRAM 2007, October 2007, Miami, Florida, USA