INL/EXT-12-26798

FY 2012 USED FUEL DISPOSITION CAMPAIGN TRANSPORTATION TASK REPORT ON INL EFFORTS SUPPORTING THE MODERATOR EXCLUSION CONCEPT AND STANDARDIZED TRANSPORTATION

D. K. Morton

August 2012

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INL/EXT-12-26798
FCRD-UFD-2012-0001958

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Idaho National Laboratory

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August 2012

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ABSTRACT

Following the defunding of the Yucca Mountain Project, it is reasonable to assume that commercial used fuel will remain in storage for a longer time period than initially assumed. Previous transportation task work in FY 2011, under the Department of Energy's Office of Nuclear Energy, Used Fuel Disposition Campaign, proposed an alternative for safely transporting used fuel regardless of the structural integrity of the used fuel, baskets, poisons, or storage canisters after an extended period of storage. This alternative assures criticality safety during transportation by implementing a concept that achieves moderator exclusion (no in-leakage of moderator into the used fuel cavity). By relying upon a component inside of the transportation cask that provides a watertight function, a strong argument can be made that moderator intrusion is not credible and should not be a required assumption for criticality evaluations during normal or hypothetical accident conditions of transportation.

This Transportation Task report addresses the assigned FY 2012 work that supports the proposed moderator exclusion concept as well as a standardized transportation system. The two tasks assigned were to (1) promote the proposed moderator exclusion concept to both regulatory and nuclear industry audiences and (2) advance specific technical issues in order to improve American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, Division 3 rules for storage and transportation containments. The common point behind both of the assigned tasks is to provide more options that can be used to resolve current issues being debated regarding the future transportation of used fuel after extended storage.

ACKNOWLEDGEMENTS

The author would like to acknowledge the technical support and translation of documentation provided by Dr. Toshiari Saegusa of Japan's Central Research Institute of Electric Power Industry. The author would also like to acknowledge two Idaho National Laboratory personnel: Ms. Sandra Birk for her management support and Mr. Brett Carlsen for his willingness to attend meetings when the author had previous commitments.

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ACRONYMS

AISI	American Iron and Steel Institute
ASME	American Society of Mechanical Engineers
BPV	Boiler and Pressure Vessel
CFR	Code of Federal Regulations
CoCs	Certificates of Compliance
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FY	Fiscal Year
HT	heat treated
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
INMM	Institute of Nuclear Materials Management
ISG	interim staff guidance
JSME	Japan Society of Mechanical Engineers
MSHPB	Modified Split Hopkinson Pressure Bar
NE	DOE Office of Nuclear Energy
NEI	Nuclear Energy Institute
NMSS	Office of Nuclear Material Safety and Safeguards
NRC	U.S. Nuclear Regulatory Commission
RT	Room temperature
SFST	Spent Fuel Storage and Transportation (a division under NRC's Office of Nuclear Material Safety and Safeguards)
SRM	Staff Requirements Memoranda
UFDC	Used Fuel Disposition Campaign

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1. INTRODUCTION

Following the defunding of the Yucca Mountain Project, the Department of Energy (DOE) transitioned the former Office of Civilian Radioactive Waste Management responsibilities to the Office of Nuclear Energy (NE). One of the new offices created under NE was the Office of Used Nuclear Fuel Disposition Research and Development (NE-53). A Used Fuel Disposition Campaign Implementation Plan was approved on March 29, 2010 with the following mission (Reference 1):

> *"The mission of the Used Fuel Disposition Campaign is to identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles."*

In the absence of a currently identified disposition path for commercial used nuclear fuel,[a] it is reasonable to assume that used fuel will remain in storage for the foreseeable future. In addition to future disposal issues, the Used Fuel Disposition Campaign (UFDC) is addressing the many issues related to the consequences of this longer than anticipated storage period. The UFDC Transportation Team, composed of a number of personnel from various DOE National Laboratories, began their efforts during Fiscal Year (FY) 2011 and are continuing to support those research and development aspects necessary to successfully carry out the transportation of used fuel, considering the potential adverse effects of long-term storage.

This report provides a summary of the assigned UFDC transportation activities completed by the Idaho National Laboratory (INL) during FY 2012. These activities were performed to support the proposed concept of achieving moderator exclusion with a standardized transportation system. This proposed concept was the assigned INL Transportation task for FY 2011.

2. BACKGROUND

The INL's assigned task during FY 2011 for UFDC Transportation was to address the issue of moderator exclusion. This concept was pursued in order to provide options for the transportation of used fuel. After extended storage, if the structural integrity of the fuel, cladding, baskets, or poisons cannot be determined or is too costly to assess, the potential for satisfying the criticality safety requirements become problematic. However, if moderator (e.g., water) is prevented from entering the cavity where the commercial used fuel is located, the used fuel cannot achieve criticality regardless of any degradation consequences due to the 5 wt. % U-235 enrichment limit of the fuel. A basic principle of defense-in-depth is the use of multiple barriers. An engineered barrier, placed inside of a transportation cask, can provide

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a. The term 'commercial used nuclear fuel' (hereafter referred to as 'used fuel') is used in this report to reflect that the material being transported may still be a resource to be recovered through processing, whereas 'spent fuel' may be considered to be more a waste. This 'used fuel' terminology (which includes the cladding) is not intended to conflict with the vast magnitude of literature, regulations, codes, and standards that have used the term 'spent fuel' or 'spent nuclear fuel'. 'Used fuel' is simply being used herein to indicate that a decision regarding its usefulness has not yet been determined. The term 'spent fuel' or 'spent nuclear fuel' will continue to be used in this report when used in a direct quotation, title, or the name of a specific item. Although DOE is also responsible for DOE-owned used fuel and high-level radioactive waste, the main focus of this report is commercial used fuel.

the solution to achieve moderator exclusion. If the storage canister can be shown to provide a watertight barrier during normal and hypothetical accident transportation conditions, moderator exclusion is achieved. If the storage canister cannot provide a watertight barrier, then an additional inner containment inside of the transportation cask can provide the necessary watertight function necessary for moderator exclusion during both normal and hypothetical accident conditions.

Current International Atomic Energy Agency (IAEA) transportation regulations for used fuel (Reference 2) do not require the assumption of moderator leakage past multiple barriers (not less than two), when each barrier can be demonstrated to remain watertight under prescribed normal and accident condition tests and each packaging (before each shipment) is tested to demonstrate the closure. A separate and distinct component inside of a transportation cask and capable of performing the watertight function for moderator exclusion is believed to satisfy the "special design features" condition of the applicable U.S. Code of Federal Regulations (CFR) requirements [10 CFR Part 71.55(c)] (Reference 3), ensuring that no single packaging error would permit in-leakage of moderator into the used fuel cavity.

This engineered concept, discussed in INL/EXT-11-22559 (Reference 4, the FY 2011 INL UFDC Transportation task report), also simultaneously supports standardized transportation. New transportation packagings need to be constructed in order to transport the large amount of available used fuel. This new design opportunity can establish a fleet of transportation packagings that can accommodate most if not all of the current used fuel storage systems. A "one size fits all" approach produces a standardized transportation system. But this does create a need to adapt to the many varied storage canister geometries so they properly fit into the one-sized transportation cask cavity (eliminate excessive rattle room). The solution is to use an adaptable insert (one or more designs as needed) that fits into the transportation cask cavity and properly supports the storage canister. This adaptable insert can also become an inner containment when needed, simply by attaching a lid. Hence, a standardized transportation system can be created that allows even degraded used fuel to be safely transported, providing the options needed to safely and efficiently transport used fuel after extended storage. Figure 1 illustrates this proposed concept.

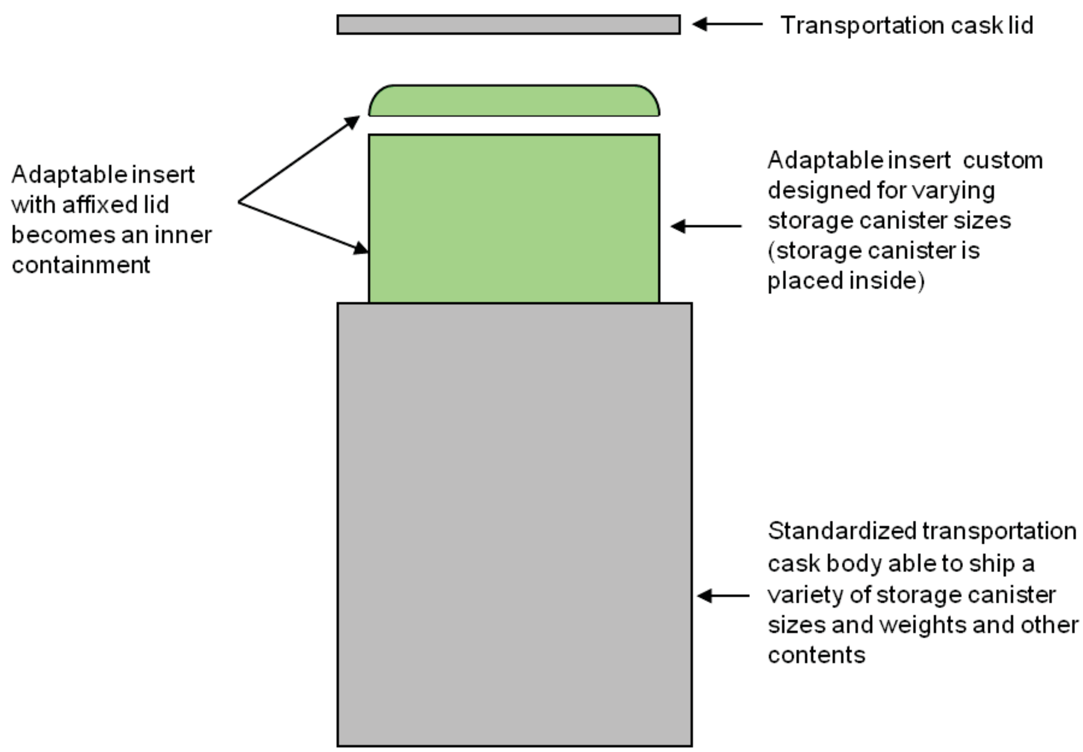

Figure 1. Proposed Concept for Moderator Exclusion

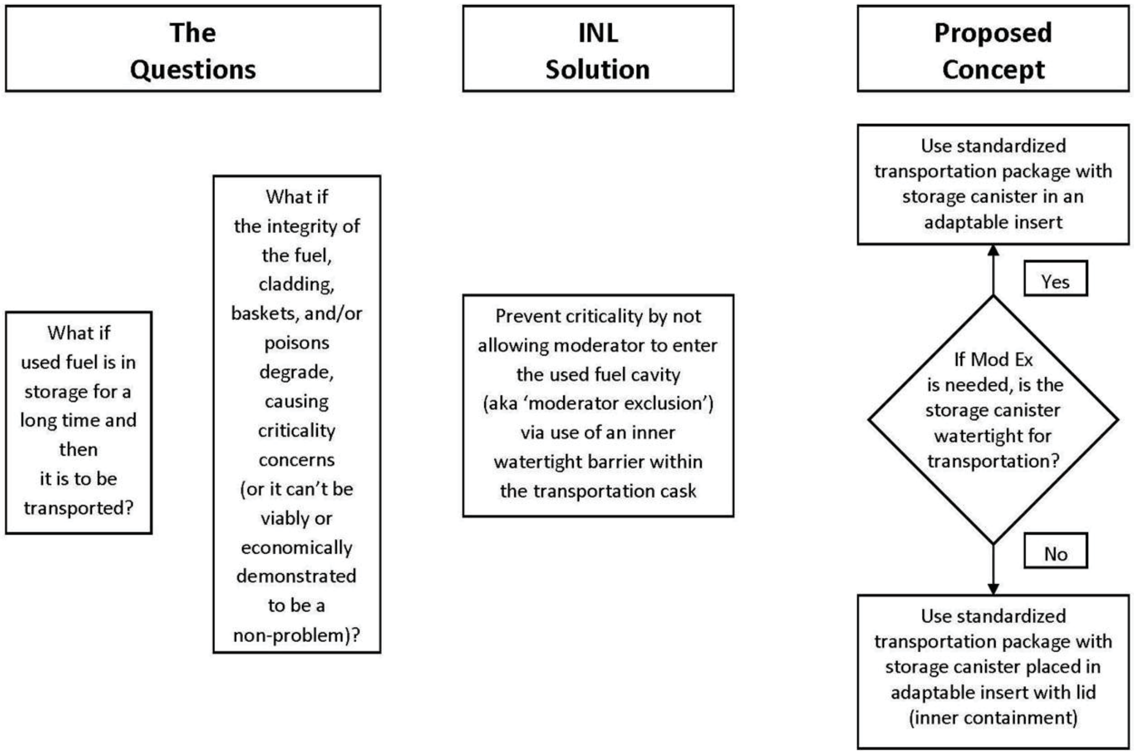

Figure 2. Inner Watertight Barrier Determination

Figure 2 illustrates the logic when evaluating whether the storage canister or the adaptable insert with an affixed lid (inner containment) will provide the watertight barrier function necessary for moderator exclusion.

3. TASK 1: PROMOTE PROPOSED CONCEPT

As explained in INL/EXT-11-22559, if the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Material Safety and Safeguards (NMSS) would accept the proposed moderator exclusion approach [essentially be willing to invoke 10 CFR Part 71.55(c)] for general approval of designs rather than on a case-by-case basis, it is believed that more parties would be willing to submit designs invoking moderator exclusion for both normal and hypothetical accident conditions. All licensing interactions with the NRC cost money to complete and there is a natural hesitancy to pursue design options that may be rejected by the NRC. As an additional deterrent, a recent NRC Commission ruling on moderator exclusion [Staff Requirements Memoranda (SRM) dated December 18, 2007 (Reference 5) regarding SECY-07-0185 (Reference 6)] indicated that the Commission rejected the NRC staff's recommendation for rulemaking to incorporate regulatory provisions addressing moderator exclusion. The Commission required the NRC staff to continue to gain more experience through processing applicant's requests and to focus its efforts on using burn-up credit. What was believed not to have been specifically considered in those deliberations was the consequences of extended storage and the presence of an inner watertight barrier, separate from and inside of the transportation containment, as required by the INL's proposed moderator exclusion concept. Other requirements such as addressing fuel retrievability add to the current hesitancy of applicants to pursue moderator exclusion approval for both normal and hypothetical accident conditions.

Therefore, the primary intent of Task 1 was to simply promote the proposed moderator exclusion concept that also incorporated a standardized transportation system. If efforts could be made to provide input to the NRC during their on-going review of storage and transportation regulations in light of extended storage, the potential for the NRC to seriously consider the proposed concept improved greatly. The INL proposed concept is not a new concept, but it is a proven concept, since it was used to transport the damaged Three Mile Island fuel and core across most of the United States to the INL. So the goal of Task 1 was to simply help keep this engineered design option fresh in the NRC's, potential applicants', and the nuclear industry's minds. This promotional effort was considered especially important if proposed extended storage used fuel demonstration tests prove too costly, if the research efforts do not yield the desired outcome, or if it becomes difficult to assure the condition of the fuel, cladding, baskets, or poisons inside any specific storage canister for whatever reason. The INL proposed concept provides alternative transportation options for the future.

3.1 NRC SFST Technical Exchange Meeting

The first opportunity to promote the INL's proposed concept came early in FY 2012. On November 1, 2011, the Division of Spent Fuel Storage and Transportation (SFST) under NMSS sponsored a technical exchange meeting. NRC, DOE, and nuclear industry representatives served on panels and presented their perspectives on a variety of issues in the areas of transportation technical issues and storage technical issues. Two concurrent meetings were held but it was at the "Interfaces Between Storage and Transportation Casks" meeting where pertinent presentations were held regarding moderator exclusion. The morning session was a presentation/discussion on high burnup fuel, including discussions on alternatives for addressing criticality safety requirements for high burnup fuel transportation. Presentations included:

- NRC's View on Cladding Material Properties – Bob Einziger
- Industry's View on Cladding - Albert Machiels from EPRI
- NRC's View on Moderator Exclusion – John Vera
- Industry's View on Moderator Exclusion – Charlie Pennington from NAC International and D. Keith Morton from the Idaho National Laboratory
- NRC's View on Reconfiguration – David Tang and Zhian Li
- Industry's View on Reconfiguration – Albert Machiels from EPRI

The afternoon session of "Interfaces Between Storage and Transportation Casks" continued the same format, including discussions on retrievability requirements (by fuel assembly or canister), casks/contents integrity after a period of storage, and the use of common criticality safety methods for satisfying both storage and transportation regulations. Presentations included:

- NRC's View on Retrievability – Earl Easton
- Industry's View on Retrievability – Adam Levin from Exelon Corporation
- NRC's View on Acceptance Testing and Aging Management – Bob Einziger
- Industry's View on Acceptance Testing and Aging Management – Jim Connell from Maine Yankee
- NRC's View on Burnup Credit versus Boron Credit – Drew Barto
- Industry's View on Burnup Credit versus Boron Credit – Prakash Narayanan from Transnuclear

Two interesting comments from the NRC staff were made at this meeting. First, Dr. John Vera mentioned in his morning presentation that the concept proposed in INL Report 11-22559 could be a "possible" option for moderator exclusion by implementing double containment. Second, Mr. Earl Easton discussed potential future paradigm shifts in regulations, where for 'retrievability', a shift from the fuel assembly to the canister could occur and that for 'criticality safety', a shift from cladding to canister could be possible. These comments supported the position of the INL presentation and were very well received by the audience. This meeting provided an excellent opportunity for the industry and NRC personnel to exchange technical ideas and opinions. The proposed moderator exclusion presentation was well received. After the presentations, in direct discussions with Mr. Earl Easton, NRC Senior Level Transportation Advisor, he indicated that there were still differing opinions within the NRC staff on various storage and transportation subjects but he believed that a new paradigm existed with the probability of extended storage intervals and felt that it was necessary for the NRC to adapt with the change. Hence, the goal of keeping moderator exclusion on the discussion forefront as an item for potential regulatory change was achieved.

3.2 27th INMM Spent Fuel Management Seminar

Mr. Paul McConnell, from Sandia National Laboratories and UFDC Technical Laboratory Lead for Transportation, gave a presentation on the UFDC Transportation Program on February 1, 2012 at the Institute of Nuclear Materials Management 27th Spent Fuel Management Seminar. The presentation included a brief summary of the proposed moderator exclusion concept. Again, more people were exposed or reminded of the potential benefits of moderator exclusion.

One of the more intriguing aspects that occurred at this three day meeting was comments made on the last day (February 2, 2012) by Mr. Doug Weaver, Acting Director for the NRC SFST Division. Some of his more interesting comments regarding possible future licensing strategies due to extended storage included:

- "If the fuel cladding is not relied upon to perform safety functions such as geometry control, degradation of fuel cladding may not pose a significant problem from the perspective of storage and transportation."
- "An engineering approach that relies on canisters or individual cans rather than cladding integrity may also lessen the burden on cask designers and regulators to do extensive research on fuel cladding properties. It should be noted however that, due to increased reliance on integrity of canisters/casks and overpacks, these safety components may have to perform to higher standards."
- "In summary, I believe that NRC's future regulatory framework should be flexible enough to consider both "scientific" and "engineering" solutions – for example, developing licensing solutions that rely both on keeping the cladding intact, as well as those which might base safety more on canisters or cans."

The good news is that all participants in the nuclear industry appear to be recognizing that past processes, evaluations, assumptions, and regulations may be inadequate in light of extended storage and that new general design approaches (e.g., using an inner containment) should be considered along with revised regulations.

3.3 EPRI Extended Storage Collaboration Program Meeting

After generating a presentation (improved over that presented at the November 1 NRC Technical Exchange Meeting), discussing the presentation and submitting the presentation with meeting organizers, the author attended the Electric Power Research Institute (EPRI) Extended Storage Collaboration Program (ESCP) meeting held Monday, May 7, 2012 in St. Petersburg, Florida. The focus of that meeting was to discuss aging effects and mitigation options for the extended storage and transportation of used fuel. Due to the fact that the meeting went long and certain agenda items were not covered, the presentation on the INL's proposed moderator exclusion concept was not given. However, after the author made a brief announcement of a willingness to discuss moderator exclusion options after the meeting, two nuclear industry participants briefly explained their future expectations and both believed that moderator exclusion provided the most likely option for future transportation of used fuel.

3.4 NEI Used Fuel Management Conference

Since the Nuclear Energy Institute (NEI) Used Fuel Management Conference began the day after the ESCP meeting at the same location, the author also attended this conference. Although no presentation was planned, attending this conference provided an opportunity to listen to a number of pertinent presentations, mainly from the nuclear industry perspective. This provided a better understanding of the nuclear industry's perspective on what needs to be accomplished in order to continue the safe storage of used fuel and the actions needed to move forward with storage, transportation, and disposal. Moderator exclusion was high on the list of NEI issues needing to be discussed and utilized for future transportation of used fuel.

3.5 Future FY2012 NRC NMSS Meetings

The NRC is organizing two meetings to be held late in FY2012, after the writing and approval of this FY2012 UFDC Transportation Task report.

3.5.1 NRC Enhancements to the Licensing and Inspection Programs for Spent Fuel Storage and Transportation

This NRC SFST meeting is scheduled to be held August 16-17, 2012 at NRC Headquarters in Rockville Maryland. As the draft agenda indicates, the following issues are to be discussed:

- Administration of Storage Certificates of Compliance (CoCs) and Amendments to CoCs
- Applicability, Compatibility, and Consistency of Spent Fuel Storage Requirements for Specific Licensees, General Licensees, and Certificate of Compliance Holders
- Regulating Stand-Alone Independent Spent Fuel Storage Installations
- Harmonization of Retrievability and Cladding Integrity Requirements for Storage and Transportation of Spent Nuclear Fuel

In particular, the last item could have interesting implications for transportation, especially if any shifts in fuel retrievability regulations are discussed. INL personnel are planning to attend/participate in this meeting but no presentation is planned.

3.5.2 NRC 2012 SFST Regulatory Conference

This NRC SFST meeting is an annual forum to discuss NRC regulatory and technical issues involving spent fuel storage and the transportation of radioactive material. The goal of the conference is for the regulators to share their perspectives on licensing, inspection, and regulatory challenges as well as for the nuclear industry to share their insights on improving regulatory oversight, all through constructive dialogue. This meeting is scheduled to be held September 12-13, 2012 at NRC Headquarters in Rockville Maryland. Per the draft agenda, the following issues are to be discussed:

- Operating Experience
- Non-Spent Fuel Transportation
- Information on NUREG-2150 and NUREG-2125
- High Burnup Fuel Storage and Transportation
- Technical Issues Related to Storage

Again, various agenda items could have interesting implications for transportation, especially the high burnup fuel discussion. INL personnel are planning to attend/participate in this meeting, although presenters and panels have not yet been finalized.

3.6 Task 1 Summary

A number of opportunities were pursued to promote the proposed moderator exclusion concept for standardized transportation systems. Presentations were made at various meeting types and interaction with meeting attendees succeeded in heightening the awareness of the beneficial aspects of moderator exclusion. Moderator exclusion is attainable and keeping this option "on the table" for future consideration by both nuclear industry and regulatory personnel was achieved.

4. TASK 2: ADVANCING TECHNICAL ISSUES

Task 2 was to perform a literature search for readily available strain rate data that would support implementing proposed strain-based acceptance criteria for the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code, Section III, Division 3 (Reference 7) rules for both storage and transportation containments. Funding was also provided to attend the ASME BPV Code Week Division 3 meetings. Therefore, Section 4.1 below addresses the completed literature search and Section 4.2 addresses the advances made in developing the proposed strain-based acceptance criteria and the progress to date of obtaining ASME approval of the proposal, along with other pertinent Section III, Division 3 rule changes.

4.1 Literature Search

This subsection describes in more detail the literature search performed in order to establish the quantity of strain rate data readily available in the technical literature. This information is expected to be used to determine future needs, such as defining test program needs and validation efforts.

4.1.1 Purpose

The purpose of this task was to perform a limited literature search in order to determine the quantity of applicable strain rate data readily available. Regulatory requirements mandate the consideration of accidental drops and impacts when designing storage and transportation containments. These energy-limited loads typically govern the structural design of these containments, especially when elastic analyses are used. But this significantly increases the cost of these containments. In recognition of this fact, the ASME BPV Code, Section III, Division 3 committees have pursued the development of strain-based acceptance criteria. These criteria will make the design of containments more efficient but will still maintain appropriate safety margins. These acceptance criteria require inelastic analyses be performed. Strain rate data are required to properly perform inelastic analyses of accidental drop or impact events on storage and transportation containments. So strain rate data support implementation of the proposed strain-based acceptance criteria, which can support the design of a new and efficient standardized transportation system.

4.1.2 Approach to Literature Search

A significant amount of strain rate research has been performed on multiple materials, at multiple temperatures, and for a variety of reasons. However, this literature search needed to obtain information pertinent to the common materials used for the containment of used fuel during storage and transportation uses. Therefore, the search parameters were narrowed to focus on strain rate data for 304, 304L, 316, or 316L stainless steels, at temperatures ranging from -40°F to 800°F, and at strain rates between 1 and 510 in/in/sec. In years past, before the late 1980's, it was common to be able to procure just one type (304, 304L, 316, or 316L) of austenitic stainless steel material. However, for new construction, one is likely to obtain material that is marked with two or more material types, such as 304/304L or 316/316L. These materials can satisfy both material types because all of the measured and controlled attributes (e.g., chemistry, mechanical properties, dimensions, and tolerances) of that material fall within the overlapping ranges of both specifications. This dual marking notation (304/304L and 316/316L) will be used herein to denote either material that satisfies each unique and separate specification (covering older testing efforts) or material that satisfies the dual specifications (covering more recent testing efforts).

Past efforts to acquire strain rate documentation within the data ranges specified above, including requests to ASME Code committee volunteers, yielded relevant documents. These documents were combined with the new FY2012 search efforts made for this task.

Obviously, in order to better understand the material performance conforming to the restricted conditions identified above, the ideal strain rate data would include digitized tensile engineering stress-strain curves. This would provide material data performance, including values for the uniform strain limit and fracture strain limit. True stress-strain curves could also be generated from this data. However, not all documentation would be expected to provide this detailed level of information. Therefore, documents with true stress-strain curves, or reports that provided information on how the strain rate effects changed the material response in relation to the quasi-static engineering or true stress-strain curve were also of importance. Even with these narrowed search parameters, it was still necessary to obtain the potential papers, reports, and other documentation, scan for the minimal data of interest, and then determine if that data would provide any beneficial insights. This determination was necessary because some data may have included pertinent data but if the quasi-static engineering or true stress-strain curve was not provided, a quantification of the material response change could not be made. Other reasons to not include documents was that the data did not go far enough in terms of strain, difficulty in reading the data, data units not specified, or the data were not within the specified parameters. Documents with compression test data were not considered viable since the behavior of these materials is different between tensile and compression loading. Another aspect not considered at this time was the effects of irradiation, due to the limited funding.

4.1.3 Results of Literature Search

A significant number of hours were invested in this literature search. However, the search results yielded only nine viable references (References 8 – 16). This was not unexpected since past efforts yielded few references. The current fiscal year effort was fruitful and did add to the total number of viable strain rate references. Due to copyright constraints, rather than providing copies of the entire reference, the search results are summarized in tabular form, differentiated by material type (304/304L or 316/316L). Table 1 provides a summary of pertinent strain rate data provided by each reference, separated by test temperature, for 304/304L base and weld material. Table 2 provides the same information for 316/316L base and weld material. Tables 1 and 2 also provide information regarding the dynamic test method used, test specimen geometry insights, and the form of the documented strain rate data.

When evaluating the results of a literature search of this nature, the issue of data completeness needs to be considered. The goal was to get viable strain rate data over a range of 1 to 510 in/in/sec and at a variety of temperatures ranging from -40°F to 800°F. Tables 3, 4, 5, and 6 were generated to provide a visual answer to the question. Tables 3 and 4 address 304/304L material and Tables 5 and 6 address 316/316L. Table 3 and 5 address base material and Tables 4 and 6 address weld material. The first realization is that only a limited number of the boxes are marked (yellow highlight with an 'X'), indicating at least one set of data is available in the indicated range. Less than 18% of the 316/316L base material ranges have data and only 12% of the 304/304L base material ranges have any data. The data coverage for welds is even lower; approximately 5% of the ranges have any data for either 304/304L or 316/316L. As one would expect, most of the strain rate data that is available is for the temperature range that includes room temperature and for the lowest strain rate range (1 to 50 in/in/sec). These data points are the easiest to obtain. Clearly, the general need is to obtain more data at higher strain rates and at higher temperatures. This insight is very useful for planning future strain rate testing needs.

Of the data that are available, a few cursory observations can be made and are presented below. However, it is necessary to incorporate additional strain rate data before any final conclusions can be stated.

Table 1. Summary of Applicable Strain Rate Literature Search Results for 304/304L

Author	Ref.	Material	Dynamic Test Method	Test Temp.	Strain Rates	Specimen	Comments
Albertini & Montagnani	8	AISI 304L	MSHPB	RT	10^{-4}, 10^{-2}, 502	Small, 8 mm active length	Engr. stress-strain curves
Albertini & Montagnani	9	AISI 304L	MSHPB	68ºF	3.8×10^{-3}, 50, 450	Small	Engr. stress-strain curves
Albertini & Montagnani	9	AISI 304L	MSHPB	752ºF	3.5×10^{-3}, 50, 500	Small	Engr. stress-strain curves
JSME	10 (B-46)	304	Amsler type accumulated gas	68ºF	5.05×10^{-4}, 6.26×10^{-2}, 54.8	1/3-in. dia. 2-in. gauge	Limited true stress-strain curve s& data
JSME	10 (B-46)	304	Amsler type accumulated gas	-87ºF	5.45×10^{-4}, 4.99×10^{-2}, 48	1/3-in. dia. 2-in. gauge	Limited data
Marschall, Landow, Wilkowski	11	304 and SAW	Hydraulic tensile	550ºF	Varying: approx. 10^{-4}, 1, 8-14	1/8-in. sheet	Engr. & true stress-strain curves
Talonen, Nenonen, Pape, & Hänninen	14	AISI 304	Hydraulic tensile	RT*	3×10^{-4}, 0.1, 200	0.04 in. thick	True stress-strain curves
Lichtenfeld, Mataya, & Van Tyne	15	304L	Hydraulic tensile	75ºF	1.25×10^{-4}, 1.25×10^{-3}, 1.25×10^{-2}, 0.125, 1.25, 10, 100, 400	0.06 in. thick etched	True stress-strain curves with yield and tensile strengths
Morton & Blandford	16	304/304L base and weld	Drop weight	-20ºF	10^{-4} to 10^{-3}, 5 - 36	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	304/304L base and weld	Drop weight	RT	10^{-4} to 10^{-3}, 5 - 33	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	304/304L base and weld	Drop weight	300ºF	10^{-4} to 10^{-3}, 5 - 35	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	304/304L base and weld	Drop weight	600ºF	10^{-4} to 10^{-3}, 5 - 23	¼ and ½-inch thick plate	Data & factored true stress-strain curves

Notes:
AISI – American Iron and Steel Institute MSHPB – Modified Split Hopkinson Pressure Bar or similar device RT – room temperature
* - assumed value based on paper inferences

Table 2. Summary of Applicable Strain Rate Literature Search Results for 316/316L

Author	Ref.	Material	Dynamic Test Method	Test Temp.	Strain Rates	Specimen	Comments
Albertini & Montagnani	9	AISI 316L	MSHPB	68ºF	4.0×10^{-3}, 15, 44, 420	Small bar	Engr. stress-strain curves
Albertini & Montagnani	9	AISI 316L weld	MSHPB	68ºF	3.5×10^{-3}, 5, 440	Small bar	Engr. stress-strain curves
JSME	10 (B-3)	AISI 316L	*	68ºF	3×10^{-3}, 12, 36, 360	*	Limited true stress-strain curves & data
JSME	10 (B-27)	316L (HT & annealed)	MSHPB	68ºF	3.9×10^{-3}, 15, 43, 410	*	Limited true stress-strain curves & data
JSME	10 (B-27)	316L (HT & annealed)	MSHPB	752ºF	2.9×10^{-3}, 44, 69, 460	*	Limited data
O'Toole	12	316L	Drop weight	RT	Approx. 10^{-4}, 0.02, 0.2, 75, 100, 130, 165, 200	0.35 in. long 1/8-in. dia.	Raw data
O'Toole	12	316L	Drop weight	175ºF	Approx. 90, 170	0.35 in. long 1/8-in. dia.	Raw data
O'Toole	12	316L	Drop weight	350ºF	Approx. 110, 145, 170	0.35 in. long 1/8-in. dia.	Raw data
Langdon & Schleyer	13	316L	Hydraulic tensile	RT	0.03, 0.2, 18, 20, 55, 118	0.12 and 0.16 thick	Engr. stress-strain curves
Morton & Blandford	16	316/316L base and weld	Drop weight	-20ºF	10^{-4} to 10^{-3}, 5 - 39	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	316/316L base and weld	Drop weight	RT	10^{-4} to 10^{-3}, 5 - 34	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	316/316L base and weld	Drop weight	300ºF	10^{-4} to 10^{-3}, 4 - 26	¼ and ½-inch thick plate	Data & factored true stress-strain curves
Morton & Blandford	16	316/316L base and weld	Drop weight	600ºF	10^{-4} to 10^{-3}, 5 - 24	¼ and ½-inch thick plate	Data & factored true stress-strain curves

Notes:
AISI – American Iron and Steel Institute; MSHPB – Modified Split Hopkinson Pressure Bar or similar; RT – Room Temperature
JSME – Japan Society of Mechanical Engineers; * - unstated but MSHPB likely with small bar test specimens; HT – heat treated

Table 3. Strain Rate Data Coverage for 304/304L Base Material

Strain Rate \ Temperature	-90ºF to 32ºF	33ºF to 100ºF	101ºF to 200ºF	201ºF to 300ºF	301ºF to 400ºF	401ºF to 500ºF	501ºF to 600ºF	601ºF to 700ºF	701ºF to 800ºF
1 - 50 in/in/sec	X	X		X			X		X
51 – 100 in/in/sec		X							
101 – 150 in/in/sec									
151 – 200 in/in/sec		X							
201 – 250 in/in/sec									
251 – 300 in/in/sec									
301 – 350 in/in/sec									
351 – 400 in/in/sec		X							
401 – 450 in/in/sec		X							
451 – 510 in/in/sec		X							X

Table 4. Strain Rate Data Coverage for 304/304L Weld Material

Strain Rate \ Temperature	-90ºF to 32ºF	33ºF to 100ºF	101ºF to 200ºF	201ºF to 300ºF	301ºF to 400ºF	401ºF to 500ºF	501ºF to 600ºF	601ºF to 700ºF	701ºF to 800ºF
1 – 50 in/in/sec	X	X		X			X		
51 – 100 in/in/sec									
101 – 150 in/in/sec									
151 – 200 in/in/sec									
201 – 250 in/in/sec									
251 – 300 in/in/sec									
301 – 350 in/in/sec									
351 – 400 in/in/sec									
401 – 450 in/in/sec									
451 – 510 in/in/sec									

Table 5. Strain Rate Data Coverage for 316/316L Base Material

Temperature / Strain Rate	-90ºF to 32ºF	33ºF to 100ºF	101ºF to 200ºF	201ºF to 300ºF	301ºF to 400ºF	401ºF to 500ºF	501ºF to 600ºF	601ºF to 700ºF	701ºF to 800ºF
1 – 50 in/in/sec	X	X		X			X		X
51 – 100 in/in/sec		X	X						X
101 – 150 in/in/sec		X			X				
151 – 200 in/in/sec		X	X		X				
201 – 250 in/in/sec									
251 – 300 in/in/sec									
301 – 350 in/in/sec									
351 – 400 in/in/sec		X							
401 – 450 in/in/sec		X							
451 – 510 in/in/sec									X

Table 6. Strain Rate Data Coverage for 316/316L Weld Material

Temperature / Strain Rate	-90ºF to 32ºF	33ºF to 100ºF	101ºF to 200ºF	201ºF to 300ºF	301ºF to 400ºF	401ºF to 500ºF	501ºF to 600ºF	601ºF to 700ºF	701ºF to 800ºF
1 – 50 in/in/sec	X	X		X			X		
51 – 100 in/in/sec									
101 – 150 in/in/sec									
151 – 200 in/in/sec									
201 – 250 in/in/sec									
251 – 300 in/in/sec									
301 – 350 in/in/sec									
351 – 400 in/in/sec									
401 – 450 in/in/sec		X							
451 – 510 in/in/sec									

4.1.3.1 Sensitivity of Austenitic Stainless Steel to Strain Rate Effects

A number of personnel have questioned the sensitivity of austenitic stainless steels to strain rate effects. It is surmised that these individuals may have misread strain rate discussions or information in the past. The final nine references selected for this literature search clearly demonstrate that austenitic stainless steels, types 304/304L and 316/316L, are indeed strain rate sensitive.

4.1.3.2 Factoring of True Stress-Strain Curves

Looking at the available true stress-strain curves from the nine strain rate references that reflect higher strain rates, a number of those curves (References 10, 14, and 15) appear to be a uniform factor higher (in the stress direction) than the corresponding quasi-static true stress-strain curve. This feature also holds true for other references (References 17 and 18) that contained true stress-strain curves at varying strain rates but did not comply with the literature search limitations established. If this feature continues to hold true with additional strain rate data, this would be a very simple way to correlate strain rate effects to readily available 304/304L and 316/316L quasi-static true stress-strain curves, as was done in Reference 16.

4.1.3.3 Variation of Uniform or Fracture Strain Limits Versus Strain Rate

Some engineers have indicated an expectation that the uniform strain limit (corresponding to the strain just before the onset of necking) and the fracture strain limit (corresponding to the strain at the point of test specimen fracture or separation) will reduce as the strain rate (over the range of 1 to 510 in/in/sec) increases. Briefly reviewing the nine strain rate references, some show engineering curves where these two strain limits do indeed show indications of reduction but at the upper limits of the strain rates of interest (Reference 8) or indications of reduction at lower and higher strain rates (References 9 and 12). On the other hand, other information collected (References 12, 13, 15, and 16) indicate no significant reductions or some increases in these strain limits as the strain rate increases. Reference 14 indicates that the elongation to fracture increases with the strain rate. Interestingly, where information was available, the earlier testing results tended to showed strain limits reduced while later testing results showed strain limits increasing or essentially remaining constant. Test methodology may have an influence as well as how the strain rate was defined. Additional strain rate data is necessary before this trend can be clarified.

4.1.3.4 Validation of Data Generated

One of the difficulties in utilizing research data from many different sources is ascertaining the validity of those data. If the researcher can perform some level of validation, that provides a major boost in data acceptability. Of the nine references that satisfied the search criteria, only two (References 13 and 16) provided any validation insights. For both of these references, the validation effort indicated that when the strain rate data was incorporated into finite element method inelastic analyses, good agreement was attained when compared to actual test results.

4.1.3.5 Test Specimen Size

Commentary in various literature have expressed concern over extending small or thin test specimen research results to situations where the actual material used involves much larger and much thicker material. Do thinner materials present different material properties than thicker materials? Are failure responses altered? At this point, any commentary will be withheld until more research data become available.

4.1.3.6 Comparison of Strain Rate Data Between References

Performing a meaningful comparison between the available strain rate data would indicate if there is agreement or significant differences. Different researchers or different test methods could introduce unknown biases. However, at a minimum, the numerous engineering or true stress-strain curves need to be digitized and plotted on the same graph in order to begin any meaningful comparison. But that preliminary step can be a time-consuming effort, too much to attempt with the limited funding provided for this task.

4.2 ASME BPV, Section III, Division 3 Activities

Another aspect of advancing technical issues that affects the proposed moderator exclusion concept and the standardized transportation system is the updating and revision of rules provided in the ASME BPV Code, Section III, Division 3. Division 3 provides the construction rules for both storage and transportation containments. Although not heavily used in the past, Division 3 has been significantly revised in the last decade to make it more useful and applicable to the storage and transportation industry. In addition, the NRC is currently reviewing Division 3 with the eventual goal of endorsement. History has shown that applicants typically use codes and standards endorsed by the NRC, rather than attempting to justify alternative rules on a case-by-case basis.

Supported by UFDC funding, the author was able to attend all four ASME BPV Code Weeks held during FY 2012. The author is a member of the Working Group on Design of Division 3 Containments, is the Secretary for the Subgroup on Containment Systems for Spent Fuel and High-Level Waste Transport Packagings (otherwise known as Subgroup NUPACK), and is a member of the BPV Standards Committee on Construction of Nuclear Facility Components.

Two Section III, Division 3 actions that directly affect the proposed moderator exclusion concept and standardized transportation were balloted through the various ASME BPV committees during FY 2012 and include:

- clarification of helium leak testing requirements for inner containments in Subsection WB-6120, and
- strain-based acceptance criteria applicable to both storage and transportation containments.

The author was the ASME Project Manager for both of these actions. The ASME Project Manager has the responsibility to develop the revision documentation, submit the action for ASME approval, and monitor the balloting process, answering any comments received during the balloting process.

Regarding the first action, the existing WB-6120, *Testing of Containments*, required all transportation containments to be pressure tested and leak tested except for any final closure welds made on inner containments. The main problem was that no requirements were provided for the final closure welds. WB-6120 was revised to include both final closure welds and final mechanical closures made on inner containments and clarified that both of these final closures shall be leak tested only. No pressure test is required on these final closures made on inner containments after being loaded with spent fuel or high-level waste. This revision received full ASME approval on July 11, 2012 and should be published in the next 2013 Edition of the ASME BPV Code.

The second action is still in the ASME balloting process. The strain-based acceptance criteria deliberations started in the Working Group on Design of Division 3 Containments back in 2006. The Working Group on Design Methodology was also involved since this was a new design approach for Section III. After revising many different proposals, a final version of the strain-based acceptance criteria was finally approved in November 2011 by these two Working Groups. The next step was to begin the ASME balloting process through higher committees and providing presentations to various ASME committees explaining the action and answering committee member questions. As of the writing of this report, the strain-based acceptance criteria have been approved by all of the appropriate committees reporting to the BPV Standards Committee on Construction of Nuclear Facility Components, including the Subgroup on Materials, Fabrication, and Examination, the Subgroup on Component Design, and the Subcommittee on Design.

The next step in the ASME balloting process will be to submit the strain-based acceptance criteria to the BPV Standards Committee on Construction of Nuclear Facility Components. This submittal is expected to be achieved at the 2012 August Code Week meetings. Actual balloting will likely begin in late August and carry into September.

The current strain-based acceptance criteria require the user to perform material testing in order to obtain the necessary true stress-strain curve material properties to implement the criteria. The criteria currently address strain rate effects separately in a conservative fashion. But the criteria can be improved and made more user friendly if ASME could provide these material data. Discussions with the ASME BPV Code,Section II material experts regarding the incorporation of appropriate true stress-strain curves and strain rate data for use with the strain-based acceptance criteria are on-going. If a more fully defined and validated database of temperature dependent true stress-strain curves and strain rate data for the austenitic stainless steels of interest can be established, certain levels of inelastic analysis conservatism are expected to be reduced, improving the accuracy of inelastic analysis predictions of structural responses to energy-limited events. The strain-based acceptance criteria are believed to be a significant step forward in more accurately evaluating the acceptability of energy-limited dynamic loadings on containments. The significance of the strain-based acceptance criteria is that future storage and transportation containments, including the inner containment (adaptable insert and lid), will be able to be designed more efficiently. The NRC has indicated support for incorporating strain-based acceptance criteria into Division 3.

5. CONCLUSIONS

Achieving moderator exclusion by utilizing a watertight inner barrier excludes the possibility of criticality of commercial used fuels during transportation. When the storage canister cannot provide that watertight function, a separate inner containment can provide the watertight function. Following this graded approach, the proposed moderator exclusion concept provides a positive path forward for DOE to transport used fuel after extended storage, regardless of the condition of the fuel, baskets, poisons, or the storage canister. This concept also supports standardization of the transportation system. The significance of what the proposed moderator exclusion concept offers is why the INL believes that it is important to be proactive in discussing the proposal and in keeping the concept fresh in the minds of applicants, regulators, and other decision makers. The assigned Task 1 supported this effort and success was achieved.

Advances on various technical issues are also very important, especially when the technical issues also support the proposed moderator exclusion concept and standardized transportation. Task 2 provided the opportunity to make significant advances in the applicable codes and standards area by revising ASME BVP Code, Section III, Division 3 rules and making progress on new design methods and acceptance criteria. Task 2 was also successfully completed.

Although the FY 2012 funding received was limited, the INL was able to successfully complete its assigned tasks and move the issue of used fuel transportation forward. Many technical decisions still have to be made. With future funding, the INL can continue making progress so that used fuel transportation can be accomplish in a safe and efficient manner.

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