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Report

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SKB burn up validation with Scale 6.1

Summary

In this report it is shown that with the SKB methodology the Scale 6.1 code package can be used for validation of spent PWR fuel at Clink and the spent fuel repository with the following result.

USL (Upper Subcritical Limit): 0.93529

The USL includes code bias, uncertainties, an administrative margin of 5 %, margin for trends in physical parameters and materials as well as an extra margin for correlation between experiments. The USL is applied to all SKBs criticality calculation on PWR spent fuel.

The USL calculation is done by comparison of calculated k_{eff} with real k_{eff} (1.0) for a number of criticality experiments. Specific criticality tools are used to pick experiments which have the same neutron physic characteristics as the compact-, transfer- and storage canisters at SKB. In addition to this a number of experiments are added to the validation suite based on engineering judgment. The validation process is described more specifically in this report.

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Content

1 Introduction

This report is a validation of burn-up calculations with the code package Scale 6.1 for use in the Swedish back-end system excluding transportation. The included facilities are

- the current interim storage facility, Clab
- the planned encapsulation plant
- the planned final repository for spent nuclear fuel

The current interim storage facility and the planned encapsulation plant is jointly called Clink.

In particular the report includes

- how the experiments have been selected
- estimated bias and uncertainties
- appropriate safety margins

2 Purpose and overview

The purpose with this validation is to establish how well the code package Scale 6.1 can predict the neutron multiplication factor k_{eff} ,with burned PWR fuel, for SKB:s systems for storage of nuclear fuel, i.e. the canisters in Clink and the final repository. This is done according to SKBdoc1369704

In SKBdoc1397015 validation of Scale 6.1 was done for fresh fuel. The main difference when calculating reactivity for spent fuel is the presence of actinides (Pu, Am, Np) and several fission products. In SKB methodology, SKBdoc1369704, it is presented which actinides and fission products that are taken into account when calculating reactivity for spent fuel. The main driver for reactivity is the different isotopes of Pu. Therefore the most important issue when validating Scale 6.1 for spent fuel is to show that Scale is predicting the reactivity worth of Pu correctly.

Since the amount of experiment with spent fuel is very limited this report will take use of mainly MOX-experiment which in contrast to fresh fuel experiments includes Pu, and in some cases also Am. A special safety margin will be added due to the fact that the experiments lack content of fission products and other minor actinides.

An Upper Subcritical Limit (USL) is calculated which must be considered in the results in all criticality analysis made with the Scale 6.1 code package at SKB, when reactivity of spent fuel is calculated.

This is done by comparison of calculated k_{eff} with real k_{eff} (1.0) for a number of criticality experiments. Specific criticality tools are used to pick experiments which have the same neutron physic characteristics as the compact-, transfer- and storage canisters at SKB. In addition to this a number of experiments are added to the validation suite based on engineering judgment, in this case experiments that have matching EALF and Pu-content. Since burn-up credit only will be used for PWR only PWR applications is validated.

A bias is calculated from the benchmarks with established statistical methods. Trends concerning materials or physical properties are examined. The variable with the strongest correlation to the calculated k_{eff} values is then used in a linear regression equation to describe the variation in k_{eff} , k_c (x), for determination of USL. This variable is then included in the results safety margins and is added to the calculated bias.

In addition to this an extra safety margin is added due to dependencies between experiments which are not handled by the applied statistical methods.

The methodology used is based on the standard ANSI/ANS-8.24-2007. More information on how the standard has been interpreted can be found in the overall criticality methodology calculation as described in SKBdoc1369704.

It should be noted that this report deals only with the uncertainty when the isotope concentration is known. The uncertainty related to predict the isotope concentration when the fuel is burned will be added as a special uncertainty directly in the criticality analysis.

3 Computer code and software system

All calculations made in this report are made with Scale 6.1 on SKB computer XP00342. The validation of the computer is described in SKBdoc1397015.

The software used in this validation is shown in table 1.

Criticality	CSAS5	ORNL 2011a
Sensitivity & Uncertainty	TSUNAMI-3D, TSUNAMI-IP	ORNL 2011b
Cross-section library	ENDF/B-VII.0, 238 group	ORNL 2011c
Statistics	USLStats 1.0.16.16	NUREG/CR-6361
Depletion	Triton	ORNL 2005a
Sequence	T5-depl	ORNL 2006

Table 1. Specification of validation software.

For software changes, table 1, a new validation report should be issued. If the hardware is changed SKB should rerun validation suite confirming that the results are the same. In that case a new validation report is not necessary.

Parameters in the code have been selected to be appropriate for the individual calculations. They are in accordance with Oak Ridge National Lab (ORNL) defaults and recommendations. The most important are presented here.

- Triton calculations
  - Number on neutron per generation (NPG): 10000
  - Minimum number of skipped per generation (NSK): 200
  - Standard deviation (SIG): 0.0001

- Forward Keno calculations for k_{eff} calculations
  - Number on neutron per generation (NPG): 10000
  - Minimum number of skipped per generation (NSK): 200
  - Standard deviation (SIG): 0.0001

- Forward Keno calculations in Tsunami for sensitivity calculations
  - Number on neutron per generation (NPG): 10000
  - Minimum of number of skipped per generation (NSK): 200
  - Standard deviation (SIG): 0.0002

- Adjoint Keno calculations in Tsunami for sensitivity calculations
  - Number on neutron per generation (APG): 30000
  - Minimum of number of skipped per generation (ASK): 200
  - Standard deviation (ASG): 0.002

4 Selection and modelling of benchmark experiments

The experiments for this validation have been selected based on the strategy below.

1. A large number of experiments (~100) have been chosen which are “similar” to our applications (see section 5). Similarity assessment have been made using Tsunami-IP, based on sensitivity data calculated with the Tsunami-3D. This process is shown in step 1-5 below.
2. To attain coverage of all important engineering parameters the selection have been complemented by picking experiments based on geometry, materials and neutron spectra. This process is shown in step 6 below.

With guidance from SKBdoc 1369704 the steps in the list below were performed.

1. Modelling of Westinghouse 15x15 Upgrade and burn-up calculations
2. The isotopic composition for burn-up calculations used as input in target systems
3. Identification, modelling and creation of sensitivity data for application cases.
4. Collecting sensitivity data for experiments in the ICSBEP handbook (OECD/NEA 2012a).
    a. Nearly 2200 experiments provided by OECD-NEA (IRPHE-ICSBEP-project (OECD/NEA 2012b).)
    b. About 600 experiments from the Oak Ridge National Lab VALID library (Marshall and Rearden 2011).
5. Selecting experiments from the sensitivity data.
    a. Selecting the 100 best matches for each application with Ck > 0.8, see appendix 1.
    b. Excluding experiments with unreliable results and questionable applicability (SKBdoc1436491)
    c. Quality assurance of sensitivity data for the selected experiments. (see section 7)
6. Selecting experiments from engineering parameters.
    a. Performing gap-analysis between range of parameters and area of application from the experiments picked in step 5, see section 8.2.
    b. Adding experiments from ICSBEP handbook, if possible, to fill gaps in validation.

7. Quality assurance for all experiment series included in the validation have been documented and stored in SKBdoc. For more details see section 7.

5 Adequacy of the validation

Applications in table 2 have been used to derive the range of parameters for the SKB system.

Compact storage canister	PWR
Transfer cansiter	PWR
Copper disposal canister	PWR

Table 2. Specification of validation applications.

The fuel and canisters in the applications have been selected to be a good representation of the fuel and geometries in the current design of Clab, encapsulation plant and final repository.

The experiments in this validation have been selected to validate the codes prediction of k_{eff} for Pu-systems with same or higher level of Pu.

Considering the applications and the different fuel types in the systems gives the range of parameters seen in table 3. Other isotopes present is not considered according to the methodology described in SKBdoc1369704.

Parameter	Parameter info	Validation range	Targetsystem
Isotopes	Materials – actinides	U-[234, 235, 238] Pu-[238, 239, 240, 241, 242] Am-241	
	Materials – other minor actinides and fission products	U-236, Np-237, Am-243, Mo-95, Tc-99, Ru-101, Rh-103, Ag-109, Cs-133 Sm-[147, 149, 150, 151, 152] Nd-[143, 145] Eu-[151, 153] Gd-155	
Materials	Other materials	Borated Steel	Yes
		Copper	Yes
		Iron	Yes
		Stainless Steel	Yes
		Zircaloy	Yes
		Water (with/without boron)	Yes (without boron)
Physical	Pin Pitch (cm)	1.0 -- 2.0	1.43
	Initial enr. (wt % U235)	2≤ 5	≤5
	Pu/(U+Pu)	≤2.6E-2	6.01E-3--1.19E-2
Physics	EALF (ev)	1.00E-1--8.00E-1	2.136E-1--4.046E-1
	Burn-up	≤60MWd/kgU	≤60MWd/kgU

Table 3. Parameter information with specification of this validation.

The validation covers all fuel types with materials and parameters as in table 3. Borated water is not used in the target systems but in the burn up calculation and. Therefore experiments containing borated water are included in the experiment suite.

EALF is the energy of average lethargy causing fission and have been calculated for the applications using Keno Va.

Plutonium uranium ratio increases with build-up of Pu. The Uranium content is decreasing with burn-up.

To ensure compatibility with other fuel types and different geometries the parameters in this validation have been extended as shown in table 4.

Analyzing the isotopic dependence is done in section 9.

6 Simplifications made and their impact on the validation

Bentonite clay is not included. The effect of bentonite clay on reactivity in the KBS-3-system (outside insert and canister) is negligible, which is described in SKBdoc 1437025, i.e. it does not need to be analyzed further.

7 Documentation and technical review

This document has been quality assured in accordance with SKB management system.
The Keno input files used in the validation have been quality assured in the following manner:

- For each experiment series 1-4 experiment with different characteristics have been picked for quality control.

- Based on a specific review template these files have been reviewed by an experienced Scale-user.
- Review results have been documented and if necessary input files included have been updated,

8 Calculations

8.1 Tsunami-IP

The scan of the sensitivity files according to step 1 in section 4 results in 300 experiments, 100 for each application. Since there is a big similarity between the different applications a lot of the experiments overlap, resulting in a total of 105 individual experiments. These experiments are presented in appendix 1 – Tsunami-IP results. Two series were excluded since they didn't contain Pu. Experiments from three other series were excluded since they are strongly correlated and will thereby heavily distort the results of the validation. More information of the exclusion of these 67 experiments (from five series) can be seen in SKBdoc1436491. This leaves us then with 38 individual experiments.

8.2 Range of parameters

In accordance to ANSI/ANS-8.24-2007 and SKBdoc1369704 the validation should cover the entire range of parameters presented in table 3, section 5. No gap was seen in the gap analysis. Nevertheless, an addition of 8 experiments (with $C_k < 0.8$) where done to gain more experiments in the validation to get as good statistics as possible. The requirements, for the addition of these experiments, are that they must have square pitch and be one of the mix-comp-therm series.

<table>
<tr><th>Parameter</th><th>Range of parameters for validation</th><th>#Experiments/ Experimental Range</th><th>Added experiments</th><th>Total # Experiments</th></tr>
<tr><td>Fissile isotopes</td><td>Pu-, U-</td><td>38</td><td>8</td><td>46</td></tr>
<tr><td>Fissile form</td><td>Ceramic</td><td>38</td><td>8</td><td>46</td></tr>
<tr><td>Materials – actinides</td><td>U-[234, 235, 238]
Pu-[238, 239, 240, 241, 242]
Am-241</td><td colspan="3" rowspan="2">The major part of the isotopes is not included in the experiments. The dependence and contribution to the safety margin is analyzed and added as described in section 9.3</td></tr>
<tr><td>Materials – other minor actinides and fission products</td><td>U-236, Np-237, Am-243, Mo-95, Tc-99, Ru-101, Rh-103, Ag-109, Cs-133
Sm-[147, 149, 150, 151, 152]
Nd-[143, 145]
Eu-[151, 153]
Gd-155</td></tr>
<tr><td rowspan="7">Other materials</td><td>Borated Steel</td><td colspan="3" rowspan="6">Analyzed in SKBdoc1397015</td></tr>
<tr><td>Copper</td></tr>
<tr><td>Iron</td></tr>
<tr><td>Stainless Steel</td></tr>
<tr><td>Zircaloy</td></tr>
<tr><td>Water (without boron)</td></tr>
<tr><td>Water (with boron)</td><td>6</td><td>0</td><td>6</td></tr>
<tr><td>Enrichment (wt % U235)</td><td>2 ≤ 5</td><td colspan="3">Analyzed in SKBdoc1397015</td></tr>
<tr><td>Pin pitch (cm)</td><td>1 -- 2</td><td>1.397--3.520</td><td>8</td><td>46</td></tr>
<tr><td>EALF (ev)</td><td>1.00E-1--8.00E-1</td><td>9.30E-2--7.69E-1</td><td>8</td><td>46</td></tr>
<tr><td>Pu/(U+Pu)</td><td>≤ 2.60E-1</td><td>1.00E-2--2.60E-1</td><td>8</td><td>46</td></tr>
</table>

Table 4. Summary of chosen experiments based on range of parameters.

By engineering judgement of applicable experiments 8 new experiments, not included in the Tsunami-IP run, were added to the validation suit. This was done to gain as many good experiments as possible.

EALF validation is not covered by the experiments. However the small difference on the high end (0.769 compared to 0.8) is within the 10% recommended in NUREG/CR-6698 (Dean and Taylor 2001) Section 5 – Extending the Area of Applicability. Hence, there is no need for extra experiments for EALF.

8.3 k_{eff} calculations

As expressed in ANSI/ANS-8.24-2007 a limit on the calculated reactivity (k_{eff}) value should be established to ensure that conditions calculated to be subcritical will actually be subcritical. This limit is referred to as the Upper Subcritical Limit (USL). The calculated k_{eff} for the application (k_c) + the sum of the biases, uncertainties and statistical margins derived from a set of critical benchmarks (Δk_c) and any additional administrative margins (Δk_m) should be less than the USL.

In this report the USL value will be calculated with and without the administrative margin. The administrative margin will be added to the results of the critical analysis and is 0.05 for normal and credible events, respectively 0.02 for unexpected event.

For the 46 experiments, selected according to the described process, k_{eff} was calculated with Keno Va. The results of the calculations can be found in appendix 2.

8.4 Test for normality

Normality test using Jarque-Bera goodness-of-fit test were performed for all experiments included in the suite.

8.4.1 Jarque-Bera goodness-of-fit test for normal distribution

The Jarque-Bera test uses the skewness and kurtosis to reject the null-hypothesis that is that the distribution can be a normal distribution. A passed test will therefore not necessarily mean that the distribution is normal instead the interpretation is that the hypothesis cannot be rejected.

From Jarque and Bera (1987) we can find that the JB constant can be derived as

$$JB = n/6(S^2 + \frac{(K-3)^2}{4})$$

Where n is the number of observations, in this case number of experiments. S and K are skewness and kurtosis. For a perfectly normal distribution the skewness is 0, kurtosis is 3 and Jarque-Bera is 0. Notification, when calculating this in Excel the negative constant, -3, is not to be used since it is included in kurtosis calculation.

The JB-number obtained from the equation above is compared to the critical limit number for a Chi^2 distribution with 2 degrees of freedom. The critical limit can be obtained from NIST (n d).

Skewness	0.090
Kurtosis	-0.256
Jarque-Bera	0.188
Chi^2 Critical value	5.99

Table 5. Values to verify normality

Since the Jarque-Bera value is lower than the Chi^2 critical value, the null-hypothesis cannot be rejected. Based on this it is assumed that the distribution can be considered as normal and the statistic from USL-stat can be used.

9 Results

The summary of the results can be seen in table 6 below.

Number of experiments	46
Calculated k_{eff}/Expected k_{eff}	0.99796
Standard deviation	0.00287

Table 6. Summary of k_{eff} results.

Calculated k_{eff} is the reactivity calculated with Scale 6.1, description can be seen in section 3, for each experiment. Expected k_{eff} are the values from ICSBEP handbook for each experiment. By dividing these values (C/E) we get a bias (before accounting the standard deviation). All calculated values can be found in appendix 2.

The USL value is calculated and used according to NUREG/CR-6361. USL includes uncertainty in each measurement point. A trending against this value by the most important aspects is done in section 9.1 and 9.2. If they show a trending below the USL-value it will be added as a safety margin. The USL run with the uncertainty included gives the following result:

K_{eff} = 0.9884

As a comparison against the 95/95 limit calculation by Owen (1958) using the k-factor for one-sided tolerance limits (2.086 sd) for normal distributions:

K_{eff} = 0.99198

9.1 Ck

The scanning of all the available experiments is shown in figure 1 for each application with 45 Mwd/kgU burn up. The 100 best experiments with Ck > 0.8 are then used in the validation.

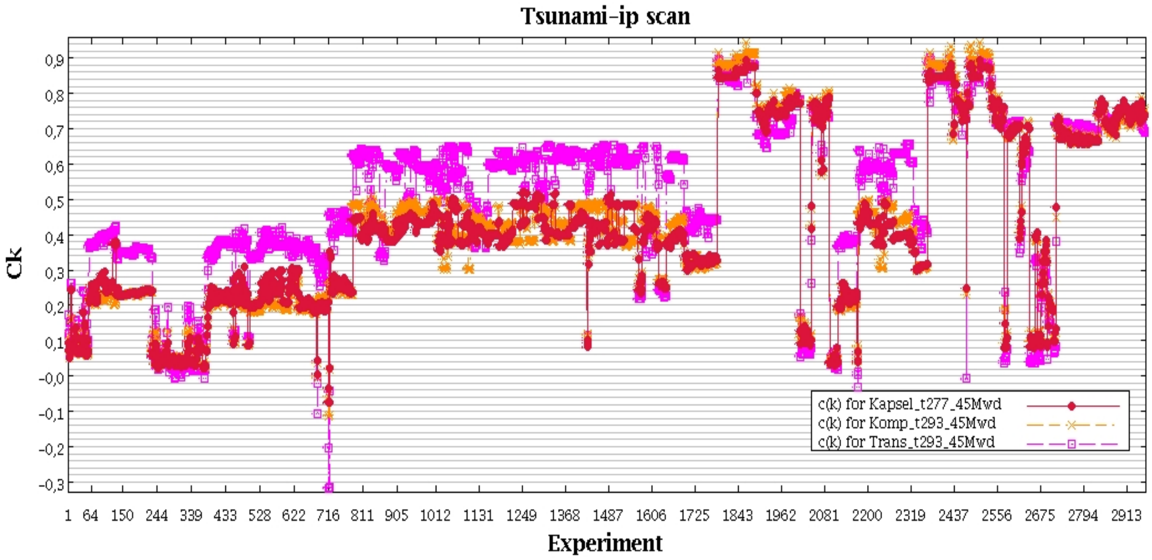

Figure 1. The graf shows the Tsunami-IP scanning of all available experiments for each target system with burn-up 45 MWd/kgU.

9.2 Materials

Most of the materials are analyzed in SKBdoc1397015. No margin will be added due to zircaloy since all the experiment series, except one, include zircaloy. However, borated water have not been analysed in the validation of fresh fuel. The experiments are grouped together and the average k_{eff} is the compared to the average k_{eff} of the whole validation suite. The results for these experiments can be seen in the table below:

	# exp	C/E k_{eff}	Δbias to total (pcm)	Considered in calculations
Borated water	6	1.00038	241	No

Table 7. Material analysis

No credit is taken for the overestimation of materials.

9.3 Fission product and minor actinide credit

Since fission products and minor actinides are not present in the experiment in the validation suite a specific margin has to be added to ensure that they are treated conservatively.

In NRC-2012 it is recommended that minor actinides and fission products can be credited with a bias of 1.5% of their worth, if the applicant

- Use the Scale code system with ENDF/B-VII cross section libraries.
- Can justify that the design is similair to the GBC-32 system design used in NUREG/CR7109
- Demonstrate that the credited minor actinides and fission products worth's is not greater than 0.1 in keff.

The code used in this validation is described in section 3

Similarity between the SKB applications and the ORNL PWR application in NUREG/CR7109 have been made using Tsunami-IP. The Tsunami-IP comparison value is in all cases above 0.9 which indicates that the systems have very similar neutron physic characteristic.

The credited minor actinides and fission product is summarized in table 8, below.

	45 MWd/kgU			60 MWd/kgU		
Credit Nuclides	**K_{eff}**	**Δk**	**%Δk**	**K_{eff}**	**Δk**	**%Δk**
Fresh fuel	1.08845					
8 Major Actinides	0.91088	0.17757	65	0.84406	0.24439	70
All Actinides	0.89682	0.01406	5	0.82641	0.01765	5
Key 6 Fission Product	0.83853	0.05828	21	0.76579	0.06062	17
All Remaining Fission Products	0.81694	0.02159	8	0.73947	0.02631	8
Total		0.27151	100		0.34898	100
Worth of minor actinides and fission products		0.09394			0.10459	
Margin (1.5 %)		**0.00141**			**0.00157**	

Table 8. Actinide and fission product worth on reactivity with burn up of 45 and 60 MWd/kgU

It can be seen that the worth of credited minor actinides and fission products, with burn up of 60 MWd/kgU, do not full fill the requirement 0.1 in k_{eff}. Since the difference is not significantly greater than 0.1 in k_{eff} an explicit validation analysis does not need to be performed according to NRC-2012.

From NRC-2012 a typical value for minor actinides and fission product has been used to calculate the 1.5% uncertainty. The result is that an extra margin of 157 pcm should be added to the validation results to ensure conservative treatment of the reactivity worth of minor actinides and fission products.

9.4 Trend analysis of physical parameters

The aim in this analysis is to identify if there are any trends in calculated k_{eff} that depends on physical parameters. Calculated k_{eff} results for all critical experiments in the validation suite were plotted as functions of the parameters EALF and plutonium uranium ratio Pu/U. These parameters were chosen based on their neutron physical importance.

The trending and calculation of USL (Upper subcritical limit) has been made by the USLstat (Lichenwalter 1998). It is a tool that handles the statistical treatment of the calculated reactivity values and calculates a 95/95 limit. i.e. 95% probability that 95% of the values are above the calculated limit. The results can be seen in table 9 and more details are found in following sections.

	95/95 limit	difference (pcm)	Considered in calculations
Trend EALF	0.9884	0	No
Trend Pu/(Pu+U)	0.9887	30	No
Trend pin pitch	0.9883	-10	Yes

Table 9. Results of trending analysis

9.4.1 EALF

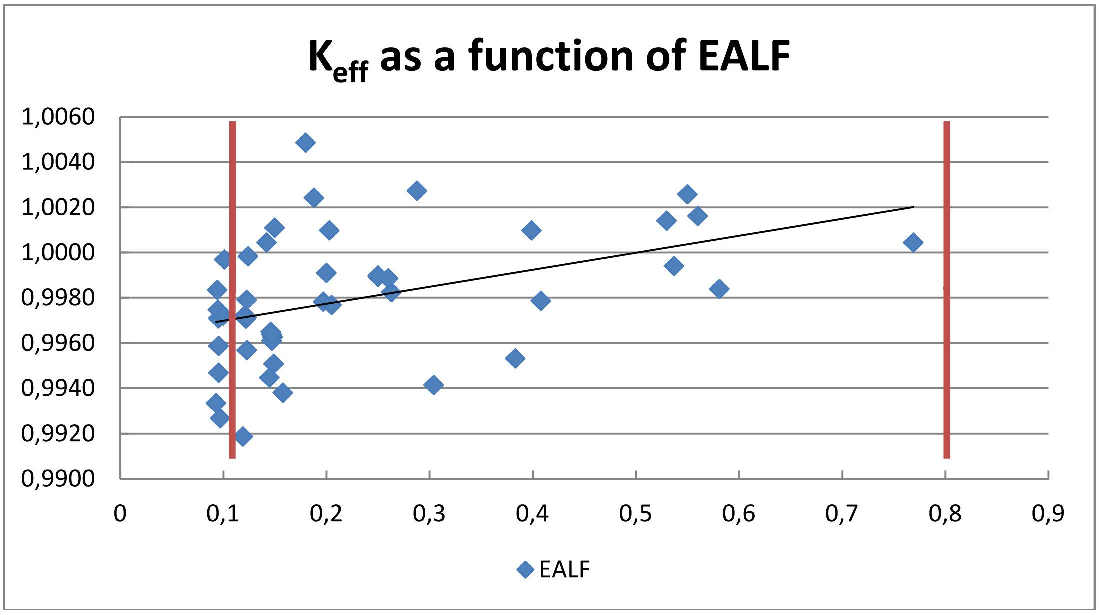

Figure 2. Trend analysis of USL as a function of EALF. no uncertainties added. The red lines indicate the limits chosen for the validation. Y-axis shows the C/E of the critical experiment and x-axis shows the EALF in eV.

	EALF (eV)		
Burn-up [MWd/kgU]	Disposal-canister	Transfer-canister	Compakt-canister
15	2.136E-01	2.321E-01	3.084E-01
30	2.467E-01	2.674E-01	3.610E-01
45	2.740E-01	2.967E-01	4.046E-01

Table 10. EALF for each application

When calculating the limiting k_{eff} with USL-stat the result is:

EALF	**0.1 eV**	**0.8 eV**
USL keff	0.9884	0.9905

Table 11. EALF trending results.

The trending is limited to EALF values below 0.8 eV. Since the highest EALF-value in the SKB applications is 0.4046 eV there is no reason to extend the trending further. In fact, the largest abbreviation is at the lower part of EALF validation. Nevertheless, since the safety margin for this variable is less than the USL limit, it can be neglected.

9.4.2 Pu/U ratio

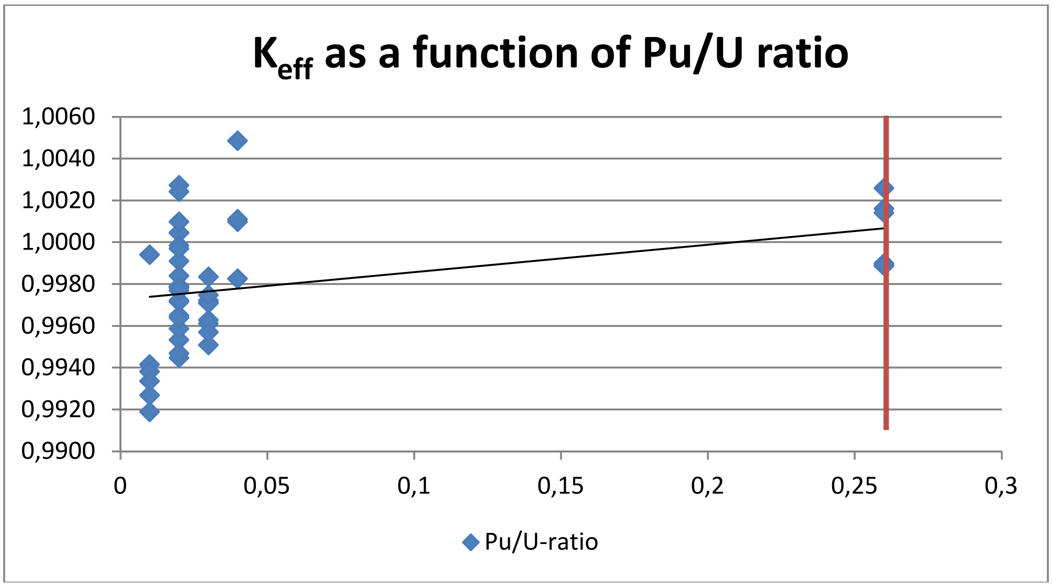

Figure 3. Trend analysis of USL as a function of Pu/U ratio, no uncertainties added. The red lines indicate the limit chosen for the validation. Y-axis shows the C/E of the critical experiment and x-axis shows the Pu/U ratio

The plutonium uranium ratio in the applications is shown in the table 12.

	Applications			Experiments	
Burn-up (Mwd/kgU)	15	30	45	Min	Max
Pu/(Pu+U)	6.01E-3	9.11E-3	1.19E-2	1.00E-2	2.60E-1

Table 12. Plutonium uranium ratio as a function of burn-up

The application range of the Plutonium content is outside the experimental range. Since a validation with fresh fuel was done in SKBdoc1397015, the validation is considered to be valid from the ratio zero to the maximal experimental range.

When calculating the limiting k_{eff} with USL-stat the result is:

Pu/(Pu+U)	**0**	**0.26**
USL keff	0.9887	0.9909

Table 12. Plutonium uranium trending results.

The trending is limited to Pu/U ratio below 0.26. Since the highest Pu/U ratio in the SKB applications is 0.012 the validation covers the whole application range. In fact, the largest abbreviation is at the lower part of Pu/U validation. Since the safety margin for this variable is less than the USL limit, it can be neglected.

9.4.3 Pin Pitch

Pin pitch trending has been analyzed and validated in SKBdoc1397015. An additional analysis, based on the experiments in this validation, the USL run gives the following results:

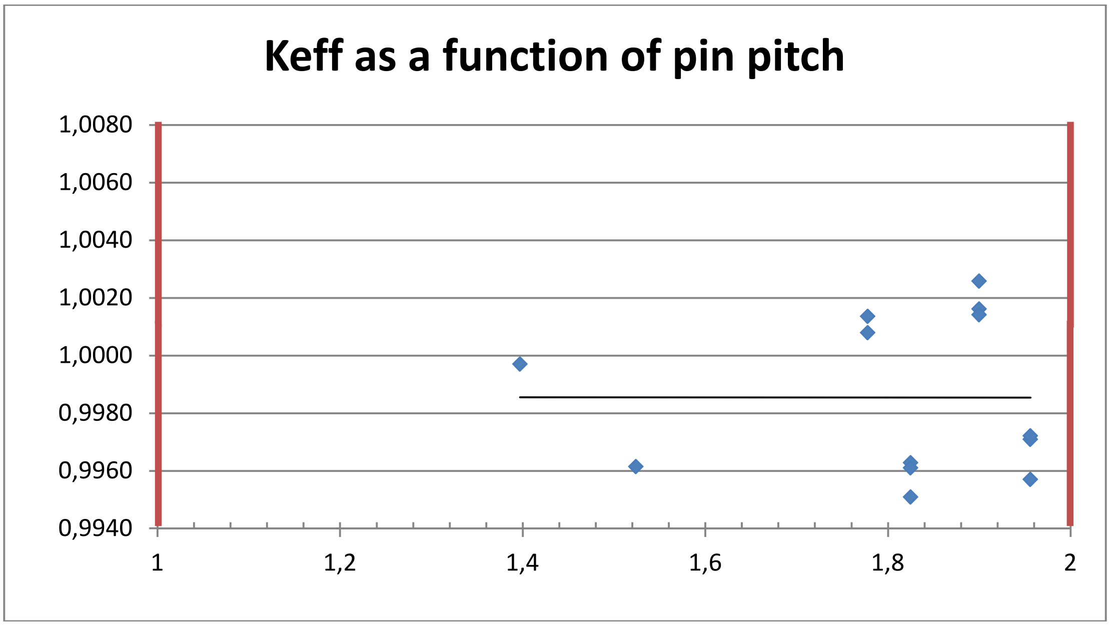

Figure 4. . Trend analysis of USL as a function of pin pitch, no uncertainties added. The red lines indicate the limit chosen for the validation. Y-axis shows the C/E of the critical experiment and x-axis shows the pin pitch

Pin Pitch (cm)	**1**	**2**	**4.3**
USL keff	0.9883	0.9892	0.9884

Table 13. Pin pitch trending results

The application range of the pin pitch is outside the experimental range at the low end. The USL run handles the lack of experiments by adding bigger uncertainty at that end. The trending shows that a margin of 10 pcm should be used to cover the validation of pin pitch 1-2 cm.

9.5 Experimental correlations

It is a well known fact that there exist dependencies between the critical experiments. There are for example only a limited numbers of fuel rods used in all available critical experiments. Many experiments have the same experiment set-up with the same pin-pitch etc. This fact has historically not been addressed, neither in Sweden nor internationally. Experiments have been treated statistically as they were independent. The traditional argumentation has been that many other conservative assumptions are done in the calculation of penalties and the safety margins, so they are covering this uncertainty.

On the behalf of SKB, ORNL have done some limited sensitivity studies of correlations. The approach was to use ORNLs program Sampler to make changes in one parameter, eg enrichment, and see the effect it has on other experiment in the same series. This will give an indication of the magnitude of the correlation between experiments. The work shows that the correlation of experiments using the same fuel rods is high, but they are not fully correlated.

To fully investigate the effect of dependencies between experiments and the implications on the validation results is a very complex task. It involves scrutinizing every critical experiment to find out how the experimental set-up has been done and to try to find the appropriate correlation factors. It will take years and needs cooperation in the international arena. In this report a simplified approach has been used to estimate an extra margin due to the uncertainty in the results due to dependencies.

Assuming that experiments within one series is so strongly correlated that it is only justified to use one experiment per group. Using the average k_{eff} of that group to represent that experiment leaves us with 8 experiments with an average k_{eff} of 0.998142, and a standard deviation of 0.002152, the result can be seen in table 14.

Another extreme assumption could be that only one experiment per ^{240}Pu enrichment (wt %) level is allowed. This would leave us with 7 experiment groups. Taking the average k_{eff} of each group to represent that experiment group and then calculate the average k_{eff} among these 7 will give us an average k_{eff} of 0.998263 and a standard deviation of 0.001870, the result can be seen in table 14.

	Average k_{eff}	Standard dev.	K1-Value	95/95 limit	Difference (pcm)
No Correlation (Owen)	0.997962	0.002867	2.079	0.991999	-
1 experiment per series	0.998142	0.002152	3.145	0.990552	-144
Full correlation fuel rods	0.998263	0.001870	3.355	0.991990	0

Table 14. Correlation analysis

The most conservative approach gives us a correlation value of 144 pcm and thereby it will be used as a safety margin.

10 Conclusion

It has been shown that the methodology and codes used by SKB can be used in the criticality analysis for Clink and the spent fuel repository with the results shown in table 15.

C/E margin (pcm)	1160	Section 9
Margin for isotopic credit	157	Section 9.3
Margin for EALF trend	-	Section 9.4.1
Margin for Pu/U ratio	-	Section 9.4.2
Margin for pin pitch	10	Section 9.4.3
Margin for correlations (pcm)	144	Section 9.5
Administrative margin (pcm)	5000	Default value
USL with admin margin	**0.93529**	
USL without admin margin	0.98529	

Table 15. Summary of Bias, extra margins and calculated USL.

This USL is valid for the computer system presented in section 3 and for applications fulfilling the specifications in table 16 and table 17.

Compact storage canister	PWR
Transfer cansiter	PWR
Copper disposal canister	PWR

Table 16. Specification of validation applications.

Fissil form	Ceramic
Isotopes	U-[234, 235, 238]
	Pu-[238, 239, 240, 241, 242]
	Am-241
	U-236, Np-237, Am-243
	Mo-95, Tc-99, Rh-101, Ru-103
	Ag-109, Cs-133
	Sm-[147, 149, 150, 151, 152]
	Nd-[143, 145]
	Eu-[151, 153]
	Gd-155
Materials	Water (with/without boron)
	Borated steel
	Sainless Steel
	Zircaloy
	Iron
	Copper
EALF	0.1 - 0.8 eV
Burn-up	≤60 MWd/kgU
Pin pitch	1.0-2.0 cm
Pu/(Pu+U)	0.26
Initial enrichment	≤ 5 % U-235

Table 17. Specification of validation validity concerning materials and parameter range.

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APPENDIX-1 – TSUNAMI IP RESULTS

PWR Compact Storage Canister

	Burn up (MWd/kgU)		
Experiment	**15**	**30**	**45**
mct002-001	0.8774 ± 0.0006	0.9176 ± 0.0005	0.9281 ± 0.0005
mct002-002	0.8768 ± 0.0005	0.9222 ± 0.0005	0.9357 ± 0.0004
mct002-003	0.8406 ± 0.0005	0.8804 ± 0.0005	0.8913 ± 0.0005
mct002-004	0.8434 ± 0.0003	0.8977 ± 0.0003	0.9171 ± 0.0003
mct002-005	0.8260 ± 0.0004	0.8683 ± 0.0004	0.8810 ± 0.0004
mct002-006	0.8275 ± 0.0002	0.8837 ± 0.0002	0.9044 ± 0.0002
mct004-001	0.8279 ± 0.0004	0.8758 ± 0.0004	0.8919 ± 0.0004
mct004-002	0.8285 ± 0.0004	0.8768 ± 0.0004	0.8932 ± 0.0004
mct004-003	0.8285 ± 0.0004	0.8771 ± 0.0004	0.8936 ± 0.0004
mct004-004	0.8181 ± 0.0004	0.8674 ± 0.0004	0.8845 ± 0.0004
mct004-005	0.8181 ± 0.0004	0.8676 ± 0.0004	0.8848 ± 0.0004
mct004-006	0.8185 ± 0.0004	0.8684 ± 0.0004	0.8859 ± 0.0003
mct004-007	0.8055 ± 0.0003	0.8576 ± 0.0003	0.8766 ± 0.0003
mct004-008	0.8053 ± 0.0003	0.8576 ± 0.0003	0.8768 ± 0.0003
mct004-009	0.8056 ± 0.0003	0.8582 ± 0.0003	0.8775 ± 0.0003
mct005-01	0.8351 ± 0.0006	0.8832 ± 0.0005	0.8989 ± 0.0005
mct005-02	0.8190 ± 0.0005	0.8670 ± 0.0005	0.8830 ± 0.0005
mct005-03	0.8035 ± 0.0004	0.8530 ± 0.0004	0.8702 ± 0.0004
mct005-04	0.7982 ± 0.0004	0.8503 ± 0.0004	0.8690 ± 0.0004
mct006-001	0.8649 ± 0.0006	0.9045 ± 0.0006	0.9148 ± 0.0005
mct006-002	0.8411 ± 0.0005	0.8815 ± 0.0005	0.8928 ± 0.0005
mct006-003	0.8263 ± 0.0005	0.8684 ± 0.0005	0.8810 ± 0.0005
mct006-004	0.8204 ± 0.0005	0.8648 ± 0.0004	0.8790 ± 0.0004
mct006-006	0.8399 ± 0.0007	0.8795 ± 0.0006	0.8903 ± 0.0006
mct006-007	0.8265 ± 0.0004	0.8690 ± 0.0004	0.8819 ± 0.0004
mct006-008	0.8263 ± 0.0004	0.8684 ± 0.0004	0.8811 ± 0.0004
mct006-009	0.8265 ± 0.0004	0.8690 ± 0.0004	0.8819 ± 0.0004
mct006-010	0.8272 ± 0.0004	0.8700 ± 0.0004	0.8831 ± 0.0004
mct006-011	0.8268 ± 0.0004	0.8695 ± 0.0004	0.8824 ± 0.0004
mct006-012	0.8273 ± 0.0004	0.8703 ± 0.0004	0.8834 ± 0.0004
mct006-013	0.8262 ± 0.0004	0.8685 ± 0.0004	0.8812 ± 0.0004
mct006-014	0.8264 ± 0.0004	0.8686 ± 0.0004	0.8814 ± 0.0004
mct006-015	0.8264 ± 0.0004	0.8691 ± 0.0004	0.8821 ± 0.0004
mct006-016	0.8275 ± 0.0004	0.8702 ± 0.0004	0.8831 ± 0.0004
mct006-017	0.8274 ± 0.0004	0.8703 ± 0.0004	0.8834 ± 0.0004
mct006-018	0.8279 ± 0.0004	0.8709 ± 0.0004	0.8839 ± 0.0004
mct006-019	0.8279 ± 0.0004	0.8707 ± 0.0004	0.8838 ± 0.0004
mct006-020	0.8282 ± 0.0004	0.8712 ± 0.0004	0.8844 ± 0.0004

mct006-021	0.8278 ± 0.0004	0.8709 ± 0.0004	0.8841 ± 0.0004
mct006-022	0.8279 ± 0.0004	0.8708 ± 0.0004	0.8839 ± 0.0004
mct006-023	0.8273 ± 0.0004	0.8702 ± 0.0004	0.8834 ± 0.0004
mct006-024	0.8273 ± 0.0004	0.8704 ± 0.0004	0.8837 ± 0.0004
mct006-025	0.8281 ± 0.0004	0.8713 ± 0.0004	0.8846 ± 0.0004
mct006-026	0.8281 ± 0.0004	0.8712 ± 0.0004	0.8844 ± 0.0004
mct006-027	0.8265 ± 0.0004	0.8694 ± 0.0004	0.8825 ± 0.0004
mct006-028	0.8278 ± 0.0004	0.8711 ± 0.0004	0.8844 ± 0.0004
mct006-037	0.8120 ± 0.0003	0.8613 ± 0.0003	0.8785 ± 0.0002
mct006-047	0.8122 ± 0.0003	0.8616 ± 0.0003	0.8788 ± 0.0002
mct007-001	0.8566 ± 0.0005	0.8981 ± 0.0005	0.9100 ± 0.0005
mct007-002	0.8420 ± 0.0004	0.8853 ± 0.0004	0.8985 ± 0.0004
mct007-003	0.8347 ± 0.0004	0.8804 ± 0.0003	0.8952 ± 0.0003
mct007-004	0.8190 ± 0.0002	0.8707 ± 0.0002	0.8893 ± 0.0002
mct007-005	0.8190 ± 0.0002	0.8707 ± 0.0002	0.8893 ± 0.0002
mct007-AL	0.8414 ± 0.0004	0.8847 ± 0.0004	0.8979 ± 0.0004
mct007-ALC	0.8423 ± 0.0004	0.8862 ± 0.0004	0.8998 ± 0.0004
mct007-B1	0.8420 ± 0.0004	0.8861 ± 0.0004	0.8999 ± 0.0004
mct007-B1C	0.8423 ± 0.0004	0.8865 ± 0.0004	0.9002 ± 0.0004
mct007-B2	0.8419 ± 0.0004	0.8859 ± 0.0004	0.8995 ± 0.0004
mct007-B3	0.8416 ± 0.0004	0.8853 ± 0.0004	0.8989 ± 0.0004
mct007-B3C	0.8421 ± 0.0004	0.8862 ± 0.0004	0.9000 ± 0.0004
mct007-B4	0.8425 ± 0.0004	0.8869 ± 0.0004	0.9007 ± 0.0004
mct007-B4C	0.8425 ± 0.0004	0.8869 ± 0.0004	0.9007 ± 0.0004
mct007-CD	0.8429 ± 0.0004	0.8879 ± 0.0004	0.9022 ± 0.0004
mct007-CDW	0.8425 ± 0.0004	0.8869 ± 0.0004	0.9008 ± 0.0004
mct007-H1	0.8422 ± 0.0004	0.8862 ± 0.0004	0.8999 ± 0.0004
mct007-H1C	0.8428 ± 0.0004	0.8872 ± 0.0004	0.9011 ± 0.0004
mct007-H2	0.8417 ± 0.0004	0.8856 ± 0.0004	0.8992 ± 0.0004
mct007-H2C	0.8425 ± 0.0004	0.8869 ± 0.0004	0.9008 ± 0.0004
mct007-H3	0.8417 ± 0.0004	0.8855 ± 0.0004	0.8991 ± 0.0004
mct007-H3C	0.8422 ± 0.0004	0.8862 ± 0.0004	0.8998 ± 0.0004
mct007-H4	0.8416 ± 0.0004	0.8853 ± 0.0004	0.8987 ± 0.0004
mct007-H4C	0.8425 ± 0.0004	0.8868 ± 0.0004	0.9006 ± 0.0004
mct007-H5	0.8417 ± 0.0004	0.8852 ± 0.0004	0.8985 ± 0.0004
mct007-H5C	0.8425 ± 0.0004	0.8868 ± 0.0004	0.9006 ± 0.0004
mct008-001	0.8886 ± 0.0005	0.9315 ± 0.0005	0.9438 ± 0.0005
mct008-002	0.8689 ± 0.0005	0.9113 ± 0.0005	0.9236 ± 0.0004
mct008-003	0.8537 ± 0.0004	0.8980 ± 0.0004	0.9117 ± 0.0004
mct008-004	0.8463 ± 0.0003	0.8928 ± 0.0003	0.9080 ± 0.0003
mct008-005	0.8321 ± 0.0002	0.8836 ± 0.0002	0.9020 ± 0.0002
mct008-AL	0.8537 ± 0.0004	0.8982 ± 0.0004	0.9121 ± 0.0004
mct008-ALC	0.8545 ± 0.0004	0.8997 ± 0.0004	0.9140 ± 0.0004
mct008-B1	0.8541 ± 0.0004	0.8992 ± 0.0004	0.9134 ± 0.0004

mct008-B1C	0.8541 ± 0.0004	0.8991 ± 0.0004	0.9133 ± 0.0004
mct008-B2	0.8542 ± 0.0005	0.8990 ± 0.0005	0.9130 ± 0.0005
mct008-B2C	0.8542 ± 0.0004	0.8994 ± 0.0004	0.9136 ± 0.0004
mct008-B3	0.8543 ± 0.0004	0.8993 ± 0.0004	0.9134 ± 0.0004
mct008-B3C	0.8545 ± 0.0004	0.8998 ± 0.0004	0.9141 ± 0.0004
mct008-B4	0.8539 ± 0.0004	0.8984 ± 0.0004	0.9123 ± 0.0004
mct008-B4C	0.8545 ± 0.0004	0.8996 ± 0.0004	0.9138 ± 0.0004
mct008-CD	0.8547 ± 0.0004	0.8999 ± 0.0004	0.9141 ± 0.0004
mct008-CDW	0.8544 ± 0.0004	0.8996 ± 0.0004	0.9139 ± 0.0004
mct008-H1	0.8539 ± 0.0004	0.8990 ± 0.0004	0.9133 ± 0.0004
mct008-H1C	0.8547 ± 0.0004	0.8999 ± 0.0004	0.9142 ± 0.0004
mct008-H2	0.8539 ± 0.0004	0.8988 ± 0.0004	0.9129 ± 0.0004
mct008-H2C	0.8546 ± 0.0004	0.9000 ± 0.0004	0.9144 ± 0.0004
mct008-H3	0.8539 ± 0.0004	0.8986 ± 0.0004	0.9126 ± 0.0004
mct008-H3C	0.8548 ± 0.0004	0.8998 ± 0.0004	0.9140 ± 0.0004
mct008-H4	0.8541 ± 0.0004	0.8987 ± 0.0004	0.9127 ± 0.0004
mct008-H4C	0.8545 ± 0.0004	0.8997 ± 0.0004	0.9140 ± 0.0004
mct008-H5	0.8542 ± 0.0004	0.8991 ± 0.0004	0.9133 ± 0.0004
mct008-H5C	0.8539 ± 0.0004	0.8989 ± 0.0004	0.9132 ± 0.0004
mct009-01	0.8670 ± 0.0004	0.9164 ± 0.0003	0.9322 ± 0.0003
mct009-02	0.8504 ± 0.0004	0.8989 ± 0.0004	0.9145 ± 0.0004
mct009-03	0.8267 ± 0.0004	0.8763 ± 0.0003	0.8930 ± 0.0003
mct009-04	0.8123 ± 0.0003	0.8640 ± 0.0003	0.8822 ± 0.0003
mct009-05	0.8002 ± 0.0002	0.8551 ± 0.0002	0.8755 ± 0.0002
mct009-06	0.7964 ± 0.0002	0.8522 ± 0.0002	0.8731 ± 0.0002
mct011-01	0.6512 ± 0.0003	0.6670 ± 0.0003	0.6695 ± 0.0003
mct011-02	0.6512 ± 0.0003	0.6669 ± 0.0003	0.6695 ± 0.0003
mct011-03	0.6521 ± 0.0003	0.6679 ± 0.0003	0.6705 ± 0.0003
mct011-04	0.6739 ± 0.0003	0.6915 ± 0.0003	0.6949 ± 0.0003
mct011-05	0.6736 ± 0.0003	0.6912 ± 0.0003	0.6946 ± 0.0003
mct011-06	0.6736 ± 0.0003	0.6913 ± 0.0003	0.6946 ± 0.0003

PWR Copper Disposal Canister

Burn up (MWd/kgU)			
Experiment	**15**	**30**	**45**
mct002-001	0.8157 ± 0.0006	0.8599 ± 0.0006	0.8741 ± 0.0006
mct002-002	0.8167 ± 0.0005	0.8652 ± 0.0005	0.8823 ± 0.0005
mct002-003	0.7908 ± 0.0005	0.8354 ± 0.0005	0.8491 ± 0.0005
mct002-004	0.7976 ± 0.0003	0.8543 ± 0.0003	0.8761 ± 0.0003
mct002-005	0.7828 ± 0.0004	0.8297 ± 0.0004	0.8447 ± 0.0004
mct002-006	0.7871 ± 0.0002	0.8456 ± 0.0002	0.8684 ± 0.0002
mct004-001	0.7824 ± 0.0004	0.8351 ± 0.0004	0.8536 ± 0.0004
mct004-002	0.7832 ± 0.0004	0.8362 ± 0.0004	0.8550 ± 0.0004
mct004-003	0.7835 ± 0.0004	0.8367 ± 0.0004	0.8555 ± 0.0004
mct004-004	0.7766 ± 0.0004	0.8306 ± 0.0004	0.8497 ± 0.0004
mct004-005	0.7769 ± 0.0004	0.8309 ± 0.0004	0.8502 ± 0.0004
mct004-006	0.7776 ± 0.0004	0.8320 ± 0.0004	0.8515 ± 0.0004
mct004-007	0.7695 ± 0.0003	0.8259 ± 0.0003	0.8465 ± 0.0003
mct004-008	0.7696 ± 0.0003	0.8261 ± 0.0003	0.8469 ± 0.0003
mct004-009	0.7700 ± 0.0003	0.8268 ± 0.0003	0.8476 ± 0.0003
mct005-01	0.7809 ± 0.0006	0.8335 ± 0.0006	0.8522 ± 0.0005
mct005-02	0.7698 ± 0.0005	0.8226 ± 0.0005	0.8413 ± 0.0005
mct005-03	0.7603 ± 0.0004	0.8147 ± 0.0004	0.8341 ± 0.0004
mct005-04	0.7586 ± 0.0004	0.8151 ± 0.0004	0.8358 ± 0.0004
mct006-001	0.8072 ± 0.0006	0.8512 ± 0.0006	0.8649 ± 0.0006
mct006-002	0.7918 ± 0.0005	0.8370 ± 0.0005	0.8510 ± 0.0005
mct006-003	0.7829 ± 0.0004	0.8296 ± 0.0004	0.8445 ± 0.0004
mct006-004	0.7805 ± 0.0004	0.8293 ± 0.0004	0.8454 ± 0.0004
mct006-006	0.7903 ± 0.0005	0.8348 ± 0.0005	0.8484 ± 0.0005
mct006-007	0.7834 ± 0.0004	0.8305 ± 0.0004	0.8456 ± 0.0004
mct006-008	0.7829 ± 0.0004	0.8298 ± 0.0004	0.8447 ± 0.0004
mct006-009	0.7835 ± 0.0004	0.8307 ± 0.0004	0.8458 ± 0.0004
mct006-010	0.7842 ± 0.0004	0.8317 ± 0.0004	0.8470 ± 0.0004
mct006-011	0.7838 ± 0.0004	0.8311 ± 0.0004	0.8463 ± 0.0004
mct006-012	0.7844 ± 0.0004	0.8319 ± 0.0004	0.8473 ± 0.0004
mct006-013	0.7830 ± 0.0004	0.8300 ± 0.0004	0.8450 ± 0.0004
mct006-014	0.7831 ± 0.0004	0.8301 ± 0.0004	0.8451 ± 0.0004
mct006-015	0.7834 ± 0.0004	0.8308 ± 0.0004	0.8460 ± 0.0004
mct006-016	0.7843 ± 0.0004	0.8315 ± 0.0004	0.8467 ± 0.0004
mct006-017	0.7843 ± 0.0004	0.8318 ± 0.0004	0.8472 ± 0.0004
mct006-018	0.7847 ± 0.0004	0.8322 ± 0.0004	0.8476 ± 0.0004
mct006-019	0.7848 ± 0.0004	0.8323 ± 0.0004	0.8476 ± 0.0004
mct006-020	0.7851 ± 0.0004	0.8327 ± 0.0004	0.8481 ± 0.0004
mct006-021	0.7849 ± 0.0004	0.8326 ± 0.0004	0.8480 ± 0.0004
mct006-022	0.7847 ± 0.0004	0.8322 ± 0.0004	0.8475 ± 0.0004

mct006-023	0.7843 ± 0.0004	0.8318 ± 0.0004	0.8472 ± 0.0004
mct006-024	0.7845 ± 0.0004	0.8322 ± 0.0004	0.8476 ± 0.0004
mct006-025	0.7851 ± 0.0004	0.8329 ± 0.0004	0.8485 ± 0.0004
mct006-026	0.7850 ± 0.0004	0.8327 ± 0.0004	0.8482 ± 0.0004
mct006-027	0.7837 ± 0.0004	0.8311 ± 0.0004	0.8464 ± 0.0004
mct006-028	0.7850 ± 0.0004	0.8328 ± 0.0004	0.8484 ± 0.0004
mct006-037	0.7769 ± 0.0003	0.8299 ± 0.0003	0.8487 ± 0.0003
mct006-047	0.7771 ± 0.0003	0.8301 ± 0.0003	0.8490 ± 0.0003
mct007-001	0.8066 ± 0.0005	0.8527 ± 0.0005	0.8674 ± 0.0005
mct007-002	0.7979 ± 0.0004	0.8456 ± 0.0004	0.8611 ± 0.0004
mct007-003	0.7942 ± 0.0004	0.8440 ± 0.0004	0.8608 ± 0.0004
mct007-004	0.7850 ± 0.0002	0.8396 ± 0.0002	0.8598 ± 0.0002
mct007-005	0.7850 ± 0.0002	0.8396 ± 0.0002	0.8598 ± 0.0002
mct007-AL	0.7975 ± 0.0004	0.8452 ± 0.0004	0.8607 ± 0.0004
mct007-ALC	0.7986 ± 0.0004	0.8468 ± 0.0004	0.8626 ± 0.0004
mct007-B1	0.7985 ± 0.0004	0.8469 ± 0.0004	0.8629 ± 0.0004
mct007-B1C	0.7988 ± 0.0004	0.8472 ± 0.0004	0.8632 ± 0.0004
mct007-B2	0.7984 ± 0.0004	0.8467 ± 0.0004	0.8626 ± 0.0004
mct007-B3	0.7980 ± 0.0004	0.8461 ± 0.0004	0.8619 ± 0.0004
mct007-B3C	0.7986 ± 0.0004	0.8470 ± 0.0004	0.8630 ± 0.0004
mct007-B4	0.7990 ± 0.0004	0.8477 ± 0.0004	0.8638 ± 0.0004
mct007-B4C	0.7990 ± 0.0004	0.8477 ± 0.0004	0.8638 ± 0.0004
mct007-CD	0.7999 ± 0.0004	0.8491 ± 0.0004	0.8656 ± 0.0004
mct007-CDW	0.7991 ± 0.0004	0.8478 ± 0.0004	0.8640 ± 0.0004
mct007-H1	0.7985 ± 0.0004	0.8468 ± 0.0004	0.8628 ± 0.0004
mct007-H1C	0.7994 ± 0.0004	0.8480 ± 0.0004	0.8641 ± 0.0004
mct007-H2	0.7982 ± 0.0004	0.8464 ± 0.0004	0.8623 ± 0.0004
mct007-H2C	0.7991 ± 0.0004	0.8478 ± 0.0004	0.8639 ± 0.0004
mct007-H3	0.7982 ± 0.0004	0.8464 ± 0.0004	0.8622 ± 0.0004
mct007-H3C	0.7986 ± 0.0004	0.8469 ± 0.0004	0.8628 ± 0.0004
mct007-H4	0.7979 ± 0.0004	0.8459 ± 0.0004	0.8616 ± 0.0004
mct007-H4C	0.7990 ± 0.0004	0.8475 ± 0.0004	0.8635 ± 0.0004
mct007-H5	0.7978 ± 0.0004	0.8457 ± 0.0004	0.8613 ± 0.0004
mct007-H5C	0.7990 ± 0.0004	0.8476 ± 0.0004	0.8636 ± 0.0004
mct008-001	0.8309 ± 0.0005	0.8775 ± 0.0005	0.8932 ± 0.0005
mct008-002	0.8178 ± 0.0005	0.8645 ± 0.0005	0.8796 ± 0.0005
mct008-003	0.8090 ± 0.0004	0.8574 ± 0.0004	0.8735 ± 0.0004
mct008-004	0.8051 ± 0.0003	0.8555 ± 0.0004	0.8728 ± 0.0003
mct008-005	0.7965 ± 0.0002	0.8510 ± 0.0002	0.8710 ± 0.0002
mct008-AL	0.8092 ± 0.0004	0.8578 ± 0.0004	0.8741 ± 0.0004
mct008-ALC	0.8102 ± 0.0004	0.8595 ± 0.0004	0.8761 ± 0.0004
mct008-B1	0.8098 ± 0.0004	0.8590 ± 0.0004	0.8756 ± 0.0004
mct008-B1C	0.8098 ± 0.0004	0.8590 ± 0.0004	0.8755 ± 0.0004
mct008-B2	0.8098 ± 0.0004	0.8587 ± 0.0004	0.8750 ± 0.0004

mct008-B2C	0.8099 ± 0.0004	0.8591 ± 0.0004	0.8757 ± 0.0004
mct008-B3	0.8098 ± 0.0004	0.8588 ± 0.0004	0.8753 ± 0.0004
mct008-B3C	0.8103 ± 0.0004	0.8596 ± 0.0004	0.8762 ± 0.0004
mct008-B4	0.8094 ± 0.0004	0.8581 ± 0.0004	0.8743 ± 0.0004
mct008-B4C	0.8101 ± 0.0004	0.8592 ± 0.0004	0.8758 ± 0.0004
mct008-CD	0.8102 ± 0.0004	0.8594 ± 0.0004	0.8761 ± 0.0004
mct008-CDW	0.8102 ± 0.0004	0.8594 ± 0.0004	0.8760 ± 0.0004
mct008-H1	0.8097 ± 0.0004	0.8589 ± 0.0004	0.8755 ± 0.0004
mct008-H1C	0.8103 ± 0.0004	0.8596 ± 0.0004	0.8762 ± 0.0004
mct008-H2	0.8095 ± 0.0004	0.8585 ± 0.0004	0.8749 ± 0.0004
mct008-H2C	0.8104 ± 0.0004	0.8598 ± 0.0004	0.8765 ± 0.0004
mct008-H3	0.8095 ± 0.0004	0.8583 ± 0.0004	0.8746 ± 0.0004
mct008-H3C	0.8103 ± 0.0004	0.8593 ± 0.0004	0.8759 ± 0.0004
mct008-H4	0.8096 ± 0.0004	0.8583 ± 0.0004	0.8747 ± 0.0004
mct008-H4C	0.8102 ± 0.0004	0.8595 ± 0.0004	0.8761 ± 0.0004
mct008-H5	0.8098 ± 0.0004	0.8588 ± 0.0004	0.8753 ± 0.0004
mct008-H5C	0.8097 ± 0.0004	0.8588 ± 0.0004	0.8754 ± 0.0004
mct009-01	0.8130 ± 0.0004	0.8647 ± 0.0004	0.8837 ± 0.0003
mct009-02	0.8031 ± 0.0004	0.8547 ± 0.0004	0.8730 ± 0.0004
mct009-03	0.7861 ± 0.0004	0.8393 ± 0.0004	0.8581 ± 0.0003
mct009-04	0.7759 ± 0.0003	0.8311 ± 0.0003	0.8512 ± 0.0003
mct009-05	0.7673 ± 0.0002	0.8252 ± 0.0002	0.8471 ± 0.0002
mct009-06	0.7643 ± 0.0002	0.8229 ± 0.0002	0.8453 ± 0.0002
mct011-01	0.6648 ± 0.0003	0.6847 ± 0.0003	0.6845 ± 0.0003
mct011-02	0.6644 ± 0.0003	0.6844 ± 0.0003	0.6842 ± 0.0003
mct011-03	0.6645 ± 0.0003	0.6846 ± 0.0003	0.6844 ± 0.0003
mct011-04	0.6901 ± 0.0003	0.7116 ± 0.0003	0.7121 ± 0.0003
mct011-05	0.6911 ± 0.0003	0.7125 ± 0.0003	0.7130 ± 0.0003
mct011-06	0.6923 ± 0.0003	0.7137 ± 0.0003	0.7142 ± 0.0003

PWR Transfer Storage Canister

	Burn up (Mwd/kgU)		
Experiment	**15**	**30**	**45**
mct002-001	0.8157 ± 0.0005	0.8668 ± 0.0005	0.8901 ± 0.0005
mct002-002	0.7793 ± 0.0004	0.8339 ± 0.0004	0.8607 ± 0.0005
mct002-003	0.8172 ± 0.0005	0.8695 ± 0.0005	0.8932 ± 0.0005
mct002-004	0.7255 ± 0.0003	0.7879 ± 0.0003	0.8209 ± 0.0003
mct002-005	0.7959 ± 0.0004	0.8506 ± 0.0004	0.8765 ± 0.0004
mct002-006	0.7057 ± 0.0002	0.7698 ± 0.0002	0.8044 ± 0.0002
mct004-001	0.7953 ± 0.0004	0.8550 ± 0.0004	0.8842 ± 0.0004
mct004-002	0.7930 ± 0.0004	0.8531 ± 0.0004	0.8825 ± 0.0004
mct004-003	0.7916 ± 0.0004	0.8518 ± 0.0004	0.8814 ± 0.0004
mct004-004	0.7824 ± 0.0004	0.8434 ± 0.0004	0.8737 ± 0.0004
mct004-005	0.7809 ± 0.0004	0.8420 ± 0.0003	0.8725 ± 0.0004
mct004-006	0.7781 ± 0.0004	0.8395 ± 0.0003	0.8702 ± 0.0004
mct004-007	0.7580 ± 0.0003	0.8212 ± 0.0003	0.8537 ± 0.0003
mct004-008	0.7559 ± 0.0003	0.8193 ± 0.0003	0.8519 ± 0.0003
mct004-009	0.7541 ± 0.0003	0.8176 ± 0.0003	0.8504 ± 0.0003
mct005-01	0.8047 ± 0.0005	0.8633 ± 0.0005	0.8910 ± 0.0005
mct005-02	0.7990 ± 0.0005	0.8583 ± 0.0005	0.8864 ± 0.0005
mct005-03	0.7821 ± 0.0004	0.8432 ± 0.0004	0.8729 ± 0.0004
mct005-04	0.7653 ± 0.0004	0.8284 ± 0.0003	0.8598 ± 0.0004
mct006-001	0.8233 ± 0.0005	0.8746 ± 0.0005	0.8976 ± 0.0005
mct006-002	0.8137 ± 0.0005	0.8666 ± 0.0004	0.8908 ± 0.0005
mct006-003	0.7972 ± 0.0004	0.8518 ± 0.0004	0.8776 ± 0.0004
mct006-004	0.7800 ± 0.0004	0.8364 ± 0.0003	0.8639 ± 0.0004
mct006-006	0.8170 ± 0.0005	0.8694 ± 0.0005	0.8930 ± 0.0005
mct006-007	0.7949 ± 0.0004	0.8498 ± 0.0004	0.8758 ± 0.0004
mct006-008	0.7963 ± 0.0004	0.8510 ± 0.0004	0.8768 ± 0.0004
mct006-009	0.7946 ± 0.0004	0.8495 ± 0.0004	0.8756 ± 0.0004
mct006-010	0.7931 ± 0.0004	0.8483 ± 0.0004	0.8746 ± 0.0004
mct006-011	0.7942 ± 0.0004	0.8492 ± 0.0004	0.8753 ± 0.0004
mct006-012	0.7928 ± 0.0004	0.8481 ± 0.0004	0.8744 ± 0.0004
mct006-013	0.7957 ± 0.0004	0.8505 ± 0.0004	0.8764 ± 0.0004
mct006-014	0.7960 ± 0.0004	0.8507 ± 0.0004	0.8766 ± 0.0004
mct006-015	0.7936 ± 0.0004	0.8487 ± 0.0004	0.8749 ± 0.0004
mct006-016	0.7945 ± 0.0004	0.8495 ± 0.0004	0.8757 ± 0.0004
mct006-017	0.7933 ± 0.0004	0.8485 ± 0.0004	0.8748 ± 0.0004
mct006-018	0.7935 ± 0.0004	0.8487 ± 0.0004	0.8750 ± 0.0004
mct006-019	0.7933 ± 0.0004	0.8485 ± 0.0004	0.8747 ± 0.0004
mct006-020	0.7928 ± 0.0004	0.8481 ± 0.0004	0.8744 ± 0.0004
mct006-021	0.7922 ± 0.0004	0.8476 ± 0.0004	0.8740 ± 0.0004
mct006-022	0.7936 ± 0.0004	0.8488 ± 0.0004	0.8750 ± 0.0004
mct006-023	0.7928 ± 0.0004	0.8481 ± 0.0004	0.8744 ± 0.0004

mct006-024	0.7919 ± 0.0004	0.8473 ± 0.0004	0.8737 ± 0.0004
mct006-025	0.7916 ± 0.0004	0.8471 ± 0.0004	0.8736 ± 0.0004
mct006-026	0.7925 ± 0.0004	0.8478 ± 0.0004	0.8743 ± 0.0004
mct006-027	0.7932 ± 0.0004	0.8484 ± 0.0004	0.8746 ± 0.0004
mct006-028	0.7913 ± 0.0004	0.8468 ± 0.0004	0.8733 ± 0.0004
mct006-037	0.7423 ± 0.0003	0.8024 ± 0.0002	0.8334 ± 0.0003
mct006-047	0.7420 ± 0.0003	0.8022 ± 0.0002	0.8332 ± 0.0003
mct007-001	0.8147 ± 0.0005	0.8683 ± 0.0004	0.8934 ± 0.0005
mct007-002	0.7986 ± 0.0004	0.8539 ± 0.0004	0.8805 ± 0.0004
mct007-003	0.7799 ± 0.0003	0.8371 ± 0.0003	0.8655 ± 0.0003
mct007-004	0.7262 ± 0.0002	0.7877 ± 0.0002	0.8204 ± 0.0002
mct007-005	0.7262 ± 0.0002	0.7877 ± 0.0002	0.8204 ± 0.0002
mct007-AL	0.7984 ± 0.0004	0.8537 ± 0.0004	0.8804 ± 0.0004
mct007-ALC	0.7954 ± 0.0004	0.8512 ± 0.0004	0.8782 ± 0.0004
mct007-B1	0.7939 ± 0.0004	0.8499 ± 0.0004	0.8770 ± 0.0004
mct007-B1C	0.7939 ± 0.0004	0.8499 ± 0.0004	0.8771 ± 0.0004
mct007-B2	0.7945 ± 0.0004	0.8504 ± 0.0004	0.8775 ± 0.0004
mct007-B3	0.7955 ± 0.0004	0.8513 ± 0.0004	0.8782 ± 0.0004
mct007-B3C	0.7940 ± 0.0004	0.8500 ± 0.0004	0.8772 ± 0.0004
mct007-B4	0.7925 ± 0.0004	0.8487 ± 0.0004	0.8760 ± 0.0004
mct007-B4C	0.7925 ± 0.0004	0.8487 ± 0.0004	0.8760 ± 0.0004
mct007-CD	0.7881 ± 0.0004	0.8448 ± 0.0003	0.8726 ± 0.0004
mct007-CDW	0.7923 ± 0.0004	0.8485 ± 0.0004	0.8758 ± 0.0004
mct007-H1	0.7947 ± 0.0004	0.8506 ± 0.0004	0.8777 ± 0.0004
mct007-H1C	0.7924 ± 0.0004	0.8486 ± 0.0004	0.8760 ± 0.0004
mct007-H2	0.7947 ± 0.0004	0.8506 ± 0.0004	0.8776 ± 0.0004
mct007-H2C	0.7922 ± 0.0004	0.8484 ± 0.0004	0.8758 ± 0.0004
mct007-H3	0.7949 ± 0.0004	0.8507 ± 0.0004	0.8778 ± 0.0004
mct007-H3C	0.7948 ± 0.0004	0.8507 ± 0.0004	0.8777 ± 0.0004
mct007-H4	0.7965 ± 0.0004	0.8521 ± 0.0004	0.8790 ± 0.0004
mct007-H4C	0.7934 ± 0.0004	0.8495 ± 0.0004	0.8767 ± 0.0004
mct007-H5	0.7975 ± 0.0004	0.8530 ± 0.0004	0.8798 ± 0.0004
mct007-H5C	0.7931 ± 0.0004	0.8493 ± 0.0004	0.8765 ± 0.0004
mct008-001	0.8111 ± 0.0005	0.8647 ± 0.0004	0.8904 ± 0.0005
mct008-002	0.8177 ± 0.0004	0.8719 ± 0.0004	0.8975 ± 0.0005
mct008-003	0.8009 ± 0.0004	0.8569 ± 0.0004	0.8842 ± 0.0004
mct008-004	0.7820 ± 0.0003	0.8398 ± 0.0003	0.8689 ± 0.0003
mct008-005	0.7366 ± 0.0002	0.7980 ± 0.0002	0.8306 ± 0.0002
mct008-AL	0.7991 ± 0.0004	0.8553 ± 0.0004	0.8828 ± 0.0004
mct008-ALC	0.7950 ± 0.0004	0.8517 ± 0.0003	0.8797 ± 0.0004
mct008-B1	0.7956 ± 0.0004	0.8523 ± 0.0003	0.8802 ± 0.0004
mct008-B1C	0.7960 ± 0.0004	0.8526 ± 0.0003	0.8805 ± 0.0004
mct008-B2	0.7978 ± 0.0004	0.8542 ± 0.0004	0.8818 ± 0.0004
mct008-B2C	0.7957 ± 0.0004	0.8524 ± 0.0003	0.8803 ± 0.0004

mct008-B3	0.7968 ± 0.0004	0.8533 ± 0.0003	0.8811 ± 0.0004
mct008-B3C	0.7947 ± 0.0004	0.8515 ± 0.0003	0.8795 ± 0.0004
mct008-B4	0.7987 ± 0.0004	0.8550 ± 0.0004	0.8825 ± 0.0004
mct008-B4C	0.7961 ± 0.0004	0.8527 ± 0.0003	0.8806 ± 0.0004
mct008-CD	0.7958 ± 0.0004	0.8524 ± 0.0003	0.8803 ± 0.0004
mct008-CDW	0.7954 ± 0.0004	0.8521 ± 0.0003	0.8800 ± 0.0004
mct008-H1	0.7956 ± 0.0004	0.8523 ± 0.0003	0.8802 ± 0.0004
mct008-H1C	0.7952 ± 0.0004	0.8519 ± 0.0003	0.8798 ± 0.0004
mct008-H2	0.7971 ± 0.0004	0.8536 ± 0.0003	0.8813 ± 0.0004
mct008-H2C	0.7943 ± 0.0004	0.8511 ± 0.0003	0.8792 ± 0.0004
mct008-H3	0.7982 ± 0.0004	0.8545 ± 0.0004	0.8821 ± 0.0004
mct008-H3C	0.7966 ± 0.0004	0.8532 ± 0.0003	0.8810 ± 0.0004
mct008-H4	0.7985 ± 0.0004	0.8547 ± 0.0004	0.8823 ± 0.0004
mct008-H4C	0.7951 ± 0.0004	0.8518 ± 0.0003	0.8798 ± 0.0004
mct008-H5	0.7970 ± 0.0004	0.8535 ± 0.0003	0.8812 ± 0.0004
mct008-H5C	0.7958 ± 0.0004	0.8524 ± 0.0003	0.8803 ± 0.0004
mct009-01	0.7421 ± 0.0003	0.7997 ± 0.0003	0.8293 ± 0.0003
mct009-02	0.7644 ± 0.0004	0.8229 ± 0.0004	0.8519 ± 0.0004
mct009-03	0.7558 ± 0.0003	0.8164 ± 0.0003	0.8468 ± 0.0003
mct009-04	0.7357 ± 0.0003	0.7981 ± 0.0003	0.8303 ± 0.0003
mct009-05	0.7073 ± 0.0002	0.7719 ± 0.0002	0.8062 ± 0.0002
mct009-06	0.6990 ± 0.0002	0.7642 ± 0.0002	0.7990 ± 0.0002
mct011-01	0.7544 ± 0.0003	0.7783 ± 0.0003	0.7870 ± 0.0004
mct011-02	0.7541 ± 0.0003	0.7780 ± 0.0003	0.7867 ± 0.0004
mct011-03	0.7537 ± 0.0003	0.7778 ± 0.0003	0.7866 ± 0.0004
mct011-04	0.7597 ± 0.0003	0.7859 ± 0.0003	0.7965 ± 0.0003
mct011-05	0.7604 ± 0.0003	0.7866 ± 0.0003	0.7971 ± 0.0003
mct011-06	0.7613 ± 0.0003	0.7875 ± 0.0003	0.7980 ± 0.0003

APPENDIX-2 - KENO K_{eff} RESULTS

Title	Expected value	Calculated value	C/E	EALF	Pu/(Pu+U)
MIX-COMP-THERM-002-001	1.00240	1.00079	0.99839	0.581	0.02
MIX-COMP-THERM-002-002	1.00090	1.00135	1.00045	0.769	0.02
MIX-COMP-THERM-002-003	1.00420	1.00202	0.99783	0.197	0.02
MIX-COMP-THERM-002-004	1.00240	1.00514	1.00273	0.288	0.02
MIX-COMP-THERM-002-005	1.00380	1.00425	1.00045	0.142	0.02
MIX-COMP-THERM-002-006	1.00290	1.00533	1.00242	0.188	0.02
MIX-COMP-THERM-004-001	1.00000	0.99509	0.99509	0.149	0.03
MIX-COMP-THERM-004-002	1.00000	0.99628	0.99628	0.148	0.03
MIX-COMP-THERM-004-003	1.00000	0.99610	0.99610	0.147	0.03
MIX-COMP-THERM-004-004	1.00000	0.99570	0.99570	0.123	0.03
MIX-COMP-THERM-004-005	1.00000	0.99708	0.99708	0.122	0.03
MIX-COMP-THERM-004-006	1.00000	0.99722	0.99722	0.121	0.03
MIX-COMP-THERM-004-007	1.00000	0.99709	0.99709	0.0951	0.03
MIX-COMP-THERM-004-008	1.00000	0.99748	0.99748	0.0948	0.03
MIX-COMP-THERM-004-009	1.00000	0.99835	0.99835	0.0944	0.03
MIX-COMP-THERM-005-001	1.00080	1.00178	1.00098	0.399	0.04
MIX-COMP-THERM-005-002	1.00110	0.99935	0.99825	0.263	0.04
MIX-COMP-THERM-005-003	1.00160	1.00646	1.00485	0.18	0.04
MIX-COMP-THERM-005-004	1.00210	1.00320	1.00110	0.15	0.04
MIX-COMP-THERM-006-001	1.00160	0.99692	0.99533	0.383	0.02
MIX-COMP-THERM-006-002	1.00170	1.00080	0.99910	0.2	0.02
MIX-COMP-THERM-006-003	1.00260	0.99706	0.99448	0.145	0.02
MIX-COMP-THERM-006-004	1.00510	1.00300	0.99791	0.123	0.02
MIX-COMP-THERM-006-006	1.00550	1.00135	0.99587	0.0954	0.02
MIX-COMP-THERM-007-001	1.00230	1.00328	1.00098	0.203	0.02
MIX-COMP-THERM-007-002	1.00240	0.99889	0.99650	0.146	0.02
MIX-COMP-THERM-007-003	1.00360	1.00074	0.99715	0.123	0.02
MIX-COMP-THERM-007-004	1.00370	1.00091	0.99722	0.1	0.02
MIX-COMP-THERM-007-005	1.00440	0.99907	0.99469	0.0954	0.02
MIX-COMP-THERM-008-001	0.99970	0.99757	0.99787	0.408	0.02
MIX-COMP-THERM-008-002	1.00080	0.99849	0.99769	0.205	0.02
MIX-COMP-THERM-008-003	1.00230	0.99868	0.99639	0.147	0.02
MIX-COMP-THERM-008-004	1.00150	1.00134	0.99984	0.124	0.02
MIX-COMP-THERM-008-005	1.00220	1.00189	0.99969	0.101	0.02
MIX-COMP-THERM-009-001	1.00030	0.99971	0.99941	0.537	0.01
MIX-COMP-THERM-009-002	1.00200	0.99615	0.99416	0.304	0.01
MIX-COMP-THERM-009-003	1.00350	0.99730	0.99382	0.158	0.01
MIX-COMP-THERM-009-004	1.00460	0.99644	0.99188	0.119	0.01
MIX-COMP-THERM-009-005	1.00590	0.99854	0.99268	0.0972	0.01
MIX-COMP-THERM-009-006	1.00670	1.00001	0.99335	0.093	0.01

MIX-COMP-THERM-011-001	1.00000	1.00162	1.00162	0.56	0.26
MIX-COMP-THERM-011-002	1.00000	1.00258	1.00258	0.55	0.26
MIX-COMP-THERM-011-003	1.00000	1.00141	1.00141	0.53	0.26
MIX-COMP-THERM-011-004	1.00000	0.99893	0.99893	0.25	0.26
MIX-COMP-THERM-011-005	1.00000	0.99899	0.99899	0.25	0.26
MIX-COMP-THERM-011-006	1.00000	0.99886	0.99886	0.26	0.26
Sum		46	46		
Average		0.99979	0.997962		
Stdav		0.00279	0.002867		