71-9246

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-

September 28, 2007

U.S. Nuclear Regulatory Commission
Document Control Desk
Director, Spent Fuel Project Office
Washington, DC 20555

Subject: Certificate of Compliance No. 9246 for NIST "ST" Shipping Container

Docket Number 71-9246

Gentlemen:

Enclosed herewith is an amendment to the subject Certificate of Compliance (COC) for the NIST "ST" Shipping Container. Please review this COC amendment package application consisting of the following documents for the NIST "ST" Container. NIST respectfully requests approval as there are no resulting impacts to any safety issues.

- NIST Drawing No. D-04-048 (Sheets 1 and 2, Rev. 4), Shipping Container Model "ST" Series, as the COC "drawing of record"; and
- NIST Calculations for changing the Criticality Safety Index of "50" (ref. Item 5(c)) to allow four fresh fuel elements to be shipped at one time.

Thank you very much for your attention to this matter.

Sincerely,

Wade J Richards

Wade J. Richards, Ph. D.
Chief, Reactor Operations and Engineering Group

I certify under the penalty of perjury that the following is true and correct.

Executed on: October 9th, 2007; by: Wade J Richards

Enclosures

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NIST

NMSS01

NMSS

Certificate of Compliance No. 9246
Engineering Drawing of Record

Drawing No. D-04-048 (Sheets 1 and 2), Revision 4

August 2007

DRAWING NO. D-04-048, REVISION 4 CHANGES FOR NIST "ST" CONTAINER PACKAGE CERTIFICATE OF COMPLIANCE #9246

SHEET 1 (of 2):

(1) Bill of Materials – added "Material" column and added "worm-drive" to Item No. 16 (Hose Clamp).

(2) View A-A and C-C – added 'blanked' holes (x8) in each corner.

(3) Assembly view – changed overall length from 70-59/64 to 70-7/8 (+/- 1/16) and increased support plate thickness from 1/8" to 1/4".

SHEET 2 (of 2):

(1) Item 1 (Container) – changed overall length from 70-35/64 to 70-1/2 (+/- 1/16), increased support plate thickness from 1/8" to 1/4", added "TYP. 8 PLCS." for 5/16 x 45 deg. chamfer, added 'blanked' holes (x4) in each corner, and converted diameter from decimal to fraction.

(2) Item 2 (Cover) – converted diameter from decimal to fraction.

(3) Item 3 (Top Support) – added "slotted flat hd." descriptor to bolt, added "23/32 plywood" & reduced bolt length to 1-3/8, and reoriented 'T'-Nuts to opposite quadrants while dimensionally showing their location.

(4) Item 5 (Nozzle Support) – reduced diameter from 5-1/8" to 5".

(5) Item 6 (Gasket) – converted diameters from decimal to fraction.

Figure Withheld Under 10 CFR 2.390

NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY
GAITHERSBURG, MARYLAND 20899

SHIPPING CONTAINER MODEL ST SERIES
FOR NBSR FUEL ELEMENT

DESIGNED BY: JACK STURROCK DATE: 8-24-90	DRAWN BY: JACK STURROCK DATE: 8-24-90
CHECKED BY: MAHESH SUTHAR DATE: 2-7-92	APPROVED BY: JOHN NICKLAS DATE: 2-7-92
ALL DIMENSIONS AND TOLERANCES ARE IN INCHES	SCALE: FULL
DIV: 856 REVISION NO: 4	DRAWING NO: D-04-048

Figure Withheld Under 10 CFR 2.390

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DIV: 856 REVISION NO: 4	DRAWING NO. D-04-048

Certificate of Compliance No. 9246 – NIST "ST" Package Supplemental Calculations for CoC Criticality Safety Index

In order to change the Criticality Safety Index of "50" in CoC No. 9246 to allow up to four (4) fresh fuel elements to be shipped at one time (i.e., Criticality Safety Index of 25), the following two criterion must result in $K_{eff} < 1$:

Criterion (1): 5*N **undamaged packages** will be sub-critical with optimal spacing and full light water reflection (see attached calculations dated 10/8/07).

Criterion (2): 2*N **damaged packages** will be sub-critical under the following hypothetical accident conditions: a 9-meter drop onto a flat unyielding surface, 1-meter drop onto a solid steel bar (puncture test), thermal fire test of 800°C for 30 minutes, and water immersion at 15 meters (see attached calculations dated 10/8/07).

Criticality Safety Evaluation for the Model "ST" Package Loaded with an Un-irradiated NBSR Fuel Element

Robert E. Williams

October 8, 2007

1 Introduction

This report describes a criticality safety analysis of the Model "ST" Package used by the NIST Center for Neutron Research (NCNR) to transport fresh fuel elements to the NBSR. Its conclusions support the request by NIST to increase the maximum number of ST Packages allowed per shipment from 2 to 4.

A series of criticality calculations was performed using the MCNP Monte Carlo neutron transport code [1]. The fuel model was developed at the NCNR for the reactor physics analyses presented in the updated Safety Analysis Report, NBSR-14 [2] as part of the on-going relicensing effort for the NBSR. The calculations show:

1. A single, undamaged, ST Package containing an un-irradiated NBSR fuel element will always be subcritical with optimal moderation and reflection.
2. An infinite array of closely-packed, un-damaged, ST Packages will be subcritical regardless of the degree of moderation inside the package, in any configuration of external flooding.
3. Four damaged ST Packages will be subcritical following complete or partial melting into potentially more reactive horizontal or vertical configurations regardless of the degree of internal or external flooding.

2 Package Description

A complete description of the ST package (refer to drawing number D-04-048) is presented elsewhere in the submittal, so just a brief description will be presented here. The package consists of a 70.5-in. (179.1 cm) long, 5.5-in. (13.97 cm) OD carbon-steel cylinder, with a 0.125-in. (0.318 cm) thick wall and square flanges at either end. Two short pieces of wood are inside the container, at each end to prevent the fuel element (FE) from contact with the flanges, and to keep it centered. The nozzle at the bottom of the FE slides into a hole in one piece of wood, while the top piece of wood has a rectangular insert that fits snugly into the head end of the FE. No additional insulating materials or neutron absorbers are present.

This description of the fuel element is taken from the SAR, including Figures 1 and 2, labeled as Figures 4.2.3 and 4.2.4:

> Figure 4.2.3 illustrates a typical fuel element assembly. The fuel is contained in curved fuel plates approximately 13 inches in length by 2.793 inches in width by 0.050 inches in thickness (33 cm length by 7.094 cm width by 0.127 cm thick). The dimensions of the core, or fuel meat, in each plate is 11 inches in length by 2.436 inches in width by 0.020 inch thick (27.94 cm by 6.187 cm by 0.0508 cm), and the cladding thickness is 0.015 inches (0.0381 cm). The radius of curvature is 5.5 inches (13.97 cm). Figure 4.2.4 illustrates top and bottom flat fuel plates. Each fuel element contains an upper and a lower fuel section separated by a 7 inch (17.78 cm), non-fueled gap. Each plate has a half-inch (1.27 cm) unfueled region in this gap, and a 1½ inch (3.81 cm) unfueled region at its opposite end. The overall length of the fuel element assembly is approximately 68.8 inches (1.75 m).
>
> Support for the fuel is provided by two curved outside plates, unfueled, and two flat side plates which form a box section for the full length of the assembly between the upper and the lower adapters. The thickness of the two unfueled outside plates is 0.065 inches (0.165 cm) (slightly thicker than a fuel plate). The thickness of the two side plates is 0.188 inches (0.478 cm). The side plates have 19 slots 0.095 inches (0.241 cm) deep to receive the 17 fuel plates and two end plates. The fuel plates and the curved outside plates are held in place by the two side plates by swaged mechanical connections.

A fresh element nominally contains 350 grams of ^{235}U so each of the 34 fuel plates contains 10.3 ± 0.1 grams. The fuel meat is a dispersion of 93% ± 1% enriched U_3O_8 and aluminum, with a density of 3.6 g cm^3. The clad, the curved, unfueled outside plates, and the flat side plates are all Al Alloy 6061.

As for the damaged package, one can only assume that the FE partially or completely melts as a result of exposure to a 800 °C fire, since the melting point of Al-6061 is about 650 °C. The carbon steel container will not melt below about 1200 °C, however, so homogeneous mixtures of the fuel ingredients are assumed to form at the bottom or along the sides of the container, with varying void fractions that will be water-filled in the analysis. Melted fuel would flow to one side of the container if it was horizontal during the fire. It is further assumed that if the melt is not confined in its containers, that it is spread widely and poses no criticality threat.

As stated in the submittal, NIST is seeking to amend the Certificate of Compliance for the Model "ST" Package to lower the Criticality Safety Index (CSI) from 50 to 25. As per 10 CFR 71.59, it is necessary to derive a number of packages, "N" such that:

a) 5 times "N" undamaged packages with nothing in between will be subcritical, and
b) 2 times "N" damaged (as per 10 CFR 71.73) packages would be subcritical.

The calculations described below will show that "N" = 2 for the ST Package containing an un-irradiated NBSR fuel element by demonstrating that:

a) An infinite array of closely packed ST Packages is subcritical, and
b) Four damaged packages would be subcritical with optimum moderation and reflection.

3 Criticality Safety Analysis Models

3.1 The ST Package with a Fuel Element

Since the ST Package is a fairly simple container, the computational model is a close representation. The square flanges at the ends are eliminated in the model so the container is just a closed cylinder, but the total length and the end cap thicknesses are the same (6.99-cm OD, 6.67-cm ID, 0.96-cm bottom, 0.64-cm top). Neither the nozzle nor the head of the FE assembly is modeled. The nozzle is simply cut off in the model at the wood interface (11.1 cm of wood). The wood insert into the FE at the top is maintained (maximum thickness 5.4 cm), but the dimensions of the FE box are uniform from top to bottom. The model of the FE extends 64.75 inches (164.5 cm) whereas the actual FE is 68.8 in. (174.8 cm). These differences are insignificant, as they are located far from the fuel, but they are indeed conservative, because they reduce the amount of neutron absorbing material. Figure 3 is an exaggerated schematic of one ST Package and fuel element; the vertical scale is 15 times the horizontal scale. Figure 4 is the same view but with normal scaling, showing the extent of the reflector, always at least 30-cm thick.

The densities and constituents of the materials are listed in Table 1. **For this analysis, the U_3O_8 loading in the fuel dispersion was increased from the nominal value of 41.54% to 42.75%, resulting in 360 grams of ^{235}U per fuel element.** The excess of 10 grams is very conservative. It is nearly three times the excess allowed in the fuel specifications; the FE excess would be just 3.4 g if each plate contained a 0.1-g excess.

The fuel element geometry is modeled exactly as it appears in the MCNP reactor physics analysis submitted to the NRC in April, 2004, as part of the reactor relicensing effort. Figure 5 shows a plan view of a fuel section. The main difference between the model and the FE itself is obvious; the plates are flat in the model. The fuel and clad thicknesses and the fuel height are exact, however, as are the channel widths between the plates. The fuel width was adjusted a half-millimeter to give the correct volume of fuel:

Fuel thickness	20 mil	0.0508 cm
Fuel height	11 in.	27.94 cm
Fuel width	2.436 in.	6.187 cm
(adjusted for model)		6.134 cm
Fuel volume (plate model)		8.706 cm^3
Fuel volume (FE model)		296.0 cm^3

In the model, the FE box has outside dimensions of 7.79 x 7.62 cm, and inside dimensions of 7.46 x 6.66 cm. The fuel plates are 0.127-cm thick, 6.66-cm wide, and 33.02-cm long. The model of the FE box contains less Al than the actual FE, but this difference is conservative because the missing Al is a neutron absorber. A sample input file, "stpac", in the Appendix contains the geometry of a single ST Package and FE.

3.2 An Infinite Array of Undamaged Packages

To achieve an infinite array of closely-packed ST Packages in MCNP, the package is placed within a hexagonal cell with periodic boundary conditions imposed on the hexagonal surfaces, and reflecting boundary conditions on the top and bottom surfaces. When the surfaces on opposite sides of the hexagon are designated as periodic [1], a neutron leaving one surface re-enters the problem geometry across the opposite surface, rather than simply being secularly (mirror) reflected at the surface, which is the case for a reflecting boundary condition. Figure 6 is a plan view of the hexagonal unit cell that will result in a close-packed triangular lattice with a pitch of 14 cm; the OD of the ST Package is 13.98 cm. The pitch can be changed by altering the parameters of the surface cards defining the hexagonal cell. Figure 7 shows the side view of the cell, again with an exaggerated horizontal scale. With periodic and reflecting surfaces as described above, this simple geometric model is the equivalent of a 3-dimensional infinite array of ST Packages.

The materials in this model are the same as those listed in Table 1, with one exception. Although Figures 6 and 7 show the package fully flooded with water, this is the least reactive configuration. Two series of calculations were performed, one with no water inside the package, and the second with varying amounts of water inside. A sample input file, "stinf", is given in the Appendix.

3.3 Arrays of Four Damaged ST Packages – Vertical or Horizontal Melting

Among the accident scenarios in 10 CFR 71.73 is an 800 °C fire of 30-min duration. Since the fuel melts at 650 °C, but the carbon steel container will not melt, the Al and U_3O_8 could mix and flow to the bottom of the packages. If the packages were standing vertically, the Al + U_3O_8 slag would form cylinders on the bottoms of the packages. If the packages were lying horizontally, the slag would flow to the low sides of the cylinders. Both cases were modeled assuming that homogeneous mixtures Al + U_3O_8 would be formed and a series of calculations was performed for each case allowing for voids in the slag that could later be filled with water. Heterogeneous cases were also analyzed in which the U_3O_8 settled into a layer beneath the Al (Section 6.3.3).

3.3.1 Vertical Melting

In the simplest scenario, it is assumed that the FE melts completely, flows to the bottom of the cylinder, and forms a solid cylinder with no voids. The slag cylinder would have the same volume as the FE box and fuel plates, so the new volume can be calculated from the volumes and densities of its constituents. Most of the mass is Al, which, for simplicity, is now taken to be pure, rather than Al-6061:

$V_{Al} = V_{box} + V_{plates}$

$V_{box} = [(7.79*7.62)-(7.46*6.66)]*164.5 = 1592\ cm^3$

$V_{plates} = 34*(0.127*6.66*33.02) - 296.0 = 654\ cm^3$ (fuel volume subtracted)

$M_{Al} = (2.7\ g/cm^3)*(1592 + 654) = 6064\ g$

The fuel meat contains 360 g of ^{235}U, 27 g of ^{238}U, 70 g of oxygen, and 612 g of Al. It is assumed that the U_3O_8 retains its chemical form and occupies a volume of (457 g)/ (8.3g/cm^3) = 55 cm^3. The total Al mass is 6676 g, occupying 2473 cm^3. The slag is assumed to be homogeneous:

$M_{slag} = 7133\ g$ $\qquad V_{slag} = 2528\ cm^3$ $\qquad \rho_{slag} = 2.822\ g/cm^3$

Since the ID of the container is 13.34 cm, the height of the slag is 18.1 cm. It is further assumed that upon cooling, water leaks into the container, filling completely the volume over the slag. The wooden spacers in the undamaged package are ignored.

Figures 8 and 9 show the geometry of the 4 ST Packages arranged in a close-packed hexagonal array. The separation of the packages, seen nearly touching in Figure 8, can be increased by increasing the pitch from its minimum value of 14 cm. The packages are surrounded by at least 30 cm of water in all directions.

Partial melting of the FE is modeled as a slag containing a void volume that is water-filled for the analyses. It is assumed that the final mixture is homogeneous. This is a very conservative assumption because a homogeneous mixture of fuel and water will be more reactive than a heterogeneous arrangement of partial crumbling fuel plates, which would likely be the case if the FE were to actually start to melt. Six such mixtures were analyzed with slag heights of 27, 36, 45, 55, 89, and 177 cm. The latter two cases, representing 50% and 100% of the package interior, are clearly un-physical, but have been included to determine the behavior of k_{eff} versus the height of the slag/water mixture. Table 2 includes the material specifications for all the slag mixtures for the vertical melt cases. Input file "stmix14", in the Appendix, has the geometry for the 36-cm mixture.

3.3.2 Horizontal Melting

Essentially the same process outlined above was followed for the horizontal melt, but rather than allow complete mixing of all the FE materials, three regions were assumed, concentrating the fuel in the center of the package. The molten slag at either end of the package contained only aluminum, whereas the center part contained the material from the fuel plates, and the 81 cm of the FE box containing the plates and gap. As a result, the center region is thicker because it contains more material. As above, several additional cases were modeled corresponding to a partial melt of the fuel plates, leaving voids that would later be water filled. For conservatism, the slag plus water material was taken to be homogeneous. The cases studied were:

1. No voids, volume of Al + U_3O_8 slag only. Thickness = 2.8 cm.
2. Equal volumes of void and Al + U_3O_8 slag. Thickness = 4.6 cm.
3. Total volume equal to the volume of 81 cm of the FE. Thickness = 5.8 cm.
4. Half the volume of the package for the 81-cm region. Thickness = 6.7 cm.
5. Full volume of the package for the 81-cm region. Thickness =13.3 cm.

Case 1 is similar to the vertical slag case above except that only a portion of the FE box is included in the calculation. The slag will contain 4515 g of Al and 457 g of U_3O_8, occupying a volume of 1727 cm^3, with an average density of 2.879 g/cm^3. The material specifications for the slag and slag/water mixtures for the horizontal melting cases are listed in Table 3. The volume of the slag lies between its horizontal surface and the cylindrical wall of the package. The cross sectional area of the segment is determined by dividing the volume by its length: (1727 cm^3)/(81.3 cm) = 21.2 cm^2. The area of a segment of a circle is given by:

$$K = \tfrac{1}{2} R^2 (\theta - \sin \theta).$$

A numerical solution is used to determine θ, the angle between the radii that intersect the chord corresponding to the surface of the slag. The distance from the axis of the cylinder to the center of the chord, d, is $d = R \cos \theta/2$, and the thickness of the slag is R – d. For Case 1, with no voids, θ = 109° (1.90 rad), d = 3.9 cm, and the thickness is 2.8 cm. Figure 10 shows the profile of the geometry of the molten Al and slag regions for Case 1. The vertical scale is greatly exaggerated. For the criticality analysis, it is assumed that after cooling, the packages are flooded and re-oriented such that cells containing the fissile material are facing each other in close contact, as shown is Figure 11. The input file, "steq14", in the Appendix, contains the geometry of Case 3 above, 5.8-cm thickness.

The pitch was adjusted to find the most reactive geometry. For the smallest pitch, right hexagonal prisms were used such that their axes are 14 cm apart. To achieve this geometry, the hexagons were defined by 2 planes perpendicular to the x-axis at x = ± 7 cm, and 4 planes with slopes of ± $\sqrt{3}$ and x intercepts of ± 14 cm. To change to a 16-cm pitch, the planes would be moved to ± 8 cm and the intercepts to ± 16 cm, moving all four packages further apart. Often, an irregular pitch resulted in the most reactive case, such as Figure 12, with 2 planes moved to x = ± 9 cm, and the slopes and intercepts at ± $\sqrt{3}$ and ± 16 cm, respectively (indicated as 9 x 16).

4 Method of Analysis

4.1 Computer Code

MCNP is a Monte Carlo neutron and photon transport code developed at LANL and is used for a wide variety of problems including criticality simulations. It features generalized surfaces and cells so that complex geometries can be defined. Criticality calculations with the code have been carefully benchmarked with respect to LANL critical experiments [3] and power reactors [4]. Many research reactors have also been successfully modeled using MCNP to analyze the possibility of conversion to low enrichment uranium (LEU) fuel, and the performance of proposed experimental facilities, such as epithermal neutron beam converters for boron neutron capture therapy (BNCT), and cold neutron sources (as discussed below). MCNP has been used to meet reactor-licensing requirements [5,6]. Hundreds of cross-section files with gamma-ray production data have been formatted for use with the code, including thermal neutron scattering kernels for all common reactor moderators, and four cold moderators.

Although MCNP formally came into existence in 1977, 30 years ago, it roots originate in the pioneering work on Monte Carlo methods at Los Alamos in the late 1940's. Now, the code has thousands of users around the world. The present version, MCNP5, represents about 500 person-years of development. The X-5 Monte Carlo Team charged with maintaining and improving the code have always adhered to rigorous quality control when adding new features and updates for new computer platforms and operating systems.

4.2 Nuclear Data

Cross section data used in this analysis were distributed with the code package in 2003. The default data (ENDF/B-6) were used for all materials. No local processing of nuclear data was required; the code uses the continuous energy data supplied with it. The nuclear data group at LANL works very closely with the code developers to format the ENDF evaluations for use in MCNP.

Sample problems distributed with the code enable the user to test the installation against provided output files. For this analysis, the code was installed on a pair of Dell Precision 670 dual-processor workstations with Windows XP operating systems. The PC executable versions of the code were installed flawlessly and used throughout.

4.3 Code Input

The input files for this work were generally quite short, but dozens of calculations were performed. A few examples are reproduced in the Appendix. Many series of calculations varied from one another by changing a single parameter such as the water density or the spacing between the ST Packages. For all of the calculations the starting neutrons had an energy distribution given by the Watt fission spectrum. Most problems were run with 500,000 starting particles, usually 1000 per cycle, skipping the first 10 cycles.

4.4 Adequacy of Calculations

In addition to verifying that there were no MCNP generated warnings about the quality of the criticality calculation (missed cells with fissionable material, statistical abnormalities) it was further required that the first and second half k_{eff} values differed by no more than 2 standard deviations. If such a case arose, the problem was re-run with more particles and a different source spatial distribution. No biasing or variance reduction techniques were employed; the importance of all cells was one.

5 Validation of Calculation Method

In addition to the MCNP benchmarks referenced above, the model of the NBSR has also been extensively benchmarked against its operating parameters. The model has evolved over about 15 years and by 2004 it was used extensively in preparing the updated SAR. In particular, the model correctly predicts the critical positions of the shim arms, the reactivity worth of the shim arms and regulating rod, the neutron flux in the beam tubes and rabbit facilities, and the performance of two liquid hydrogen cold neutron sources. The fuel geometry from the NBSR model was used in the current study.

It is difficult to establish a benchmark critical experiment, however, that can directly be compared to the model of the fuel element in the ST Package. The core benchmark contains fuel that has been burned in the reactor for as many as 8 reactor cycles. Any "bias" derived from a core calculation is most likely to be caused by the fission product concentrations from burnup calculations, rather than the fuel element model. The present work uses fresh fuel only.

The acceptance criterion for k_{eff} used here, then, is very simple. $K_{eff} + 2\sigma$ must be less than 0.95, using the required margin of subcriticality established by NRC, where σ is one standard deviation in the combined collision/absorption/track length value of k_{eff} from MCNP (the recommended value).

6 Criticality Calculations and Results

6.1 Single Package

Table 4 lists the results of a series of criticality calculations for a single ST Package with an undamaged FE. *The package remains far subcritical with optimum interspersed moderator and surrounded by a reflector of 30-cm of water.* The undamaged package (no water inside) has a maximum k_{eff} of 0.153 immersed in the reflector. If the package were damaged, allowing water to flood the FE and the volume between the FE and the container wall, k_{eff} increases to 0.358.

6.2 Infinite Array of Undamaged Packages

Two series of calculations were performed for the hexagonal close-packed infinite array of ST Packages described earlier. In the first series, it is assumed that the packages are immersed in water but remain sealed and are dry inside. Table 5 lists k_∞ as a function of the pitch of the array. The minimum pitch is 14 cm because the OD of the package is 6.99 cm. The maximum value of k_∞ is 0.712, which occurs with a pitch of 15.0 cm.

For the second series, it is assumed that the container wall is compromised and that water either leaks into the FE but not into the volume outside of the FE, or that water leaks into both volumes. Each case was evaluated with and without external flooding. The water density inside the package was varied from 0.1 to 1.0 g/cm^3 to model partial filling of the package. The maximum k_∞ is 0.90216 ± 0.0076, which occurs for the case of water flooding the FE only, with no water between the FE and the container wall, and no water outside the packages (Table 6). The fully flooded case has $k_\infty = 0.746$, showing that from the reactor physics perspective, this system is substantially over-moderated, and that there is no need to increase the pitch. If the water density is very low inside the package, however, k_∞ increases if the pitch is 15 cm because external flooding provides the needed moderator.

Figure 13 shows a plot of the k_∞ data in Table 6 versus the density of water inside the package. *The results of the calculations show that an infinite array of ST Packages will remain subcritical regardless of the degree of flooding inside or outside the packages.* The large diameter of the package and the 7-inch separation between the upper and lower fuel sections combine to prevent criticality of any number of undamaged packages.

6.3 Arrays of 4 Damaged Packages

6.3.1 Vertical Melting

For each of the seven assumed slag heights discussed in Section 3.3.1, k_{eff} was determined as a function of the pitch of the hexagonal array of 4 packages. A few irregular pitches were modeled also to be sure that potentially more reactive configurations were sampled. (This is more likely in the horizontal melt cases discussed in Section 6.3.2.) Water surrounds the packages and fills the package above the slag/water mixture. The results are listed in Table 7. The greatest value of k_{eff} is 0.77792 ± 0.00104, for a height of 54.5 cm. Since the active fuel height in a section is 28 cm, this maximum k_{eff} case could be thought of as a rough equivalent of the two fuel sections slumping with one resting on top of the other. The calculation is very conservative, however, as the slag/water mixture is homogeneous. For the most reactive cases, the density of the water component was also varied to check that the mixture itself was not over-moderated.

For a pitch of 14 cm, k_{eff} is plotted as a function of height in Figure 14. The plot gives assurance that no highly reactive configuration has been missed between the 7 heights analyzed. *The calculations show that an array of four ST Packages will remain subcritical in any configuration created as a result of fuel melting inside vertical packages.*

6.3.2 Horizontal Melting

For each of the 5 slag thicknesses discussed in Section 3.3.2, Table 8 lists k_{eff} as a function of the pitch of the hexagonal array of the four packages. Many irregular pitches are included also, because except for the slag occupying the entire diameter, the most reactive cases had irregular geometry. The most extreme example is the 2.8-cm thick slag of Al + U_3O_8 only (no voids in this case), shown in Figures 11 and 12. Here the packages must be separated (9 x 16) to reach optimum moderation, but k_{eff} is still less than 0.5.

A plot of k_{eff} versus thickness is shown in Figure 15, where the maximum values of k_{eff} are plotted, regardless of pitch. The curve is asymptotically increasing to its maximum possible value of 0.749 with the container completely filled with a homogeneous mixture of Al + U_3O_8 + H_2O, 81.2-cm long. This geometry is very similar to the vertical mixture of height 88.7 cm, with $k_{eff} = 0.709$. K_{eff} is greater for the 81.2-cm horizontal melt because both the U and H densities are greater, but the Al density is lower. The scenario is un-physical, however, as a partially melted FE would occupy a smaller volume than the original FE.

The greatest value of k_{eff} for the horizontal melt cases is less than the greatest value for the vertical melt cases. *An array of four ST Packages will remain subcritical in any configuration created as a result of fuel melting inside horizontal packages.*

6.3.3 Layered Slag – Inhomogeneous Melting

It is possible that a complete melt of the FE could result in a segregation of the U_3O_8 from the Al, given that it has a density over 3 times that of Al. In the vertical case, the 55 cm^3 of oxide would settle into a disk on the bottom of the container, 0.394-cm thick. The maximum k_{eff} for this geometry is 0.2730, which occurs at a pitch of 16 cm. From Table 7 the homogeneous slag of Al + U_3O_8 has a maximum $k_{eff} = 0.4247$. Thus, the assertion that the homogeneous mixture will be more reactive is verified.

For the horizontal melt, it was assumed that the U_3O_8 forms an 81-cm long, thin "puddle" along the cylinder wall. The maximum depth would be 0.27 cm, as shown in Figure 16, with the packages rotated to face each other. In the most reactive geometry, the irregular pitch of 9 x 16, $k_{eff} = 0.3625$, compared to $k_{eff} = 0.4826$ for the homogeneous slag, again confirming the assumption that the homogeneous slag is more reactive than a layer of oxide under a layer of Al.

6.4 Criticality Safety Index

The Criticality Safety Index is given by:

$$CSI = 50 \div N.$$

"N" can be derived from the criticality safety evaluation presented in this report. 10 CFR 71.79 requires that:

(1) Five times "N" undamaged packages with nothing in between the packages would be subcritical, and
(2) Two times "N" damaged packages (as per 10 CFR 71.73) would be subcritical with optimum interspersed hydrogenous moderation.

The calculations presented herein have shown:

> An **infinite** array of closely-packed, un-damaged, ST Packages will be subcritical regardless of the degree of moderation inside the package, in any configuration of external flooding. This result imposes no limit on "N".
>
> **Four** damaged ST Packages will be subcritical following complete or partial melting into more potentially reactive horizontal or vertical configurations regardless of the degree of internal or external flooding. This result supports the determination that "N" equals 2.

N = 2

CSI = 25

7 Conclusion

The results of the criticality analyses of the Model ST Package containing an un-irradiated NBSR fuel element show that the CSI for these packages is 25. Therefore, up to four packages can be shipped together, rather than the current limit of two packages.

8 References

1. X-5 Monte Carlo Team, *MCNP – A General Monte Carlo N-Particle Transport Code, Version 5,* LA-CP-03-0245, Los Alamos National Laboratory, Los Alamos, New Mexico (2003).

2. NIST Center for Neutron Research, "Safety Analysis Report (SAR) for License Renewal for the National Institute of Standards and Technology Research Reactor - NBSR," NBSR-14 (2004).

3. Whalen, Daniel J. et al, *MCNP: Neutron Benchmark Problems.* LA-12212, Los Alamos National Laboratory, Los Alamos, New Mexico. (1991).

4. Sitarman, S., *MCNP: Light Water Reactor Critical Benchmarks*, General Electric Nuclear Energy, NEDO-32028 (1992).

5. Ougouag, A. M. et al, *MCNP Analysis of the Foehn Critical Experiment*, ORNL/TM-12466, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1993).

6. Bretscher, M. M., *Perturbation-Independent Methods for Calculating Research Reactor Kinetic Parameters*, ANL/RERTR/TM-30, Argonne National Laboratory, Argonne, Illinois. (1997).

Table 1. Material Specifications for the Un-damaged ST Package with an Un-irradiated NBSR Fuel Element

Material	MCNP Number	Density (g/cc)	Constituent	Atom Density (atoms/b-cm)	Mass Fraction
Fuel Meat	71	3.612	U-235	3.116E-03	3.367E-01
			U-238	2.303E-04	2.520E-02
			O	8.921E-03	6.560E-02
			Al	4.615E-02	5.725E-01
Al Alloy 6061	2	2.713	Al	8.552E-02	9.741E-01
			Si	5.061E-04	6.000E-03
			Mg	9.747E-04	1.000E-02
			Ti	3.464E-05	7.000E-04
			Mn	3.020E-05	7.000E-04
			Cr	8.720E-05	2.000E-03
			Fe	1.471E-04	3.500E-03
			Cu	1.120E-04	3.000E-03
Carbon Steel	1	7.821	C	3.925E-03	1.000E-02
			Fe	8.350E-02	9.900E-01
Plywood	4	0.450	H	1.671E-02	6.217E-02
			C	1.003E-02	4.443E-01
			O	8.357E-03	4.935E-01
Water	3	1.000	H	6.687E-02	1.119E-01
			O	3.344E-02	8.881E-01

Table 2. Material Specifications - Vertical Melt

Fuel/Aluminum Slag in Damaged Package
Height 18 cm

Material	MCNP Number	Density (g/cc)	Constituent	Atom Density (atoms/b-cm)	Mass Fraction
Fuel + Al (slag)	5	2.822	U-235	3.653E-04	5.050E-02
			U-238	2.713E-05	3.800E-03
			O	1.041E-03	9.800E-03
			Al	5.895E-02	9.359E-01
Fuel/Aluminum Slag Plus Water in Damaged Package					
Height 27 cm					
Fuel-Al-water (mixture)	5	2.214	U-235	2.427E-04	4.280E-02
			U-238	1.793E-05	3.200E-03
			O	1.185E-02	1.421E-01
			Al	3.930E-02	7.952E-01
			H	2.209E-02	1.670E-02
Height 36 cm					
Fuel-Al-water (mixture)	5	1.910	U-235	1.815E-04	3.710E-02
			U-238	1.354E-05	2.800E-03
			O	1.724E-02	2.398E-01
			Al	2.947E-02	6.912E-01
			H	3.321E-02	2.910E-02
Height 45 cm					
Fuel-Al-water (mixture)	5	1.735	U-235	1.467E-04	3.300E-02
			U-238	1.097E-05	2.500E-03
			O	2.039E-02	3.118E-01
			Al	2.379E-02	6.145E-01
			H	3.960E-02	3.820E-02
Height 55 cm					
Fuel-Al-water (mixture)	5	1.607	U-235	1.210E-04	3.940E-02
			U-238	8.950E-06	2.200E-03
			O	2.266E-02	3.745E-01
			Al	1.965E-02	5.478E-01
			H	4.427E-02	4.610E-02
Height 89 cm					
Fuel-Al-water (mixture)	5	1.373	U-235	7.417E-05	2.110E-02
			U-238	5.550E-06	1.600E-03
			O	2.682E-02	5.190E-01
			Al	1.207E-02	3.939E-01
			H	5.283E-02	6.440E-02
Height 177 cm					
Fuel-Al-water (mixture)	5	1.186	U-235	3.708E-05	1.220E-02
			U-238	2.700E-06	9.000E-04
			O	3.013E-02	6.749E-01
			Al	6.033E-03	2.279E-01
			H	5.960E-02	8.410E-02

Table 3. Material Specifications - Horizontal Melt

Fuel/Aluminum Slag in Damaged Package
Thickness 2.8 cm

Material	MCNP Number	Density (g/cc)	Constituent	Atom Density (atoms/b-cm)	Mass Fraction
Fuel + Al (slag)	5	2.879	U-235	5.341E-04	7.240E-02
			U-238	3.933E-05	5.400E-03
			O	1.550E-03	1.430E-02
			Al	5.834E-02	9.079E-01
Fuel/Aluminum Slag Plus Water in Damaged Package					
Thickness 4.6 cm					
Fuel-Al-water (mixture)	5	1.940	U-235	2.669E-04	5.380E-02
			U-238	1.966E-05	4.000E-03
			O	1.751E-02	2.397E-01
			Al	2.917E-02	6.738E-01
			H	3.326E-02	2.870E-02
Thickness 5.8 cm					
Fuel-Al-water (mixture)	5	1.673	U-235	1.916E-04	4.470E-02
			U-238	1.397E-05	3.300E-03
			O	2.203E-02	3.497E-01
			Al	2.090E-02	5.596E-01
			H	4.268E-02	4.270E-02
Thickness 6.6 cm					
Fuel-Al-water (mixture)	5	1.572	U-235	1.627E-04	4.040E-02
			U-238	1.193E-05	3.000E-03
			O	2.273E-02	4.010E-01
			Al	1.777E-02	5.064E-01
			H	4.621E-02	4.920E-02
Thickness 13.3 cm					
Fuel-Al-water (mixture)	5	1.280	U-235	8.138E-05	2.470E-02
			U-238	6.180E-06	1.900E-03
			O	2.861E-02	5.909E-01
			Al	8.878E-03	3.093E-01
			H	5.625E-02	7.320E-02

Table 4. Single ST Package Loaded with an NBSR Fuel Element

Cells Filled with Light Water: Inside FE	Outside FE	Reflector	Output File	K-eff	Standard Deviation
No	No	No	ostpaca	0.00641	0.00002
No	No	Yes	ostpacz	0.15317	0.00038
Yes	No	Yes	ostpacy	0.25148	0.00048
Yes	Yes	Yes	ostpag	0.35789	0.00068
No	Yes	Yes	ostpacb	0.20239	0.00042

Table 5. K-infinity vs. Pitch

Infinite Array of ST Packages in Water
(No Water Inside Package)

Pitch (cm)	Output File	K-infinity	Standard Deviation
14.0	ostinfx	0.66794	0.00094
14.5	ostinf4	0.70765	0.00089
15.0	ostinf2	0.71224	0.00089
15.5	ostinf5	0.69794	0.00091
16.0	ostinf3	0.67405	0.00086

Table 6. Infinite Arrays of ST Packages with NBSR Fuel Elements (Vary Moderator Density, with and without External Flooding)

	NO EXTERNAL FLOODING				EXTERNAL FLOODING			
	Water Inside FE but NOT Outside FE		Water Inside and Outside FE		Water Inside FE but NOT Outside FE		Water Inside and Outside FE	
Water Density (g/cc)	Output File	K-infinity	Output File	K-infinity	Output File	K-infinity	Output File	K-infinity
1.00	ostinfz	0.90216	ostinfw	0.79017	ostinfy	0.86888	ostinf	0.74583
0.90	ostz90	0.88225	ostz92	0.79680	ostz93	0.85345	ostz91	0.74743
0.80	ostz80	0.86468	ostz83	0.80041	ostz81	0.83875	ostz82	0.75079
0.70	ostz70	0.84053	ostz72	0.80353	ostz73	0.82092	ostz71	0.75309
0.60	ostz60	0.81947	ostz61	0.80782	ostz63	0.80678	ostz62	0.75433
0.50	ostz50	0.78916	ostz52	0.80530	ostz53	0.78816	ostz51	0.75275
0.40	ostz40	0.75640	ostz42	0.80140	ostz43	0.77181	ostz41	0.75197
0.30	ostz30	0.71334	ostz32	0.79182	ostz33	0.75325	ostz31	0.74755
					ostz35*	0.72367		
0.20	ostz20	0.65301	ostz24	0.76555	ostz25	0.72987	ostz21	0.74299
					ostz26*	0.71937	ostz22	0.68403
0.10	ostz10	0.56246	ostz13	0.68899	ostz14	0.70442	ostz11	0.72346
					ostz15*	0.71718	ostz12	0.69797
					ostz16**	0.67200		

Uncertainties (one standard deviation) all between 0.0008 and 0.0011.

*** 15-cm pitch** **** 16-cm pitch**

Table 7. K-eff for 4 Damaged ST Packages (Vertical Melt)

Height (cm)	**18.2**	**27.3**	**36.4**	**45.0**	**54.5**	**88.7**	**177.5**
Output files	**osthex..**	**ostmx..**	**ostmix..**	**ostpk..**	**ostmx3..**	**osthaf..**	**ostmax..**
Pitch (cm)	**K-eff**	**K-eff**	**K-eff**	**K-eff**	**K-eff**	**K-eff**	**K-eff**
14	0.3640	0.6143	0.7551	0.7710	0.7779	0.7078	0.5167
15	0.4000	0.6310	0.7507	0.7593	0.7613	0.6875	0.4974
16	0.4220	0.6262	0.7324	0.7360	0.7348	0.6610	0.4762
17	0.4247	0.6088	0.7071	0.7076	0.7052	0.6327	0.4555
18	0.4135	0.5821	0.6749	0.6769	0.6762	0.6066	0.4389
19	0.3982	0.5527	0.6405	0.6440	0.6429	0.5795	0.4188
Irregular pitches							
7.5 x 14			0.7571	0.7700	0.7746	0.7058	
8.0 x 14			0.7557	0.7730	0.7712	0.7009	
8.5 x 14			0.7524	0.7634	0.7664	0.6952	
Density of water in voids (g/cc)							
0.9			0.7219	0.7384	0.7460		
0.8			0.6848	0.7014	0.7096		
0.6			0.6067	0.6194	0.6305		
0.4			0.5229	0.5264	0.5326		
0.2			0.4400	0.4314	0.4308		
0			0.3642	0.3419	0.3317		

Uncertainties (one standard deviation) all between 0.0008 and 0.0011.

Table 8. K-eff for 4 Damaged ST Packages
(Horizontal Melt)

Thickness (cm)	2.8	4.6	5.8	6.6	13.3
Output Files	ostmid..	osth..	osteq..	osthf..	ostfu..
Pitch (cm)	K-eff	K-eff	K-eff	K-eff	K-eff
14	0.4033	0.6061	0.6842	0.7206	0.7491
15	0.4487	0.6251	0.6878	0.7154	0.7249
16	0.4705	0.6234	0.6738	0.6974	0.7015
17	0.4712	0.6042	0.6488	0.6687	0.6696
18	0.4575	0.5767	0.6158	0.6351	0.6421
19	0.4351	0.5437	0.5819	0.6008	0.6149
Irregular pitches					
7.5 x 14	0.4234	0.6167	0.6915	0.7228	0.7463
8.0 x 14	0.4371	0.6322	0.6939	0.7242	0.7399
8.5 x 14	0.4461	0.6215	0.6917	0.7211	0.7335
9.0 x 14	0.4502		0.6876		0.7301
13 x 14	0.4817				
9.0 x 15	0.4757				
9.0 x 16	0.4826				
9.0 x 17	0.4739				

Uncertainties (one standard deviation) all between 0.0008 and 0.0011.

Figures 1 and 2, on the following pages, are taken directly from NBSR-14 [2].

Figure Withheld Under 10 CFR 2.390

Figure 4.2.3: Fuel Element Assembly (see Figure 4.2.4 for Fuel Plate Detail)

Figure Withheld Under 10 CFR 2.390

Figure 4.2.4: Typical Top and Bottom Flat Fuel Plate

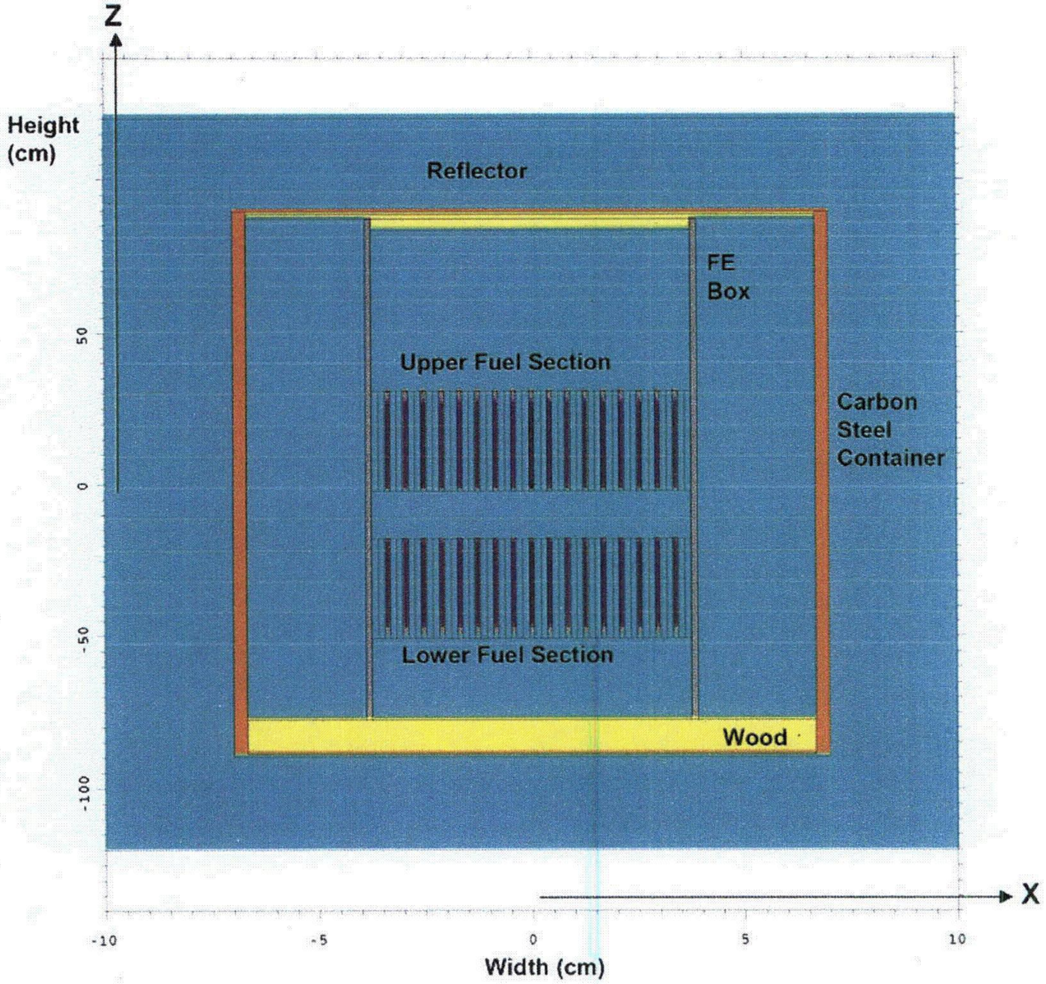

Figure 3. Side view of the ST Package with an NBSR fuel element. Note the z-axis spans 300 cm, while the x-axis spans 20 cm. Materials are shaded as follows: water – blue; wood – yellow; carbon steel – orange; Al Alloy 6061 – gray; dispersion fuel – purple.

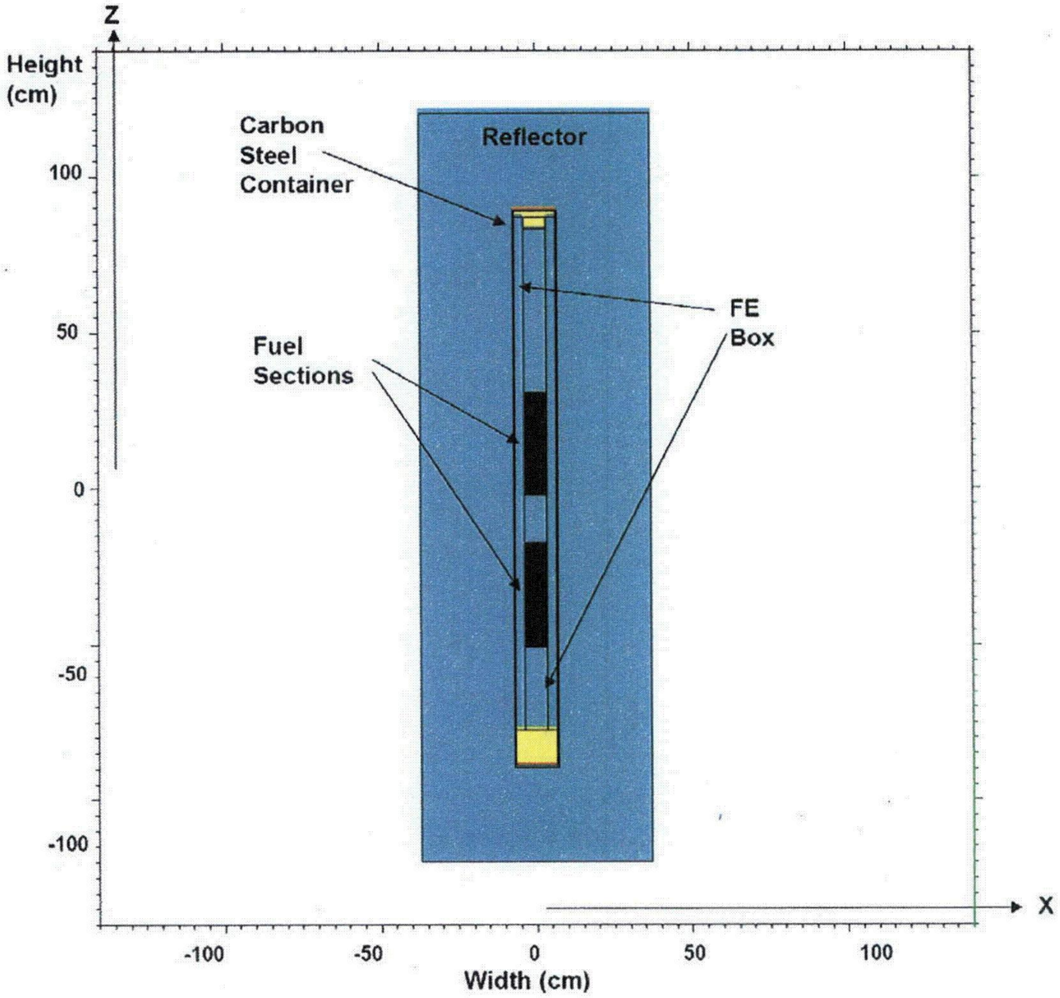

Figure 4. Side view of the ST Package showing the extent of the water reflector.

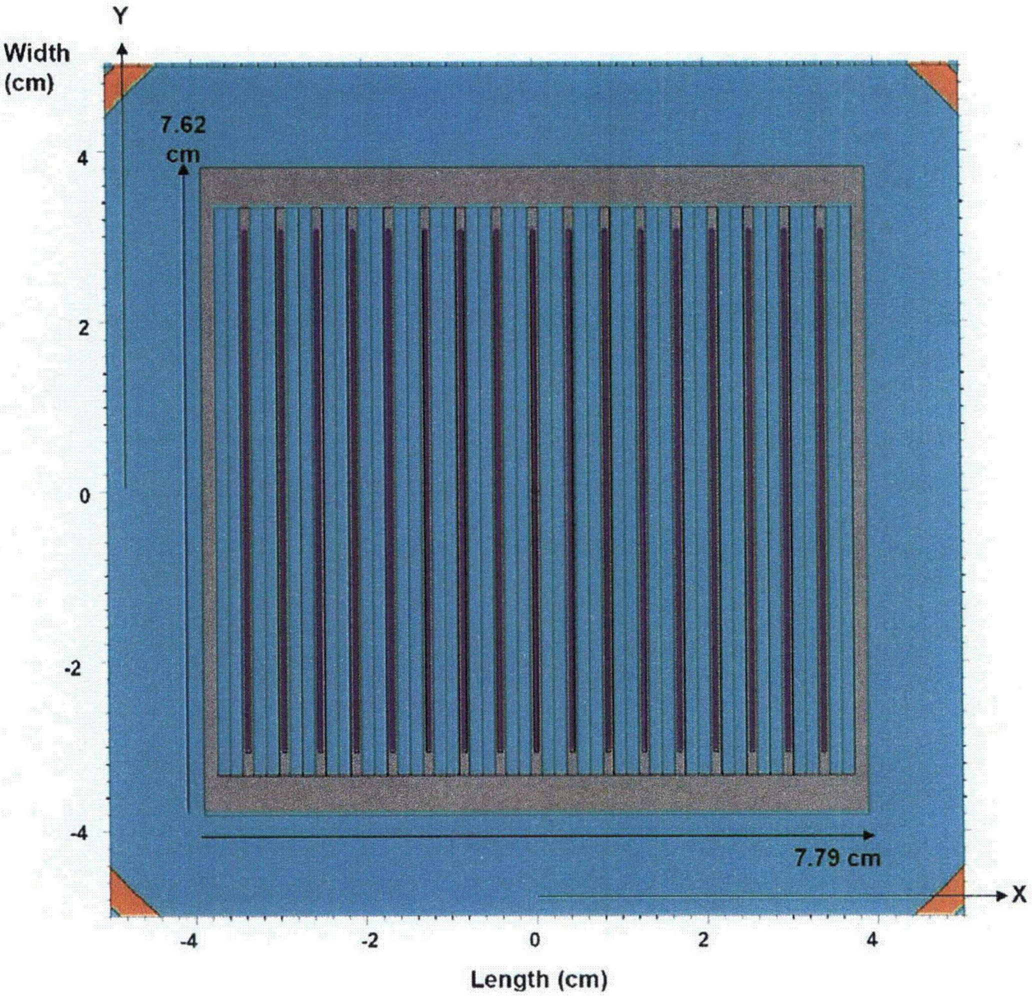

Figure 5. Plan view of a fuel section in the MCNP model. The ST Package container is visible in the corners; the colors are the same as Figure 3. The fuel element geometry is taken from the model of the NBSR core.

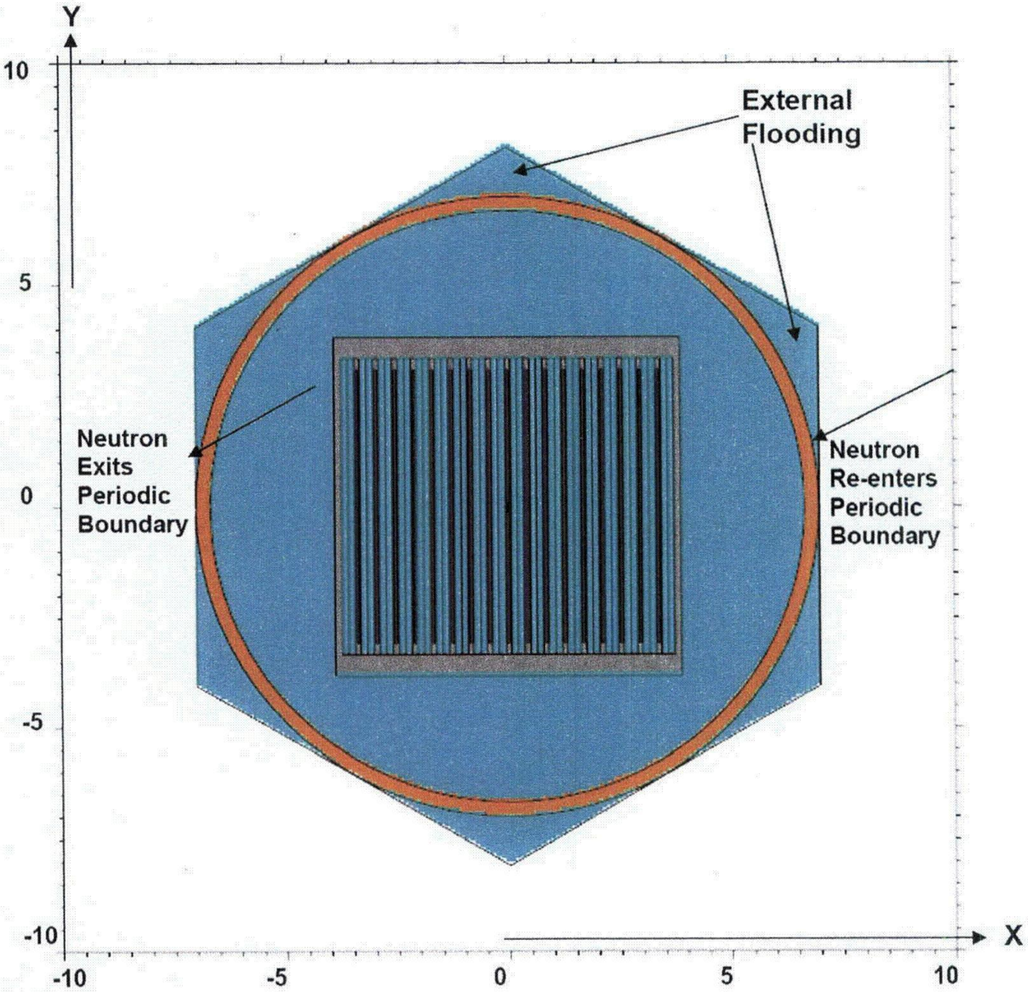

Figure 6. The ST package and NBSR fuel element inside a hexagonal cell (same colors). With periodic boundary conditions imposed on the sides of the hexagon, the geometry is the equivalent of an infinite plane of packages with the same fuel plate orientation, perpendicular to the x-axis.

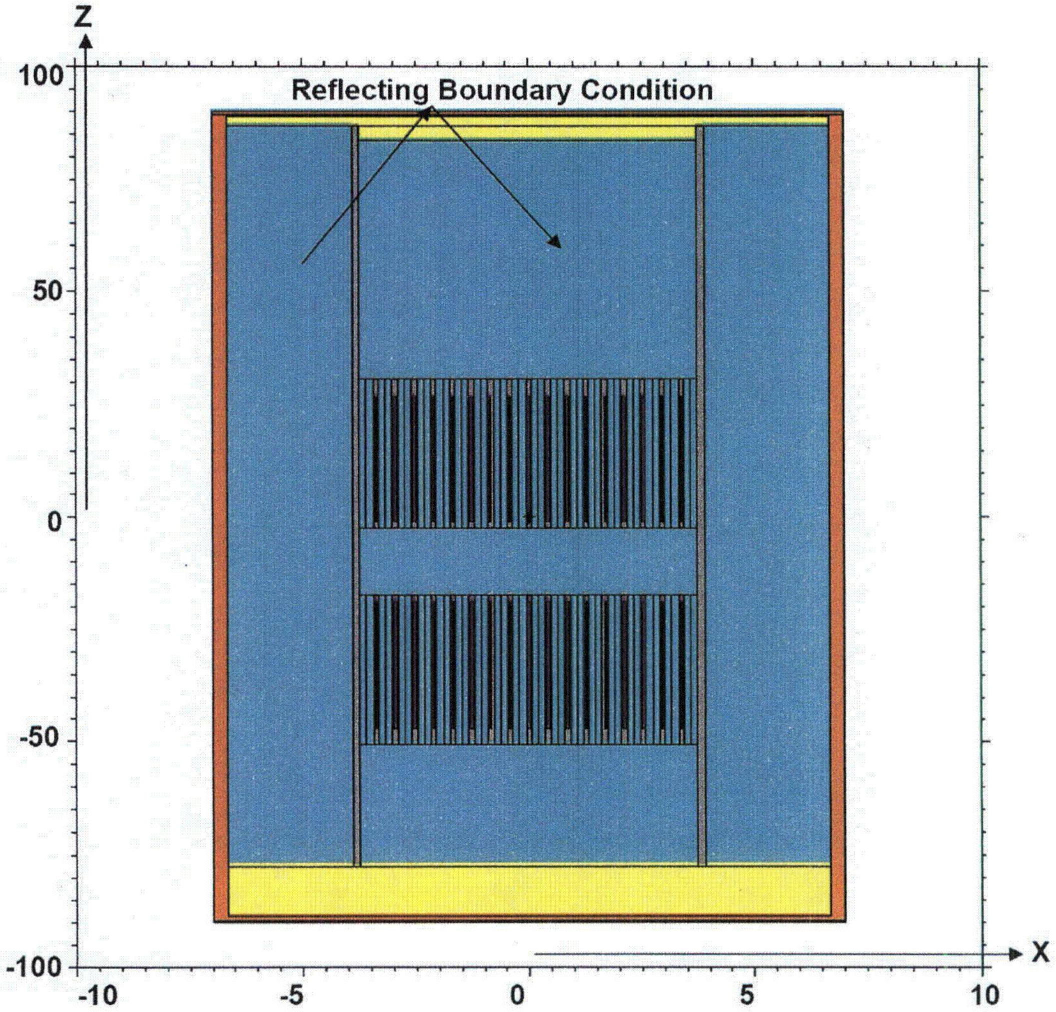

Figure 7. Side view of the ST Package and NBSR fuel element. Reflecting boundary conditions imposed on the top and bottom surfaces are the equivalent of an infinite vertical stack of cells. The material colors are the same as those in Figure 3.

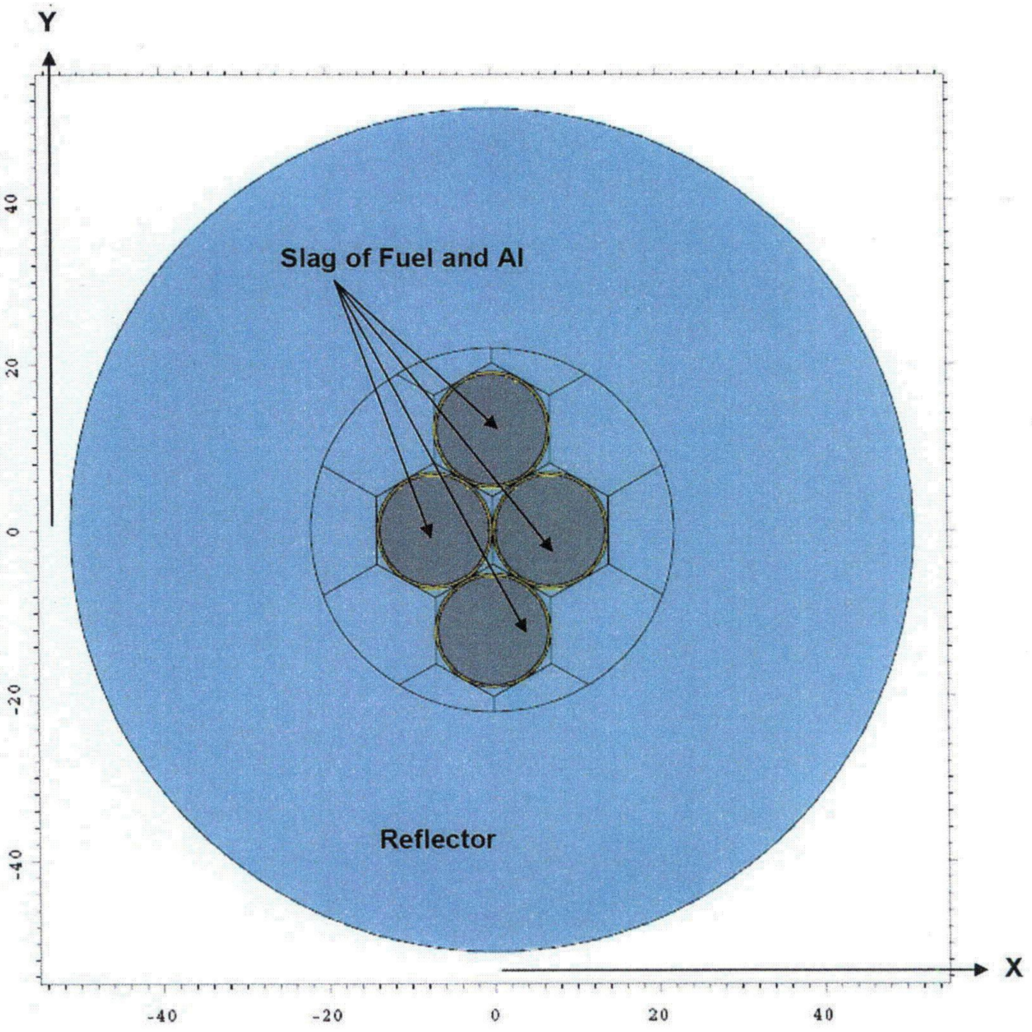

Figure 8. Plan view of 4 ST Packages with Al + U_3O_8 slag at the bottom. The color scheme is: gray – Al + U_3O_8 slag; yellow – carbon steel; blue – water. The hexagons and the circle filled with them are MCNP cell boundaries, not materials.

Figure Withheld Under 10 CFR 2.390

Figure 9. Side view (plane y = 0 in Figure 8) of 2 of the 4 damaged ST Packages in which the molten fuel is assumed to have flowed to the bottom of the container into a homogeneous mixture. The package is later flooded.

Figure Withheld Under 10 CFR 2.390

Figure 10. Side view of the distribution of the slag and Al for Case 1 of the horizontal melt. It is assumed that the material from the fuel plates (dark gray) remains in the center 81 cm, and the regions at either end are just aluminum (gray). Note the extremely exaggerated scales emphasizing the slag thickness; the vertical extent is just 5 cm compared to 300 cm for the length.

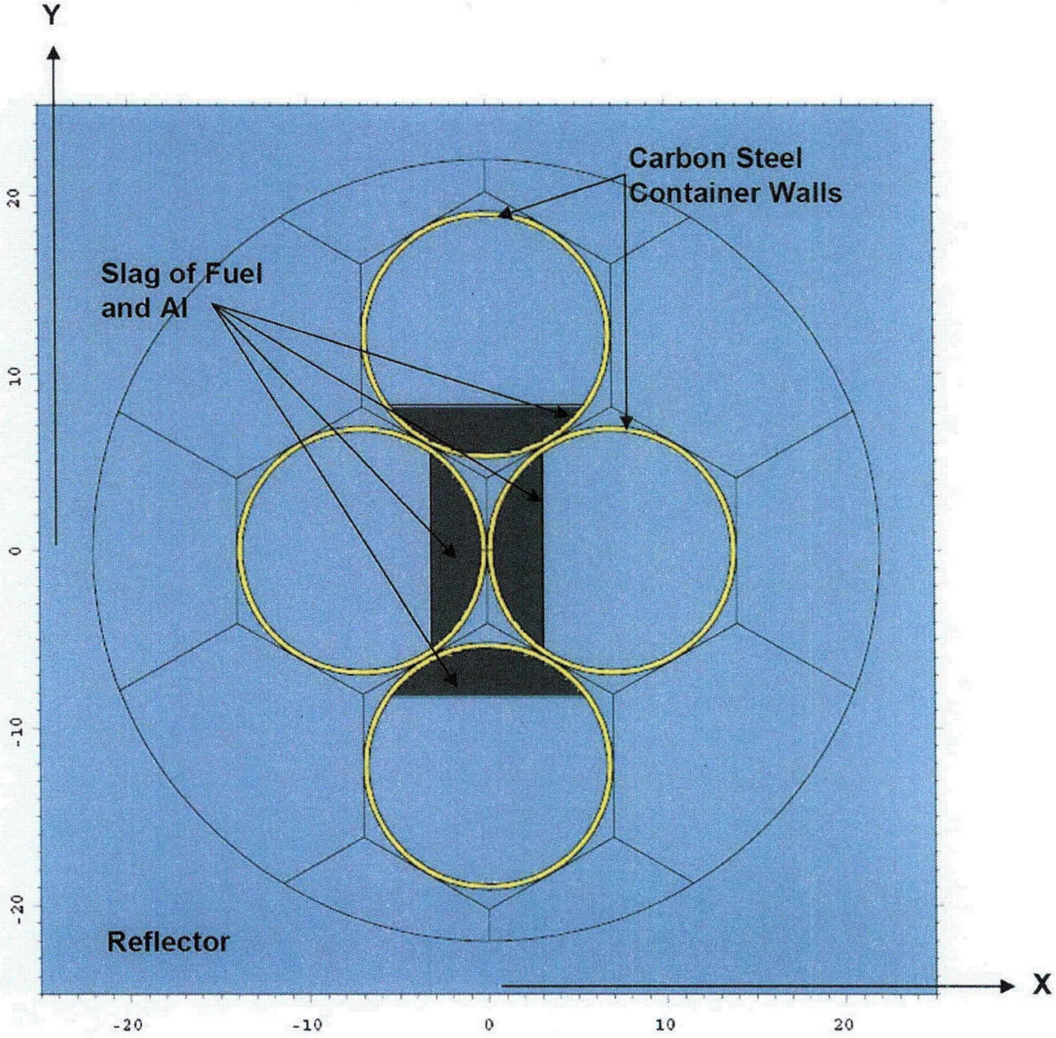

Figure 11. View along the axis of 4 ST Packages that are assumed to have melted in a horizontal position, later filled with water, and re-oriented such that the fissile material is closely packed. The pitch in this case is 14 cm.

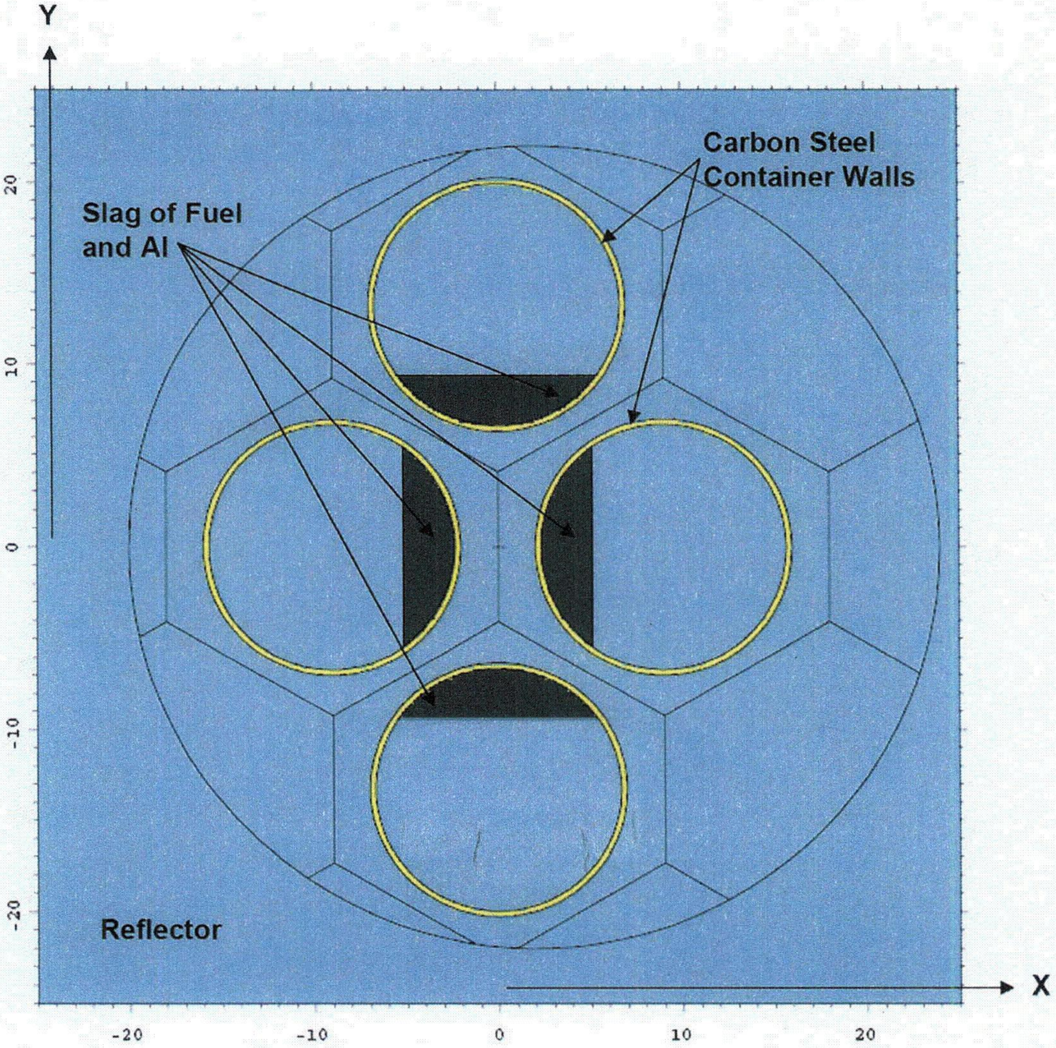

Figure 12. Most reactive case for the horizontal melt with no voids. Comparing this configuration to Figure 11, the irregular pitch (9 x 16) separates the packages centered on the x-axis (y = 0) and allows the optimum moderation between the packages for this case.

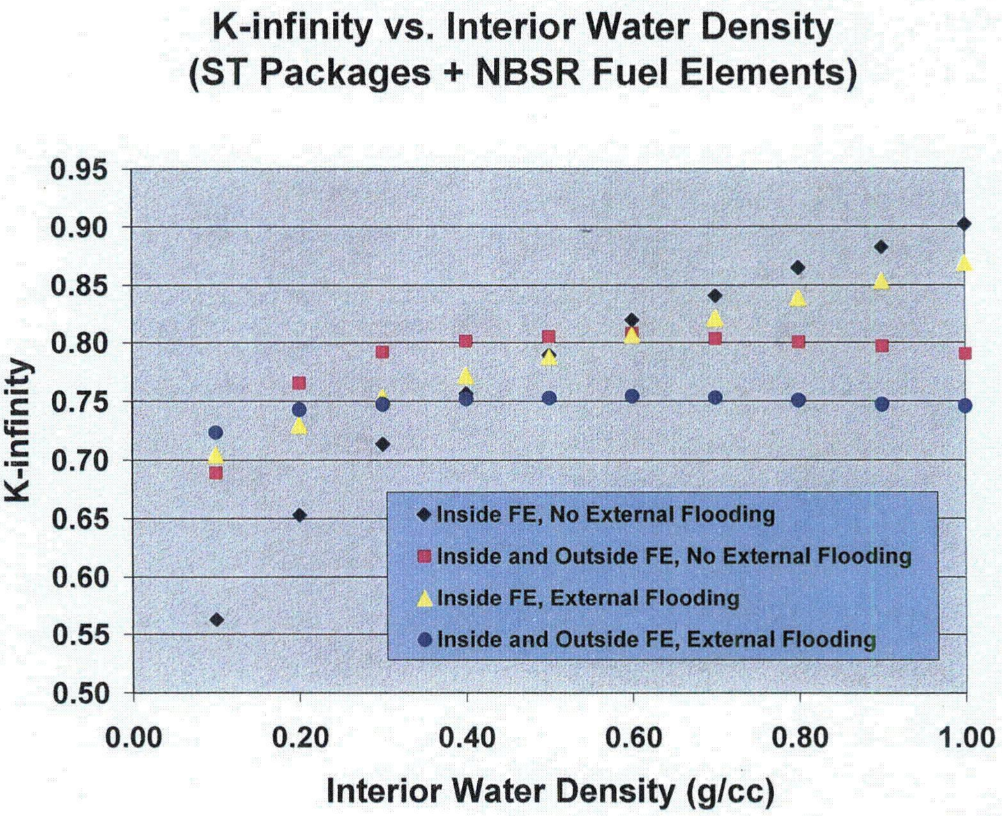

Figure 13. K-infinity (infinite number of packages) as a function of water density inside a partially flooded ST Package with and without external flooding.

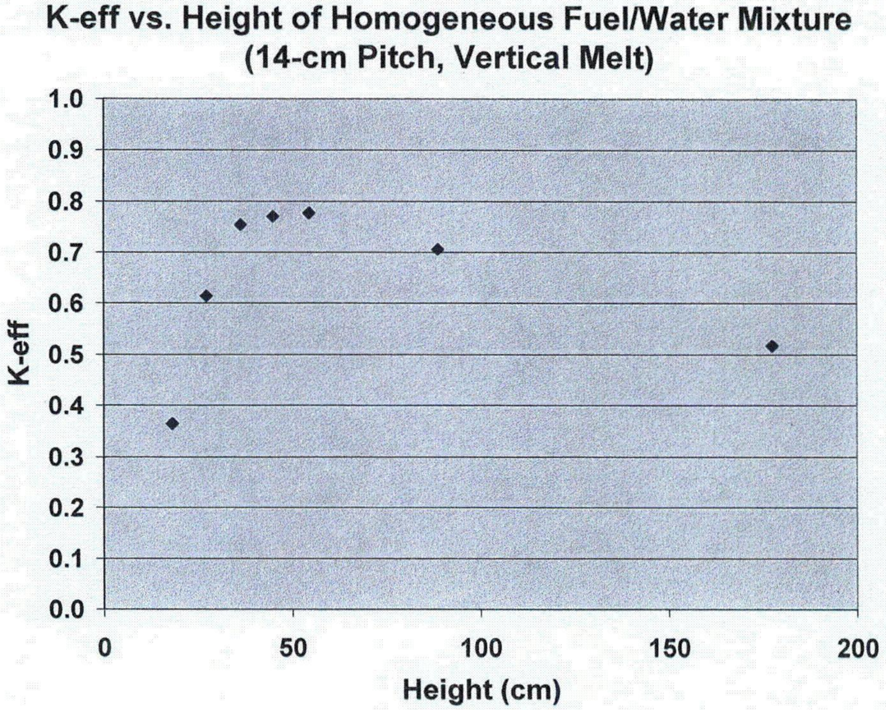

Figure 14. K_{eff} as a function of the height of the Al + U_3O_8 + H_2O mixtures resulting from vertical melting of an NBSR fuel element inside the ST Package.

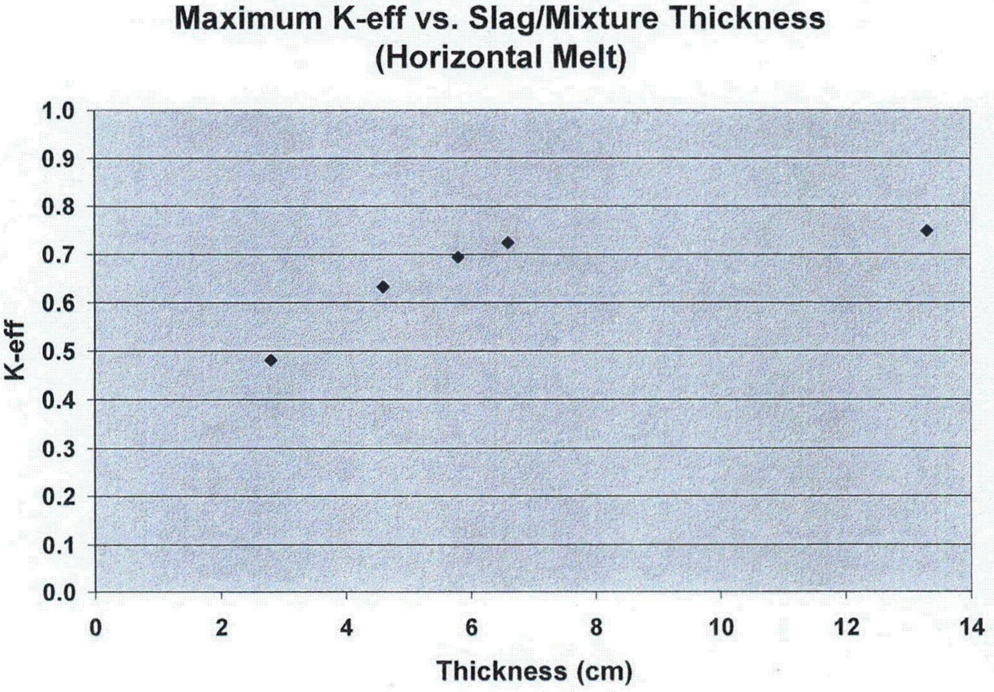

Figure 15. K_{eff} in the most reactive configuration as a function of the thickness of the Al + U_3O_8 + H_2O mixture resulting from horizontal melting.

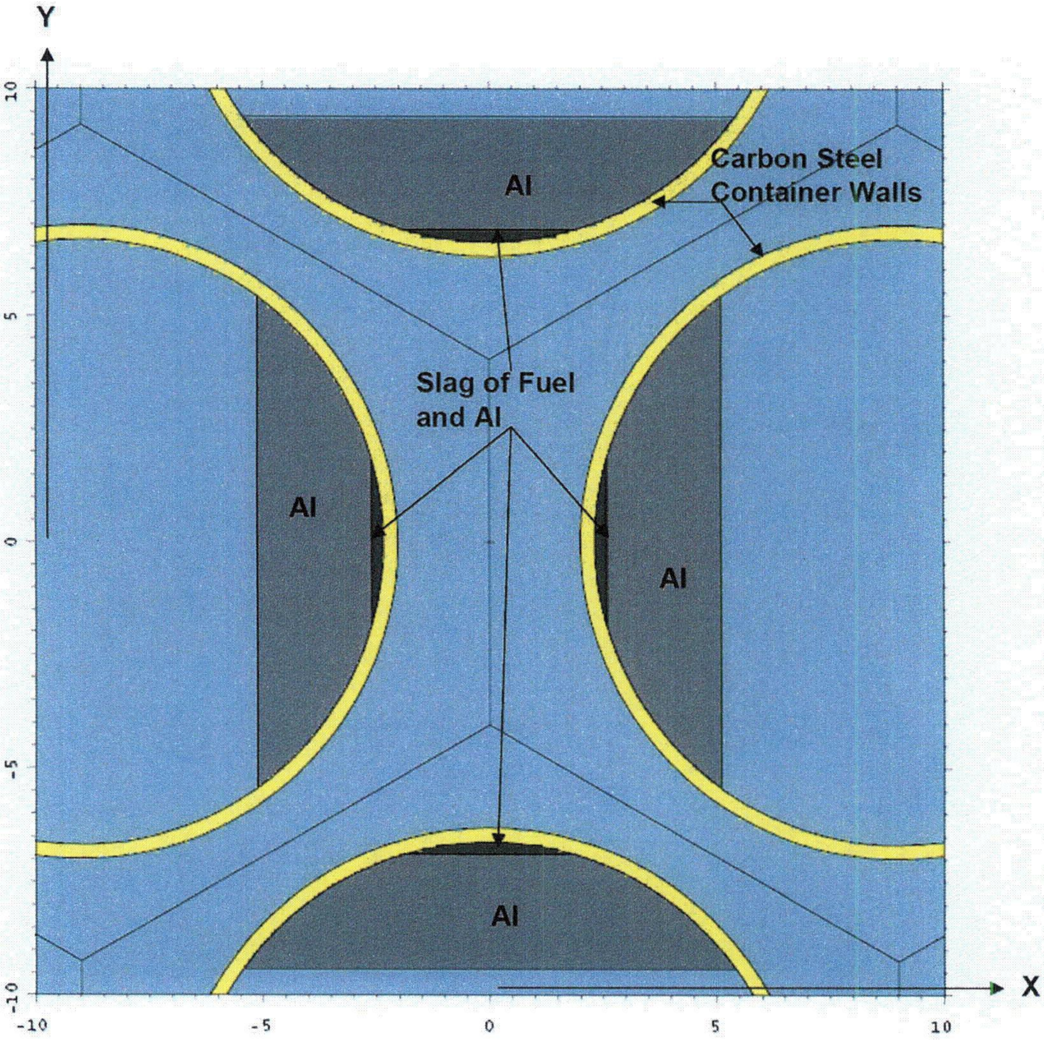

Figure 16. Horizontal melt in which the U_3O_8 is assumed to separate from the Al creating a thin 81-cm long puddle along the bottom. It is further assumed that the packages are later flooded and re-oriented into the most reactive geometry.

Appendix

Sample MCNP Input Files

1. stpac – One ST Package and NBSR Fuel Element plus H_2O reflector
2. stinf - Infinite array of ST Packages, 14-cm pitch
3. stmix14 – 4 ST Packages, vertical melt, Al+U_3O_8+H_2O slag, 36 cm
4. steq14 – 4 ST Packages, horizontal melt, 5.8-cm thickness

```
stpac:  k-eff ST Package, 1 FE, h2o present inside, outside FE, + reflector
c
1  3 -1.00   -10 -9  8 #(-6 -5 1)    imp:n=1
c  container cells:
2   1 -7.821    -6 -5 1 #(-7 -4 2)   imp:n=1
3   4 -0.45   -7 -4  954          imp:n=1
4   4 -0.45   -7 2  -955          imp:n=1
c
99  0        10:9:-8             imp:n=0  $ outside world
c
c  *************************************
c   FUEL ELEMENTS
2200  0 -940 939 -942 941 -922 920 imp:n=1 fill=200   $ Top Fuel Section
c
2230  3 -1.0000 -934 933 -946 945 -924 925 imp:n=1 u=200 lat=1 $ lat cell
              fill=-9:9 0:0 0:0 200 240 16r 200
c     ******* u=240  fuel plates  ******
2260 71  -3.612  -948 947 -950 949 -956 937 imp:n=1 u=240 $ vol=148
2300  2 -2.713  -936 935 #(-948 947 -950 949 -956 937) imp:n=1 u=240  $ clad
2330  3 -1.0000 -935  :  936          imp:n=1 u=240  $ d2o
c
1200  0 -940 939 -942 941 -921 923 imp:n=1 fill=100   $ Bottom Fuel Section
c
1230  3 -1.0000 -934 933 -946 945 -929 930 imp:n=1 u=100 lat=1 $ lat cell
              fill=-9:9 0:0 0:0 100 140 16r 100
c     ******* u=140  fuel plates  ******
1260 71  -3.612  -948 947 -950 949 -938 957 imp:n=1 u=140 $ vol=148, fuel meat
1300  2  -2.713  -936 935 #(-948 947 -950 949 -938 957) imp:n=1 u=140  $ clad
1330  3 -1.0000 -935  :  936          imp:n=1 u=140  $ d2o
c
1430  3 -1.0000 -940 939 -942 941 -923 955 imp:n=1     $ Entrance
1460  3 -1.0000 -940 939 -942 941 -920 921 imp:n=1     $ Center
1500  3 -1.0000 -940 939 -942 941 -3  922 imp:n=1    $ Chimney
1510  4 -0.45  -940 939 -942 941 -954  3 imp:n=1     $ top wood
c
1530  2 -2.713   -932 931 -928 927 -954  955
          #(-940 939 -942 941)   imp:n=1    $ FE box
1560  3 -1.0000 -7 -954 955 #(-932 931 -928 927 -954 955)
                              imp:n=1    $ outside FE
c  ****************************************************************
c   SURFACES:

c  container surfaces:
1  pz  -79.69
2  pz  -78.73
3  pz   93.38
4  pz   98.77
5  pz   99.41
c
6  cz  6.99
7  cz  6.67
c
c  reflector surfaces:
8  pz  -110.
9  pz   130.
10  cz   37.
c  surfaces for modified FE geom (8/31/02):
920  pz   7.62
921  pz  -7.62
922  pz  40.64
923  pz -40.64
924  pz  40.70
925  pz   7.50
927  px  -3.8964
928  px   3.8964
929  pz  -7.50
930  pz -40.70
c
```

```
931  py  -3.810
932  py  3.810
933  px  -0.2110
934  px   0.2110
935  px  -.0635
936  px   .0635
937  pz  8.890
938  pz -8.890
c
939   py  -3.3325
940   py   3.3325
941   px  -3.7313
942   px   3.7313
945   py  -3.40
946   py   3.40
947   px  -.0254
948   px   .0254
949   py  -3.067
950   py   3.067
c
956   pz 36.83
957   pz -36.83
954   pz   96.87  $ end of FE cells
955   pz  -67.62  $ bottom of FE
c

m71  92235  -3.367E-01     92238  -2.520E-02  $ 360 g U-235
     8016   -6.560E-02     13027  -5.725E-01
c
c  Al-6061 (10/12/02) rho=2.713 g/cc:
c     Mid-range concentrations of constituents:
m2    13027 -.9741   14000 -.0060   12000 -.010
      22000 -.0007   25055 -.0007
      24050 -8.70e-5   24052 -1.68e-3 $ .2 wt% Cr
      24053 -1.90e-4   24054 -4.72e-5
      26054 -2.05e-4   26056 -3.21e-3 $ .35 wt% Fe
      26057 -7.42e-5   26058 -9.80e-6
      29063 -2.08e-3   29065 -9.25e-4 $ .3 wt% Cu (.03 for Zn)
c
m3   8016   1 1001 2 $ H2O
mt3  lwtr.60t
c
c    plywood, 0.45 g/cc
m4    1001 1.671e-2  6012 1.003e-2   8016 8.357e-3 $ from NUREG-5661, p 35
mt4   lwtr.60t
c
c    carbon steel, 7.821 g/cc:
m1   6012 3.9250-3  26054 4.881-3  26056 7.661-2  26057 1.77-3  26058 2.355-4
c
f7:n  2260 1260
c
mode  n
c
sdef  x d1 y d2 z d3 erg d4
si1  -3.7 3.7
si2  -3.0 3.0
si3  -36.8 36.8
sp1   0 1
sp2   0 1
sp3   0 1
sp4  -3
c
kcode  2000 1 10 510
c
print  40 110 128 130 140 -160 -161 -162
c
```

```
stinf:  k-infinity for ST Package, 1 FE, h2o in FE, outside, reflector
c
1   3  -1.00    -301 302 -303 304 -305 306 -9  8 #(-6 -5 1)    imp:n=1
c   1   0     -301:302 -303 304 -305 306 -9  8 #(-6 -5 1)    imp:n=1
c   container cells:
2    1  -7.821     -6 -5 1 #(-7 -4 2)    imp:n=1
3    4  -0.45    -7  -4  954           imp:n=1
4    4  -0.45    -7 2   -955           imp:n=1
c
99    0        301:-302:303:-304:305:-306:9:-8  imp:n=0   $ outside world
c   *************************************
c    FUEL ELEMENTS
2200  0 -940 939 -942 941 -922 920 imp:n=1  fill=200    $ Top Fuel Section
c
2230   3  -1.000 -934 933 -946 945 -924 925 imp:n=1 u=200 lat=1 $ lat cell
                fill=-9:9 0:0 0:0  200 240 16r 200
c      ******* u=240   fuel plates   ******
2260  71  -3.612  -948 947 -950 949 -956 937 imp:n=1 u=240 $ vol=148
2300   2  -2.713  -936 935 #(-948 947 -950 949 -956 937) imp:n=1 u=240   $ clad
2330   3  -1.000 -935  :  936           imp:n=1 u=240   $ d2o
c
1200   0 -940 939 -942 941 -921 923 imp:n=1 fill=100    $ Bottom Fuel Section
c
1230   3  -1.000 -934 933 -946 945 -929 930 imp:n=1 u=100 lat=1 $ lat cell
                fill=-9:9 0:0 0:0  100 140 16r 100
c      ******* u=140   fuel plates   ******
1260  71  -3.612  -948 947 -950 949 -938 957 imp:n=1 u=140 $ vol=148, fuel meat
1300  2  -2.713  -936 935 #(-948 947 -950 949 -938 957) imp:n=1 u=140   $ clad
1330  3  -1.000 -935  :  936           imp:n=1 u=140   $ d2o
c
1430  3  -1.000 -940 939 -942 941 -923 955 imp:n=1      $ Entrance
1460  3  -1.000 -940 939 -942 941 -920 921 imp:n=1      $ Center
1500  3  -1.000 -940 939 -942 941 -3   922 imp:n=1     $ Chimney
1510  4  -0.45   -940 939 -942 941 -954   3 imp:n=1      $  top wood
c
1530  2  -2.713   -932 931 -928 927  -954  955
           #(-940 939 -942 941)    imp:n=1     $ FE box
1560 3 -1. -7 -954 955 #(-932 931 -928 927 -954 955) imp:n=1 $ outside FE
c     1560  0        -7 -954 955 #(-932 931 -928 927 -954 955) imp:n=1 $ outside FE
c    ******************************************************************
c    SURFACES:

c   container surfaces:
1   pz  -79.69
2   pz  -78.73
3   pz  93.38 $ fixed
4   pz  98.77
5   pz  99.41
c
6   cz  6.99
7   cz  6.67
c
c   reflector surfaces:
*8  pz  -80.
*9  pz  100.
c
301 -302   px  7.0  $ periodic with surf 302
302 -301   px -7.0
303 -304   p  1  1.7320508  0  14.0
304 -303   p  1  1.7320508  0 -14.0
305 -306   p -1  1.7320508  0  14.0
306 -305   p -1  1.7320508  0 -14.0
c
c   surfaces for modified FE geom (8/31/02):
920  pz  7.62
921  pz  -7.62
922  pz  40.64
923  pz -40.64
```

```
924  pz  40.70
925  pz   7.50
927  px  -3.8964
928  px   3.8964
929  pz  -7.50
930  pz -40.70
c
931  py  -3.810
932  py   3.810
933  px  -0.2110
934  px   0.2110
935  px  -.0635
936  px   .0635
937  pz  8.890
938  pz -8.890
c
939   py  -3.3325
940   py   3.3325
941   px  -3.7313
942   px   3.7313
945   py  -3.40
946   py   3.40
947   px  -.0254
948   px   .0254
949   py  -3.067
950   py   3.067
956   pz 36.83
957   pz -36.83
c
954   pz  96.87  $ end of FE cells
955   pz  -67.62  $ bottom of FE
c

m71   92235  -3.367E-01     92238  -2.520E-02  $ 360 g U-235
    8016   -6.560E-02     13027  -5.725E-01
c
c  Al-6061 (10/12/02) rho=2.713 g/cc:
c    Mid-range concentrations of constituents:
m2    13027 -.9741   14000 -.0060   12000 -.010
      22000 -.0007  25055 -.0007
      24050 -8.70e-5  24052 -1.68e-3 $ .2 wt% Cr
      24053 -1.90e-4  24054 -4.72e-5
      26054 -2.05e-4  26056 -3.21e-3 $ .35 wt% Fe
      26057 -7.42e-5  26058 -9.80e-6
      29063 -2.08e-3  29065 -9.25e-4 $ .3 wt% Cu (.03 for Zn)
c
m3   8016   1 1001 2 $ H2O
mt3  lwtr.60t
c
m9   8016   1 1001 2 $ H2O
mt9  lwtr.60t
c
c    plywood, 0.45 g/cc
m4    1001 1.671e-2   6012 1.003e-2   8016 8.357e-3 $ from NUREG-5661, p 35
mt4  lwtr.60t
c
c    carbon steel, NUREG-5661  7.821 g/cc:
m1   6012 3.9250-3  26054 4.881-3  26056 7.661-2  26057 1.77-3  26058 2.355-4
c
mode  n
c
c    source pts in centers
sdef  pos d1 erg d2
si1 l  0 0 -25  0 0 25
sp1   .5 r
sp2  -3
kcode  1000 1 10 510
print  40 110 128 130 140 -160 -161 -162
```

```
stmix14: 14-cm pitch, k-eff 4 ST Packages, un-even vertical melt + h2o
c
c      Al+u3o8 melts with 50% void, later filled w/ h2o
c
2  3  -1.00   -100 -99 98 #(-10 -9 8) imp:n=1   $ reflector
99  0           100:99:-98             imp:n=0  $ outside world
10   3  -1.0   -10 -9 8      imp:n=1 fill=99   $ "core"
c
1   3 -1.0 -301 302 -303 304 -305 306  lat=2 u=99 imp:n=1 fill=-4:2 -3:3 0:0
     99  99  99  99  99  99  99
       99  99  99  99  99  99  99
         99  99  99  99  70  99  99
           99  99  99  70  70  99  99
             99  99  99  70  99  99  99
               99  99  99  99  99  99  99
                 99  99  99  99  99  99  99
c
c   container cells:
11    1  -7.821     -6 -5 1 #(-7 -4 2) u=70    imp:n=1 $  container
12    3  -1.00      -7  3  -4         u=70    imp:n=1 $  h2o
13    5  -1.910     -7 -3  2          u=70    imp:n=1 $  Al+u3o8 slag + h2o
14    3  -1.00      -1:5:6            u=70    imp:n=1 $  h2o outside package
c    SURFACES:

c   container surfaces:
1  pz  -79.69
2  pz  -78.73
3  pz  -36.35  $ top of slag/h2o mix
4  pz   98.77
5  pz   99.41
6  cz  6.99
7  cz  6.67
c
c  core surfaces:
8   pz  -85.
9   pz  105.
10  c/z  -7 0   22.
c
98  pz  -110.
99  pz   130.
100  c/z -7 0   52.
c
301   px  7.0
302   px -7.0
303   p  1  1.7320508  0  14.0
304   p  1  1.7320508  0 -14.0
305   p -1  1.7320508  0  14.0
306   p -1  1.7320508  0 -14.0
c


c
m2    13027 1   $ Al
c
m3   8016   1 1001 2 $ H2O
mt3  lwtr.60t
c
c     slag of Al + u3o8 + h2o mix: @ 1.910 g/cc
m5    13027 -.6912  92235 -.0371  92238 -.0028   8016 -.2398  1001 -.0291
c
c    carbon steel, from NUREG-5661, rho = 7.821 g/cc:
m1   6012 3.9250-3  26054 4.881-3  26056 7.661-2  26057 1.77-3  26058 2.355-4
c
mode  n
c
f7:n   13
c
kcode  1000 1 10 510
c
print  40 110 128 130 140
```

```
c
c    source pts in centers
sdef  pos d1 erg d2
si1 l  0 0 -70  0 0 -80
sp1   .5 r
sp2   -3
c
```

```
steq14:  k-eff for ST Package, 4 FEs, uneven horizontal melt, vol=FE vol
c
c    u3o8 confined to middle 80 cm, extent of plates before melt, no gap
c    vol of center slag = vol of 81.2-cm section of FE, but homogeneous
c          mix with rho = 1.673
c
2  3  -1.00   -100 -99 98 #(-10 -9 8) imp:n=1   $ reflector
99  0         100:99:-98            imp:n=0   $ outside world
10    3  -1.0  -10 -9 8     imp:n=1 fill=99   $ "core"
c
1   3 -1.0 -301 302 -303 304 -305 306   lat=2 u=99 imp:n=1 fill=-4:2 -3:3 0:0
     99  99  99  99  99  99  99
       99  99  99  99  99  99  99
         99  99  99  99  71  99  99
           99  99  99  72  70  99  99
             99  99  99  73  99  99  99
               99  99  99  99  99  99  99
                 99  99  99  99  99  99  99
c
c   container cells:
11    1  -7.821    -6 -5 1 #(-7 -4 2) u=70    imp:n=1 $  container
12    3  -1.00     -7  2  -4  21 #13  u=70    imp:n=1 $  h2o
15    2  -2.70     -7  2  -4 -21 #13  u=70    imp:n=1 $  Al from box
13    5  -1.673    -7 15 -16 -11      u=70    imp:n=1 $  Al+u3o8 slag
14    3  -1.00     -1:5:6             u=70    imp:n=1 $  h2o outside package
c
21    1  -7.821    -6 -5 1 #(-7 -4 2) u=71    imp:n=1 $  container
22    3  -1.00     -7  2  -4 -22 #23  u=71    imp:n=1 $  h2o
25    2  -2.70     -7  2  -4  22 #23  u=71    imp:n=1 $  Al
23    5  -1.673    -7 15 -16  12      u=71    imp:n=1 $  Al+u3o8 slag
24    3  -1.00     -1:5:6             u=71    imp:n=1 $  h2o outside package
c
31    1  -7.821    -6 -5 1 #(-7 -4 2) u=72    imp:n=1 $  container
32    3  -1.00     -7  2  -4 -23 #33  u=72    imp:n=1 $  h2o
35    2  -2.70     -7  2  -4  23 #33  u=72    imp:n=1 $  Al
33    5  -1.673    -7 15 -16  13      u=72    imp:n=1 $  Al+u3o8 slag
34    3  -1.00     -1:5:6             u=72    imp:n=1 $  h2o outside package
c
41    1  -7.821    -6 -5 1 #(-7 -4 2) u=73    imp:n=1 $  container
42    3  -1.00     -7  2  -4  24 #43  u=73    imp:n=1 $  h2o
45    2  -2.70     -7  2  -4 -24 #43  u=73    imp:n=1 $  Al
43    5  -1.673    -7 15 -16 -14      u=73    imp:n=1 $  Al+u3o8 slag
44    3  -1.00     -1:5:6             u=73    imp:n=1 $  h2o outside package
c
c    SURFACES:

c    container surfaces:
1   pz  -79.69
2   pz  -78.73
4   pz   98.77
5   pz   99.41
c
6   cz  6.99
7   cz  6.67
c
21   px -5.04
22   py  5.04
23   px  5.04
24   py -5.04
c
11   px -0.865
12   py  0.865
13   px  0.865
14   py -0.865
c
15   pz -40.6
16   pz  40.6
c
```

```
c  core surfaces:
8   pz -85.
9   pz 105.
10  c/z -7 0  24.
c
c  reflector surfaces:
98  pz -110.
99  pz  130.
100 c/z -7 0  55.
c
301   px 7.0
302   px -7.0
303   p 1  1.7320508  0  14.0
304   p 1  1.7320508  0 -14.0
305   p -1  1.7320508  0  14.0
306   p -1  1.7320508  0 -14.0
c

c
m2   13027 1   $ Al
c
m3   8016   1 1001 2 $ H2O
mt3  lwtr.60t
c
m9   8016   1 1001 2 $ H2O
mt9  lwtr.60t
c
c    slag of Al + u3o8 + h2o @ 1.673 g/cc (mat from plates+box in middle):
m5   13027 -.5596  92235 -.0447  92238 -.0033   8016 -.3497  1001 -.0427
c
c    carbon steel, 7.821 g/cc:
m1   6012 3.9250-3  26054 4.881-3  26056 7.661-2  26057 1.77-3  26058 2.355-4
c
mode  n
c
f7:n  13 23 33 43
sd7   1  1  1  1
c
c    source pts in centers
sdef  pos d1 erg d2
si1 l  -5 0 -20  -5 0  20
sp1   .5 r
sp2  -3
c
kcode  1000 1 10 510
c
print  40 110 128 130 140 -160 -161 -162
c
```