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APPENDIX E
FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	"TSL-CALVIN Software Verification and Validation" FCRD-NFST-2014-000533
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Responsible Work Package Manager	Elena A. Kalinina [signature] (Name/Signature)
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This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☒ Technical Review ☐ Peer Review

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TSL-CALVIN Software Verification and Validation

Fuel Cycle Research & Development

Prepared for U.S. Department of Energy
Nuclear Fuels Storage and Transportation Planning Project
Elena Kalinina, Sandia National Laboratories

September 30, 2014
FCRD-NFST-2014-000533 Rev. 0

It should be noted that this is a technical report that does not take into account the contractual limitations under the Standard Contract (10 CFR 961). Under the provisions of the Standard Contract, DOE does not consider spent fuel in canisters to be an acceptable waste form, absent a mutually agreed to contract modification.

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SUMMARY

This report documents the verification and validation (V&V) of TSL-CALVIN 4.5.3. The new software verification and validation was required to address the substantial changes to the code and the database made in 2013. The new functionalities include repository acceptance priority; bare fuel handling at the Interim Storage Facility; cost calculations; site specific acceptance priority; thermal management; and accelerated transfer from pools to dry storage.

The scope of the FY14 work was limited to testing selected functionalities. The verification and validation approach consisted of simulating the movement of small amounts of spent nuclear fuel during a limited period of time (10 years). This approach allowed for verifying the simulation results by hand calculations.

The hand calculations were performed to check pool allocation; heat calculations; ISF infrastructure requirements; ISF cost calculations; and pool capacity calculations.

The V&V uncovered a few issues that need to be addressed in FY15. The FY15 V&V effort will target more detailed testing of all the features, including the ones not tested in FY14. The FY15 scope will also include V&V of Transportation Operations Model (TOM).

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ACRONYMS

BWR	boiling water reactor
DOE	U.S. Department of Energy
FCRD	Fuel Cycle Research and Development
FY	fiscal year
ISF	interim storage facility
LLW	low-level radioactive waste
MTU	metric tons of uranium
MGR	monitored geologic repository
NFST	Nuclear Fuels Storage and Transportation Planning Project
OFF	oldest fuel first
PWR	pressurized water reactor
SNF	spent nuclear fuel
TOM	Transportation Operations Model (ORNL)
TSL-CALVIN	Transportation Storage Logistics- CRWMS (Civilian Radioactive Waste Management System) Analysis and Logistics Visually Interactive
YFF	youngest fuel first

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TSL-CALVIN SOFTWARE VERIFICATION AND VALIDATION

1. INTRODUCTION

TSL-CALVIN (Ref. 1) is a part of the Transportation and Storage Logistics (TSL) model. TSL is a new tool developed to support the Nuclear Fuel Storage and Transportation Planning Project (NFSTPP) in the on-going system architecture analysis and related studies.

TSL-CALVIN was first released in 2012 (Ref. 2). The 2012 version was largely based on CALVIN 4.0 (Ref. 3). CALVIN 4.0 has well-tested comprehensive algorithms specifically designed for modeling spent nuclear fuel (SNF) logistics at the reactor sites, an interim storage facility (ISF), and a monitored geologic repository (MGR). It also includes a large database that contains the detailed reactor site data, historic fuel discharge data, projection of the future fuel discharge, and many other data required for the logistics and heat calculations to support these calculations.

In 2012 CALVIN 4.0 was modified to incorporate new utility cost algorithm and to add waste re-packaging at the consolidated storage facility. The 2012 version of TSL-CALVIN includes these two modifications. Because the changes made to the code were not substantial, the verification and validation of TSL-CALVIN was limited to testing the new features. The details of this testing are documented in Ref. 4.

The supporting database was also revised in 2012 to incorporate new fuel projection and to update the reactor site and other data. The modifications to the database are described Ref. 5.

In 2013 TSL-CALVIN was substantially revised and modified. The revisions and modifications concerned the functionalities, the calculations, and the outputs. The major goal was to enable TSL-CALVIN to simulate all the major features that will be needed to support the on-going and future waste management system architecture evaluations. The 2013 version of TSL-CALVIN is documented in Ref. 1. The current version considered in this report is TSL-CALVIN 4.5.3.

Note that the transportation analysis was removed from TSL-CALVIN 4.5.3 as a part of the TSL-CALVIN modification in 2013. This was done because this analysis was limited in its capability and did not represent the actual routing. The transportation analysis is performed in the different TSL module - Transportation Operations Model (TOM) (Ref. 6). The only TSL-CALVIN function with regard to transportation analysis is to generate the SNF pickup schedules at the reactor sites and consolidated interim storage facility. TOM uses these pickup schedules to simulate actual routing, logistics costs, and scheduling of shipments.

The 2012 TSL-CALVIN database was also significantly revised in 2013. The old data tables were deleted. A number of tables were updated with the most current information. The format of some tables was changed to accommodate new data fields. The standard casks of different sizes were added to the cask table. The new fuel projection entitled “2013 Projection” was incorporated. The data collection effort and the 2013 fuel projection are documented in Ref. 7. As a result of the format changes, TSL-CALVIN 4.5.3 cannot be executed using the old database.

The new version of TSL-CALVIN was tested as a part of the development process. A few additional changes were made to the code to address some minor issues uncovered while running simulations for the FY13 system architecture study (Ref. 8) and FY14 standardization study (Ref. 9). The final version, TSL-CALVIN 4.5.3, was released in June 2014. This version comes with the corresponding final version of the database.

The new software verification and validation (V&V) is required to address the substantial changes to the code and the database. As opposed to the previous V&V (Ref. 4), the new V&V has to test the old functionalities as well as the new ones to confirm that the code modifications did not alter any of the existing algorithms. The new V&V cannot take advantage of the previous tests because some algorithms were modified and the results of the previous simulations would not be reproducible with the new revision of the code. As a result, the V&V of TSL-CALVIN 4.5.3 is a significantly larger effort than V&V of the previous version of TSL-CALVIN.

This report documents the initial V&V of TSL-CALVIN 4.5.3. This initial V&V focused on testing major code functionalities. It was envisioned that the issues (if any) uncovered during this stage would be resolved in FY15. The V&V effort will continue in FY15 and will target more detailed testing of all the features, including the ones not tested in FY14.

The FY15 scope also includes V&V of Transportation Operations Model (TOM). A limited V&V of TOM was done in 2012 (Ref. 4). However, TOM was significantly revised in 2013 to accommodate the changes in TSL-CALVIN and the new transportation analysis needs. These modifications need to be tested. Note that TOM has its own database. The consistency between TSL-CALVIN and TOM databases needs to be examined as well.

The results of the FY15 V&V will be documented in the separate V&V report.

2. SUMMARY OF 2013 SOFTWARE MODIFICATIONS

The modifications incorporated in TSL-CALVIN 4.5.3 are summarized below. More detailed descriptions of these modifications can be found in the new revision of the TSL-CALVIN User Manual (Ref. 1).

Monitored Geologic Repository (MGR) Acceptance Priority

TSL-CALVIN was modified to allow a user to specify the acceptance priority for transporting SNF from either the reactor sites or the ISF to the MGR. If the priority is assigned to the reactors, SNF is transported from the reactor sites to the MGR until all the sites are unloaded. If the priority is assigned to the ISF, SNF is transported from the reactor sites to the ISF first, then from the ISF to the MGR. The exception is in the case when the re-packaging option is selected. In this case all SNF is transported first from the reactors to the ISF for re-packaging. In the previous version this priority was given to ISF.

Interim Storage Facility (ISF)

Two major modifications to the code related to the interim storage facility incorporate bare fuel handling (receiving and storing) and cost analysis. The cost analysis was developed for both the ISF and re-packaging facility located at ISF. The previous version of the code did not allow for receiving and storing bare fuel at the ISF and did not calculate the ISF and re-packaging facility costs.

The cost analysis methodology and supporting data were developed in 2013 and are documented in Appendix A of the FY13 system architecture study report (Ref. 8). This information can be also found in the TSL-CALVIN user manual (Ref. 1).

The following infrastructures were added to the ISF in relation with bare fuel handling:

- Bare Fuel Receipt Bays
- Bare Fuel Shipping Bays
- Bare fuel storage modules (separate BWR and PWR)

The code calculates the number of bare fuel cask processing bays (receipt and release) required each year. This number is used to calculate the maximum amount that need to be deployed over the operating life of the facility.

The ISF costs incorporated in TSL-CALVIN are summarized below.

The capital costs include the following:

- Infrastructure cost: all infrastructure development costs associated with deploying an ISF as a single cost incurred when the ISF becomes operational.
- Dry canister receipt and transfer bays cost: the bays are deployed when needed and cost is incurred then.
- Canister dry storage cost: the dry storage modules are constructed when needed and the cost is incurred then. There are three types of the dry storage modules – vertical, horizontal, and standard.
- Bare fuel cask processing bays cost (excluding re-packaging at receipt case): the bays are assumed to be constructed when the ISF bare fuel storage facility is built and costs are incurred then. The number of bays is equal to the maximum number of bays required during the ISF operational life.
- Bare fuel cask processing bays cost (re-packaging at receipt case): no costs because cost is incurred as part of the re-packaging facility.
- Bare fuel storage cost: bare fuel storage modules (BWR and PWR) are deployed when needed and costs are incurred then.
- Procurement of new canisters loaded at the ISF.

The operational costs include the following:

- Dry fuel handling annual labor cost: calculated as a function of a number of operating dry canister bays, number of crews per bay, and the required labor force.
- Bare fuel handling annual labor cost: calculated as a function of a number of bare fuel bays, number of crews per bay, and the labor force.
- Utility annual cost: calculated based on the number of crews working each year assuming a minimum of one crew will be required to be in place even when the ISF is not handling fuel.
- Annual materials and contracts cost (equipment leases, janitorial, and project costs): calculated as a fraction of total annual labor cost.
- Decommissioning and demolition cost: incurred when the ISF has completed shipment of all fuel as a fractional multiplier on the total capital cost.

Note that the number of operating bays is calculated from the ISF annual operational hours and dry canister/bare fuel processing time. The number of crews is calculated from the number of bays and the number of crews per bay. The labor force (number of managers, exempt, and non-exempt employees) is calculated from the linear equations.

The new functions were added to the re-packaging facility to handle bare fuel arriving to the ISF.

The re-packaging facility capital and operational costs are described below. The same cost algorithm is used when the re-packaging facility is located at the MGR.

Re-packaging facility capital costs include:

- Infrastructure: cost of all infrastructure development costs associated with deploying a re-packaging facility as a single cost incurred when the facility becomes operational.
- Low Level Waste (LLW) processing: the LLW processing facility cost is incurred when the re-packaging facility is constructed.
- Canister/cask receipt bays: the required number of dry canister and/or bare fuel cask receipt bays is calculated for each year. The number of bays is set equal to the maximum number calculated for the operating life of the facility. The bays are assumed to be constructed when the re-packaging facility is built and costs are incurred then.
- Fuel assembly lag storage: BWR and PWR lag storage is assumed to be half of the maximum fuel assembly throughput rate during the operational life of the facility. Costs are incurred when the re-packaging facility is constructed.
- Pool support: pool support cost is incurred when the re-packaging facility is constructed.
- HVAC cost: the maximum number of closure stations needed at the re-packaging facility over its operational life is calculated and the cost incurs when the re-packaging facility is constructed.
- Fuel transfer station cost: the maximum number of fuel transfer stations needed at the re-packaging facility over its operational life is calculated and the cost incurs when the re-packaging facility is constructed.
- Canister opening station cost: the maximum number of canister opening stations needed at the re-packaging facility over its operational life is calculated and the cost incurs when the re-packaging facility is constructed.
- Canister closure station cost: the maximum number of canister closure stations needed at the re-packaging facility over its operational life is calculated and the cost incurs when the re-packaging facility is constructed.
- Outbound release station cost: the maximum number of outbound release stations needed at the re-packaging facility over its operational life is calculated and the cost incurs when the re-packaging facility is constructed.

Re-packaging facility operational costs include:

- Re-packaging facility annual labor cost: calculated as a function of the number of closure stations, number of crews per station, and the required labor force.
- Utility annual cost: the utility annual cost is determined based on the number of closure crews working each year assuming a minimum of one crew will be required to be in place even when the re-packaging is not handling fuel.
- Annual materials and contracts cost: equipment leases (function of closure station number), janitorial (function of closure station number), and materials (fraction of total annual labor cost).
- New canister cost: the cost of each new canister is incurred and tracked annually.
- Discarded canister cost: the cost of each discarded canister is incurred and tracked annually.
- Decommissioning and demolition cost: decommissioning and demolition costs are fraction of the capital costs and are incurred when the re-packaging facility has completed processing of all fuel.

Note that when calculating the labor cost, the number of crews is determined from the number of closure stations and the number of crews per station. The labor force (number of managers, exempt, and non-exempt workers) is calculated from the linear equations.

Site Specific Acceptance Priority

The modifications to TSL-CALVIN were done to incorporate the capability to specify a site-specific allocation strategy. This capability allows the assignment of acceptance priority to specific sites over specified time periods. Once site-specific allocation is complete, TSL-CALVIN reverts back to the default Older Fuel First (OFF) priority. The site-specific allocation is entered through an Excel spreadsheet.

Thermal Management

Significant modifications were done to the code to improve the thermal management routines.

The first modification concerns the incorporation of the thermal constraints on the dry storage overpacks. The new version of TSL-CALVIN checks the thermal output when loading each dry storage canister. If the thermal output exceeds the dry storage overpack thermal limit, the canister is not loaded. TSL-CALVIN tracks the thermal output of the dry storage overpacks loaded at the reactor sites. It also tracks the dry storage canisters that failed to be loaded. The previous version of the code ignored the dry storage overpack thermal limits and did not provide the thermal output data for the dry storage canisters loaded at the reactor sites. The new revision of the code also provides the thermal output for each transportation cask loaded at the reactor site. The previous version of the code checked the transportation cask thermal limits, but did not provide the cask thermal output data.

The second modification provides the capability to link the MGR emplacement thermal constraints to shipments of SNF from the reactors and ISF. The canister/cask is only shipped when its thermal output is equal to or smaller than the specified repository emplacement thermal limit. This is a new capability that was not available in the previous version of the code.

The third modification provides the capability for blending of SNF during packaging/re-packaging at the ISF. The previous version of the code had this capability implemented for MGR. Blending option was not available at the ISF.

Accelerated transfer from pools to dry storage

TSL-CALVIN was modified to allow the user to accelerate the transfer of SNF from pools (wet storage) to dry storage. The maximum pool capacity is specified globally as a percentage of total pool capacity. Also specified are the year in which to start the acceleration, the number of years to achieve the new maximum pool capacity, and the minimum age of SNF for transfer.

Database Modifications

The modifications to TSL-CALVIN database were done to (1) delete obsolete data; (2) update reactor site and cask information and fuel projection data; and (3) incorporate data and parameters required to simulate the standard canisters and casks. For example, the field “array size” in the cask table is used to in the new version of the code to define storage and transportation casks/overpacks that can accommodate multiple SNF-bearing canisters (multi-canister overpacks). This field was not used in the previous version of the code.

3. VERIFICATION AND VALIDATION SCOPE AND APPROACH

A substantial effort is required to conduct verification and validation of TSL-CALVIN due to a large number of significant modifications to the code made in 2013 and incorporated in TSL-CALVIN 4.5.3. The scope of the FY14 work was limited to testing selected functions as described below. Note that TSL-

CALVIN does not predict physical phenomena and, as such, cannot be validated using experimental data. The validation in this case is limited to testing the accuracy of the calculations performed by the code.

The verification and validation approach used in the FY14 analysis consisted of simulating the movement of small amounts of SNF and related operations during a limited period of time. When the SNF amounts are small, it is possible to verify the simulation results by hand calculations. In FY15 this approach will be supplemented by the analysis of the major arrays generated by TSL-CALVIN that store all the simulation variables.

The FY14 verification and validation tested the following functions:

- Calculation of the pool allocation.
- Removing SNF from dry storage at the reactor sites to be transported to the ISF.
- Removing SNF wet storage (pool) at the reactor sites to be transported to the ISF.
- Calculation of the pool inventory.
- Shipping SNF from the reactor sites to the ISF.
- Processing SNF arriving at the ISF.
- Calculating ISF infrastructure requirements.
- Calculating ISF capital and operational costs.
- Calculating the thermal output of a canister.
- Checking the calculated cask thermal output against the cask thermal limit.

The scenario simulated with TSL-CALVIN assumed that an ISF becomes operational in 2020. Until 2020, the SNF is accumulated at the reactors sites. The SNF is discharged in the pools first. The SNF from the pool is loaded in the existing dry storage canisters and is moved to the on-site dry storage facility when the pool reaches its capacity. In 2020 the ISF begins accepting canistered SNF from the reactor sites. The acceptance rate is 200 MTU/yr during the first 10 years of operations (2020 to 2029).

Section 4 describes the calculations and the results of the verification and validation tests.

4. VERIFICATION AND VALIDATION TESTS

4.1 Calculation of the Pool Allocation

The pool allocation specifies what pools are to be granted priority allocations and the number of such allocations. TSL-CALVIN calculates the pool allocation based on the discharge order using the data in the fuel projection table of the database. The code runs chronologically through the SNF discharge data, summing up the MTU in each batch record with an age greater than the minimum fuel age until it reaches the acceptance rate specified for the year.

After the allocation is calculated, the code attempts to select fuel from each pool that has an allocation greater than zero. Two basic methods of fuel selection are incorporated in TSL-CALVIN: Oldest Fuel First (OFF) and Youngest Fuel First greater than a certain age (YFFx), where x indicates the age of fuel to begin accepting first. In the scenario considered, the OFF method is specified.

Note that if no fuel that meets the cask limits is available, the pool's allocation is deferred to the next year and an additional pool allocation is created to compensate for the deferred allocation.

The total amount of fuel shipped in a year and accepted at the ISF (or MGR) may be somewhat different from the allocated amount due to the fuel unavailability or other reasons (the code tries to load a cask to its full capacity). The annual acceptance rates are tracked by the code.

The goal of this test was to check the pool allocation calculated by the code for the first year of acceptance (2020) and the subsequent 10 years of acceptance.

The acceptance rates calculated by the code for the first 10 years of ISF operations are provided in Table 1.

Table 1. ISF Acceptance Rate Calculated by TSL-CALVIN.

Year	Acceptance (MTU)
2020	258.1
2021	209.7
2022	239.9
2023	210.5
2024	251.2
2025	194.2
2026	222.2
2027	216.8
2028	186.4
2029	226.8
Total	**2215.8**

The acceptance rate in 2020 was 258 MTU. The pool allocation can be obtained from the shipping schedule. The shipments that took place in 2020 are provided in Table 2.

Table 2. Shipments in 2020 Calculated by TSL-CALVIN.

Year	Reactor Site	Source
2020	Dresden 1 (in Dresden 3 pool)	Dry storage
2020	Dresden 1	Dry storage
2020	Haddam Neck	Dry storage
2020	Haddam Neck at Morris	Pool
2020	Humboldt Bay	Dry storage
2020	Morris (Dresden 2)	Pool
2020	Nine Mile Point 1	Pool
2020	Oyster Creek 1	Pool
2020	San Onofre 1 in 2	Dry storage
2020	San Onofre 1	Dry storage
2020	Son Onofre 1 at Morris	Pool
2020	Yankee-Rowe 1	Dry storage

The fuel projection table in the TSL-CALVIN database was used to calculate the pool allocation by hand. The records in the fuel projection are arranged from the earliest discharge to the latest one. The MTU in these records were summed until the cumulative amount was equal to 258 MTU, which is the acceptance rate in 2020. The batches in these discharges were mapped to the reactors sites. The results are summarized in Table 3. With the exception of Big Rock Point, the sites in Table 3 match the sites in Table 2.

Table 3. Pool Allocation Calculated from Fuel Projection for the First Year of Acceptance (2020).

Reactor Site	MTU	Number of Assemblies
Big Rock Point 1	1.4	11
Dresden 1	21.1	207
GE Morris	131.1	680
Ginna	4.6	12
Haddam Neck	43.3	103
Humboldt Bay	3.1	40
Nine Mile Point 1	3.3	17
Oyster Creek 1	4.6	24
San Onofre 1	35.6	97
Yankee-Rowe 1	9.8	36
Total	**258.0**	**1227**

Similar calculations were done for the first 10 years of ISF operations. The total amount accepted during this period of time was 2216 MTU. The pool allocation calculated from the fuel projection and the pools from which the fuel was shipped are summarized in Table 4. The site selection is the same, except the McGuire site has no allocation in the hand calculations. The reason for this can be deferral of the allocation. A more detailed examination should be done in FY15 to analyze these differences.

Table 4. Pool Allocation Calculated by Hand and Calculated by TSL-Calvin for the First 10 Years of Acceptance (2020 to 2029).

Hand Calculations	TSL-CALVIN Shipping Schedule
Three Mile Island 1	Three Mile Island 1
Big Rock Point 1	Big Rock Point 1
Brunswick 2	Brunswick 2
Cooper	Cooper at Morris
Dresden 1	Dresden 1
Dresden 2	Dresden 2
Dresden 3	Dresden 3
Duane Arnold	Duane Arnold
Fort Calhoun	Fort Calhoun
GE Morris	Haddam Neck at Morris
Ginna	Ginna
Haddam Neck	Haddam Neck

Hand Calculations	TSL-CALVIN Shipping Schedule
Humboldt Bay	Humboldt Bay
Indian Point 1	Indian Point 1
Indian Point 2	Indian Point 2
Kewaunee	Kewaunee
Lacrosse	Lacrosse
Maine Yankee	Maine Yankee
Millstone 1	Millstone 1
	McGuire 1
	McGuire 2
Monticello	Monticello
Nine Mile Point 1	Nine Mile Point 1
Oconee 1	Oconee 1
Oconee 2	
Oconee 3	
Oyster Creek 1	Oyster Creek 1
Palisades	Palisades
Peach Bottom 2	Peach Bottom 2
Peach Bottom 3	
Pilgrim 1	Pilgrim 1
Point Beach 1	Point Beach 1
Point Beach 2	
Prairie Island 1	Prairie Island 1
Prairie Island 2	
Quad Cities 1	Quad Cities 1
Quad Cities 2	
Robinson 2	Robinson 2
San Onofre 1	San Onofre 1
Surry 1	Surry 1
Surry 2	
Turkey Point 3	Turkey Point 3
Turkey Point 4	
Vermont Yankee 1	Vermont Yankee 1
Yankee-Rowe 1	Yankee-Rowe 1
Zion 1	Zion 1

4.2 Heat Calculations

The heat calculations are performed every time the canister or the cask or the waste package thermal output needs to be checked against the specified heat limit. TSL-CALVIN calculates the heat output for an assembly by interpolating (or extrapolating) the data in the five tables in TSL-CALVIN database:

"Heat_BWR," "Heat_BWRSS," "Heat_PWR," "Heat_PWRSS," and "HTTIMES". The "Heat" data tables list heat output data (in watts) for BWR zirconium-clad fuel, BWR stainless steel-clad fuel, PWR zirconium-clad fuel, and PWR stainless steel-clad fuel as a function of burnup, enrichment, and age (time after discharge) of the fuel. Twelve burnup values and eleven enrichment values are listed per fuel type. Heat values for 180 decay times are listed for each burnup / enrichment combination.

One BWR canister was selected to check the heat calculations. This canister was loaded in 2002 at the Quad Cities (Unit 1) reactor site. According to the dry storage activities output file, 68 assemblies at this site were loaded from the pool into the Holtec MPC dry storage canister. The dry storage canister heat limit specified in the database is 34 kW. This was the first dry storage canister loaded at this site. Because the oldest fuel in the pool is selected first, it was possible to identify the assemblies in the fuel projection that were candidates for loading. These assemblies are listed in Table 5. The assemblies are 28, 27, and 26 years old. All the assemblies have the enrichment of 2.1%. The heat output values for the enrichment of 2%, burnup of 1, 10, and 20 GWd/MTU, and fuel age 26, 27, and 28 years in the Heat_BWR table in the database were used to calculate the assembly heat. These data are plotted in Figure 1. The log interpolation was done to calculate the heat corresponding to the specific burnup value. The results of these calculations are summarized in Table 5.

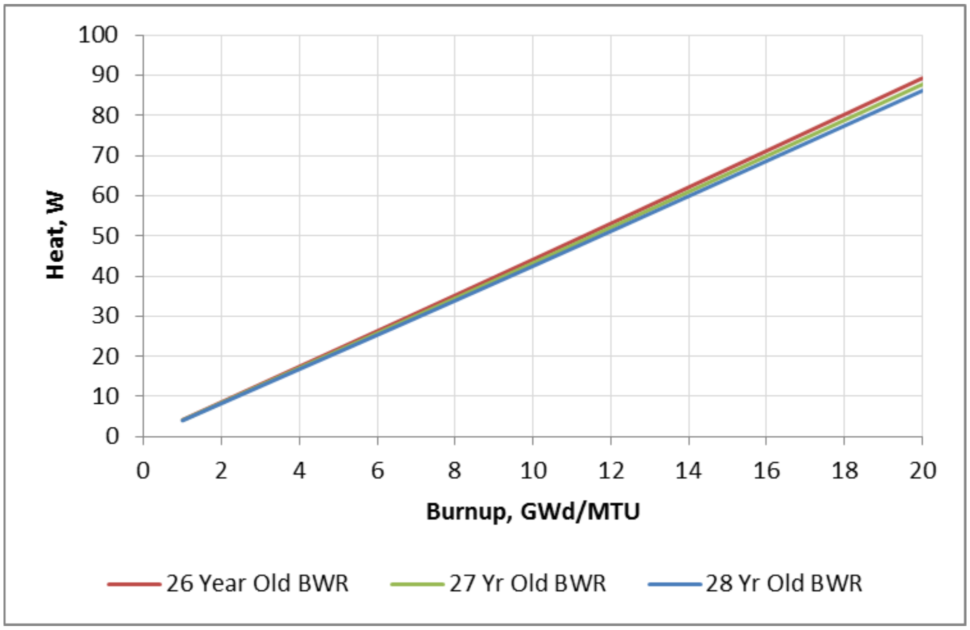

Figure 1. BWR Assembly Heat as a Function of Burnup for the 2% Enrichment.

Note that there are 179 26-year old assemblies. Only 35 out of these 179 assemblies were loaded into the canister. These 35 assemblies were arbitrarily selected for the hand calculations. If all 26-year old assemblies had 16.7 burnup (closer to the higher end burnup in this age group), the total heat output would be 3,120 W instead of 2,770 W (Table 5). The heat output calculated by TSL-CALVIN was 2,932 W, which is within the hand calculated range. The cask heat limit was higher than the heat output and the cask was loaded and moved to a dry storage

Table 5. Oldest Assemblies in the Pool at the Quad Cities (Unit 1) Reactor Site.

Batch ID	Number of Assemblies	Age (years)	Enrichment (%)	Burnup (GWd/MTU)	Calculated Heat (W)	
					per Assembly	per Batch
426	1	28	2.1	8.6	18.6	18.6
427	3	28	2.1	7.8	16.4	49.2
428	3	28	2.1	8.6	18.7	56.2
429	2	28	2.1	9.6	21.9	43.8
430	1	28	2.1	7.6	15.8	15.8
431	15	28	2.1	9.0	19.7	296.0
432	7	28	2.1	9.4	21.1	148.0
586	1	27	2.1	11.3	29.2	29.2
912	1	26	2.1	12.7	37.4	37.4
911	1	26	2.1	8.6	19.2	19.2
906	1	26	2.1	13.0	39.2	39.2
910	1	26	2.1	17.1	74.3	74.3
908	2	26	2.1	17.1	75.3	150.5
913	5	26	2.1	15.6	58.9	294.3
909	6	26	2.1	16.3	65.6	393.9
904	12	26	2.1	15.4	56.9	682.4
905	6	26	2.1	16.7	70.4	422.2
Total	**68**					**2770.2**

Note that TSL-CALVIN uses the log interpolation of the burnup-heat data. As it is shown in Figure 2, this interpolation is adequate for the burnup range 15 to 60 GWd/MTU. For the lower burnup values, the linear interpolation would be more appropriate. Using log interpolation for the lower burnup values results in the lower heat output estimate. If a linear approximation was used in the considered example, the canister heat output would have been 3,700W instead of 2,770W.

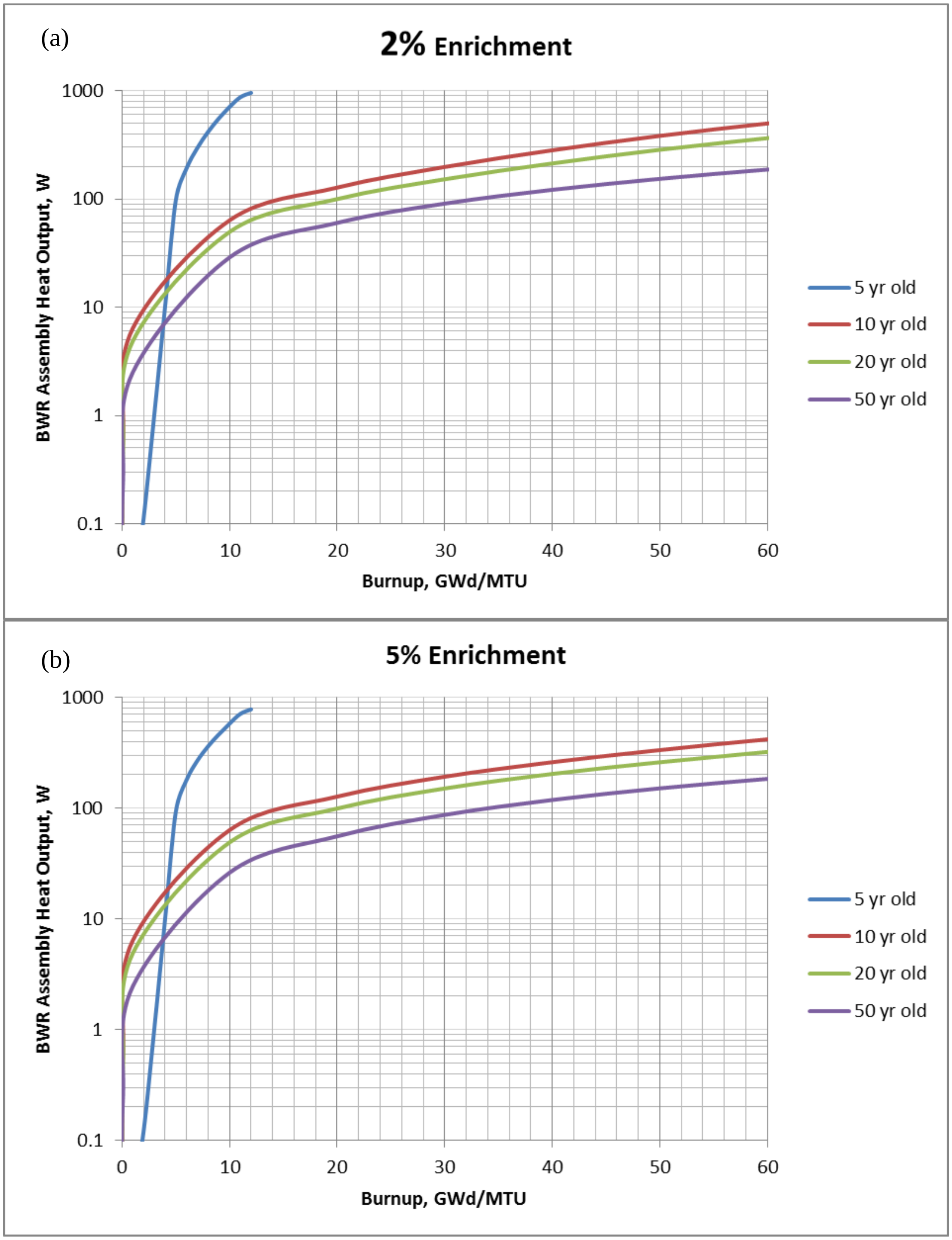

Figure 2. BWR Assembly Heat Output as a Function of Burnup and Age for (a) 2% Enrichment and (b) 5% Enrichment.

4.3 ISF Infrastructure Requirements

The infrastructures required at the ISF depend on the number and the types of canisters/casks arriving at the ISF. In the case if no bare fuel is accepted at the ISF, the required infrastructures include:

- Dry canister receipt and transfer bays (both for arriving canisters and canisters being shipped).

- Horizontal dry storage modules.
- Vertical dry storage modules.

The required number of dry canister receipts and transfer bays and dry storage modules needed is calculated for each year. It is assumed that the infrastructures are deployed when needed.

No shipments from the ISF took place in the scenario considered. Consequently, only the arriving canister bays were required. The number of canisters per horizontal module was set equal to twelve. The number of canisters per horizontal module was set equal to eight.

The shipping schedule generated by TSL-CALVIN for 2020 to 2029 is provided in Table 6. The schedule was post-processed to show only the canisters shipped during this period of time. The NUHOMs canisters (shaded in Table 6) require horizontal dry storage modules. The other canisters require vertical dry storage modules.

First, the canisters shipped from the reactor sites were checked against the canisters received at the ISF (Table 7). It was shown that all the canisters shipped were received at the ISF.

At the next step, the data on the horizontal and vertical canisters arriving at the ISF from the ISF handling output file were checked against the data in the shipping schedule (Table 6). The number of modules required each year to store the dry storage canisters was calculated using the information on number of canisters per pad and compared with the TSL-CALVIN output (Table 8).

The number of the canister receipts and transfer bays N_b in a specific year was calculated from the following formula:

$$N_b = \frac{T_{handl}}{H_{op}} \qquad (1)$$

where H_{op} is the ISF operating hours per year and T_{handl} is the required total operating time for canister handling process. This time includes all processing steps for preparing arriving dry canisters for SNF processing. Note that Eq. (1) is different from the one in TSL-CALVIN user manual (Ref. 1). The formula in the user manual is believed to have an error.

The total operating time (T_{handl}) in a specific year is calculated as (Ref. 1):

$$T_{handl} = \sum_{i=1}^{M} T_i \cdot N_i \qquad (2)$$

where T_i is the processing time for the canister of type i; N_i is the number of canisters of type i, and M number of different canisters types arriving at the ISF in a specific year. The processing times for each canister type arriving at the ISF within the first 10 years are provided in Table 8.

The number of ISF operating hours per year (H_{op}) is calculated as (Ref. 1):

$$H_{op} = N_{shift} \cdot H_{shift} \cdot (D_{week} \cdot 52 - H_{hol}) \qquad (3)$$

where N_{shift} is the number of shifts per day, H_{shift} is the hours per shift, D_{week} is the number of working days per week, and H_{hol} is the number of holidays (in hours) per year. The scenario considered assumed 2 shifts per day, 8 hours per shift, 7 days per week, and 90 hours of holidays per year. The resulting number of operating hours is 4384.

Table 6. Types and Number of Canisters Shipped from the Reactor Sites to ISF from the Shipping Schedule Calculated by TSL-CALVIN.

Year	VSC-24	W150 (BRP)	HOLTEC MPC68	HOLTEC MPC32	HOLTEC MPC80	NUHOMS 24PT	NUHOMS 61BT	NUHOMS 32PT	NAC MPC-36	NAC UMS 24	NAC MPC-26	NAC MPC68-	TN-32
2020	0	0	14	7	1	2	0	0	1	0	1	0	0
2021	0	0	9	6	1	0	0	0	1	0	2	1	0
2022	0	0	12	7	0	1	0	0	0	0	2	0	0
2023	0	1	7	6	0	0	0	0	1	3	1	0	0
2024	0	0	10	8	1	2	0	0	0	0	0	0	1
2025	0	0	5	5	0	0	1	0	0	5	0	0	1
2026	0	0	11	2	0	0	1	0	0	1	1	1	2
2027	9	0	5	3	0	0	1	0	1	1	0	0	0
2028	0	0	7	6	0	1	0	1	0	0	0	0	0
2029	0	0	8	5	2	0	0	0	0	0	2	0	2
Total	**9**	**1**	**88**	**55**	**5**	**6**	**3**	**1**	**4**	**10**	**9**	**2**	**6**
Processing Time, min	2826	2826	2826	2826	2826	2826	2826	2826	2826	2826	2826	2826	2826

Table 7. Comparison of TSL-CALVIN Output and Calculated Dry Storage Infrastructures.

Year	Shipping Schedule		ISF Activities				Calculated Dry Storage	
	Number of Canisters Shipped		Number of Canisters Received		Cumulative Number of Modules		Cumulative Number of Modules	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
2020	2	24	2	24	1	3	1	3
2021	0	20	0	20	1	6	1	6
2022	1	21	1	21	1	9	1	9
2023	0	19	0	19	1	11	1	11
2024	2	20	2	20	1	13	1	13
2025	1	16	1	16	1	15	1	15
2026	1	18	1	18	1	18	1	18
2027	1	19	1	19	1	20	1	20
2028	2	13	2	13	1	22	1	22
2029	0	19	0	19	1	24	1	24

Table 8. Summary of Canisters Shipped from the Reactor Sites and Received at the ISF.

Year	Shipped	Received
2020	26	26
2021	20	20
2022	22	22
2023	19	19
2024	22	22
2025	17	17
2026	19	19
2027	20	20
2028	15	15
2029	19	19
Total	**199**	**199**

The calculation of the number of the processing bays required each year (Eq. 1 and 2) are summarized in Table 9. These results are consistent with the values calculated by TSL-CALVIN (ISF activities output file).

Table 9. Summary of Number of Processing Bay Calculations.

Year	Processing Time (hours)	Handling Time/Operation Hours (Eq. 1)	Number of Processing Bays
2020	1224.6	0.28	1
2021	942	0.21	1
2022	1036.2	0.24	1
2023	1789.8	0.41	1
2024	2072.4	0.47	1
2025	1601.4	0.37	1
2026	1789.8	0.41	1
2027	1460.1	0.33	1
2028	1413	0.32	1
2029	1789.8	0.41	1

4.4 ISF Cost Calculations

The ISF capital and operational costs for the scenario considered were calculated by hand for the first 10 years of the ISF operations and were compared to the costs calculated by TSL-CALVIN.

4.4.1 ISF Capital Costs

The capital costs associated with the ISF that does not handle bare fuel are limited to the following:

- Infrastructure cost: all infrastructure development costs associated with deploying an ISF as a single cost incurred when the ISF becomes operational.
- Dry canister receipt and transfer bays cost: the bays are deployed when needed and cost is incurred then.
- Canister dry storage cost: the dry storage modules are constructed when needed and the cost is incurred then. There are three types of the dry storage modules – vertical, horizontal, and standard.

The costs assumed in the scenario were:

– Infrastructure cost: $116.3M

– Canister bay cost: $73.8M per bay

– Horizontal dry storage module cost: $15.8M per module

– Vertical dry storage module cost: $8.2M per module

The numbers of canister bays and horizontal and vertical dry storage modules may change from year to year because they are deployed as needed. The related costs incur in the year during which they are deployed. The required infrastructures (number of dry storage modules and receiving bays) were calculated in Section 4.3.

The calculations of the capital costs are summarized in Table 10. These results are consistent with the values calculated by TSL-CALVIN (fuel handling costs output file).

Table 10. Summary of the Capital Cost Calculations.

Year	Infrastructure Cost ($M)	Dry Storage Modules				Receiving Bay Cost ($M)	Capital Cost ($M)
		Horizontal		Vertical			
		Number of Pads	Pad Cost ($M)	Number of Pads	Pad Cost ($M)		
2020	116.3	1	15.8	3	24.6	73.8	391.2
2021		0	0	3	24.6		24.6
2022		0	0	3	24.6		24.6
2023		0	0	2	16.4		16.4
2024		0	0	2	16.4		16.4
2025		0	0	2	16.4		16.4
2026		0	0	3	24.6		24.6
2027		0	0	2	16.4		16.4
2028		0	0	2	16.4		16.4
2029		0	0	2	16.4		16.4

4.4.2 ISF Operational Costs

The operational costs associated with the ISF that does not handle bare fuel are limited to the following:

- Dry fuel handling annual labor cost: calculated as a function of a number of operating dry canister bays, number of crews per bay, and the required labor force.

- Utility annual cost: calculated based on the number of crews working each year assuming a minimum of one crew will be required to be in place even when the ISF is not handling fuel.
- Annual materials and contracts cost (equipment leases, janitorial, and project costs): calculated as a fraction of total annual labor cost.

The decommissioning costs are not considered in this test case because they occur after ISF has completed shipment of all fuel.

The dry fuel handling annual labor cost (C_{handl}) in $M per year is calculated as (Ref. 1):

$$C_{handl} = \left[N_{mng} \cdot C_{mng} + N_{exm} \cdot C_{exm} + N_{nexm} \cdot C_{nexm}\right] \cdot [1 + C_{ovrh}] \qquad (4)$$

where N_{mgr} and C_{mng} are the number of managers and managers' salary; N_{exm} and C_{exm} are the number of exempt workers and their salary; N_{nexm} and C_{nexm} are the number of non-exempt workers and their salary; C_{ovrh} is the overhead rate.

The number of workers is calculated as follows:

$$N_{mn} = a_1 + b_1 \cdot N_{crew} \qquad (5a)$$

$$N_{exm} = a_2 + b_2 \cdot N_{crew} \qquad (5b)$$

$$N_{nexm} = a_3 + b_3 \cdot N_{crew} \qquad (5c)$$

where N_{crew} is the number of crews required to operate the dry canister bays in a specific year and $a_{i=1,2,3}$ and $b_{i=1,2,3}$ are fixed coefficients. Note that even when the number of crews is equal to 0, the number of workers is greater than zero and equal to $a_1+a_2+a_3$.

The number of crews required to operate the dry canister bays in a specific year is calculated as:

$$N_{crew} = N_b \cdot B_{crew} \qquad (6)$$

where B_{crew} is the number of crews per bay.

Note that Eq. (4) is different from the one in Appendix A-1.6.2 in the TSL-CALVIN user manual (Ref. 1). It is believed that the formula in the user manual has an error – the number of crews is counted twice.

The utility annual cost (C_{util}) is calculated as (Ref. 1):

$$C_{util} = \max[1, N_{crew}] \cdot c_{util} \qquad (7)$$

where c_{util} is the utility cost per crew ($M).

The annual materials and contracts costs ($M) are calculated as (Ref. 1):

$$C_{mtr} = C_{eq} + C_{jan} + C_{prj} \cdot f_{labor} \qquad (8)$$

where C_{eq} is the annual equipment lease; C_{jan} is the janitorial cost; C_{prj} is the materials and project costs; and f_{labor} is the fraction of total labor cost.

The following parameters were assumed in this scenario:

– Crews per bay: 1

– Manager salary: $0.15M

– Exempt worker salary: $0.15M

– Non-exempt worker salary: $0.083M

– a_1=7 and b_1=5

- a_2=30 and b_2=20
- a_3=39 and b_3=30
- Overhead: 0.29
- Annual utility cost per crew: $1.7M
- Equipment: $0.05M
- Janitorial: $0.1M
- Materials and projects: $0.1M
- Fraction of labor for materials: 0.1

During the first 10 years of the ISF operations there is only one receiving bay. Consequently, the annual labor cost is the same during this period of time and is equal to $19.38M as calculated from Eq. 4-6 and the scenario parameters. The number of workers includes 12 managers, 50 exempt workers, and 69 non-exempt workers.

The annual utility cost is $1.7M as calculated from Eq. 7 and the scenario parameters.

The annual materials and contracts cost are $2.19M as calculated from Eq. 8 and the scenario parameters and using annual labor cost of $19.38M.

The annual labor, utility, and materials and contracts cost are consistent with the values calculated by TSL-CALVIN (fuel handling costs output file).

4.5 Pool Capacity Calculations

TSL-CALVIN calculates pool capacities each year. The capacities are reported in the pool storage report. The capacity in a specified year is equal to the capacity in the previous year plus the MTU (assemblies) discharged minus the MTU (assemblies) loaded into the dry storage minus the MTU (assemblies) loaded for shipping from the sites. These calculations were checked for two sites as described below.

<u>Oyster Creek</u>

According to the fuel projection, the last discharge at the Oyster Creek reactor site will occur in 2019. The first shipping from this site, as calculated for the scenario considered, is in 2020. The assemblies from the pool are loaded in the dry canisters and shipped to the ISF. The TSL-CALVIN outputs were examined to see if the last discharge and pool capacities were calculated correctly. The data that were checked are summarized in Table 11. The pool capacities calculated by TSL-CALVIN are consistent with the last discharge data and shipping schedule data.

Table 11. Oyster Creek Pool Capacity Data.

Year	Pool Capacity (MTU)	Loaded from the Pool (MTU)	Discharged into the Pool (MTU)
2018	+	0	0
2019	518.94	0	96.12
2020	507.24	11.7	0
2021	483.85	23.39	0
2022	460.46	23.39	0
2023	448.76	11.7	0
2024	437.06	11.7	0
` **Total**		**81.88**	

West Valley (PWR and BWR) and INEEL (PWR and BWR)

The pool capacities at West Valley (PWR and BWR) and INEEL (PWR) sites are zero during the simulation period. However, according to the shipping schedule generated by TSL-CALVIN, the canisters are shipped from the pools at these sites to the ISF.

The pool capacity at the INEEL (BWR) site is greater than 0 in 2018 and 0 starting from 2019. The first shipment at this site takes place in 2020 and the assemblies are loaded from the pool.

TSL-CALVIN shipping schedule for these sites is provided in Table 12.

Table 12. Shipping Data for WVDP and INEEL Sites.

Year	Source	Origin	Destination	Number of Casks Shipped	
				HOL MPC68	HOL MPC32
2020	INEEL-BWR	Pool	ISF	1	0
2020	WVDP-BWR	Pool	ISF	1	0
2020	WVDP-PWR	Pool	ISF	0	1
2021	INEEL-PWR	Pool	ISF	0	1
2021	WVDP-PWR	Pool	ISF	0	1
2022	WVDP-BWR	Pool	ISF	1	0

These issues need to be addressed in the FY15 analysis.

5. SUMMARY

This report documents the verification and validation (V&V) of TSL-CALVIN 4.5.3. The new software verification and validation was required to address the substantial changes to the code and the database made in 2013. The new functionalities added to the code include the following:

- Monitored geologic repository (MGR) acceptance priority
- Bare fuel handling at the interim storage facility (ISF)
- ISF cost calculations
- Repackaging cost calculations

- Site specific acceptance priority
- Thermal management
- Accelerated transfer from pools to dry storage

The scope of the FY14 work was limited to testing selected functionalities. The verification and validation approach consisted of simulating the movement of small amounts of SNF during a limited period of time (10 years). This approach allowed for verifying the simulation results by hand calculations. The hand calculations were performed to check the following calculations:

- Pool allocation
- Heat calculations
- ISF infrastructure requirements
- ISF cost calculations
- Pool capacity calculations

The V&V uncovered a few issues that need to be addressed in FY15. It is recommended to do a more detailed analysis of the pool allocation. Pool capacity calculations at a few sites (West Valley and INEEL) should be examined to understand the inconsistencies in pool inventories.

The calculations of the assembly thermal output demonstrated that using log interpolation for the lower burnup values results in a lower heat output estimate. A linear interpolation is more adequate for the low burnups.

In addition, the TSL-CALVIN user manual should be revised to correct the errors in a few formulae.

The FY15 V&V effort will target more detailed testing of all the features, including the ones not tested in FY14. The testing approach will be supplemented by the analysis of the major arrays generated by TSL-CALVIN that store all the simulation variables. The FY15 scope will also include V&V of the Transportation Operations Model (TOM). The results of the FY15 V&V will be documented in a separate V&V report.

6. REFERENCES

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