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Nuclear Criticality Calculations for Canister-Based Facilities - DOE SNF

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NOTICE OF OPEN CHANGE DOCUMENTS - THIS DOCUMENT IS IMPACTED BY THE LISTED CHANGE DOCUMENTS AND CANNOT BE USED WITHOUT THEM.

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1) CACN-001, DATED 02/08/2008

Attachments	Total Number of Pages
Attachment 1: Materials Description	17
Attachment 2: Digital Video Disc Listing	1
Attachment 3: Digital Video Disc	N/A

RECORD OF REVISIONS

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DISCLAIMER

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ACRONYMS AND ABBREVIATIONS

Acronyms

Al-$GdPO_4$	Aluminum Gadolinium Phosphate
ATR	Advanced Test Reactor
BOL	Beginning Of Life
BSC	Bechtel SAIC Company, LLC
DHLW	Defense High Level Waste
DFA	Driver Fuel Assembly
DOE	Department of Energy
DVD	Digital Video Disc
EF	Enrico Fermi
EOL	End Of Life
FFTF	Fast Flux Test Facility
FSV	Fort St. Vrain
$GdPO_4$	Gadolinium Phosphate
HLW	High Level Waste
IHF	Initial Handling Facility
MCNP	Monte Carlo N-Particle
NSNFP	National Spent Nuclear Fuel Program
SNF	Spent Nuclear Fuel
SLWBR	Shippingport Light Water Breeder Reactor
SPWR	Shippingport Pressurized Water Reactor
TEV	Transport and Emplacement Vehicle
TMI	Three Mile Island
TRIGA	Training, Research, Isotope, General Atomics
USL	upper subcritical limit
UAl_x	Uranium Aluminide
WHF	Wet Handling Facility
WP	Waste Package

Abbreviations

˚C	degrees Celsius
cm^2	square centimeter
cm^3	cubic centimeters
cm	centimeter
ft	feet
g	grams
in.	inch
k_{eff}	effective neutron multiplication factor
Δk_{EROA}	penalty on the USL to account for extension of the range of applicability
kg	kilogram
L	liter
mg	milligram
mol	mole
nm	nanometer
wt.%	weight percent
yr	year

1. PURPOSE

The purpose of this calculation is to perform waste-form specific nuclear criticality safety calculations to aid in establishing criticality safety design criteria, and to identify design and process parameters that are potentially important to the criticality safety of Department of Energy (DOE) standardized Spent Nuclear Fuel (SNF) canisters.

It is intended that the results of the criticality safety calculations provided in this document will be used to support the criticality safety analysis of normal operations and off-normal conditions associated with the receipt, handling and loading of DOE SNF canisters into 5-DHLW/DOE SNF Waste Packages (WPs) in the surface facilities, in addition to the emplacement of loaded and sealed WPs in the sub-surface facility. With respect to surface facilities; it is noted that the Wet Handling Facility (WHF) and Initial Handling Facility (IHF) are specifically excluded from the scope of this calculation. Normally, DOE SNF canisters and WPs will not reside in the WHF and IHF.

The criticality safety calculations are performed according to a systematic analytical method (Section 6.2) to ensure that the configurations analyzed clearly bound those representative of normal conditions, and to provide assurance that sufficient information is available to establish trends and to determine control parameters and their limits for off-normal conditions. The calculation methodology (Section 6.2) employed for this analysis is completely independent of event sequence analyses, although the off-normal conditions examined may represent or bound potential end-states of category 1 and 2 event sequences. The main elements of the calculation method include:

1. *Simplification,* to reduce or eliminate reliance on design features (e.g. modeling an extensive range of close-fitting full thickness (i.e. 30 cm) reflectors to account for non-fissile materials situated outside the environs of the DOE SNF canisters and WPs);
2. *Conservatism,* to reduce or eliminate reliance on design parameters or variation in design parameter values (e.g. a variety of conservative modeling treatments are applied to the DOE SNF canister models); and
3. *Comprehensiveness,* to assure that an in-depth analysis is performed to completely characterize and establish the relative importance of the key aspects of each DOE SNF canister design.

1.1 SCOPE

The criticality safety calculations performed and recorded in this document are based solely on DOE standardized SNF canisters, High Level Waste (HLW) glass canisters and WPs. Design information related to the DOE SNF canister, HLW glass canister, and WP types included in the scope of this document is primarily obtained from Reference 2.2.1. All design information is referenced at the point of citation.

1.1.1 DOE SNF Canisters Evaluated

Due to the variety of DOE Environmental Management owned spent nuclear fuel, the National Spent Nuclear Fuel Program (NSNFP) has designated nine representative fuel groups for criticality analyses based on fuel matrix and primary fissile isotope (Ref. 2.2.29, Section 6.6). For each fuel group, a fuel type that represents the characteristics of the fuels in that group has been selected for detailed analysis. The nine fuel groups and the representative fuel types for criticality analysis are listed in Table 1-1. The scope of this calculation is limited to the first seven types and does not include the N-Reactor or Three Mile Island (TMI) SNF because they have been evaluated previously.

Table 1-1: Representative DOE SNF Fuel Groups for Criticality Analyses

Fuel Group	Representative Fuel Type
Mixed Oxide (MOX)	Fast Flux Test Facility (FFTF) Driver Fuel
Uranium-Zirconium Hydride (UZrH)	Training, Research, Isotope, General Atomics (TRIGA) Fuel
Mo and U-Zr Alloys	Enrico Fermi (EF) Fast Reactor Fuel
Highly Enriched Uranium (HEU) Oxide	Shippingport Pressurized Water Reactor (SPWR) Fuel
^{233}U/Th Oxide	Shippingport Light Water Breeder Reactor (SLWBR) Seed Assembly Fuel
HEU-Al	Advanced Test Reactor (ATR) Fuel
U/Th Carbide	Fort St. Vrain (FSV) Fuel
U Metal	N-Reactor Fuel
Low Enriched Uranium (LEU) Oxide	Three Mile Island (TMI) Unit 2 Fuel

1.1.2 High Level Waste (HLW) Glass Canisters Evaluated

Each loaded WP will contain a single standardized DOE SNF canister surrounded by five HLW canisters. The HLW canisters consist of two variants; a short (length) canister and a long (length) canister. Both variants are otherwise identical (e.g. have equivalent diameters).

The Savannah River Site high-level waste glass degraded composition (Attachment 1, Table A1-17) is used as the reference HLW glass composition for all calculations examined in this document.

1.1.3 DOE SNF Waste Packages Evaluated

The DOE SNF canisters and HLW glass canisters described in this document are to be packaged in WPs. The WPs comprise two variants; a short (length) WP and a long (length) WP. Both variants are otherwise identical (e.g. have the same internal structure).

1.1.4 Operations Evaluated

All of the DOE SNF canisters evaluated in this document are received hermetically sealed with a dry, intact, basket loaded with intact SNF. Operations associated with receipt, handling and loading of DOE SNF canisters into WPs in the surface facilities[1], in addition to the emplacement of loaded, sealed, WPs in the sub-surface facility, are not expected to alter these conditions.

1.1.4.1 Anticipated Surface Facility and Intra-site Operations

Operations conducted in the surface facilities[1] (which include intra-site operations) concern the receipt of DOE SNF canisters in transportation casks, their subsequent unloading, handling and staging, subsequent loading into WPs and transfer to the sub-surface facility for emplacement. These preparatory operations primarily entail:

- Receipt of DOE transportation casks containing DOE SNF canisters;
- Receipt of DOE transportation casks containing HLW canisters;
- Upending and removal of DOE transportation casks from their conveyance, including unbolting and removal of lids from casks;
- Transfer of DOE SNF canisters (individually) from their transportation cask to an awaiting WP or to a DOE canister staging rack position;
- Transfer of HLW canisters (individually) from their transportation cask to an awaiting WP or to a designated DOE canister staging rack position;
- Loading of a WP with one DOE SNF canister (placed into the center support tube of the WP) and five HLW canisters (placed into the surround positions);
- Installation and welding of the WP inner and outer lids; and
- Transfer of completed sealed WPs, using the Transport and Emplacement Vehicle (TEV), to the sub-surface facility.

1.1.4.2 Anticipated Sub-Surface Facility Operations

Operations conducted in the sub-surface facility concern the receipt of the TEV and subsequent unloading and placement of sealed WPs in the repository disposal drift.

[1] Note that the Wet Handling Facility (WHF) and Initial Handling Facility (IHF) are excluded from the scope of Surface Facilities in this criticality safety calculation. DOE SNF canisters and DOE SNF WPs are not expected to reside in either facility.

2. REFERENCES

This section details the references used in this calculation. The Document Input Reference system (DIRS) number is provided (within parenthesis) for each applicable reference.

2.1 PROCEDURES/DIRECTIVES

2.1.1 BSC 2007. Calculations and Analyses. EG-PRO-3DP-G04B-00037, Rev.10. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071018.0001.

2.1.2 BSC 2007. Preclosure Safety Analysis Process. LS-PRO-0201, Rev. 05. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071010.0021.

2.1.3 BSC 2007. Rev. 07, Software Management. IT-PRO-0011, Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20070905.0001.

2.1.4 BSC 2007. *Quality Management Directive*, QA-DIR-10, Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20070330.0001.

2.1.5 BSC 2007. *Qualification of Software*. IT-PRO-0012, Rev. 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20070319.0014.

2.1.6 BSC 2007. *Desktop Information for Using CalcTrac***.** EG-DSK-3013, Rev. 02., Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070516.0024.

2.2 DESIGN INPUTS

2.2.1 BSC (Bechtel SAIC Company) 2006. *Dimension and Material Specification Selection for Use in Criticality Analyses.* CAL-DSU-NU-000017 REV 0A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20060906.0004 (DIRS 177193).

2.2.2 Briesmeister, J.F., ed. 1997. *MCNP-A General Monte Carlo N-Particle Transport Code. LA-12625-M, Version 4B.* Los Alamos, New Mexico: Los Alamos National Laboratory. ACC: MOL.19980624.0328 (DIRS 103897).

2.2.3 CRWMS M&O 1998. *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code.* CSCI: 30033 V4B2LV. DI: 30033-2003, Rev. 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980622.0637 (DIRS 102836).

2.2.4 BSC (Bechtel SAIC Company) 2004. *Criticality Model.* CAL-DS0-NU-000003 REV 00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040913.0008; DOC.20050728.0007 (DIRS 168553).

2.2.5 Baum, E.M.; Knox, H.D.; and Miller, T.R. 2002. *Nuclides and Isotopes.* 16th edition. [Schenectady, New York]: Knolls Atomic Power Laboratory. TIC: 255130. (DIRS 175238).

2.2.6 NRC (U.S. Nuclear Regulatory Commission) 2000. *Standard Review Plan for Spent Fuel Dry Storage Facilities.* NUREG-1567. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 247929 (DIRS 149756).

2.2.7 Lide, D.R., ed. 2006. *CRC Handbook of Chemistry and Physics.* 87th Edition. Boca Raton, Florida: CRC Press. TIC: 258634 (DIRS 178081).

2.2.8 Gelest. 2004. Gelest Silicone Fluids: Stable, Inert Media. Morrisville, Pennsylvania: Gelest. TIC: 256122 (DIRS 169915).

2.2.9 Stout, R.B. and Leider, H.R., eds. 1991. *Preliminary Waste Form Characteristics Report*. Version 1.0. Livermore, California: Lawrence Livermore National Laboratory. ACC: MOL.19940726.0118 (DIRS 102813).

2.2.10 GS000308313211.001. Geochemistry of Repository Block. Submittal date: 03/27/2000 (DIRS 162015).

2.2.11 MCNP V. 4B2LV.2002. WINDOWS 2000.STN: 10437-4B2LV-00 (DIRS 163407).

2.2.12 BSC (Bechtel SAIC Company) 2007. *IED Geotechnical and Thermal Parameters*. 800-IED-MGR0-00401-000 Rev 00G. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070601.0020 (DIRS 179928).

2.2.13 Paige, B.E. 1969. *Description of Test Reactor Fuel Elements and Associated Behavior in Reprocessing*. CI-1152. Idaho Falls, Idaho: U.S. Atomic Energy Commission, Idaho Operations Office. ACC: MOL.20040303.0031 (DIRS 167978).

2.2.14 DOE (U.S. Department of Energy) 1999. *Fermi (U-Mo) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-035, Rev. 0. Washington, D.C.: U.S. Department of Energy. TIC: 242461. (DIRS 104110).

2.2.15 INEEL (Idaho National Engineering and Environmental Laboratory) 2002. *FFTF (MOX) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-032, Rev. 1. Idaho Falls, Idaho: U.S. Department of Energy, Idaho National Operations Office. TIC: 252933. (DIRS 158820).

2.2.16 Taylor, L.L. 2001. *Fort Saint Vrain HTGR (Th/U Carbide) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-060, Rev. 0. [Washington, D.C.]: U.S. Department of Energy, Office of Environmental Management. TIC: 249783. ACC: DOC.20030905.0002. (DIRS 154726).

2.2.17 DOE (U.S. Department of Energy) 1999. *Shippingport LWBR (Th/U Oxide) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-051, Rev. 0. Washington, D.C.: U.S. Department of Energy, Office of Environmental Management. TIC: 245631. ACC: DOC.20030905.0016. (DIRS 105007).

2.2.18 CRWMS M&O 2000. *Intact and Degraded Criticality Calculations for the Codisposal of Shippingport LWBR Spent Nuclear Fuel in a Waste Package*. CAL-EDC-NU-000004 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000922.0093. (DIRS 151722).

2.2.19 DOE (U.S. Department of Energy) 1999. *Shippingport PWR (HEU Oxide) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-040, Rev. 0. Washington, D.C.: U.S. Department of Energy. TIC: 243528. (DIRS 104940).

2.2.20 Olson, G.L.; McCardell, R.K.; and Illum, D.B. 2002. *Fuel Summary Report: Shippingport Light Water Breeder Reactor*. INEEL/EXT-98-00799, Rev. 2. Idaho Falls, Idaho: Idaho National Engineering and Environmental Laboratory. ACC: MOL.20041005.0233. (DIRS 171913).

2.2.21 Windes, W.E. and Sterbentz, J.W. 1999. *Shippingport PWR Core 2 Fuel Summary Report*. INEEL/EXT-99-00263. Idaho Falls, Idaho: Idaho National Engineering and Environmental Laboratory. TIC: 243736. (DIRS 126085).

2.2.22 DOE (U.S. Department of Energy) 1999. *TRIGA (UZrH) Fuel Characteristics for Disposal Criticality Analysis*. DOE/SNF/REP-048, Rev. 0. Washington, D.C.: U.S. Department of Energy. TIC: 244162. (DIRS 103891).

2.2.23 DOE (U.S. Department of Energy) 2006. *Design Considerations for the Standardized DOE SNF Canister Internals*. DOE/SNF/DSN-019, Rev. 0. Idaho Falls, Idaho: U.S. Department of Energy, Idaho Operations Office. ACC: LLR.20070402.0002. (DIRS 179793).

2.2.24 Inco Alloys International 1988. Product Handbook. Huntington, West Virginia: Inco Alloys International. TIC: 239397. (DIRS 130835).

2.2.25 ASM (American Society for Metals) 1961. "Properties and Selection of Metals." Volume 1 of *Metals Handbook*. 8th Edition. Lyman, T.; ed. Metals Park, Ohio: American Society for Metals. TIC: 257281. (DIRS 170284).

2.2.26 ASM International. 1990. *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*. Volume 2 of *ASM Handbook*. Formerly Tenth Edition, Metals Handbook. 5th Printing 1998. [Materials Park, Ohio]: ASM International. TIC: 241059. (DIRS 141615).

2.2.27 Taylor, L.L. 2005. *Using Fuel Parameters to Predict DOE SNF Canister Loadings*. EDF-NSNF-046, Rev. 0. [Washington, D.C.]: U.S. Department of Energy, National Spent Nuclear Fuel Program. ACC: LLR.20070515.0108. (DIRS 180657).

2.2.28 BSC 2007. *Preclosure Criticality Analysis Process Report*. TDR-DS0-NU-000001, Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20071023.0011 (DIRS 182214).

2.2.29 DOE (U.S. Department of Energy) 2000. *DOE Spent Nuclear Fuel Grouping in Support of Criticality, DBE, TSPA-LA*. DOE/SNF/REP-046, Rev. 0. Idaho Falls, Idaho: U.S. Department of Energy, Idaho Operations Office. ACC: DOC.20030905.0021. (DIRS 118968).

It is also noted that References 2.2.13, 2.2.20, 2.2.21 and 2.2.23 are "inputs from outside sources". These references provide design information for the ATR, SLWBR and SPWR fuel, and the TRIGA fuel basket. The information used from these references is suitable for the intended use in this document because the data is considered the most authoritative data available, and the safety limits established in this document are considered insensitive to the exact values used.

2.3 DESIGN CONSTRAINTS

None.

2.4 DESIGN OUTPUTS

2.4.1 Preclosure Criticality Safety Analysis.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 Upper Subcritical Limit

Assumption: The Upper Subcritical Limit (USL) for all calculations reported in this document is assumed to be 0.88, which includes a 0.05 administrative margin.

Rationale: The largest bias and uncertainty for benchmarks applicable to the DOE SNF configurations examined in this document, as summarized in Table 5 of the Criticality Model (Reference 2.2.4), is 0.048 (based on degraded moderated UO_2 solutions). Range of applicability extension to cover the range of parameters for all normal and potential off-normal conditions may necessitate the use of additional benchmarks or the establishment of a penalty on the USL (Δk_{EROA}) to account for extension of the range of applicability. The extension of the range of applicability is not expected to result in a bias and uncertainty larger than 0.07.

Use: This assumption applies to the results and conclusions of all calculations described in this document.

Confirmation Status: This assumption requires confirmation by analysis and is tracked via CalcTrac (Reference 2.1.6).

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Depleted Uranium Composition

Assumption: Depleted uranium metal is modeled as naturally enriched uranium metal.

Rationale: Depleted uranium metal may be used as a radiation shield associated with transportation casks or the TEV. The depleted uranium associated with these shields (if present) would, by definition, have a ^{235}U content less than what is found naturally. The exact content, however, may vary depending on source. Therefore, for the purpose of this calculation, the ^{235}U content is conservatively set to that found in naturally occurring uranium with the balance being ^{238}U. From a criticality safety perspective, this is conservative because it assumes the presence of additional fissile material (used as a reflector in this assessment) than would be present in practice.

According to *Nuclides and Isotopes* (Ref. 2.2.5, pg. 70), the ^{235}U abundance in natural uranium is 0.72 atom percent. The balance (i.e. ^{238}U) represents 99.28 atom percent.

Use in the Calculation: The natural uranium isotopic content of ^{235}U is used to define the composition of depleted uranium which is used as a reflector in the criticality safety analysis (Attachment 1, Table A1-15).

3.2.2 Barium Cross Section Substitution

Assumption: Since the ^{137}Ba cross section libraries are unavailable, it is assumed that representing the ^{137}Ba material composition in Savannah River Site High-Level Waste Glass as ^{138}Ba maintains similar neutronic characteristics.

Rationale: The rationale for this assumption is that the thermal neutron capture cross-section and resonance integral of ^{137}Ba (Ref. 2.2.5, pg. 56) are greater than the thermal neutron capture cross-section and the resonance integral of ^{137}Ba (Ref. 2.2.5, pg. 56), which results in less parasitic neutron capture, and is therefore conservative with respect to criticality safety evaluations.

Use in the Calculation: This assumption is used in Attachment 1, Table A1-17.

3.2.3 Hydraulic Fluid Composition

Assumption: It is assumed that the hydraulic fluid considered as an alternative moderator material in this calculation is a conventional silicone fluid (polysiloxane fluid) with a viscosity of 10 cSt with a degree of polymerization of four (which is necessary for a viscosity of 10 cSt at 25°C (Ref. 2.2.8, p.11).

Rationale: The basis for this assumption is that polysiloxane fluid is a common silicone-based hydraulic fluid (Ref. 2.2.8, p. 7), and is therefore representative for the purpose of evaluating the moderating effectiveness of hydraulic fluid in this calculation.

Use in the Calculation: This assumption is used in Section 7.1.2.1.1.3 and Attachment 1, Table A1-25.

3.2.4 Zinc Cross Section Substitution

Assumption: Since the zinc cross section libraries are unavailable, it is assumed that representing the zinc material composition in the Savannah River Site High-Level Waste Glass material specification as aluminum maintains similar neutronic characteristics.

Rationale: The rationale for this assumption is that the thermal neutron absorption cross-section and resonance integral for these two elements are sufficiently similar and very small (0.230 barns, 0.17 barns for Al, and 1.1 barns, 2.8 barns for Zn) (Ref. 2.2.5, pg. 42 and 48), with Al being slightly less than Zn which is conservative for eigenvalue calculations. In addition, Zn is present in only trace quantities (Attachment 1, Table A1-17) and therefore the reaction rate impact on the system would be negligible in terms of neutron spectrum influence.

Use in the Calculation: This assumption is used in Attachment 1, Table A1-17.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation is prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1) and LS-PRO-0201, *Preclosure Safety Analysis Process* (Ref. 2.1.2). Therefore, the approved record version has a quality assurance designation of 'QA:QA'. This calculation is subject to the *Quality Management Directive* (QMD) (Ref. 2.1.4).

4.2 USE OF SOFTWARE

4.2.1 MCNP

The base-lined Monte Carlo N-Particle (MCNP) code (Ref. 2.2.11) is used to calculate the effective neutron multiplication factor (k_{eff}) of the configurations of DOE SNF canisters, HLW canisters and WPs. The MCNP software specification is as follows:

- Software Title: MCNP
- Version/Revision Number: Version 4B2LV
- Status/Operating System: Qualified/Microsoft Windows 2000 Service Pack 4
- Software Tracking Number: 10437-4B2LV-00 (Computer Software Configuration Item Number)
- Computer Type: Dell OPTIPLEX GX260 Workstations

The input and output files for the MCNP calculations are contained on a Digital Video Disc (DVD) attachment to this calculation report (Attachment 3), as detailed in Attachment 2. The MCNP software has been validated as being appropriate for use in modeling a range of radiation transport problems as documented in *Software Qualification Report for MCNP Version 4B2, A General Monte Carlo N-Particle Transport Code* (Ref. 2.2.3). The range of validated problems includes cases where MCNP is used to determine k_{eff} of systems containing fissile material. The use of MCNP in determining k_{eff} values is further documented in Reference 2.2.2. The MCNP software was obtained from Software Configuration Management in accordance with the appropriate procedure IT-PRO-0011, *Software Management* (Ref. 2.1.3).

The software qualification report (Reference 2.2.3) was performed prior to the effective date of IT-PRO-0012, *Qualification of Software* (Reference 2.1.5), however, MCNP Version 4B2 was qualified software in the centralized baseline as of the effective date of IT-PRO-0012 and is therefore considered acceptable and part of the established software baseline available for level 1 usage (Paragraph 1.2.3 of Reference 2.1.5).

4.2.2 EXCEL

- Software Title: Excel
- Version/Revision number: Microsoft® Excel 2003 SP-2 (on an OPTIPLEX GX620 Workstation)
- Computer Environment for Microsoft® Excel 2003: Software is installed on a DELL OPTIPLEX GX620 personal computer, running Microsoft Windows XP Professional, Version 2002, Service Pack 2.

Microsoft Excel for Windows is used in calculations and analyses to process the results of the MCNP calculations, using standard mathematical expressions and operations. It is also used to tabulate and chart the MCNP results. The user-defined formulas, inputs, and results are documented in sufficient detail to allow an independent repetition of computations. Thus, Microsoft Excel is used only as a worksheet and not as a software routine. The use of Excel in the calculation constitutes Level 2 software usage, which does not require qualification (Ref. 2.1.3, Attachment 12).

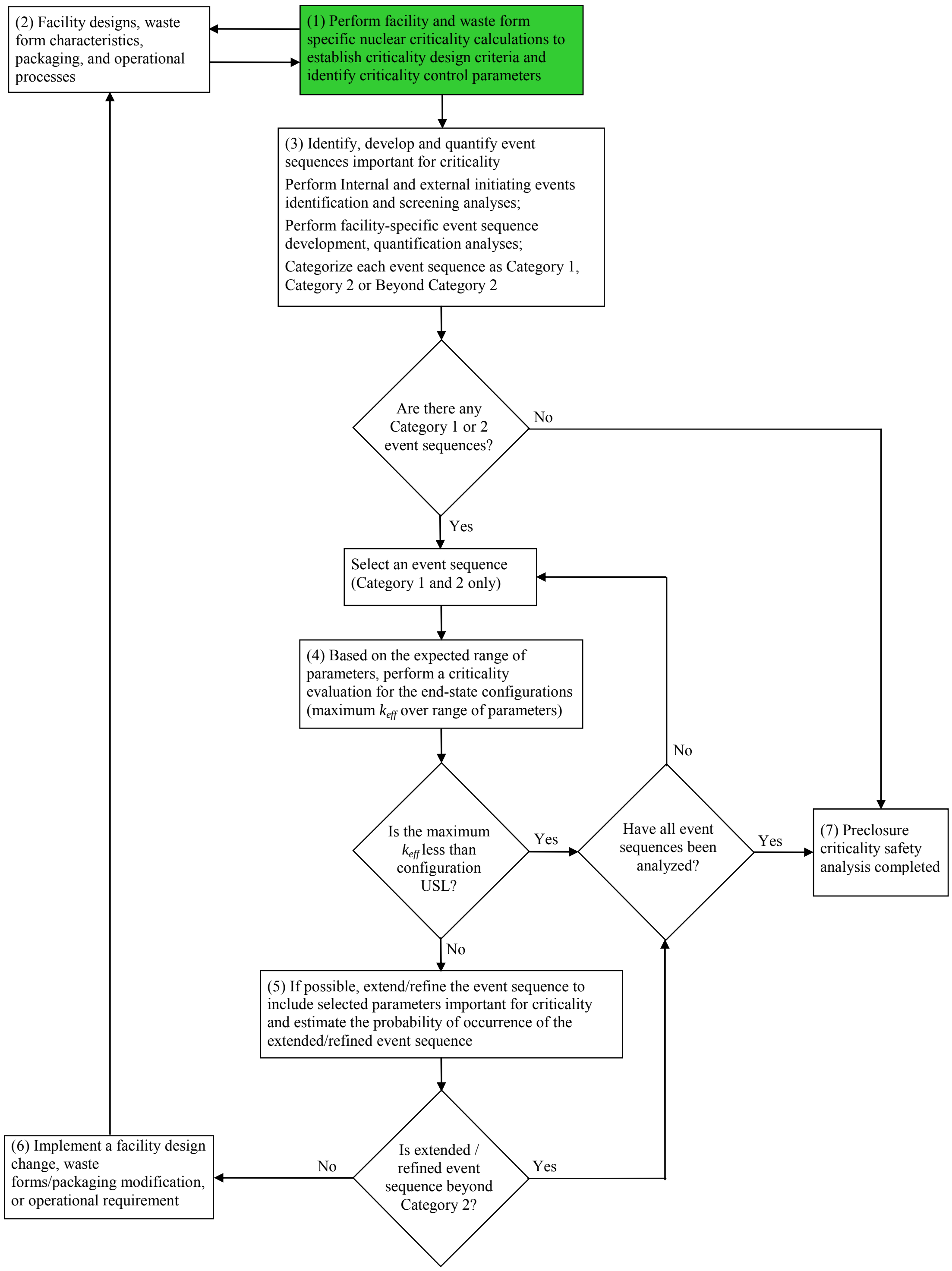
The Microsoft Excel spreadsheets generated for the calculations developed in support of this document are provided in Microsoft Excel workbooks (suffixed ".xls") included on the DVD of Attachment 3. The Excel calculations and graphical presentations were verified by hand calculations and visual inspection.

4.3 ANALYSIS PROCESS

This calculation is performed in accordance with the criticality safety analysis process described in the *Preclosure Criticality Analysis Process Report* (Reference 2.2.28, Figure 3-1). The key elements of the criticality safety analysis process are detailed in Figure 4-1. The calculations reported in this document specifically address function (1), highlighted in Figure 4-1. This is accomplished by determining the k_{eff} of DOE SNF canisters and loaded WPs, under normal and potential off-normal conditions. The results of the calculations are used to establish criticality safety design criteria, and to identify design and process parameters that are important to the criticality safety in all surface and sub-surface facilities, with the exception of the WHF and IHF.

For all calculations documented, a prescriptive method (Section 6.3) has been applied to ensure that the configurations analyzed clearly bound those representative of normal conditions, and provide sufficient information to establish trends and to determine control parameters and their limits for off-normal conditions.

A significant number of the k_{eff} calculations documented pertain to the examination of off-normal conditions. For these cases, the analysis approach is to comprehensively characterize the system behavior and response to changes in important parameters, such as geometry, moderation and neutron absorber. This systematic approach results in a very large parametric study but is important in that it affords an in-depth understanding of the system behavior and sensitivity to single and multi-parameter perturbations, that is not achieved with a case-specific end-state evaluation.



Source: Ref. 2.2.28, Figure 3-1

Figure 4-1: Preclosure Criticality Safety Process Flow Diagram

5. LIST OF ATTACHMENTS

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1	Materials Description	17
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6. BODY OF CALCULATION

This section provides a detailed description of the DOE SNF waste forms examined, describes their representation in the criticality safety models, and details the specific MCNP calculations undertaken to provide an understanding of system behavior and to identify potential limits. The following structure is used:

- Section 6.1 summarizes the design of the DOE SNF canisters and WPs examined, and details their explicit representation in the MCNP calculation models; and
- Section 6.2 describes the calculations performed to bound normal conditions and details the approach used to establish the conditions under which the examined waste forms remain safely subcritical under potential off-normal conditions.

6.1 DOE SNF WASTE FORM, CANISTER AND WASTE PACKAGE DESCRIPTION

This section provides physical descriptions of the DOE SNF canisters and WPs containing the various DOE SNF waste forms and HLW glass included in the scope of this document (Section 1.1.1). The physical descriptions include geometry data and material listings, which are used to construct the base-case MCNP models (also described in this section). The compositions of SNF materials (which are specific to the each DOE SNF canister) are provided in this section. However, the compositions of generic materials (e.g. canister structure, WP and reflector materials) are provided in Attachment 1.

This section is structured as follows:

- Section 6.1.1 describes the two **DOE WP variants**; i.e. the short WP and long WP, and details their explicit representation in the MCNP calculation models.
- Section 6.1.2 describes the two **DOE SNF canister variants**; i.e. the short canister and long canister, and details their explicit representation in the MCNP calculation models.
- Section 6.1.3 describes the seven **DOE SNF/canister basket variants** examined, and details their explicit representation in the MCNP calculation models.
- Section 6.1.4 describes the two **HLW glass canister variants**; i.e. the short canister and long canister, and details their explicit representation in the MCNP calculation models.

The design information provided in the following sub-sections (6.1.1 through 6.1.4) is based on the reference documents cited. However, minor modeling simplifications have been adopted in the base-case MCNP models to provide model conservatism and to reduce the complexity of neutronically unimportant regions. For example, minor features of the DOE SNF canister WP (e.g. the spread ring and interface ring associated with the WP lids) are neglected in the base-case MCNP models to reduce the model complexity of neutronically unimportant regions. More pronounced deviations between the base-case MCNP models and the cited design information exist for the ATR, FFTF and TRIGA DOE SNF canisters on account of continuing evolution of the DOE SNF canister designs (ATR and TRIGA), and to bound canister over-loading scenarios (FFTF). Specifically:

- The ATR DOE SNF canister examined in the MCNP calculations is based on a long DOE SNF canister with a tri-level basket structure accommodating a total of thirty (30)

ATR SNF elements. Earlier designs were based on a short DOE SNF canister accommodating a total of twenty (20) ATR SNF elements.

- The FFTF DOE SNF canister MCNP model features five (5) DFAs in addition to a Ident-69 container, whereas the current intent is to only load a FFTF DOE SNF canister with a maximum of four (4) DFAs in positions outside the basket center-tube.
- The TRIGA DOE SNF canister examined in the MCNP calculations is based on a basket structure with positions for thirty-one (31) fuel elements, compared with the thirty-seven (37) fuel elements associated with earlier designs.

Each DOE SNF waste form has a unique basket configuration that fits into one of two DOE SNF canisters (Long or Short). Each canister variant is positioned in the center support tube of a compatible WP (i.e. Long or Short) and is surrounded by five HLW glass pour canisters. The DOE SNF, canister and WP combinations are detailed in Table 6-1.

Table 6-1: DOE SNF, Canister, and Waste Package Combinations

DOE SNF	Canister/Container	Waste Package
ATR	DOE Long	DOE Long
EF	DOE Short	DOE Short
FFTF	DOE Long	DOE Long
FSV	DOE Long	DOE Long
SLWBR	DOE Long	DOE Long
SPWR	DOE Long	DOE Long
TRIGA	DOE Short	DOE Short

6.1.1 5 DHLW/DOE SNF WP Variants

6.1.1.1 Long WP

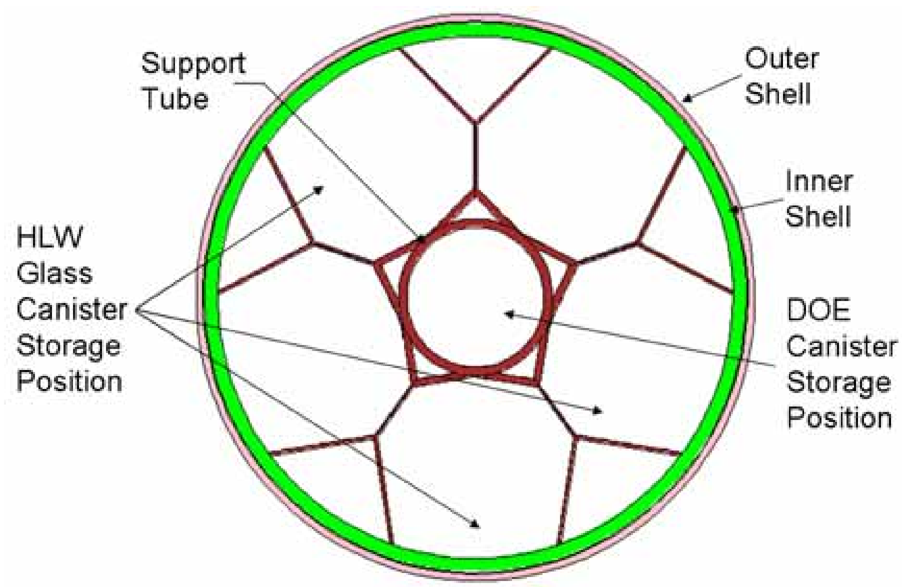
The DOE SNF Long WP contains five high-level waste glass pour canisters spaced radially around an 18” diameter standardized DOE SNF canister (Ref. 2.2.1, Section 6).

The DOE SNF canister is placed in a centralized carbon steel support tube. The support tube is held in place by carbon steel support plates that form five emplacement positions for the high-level waste glass pour canisters, in an equally spaced arrangement surrounding the center support tube. A summary of pertinent dimensions and material specifications (obtained from Reference 2.2.1) is provided in Table 6-2. A Radial cross-section plot of the MCNP model of the Long WP are provided in Figure 6-1.

Table 6-2: 5-DHLW/DOE SNF Long Waste Package

Component	Material	Parameter	Dimension (cm)
Outer Shell	Alloy 22 (UNS N06022)	Outer diameter	~204.47
		Inner diameter	~199.39
		Total length	~505.94
Inner Shell	SA-240 S31600	Outer diameter	~198.44
		Inner diameter	~188.28
		Inner cavity length	~461.96
Divider Plate Tube / Divider Plate	SA-516 K02700	Length	~460.69
		Thickness	~3.18 (tube) / ~1.27 (plate)

Source: Ref. 2.2.1, Table 23.



Source: Original

Figure 6-1: Radial Cross-section of the 5-DHLW/DOE SNF DOE Short/Long Waste Package MCNP Model (Fuel and HLW Glass Canisters omitted for clarity)

6.1.1.2 Short WP

The 5-DHLW/DOE SNF short WP and its internal structures are essentially the same as the long waste package described in Section 6.1.1.1 except that it is shorter (345.28 cm total length) to accommodate the 10 ft. SNF canister. The waste package contains five short HLW glass pour canisters spaced radially around an 18” diameter standardized DOE SNF canister (short). A summary of pertinent dimensions and material specifications (obtained from Reference 2.2.1) is provided in Table 6-3.

Table 6-3. 5-DHLW/DOE SNF Short Waste Package Description

Component	Material	Parameter	Dimension (cm)
Outer Barrier	Alloy 22 (UNS N06022)	Outer diameter	~204.47
		Inner diameter	~199.39
		Total length	~345.28
Inner Vessel	SA-240 S31600	Outer diameter	~198.44
		Inner diameter	~188.28
		Inner cavity length	~301.31
Divider Plate Tube/ Divider Plate	SA-516 K02700	Length	~300.04
		Thickness	~3.18 (tube) / ~1.27 (plate)

Source: Ref. 2.2.1, Table 22.

6.1.2 DOE SNF Canister Variants

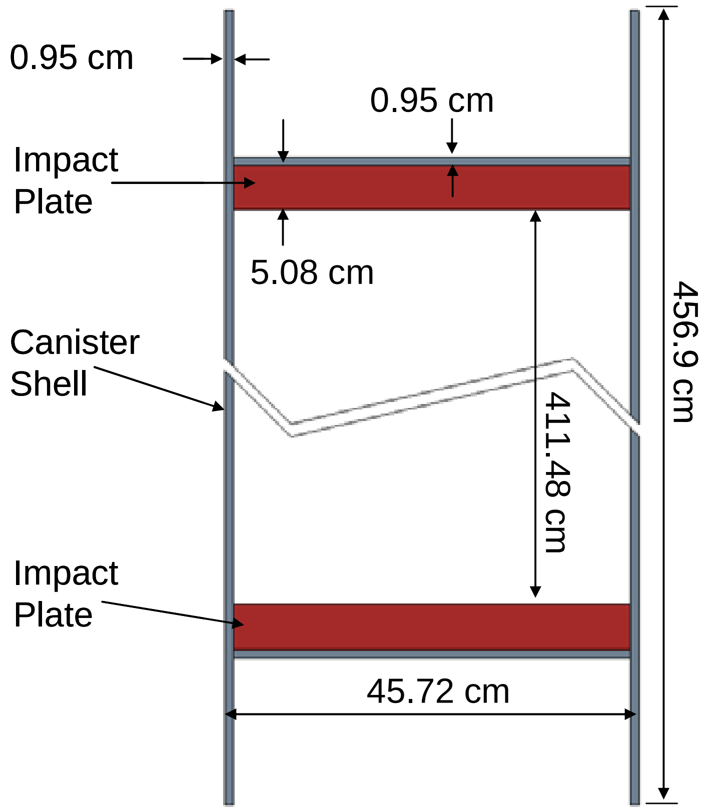
6.1.2.1 Long Canister

The DOE SNF Long canister is a right circular cylinder made of stainless steel. A summary of pertinent dimensions and material specifications for the DOE SNF Long canister is provided in Table 6-4 (obtained from Reference 2.2.1). An axial cross-section plot of the MCNP model of the DOE SNF Long canister is provided in Figure 6-2. Note that the dished heads of the canister are modeled as simple flat ends. Also note that the curved impact plates are modeled as simple flat circular plates at the maximum nominal thickness.

Table 6-4. DOE SNF Long Canister

Component	Material	Parameter	Dimension (cm)
Canister Shell	SA-312 SS 316L	Outer length	~457.0 (max)
		Interior cavity length (Inside of Impact Plates)	~411.48 (min)
		Nominal outer diameter	~45.72 (18.00 in.)
		Wall Thickness	~0.95 ($^3/_8$ in.)
Heads	SA-240 SS 316L	Thickness	~0.95 ($^3/_8$ in.)
Impact plates	Carbon Steel	Outer diameter	~43
		Thickness	Curved, varies from 1.20 to 5.08 (2.00 in.) (Modeled as 5.08)

Source: Ref. 2.2.1, Table 25.



Source: Original

Figure 6-2: Axial Cross-section of the DOE SNF Long Canister MCNP Model (Internal Structure omitted for clarity)

6.1.2.2 Short Canister

The DOE SNF Short canister is essentially the same as the DOE SNF Long canister described in Section 6.1.2.1, except that it is shorter (i.e. 10 ft. as opposed to 15 ft.). A summary of pertinent dimensions and material specifications for the DOE SNF Short canister is provided in Table 6-5 (obtained from Reference 2.2.1).

Table 6-5. DOE Standardized SNF Short Canister Design Parameters

Component	Material	Parameter	Dimension (cm)
Canister Shell	SA-312 SS 316L	Outer length, short canister	~300.0 (max)
		Interior cavity length, short canister	~254.0 (min)
		Nominal outer diameter	45.72 (18.00 in.)
		Wall Thickness	~0.95 ($^3/_8$ in.)
Heads	SA-240 SS 316L	Thickness	~0.95 ($^3/_8$ in.)
Impact plates	Carbon Steel	Outer diameter	~43
		Thickness	Curved, varies from 0.9 to 5.08 mm (2.00 in.) (Modeled as 5.08)

Source: Ref. 2.2.1, Table 25.

6.1.3 DOE SNF/Canister Basket Variants

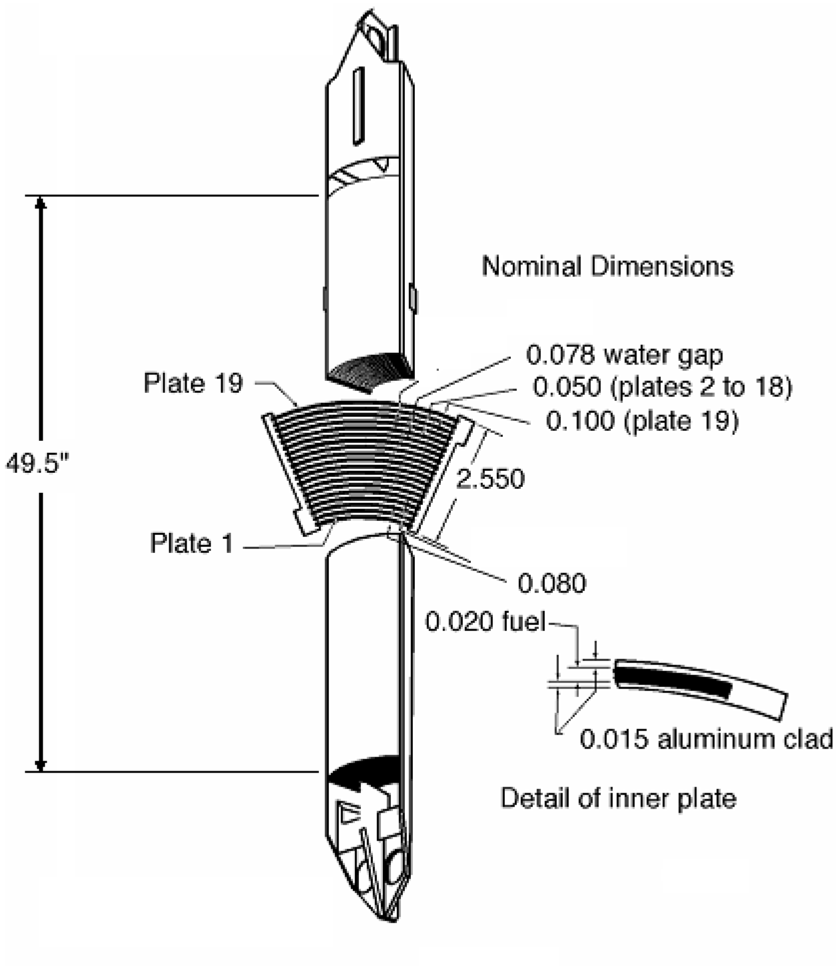
6.1.3.1 ATR

6.1.3.1.1 ATR SNF

The ATR fuel element consists of nineteen curved aluminum clad uranium aluminide (UAl_x) plates containing highly enriched uranium. The ATR 7F fuel element (Ref. 2.2.13, pg. 39 and 40) is modeled in the MCNP calculations reported in this document.

Figure 6-3 presents a simplified view of an ATR 7F fuel element. For the purpose of disposal, the fuel elements are cropped to a nominal length of 49.5 in. (length of the fuel plates) by removing the upper and lower end boxes. The fuel plates are 49.5 inches (125.73 cm) long with a fuel zone that is ~48 inches (121.92 cm) long.

The design of the ATR 7F fuel element is summarized in Table 6-6. Cross-sectional views of the ATR fuel element, as modeled in MCNP, are portrayed in Figure 6-4 and Figure 6-5.



Source: Ref. 2.2.13, pg. 31

Figure 6-3: Simplified View of the ATR Fuel Element

Table 6-6. Dimensions and Fissile Loading for Individual Plates in ATR Fuel Element

Plate Number	Inner Radius (cm)	Outer Radius (cm)	Overall Plate Thickness (cm)	Plate Arc Length (cm)	Fuel Meat Arc Length (cm)
1	7.658	7.861	0.203	5.410	4.133
2	8.059	8.186	0.127	5.542	4.925
3	8.385	8.512	0.127	5.799	5.182
4	8.710	8.837	0.127	6.050	5.433
5	9.035	9.162	0.127	6.309	5.692
6	9.360	9.487	0.127	6.563	5.946
7	9.685	9.812	0.127	6.820	6.203
8	10.010	10.137	0.127	7.074	6.457
9	10.335	10.462	0.127	7.330	6.713
10	10.660	10.787	0.127	7.584	6.967
11	10.986	11.113	0.127	7.841	7.224
12	11.311	11.438	0.127	8.098	7.480
13	11.636	11.763	0.127	8.352	7.734
14	11.961	12.088	0.127	8.608	7.991
15	12.286	12.413	0.127	8.862	8.244
16	12.611	12.738	0.127	9.119	8.501
17	12.936	13.063	0.127	9.373	8.755
18	13.261	13.388	0.127	9.629	8.885
19	13.586	13.840	0.254	10.086	8.809

Source: Ref. 2.2.13, pg. 38

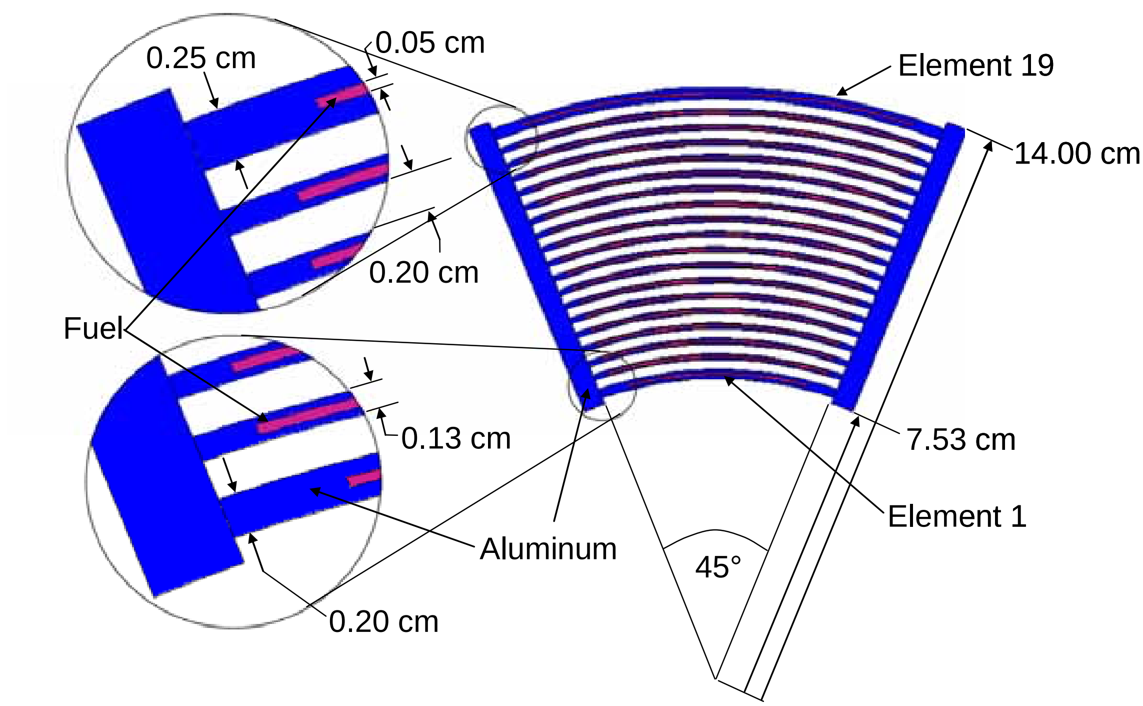


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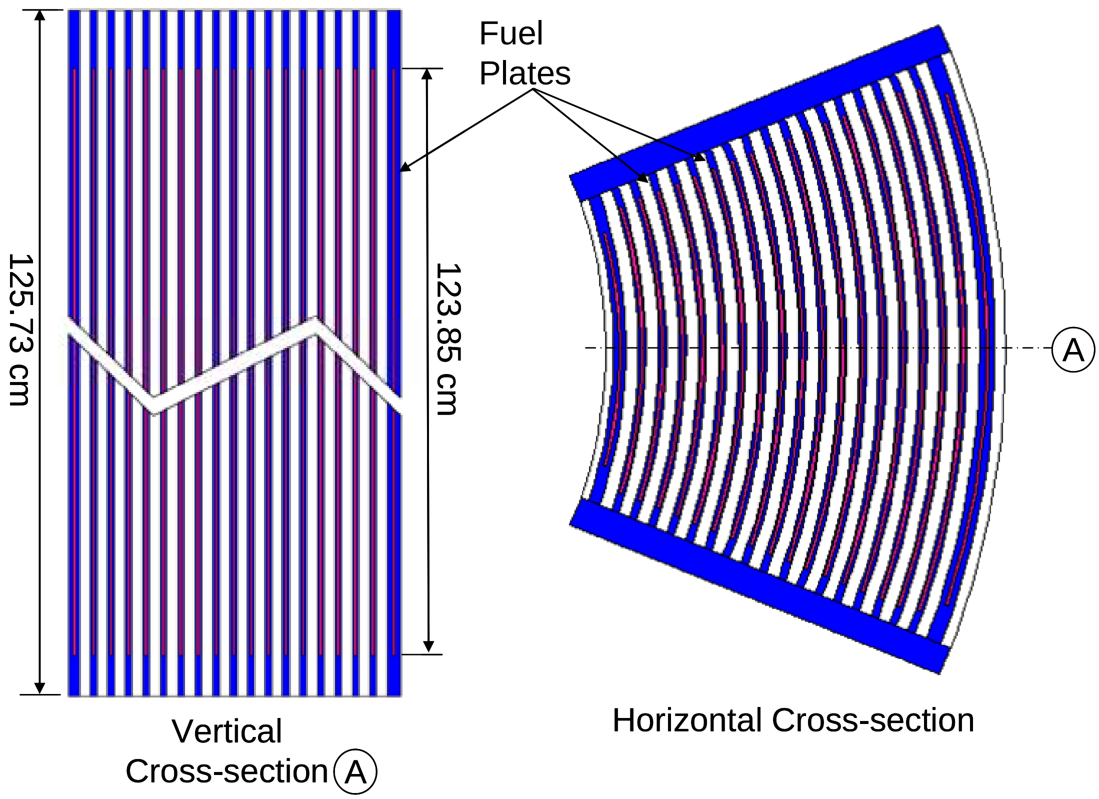
Figure 6-4: Horizontal Cross-section of the ATR Fuel Element MCNP Model



Source: Original

Figure 6-5: Cross-sections of the ATR Fuel Element MCNP Model

The ATR fuel composition used in the MCNP calculations is detailed in Table 6-7. For conservatism, the ATR fuel composition is based on the fuel element plate with the greatest ^{235}U enrichment (i.e. plate 15). Note that the nominal fuel composition includes 10 vol % water fraction.

Table 6-7. Material Specifications for ATR Fuel

Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{235}U	92235.50c	39.558	38.548	37.587	36.674	35.804	34.974
^{238}U	92238.50c	1.703	1.659	1.618	1.579	1.541	1.506
^{234}U	92234.50c	0.505	0.492	0.480	0.468	0.457	0.446
^{236}U	92236.50c	0.294	0.286	0.279	0.273	0.266	0.260
^{27}Al	13027.50c	57.940	56.460	55.054	53.716	52.441	51.226
^{16}O	8016.50c	0.000	0.286	0.557	0.816	1.062	1.297
^{1}H	1001.50c	0.000	2.269	4.424	6.475	8.428	10.291
Density (g/cm^3)		3.8081	3.9079	4.0077	4.1076	4.2074	4.3072

Source: The ATR fuel element fuel plate composition is based on the fuel plate with the highest fissile loading (i.e. plate 15). The fuel density and composition for plate 15 (with no moisture content, i.e. 0 vol % water fraction) is derived in the Attachment II, Homog_mats.xls, sheet *ATR,* of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

6.1.3.1.2 ATR Basket

A Type 1A basket is to be used for disposing ATR SNF. The basket is constructed of low-carbon nickel-chromium-molybdenum-gadolinium alloy (refer to Attachment 1 for composition). The basket is composed of orthogonally arranged basket plates which have a thickness of 0.9525 cm (0.375 in.). A cross sectional view of the ATR basket is provided in Figure 6-6.

Three baskets are to be axially stacked in a 15 ft. SNF canister providing a total payload capacity of 30 ATR elements per canister. Figure 6-6 shows cross-sections of the Type 1A basket as modeled in MCNP. Figure 6-7 and Figure 6-8 are cross-sections of the MCNP models of the loaded Type 1A basket with ATR fuel in the DOE SNF Long canister and in the DOE Long WP.

A summary of pertinent dimensions and material specifications is provided in Table 6-8.

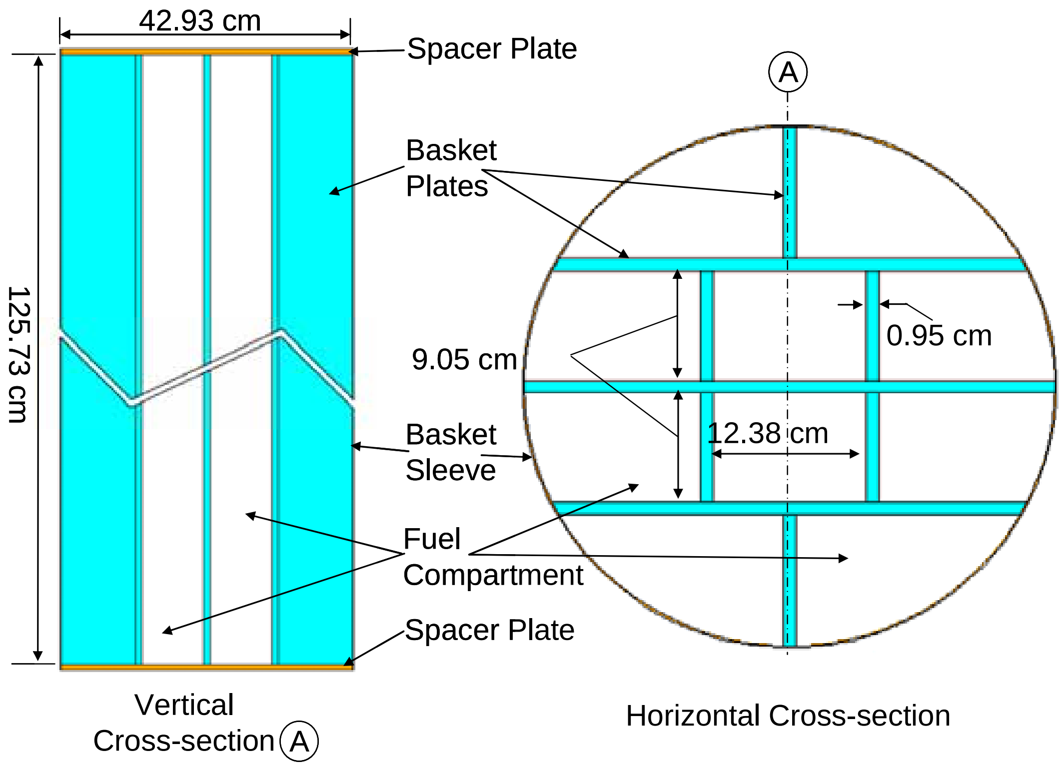


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Figure 6-6: Cross-sections of the Type 1A ATR Fuel Basket MCNP Model (Fuel elements not shown for clarity)

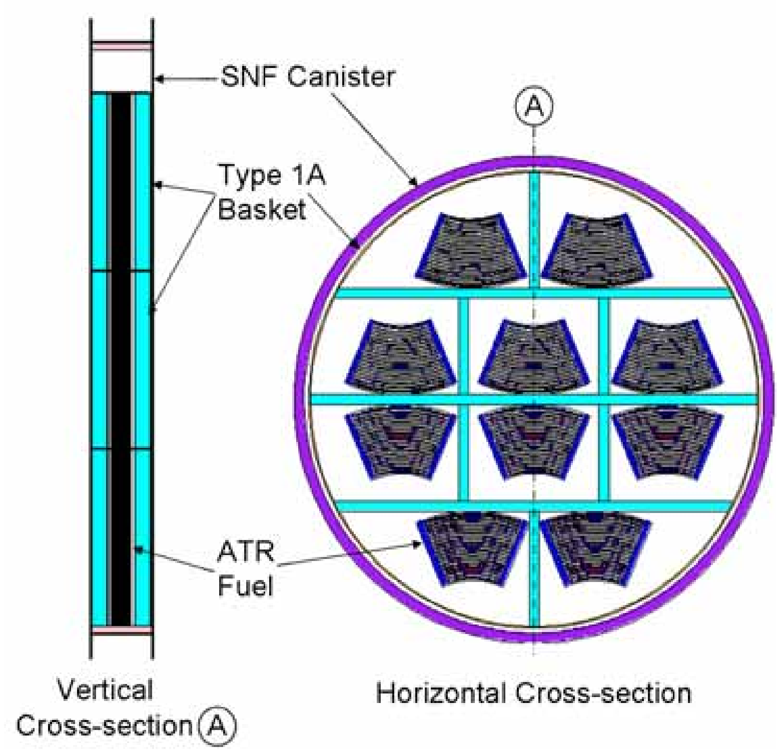

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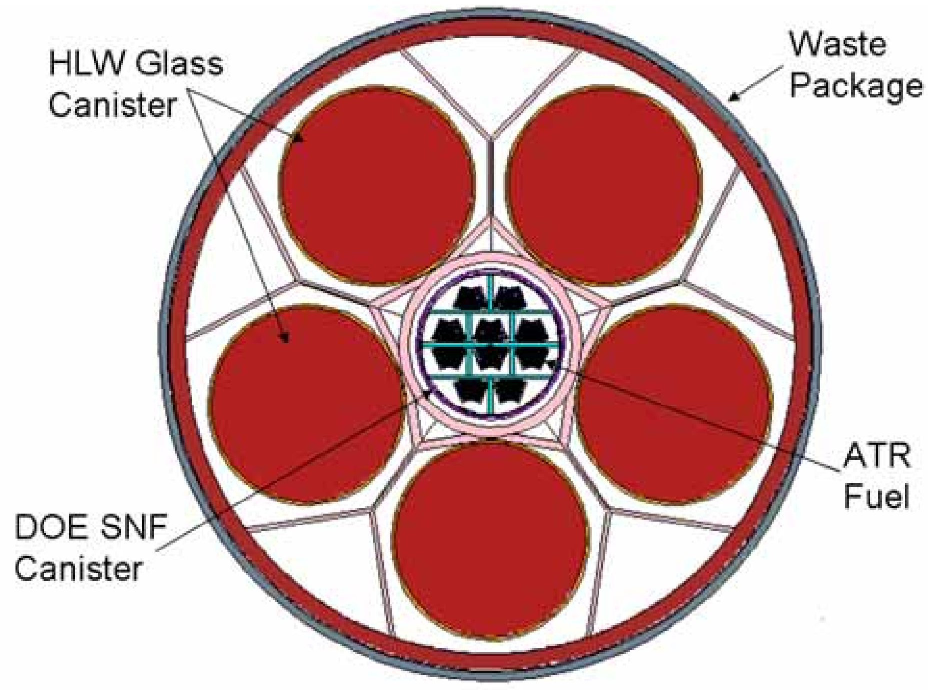
Figure 6-7: Cross-sections of MCNP Model of ATR Fuel loaded in DOE SNF Long Canister



Source: Original

Figure 6-8. Cross-sectional View of ATR SNF in the WP

Table 6-8. Key ATR Fuel and Packaging Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Fuel Element				
Fuel Plate Cores	UAl_x / Al powder/ B_4C	Length	~121.92	~123.85
		Radius	See Table 6-6	See Table 6-6
		Arc Length	See Table 6-6	See Table 6-6
		Thickness	~0.05	~0.05
Fuel Plate Cladding	Aluminum 6061	Length	~125.7	~125.7
		Radius	See Table 6-6	See Table 6-6
		Arc Length	See Table 6-6	See Table 6-6
		Thickness	See Table 6-6	See Table 6-6
Fuel Plate Gap	Void	Radial Thickness	See Table 6-6	See Table 6-6
Side Plates	Aluminum 6061	Length	~125.7	~125.7
		Width	~6.48	~6.48
		Inner Radius	Not explicitly given	~7.53 [b]
		Outer Radius	Not explicitly given	~14.00 [b]
Fuel Basket				
Basket Sleeve	SS 304L	Inner Diameter	~42.61 (calculated)	~42.61
		Outer Diameter	~42.93	~42.93
		Length	Not explicitly given	~125.73 [c]
Basket Plates	C-4 Alloy (Ni-Gd Alloy)	Length	Not explicitly given	~125.73 [c]
		Thickness	~0.95	~0.95
		Horizontal Spacing	~12.38 mm apart	~12.38 cm apart
		Vertical Spacing	~9.05 mm apart	~9.05 cm apart
Spacer Plate	SS 304L	Outer Diameter	Not explicitly given	~43.82 [a]
		Thickness	~0.64 to 0.95	~0.95

Source: Ref. 2.2.1 Table 37, with adjustment to reflect the new preferred basket design (Figure 10, Ref. 2.2.23)
NOTES: [a] Based on the inner diameter of the SNF canister.
[b] Derived in Reference 2.2.1, Attachment II, *Homog_mats.xls*, sheet *ATR*.
[c] Based on the length of the fuel plate cladding and the side plates.

6.1.3.2 EF

6.1.3.2.1 EF SNF

The EF fuel pin matrix is made of uranium-molybdenum alloy (approximately 10 wt% molybdenum alloyed with uranium of 25.69 wt% ^{235}U enrichment) (Ref, 2.2.14, Section 3). The fuel is metallurgically bonded to a zirconium tube that serves as cladding. The bonding process results in there being no gap between the cladding and fuel. Zirconium end pieces are fitted to the fuel rods, and 140 fuel rods plus 4 stainless steel connecting rods are assembled to form a fuel assembly.

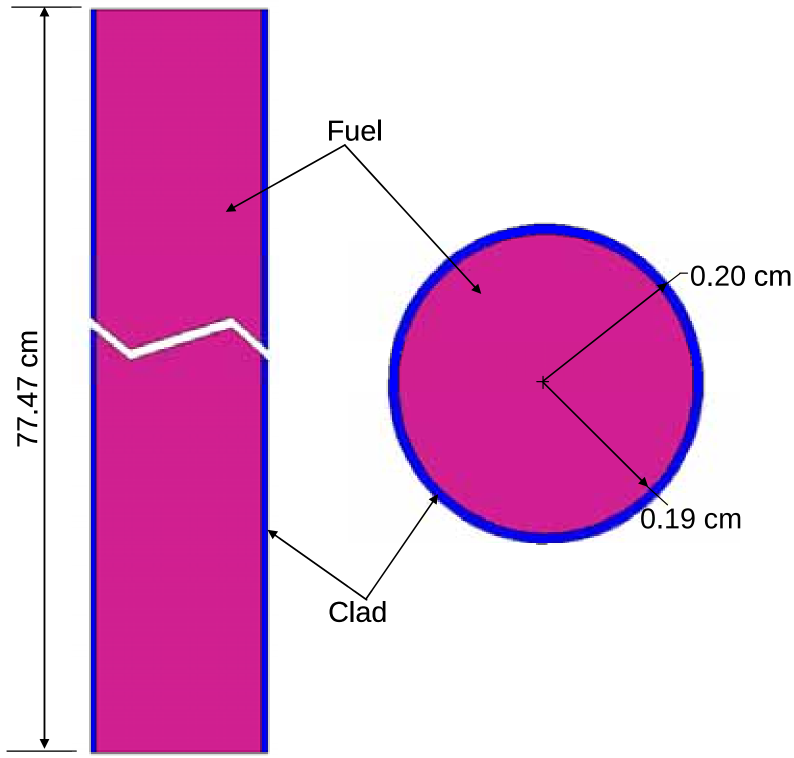


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Figure 6-9: Cross-sections of the EF Fuel Pin as Modeled in MCNP

For disposal the EF fuel assemblies were derodded (i.e. the individual fuel pins were removed from the assemblies), and the loose fuel pins were packaged in aluminum shipping canisters that were over-packed with another aluminum canister. The EF fuel pins are placed inside canisters known as "–04" canisters, which are in turn placed in (concentric) "–01" canisters. Each –01 canister contains one –04 canister, and each –04 canister contains 140 loose fuel pins with no supporting or spacing mechanism. In general the fuel pins are not in any particular configuration and are therefore examined under a wide variety of conditions in the calculations. However, the fuel pins are treated as uniformly spaced within the -04 canister as a nominal condition. The -01 and -04 canister arrangement, as modeled in MCNP, is shown in Figure 6-10.

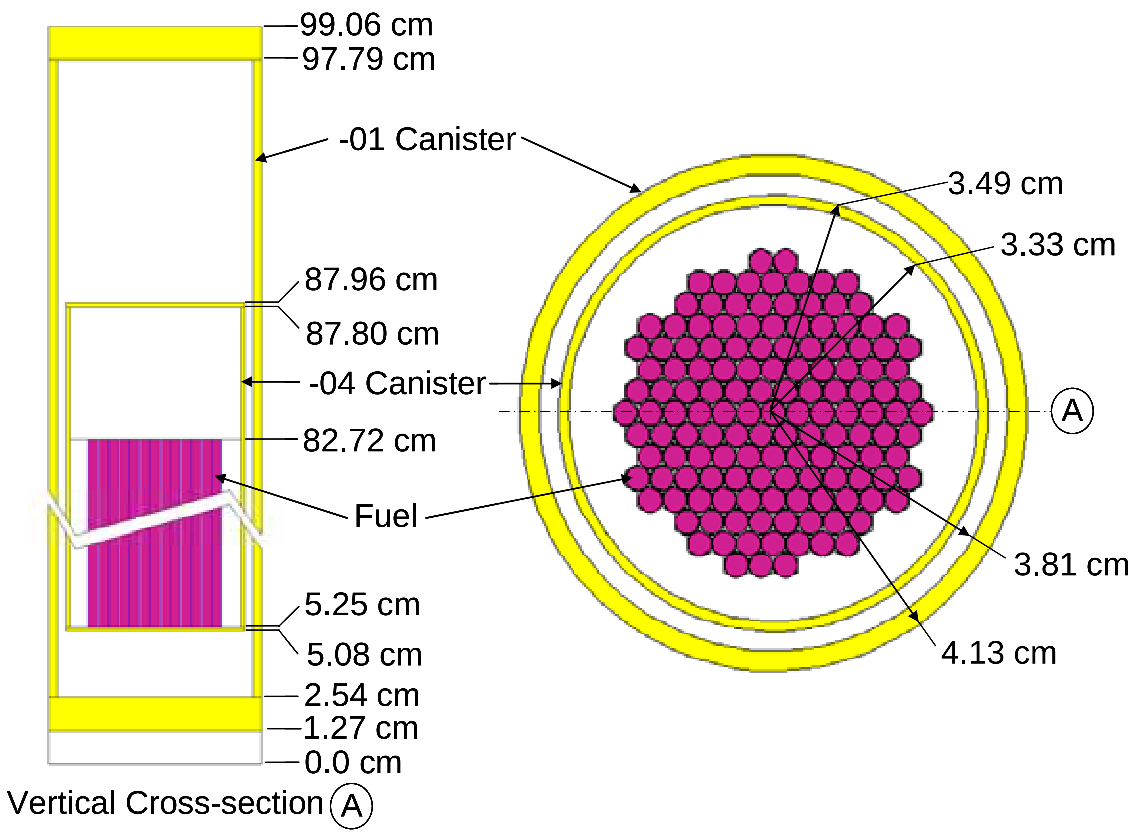

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Figure 6-10: Cross-sections of the -01 and -04 Canisters as Modeled in MCNP

The EF fuel composition used in the MCNP calculations is detailed in Table 6-9. Note that the nominal fuel composition includes 10 vol % water fraction.

Table 6-9. Material Specifications for EF Fuel

Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{235}U	92235.50c	22.961	22.830	22.701	22.573	22.447	22.322
^{238}U	92238.50c	66.413	66.035	65.661	65.291	64.926	64.564
Mo	42000.50c	10.625	10.565	10.505	10.446	10.387	10.330
^{1}H	1001.50c	0.000	0.064	0.127	0.189	0.251	0.312
^{16}O	8016.50c	0.000	0.506	1.006	1.501	1.990	2.473
Density (g/cm^3)		17.4242	17.5240	17.6238	17.7237	17.8235	17.9233

Source: The EF fuel composition and density is derived in the Attachment II, Homog_mats.xls, sheet *Fermi*, of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

6.1.3.2.2 EF Basket

A basket assembly that consists of 12 nickel-gadolinium alloy tubes attached to a stainless steel base plate is used for placement of EF fuel within a DOE SNF canister. Each basket support tube contains a –01 canister, and the DOE SNF canister contains two basket assemblies. The space between the nickel-gadolinium alloy tubes is filled with iron shot (Fe) and gadolinium phosphate ($GdPO_4$). The gadolinium phosphate is a neutron absorber, and the iron shot serves as a dispersant for the gadolinium. Figure 6-11 and Figure 6-12 show cross-sections of the EF fuel basket in the DOE SNF canister.

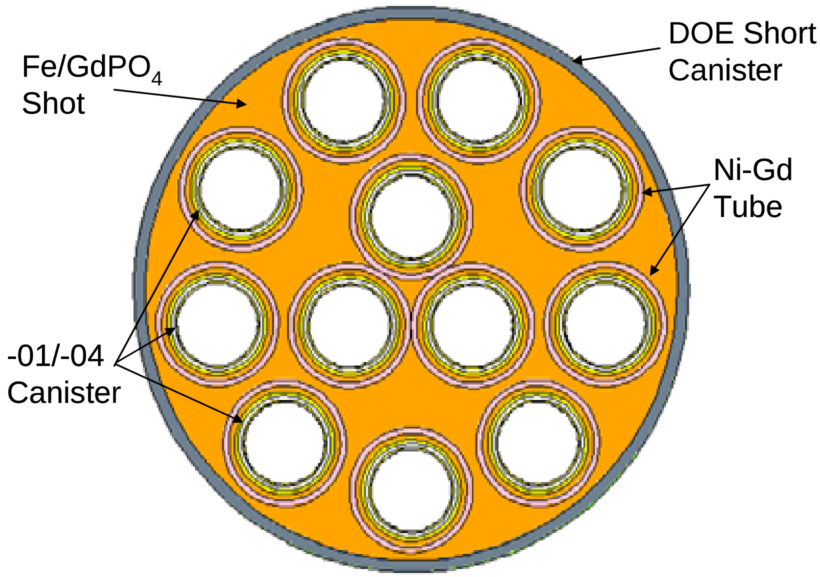

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Figure 6-11: Horizontal Cross-section of the EF Storage Basket in a DOE Short Canister as Modeled in MCNP

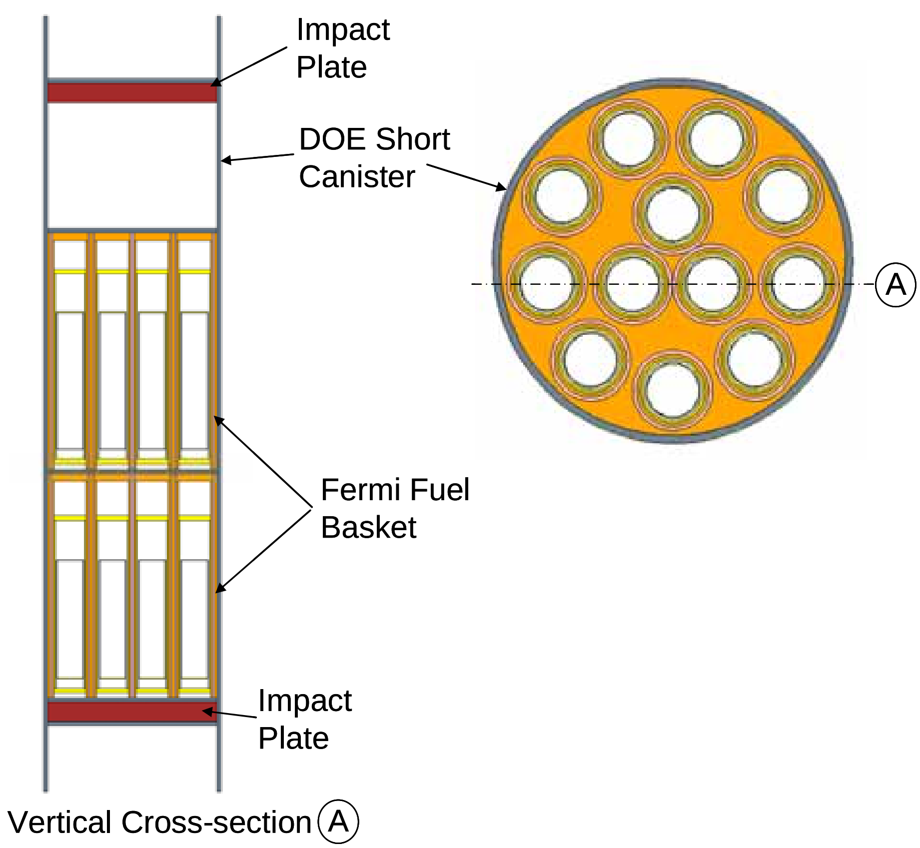

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Figure 6-12: Vertical Cross-section of EF Fuel Baskets in a DOE Canister as Modeled in MCNP

A summary of pertinent dimensions and material specifications is provided in Table 6-10.

Table 6-10. Key EF Fuel and Packaging Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Fuel	U/Mo Alloy	Outer Diameter	~0.38	~0.38
		Length	~77.47	~77.47
Cladding	Zirconium	Inner Diameter	~0.38	~0.38
		Outer Diameter	~0.40	~0.40
Entire Fuel Pin	--------------	Pin Pitch	Varies (loose)	~0.40 (hexagonal)
-04 Canister Walls	Aluminum 6061	Inner Diameter	~6.65	~6.65
		Outer Diameter	~6.99	~6.99
Entire -04 Canister	--------------------	Inner Length	~82.55	~82.55
		Outer Length	~90.17	~82.88 [b]
-01 Canister Walls	Aluminum 6061	Inner Diameter	~7.62	~7.62
		Outer Diameter	~8.26	~8.26
Entire -01 Canister	--------------------	Inner Length	~95.25	~95.25
		Outer Length	~107.95	~97.79 [c]
Support Tubes	SS 316L [d]	Inner Diameter	~9.20	~9.20
		Outer Diameter	~10.16	~10.16
		Length	~110.00	~110.00
Base/Spacer Plate	SS 316L	Diameter	~42.60	~43.82 [f]
		Thickness	~0.95	~0.95
Spacer	Void	Length	~33.55	~33.55

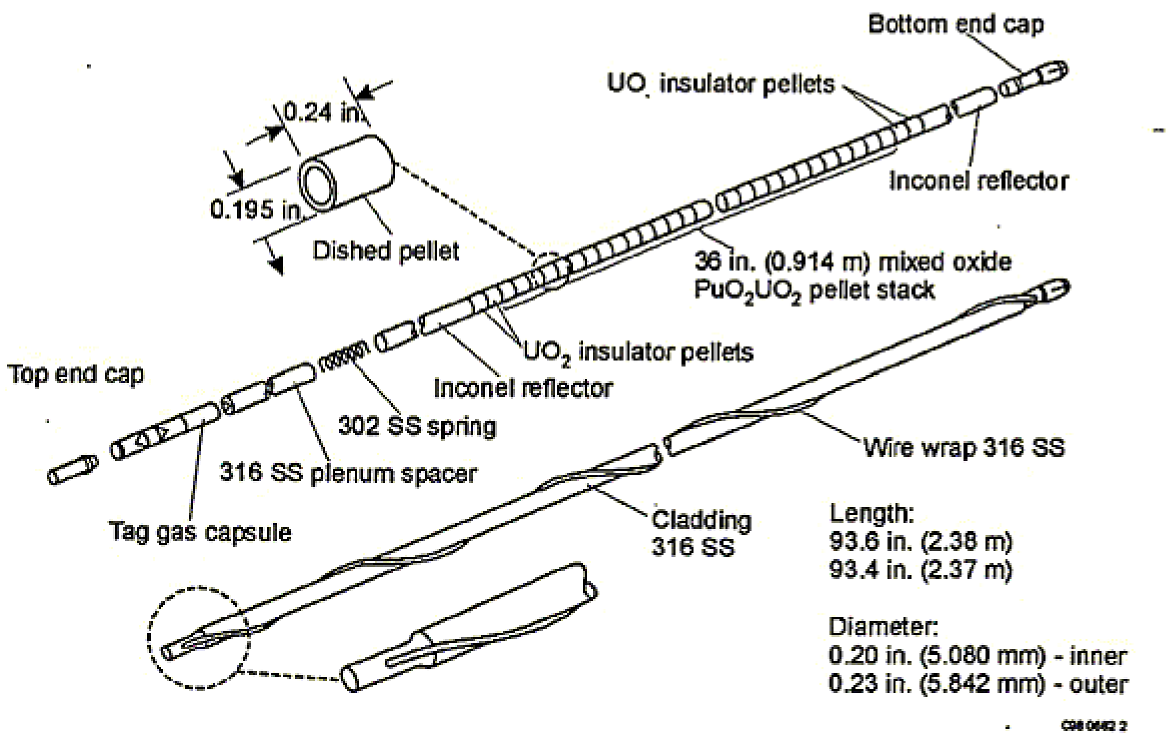
Source Reference 2.2.1, Table 34

NOTES:
[b] The –04 canister end plugs were represented as a lid with the same thickness as the plug material and an adjacent region of void for the remainder of the hollow plug length. This is considered conservative for criticality safety applications since the solid region is a better axial reflector than a hollow plug.
[c] The –01 end fittings were represented as a solid lid and an adjacent void region for the remainder of the fitting length. This is considered conservative for criticality safety applications since the solid region provides better axial reflection than a hollow cap.
[f] As a geometry simplification, the diameter was made consistent with the inner diameter of the SNF canister. This has a negligible impact on the results, as demonstrated in Ref. 2.2.1, Attachment I.

6.1.3.3 FFTF Spent Nuclear Fuel

6.1.3.3.1 FFTF Fuel Pins

The FFTF fuel pins have a number of variants. These include four basic types and one experimental variant. The overall height of a fuel pin is between 237 and 238 cm for all variants.



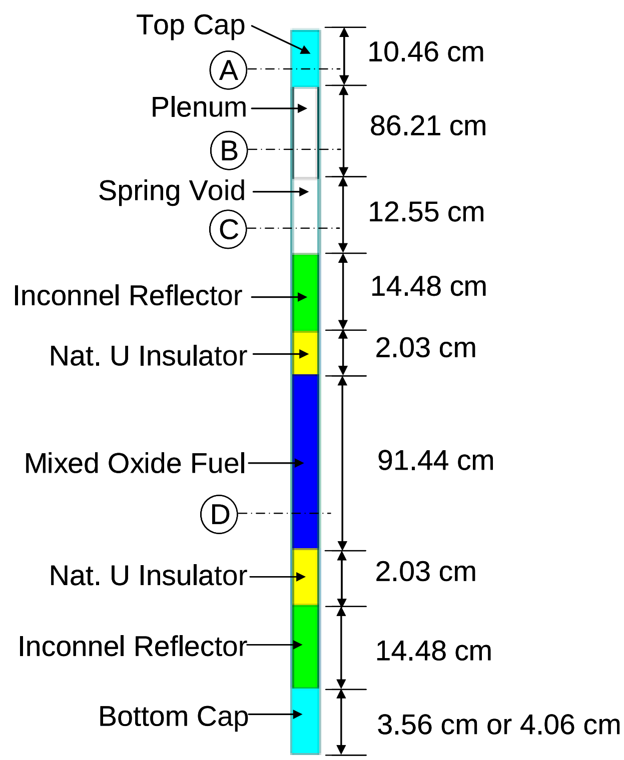
Source: Original

Figure 6-13. Simplified Axial View of a Standard FFTF Driver Fuel Assembly Fuel Pin

Each fuel pin has a ~91 cm long mixed oxide (MOX – $UO_{1.96}$ and $PuO_{1.96}$) fuel region composed of fuel pellets. The fuel region is centered ~166 cm from the bottom of the fuel pin. The mixed oxide fuel region is followed on both ends by ~2 cm of natural UO_2 insulator pellets and ~15 cm of Inconel 600 (which serves as a reflector).

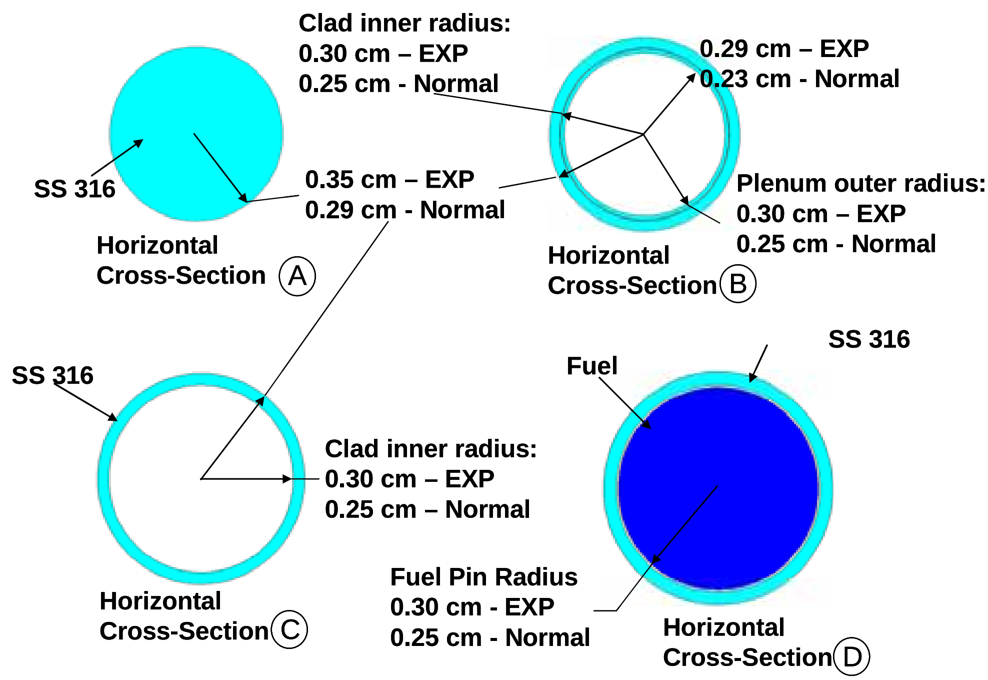
Type 4.1 fuel pins are modeled in the MCNP calculations based on their higher fissile material content compared with other variants. Figure 6-14 and Figure 6-15 provide cross-section views of the FFTF fuel pin as modeled in MCNP.

Similar to a previous analysis (Ref. 2.2.1), an experimental variant of MOX fuel pins is also modeled in the MCNP calculations to represent loose fuel pins that are stored in a dedicated container positioned within the center of the DOE SNF canister. The geometry of these pins is similar to that of Type 4.1 pins, except the diameters of the pellets and cladding are proportionally larger.



Source: Original

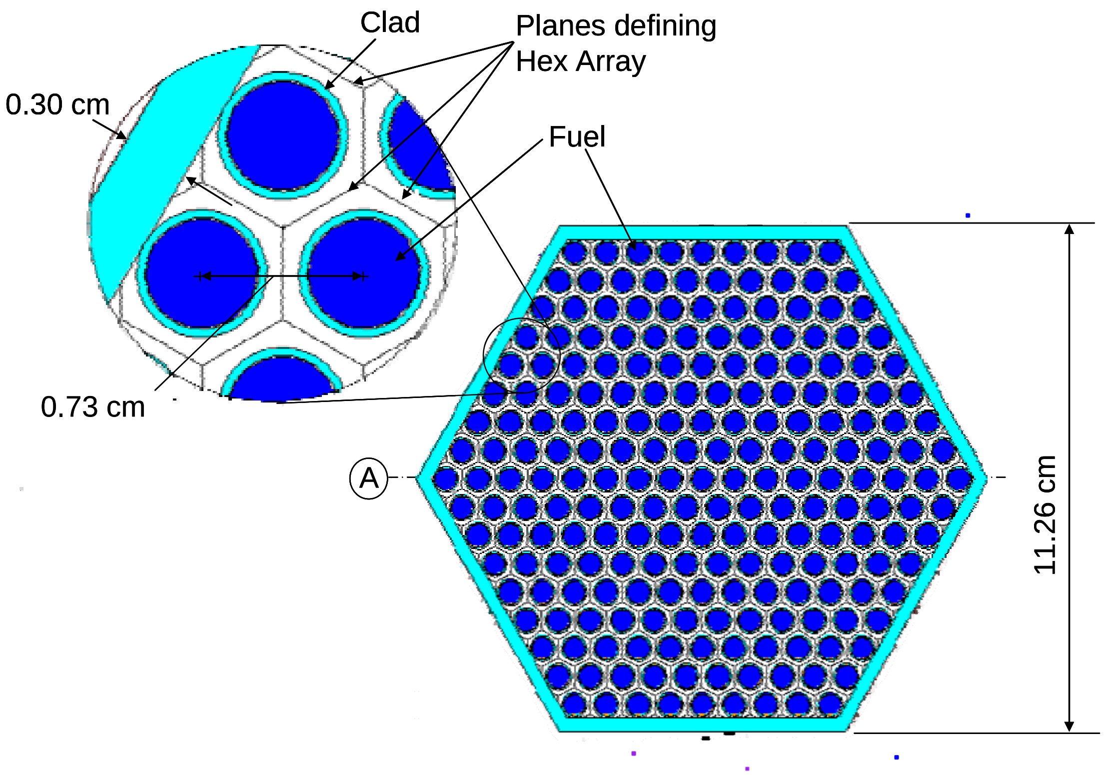
Figure 6-14: Vertical Cross-section of a FFTF Fuel Pin as Modeled in MCNP



Source: Original

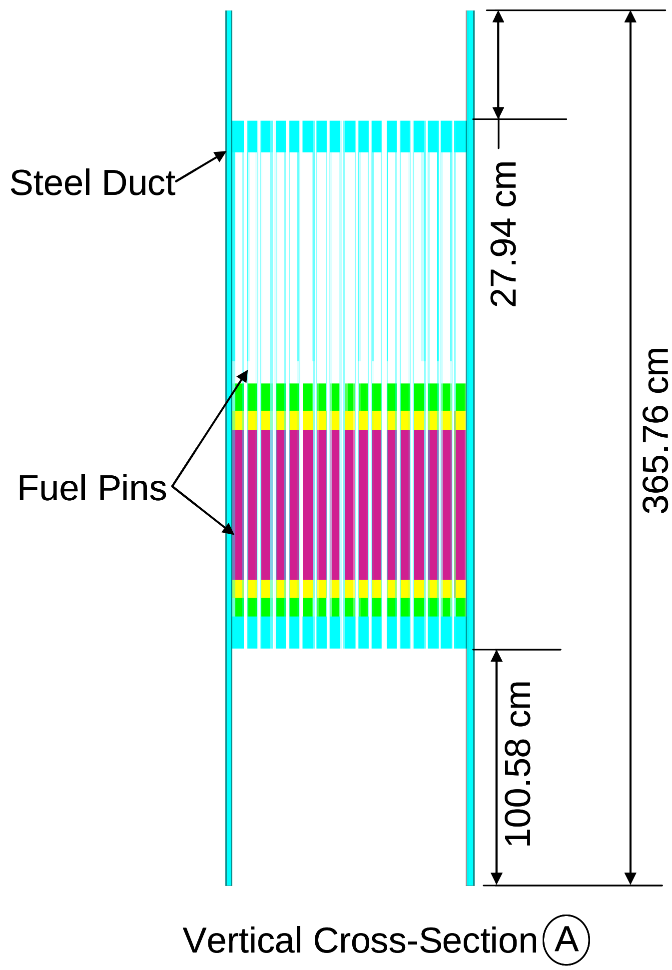
Figure 6-15: Horizontal Cross-Sections of a FFTF Fuel Pin as Modeled in MCNP, depicting Dimensions for the Experimental (EXP) and Type 4.1 Pins

The FFTF standard driver fuel assembly (DFA) contains 217 FFTF fuel pins and is hexagonally shaped. The assembly is ~366 cm long. The DFA has a stainless steel ~0.31 cm thick Type 316 hexagonal duct that surrounds the fuel pins. The duct-tube outer dimension is ~11.62 cm across the hexagonal flats. The fuel pins are arranged with a triangular pitch within the hexagonal assembly duct. The fuel pin pitch is ~0.73 cm. Cross-section views of the FFTF DFA MCNP model are provided in Figure 6-16 and Figure 6-17.



Source: Original

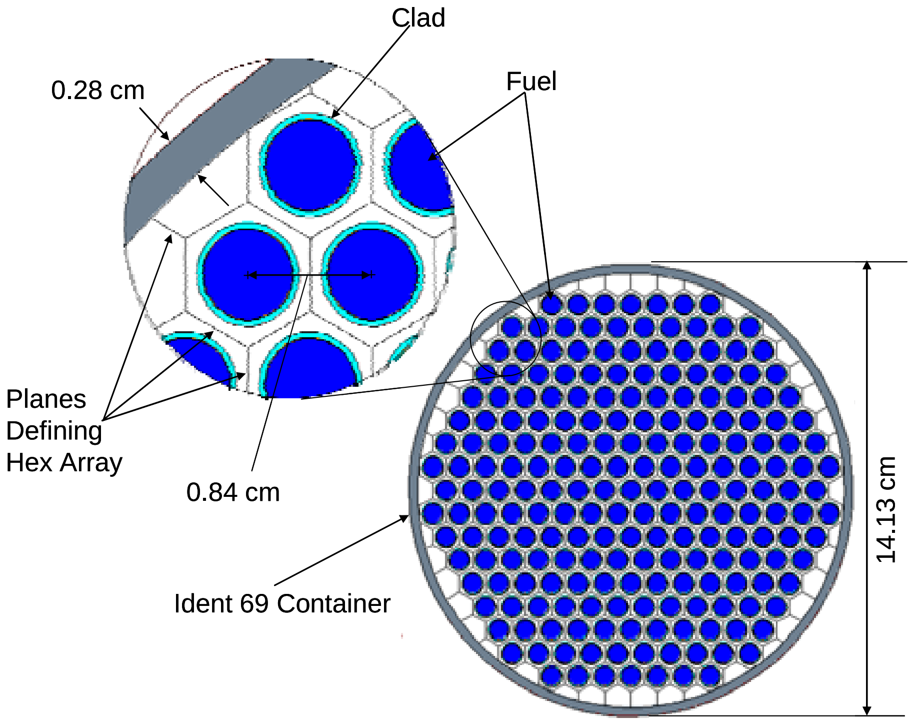
Figure 6-16: Horizontal Cross-section of FFTF Driver Fuel Assembly MCNP Model



Source: Original

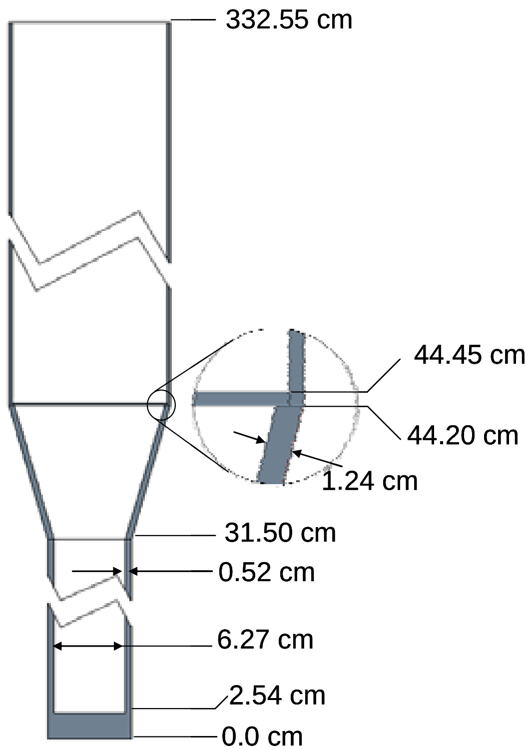
Figure 6-17: Vertical Cross-section of FFTF Driver Fuel Assembly MCNP Model (Not to Scale)

Some assemblies have been disassembled, and the fuel pins placed in fuel pin containers named Ident-69 containers. Although there are several types of pin containers, the most highly loaded can hold up to 217 fuel pins. The total container length is ~366 cm. The Ident-69 containers are made with a ~14.13 cm diameter stainless steel Type 304L pipe that transitions (Figure 6-19) to a ~7.30 cm diameter pipe ~43.18 cm from the base. The experimental MOX fuel pins described above are modeled in the Ident-69 container. Figure 6-18 and Figure 6-19 provide cross-section views of the Ident 69 container as modeled in the MCNP calculations.



Source: Original

Figure 6-18: Horizontal Cross-section of MCNP model of FFTF Fuel in an Ident 69 Container



Source: Original

Figure 6-19: Vertical Cross-section of Ident 69 Container MCNP Model (Fuel not shown for Clarity)

A summary of pertinent dimensions and material specifications is provided in Table 6-11.

Table 6-11. Key FFTF Fuel and Packaging Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
FFTF Type 4.1 Driver Fuel Pins				
Fuel	70.72 wt% $UO_{1.96}$ and 29.28 wt% $PuO_{1.96}$	Outer Diameter	0.49	0.49
		Length	91.44	91.44
Insulator	Natural UO_2	Outer Diameter	0.49	0.49
		Length, Top	2.03	2.03
		Length, Bottom	2.03	2.03
Reflector	Inconel 600	Outer Diameter	0.48	0.49 [i]
		Length, Top	14.48	14.48
		Length, Bottom	14.48	14.48
Cladding	SS 316	Inner Diameter	0.51	0.51
		Outer Diameter	0.58	0.58
Entire Fuel Pin	--------------	Length	237.24	237.24
FFTF Type 4.1 Driver Fuel Assembly				
Fuel Pin Region	--------------	Length	237.24	237.24
		Location (center of fuel)	166.37 cm from bottom of DFA	166.37 cm from bottom of DFA
		Pin Pitch	0.73	0.73
		Number of Pins	217	217
Entire DFA	SS 316	Length	365.76	365.76
		Diameter (across flats)	11.62	11.62
		Wall Thickness	0.30	0.30
Fuel Pins in Ident-69 Container				
Fuel	68.8 wt% $UO_{1.96}$ and 31.2 wt% $PuO_{1.96}$	Outer Diameter	Not explicitly given	0.56 [d]
		Length	Not explicitly given	91.44 [d]
Insulator	Natural UO_2 [e]	Outer Diameter	Not explicitly given	0.56 [d]
Reflector	Inconel 600	Outer Diameter	Not explicitly given	0.56 [d]
Cladding	SS 316	Inner Diameter	Not explicitly given	0.61 [d]
		Outer Diameter	0.69	0.69
Ident-69 Container				
Ident-69 Canister, Top Portion	SS 304L	Length	322.58	322.58
		Inner Diameter	13.58	13.58
		Outer Diameter	14.13	14.13
Ident-69 Canister, Bottom Portion	SS 304L	Length	43.18	43.18
		Inner Diameter	Not explicitly given	13.58 [f]

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
		Outer Diameter	7.30	14.13 [h]

Source Reference 2.2.1, Table 45
NOTES: [d] Value derived in Reference 2.2.1, Attachment II *Homog_Mats.xls* sheet *FFTF.*
[f] Based on inner diameter of top portion of the Ident-69 canister.
[h] Based on the outer diameter of the top portion of the Ident-69 canister.
[i] Based on the outer diameter of the fuel and insulator.

The FFTF fuel compositions used in the MCNP calculations are detailed in Table 6-12 and Table 6-13, for the Type 4.1 DFA pins and Experimental Ident-69 Container pins, respectively. Note that the nominal fuel composition for both pin types include 10 vol % water fraction. The composition of the natural UO_2 insulator pellets associated with the FFTF fuel pins is provided in Attachment 1 (Table A1-20).

Table 6-12. Material Specifications for FFTF Type 4.1 Fuel Pins

Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{239}Pu	94239.55c	22.595	22.372	22.154	21.939	21.729	21.523
^{240}pu	94240.50c	3.017	2.987	2.958	2.929	2.901	2.874
^{241}Pu	94241.50c	0.265	0.262	0.260	0.257	0.255	0.252
^{235}U	92235.50c	0.125	0.124	0.123	0.121	0.120	0.119
^{238}U	92238.50c	62.373	61.758	61.155	60.563	59.983	59.414
^{16}O	8016.50c	11.626	12.387	13.134	13.866	14.584	15.288
^{1}H	1001.50c	0.000	0.110	0.219	0.325	0.429	0.531
Density (g/cm^3)		10.0200	10.1198	10.2196	10.3195	10.4193	10.5191

Source: The FFTF Type 4.1 fuel pin composition is derived in the Attachment II, Homog_mats.xls, sheet *FFTF,* of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

Table 6-13. Material Specifications for FFTF Experimental Ident-69 Container Fuel Pins

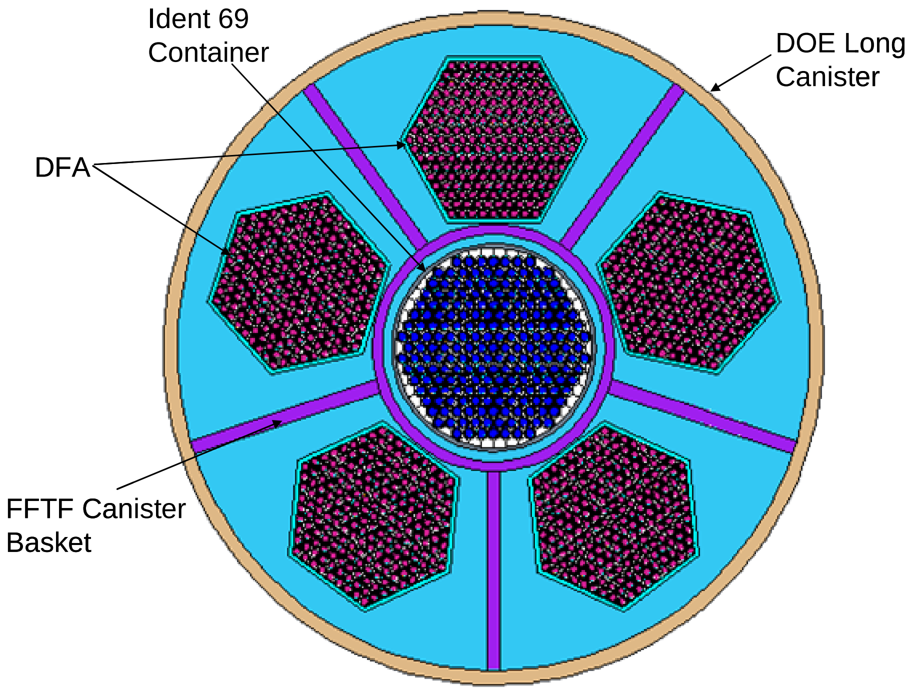
Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{239}Pu	94239.55c	24.077	23.840	23.607	23.378	21.729	22.935
^{240}pu	94240.50c	3.214	3.182	3.151	3.121	2.901	3.062
^{241}Pu	94241.50c	0.282	0.279	0.276	0.274	0.255	0.269
^{235}U	92235.50c	0.122	0.121	0.120	0.118	0.120	0.116
^{238}U	92238.50c	60.681	60.082	59.496	58.920	59.983	57.802
^{16}O	8016.50c	11.625	12.386	13.133	13.865	14.584	15.287
^{1}H	1001.50c	0.000	0.110	0.219	0.325	0.429	0.531
Density (g/cm^3)		10.0200	10.1198	10.2196	10.3195	10.4193	10.5191

Source: The FFTF Experimental fuel pin composition is derived in the Attachment II, Homog_mats.xls, sheet *FFTF,* of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

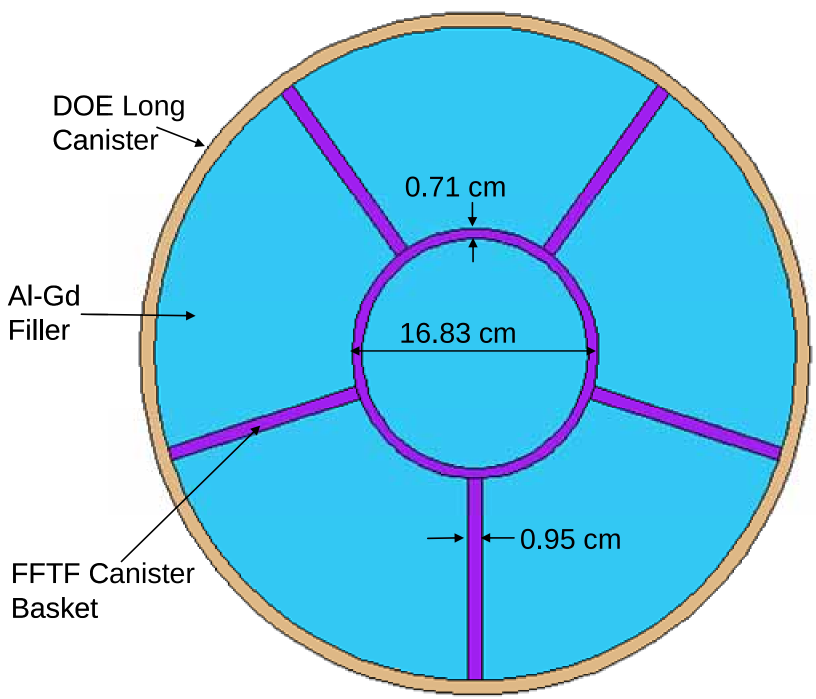
6.1.3.3.2 FFTF Canister Basket

The FFTF basket provides structural support to the fuel, acts as a guide during fuel loading and contains neutron poison. The FFTF fuel basket consists of a cylindrical center tube, or basket tube, and five divider plates, or spokes, extending radially from the center tube to either the inside wall of the DOE SNF canister or an outer sleeve. The center tube has an outside diameter of ~16.83 cm and a ~0.71 cm wall thickness. The spokes (divider plates) have a thickness of ~0.95 cm, and the basket height is ~411 cm. The basket analyzed is composed of Ni-Gd alloy. The basket contains a total of six basket locations: one center position surrounded by five outer positions. Either an Ident-69 fuel pin container (as shown in Figure 6-20) or a DFA can be placed in the center position, i.e., inside the basket tube. Only DFAs will fit in the outer five basket positions, although it is noted that the intent is to only load five of the six basket positions (the outer five positions plus the center position). For conservatism, all six positions are modeled occupied in the MCNP calculations. A cross-section view of the basket containing five DFAs and an Ident-69 container is provided in Figure 6-20. An aluminum-Gd filler material (beads) fills open spaces inside the canister but outside the DFAs and the Ident-69 container. Figure 6-20 through Figure 6-22 provide cross-section views of the MCNP model for the FFTF basket in a DOE Long SNF canister.



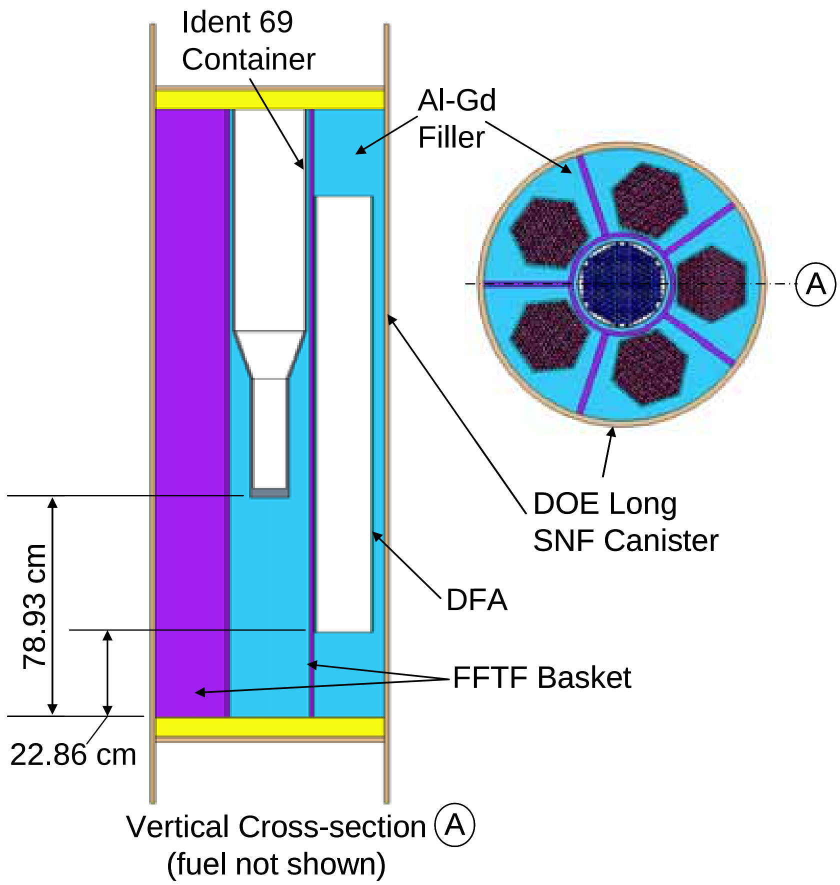
Source: Original

Figure 6-20. Representation of FFTF Fuel Units Emplaced in DOE SNF Canister Based on MCNP Model



Source: Original

Figure 6-21: Horizontal Cross-section of FFTF Canister Basket Model (Fuel not shown for Clarity)



Source: Original

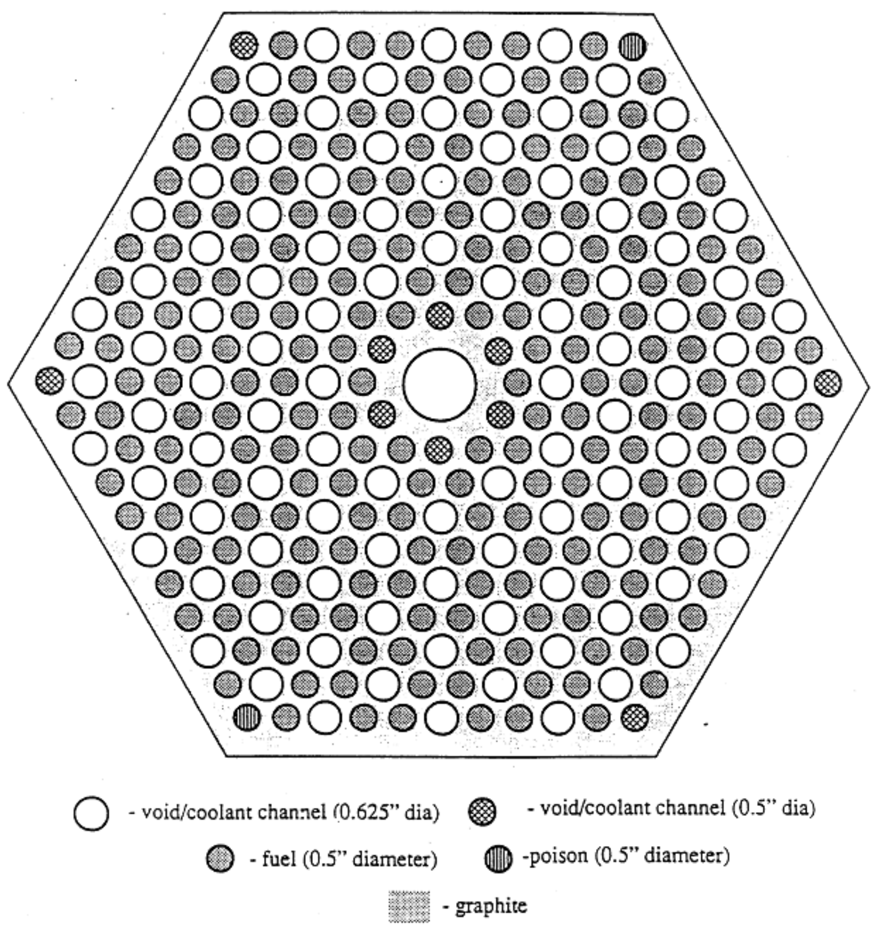
Figure 6-22: Vertical Cross-section of FFTF Basket in a DOE Long SNF Canister

6.1.3.4 FSV SNF

Fort Saint Vrain (FSV) fuel consists of a mixture of small spherical particles of uranium and thorium carbide. The individual particles are coated with multiple thin layers of pyrolytic carbon (pyrocarbon) and silicon carbide, which serve as tiny pressure vessels to contain fission products and the Th/U carbide matrix. In the FSV fuel elements, the mixture coated particles are bound in a carbonized matrix, which form fuel compacts that are loaded into drilled holes in the large hexagonal graphite prisms. Each graphite block, loaded with fuel compacts, comprises one fuel element (Ref. 2.2.16, Section 2.1.2).

The FSV fuel element is hexagonal in cross-section with dimensions of ~36 cm across flats by ~79 cm high. The active fuel is contained in an array of small-diameter holes, which are parallel with the coolant channels, and occupy alternating positions in a triangular array within the graphite structure. The fuel holes, 1.27 cm in diameter, are drilled from the top face of the element to within ~0.76 cm of the bottom face, and cemented graphite plugs 1.27 cm long seal the tops of the fuel holes. The fuel compacts, 1.25 cm in diameter, containing the coated fuel particles are stacked within the holes. The fuel holes and coolant channels are distributed in a triangular array with a pitch spacing of ~ 1.88 cm, which gives a unit cell pitch of ~3.26 cm (Ref. 2.2.16, pp. 12-13). A cross-sectional view of the FSV assembly is provided in Figure 6-23.

The FSV fuel elements are loaded into the DOE standardized SNF canister with no internal basket and no added neutron absorber. Each DOE standardized SNF canister can contain up to five FSV fuel elements, stacked axially. A summary of pertinent dimensions and material specifications is provided in Table 6-14.



Source: Ref. 2.2.16, pg. 14

Figure 6-23. Cross-section of Standard FSV Fuel Element

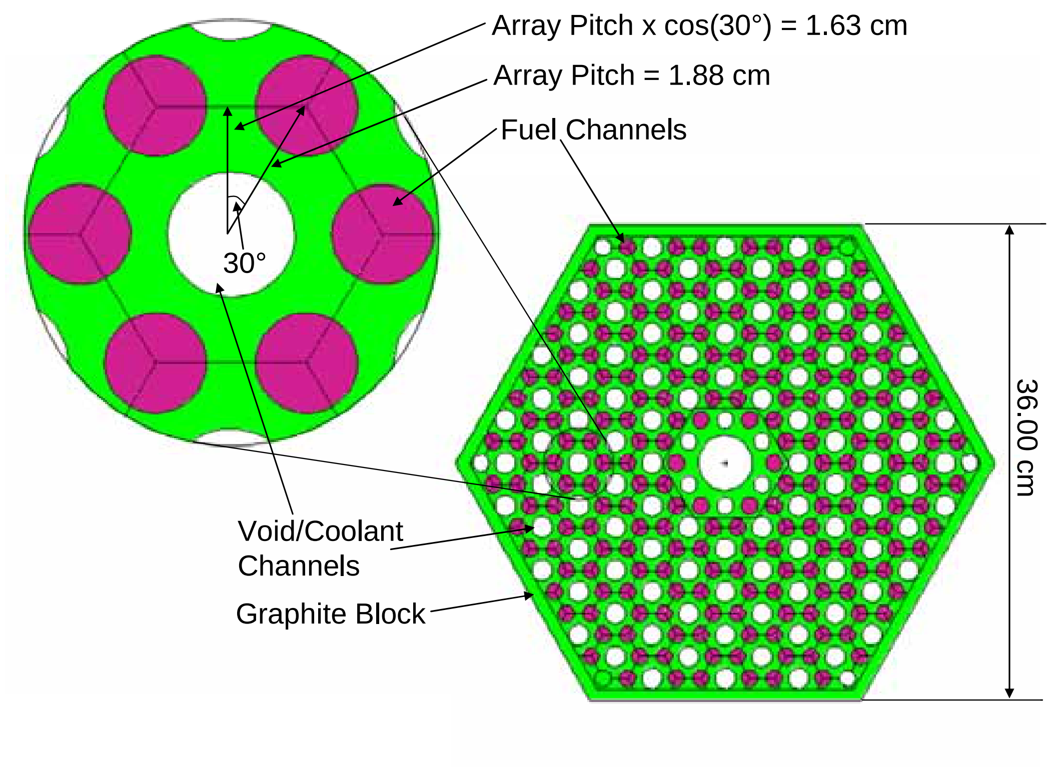
Table 6-14. FSV Fuel and Packaging Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Fuel Compact	Uranium or thorium carbide matrix	Outer Diameter	~1.25	~1.25
		Length	~4.93	~4.93
		Number per Fuel Channel	14 or 15	15
Fuel Channels	Void	Diameter	~1.27	~1.27
		Length [b]	~78.54	~78.54
		Number	210	210
Top Plug for Fuel Channels	H-327 or H-451 graphite	Diameter	~1.27	~1.27
		Length	~1.27	~1.27
Void / Coolant Channels	Void	Diameter, innermost ring	~1.27	~1.27
		Diameter, standard	~1.59	~1.59
		Length	Not explicitly given	~79.30 [d]
		Number	108	108
Burnable Poison Channels	Void [c]	Diameter	~1.27	~1.27
		Length	Not explicitly given	79.30 [d]
		Number	6	6
Central Fuel Handling Hole	Void	Diameter	~4.13	~4.13
		Length	~38.10	~38.10
Fuel Element	H-327 or H-451 graphite	Diameter (across flats)	~36.06	~36.06
		Length	~79.30	~79.30
		Channel Pitch	~1.88	~1.88

Source Reference 2.2.1, Table 32

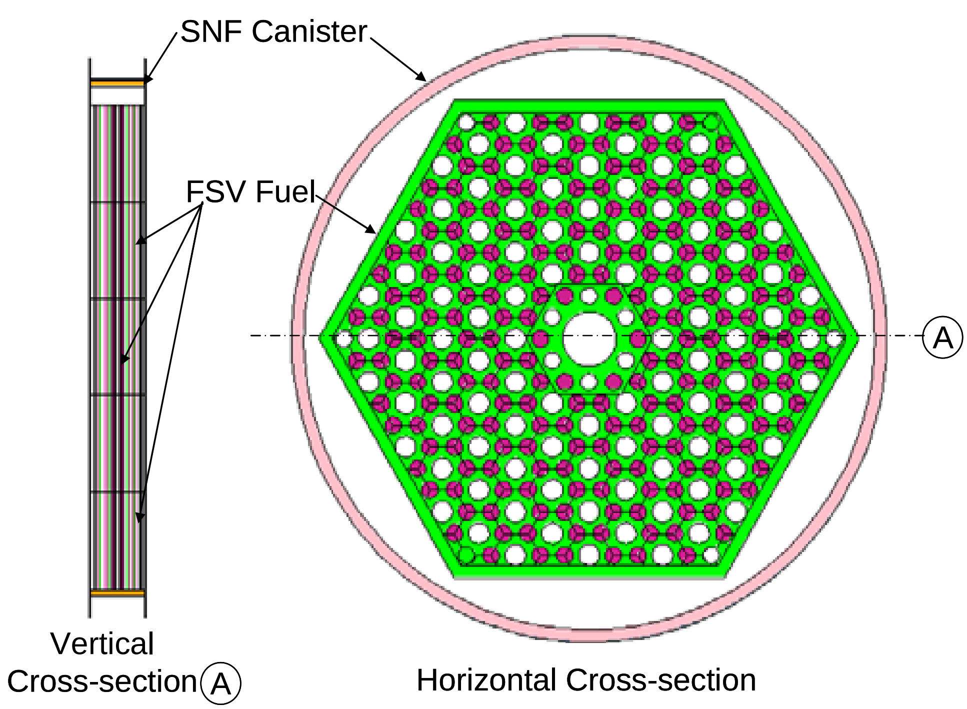
NOTES: [b] The fuel channel length is the length of the non-plugged hole as measured from the top of the fuel element.
[c] No credit is taken for burnable poison; these channels are modeled as empty.
[d] Set equal to fuel element length.

The MCNP model of the FSV fuel element is based upon the information provided in Figure 6-23 and Table 6-14. The models utilize a hexagonal prism array centered around the void/coolant channels. The fuel channels are located at the corners of the hexagonal prism. Refer to Figure 6-24 through Figure 6-26.



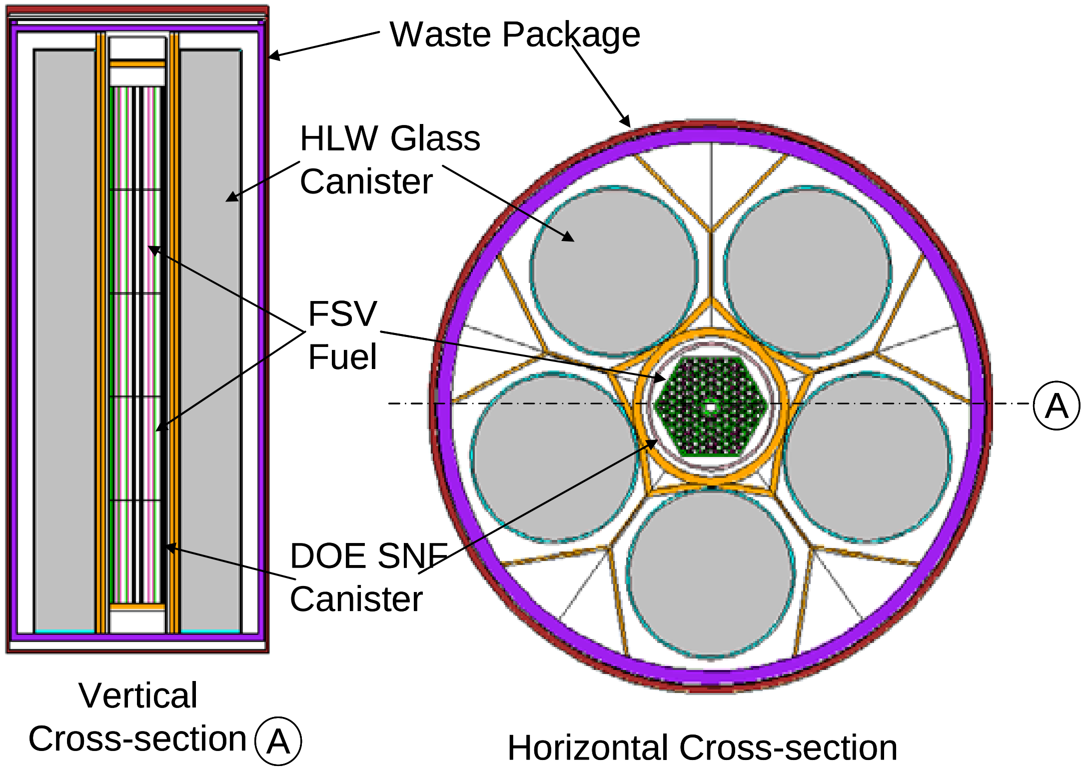
Source: Original

Figure 6-24: Horizontal Cross-section of FSV Fuel Element MCNP Model



Source: Original

Figure 6-25: Cross-sections of the FSV Fuel in the DOE SNF Long Canister MCNP Model



Source: Original

Figure 6-26: Cross-sections of FSV Fuel Loaded into a DOE Long Waste Package MCNP Model

The FSV fuel compositions modeled in the MCNP calculations reported in this document are based on a composite fuel composition derived from actual BOL and EOL fuel values. The FSV composite fuel compositions used in the MCNP models are detailed in Table 6-15. Note that the nominal fuel composition includes 10 vol % water fraction.

Table 6-15. Material Specifications for FSV Fuel

Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{235}U	92235.50c	3.535	3.366	3.213	3.073	2.945	2.826
^{232}Th	90232.50c	25.689	24.463	23.348	22.330	21.398	20.540
Si	14000.50c	5.962	5.677	5.419	5.183	4.966	4.767
^{239}Pu	94239.55c	0.006	0.006	0.005	0.005	0.005	0.005
^{12}C	6012.50c	64.808	61.714	58.902	56.335	53.983	51.819
^{1}H	1001.50c	0.000	0.534	1.020	1.463	1.869	2.243
^{16}O	8016.50c	0.000	4.240	8.093	11.611	14.835	17.800
Density (g/cm^3)		1.9911	2.0909	2.1907	2.2906	2.3904	2.4902

Source: The FSV fuel composition and density is derived in the Attachment II, Homog_mats.xls, sheet *FSV*, of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

6.1.3.5 Shippingport LWBR Spent Nuclear Fuel

The SLWBR was designed as a pressurized, light-water moderated and cooled thermal reactor that utilized the Th/U (U-233) oxide fuel cycle. The central portion of the core consisted of 12 movable-fuel seed assemblies each surrounded by a stationary blanket assembly. The UO_2-rich seed assemblies generated neutrons that were absorbed in the fertile fuel of the blanket/reflector assemblies producing additional fissile material and fissions. Since the seed assembly is the only assembly that will fit in an 18-in.-diameter DOE SNF canister without disassembly, it was chosen as the representative fuel for the Th/U fuel group.

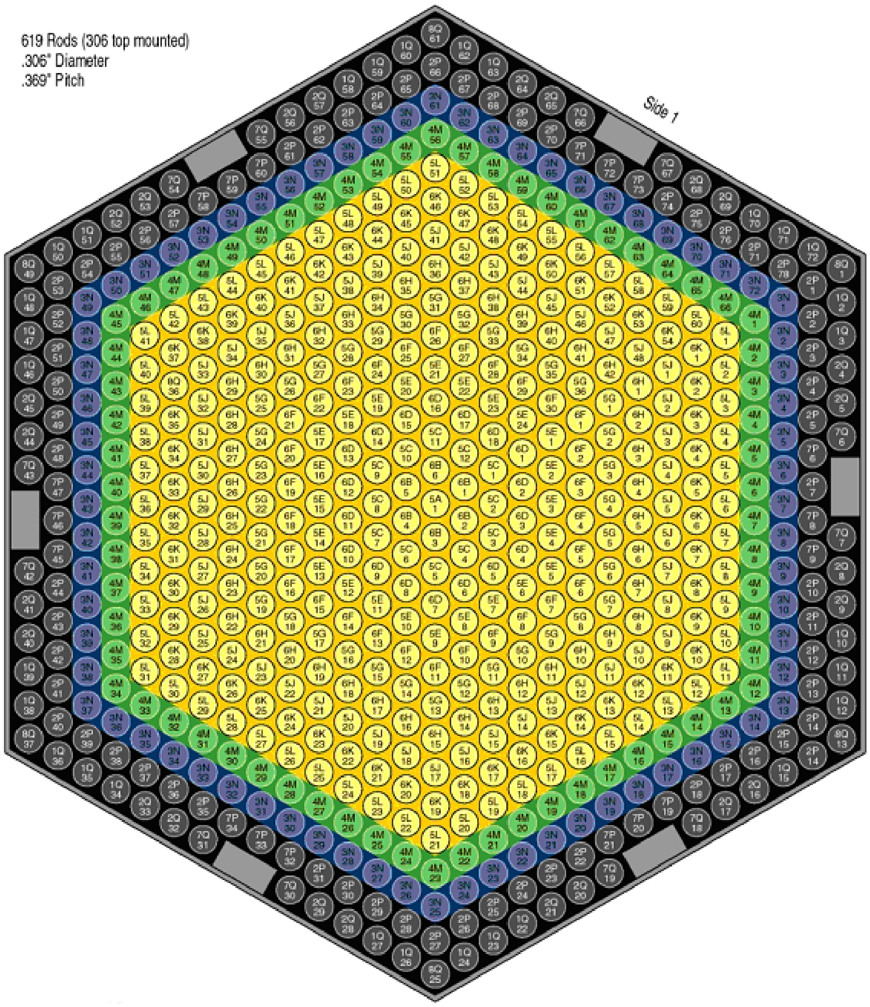
The LWBR core was fueled with fertile Th-232 and fissile U-233, the relative concentrations of which varied axially and radially across the core. The uranium that was used in fabricating the fuel was very highly enriched in U-233 with some isotopic impurities as shown in Table 6-16. The assembly is composed of cylindrical fuel rods on a triangular pitch where the space between fuel rods serves as coolant passages. The fuel rods were loaded with ceramic fuel pellets, some composed of thoria (ThO_2) and the rest composed of a mixture of thoria and UO_2.

Table 6-16. Isotopic Composition of the Uranium Used in Fabricating the SLWBR Fuel

Isotope	Weight Percent (wt%)
U-232	<0.001
U-233	98.23
U-234	1.29
U-235	0.09
U-236	0.02
U-238	0.37

Source: Ref. 2.2.17, Table 3-1

Two different enrichments (defined as the ratio of the mass of fissile to the total heavy metal mass) of the binary UO_2-ThO_2 matrix were used in seed rods. A cross-sectional plot shows the 619 fuel rods in the LWBR seed assembly in Figure 6-27. The radial zoning of the seed rods is shown in this plot. This figure shows that there are eight different types of seed rods that compose the four different fuel regions. Additional fuel rod information including the BOL fissile mass loading for each rod type is detailed in Figure 6-27 and Figure 6-28. The axial zoning and some axial dimensions of the seed rods are shown in Figure 6-29.



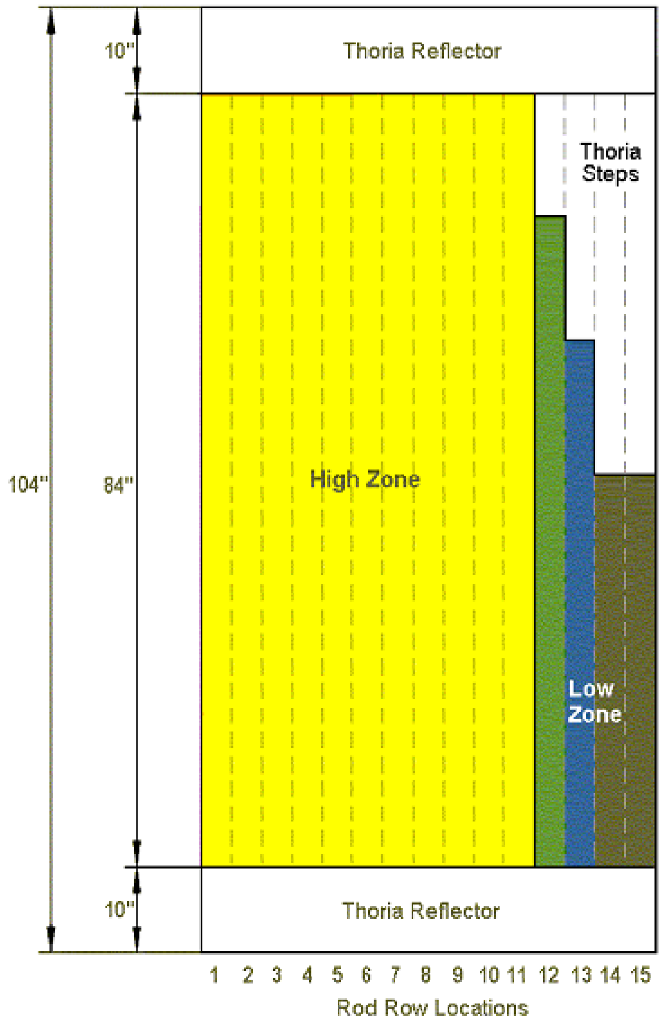
Source: Ref. 2.2.20, Figure 3-2

Figure 6-27. Layout of LWBR Fuel Rods in a Seed Assembly

	Rod Type	Binary Stack Length	Enrichment (U-fissile wt %)	Theoretical Density (g/cm^3)	Mass Initial Fissile (g)/Rod	Number of Rods/Core	Mass Initial Fissile (g)/Core
	05, 06	84"	5.195	10.042	34.57	3,972	137,312
	04	70"	4.327	10.035	23.92	792	18,945
	03	56"	4.327	10.035	19.14	864	16,537
	01, 02, 07, 08	42"	4.327	10.035	14.33	1,800	25,794
						7,428	198,586

Source: Ref. 2.2.20, Figure 3-2

Figure 6-28: Key Table for Figure 6-27



Source: Ref. 2.2.20, Figure 3-1

Figure 6-29: R-Z Schematic of an LWBR Seed Assembly

Pertinent dimensions and densities for the two types of SLWBR fuel pellets are detailed in Table 6-17.

Table 6-17. Characteristics of Pellets in the SLWBR Seed Region

Property (units)	**Seed Region Enrichment Zone**		
	High (5.202 wt% U-fissile enriched)[a]	**Low (4.337 wt % U-fissile enriched)[a]**	**ThO_2**
Diameter[b] , mm (in)	6.4008 (0.2520)	6.4008 (0.2520)	6.49224 (0.2556)
Diameter[c] , mm (in)	6.4008 ± .0127 (0.252 ± 0.0005)	6.4008 ± .0127 (0.252 ± 0.0005)	6.4897 ± .0127 (0.2555 ± .0005)
Length[b] , mm (in)	15.621 (0.615)	11.2776 (0.444)	13.462 (0.530)
Length[c] , mm (in)	15.621 ± .508 (0.615 ± .020)	11.303 ± .508 (0.445 ± .020)	13.462 ± .508 (0.530 ± .020)
Void Fraction[b] (of chamfers, dishes, and chip defects)	0.01172	0.01704	0.01253
Percent Theoretical Density[b]	97.554	97.712	98.013
Theoretical Density, g/cm^3	10.042	10.035	9.999
Bulk Density[d], g/cm^3	9.710	9.665	9.678

Source: Reference 2.2.17, Table 3-5, unless otherwise noted.

NOTES: [a] Weight percent fissile (U-233+U-235)·100/(Th+U).
[b] Average as built.
[c] Design specification.
[d] Ref. 2.2.18, Attachment III, EXCEL Spreadsheet *sheet1*.

The fuel pins have a uniform center-to-center spacing (pitch) along the length of the assembly, and are supported by nine stainless steel grid plates. The outer support shell of the assembly is a ~2 mm thick hexagonal duct (shroud) made of Zircaloy-4.

A rectangular basket structure insert is used to position the SLWBR fuel assembly in a 15 ft. DOE SNF canister. The basket plates are made of 0.95 cm thick stainless steel (Type 316L or UNS S31603) and the inner widths of the plates are 2.95 cm and 2.57 cm, respectively. Figure 6-32 shows a cross-sectional view of the MCNP model of a DOE SNF canister loaded with a SLWBR seed assembly.

A summary of pertinent dimensions and material specifications for SLWBR SNF is provided in Table 6-18. The SLWBR fuel composition used in the MCNP calculations is detailed in Table 6-19. Note that the nominal fuel composition includes 10 vol % water fraction. The composition of the ThO_2 pellets associated with the SLWBR fuel pins is provided in Attachment 1 (Table A1-21).

Table 6-18. Shippingport LWBR Fuel and Packaging Dimensions and Materials

Component	**Material**	**Parameter**	**Source Dimension (mm)**	**Modeled Dimension (cm)**
Fuel	UO_2-ThO_2	Diameter (High Enriched Pin)	~6.40 (0.2520 in.)	~6.40
		Diameter (Low Enriched Pin)	~6.40 (0.2520 in.)	~6.40
		Diameter (Thoria Pin)	~6.49	~6.49
		Length - High Enriched Zone	~2133.60	~2133.60
		Length - Low Enriched Zones	~1778.00 ~1422.40 ~1066.80	~1778.00 ~1422.40 ~1066.80
		Length – Thoria Reflector Zones	~254.00	~254.00
		Total Length of All Zones	~2641.60	~2641.60
		Pin pitch	~9.36	~9.36
		Number per basket	619	619
Assembly	---------	Inside Dimension (Hexagonal)	~243.59	~243.59
		Shell Thickness	~2.03	~2.03
Cladding	Zircaloy-4	Outer Diameter	~7.78	~7.78
		Inner Diameter	~6.65	~6.65
		Thickness	~0.56	~0.56
Outer Support Shell	Zircaloy-4	Wall Thickness	~2.03	~2.03
Basket	SS 316L	Inner Widths of Basket Plates	257 – x-direction 295 – y-direction	257 – x-direction 295 – y-direction
		Thickness of Basket Plates	~9.50	~9.50

Source: Reference 2.2.1, Table 40

Table 6-19. Material Specifications for SLWBR Fuel

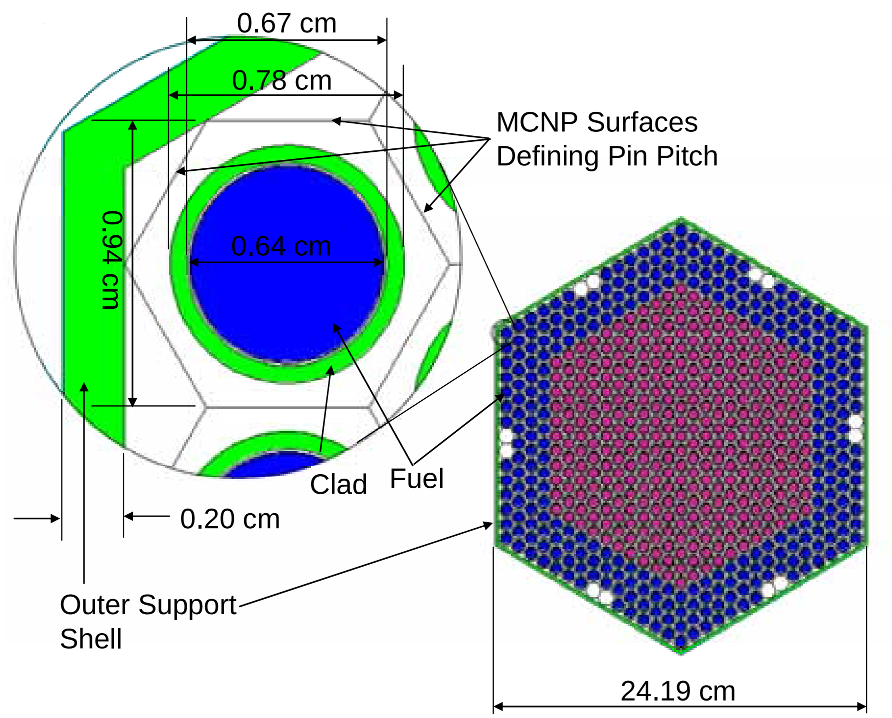
Element/ Isotope	ZAID	Fuel Zone Fissile Enrichment wt. % [($^{233}U+^{235}U$)/U-Th]	Weight Fraction (%) Fuel Matrix Water Fraction (Vol %)					
			0.0	10.0	20.0	30.0	40.0	50.0
^{232}Th	90232.50c	High (5.2)	83.276	82.429	81.598	80.785	79.987	79.205
^{233}U	92233.50c		4.570	4.523	4.478	4.433	4.389	4.347
^{234}U	92234.50c		0.060	0.059	0.059	0.058	0.058	0.057
^{235}U	92235.50c		0.004	0.004	0.004	0.004	0.004	0.004
^{236}U	92236.50c		0.001	0.001	0.001	0.001	0.001	0.001
^{238}U	92238.50c		0.017	0.017	0.017	0.016	0.016	0.016
^{16}O	8016.50c		12.072	12.853	13.618	14.368	15.103	15.824
^{1}H	1001.50c		0.000	0.114	0.225	0.335	0.442	0.547
Density (g/cm^3)			9.7100	9.8098	9.9096	10.0095	10.1093	10.2091
^{232}Th	90232.50c	Low (4.3)	84.050	83.191	82.349	81.524	80.715	79.923
^{233}U	92233.50c		3.810	3.771	3.733	3.695	3.659	3.623
^{234}U	92234.50c		0.050	0.049	0.049	0.048	0.048	0.048
^{235}U	92235.50c		0.003	0.003	0.003	0.003	0.003	0.003
^{236}U	92236.50c		0.001	0.001	0.001	0.001	0.001	0.001
^{238}U	92238.50c		0.014	0.014	0.014	0.014	0.013	0.013
^{16}O	8016.50c		12.072	12.856	13.625	14.378	15.116	15.840
^{1}H	1001.50c		0.000	0.114	0.226	0.336	0.444	0.549
Density (g/cm^3)			9.6650	9.7648	9.8646	9.9645	10.0643	10.1641

Source: The SLWBR fuel composition and density is derived in the Attachment II, Homog_mats.xls, sheet *Shipping*, of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

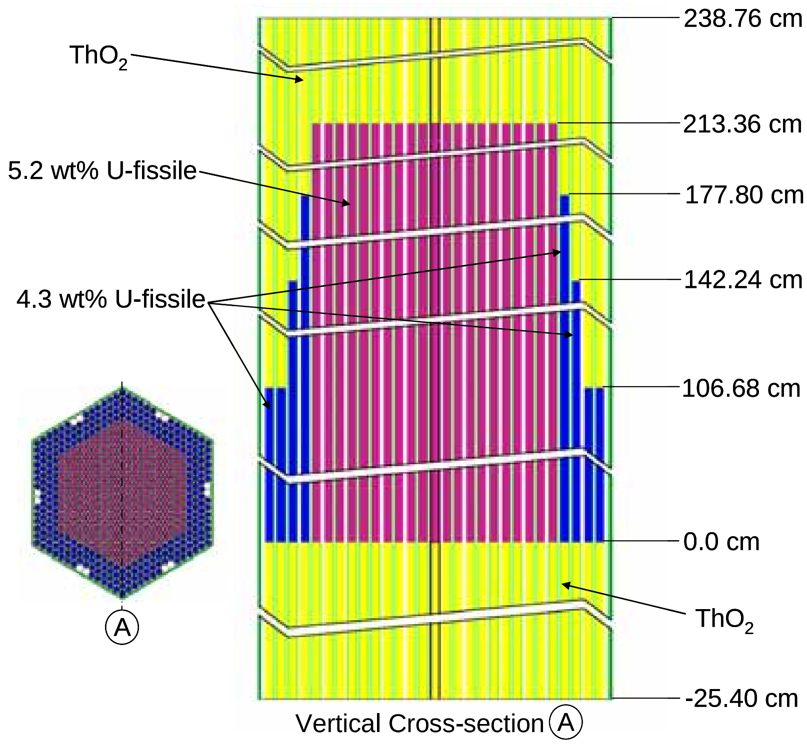
Compositions for the aluminum shot fill material that is used as filler in the DOE SNF canister is provided in Attachment 1. The shot is composed primarily of aluminum with some small amount of $GdPO_4$ that is used as a neutron absorber. The void fraction of the shot is 0.4667.

Figure 6-30 through Figure 6-34 provide cross-sections of the SLWBR SNF MCNP models.



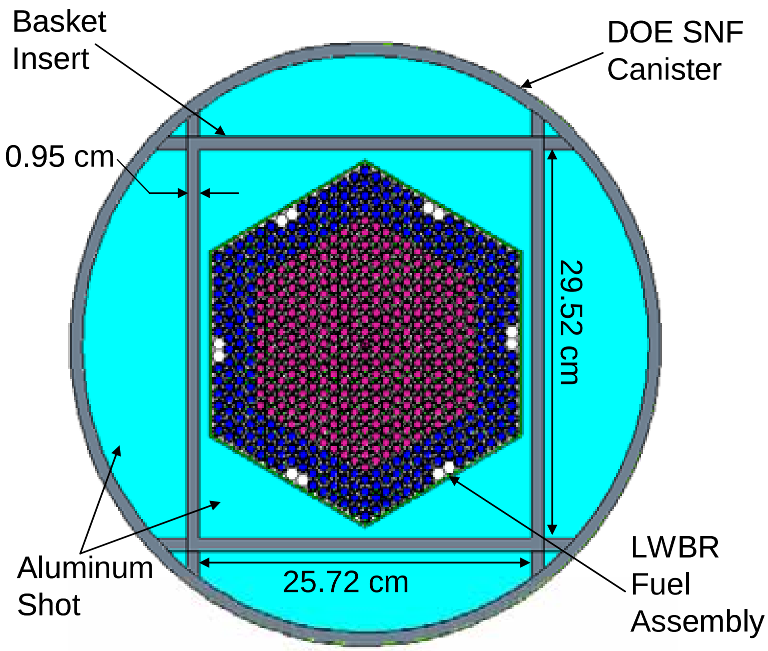
Source: Original

Figure 6-30: Horizontal Cross-section of LWBR SNF Assembly MCNP Model



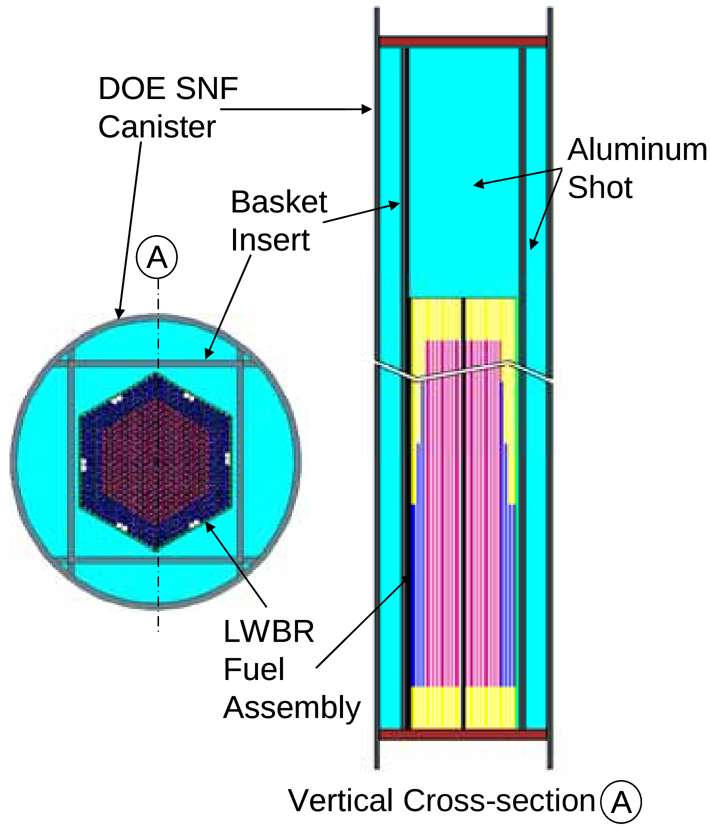
Source: Original

Figure 6-31: Vertical Cross-section of LWBR SNF Assembly MCNP Model



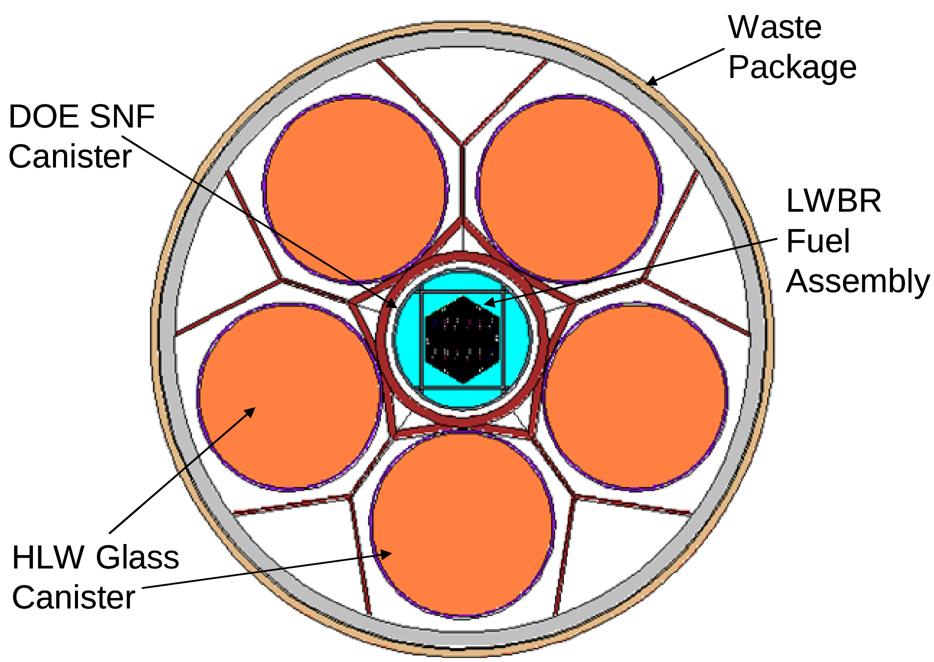
Source: Original

Figure 6-32: Horizontal Cross-section of MCNP Model of the LWBR Fuel Assembly Basket Insert for a DOE SNF Canister



Source: Original

Figure 6-33: Vertical Cross-Section of MCNP Model of the LWBR Fuel Assembly in a DOE SNF Canister



Source: Original

Figure 6-34: Horizontal Cross-section of MCNP Model of LWBR Fuel in a Waste Package

6.1.3.6 Shippingport PWR Spent Nuclear Fuel

The Core 2 Seed 2 (C2 S2) is examined in the MCNP calculations because it has a higher U-235 loading per cluster than the other fuel types. The SPWR C2 S2 fuel cluster is composed of four fuel subclusters arranged in a square array with ~1.2 cm spacing between them to form a cruciform-shaped channel in the center of the fuel cluster. A detailed cross-sectional view of the fuel cluster is shown in Figure 6-36. The subclusters are identical, i.e., the plates are arranged identically, but each subcluster is rotated 90° relative to its adjacent subclusters.

The C2 S2 subclusters are ~8.7 cm square, with the active fuel length of ~246 cm. The C2 S2 subclusters contain nineteen fuel and two neutron absorber (end) plates. The fuel plates are formed (see Figure 6-37) by sandwiching enriched UO_2-ZrO_2-CaO alloy wafers between two Zircaloy-4 cover plates and four side strips. The uranium (U-235) enrichment at the beginning of life is ~93.2%. The fuel meat production density is ~87.5% of the theoretical density. Additional void space results because the volume of the fuel wafers is smaller than the volume of the channel in which they are fitted. The neutron absorbing material in the two end plates is neglected in the MCNP models. The C2 S2 subcluster has three zones of fuel wafers (see Figure 6-36 and Figure 6-38) with varying uranium loadings (summarized in Table 6-20).

Table 6-20. Fuel Wafer Compositions for the SPWR C2 S2 fuel

Fuel Zone	UO_2-ZrO_2-CaO	Fissile Loading (kg)
Zone 1 (inner)	54.9 w/o UO_2 39.9 w/o ZrO_2 5.2 w/o CaO	7.076
Zone 2 (middle)	40.2 w/o UO_2 54.0 w/o ZrO_2 5.8 w/o CaO	8.987
Zone 3 (outer)	26.5 w/o UO_2 67.1 w/o ZrO_2 6.4 w/o CaO	3.437
Total BOL/Cluster		19.500

Source: Ref. 2.2.19, Table 3-2

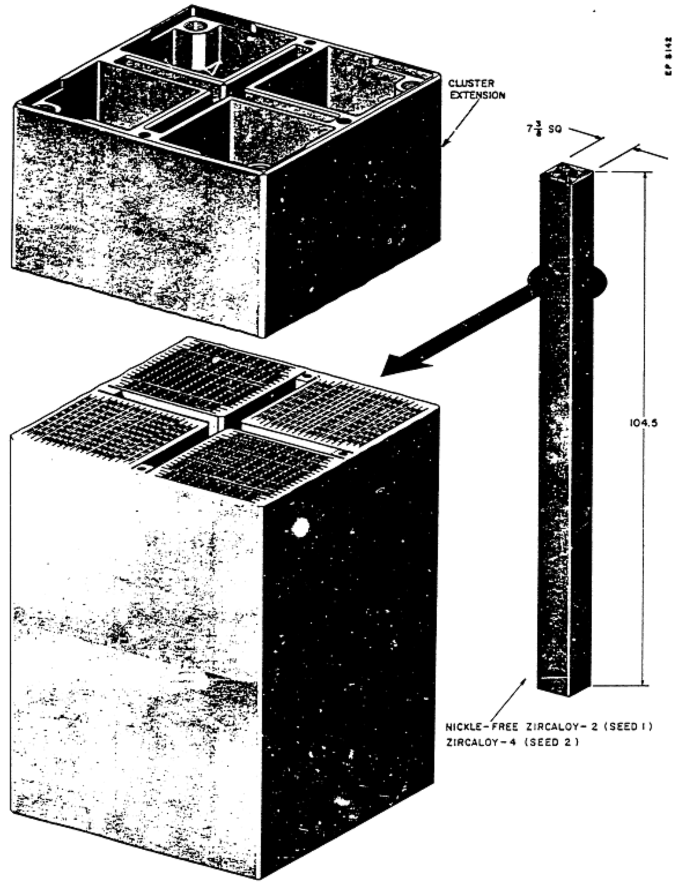
The SPWR fuel composition used in the MCNP calculations is detailed in Table 6-21. Note that the nominal fuel composition includes 10 vol % water fraction.

Table 6-21. Material Specifications for SPWR Fuel

Element/ Isotope	ZAID	Fuel Zone	Weight Fraction (%)					
			Fuel Matrix Water Fraction (Vol %)					
			0.0	10.0	20.0	30.0	40.0	50.0
^{235}U	92235.50c	Zone 1 (inner)	45.040	44.344	43.669	43.015	42.380	41.763
^{238}U	92238.50c		3.286	3.235	3.186	3.138	3.092	3.047
Zr	40000.60c		29.539	29.082	28.640	28.210	27.794	27.389
Ca	20000.50c		3.716	3.659	3.603	3.549	3.497	3.446
^{16}O	8016.50c		18.418	19.506	20.561	21.584	22.577	23.541
^{1}H	1001.50c		0.000	0.173	0.341	0.503	0.661	0.814
Density (g/cm^3)			6.3600	6.4598	6.5596	6.6595	6.7593	6.8591
^{235}U	92235.50c	Zone 2 (middle)	32.980	32.421	31.881	31.358	30.853	30.363
^{238}U	92238.50c		2.406	2.366	2.326	2.288	2.251	2.215
Zr	40000.60c		39.977	39.300	38.645	38.011	37.398	36.805
Ca	20000.50c		4.145	4.075	4.007	3.941	3.878	3.816
^{16}O	8016.50c		20.491	21.649	22.768	23.851	24.898	25.913
^{1}H	1001.50c		0.000	0.190	0.373	0.550	0.722	0.888
Density (g/cm^3)			5.7900	5.8898	5.9896	6.0895	6.1893	6.2891
^{235}U	92235.50c	Zone 3 (outer)	21.741	21.343	20.959	20.588	20.231	19.886
^{238}U	92238.50c		1.586	1.557	1.529	1.502	1.476	1.451
Zr	40000.60c		49.675	48.765	47.888	47.042	46.225	45.437
Ca	20000.50c		4.574	4.490	4.409	4.332	4.256	4.184
^{16}O	8016.50c		22.424	23.640	24.812	25.943	27.034	28.088
^{1}H	1001.50c		0.000	0.205	0.403	0.593	0.777	0.955
Density (g/cm^3)			5.3500	5.4498	5.5496	5.6495	5.7493	5.8491

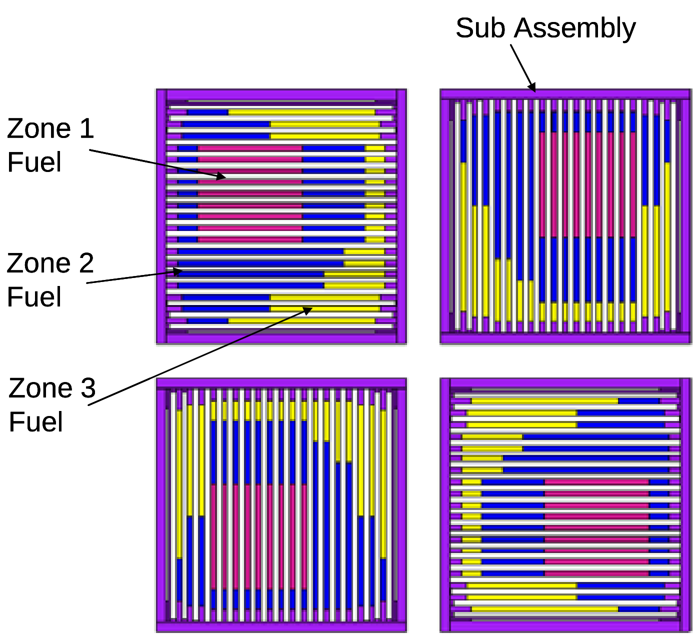
Source: The SPWR fuel compositions and densities are derived in the Attachment II, Homog_mats.xls, sheet *Shipping*, of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).



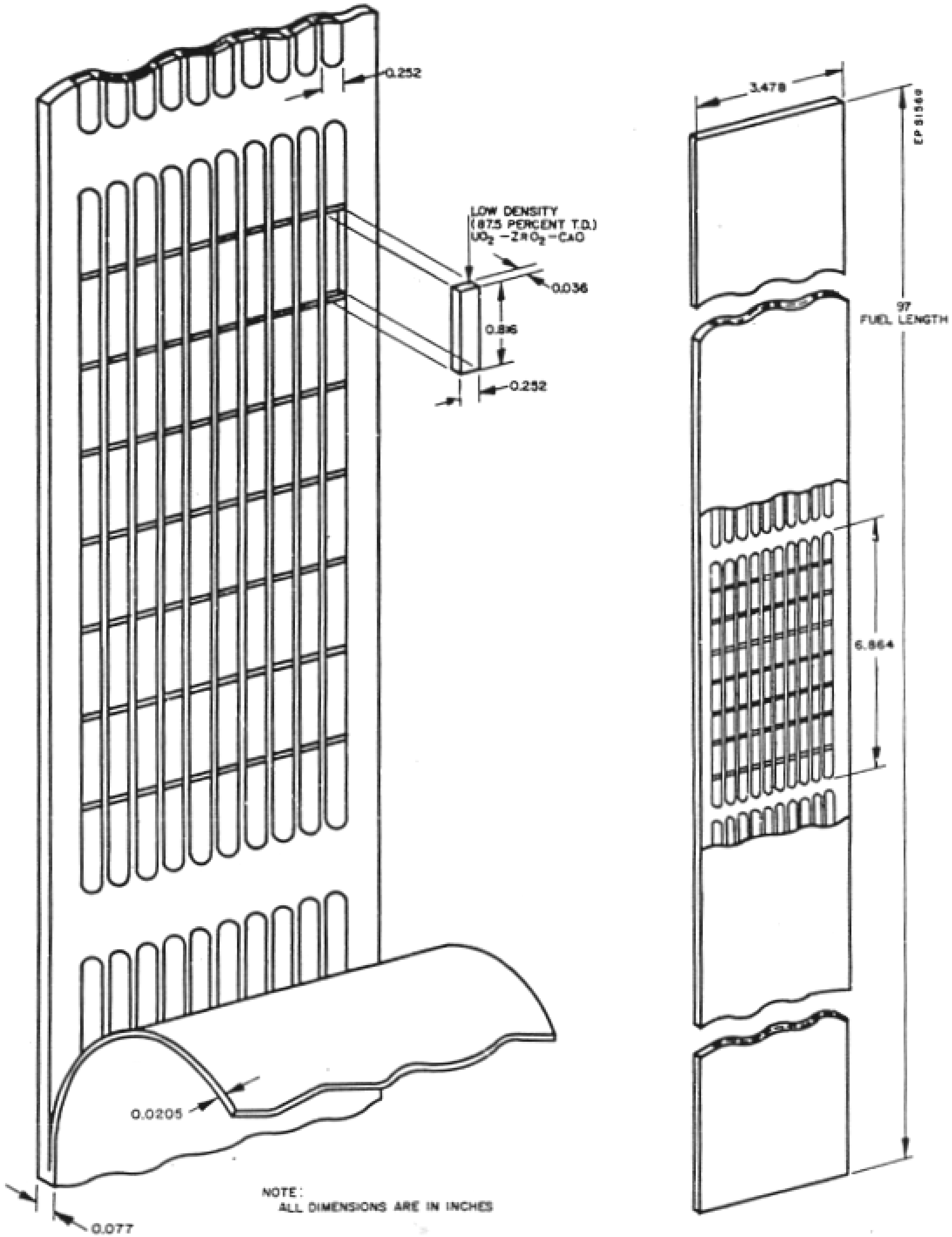
Source: Ref. 2.2.19, Figure 3-2

Figure 6-35. SPWR Seed Fuel Cluster with Cruciform Control Rod Channel



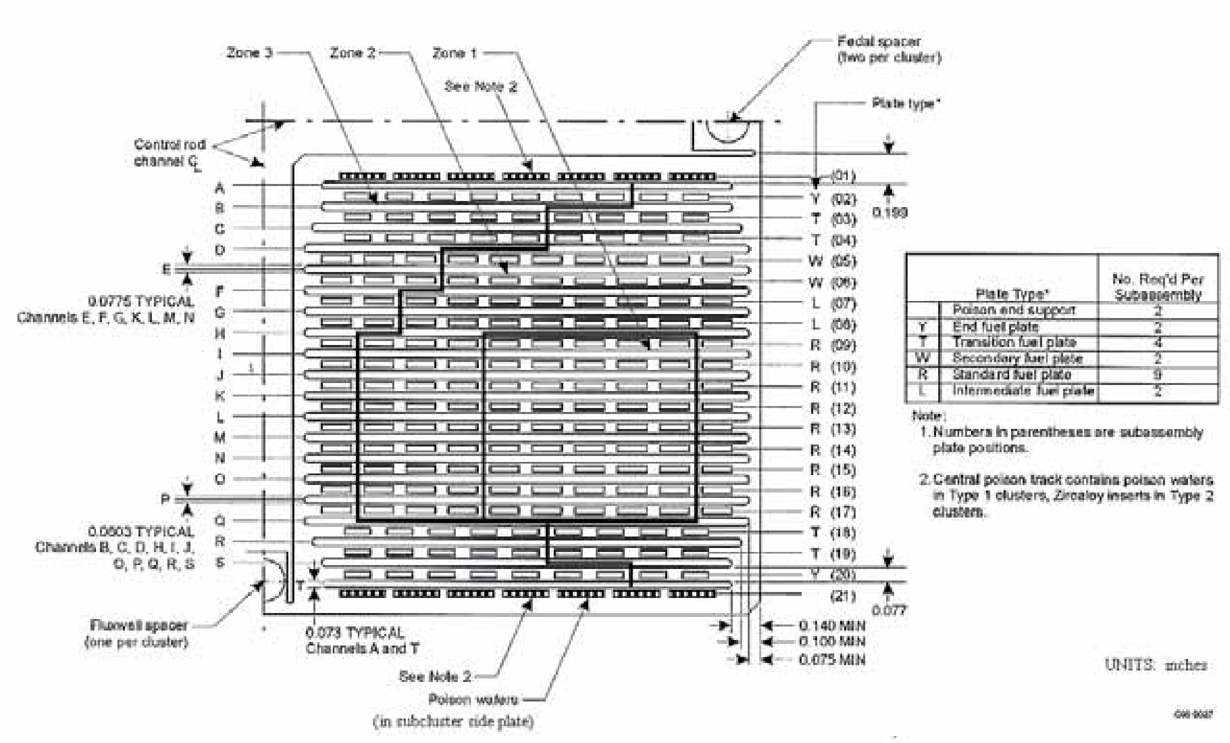
Source: Original

Figure 6-36: Cross-Section of SPWR Fuel Assembly MCNP Model



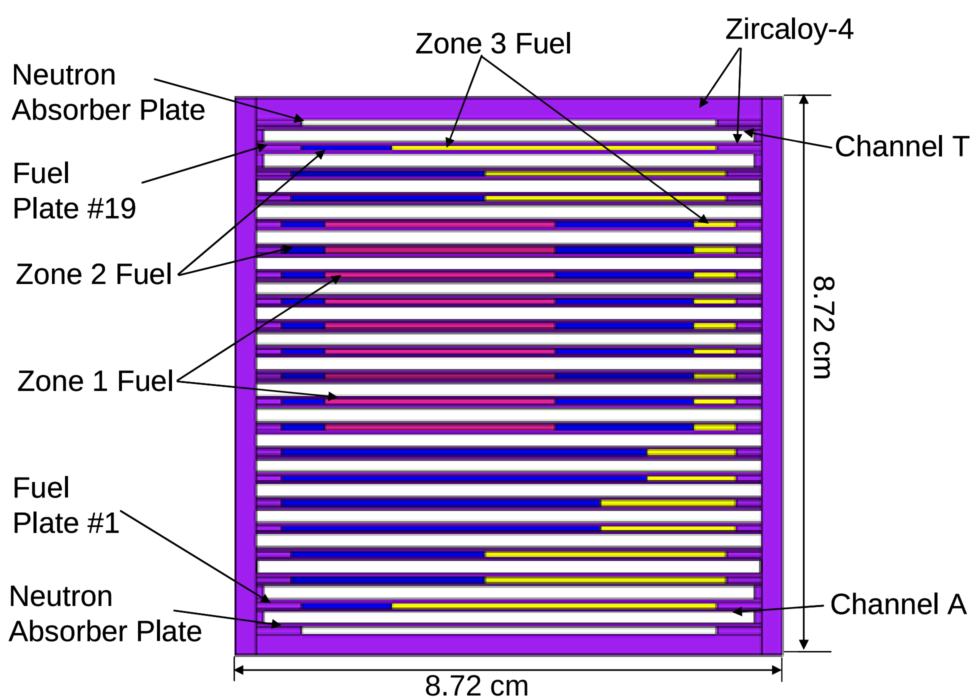
Source: Ref. 2.2.19, Figure 3-1

Figure 6-37. SPWR Seed Plate Cross-Section Showing Fuel Wafer Compartments



Source: Ref. 2.2.21, Figure 17

Figure 6-38. SPWR Core 2 Seed 2 Subcluster Cross Section



Source: Original

Figure 6-39: Horizontal Cross-section of SPWR Sub Assembly MCNP Model

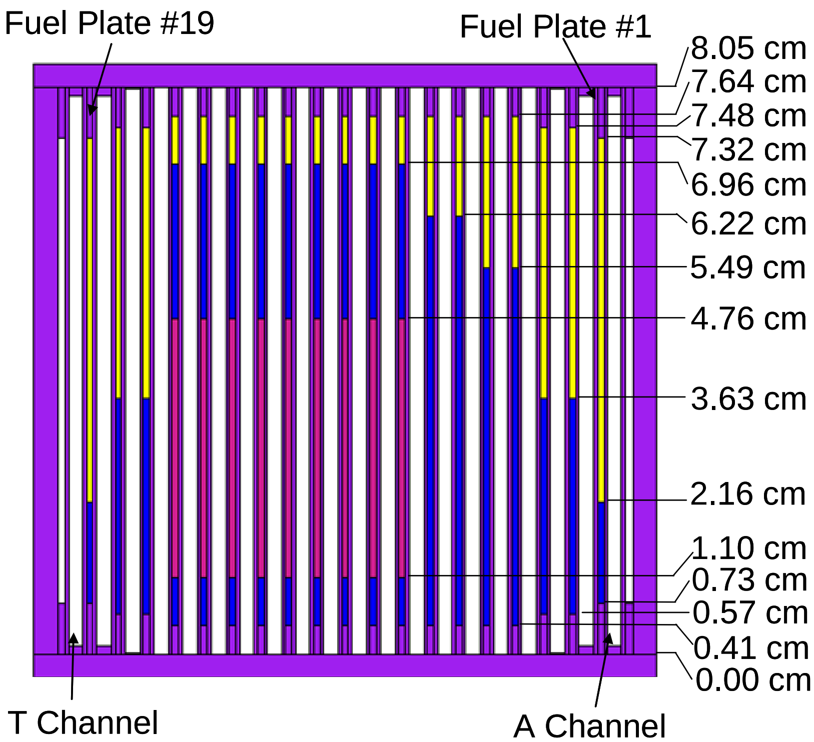


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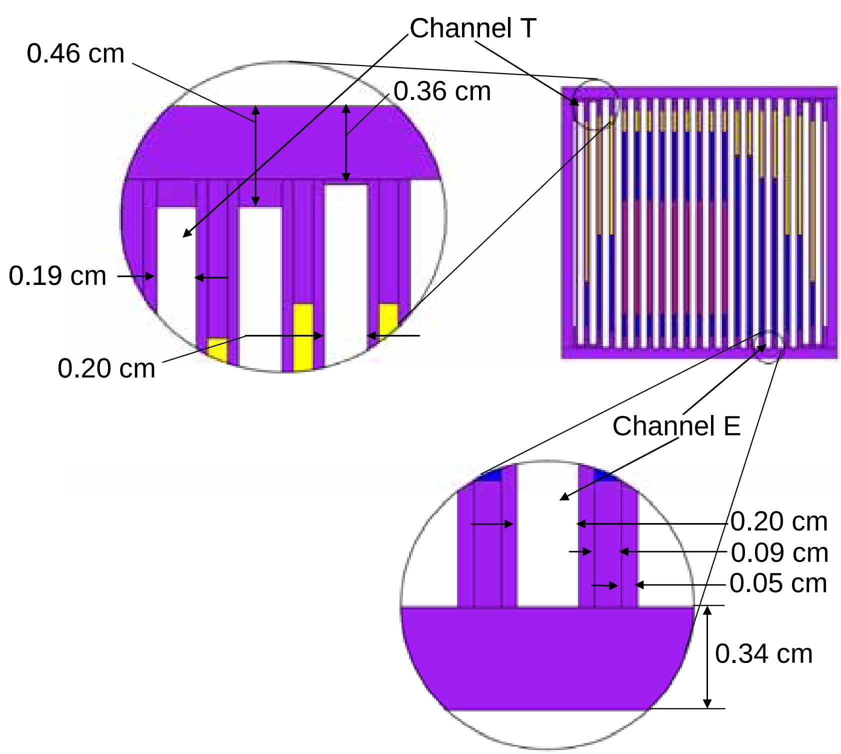
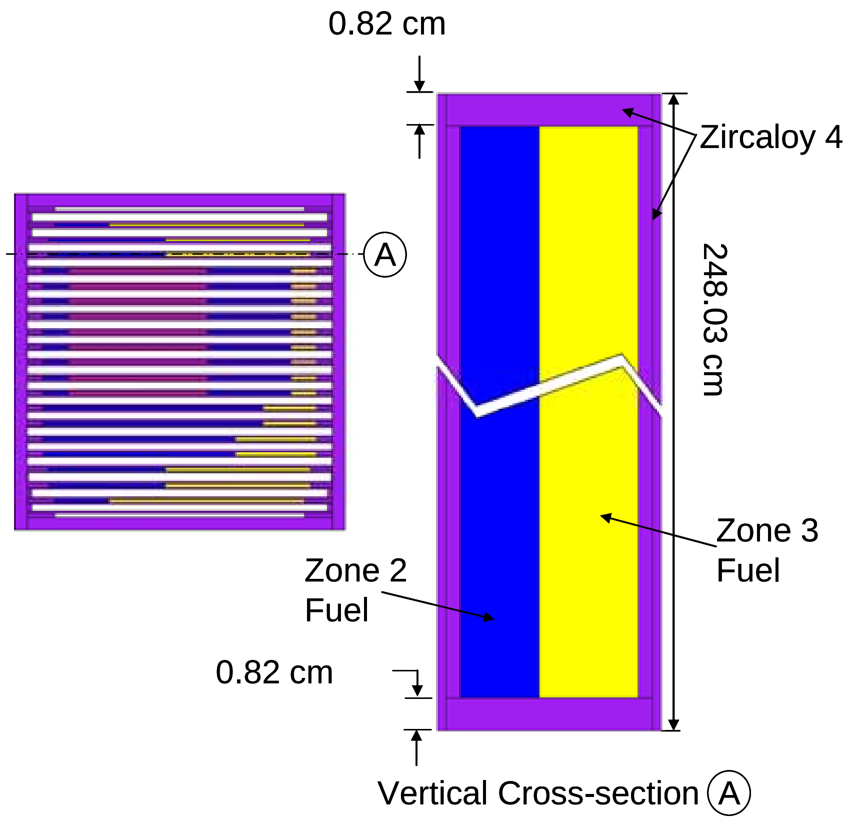
Figure 6-40: Horizontal Cross-section of SPWR Sub Assembly MCNP Model – Additional Detail



Source: Original

Figure 6-41: Fuel Plate Detail for SPWR Fuel MCNP Model

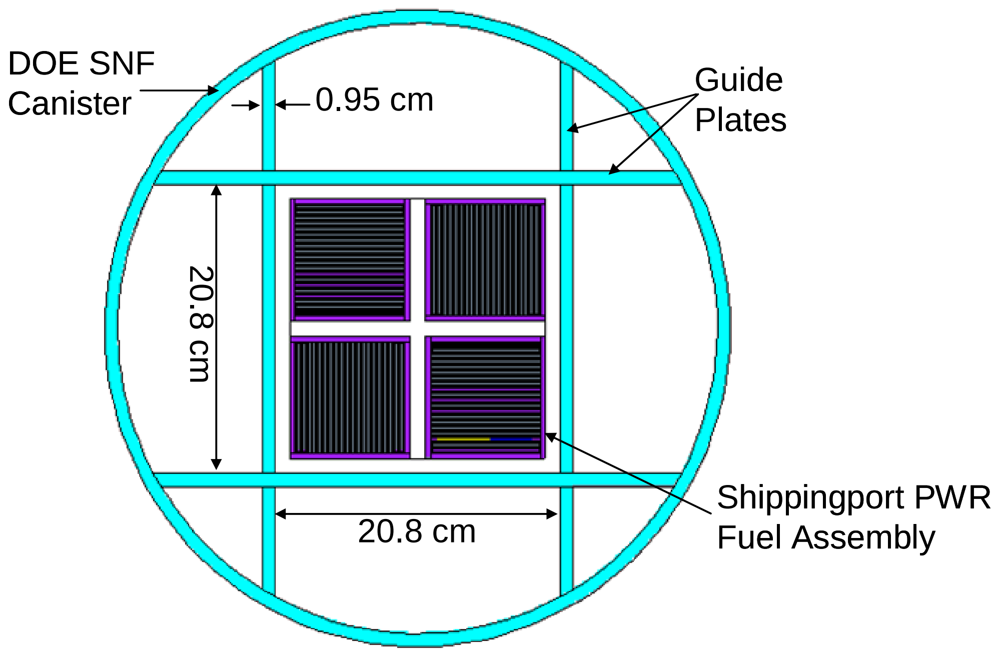


Source: Original

Figure 6-42: Vertical Cross-section of SPWR Sub Assembly MCNP Model

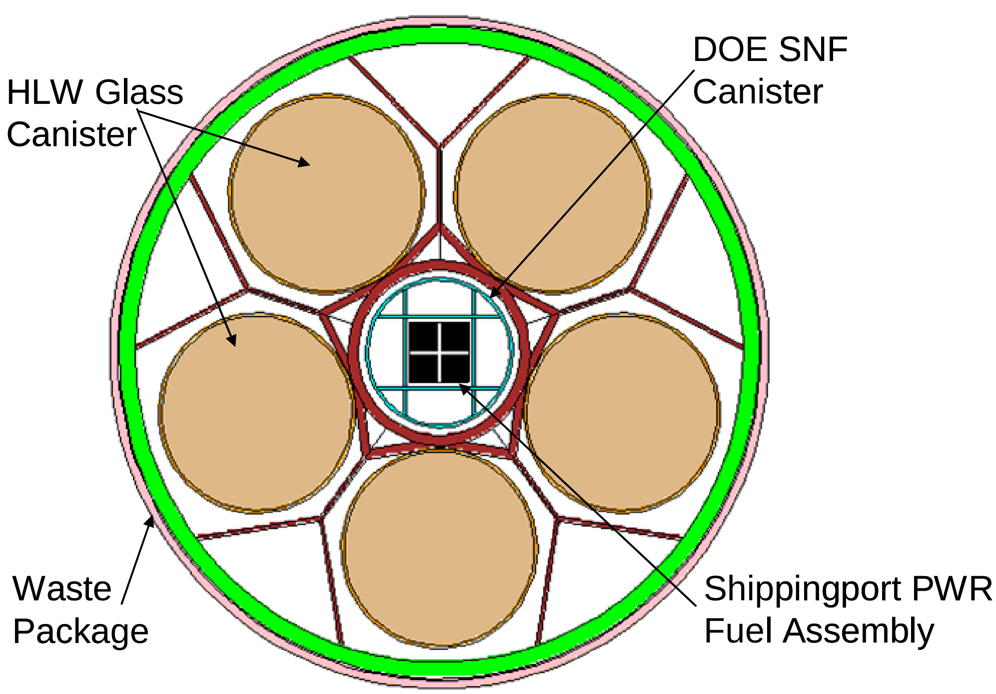
A guide plate assembly is used to position the SPWR SNF cluster in the DOE SNF canister. The plates that form the guide assembly are ~0.95 cm thick stainless steel (Type 316L). The center position of the guide assembly forms a ~20.80 cm square that holds one cluster assembly. Figure 6-43 shows a cross-sectional view of the guide assembly in the DOE SNF canister. Figure 6-44 shows a cross-sectional view of the DOE SNF canister with a SPWR assembly loaded in a DOE SNF WP. The fuel assembly is centered in the basket insert guide plates inside the SNF canister.

A summary of pertinent dimensions and material specifications is provided in Table 6-22.



Source: Original

Figure 6-43: Cross-Sectional View of the Canister and Guide Assembly for SPWR



Source: Original

Figure 6-44: Horizontal Cross-Section of Waste Package MCNP Model with SPWR Assembly

Table 6-22. SPWR Fuel and Packaging Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Fuel	UO_2-ZrO_2-CaO	Fuel Wafer Thickness	~0.09	~0.09
		Fuel Wafer Width	~0.64	~0.64
		Separation between Fuel Wafers	~0.10	~0.10
		Active Fuel Length	~246.38	~246.38
		Length of Fuel Plate	~248.02	~248.02
		Fuel Assembly Width	~18.73	~18.73
		Fuel Assembly Length	~265.43	~265.43
		Number of assemblies	4 (forming 1 cluster)	4
Cladding	Zircalloy-4	Thickness	~0.05	~0.05
Channels	--------	Channels A & T Thickness	~0.19	~0.19
		Channels B, C, D, H, I, J, O, P, Q, R, & S Thickness	~0.20	~0.20
		Channels E, F, G, K, L, M, & N Thickness	~0.20	~0.20
Guide Plates	SS 316L	Inner Widths of Guide Plates	~20.80	~20.80
		Thickness of Guide Plates	~0.95	~0.95

Source: Ref. 2.2.1, Table 41

6.1.3.7 TRIGA SNF

TRIGA fuel contains various uranium loadings as a fine metallic dispersion in a uranium-zirconium hydride matrix ($UZrH_x$). The H/Zr ratio, i.e., the subscript x, is nominally 1.6 (in the face-centered cubic delta phase); although earlier fuels used an H/Zr ratio of 1.0. The highly enriched version of TRIGA fuel (up to 93.15 % and discontinued after 1979), as well as newer fuels with higher fissile loadings of low-enriched uranium, contain up to about 3 wt% erbium as a burnable absorber.

The MCNP calculations performed in support of this document utilize the Fuel Life Improvement Program (FLIP) type fuel (70% U-235 enrichment) with a standard-streamline stainless steel clad as the basis for the TRIGA fuel model. Table 6-23 provides the as modeled dimensions of the TRIGA fuel element. The modeled fuel is intended to conservatively describe the TRIGA FLIP highly enriched uranium elements. It contains a slightly larger fissile mass and neglects neutron poisons. Figure 6-45 provides cross-sectional views of the TRIGA fuel element as modeled in the MCNP models.

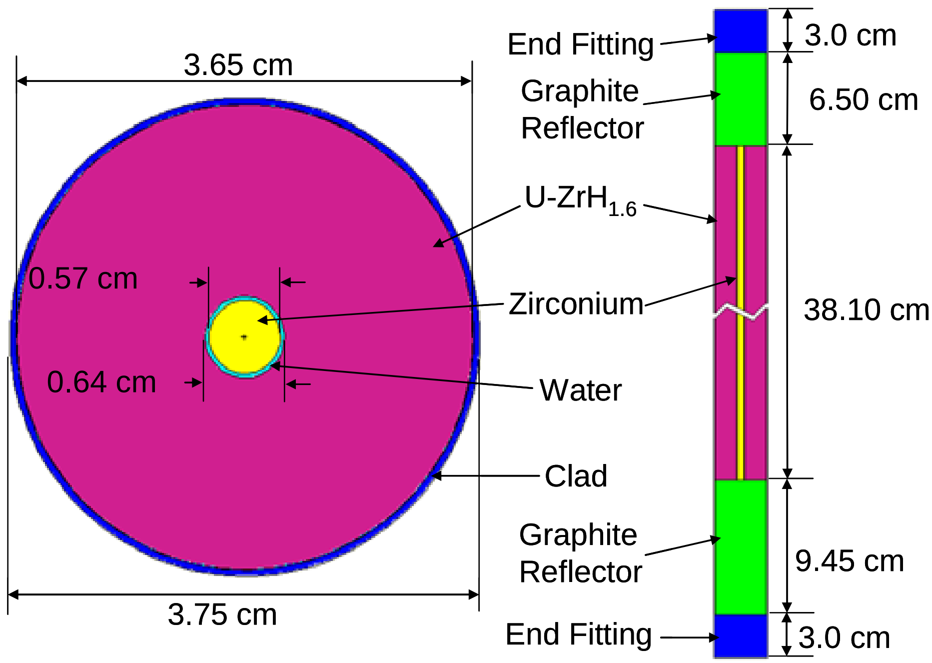
Table 6-23. TRIGA Fuel Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Zr Core	Zirconium	Outer Diameter	~0.57	~0.57
		Length	~38.10	~38.10
Fuel	U-$ZrH_{1.6}$	Inner Diameter	~0.64	~0.64
		Outer Diameter	~3.64	~3.64
		Length	~38.10	~38.10
Upper Reflector	Graphite	Outer Diameter	~3.64	~3.64
		Length	~6.50	~6.50
Lower Reflector	Graphite	Outer Diameter	~3.64	~3.64
		Length	~9.45	~9.45
Cladding	SS 304L	Inner Diameter	~3.65	~3.65
		Outer Diameter	~3.75	~3.75
		Length	Not given	~54.05 [c]
End-Fitting	SS 304L	Length	N/A	~3.0 [b]

Source Reference 2.2.1, Table 30

NOTES: [b] The end-fittings were represented as a solid right circular cylinder with a length of 30 mm each based on conservation of mass, and an adjacent region of void for the remainder of the fuel pin length.

[c] Calculated based on the distance from the bottom of the upper end fitting to the top of the lower end fitting.



Source: Original

Figure 6-45: Cross-sections of the TRIGA Fuel Element as Modeled in MCNP

The TRIGA fuel composition used in the MCNP calculations is detailed in Table 6-24. Note that the nominal fuel composition includes 10 vol % water fraction.

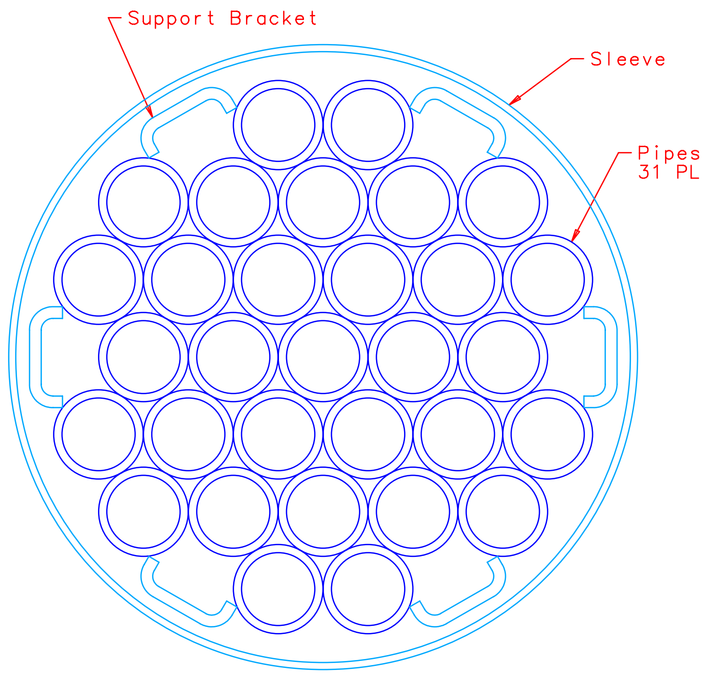
Table 6-24. Material Specifications for TRIGA Fuel

Element/ Isotope	ZAID	Weight Fraction (%)					
		Fuel Matrix Water Fraction (Vol %)					
		0.0	10.0	20.0	30.0	40.0	50.0
^{235}U	92235.50c	5.940	5.851	5.765	5.682	5.600	5.521
^{238}U	92238.50c	2.558	2.520	2.483	2.447	2.412	2.378
Zr	40000.60c	89.911	88.568	87.265	86.000	84.770	83.576
^{1}H	1001.50c	1.591	1.734	1.873	2.009	2.140	2.267
^{16}O	8016.50c	0.000	1.326	2.614	3.863	5.078	6.258
Density (g/cm^3)		6.5844	6.6842	6.7840	6.8839	6.9837	7.0835

Source: The TRIGA fuel composition and density is derived in the Attachment II, Homog_mats.xls, sheet *TRIGA*, of Ref. 2.2.1. The fuel composition and density for the 10, 20 ,30, 40 and 50 vol % water fraction scenarios are based on the dry (i.e. 0 vol % water fraction) fuel composition value, with adjustment for water fraction. The fuel water content is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

NOTES: The nominal fuel composition includes a 10 vol% water fraction, which is conservatively added to the fuel matrix without fuel displacement (i.e. no fuel reduction).

The TRIGA fuel basket is designed to fit within the short DOE SNF fuel canister. The basket design is based upon a revised basket design developed to address dimensional tolerance considerations (Ref. 2.2.23, Appendix F, Section F1.4). The TRIGA fuel basket is designed to hold 31 fuel elements. To provide neutron poisoning, each of the basket tubes is constructed from nickel-gadolinium alloy. Three baskets are stacked in the canister to provide a total of 93 fuel element positions. A stainless steel sleeve surrounds each basket. The basket layout is sketched in Figure 6-46 and relevant dimensions are provided in Table 6-25. This table also provides a summary of pertinent dimensions and material specifications.



Source: Ref. 2.2.23, Figure F-4

Figure 6-46. Cross-Sectional View of DOE SNF Canister with Basket for TRIGA Fuel

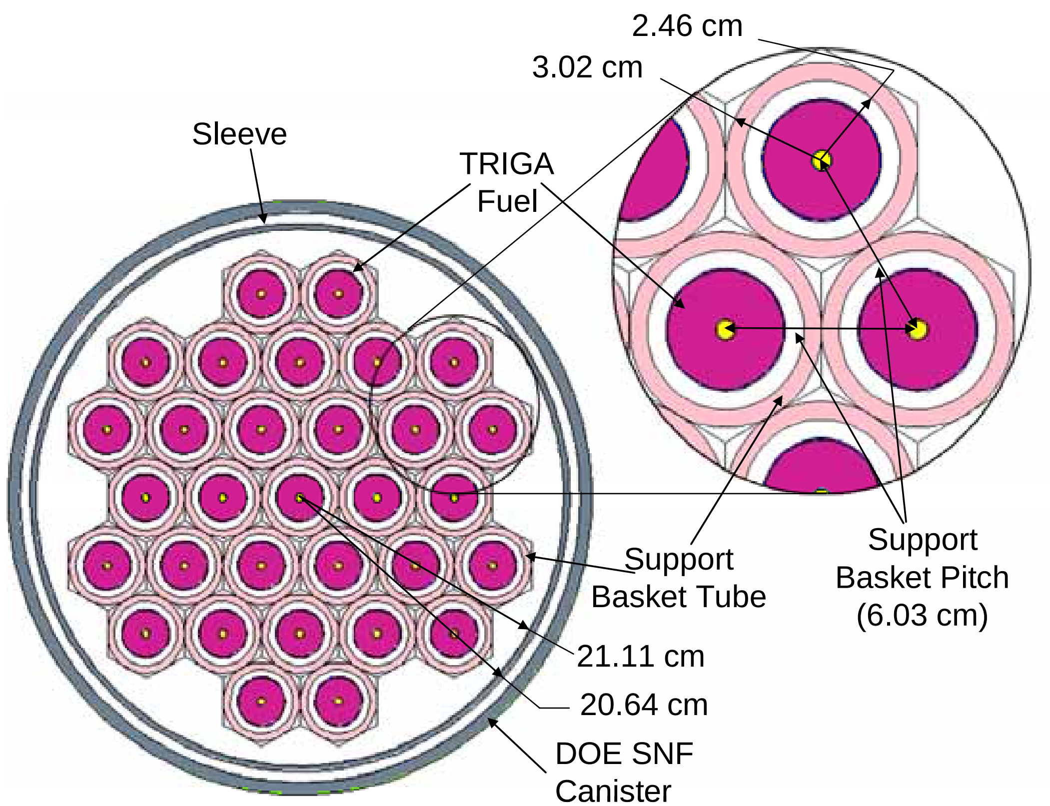
Table 6-25. TRIGA Support Basket Dimensions and Materials

Component	Material	Parameter	Source Dimension (cm)	Modeled Dimension (cm)
Support Basket (each tube)	Ni-Gd	Inner Diameter	~4.93	~4.93
		Outer Diameter	~6.03	~6.03
		Length	~83.82	~83.60
		Pitch	~6.03	~6.03
Basket Support Bracket	SS 316L	Thickness	~0.79	Omitted [c]
		Length	~15.0	Omitted [c]
Base Plate	SS 316L	Thickness	~0.95	~0.95

Source Reference 2.2.1, Table 30

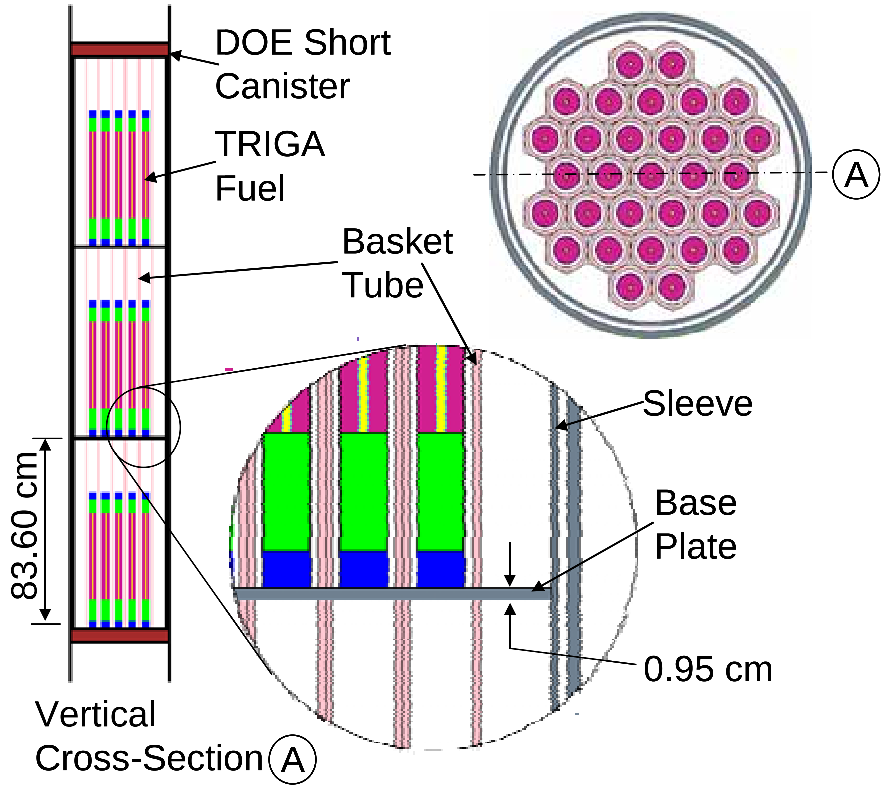
NOTES: [c] For modeling simplifications, certain structural components were omitted from the representations. The impact of removing these from the representations results in more effective neutron moderation and is therefore conservative with respect to criticality safety applications.

Figure 6-47 through Figure 6-49 present cross-sections of the TRIGA fuel loaded into the baskets and the short DOE canister. Figure 6-49 shows a horizontal cross-section of the MCNP model of the TRIGA fuel in the short DOE WP.



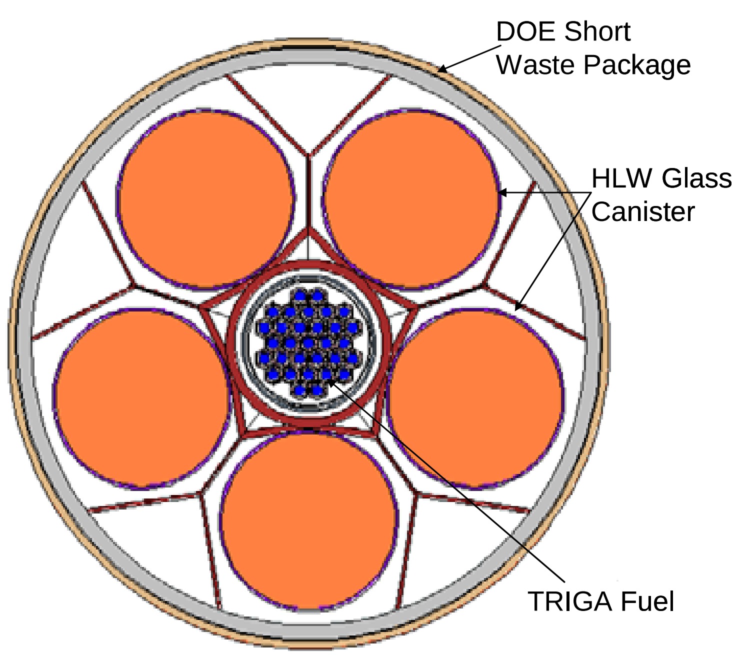
Source: Original

Figure 6-47: Horizontal Cross-section of TRIGA Fuel Basket MCNP Model



Source: Original

Figure 6-48: Vertical Cross-section of TRIGA Fuel Baskets in a Short DOE Canister as Modeled in MCNP



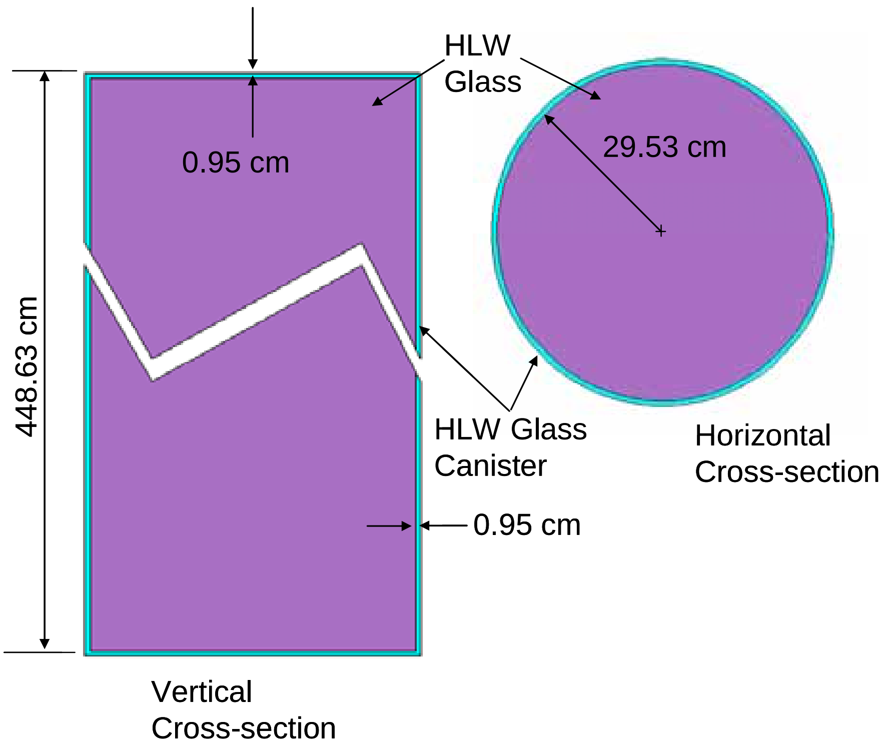
Source: Original

Figure 6-49: Horizontal Cross-section of the DOE Short Waste Package with TRIGA Fuel as Modeled in MCNP

6.1.4 High-Level Waste Glass Pour Canister Variants

6.1.4.1 Long Canister

Figure 6-50 presents cross-sections of, and details dimensions used, in the MCNP model of the HLW glass canister. The HLW glass material composition and density used in the MCNP calculations is detailed in Attachment 1, Table A1-17.



Source: Original

Figure 6-50: Cross-sections of the HLW Glass Canister MCNP Model

6.1.4.2 Short Canister

The short HLW glass pour canister used in the short WP is the same as the long version described in Section 6.1.1.2 except for the length which is shortened to 300 cm in order to fit within the short WP. The HLW glass material composition and density used in the MCNP calculations is detailed in Attachment 1, Table A1-17.

6.2 CALCULATION DESCRIPTION

This section describes the specific DOE SNF canister and WP configurations examined in the MCNP calculations. The configurations examined are grouped into two categories; *normal conditions* and *potential off-normal conditions*.

6.2.1 Normal Conditions

DOE SNF canisters received and accepted in the surface facilities will be hermetically sealed, with a dry, intact, basket containing intact spent nuclear fuel. Operations conducted in the surface facilities are not expected to alter these conditions.

Under normal conditions, DOE SNF WPs received and emplaced in the sub-surface facility will consist of a sealed WP containing five HLW glass canisters and one (centralized) DOE SNF canister.

6.2.1.1 Anticipated Surface Facility and Intra-site Operations

Operations conducted in the surface facilities (which include intra-site operations) concern the receipt of DOE SNF canisters and HLW glass canisters in transportation casks, their unloading, handling and staging, subsequent loading into WPs and transfer to the sub-surface facility for emplacement. These preparatory operations primarily entail:

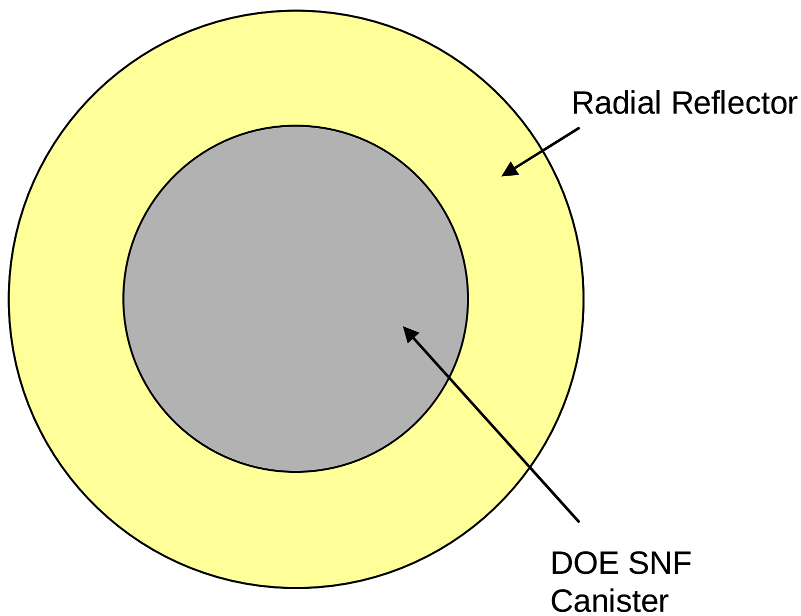
- Receipt of DOE transportation casks containing DOE SNF canisters;
- Receipt of DOE transportation casks containing HLW canisters;
- Upending and removal of DOE transportation casks from their conveyance, including unbolting and removal of lids from casks;
- Transfer of DOE SNF canisters (individually) from their transportation cask to an awaiting WP or to a DOE canister staging rack position;
- Transfer of HLW canisters (individually) from their transportation cask to an awaiting WP or to a DOE canister staging rack position;
- Loading of a WP with one DOE SNF canister (placed in the WP center support tube position) and five HLW glass canisters (placed in the surrounding positions);
- Installation and welding of the WP inner and outer lids; and
- Transfer of completed sealed WPs, using the Transport and Emplacement Vehicle (TEV), to the sub-surface facility.

6.2.1.1.1 DOE SNF Canisters

Based on the abovementioned operations, it is evident that under normal conditions all DOE SNF canisters will comprise a dry intact basket containing intact spent nuclear fuel, and will be handled individually and staged only in an awaiting WP or a DOE canister staging rack position. Furthermore, it is seen that under normal conditions only one DOE SNF canister will be situated within a WP at any one time.

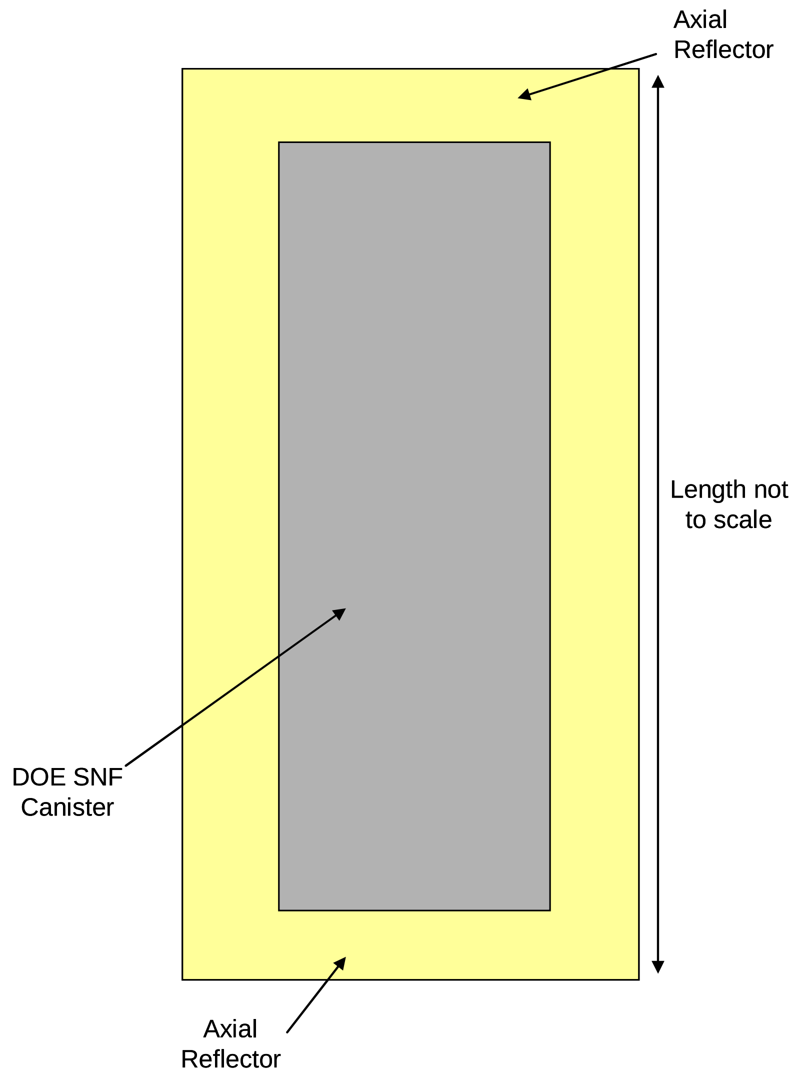
To demonstrate the subcriticality of DOE SNF canisters under the abovementioned normal conditions within the surface facilities, the DOE SNF canisters containing the various SNF/basket types (Section 6.1.3) are evaluated individually (i.e. as a single isolated canister). The explicit arrangement of DOE SNF canisters situated in the DOE canister staging racks is not specifically examined because the normal configuration of canisters in the staging racks is bounded by the configuration (i.e. spacing) of DOE SNF canisters in the infinite planar array calculations reported under the off-normal conditions analysis (Section 6.2.2).

The single DOE SNF canister MCNP models are based on the MCNP models described in Section 6.1 but with incorporated close fitting full-thickness (i.e. 30 cm) reflection adjacent to all surfaces of the canister. A series of reflector materials (Attachment 1) are examined to quantify the sensitivity of k_{eff} to the canister reflection condition. Based on neutron mean free paths in the various reflecting materials or the maximum thickness of the materials that would reasonably be present in the facilities, the reflection conditions accounted for in the single DOE SNF canister MCNP calculations are considered to bound the reflection conditions that could be realized in the surface facilities. This is supported by results of additional calculations recorded in workbook *Ancillary Results* (Attachment 3) which investigate the effect on k_{eff} resultant from progressively increasing reflector thickness from 30 cm to 1 m. Refer to Figure 6-51 and Figure 6-52 for a cross-section view of a single DOE SNF canister model with incorporated close-fitting full thickness reflector.



Source: Original

Figure 6-51: Radial Cross-Section of the DOE SNF Canister MCNP Model with Incorporated Reflector (canister contents not illustrated)



Source: Original

Figure 6-52: Axial Cross-Section of the DOE SNF Canister MCNP Model with Incorporated Reflector (canister contents not illustrated)

6.2.1.1.2 DOE 5-DHLW/DOE SNF WP

Under normal conditions all loaded DOE WPs will comprise five HLW glass canisters and one (centralized) DOE SNF canister containing a dry, intact, basket with intact spent nuclear fuel. Each loaded DOE SNF WP will be handled individually, however, it is recognized that DOE SNF WPs could be placed within close proximity to other WPs prior to transfer to the sub-surface facility for emplacement.

To demonstrate the subcriticality of the DOE SNF WPs under normal conditions within the surface facilities, the DOE SNF WPs are evaluated individually (i.e. as a single isolated system) and in an infinite planar array configuration.

The single WP MCNP models are based on the MCNP models described in Section 6.1 but with incorporated close fitting full-thickness (i.e. 30 cm) reflection adjacent all surfaces of the WP. A series of reflector materials (Attachment 1) are examined to quantify the sensitivity of k_{eff} to the WP reflection condition. Based on neutron mean free paths in the various reflecting materials or the maximum thickness of the materials that would reasonably be present in the facilities, the reflection conditions accounted for in the single DOE SNF WP MCNP calculations are considered to bound the reflection conditions that could be realized in the surface facilities. Refer to Figure 6-53 and Figure 6-54 for a cross-section view of a single DOE SNF WP model with incorporated close-fitting full thickness reflector.

To account for potential displacement of canisters within their WP compartments, the HLW glass canisters are ‘bunched’ by preferential displacement within their compartments. The bunched canister configurations are illustrated in Figure 6-53. The ‘bunched’ HLW glass canister configuration is conservative for the individual WP models because the HLW glass serves as a neutron reflector, and its closer proximity to the DOE SNF canister results in more effective reflection. The ‘bunched’ HLW glass canister configuration is appropriate for use in the infinite planar array configuration calculations because based on the results of the WP calculations (Section 7.1), it is found that WPs are effectively neutronically isolated from one another. Therefore, the exact positioning of the HLW glass canister in the WP is not important for the infinite planar array configuration calculations.

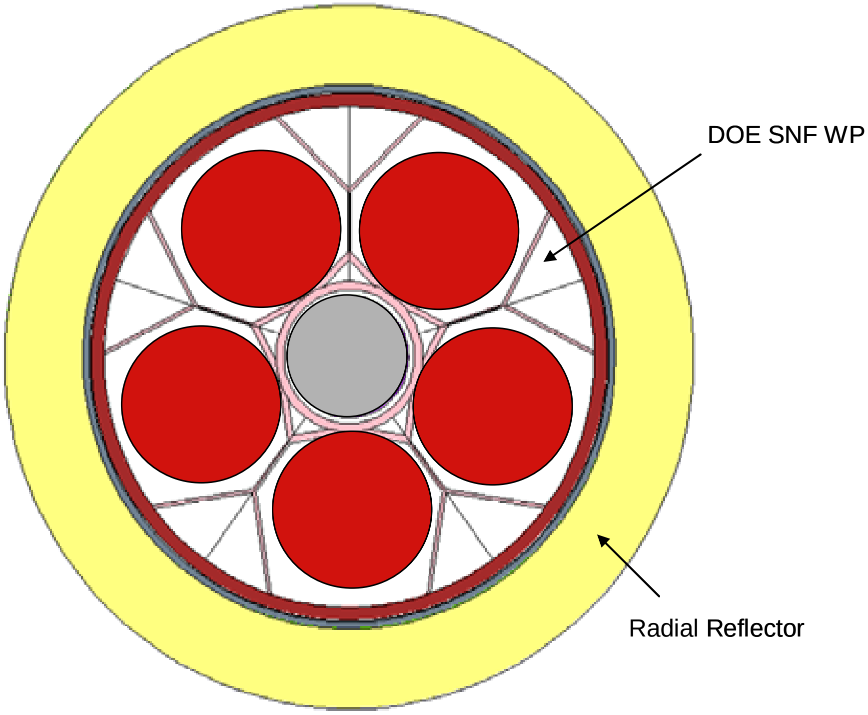


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Figure 6-53: Radial Cross-Section of the 5-DHLW/DOE SNF WP MCNP Model with Incorporated Reflector (DOE SNF canister contents not illustrated)

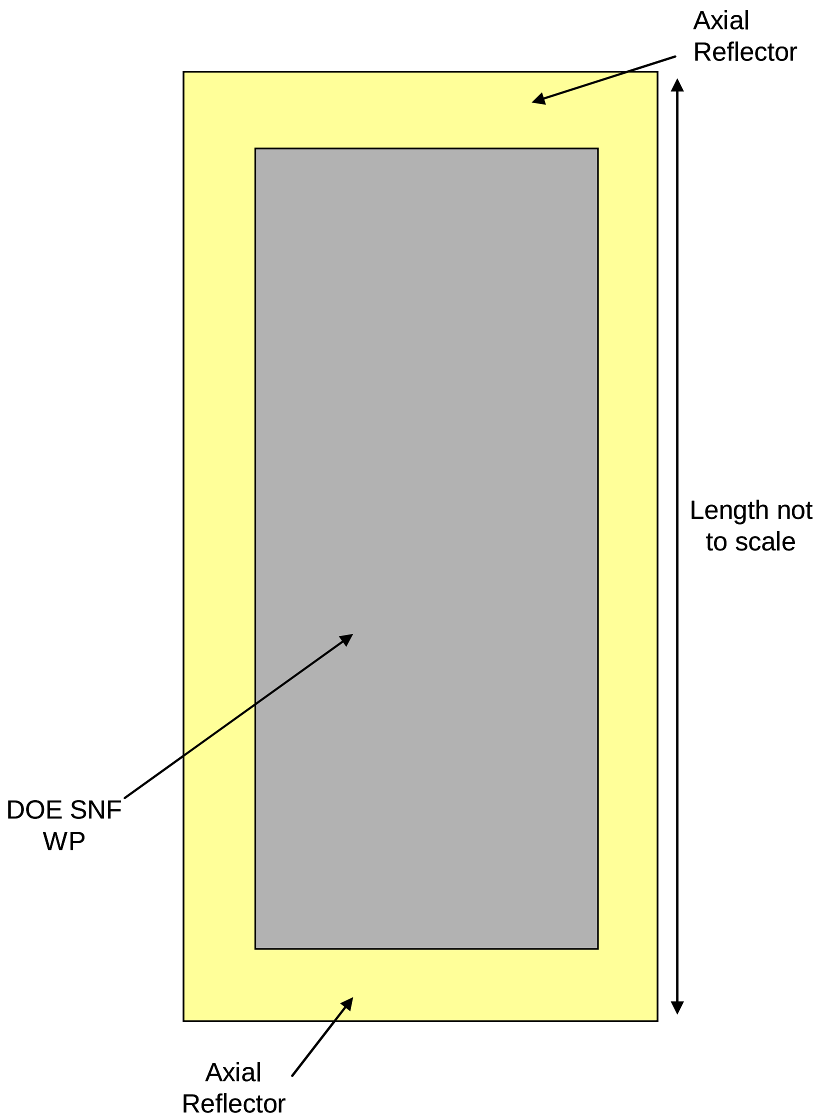

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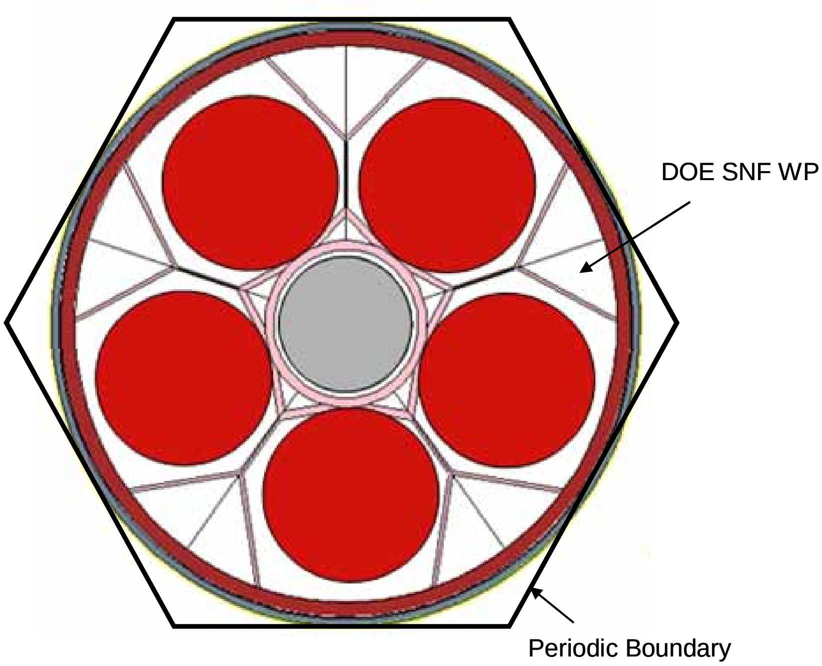
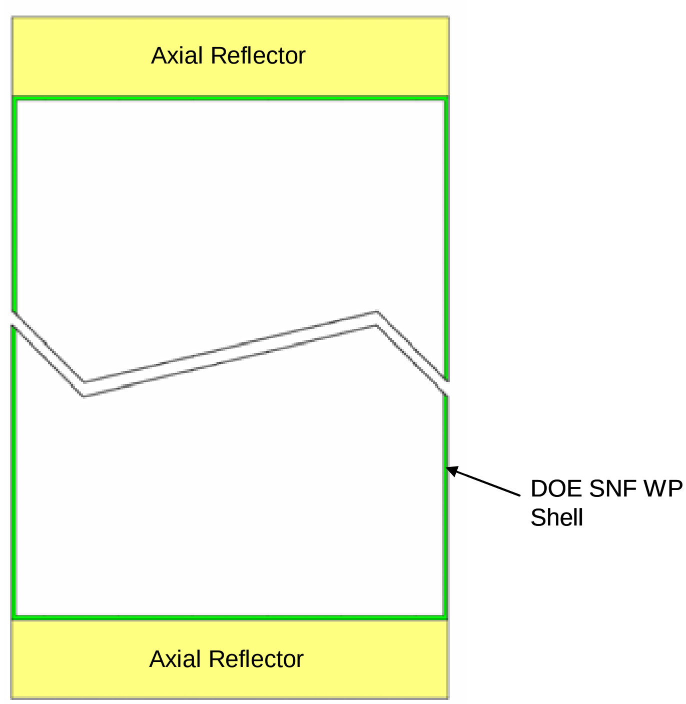
Figure 6-54: Axial Cross-Section of the 5-DHLW/DOE SNF WP MCNP Model with Incorporated Reflector (DOE SNF canister contents not illustrated)

The WP infinite planar array configuration models are based on the WP models described in Section 6.1 but include close fitting full-thickness (30 cm) reflection (Attachment 1) adjacent the upper and lower surfaces of the WP, equivalent to the axial reflection conditions considered for the single (i.e. isolated) WP calculation models. A periodic boundary hexagonal lattice is applied directly adjacent the cylindrical surface of the WP to simulate an infinite planar array of WPs in a close packed, triangular-pitched, configuration. The space between the periodic boundary and the WP shell represents the interstitial space between the WPs in the array. The interstitial space is evaluated as void and is separately evaluated with variably dense water. Refer to Figure 6-55 and Figure 6-56 for a cross-section view of the WP infinite planar array MCNP model with incorporated periodic boundary condition and close-fitting full-thickness axial reflectors.



Source: Original

Figure 6-55: Radial Cross-Section of the 5-DHLW/DOE SNF WP MCNP Model with Incorporated Periodic Boundary Condition to simulate an infinite planar array of WPs (DOE SNF canister contents not illustrated)



Source: Original

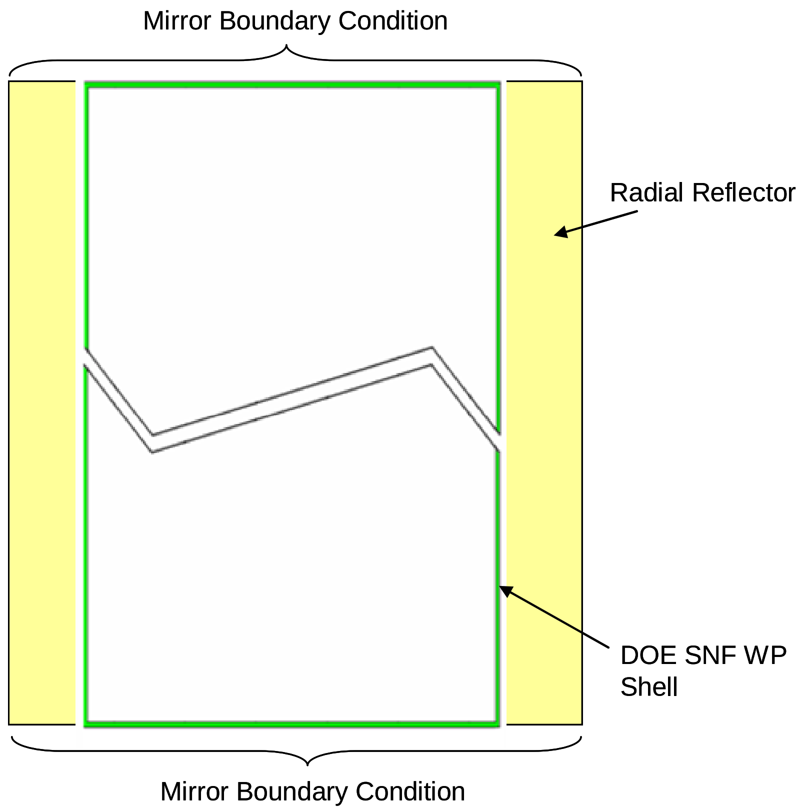
Figure 6-56: Axial Cross-Section of the 5-DHLW/DOE SNF WP Infinite Planar Array MCNP Model with Incorporated Axial Reflectors (DOE SNF WP contents not illustrated)

6.2.1.2 Anticipated Sub-Surface Facility Operations

In context of the waste forms examined in this document, operations conducted in the sub-surface facility concern the receipt and placement of loaded, sealed WPs containing DOE SNF canisters and HLW glass canisters.

Within the sub-surface facility, WPs are arranged in a continuous row within the emplacement drifts. Due to their emplacement configuration (which only provides for close proximity between adjacent WPs, axially), it is expected that there is little neutron interaction between each WP, and thus, it is expected that the reactivity of a single fully reflected WP will be very similar to the reactivity of a fully reflected continuous row of WPs positioned in an emplacement drift.

To demonstrate the subcriticality of the WPs under normal conditions within the sub-surface facility, the WPs containing the various DOE SNF canisters are evaluated in an emplacement configuration. The single WP MCNP models described in Section 6.1 are employed for this analysis, but with modification to apply a mirror boundary condition to the axial ends of the WP, and to incorporate a close fitting full-thickness (30 cm) reflector adjacent the cylindrical surface of the WP. Similar to the surface facility calculations, a series of reflector materials (Attachment 1) are examined to quantify the sensitivity of k_{eff} to the WP reflection condition. Based on neutron mean free paths in the various reflecting materials, the reflection conditions accounted for in the MCNP calculations are considered to bound the reflection conditions that could be realized in the sub-surface facility. Furthermore, owing to the mirror boundary condition applied to the axial ends of the WP, the emplacement MCNP models are considered to bound the actual conditions that could be realized in the subsurface facility. Refer to Figure 6-57 for a cross-section view of the WP emplacement MCNP models with the incorporated close-fitting full-thickness radial reflector and axial mirror boundary condition.



Source: Original

Figure 6-57: Axial Cross-Section of the Emplacement Configuration 5-DHLW/DOE SNF WP MCNP Model (WP Contents Not Illustrated)

6.2.2 Potential Off-Normal Conditions

6.2.2.1 Surface Facilities and Intra-site Operations

The scope of normal operations pertinent to the surface facilities is summarized in Section 6.2.1.1. Any deviation from the scope of normal operations (e.g. dropping of a DOE SNF canister during handling or misloading a DOE SNF WP) could potentially erode the criticality safety margin established for normal operations (refer to Section 7.1).

To provide an understanding of fault tolerance, DOE SNF canisters and loaded WPs are examined under various off-normal conditions. The off-normal conditions examined include those conditions that are resultant from misloading, incorrect storage/staging and physical damage. Misloading concerns operations involving incorrect loading of a WP. Incorrect storage/staging concerns placement of DOE SNF canisters in any location other than the center tube of a WP or a DOE canister staging rack position. Physical damage concerns deformation of a DOE SNF canister resulting in a rearrangement of its content. Note that the physical damage scenarios examined are limited to individual (i.e. single) DOE SNF canisters only because all canisters are handled individually. Consequently, physical damage is not considered for canisters in an array configuration (i.e. canisters positioned in the DOE canister staging racks) or canisters loaded in a WP.

To summarize, three basic types off-normal conditions are examined in this document:

1. Incorrect staging of undamaged dry DOE SNF canisters, including misloading of a DOE SNF WP with six DOE SNF canisters, instead of one DOE SNF canister and five HLW glass canisters.
2. Damage to an individual DOE SNF canister during handling, resulting in canister damage without breach.
3. Damage to an individual DOE SNF canister during handling, resulting in canister damage and breach, coincident with entrainment of liquid moderator.

Note that for the two 'damage' off-normal conditions detailed above (i.e. bullet 2 and 3 above), the neutron absorber content of the basket structure (if any), and the basket filler material (if any), is varied to establish the sensitivity of k_{eff} to reduced neutron absorber content.

6.2.2.1.1 DOE SNF Canister Staging/WP Loading Error

6.2.2.1.1.1 DOE SNF Canister Staging Error

Under normal operating conditions, all DOE SNF canisters will comprise a dry intact basket containing intact spent nuclear fuel, and will be handled individually and staged only in an awaiting WP or a DOE canister staging rack position. On this basis, neutron interaction between DOE SNF canisters is minimized and essentially restricted to the DOE canister staging racks only. However, in the event of a staging error resulting in a congregation of DOE SNF canisters outside the environs of the DOE canister staging racks, the increased neutron interaction between canisters could potentially result in a condition in which k_{eff} exceeds the USL.

To establish the minimum safe spacing requirement for the various DOE SNF canisters, the DOE SNF canisters are evaluated in an infinite planar array configuration with variable surface-to-surface spacing. The DOE SNF canister MCNP models employed for this analysis are based on the MCNP models described in Section 6.1 but include close fitting full-thickness (30 cm) reflection (Attachment 1) adjacent the upper and lower surfaces of the canister, equivalent to the axial reflection conditions considered for the single (i.e. isolated) DOE SNF canister calculation models. A periodic boundary hexagonal lattice is applied directly adjacent the cylindrical surface of the canister to simulate an infinite planar array of canisters in a close packed, triangular-pitched configuration. The space between the periodic boundary and the canister shell represents the interstitial space between the canisters in the array. The interstitial space is evaluated as void and is separately evaluated with variably dense water. Refer to Figure 6-58 and Figure 6-59 for a cross-section view of the DOE SNF canister infinite planar array MCNP model with incorporated periodic boundary condition and close-fitting full-thickness axial reflectors.

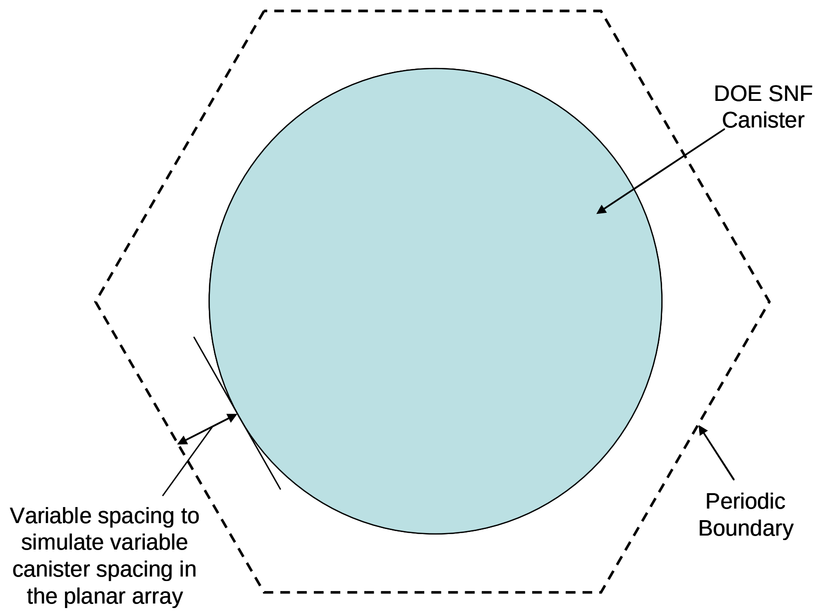


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Figure 6-58: Radial Cross-Section of the DOE SNF Canister MCNP Model with Incorporated Periodic Boundary Condition to Simulate an Infinite Planar Array of Canisters with Variable Spacing (DOE SNF canister contents not illustrated)

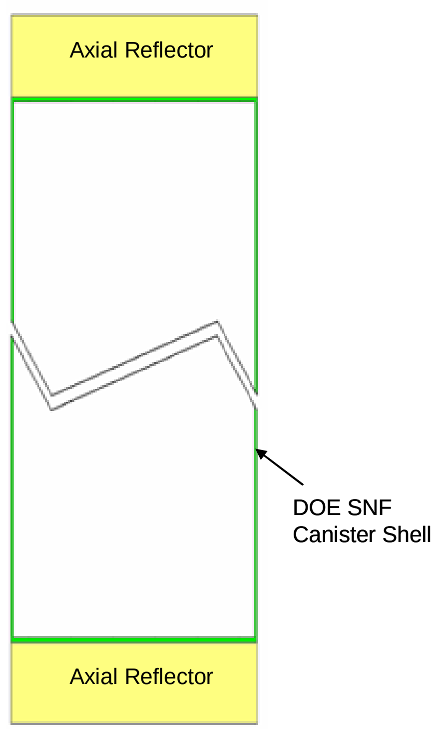

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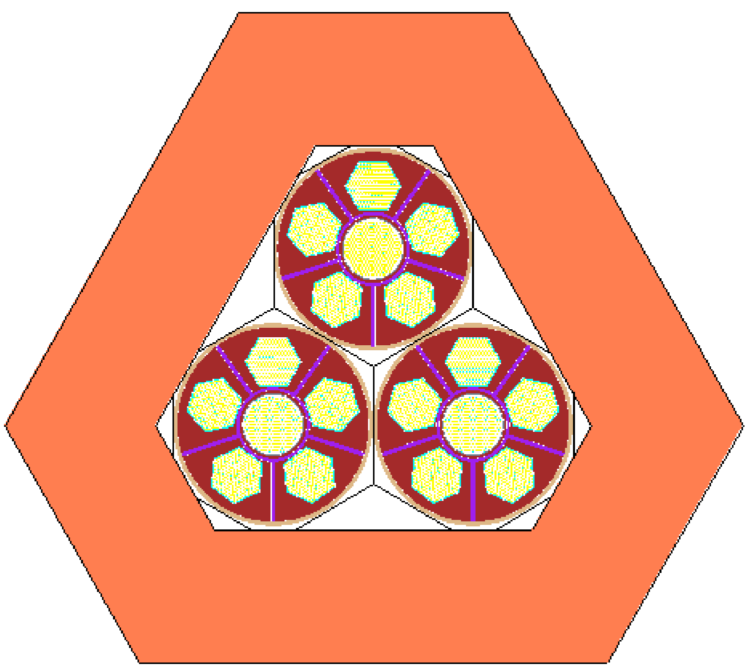
Figure 6-59: Axial Cross-Section of the DOE SNF Canister Infinite Planar Array MCNP Model with Incorporated Axial Reflectors (DOE SNF canister contents not illustrated)

To supplement the DOE SNF canister infinite planar array calculations, a further calculation is performed to establish the maximum safe number of canisters under a loss of spacing scenario; i.e. in a triangular pitched close packed configuration. This supplemental calculation is limited to FFTF DOE SNF canisters only, because based on the results of the infinite planar array calculations (Section 7.1.2.1.1.1), the FFTF canister is established as the limiting DOE SNF canister from a neutron interaction standpoint (i.e. yields the highest k_{eff} value). Similar to the other canister calculations, close fitting full thickness reflection is modeled around the canister cluster, encompassing a wide variety of reflector materials (Attachment 1).

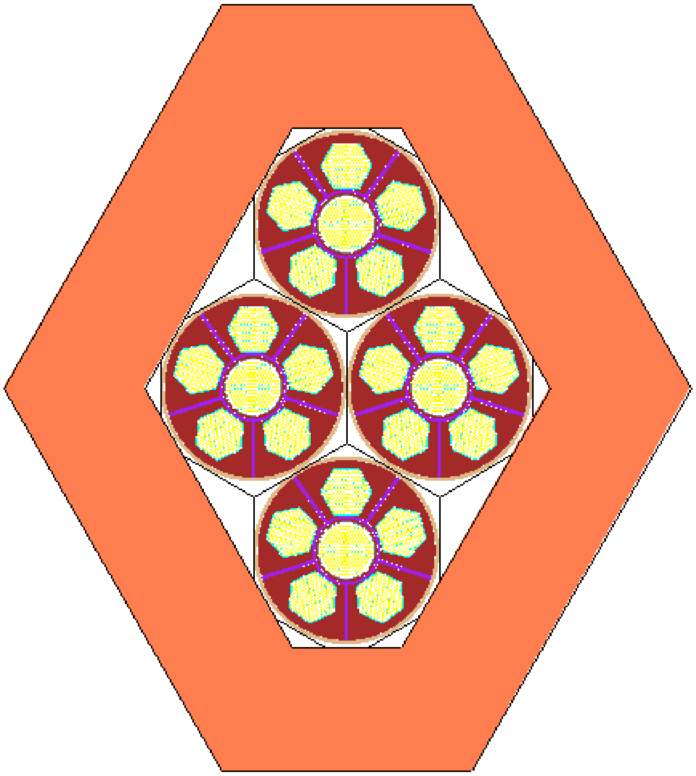
In respect of the canister cluster calculations it is noted that canister mixing scenarios (i.e. grouping or clustering of multiple canisters of difference type) are not considered. This approach is used because, based on the results of the DOE SNF canister infinite planar array calculations (Section 7.1.2.1.1.1), the reduction in k_{eff} with the addition of interstitial moderator between canisters suggests that a 'mixed' canister array would not result in a k_{eff} value greater than the largest k_{eff} value observed for non-mixed (i.e. single type) canister arrays. This statement is supported by the result of an additional calculation recorded in worksheet *Mixed Can Cluster Data* of workbook *Ancillary Results* (Attachment 3). This additional calculation is based (exactly) on the configuration depicted in Figure 6-64, except that the center FFTF DOE SNF canister is replaced with a FSV DOE SNF canister.

Based on the above discussion, only void is modeled in the interstitial space between the DOE SNF canisters. Figure 6-60 through Figure 6-64 present cross-section views of the DOE SNF canister cluster MCNP models with close-fitting full-thickness reflectors.



Source: Original

Figure 6-60: Horizontal Cross-Section View of the DOE SNF Canister Cluster MCNP Model Comprising Three FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector



Source: Original

Figure 6-61: Horizontal Cross-Section View of the DOE SNF Canister Cluster MCNP Model Comprising Four FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

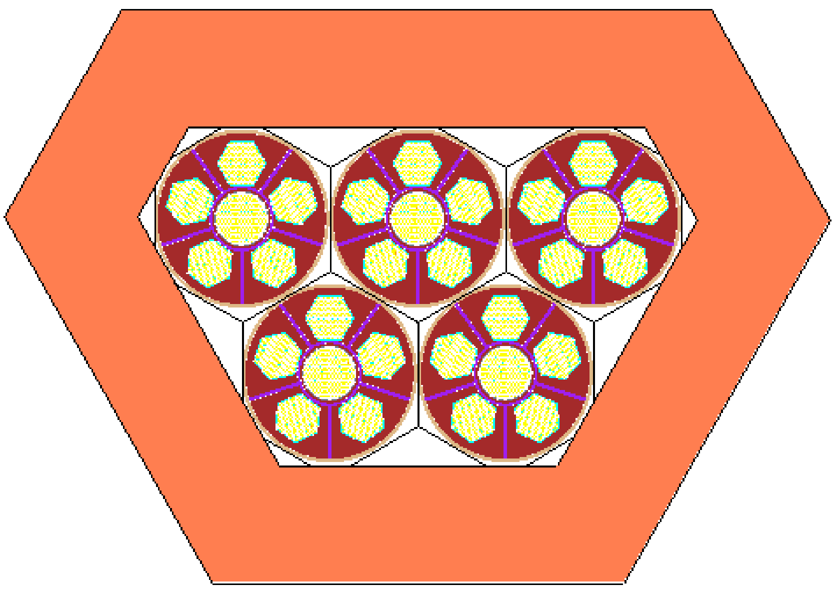


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Figure 6-62: Horizontal Cross-Section View of the DOE SNF Canister Cluster MCNP Model Comprising Five FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

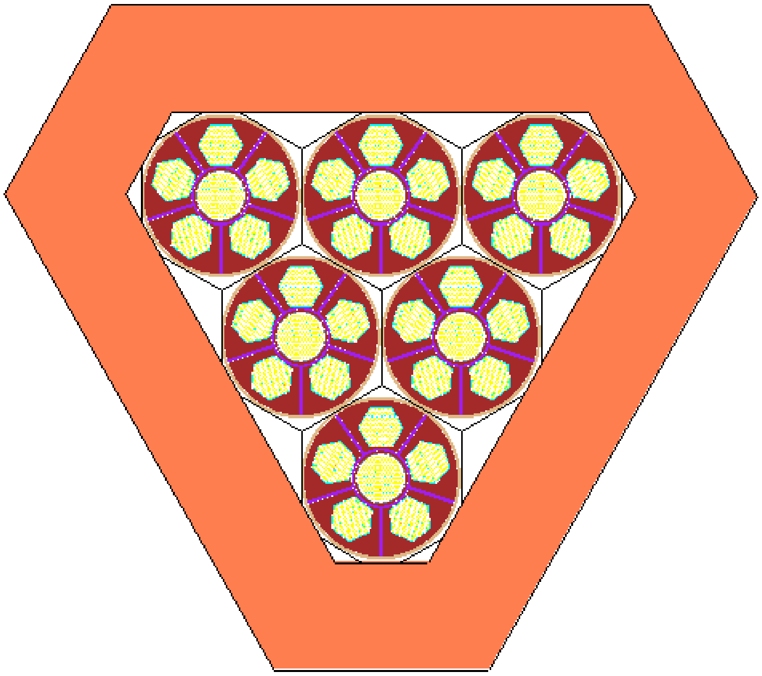

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Figure 6-63: Horizontal Cross-Section View of the DOE SNF Canister Cluster MCNP Model Comprising Six FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

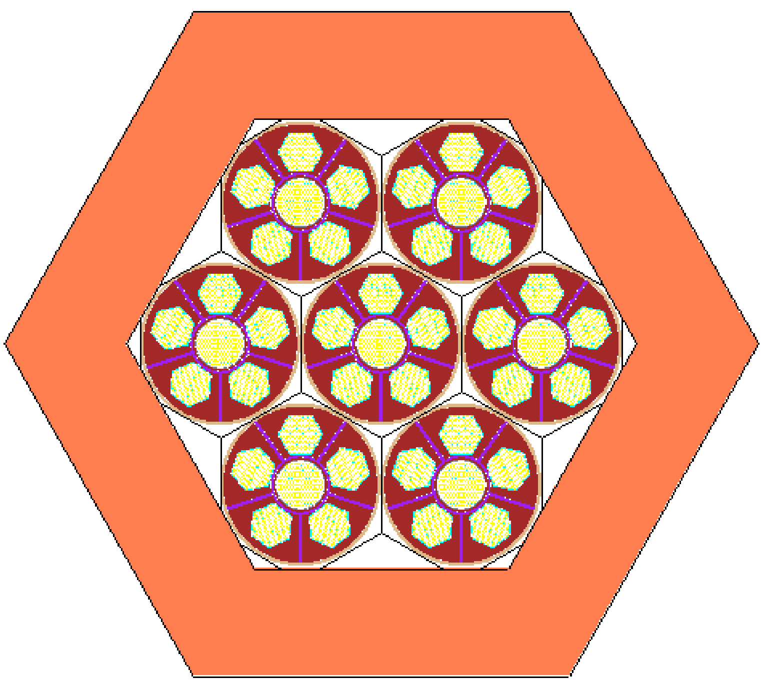

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Figure 6-64: Horizontal Cross-Section View of the DOE SNF Canister Cluster MCNP Model Comprising Seven FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

6.2.2.1.1.2 DOE SNF WP Loading Error

Under normal operating conditions, all loaded WPs contain only one 18” DOE SNF canister. However, in the event of operating error it is possible that more than one 18” DOE SNF canister could be loaded into the same WP (i.e. a WP could be misloaded). To determine the potential safety consequences of misloading an individual WP, calculations are performed to evaluate k_{eff} for individual WPs containing a maximum possible inventory of six DOE SNF canisters (i.e. one normally loaded DOE SNF canister together with five misloaded DOE SNF canisters).

The WP misloading calculation is not constrained to a particular DOE SNF canister type; i.e. all seven DOE SNF variants considered in the scope of this calculation (Section 1.1.1) are examined. However, canister mixing scenarios are not considered because, based on the results of the DOE SNF canister infinite planar array calculations (Section 7.1.2.1.1.1), the reduction in k_{eff} with the addition of interstitial moderator between canisters suggests that a ‘mixed’ canister array would not result in a k_{eff} value greater than the largest k_{eff} value observed for non-mixed (i.e. single type) canister arrays. This statement is supported by the result of an additional calculation recorded in worksheet *Mixed Can Cluster Data* of workbook *Ancillary Results* (Attachment 3). This additional calculation is based (exactly) on the configuration depicted in Figure 6-64, except that the center FFTF DOE SNF canister is replaced with a FSV DOE SNF canister.

Similar to the normal condition DOE SNF WP calculations, close fitting full thickness radial and axial reflection is modeled surrounding the WP. A series of reflector materials (Attachment 1) are examined to quantify the sensitivity of k_{eff} to the misloaded WP reflection condition. Based on neutron mean free paths in the various reflecting materials, the reflection conditions accounted for in the misloaded WP MCNP calculations are considered to bound the reflection conditions that could be realized in the surface facilities. Refer to Figure 6-65 through Figure 6-71 for radial cross-section views of the misloaded DOE SNF WP MCNP models with incorporated close-fitting full thickness reflector. Note that the misloaded DOE SNF canisters are ‘bunched’ by preferential displacement within their compartments to account for potential displacement within the WP compartments.

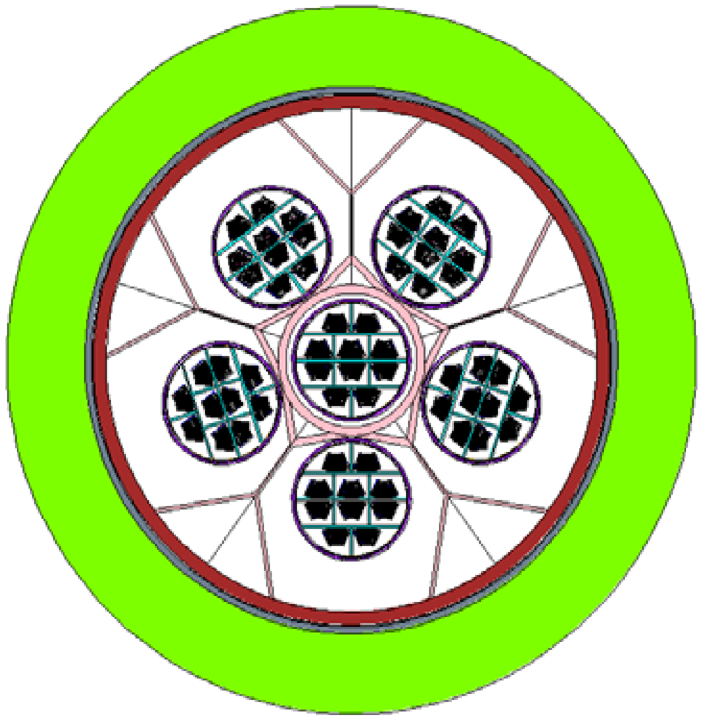

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Figure 6-65: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six ATR DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

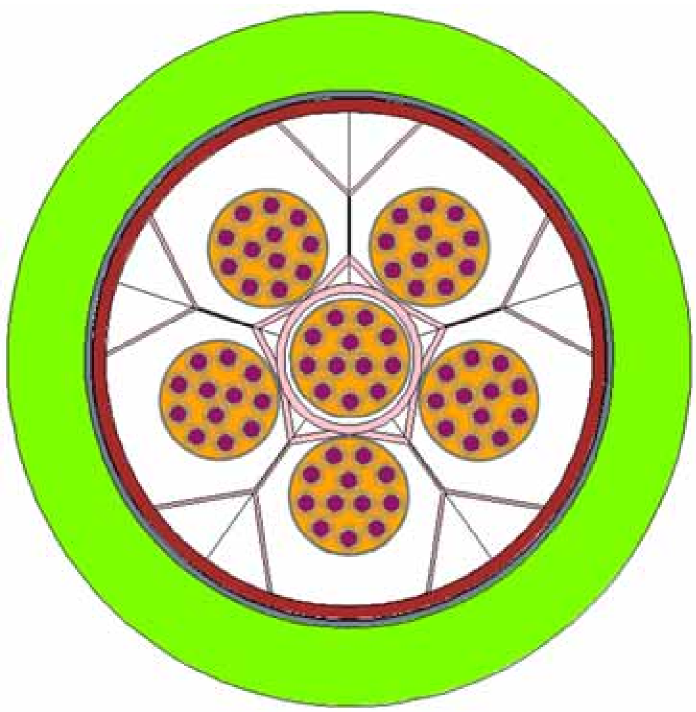

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Figure 6-66: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six EF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

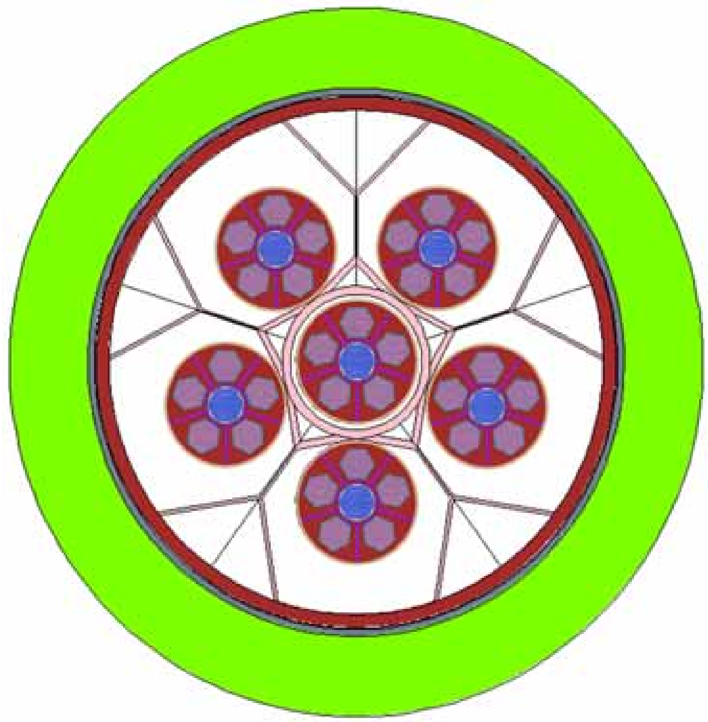

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Figure 6-67: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six FFTF DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

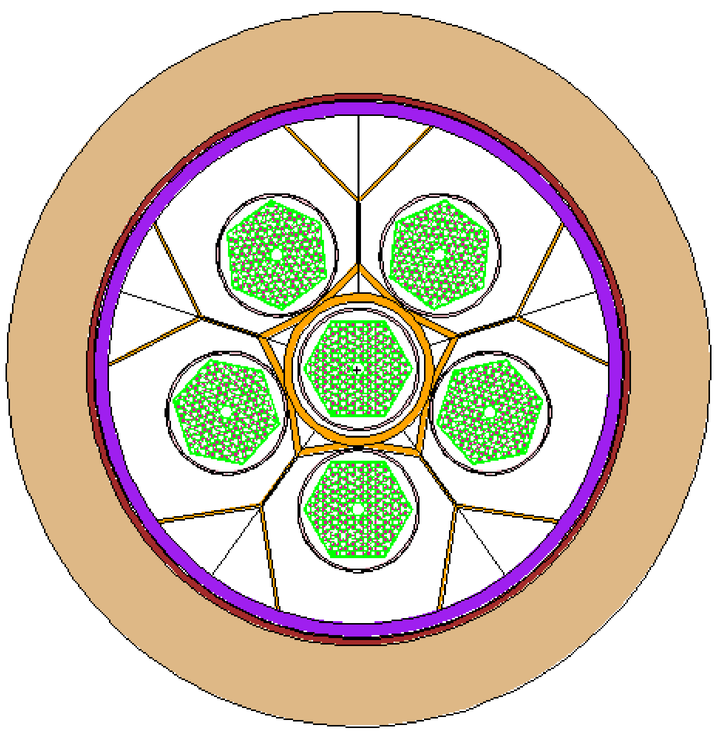

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Figure 6-68: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six FSV DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

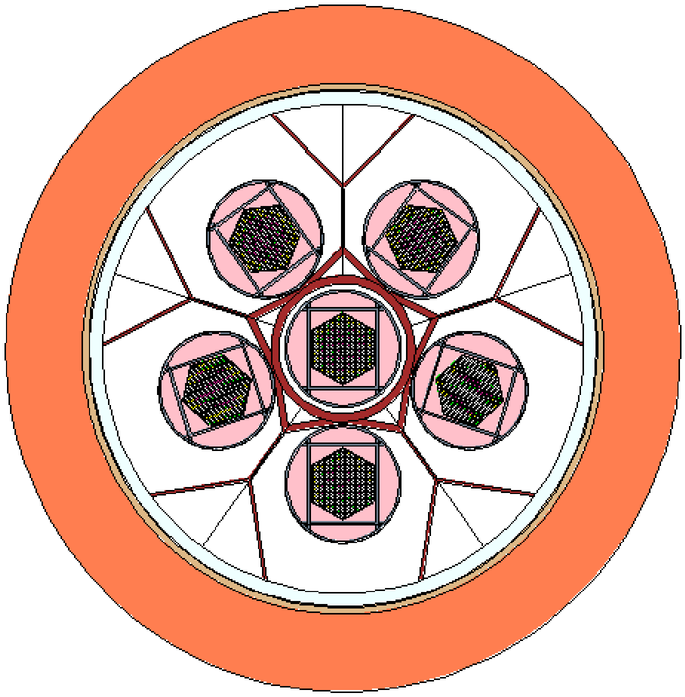

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Figure 6-69: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six SLWBR DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

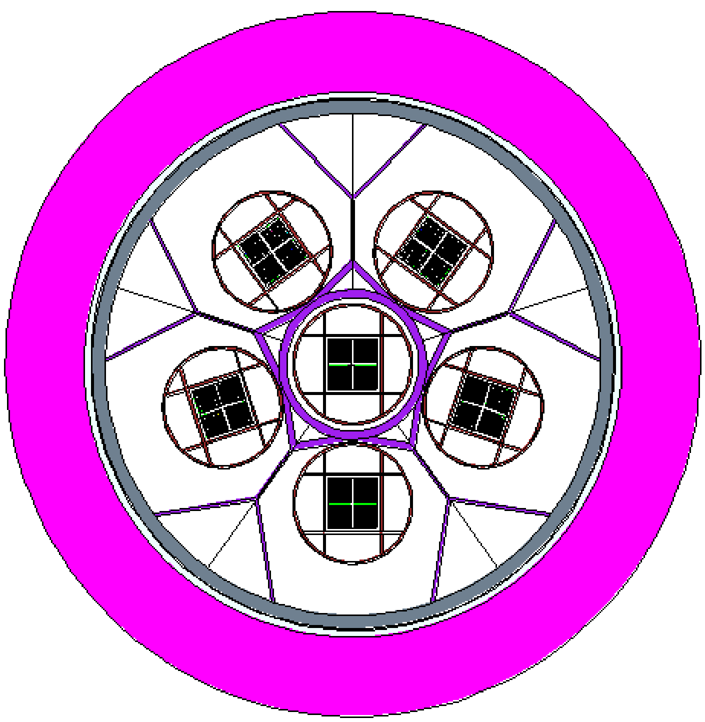

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Figure 6-70: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six SPWR DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

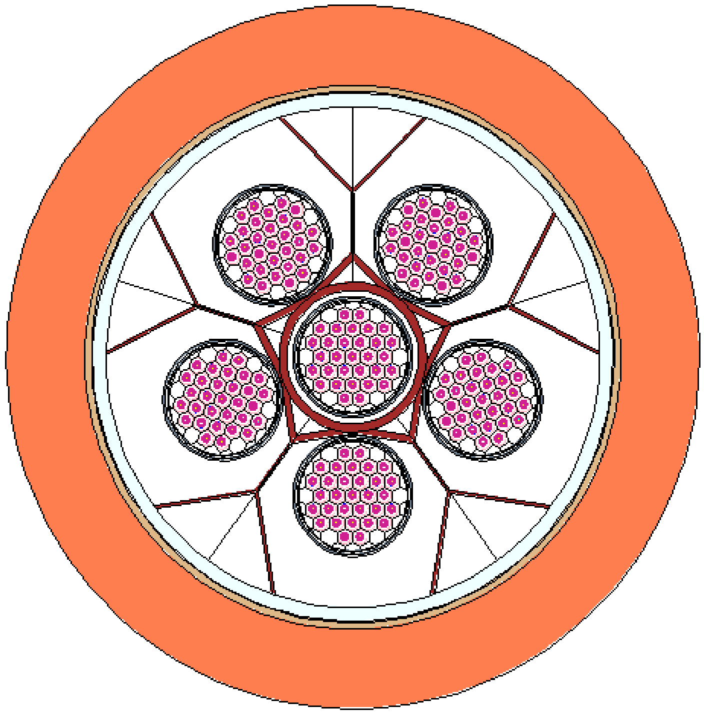

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Figure 6-71: Radial Cross-Section of a Misloaded 5-DHLW/DOE SNF WP MCNP Model Containing Six TRIGA DOE SNF Canisters with Close-Fitting Full Thickness (30 cm) Reflector

6.2.2.1.2 Single Canister Damage without Breach

Under normal operating conditions, DOE SNF Canisters are handled individually. In the event of a process upset resulting in the inadvertent release of a DOE SNF Canister during handling, it is possible that the canister (and its content) could be damaged.

This section describes the MCNP calculations performed for off-normal conditions consisting of damage to an individual DOE SNF canister, without actual breach of the canister shell. The key aspects of this off-normal conditions analysis involve postulated damage to the DOE SNF canister resulting in:

1. a rearrangement of its internal structure (e.g. repositioning of SNF and basket structure), but not resulting in a physical release of material (i.e. creation of fuel debris). This configuration is referred to as a *dry damaged intact* configuration.
2. complete or partial release of its internal structure, forming 'debris' (i.e. a mixture of SNF, basket structure and basket filler material). This configuration is referred to as a *dry damaged degraded* configuration.

Similar to the evaluation of normal conditions, the single canister *dry damage* models incorporate close fitting full-thickness (30 cm) reflection adjacent all surfaces of the canister. A series of reflector materials (Attachment 1) are examined to determine the limiting reflection condition for each DOE SNF canister. Examination of alternate reflectors is performed for the *dry damage* off-normal conditions analysis (rather than using the worst-case reflector established from the normal conditions analysis) in recognition of potential alteration of the neutron spectrum resultant for the rearrangement of SNF and basket structure examined in the calculations.

6.2.2.1.2.1 Dry Damaged Intact Configurations

The *dry damaged intact* configuration calculations are based on progressive degrees of canister basket and SNF damage that result in a gradual rearrangement of basket structure and SNF that would be expected to result in an increase in k_{eff} under dry, un-moderated, conditions. Under dry conditions this type of damage is characterized by a conglomeration of SNF, which typically results in an increase in k_{eff} due to an increase in the fissile areal density. Since this analysis is focused on examining geometric perturbations that result in an increase in k_{eff}, rather than examining geometric perturbations that would realistically characterize the canister contents under canister impact scenarios, the damage conditions examined are considered conservative approximations of potential damage.

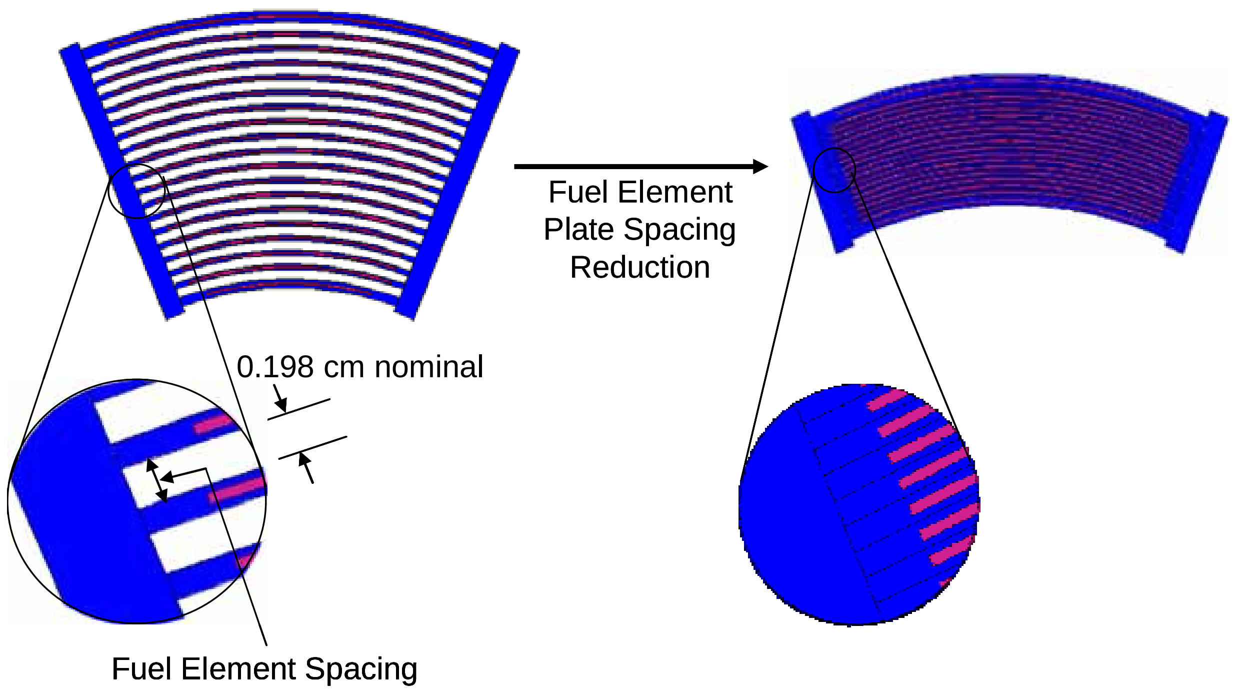
Given that the seven fuel basket/waste forms examined in this calculation have unique designs (i.e. are entirely different from each other), the damage conditions examined for each DOE SNF canister are also unique. The explicit *dry damage intact* conditions examined for each DOE SNF canister are described in detail in the following sub-sections. Cross-sectional views of the MCNP models are provided to depict the progressive levels of damage examined for each canister. The degree of damage is expressed as a percentage of the maximum potential damage for which k_{eff} would be maximized. In addition, each damage condition examined in the calculations is quantified (in a tabulated numeric form) in terms of the actual change in dimensions or positions of SNF and basket structure in the MCNP models.

In addition to geometric perturbations, for each *dry damaged intact* configuration calculation described in the following sub-sections, the neutron absorber content of the basket structure (if any) and the basket filler material (if any) is varied to establish the sensitivity of the system to reduction of neutron absorber content.

A limited series of additional calculations are performed for the EF, FFTF and TRIGA DOE SNF canisters to quantify the increase in k_{eff} in the event of absence of a basket structure within a canister. This off-normal scenario can provide a more acute conglomeration of SNF due to the absence of a basket structure, and hence, absence of a mechanism for spacing or ordering the SNF. The specific configuration of SNF considered under the described ‘no basket present’ scenarios are discussed and illustrated in Section 6.2.2.1.2.1.8.

6.2.2.1.2.1.1 ATR

The ATR DOE SNF canister is described in detail in Section 6.1.3.1. The ATR DOE SNF canister comprises thirty ATR fuel elements arranged in a stacked tri-level basket structure that provides ten fuel elements per basket. Each fuel element consists of nineteen curved aluminum clad uranium aluminide (UAl_x) plates containing highly enriched uranium. The plates are held in place by aluminum side plates that serve to provide a fixed separation between each plate. The nominal plate separation is 0.198 cm. Under *dry damaged intact* conditions the fuel element plate separation is gradually reduced from its nominal value to zero (i.e. a no plate separation condition). Refer to Figure 6-72 for an illustration of the fuel element plate spacing parameter examined in the *dry damaged intact* condition MCNP calculations.



Source: Original

Figure 6-72: Horizontal Cross-section of the ATR Fuel Element Depicting the *Fuel Element Plate Separation* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The ATR DOE SNF canister fuel basket consists of a series of a perpendicularly arranged plates conforming to a symmetric pattern. The compartments formed by the arrangement of basket plates accommodate the ATR fuel elements, and ensure spacing between adjacent fuel elements. The nominal fuel basket plate separation is 9.049 cm. Under *dry damaged intact* conditions the basket plate separation is gradually reduced from its nominal value to the smallest achievable separation distance without impinging the fuel elements. Refer to Figure 6-73 for an illustration of the basket plate spacing parameter examined in the *dry damaged intact* condition MCNP calculations.

It is noted that since the fuel element cross-sectional area is dependent on the degree of fuel element plate separation considered, the smallest achievable basket plate separation distance is dependent on the fuel element plate separation examined.

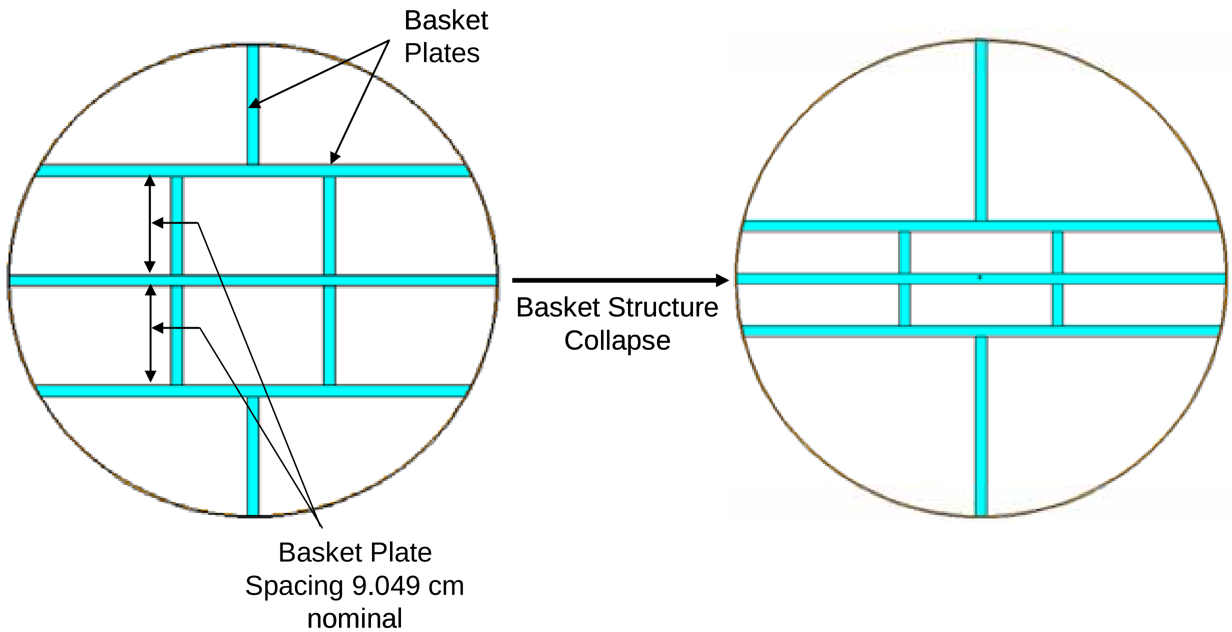


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Figure 6-73: Horizontal Cross-section of the ATR DOE SNF Canister Basket Structure Depicting the *Basket Plate Separation* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the ATR DOE SNF Canister *dry damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the ATR DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-26. Note that all permutations of the parameters detailed in Table 6-26 are examined. Cross-section views of the ATR DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-74.

Table 6-26. Geometry and Neutron Absorber Perturbations Examined for the ATR DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
ATR Fuel Element	Fuel Element Plate Separation	Fuel Element Plate Spacing Reduction	0 %	0.198 cm	0.198 cm
			20 %	0.158 cm	
			40 %	0.119 cm	
			60 %	0.079 cm	
			80 %	0.040 cm	
			100 %	0.0 cm	
ATR Fuel Basket	Fuel Basket Plate Separation	Basket Structure Collapse[1]	0 %	9.049 cm	9.049 cm
			20 %	8.296 cm	
			40 %	7.544 cm	
			60 %	6.791 cm	
			80 %	6.039 cm	
			100 %	5.286 cm	
ATR Fuel Basket	Fuel Basket Plate Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
Total Permutations (Number of Cases Examined): 216					

[1] Note that since the fuel element cross-sectional area is dependent on the degree of fuel element plate separation considered, the smallest achievable basket plate separation distance is dependent on the fuel element plate separation examined. The values provided for basket structure collapse in the table are based on a fully damage fuel element (i.e. the 100% fuel element spacing reduction case).

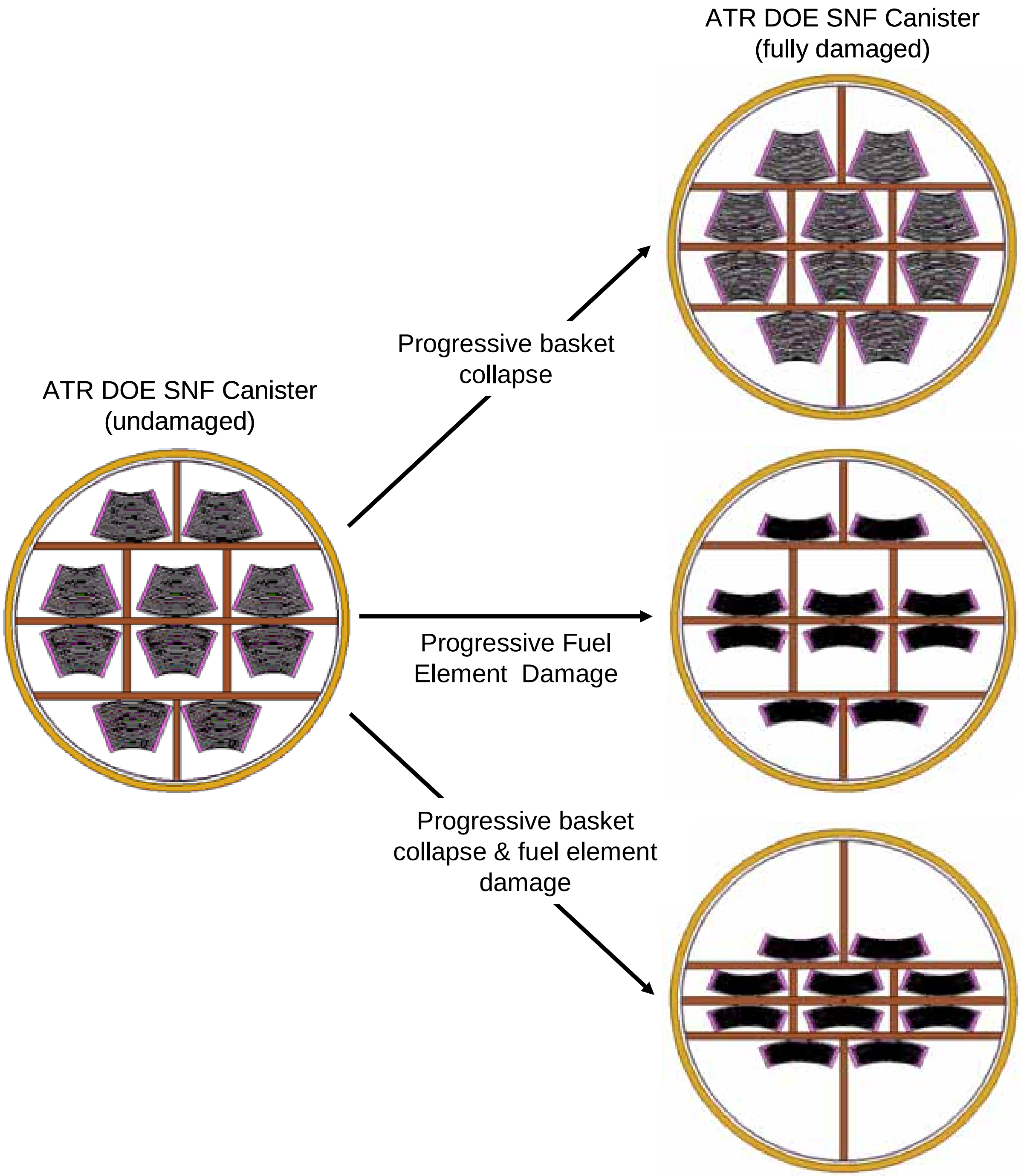

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Figure 6-74: Radial Cross-Section Views of the ATR DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.2 EF

The EF DOE SNF canister is described in detail in Section 6.1.3.2. The EF DOE SNF canister comprises twenty four basket tubes arranged in a stacked bi-level structure that provides twelve basket tubes, or compartments, per basket. Each basket tube position accommodates 140 fuel pins, which are sealed in an -04 canister, that is enclosed in an -01 canister. The 140 fuel pins positioned in each -04 canister are loaded loose, and have no supporting or spacing mechanism. The fuel pins are treated as uniformly spaced within the -04 canister as a nominal condition. Under *dry damaged intact* conditions the fuel pin pitch is progressively reduced from its nominal value to a minimum possible pitch, equivalent to a close-packed configuration of pins. Refer to Figure 6-75 for an illustration of the fuel pin pitch parameter examined in the *dry damaged intact* condition MCNP calculations.

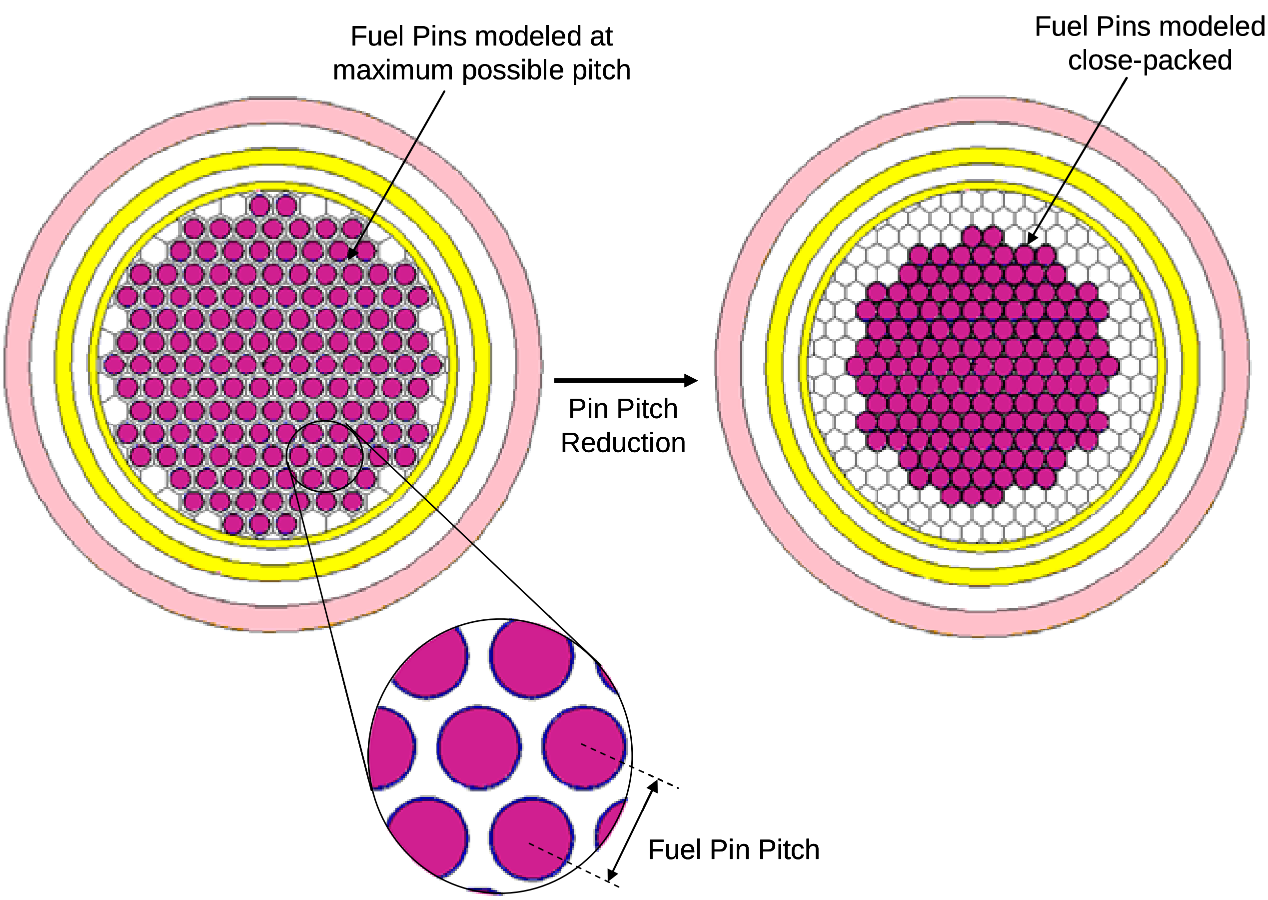

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Figure 6-75: Horizontal Cross-section of the EF -04 Canister Depicting the *Fuel Pin Pitch* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The EF DOE SNF canister basket assembly consists of twelve nickel-gadolinium alloy tubes attached to a stainless steel base plate. The void space between the twelve tubes is filled with iron shot (Fe) and gadolinium phosphate ($GdPO_4$). The nominal basket assembly design is portrayed in Figure 6-76.

It is seen in Figure 6-76 that the basket tubes have a non-uniform distribution (i.e. are not equally spaced). Under *dry damaged intact* conditions the basket tube separation is gradually reduced from its nominal value to the smallest achievable separation distance (equivalent to a bunched basket tube configuration). Refer to Figure 6-76 for an illustration of the basket tube spacing parameter examined in the *dry damaged intact* condition MCNP calculations.

In conjunction with basket tube spacing reduction, the basket tube diameter is also progressively reduced. At the fully reduced basket tube separation condition, the basket tube diameter is fully reduced so that it is completely collapsed onto the -01 canister (which is also progressively collapsed onto the -04 canister). Refer to Figure 6-76 for an illustration of the basket tube diameter reduction parameter (termed 'basket tube collapse').

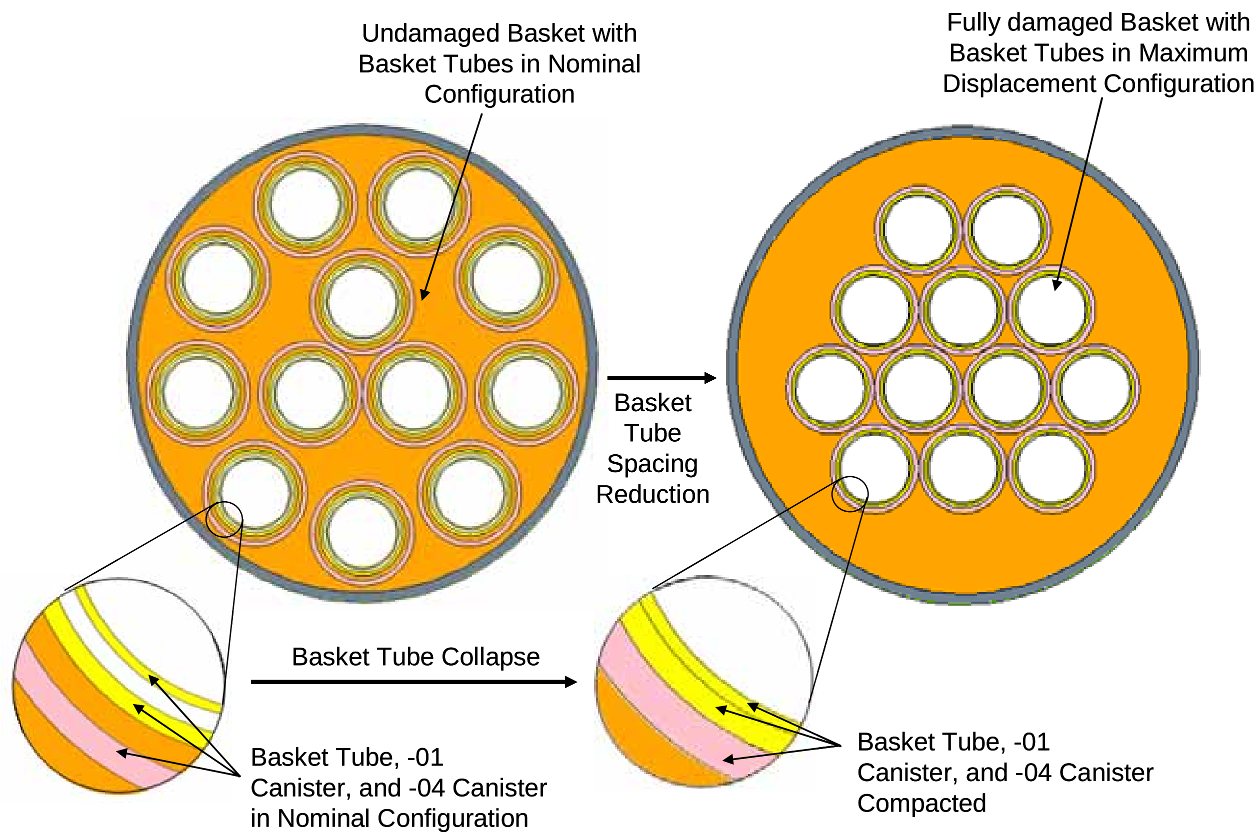

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Figure 6-76: Horizontal Cross-section of the EF DOE SNF Canister Depicting the *Basket Tube Separation* Parameter (and *Basket Tube Collapse* Parameter) Examined in the Dry Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the EF DOE SNF Canister *dry damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure, and independently the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the EF DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-27. Note that all permutations of the parameters detailed in Table 6-27 are examined. Cross-section views of the EF DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-77.

Table 6-27. Geometry and Neutron Absorber Perturbations Examined for the EF DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
EF Fuel Pin	Pin Pitch	Pin Pitch Reduction	0 %	0.5 cm	0.5 cm[3]
			20 %	0.480 cm	
			40 %	0.460 cm	
			60 %	0.441 cm	
			80 %	0.421 cm	
			100 %	0.401 cm	
EF Fuel Basket Tube	Basket Tube Separation	Basket Tube Spacing Reduction[1]	0 %	4.164 cm	4.164 cm[4]
			20 %	3.331 cm	
			40 %	2.498 cm	
			60 %	1.666 cm	
			80 %	0.833 cm	
			100 %	0.0 cm	
EF Fuel Basket Tube	Basket Tube Outer Diameter	Basket Tube Collapse[1,2]	0 %	5.08 cm	5.08 cm
			20 %	4.702 cm	
			40 %	4.324 cm	
			60 %	3.947 cm	
			80 %	3.569 cm	
			100 %	3.191 cm	
EF Fuel Basket Tube	Basket Tube Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
EF Basket Filler Material	Basket Filler Neutron Absorber ($GdPO_4$) Content	Basket Filler Gd content	0 %	0.0 vol% $GdPO_4$	3.0 vol% $GdPO_4$
			20 %	0.6 vol% $GdPO_4$	
			40 %	1.2 vol% $GdPO_4$	
			60 %	1.8 vol% $GdPO_4$	
			80 %	2.4 vol% $GdPO_4$	
			100 %	3.0 vol% $GdPO_4$	
Total Permutations (Number of Cases Examined): 1296					

[1] Note that the Basket Tube Spacing Reduction and Basket Tube Collapse are considered in conjunction with

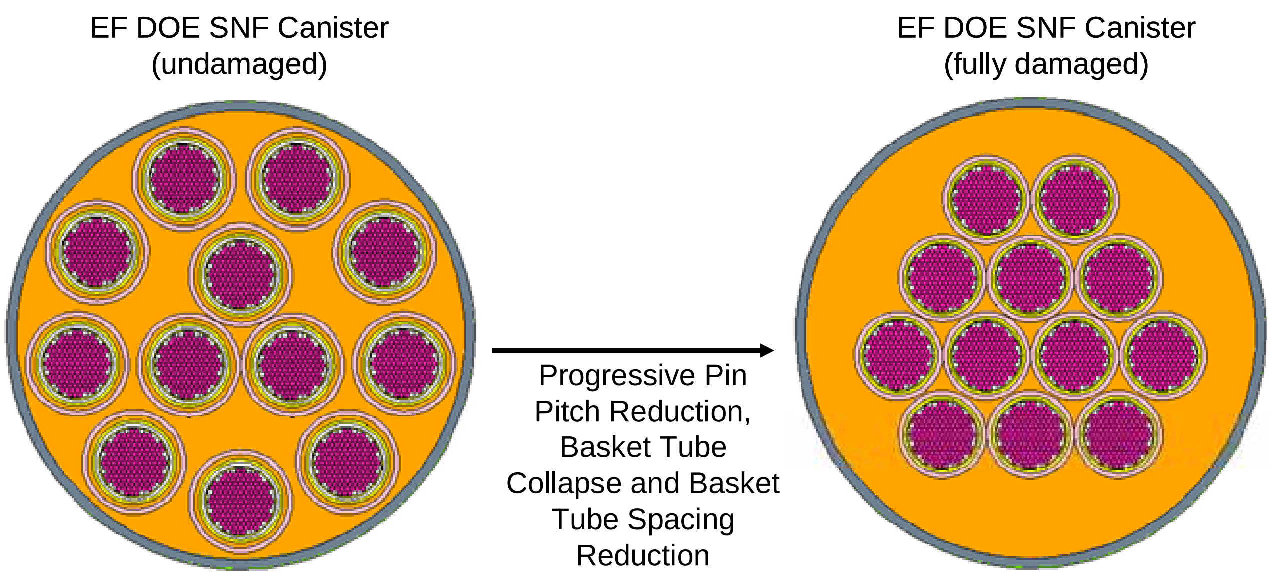
Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value

each other (i.e. are not examined independently).

[2] The 'Model Value Used' data provided for Basket Tube Collapse are based on a fully reduced pin pitch, and fully reduced -04 and -01 canister diameters, which provides for the largest possible Basket Tube Diameter reduction.

[3] The fuel pins are treated as uniformly spaced within the -04 canister as a nominal condition for the *dry damaged intact* MCNP calculations.

[4] The Basket Tube Separation values provided are based on (and therefore apply only to) the Basket Tube positioned the furthest from the center of the canister (i.e. the Basket Tube situated in the "6-oclock' position).



Source: Original

Figure 6-77: Radial Cross-Section Views of the EF DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.3 FFTF

The FFTF DOE SNF canister is described in detail in Section 6.1.3.3. The FFTF DOE SNF canister comprises five standard driver fuel assemblies (DFAs), with each DFA containing 217 fuel pins, in addition to a centralized Ident-69 container which is used to accommodate loose fuel pins from disassembled DFA. The Ident-69 container is positioned in the center of the canister within a cylindrical basket center tube. The five DFAs are distributed amongst five compartments created by five basket divider plates, or spokes, that extend radially from the center basket tube to the inside wall of the DOE SNF canister.

Under *dry damaged intact* conditions the fuel pin pitch associated with the DFAs and Ident-69 container is progressively reduced from its nominal value to a minimum possible pitch, equivalent to a close-packed triangularly pitched configuration of pins. Refer to Figure 6-78 and Figure 6-79 for an illustration of the fuel pin pitch parameter examined in the *dry damaged intact* condition MCNP calculations.

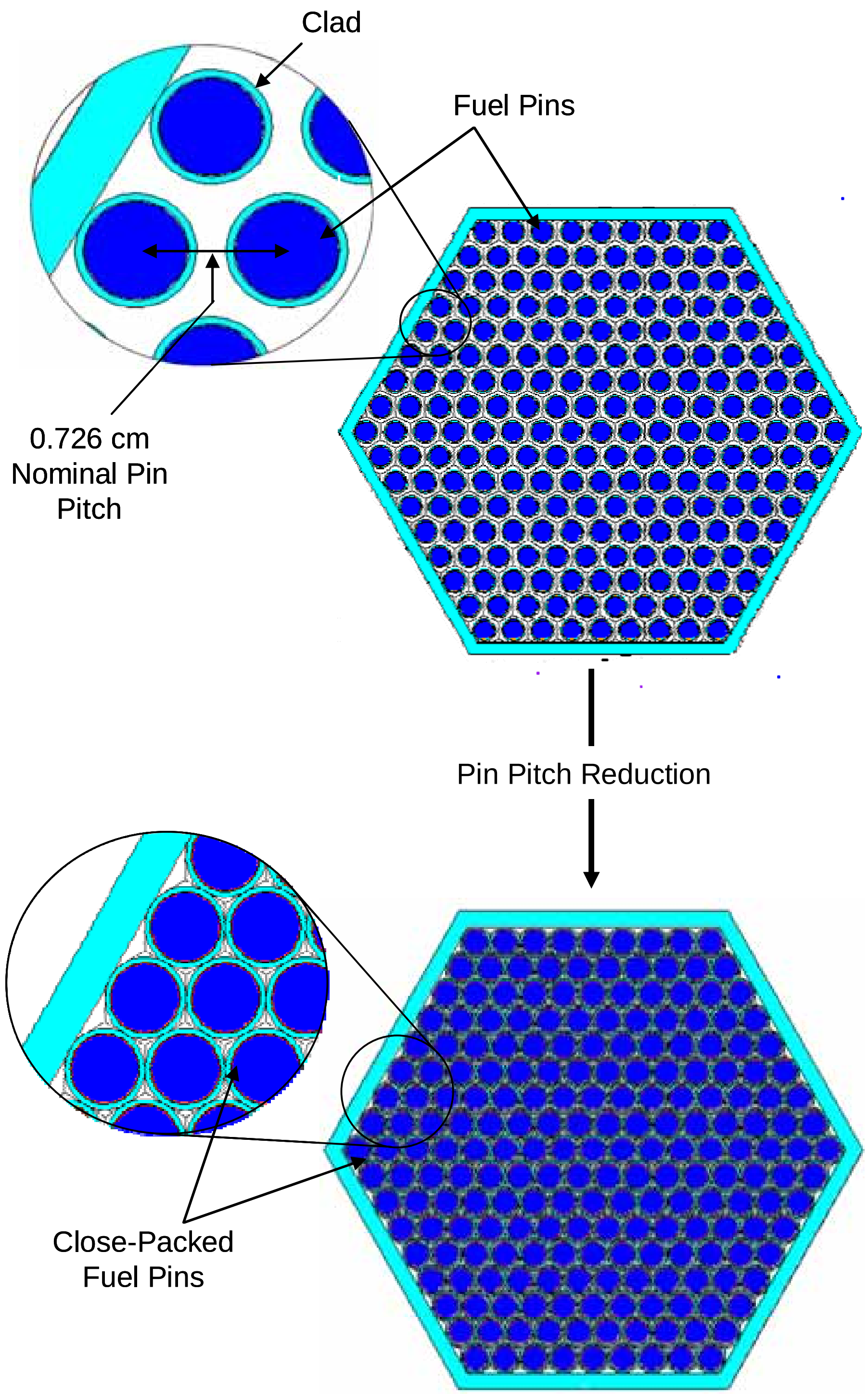


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Figure 6-78: Horizontal Cross-section of the FFTF DFA Container Depicting the *Fuel Pin Pitch* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

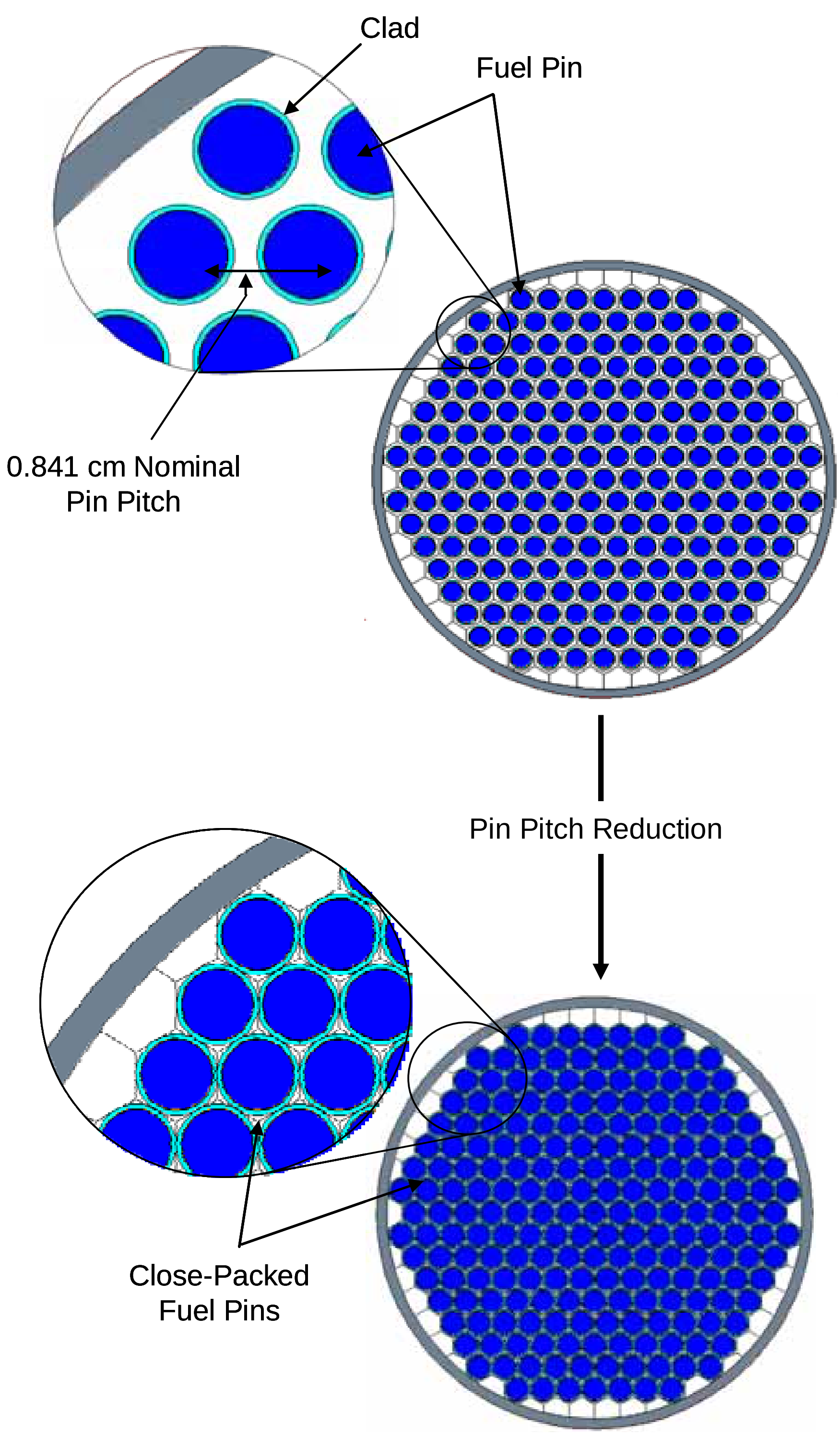

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Figure 6-79: Horizontal Cross-section of the FFTF Ident-69 Container Depicting the *Fuel Pin Pitch* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The FFTF DOE SNF canister basket tube and divider plates consist of nickel-gadolinium alloy tubes and plates. The void space between the tube/divider plates is filled with aluminum gadolinium phosphate (Al-$GdPO_4$) shot (filler material). The nominal basket assembly design is portrayed in Figure 6-80.

Under *dry damaged intact* conditions the centralized basket tube diameter is progressively reduced from its nominal value until it is completely collapsed onto the Ident-69 container. Refer to Figure 6-80 for an illustration of the centralized basket tube diameter parameter examined in the *dry damaged intact* condition MCNP calculations.

In conjunction with basket tube diameter reduction, the positioning of the surrounding DFAs is simultaneously adjusted so that the distance between the DFAs and the Ident-69 container is always minimized. Refer to Figure 6-81 for an illustration of the DFA positioning adjustment.

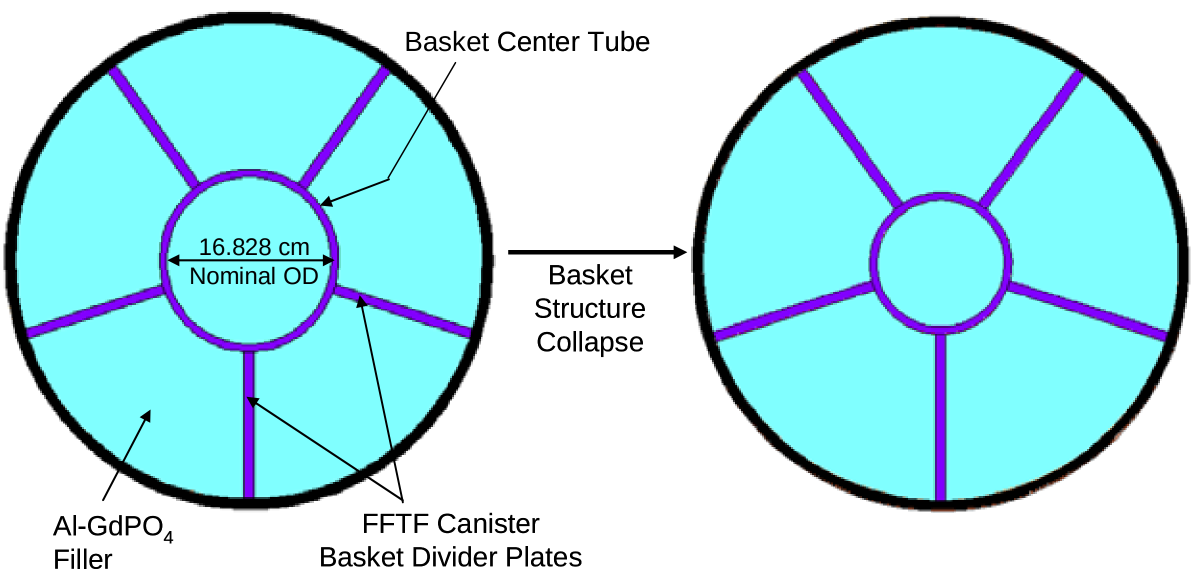

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Figure 6-80: Horizontal Cross-section of the FFTF DOE SNF Canister Depicting the *Basket Tube Diameter* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the FFTF DOE SNF Canister *dry damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure, and independently the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

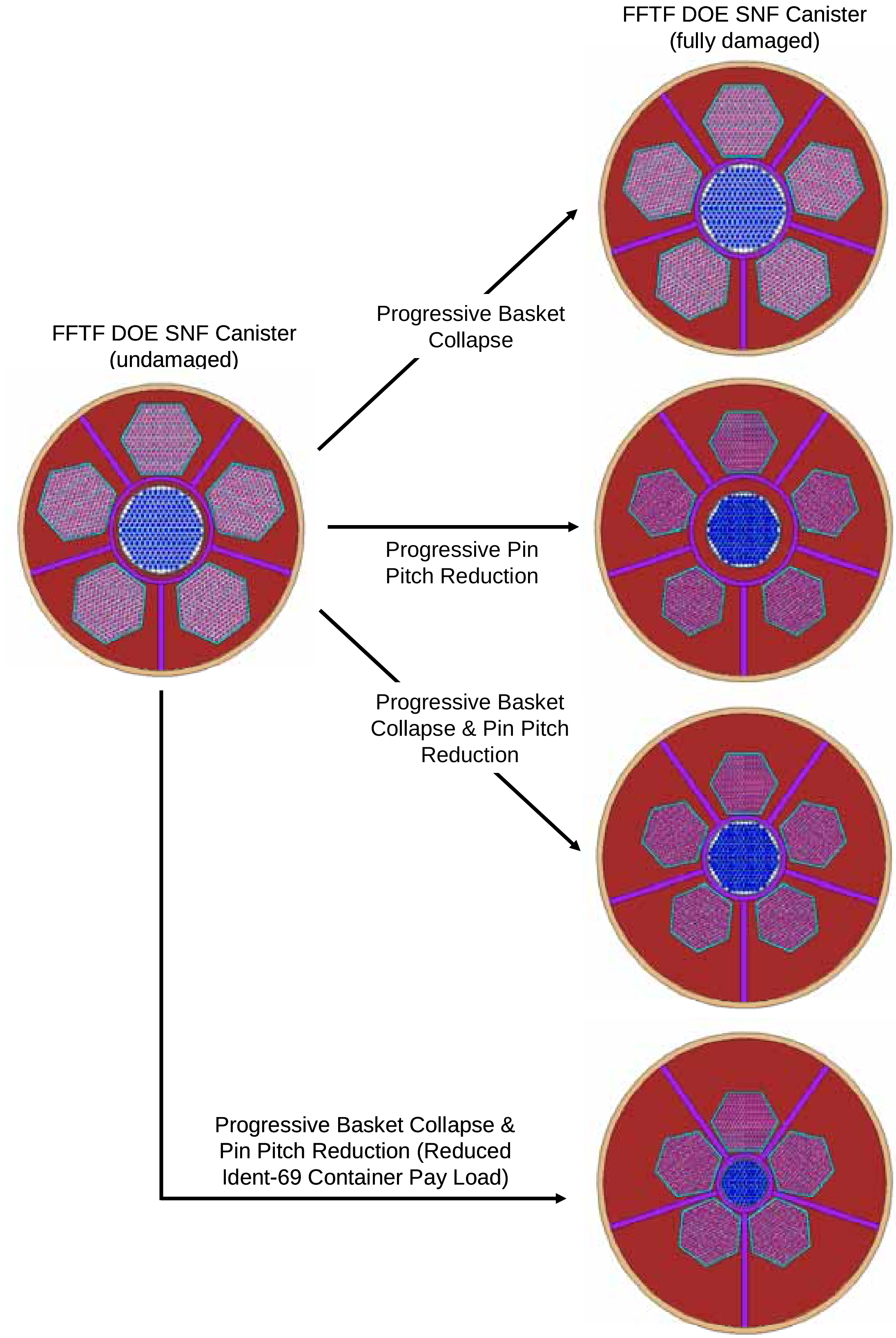
The specific geometry and neutron absorber perturbations examined (and described above) for the FFTF DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-28. Note that all permutations of the parameters detailed in Table 6-28 are examined. Cross-section views of the FFTF DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-81.

Table 6-28. Geometry and Neutron Absorber Perturbations Examined for the FFTF DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
FFTF DFA Fuel Pin	DFA Pin Pitch	Pin Pitch Reduction	0 %	0.726 cm	0.726 cm
			20 %	0.698 cm	
			40 %	0.669 cm	
			60 %	0.641 cm	
			80 %	0.612 cm	
			100 %	0.584 cm	
FFTF Ident-69 Container Fuel Pin	Ident-69 Container Pin Pitch	Pin Pitch Reduction	0 %	0.841 cm	0.841 cm[1]
			20 %	0.811 cm	
			40 %	0.781 cm	
			60 %	0.750 cm	
			80 %	0.720 cm	
			100 %	0.690 cm	
FFTF Fuel Basket Tube	Basket Tube Outer Diameter	Basket Structure Collapse[2]	0 %	16.828 cm	16.828 cm
			20 %	16.087 cm	
			40 %	15.345 cm	
			60 %	14.604 cm	
			80 %	13.862 cm	
			100 %	13.121 cm[2]	
FFTF Fuel Basket Tube	Basket Tube Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
FFTF Basket Filler Material	Basket Filler Neutron Absorber (Gd) Content	Basket Filler Gd content	0 %	0.0 wt% Gd	4.3 wt% Gd
			20 %	0.86 wt% Gd	
			40 %	1.72 wt% Gd	
			60 %	2.58 wt% Gd	
			80 %	3.44 wt% Gd	
			100 %	4.3 wt% Gd	
Total Permutations (Number of Cases Examined): 1296					

[1] Note that the Ident-69 container nominal fuel pin pitch is based on a 219 fuel pin complement with a uniform pin pitch utilizing all space within the container.

[2] The fully collapsed basket tube diameter is dependent on the diameter of the Ident-69 container, which is dependent on the degree of pin pitch reduction considered. The minimum 'Model Value Used' value provided is based on a fully reduced pin pitch.



Source: Original

Figure 6-81: Radial Cross-Section Views of the FFTF DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.4 FSV

The FSV DOE SNF canister is described in detail in Section 6.1.3.4. The FSV DOE SNF canister fuel element consists of a solid, single piece, block of graphite with an array of drilled channels to accommodate fuel compacts. Based on this design no potential damage configurations were identified for potential *dry damaged intact* conditions. Consequently, there are no specific MCNP calculations for the FSV DOE SNF canister under *dry damaged intact* conditions.

6.2.2.1.2.1.5 SLWBR

The SLWBR DOE SNF canister is described in detail in Section 6.1.3.5. The SLWBR DOE SNF canister comprises a single hexagonal fuel assembly containing 619 fuel pins positioned on a triangular lattice. Under *dry damaged intact* conditions the fuel pin pitch is progressively reduced from its nominal value to a minimum possible pitch, equivalent to a close-packed configuration of pins. Refer to Figure 6-82 for an illustration of the fuel pin pitch parameter examined in the *dry damaged intact* condition MCNP calculations.

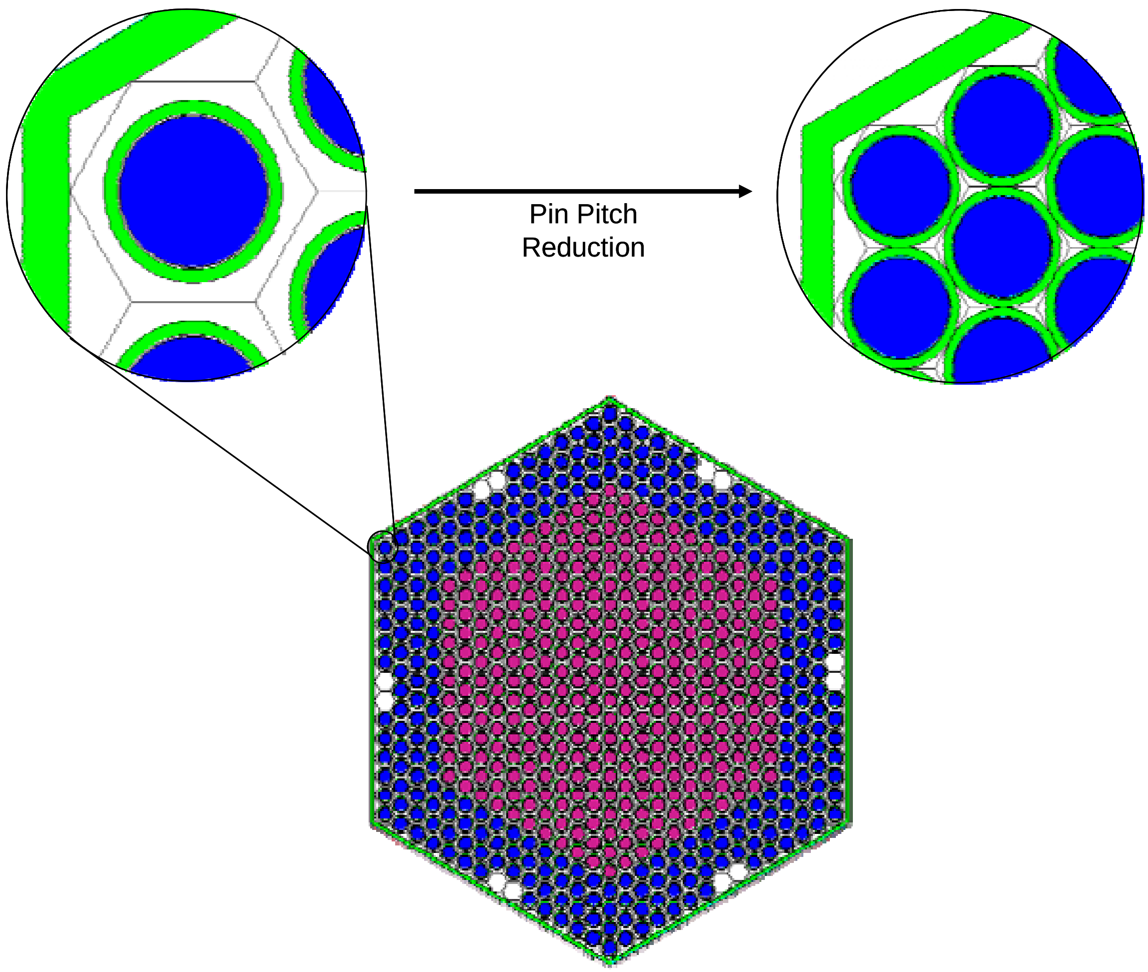


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Figure 6-82: Horizontal Cross-section of the SLWBR Fuel Assembly Depicting the *Fuel Pin Pitch* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The SLWBR DOE SNF canister contains a rectangular stainless steel basket structure within which the fuel assembly is positioned. The void spaces within the canister are filled with aluminum gadolinium phosphate (Al-$GdPO_4$) shot (filler material). The SLWBR DOE SNF Canister *dry damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the SLWBR DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-29. Note that all permutations of the parameters detailed in Table 6-29 are examined. Cross-section views of the SLWBR DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-83.

Table 6-29. Geometry and Neutron Absorber Perturbations Examined for the SLWBR DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
SLWBR Fuel Pin	Pin Pitch	Pin Pitch Reduction	0 %	0.936 cm	0.936 cm
			20 %	0.904 cm	
			40 %	0.873 cm	
			60 %	0.841 cm	
			80 %	0.810 cm	
			100 %	0.778 cm	
SLWBR Basket Filler Material	Basket Filler Neutron Absorber (Gd) Content	Basket Filler Gd content	0 %	0.0 wt% Gd	0.1 wt% Gd
			20 %	0.02 wt% Gd	
			40 %	0.04 wt% Gd	
			60 %	0.06 wt% Gd	
			80 %	0.08 wt% Gd	
			100 %	0.1 wt% Gd	
Total Permutations (Number of Cases Examined): 36					

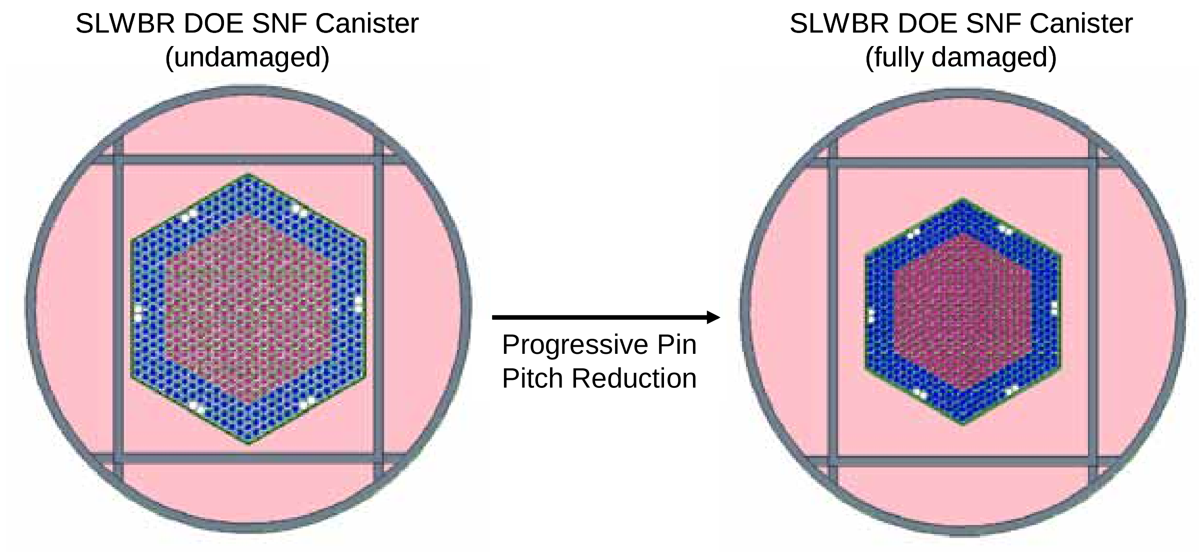

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Figure 6-83: Radial Cross-Section Views of the SLWBR DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.6 SPWR

The SPWR DOE SNF canister is described in detail in Section 6.1.3.6. The SPWR DOE SNF canister comprises a single fuel cluster which is composed of four fuel subclusters arranged in a square array with 1.2 cm spacing between each subcluster to form a cruciform-shaped channel in the center of the fuel cluster. Each subcluster comprises nineteen fuel and two neutron absorber (end) plates/wafers. Under *dry damaged intact* conditions the fuel plate/wafer separation is progressively reduced from its nominal value to a no separation condition. Refer to Figure 6-84 for an illustration of the fuel plate/wafer separation parameter examined in the *dry damaged intact* condition MCNP calculations.

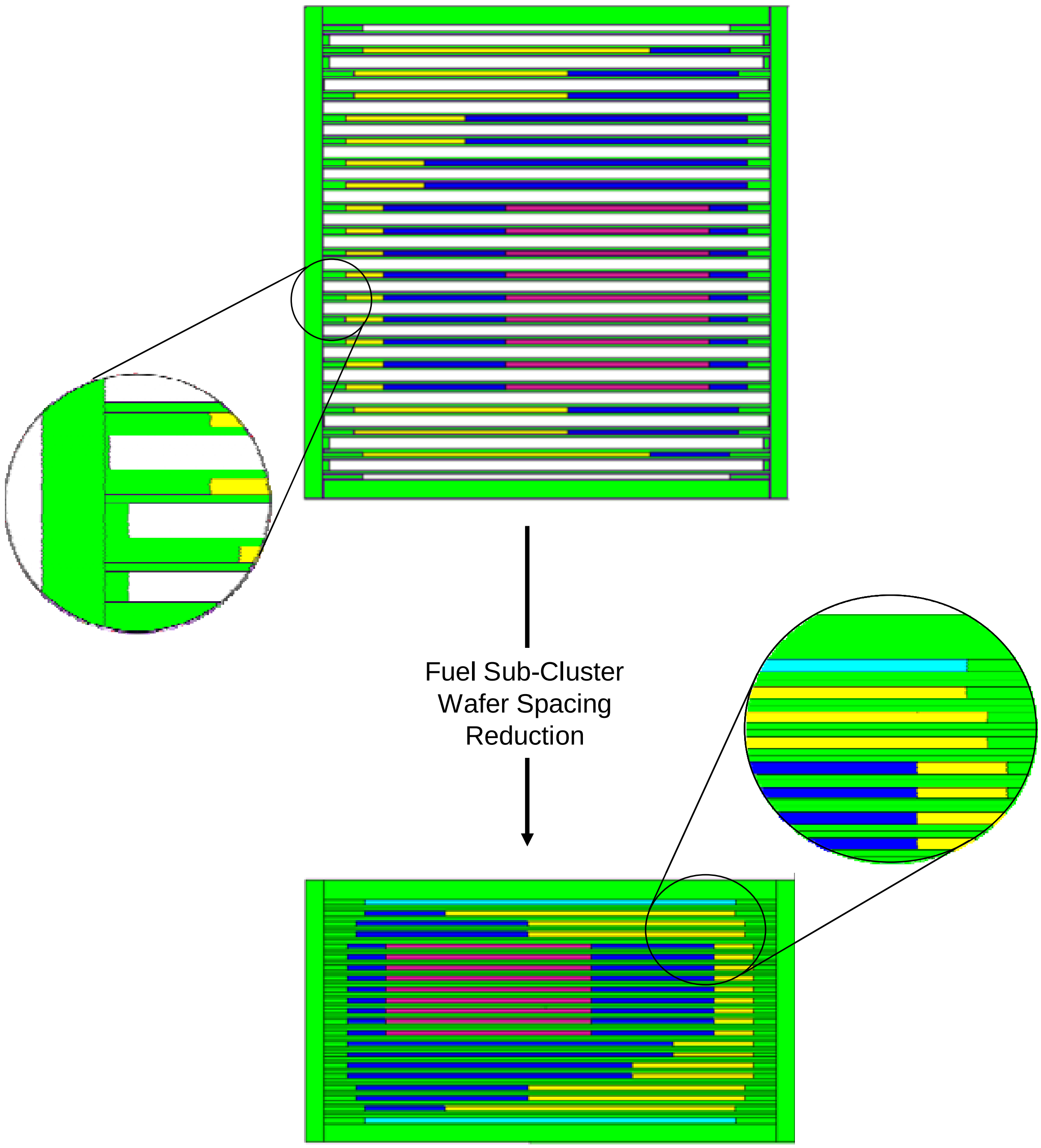

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Figure 6-84: Horizontal Cross-section of the SPWR Fuel Assembly Depicting the *Fuel Wafer Separation* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The fuel subcluster spacing is also examined independently to the fuel subcluster wafer spacing. Under *dry damaged intact* conditions the fuel subcluster separation is progressively reduced from its nominal value to a no separation condition. Refer to Figure 6-85 for an illustration of the fuel sub-cluster separation parameter examined in the *dry damaged intact* condition MCNP calculations. Note that a rotated sub-cluster orientation is used for these MCNP calculations to allow a more onerous conglomeration of SNF under damage conditions.

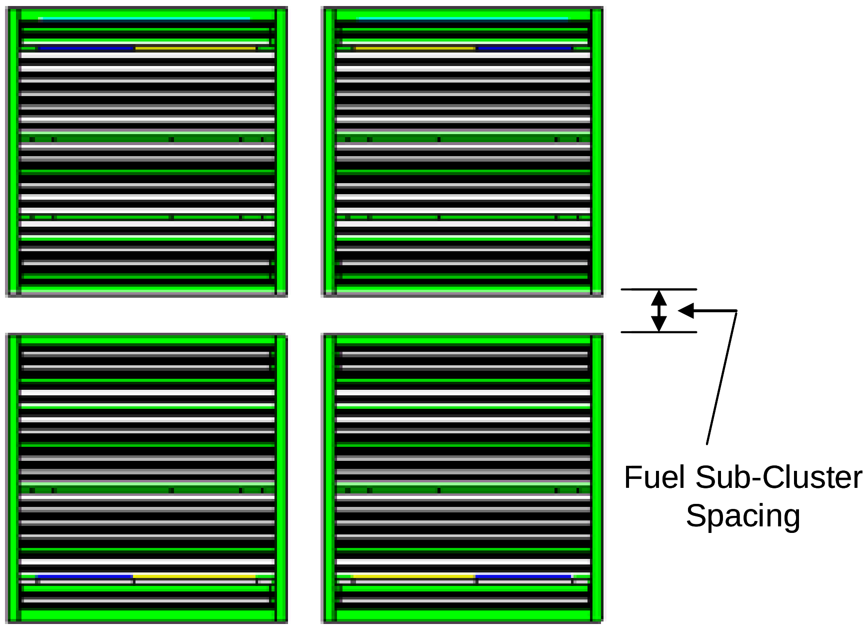

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Figure 6-85: Horizontal Cross-section of the SPWR Fuel Assembly Depicting the *Fuel SubCluster Separation* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

The specific geometry perturbations examined (and described above) for the SPWR DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-30. Note that all permutations of the parameters detailed in Table 6-30 are examined. Cross-section views of the SPWR DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-86.

Table 6-30. Geometry Perturbations Examined for the SPWR DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
SPWR Fuel Cluster	Fuel SubCluster Wafer Separation	Fuel SubCluster Wafer Spacing Reduction	0 %	0.204 cm	0.204 cm[1]
			20 %	0.163 cm	
			40 %	0.122 cm	
			60 %	0.082 cm	
			80 %	0.041 cm	
			100 %	0.0 cm	
SPWR Fuel Cluster	Fuel SubCluster Separation	Fuel SubCluster Spacing Reduction	0 %	1.2 cm	1.2 cm
			20 %	0.960 cm	
			40 %	0.720 cm	
			60 %	0.480 cm	
			80 %	0.240 cm	
			100 %	0.0 cm	
Total Permutations (Number of Cases Examined): 36					

[1] The nominal fuel wafer separation distance provided corresponds to largest of the fuel wafer separation distances.

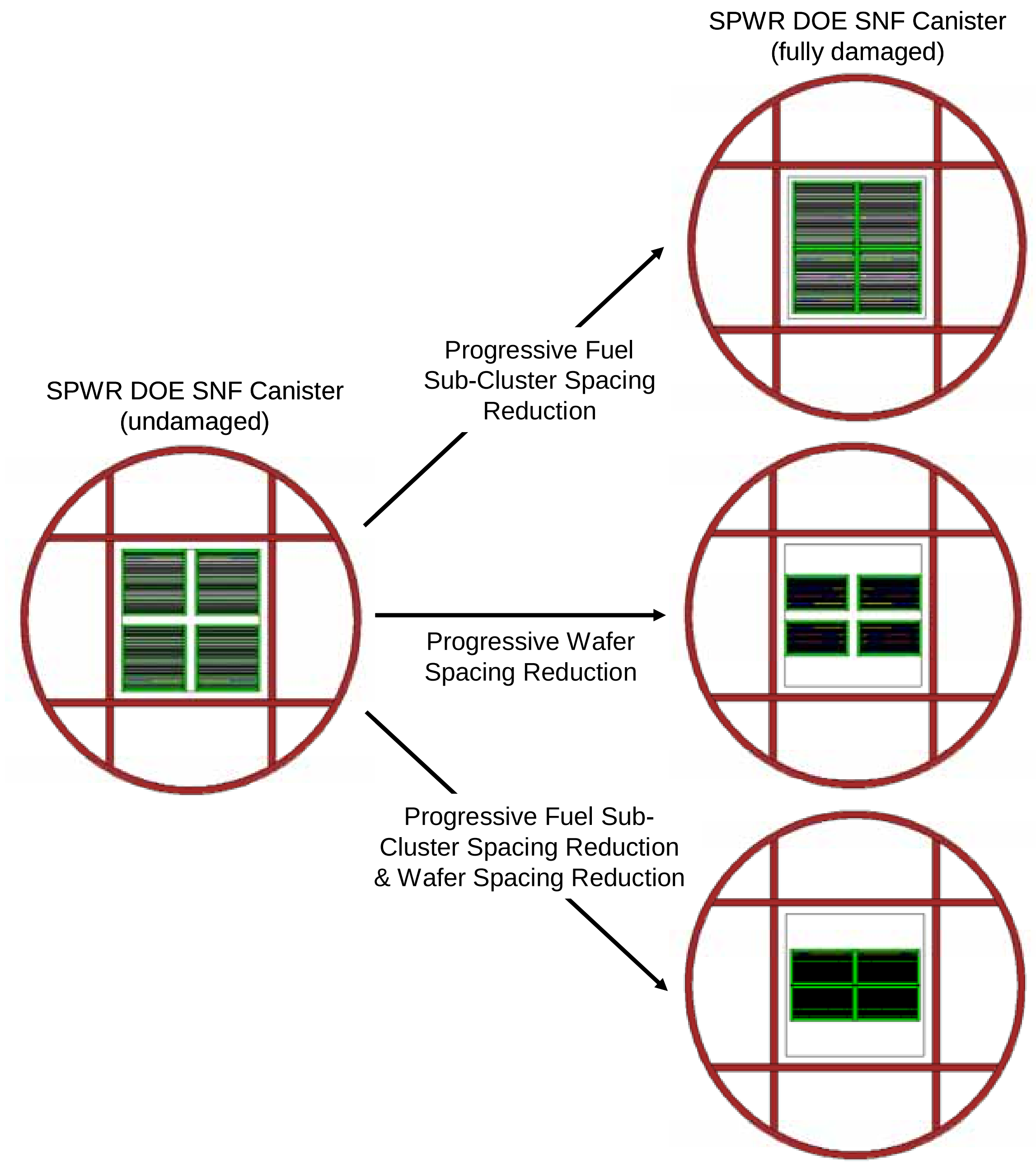

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Figure 6-86: Radial Cross-Section Views of the SPWR DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.7 TRIGA

The TRIGA DOE SNF canister is described in detail in Section 6.1.3.7. The TRIGA DOE SNF canister comprises ninety three TRIGA fuel elements arranged in a stacked tri-level basket structure that provides thirty one fuel elements per basket. Each fuel element is solid uranium-zirconium hydride containing highly enriched uranium. The fuel elements are loaded basket tubes constructed of nickel-gadolinium alloy. Under *dry damaged intact* conditions the fuel element-basket tube separation distance is gradually reduced from its nominal value to zero (i.e. a no separation condition). Refer to Figure 6-87 for an illustration of the basket tube diameter parameter examined in the *dry damaged intact* condition MCNP calculations.

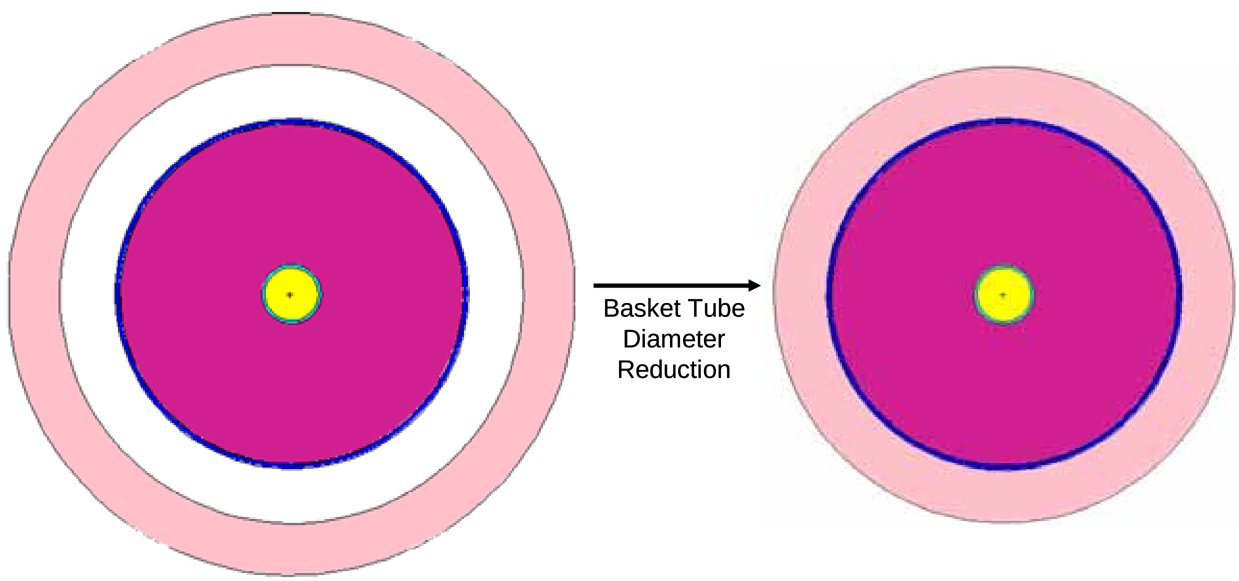

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Figure 6-87: Horizontal Cross-section of the TRIGA Fuel Element Depicting the *Basket Tube Diameter* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

Under nominal, i.e. un-damaged conditions, the TRIGA fuel basket tubes are close-packed (i.e. touching). As the basket tube diameter is varied in the *dry damaged intact* condition calculations, spacing is introduced between each basket tube. This spacing is independently re-adjusted. Refer to Figure 6-88 for an illustration of the basket tube diameter spacing parameter examined in the *dry damaged intact* condition MCNP calculations.

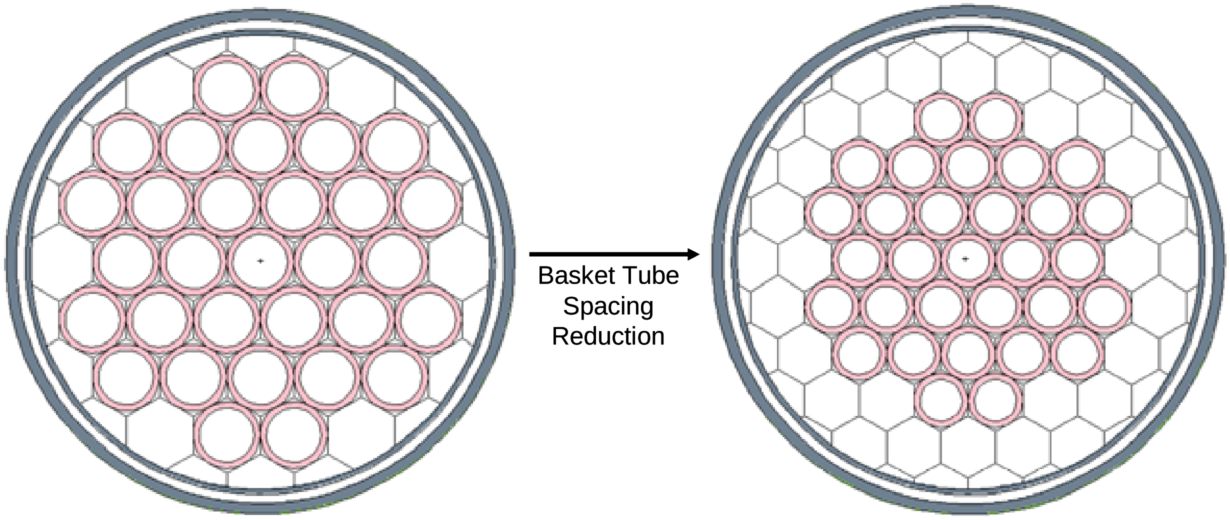

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Figure 6-88: Horizontal Cross-section of the TRIGA DOE SNF Canister Basket Structure Depicting the *Basket Tube Separation* Parameter Examined in the Dry Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the TRIGA DOE SNF Canister *dry damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket tubes to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the TRIGA DOE SNF canister under *dry damaged intact* conditions are explicitly quantified in Table 6-31. Note that all permutations of the parameters detailed in Table 6-31 are examined. Cross-section views of the TRIGA DOE SNF canister MCNP models under the described *dry damaged intact* configurations are provided in Figure 6-89.

Table 6-31. Geometry and Neutron Absorber Perturbations Examined for the TRIGA DOE SNF Canister Under Dry Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
TRIGA Fuel Basket Tube	Fuel Basket Tube Inner Diameter	Basket Tube Inner Diameter Reduction	0 %	4.925 cm	4.925 cm
			20 %	4.691 cm	
			40 %	4.457 cm	
			60 %	4.222 cm	
			80 %	3.988 cm	
			100 %	3.754 cm	
TRIGA Fuel Basket	Fuel Basket Tube Separation	Basket Tube Spacing Reduction	0 %	1.171 cm	0.0 cm[1]
			20 %	0.937 cm	
			40 %	0.703 cm	
			60 %	0.468 cm	
			80 %	0.234 cm	
			100 %	0.0 cm	
TRIGA Fuel Basket	Fuel Basket Tube Neutron Absorber (Gd) Content	Basket Gd Content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
Total Permutations (Number of Cases Examined): 216					

[1] As the basket tube diameter is varied in the dry damaged intact condition calculations, spacing is introduced between each basket tube. Normally there is no space between each tube. In the event of complete collapse of the basket tubes onto their respective fuel elements, a maximum basket tube separation of 1.171cm is created. This maximum value is reflected in the Table.

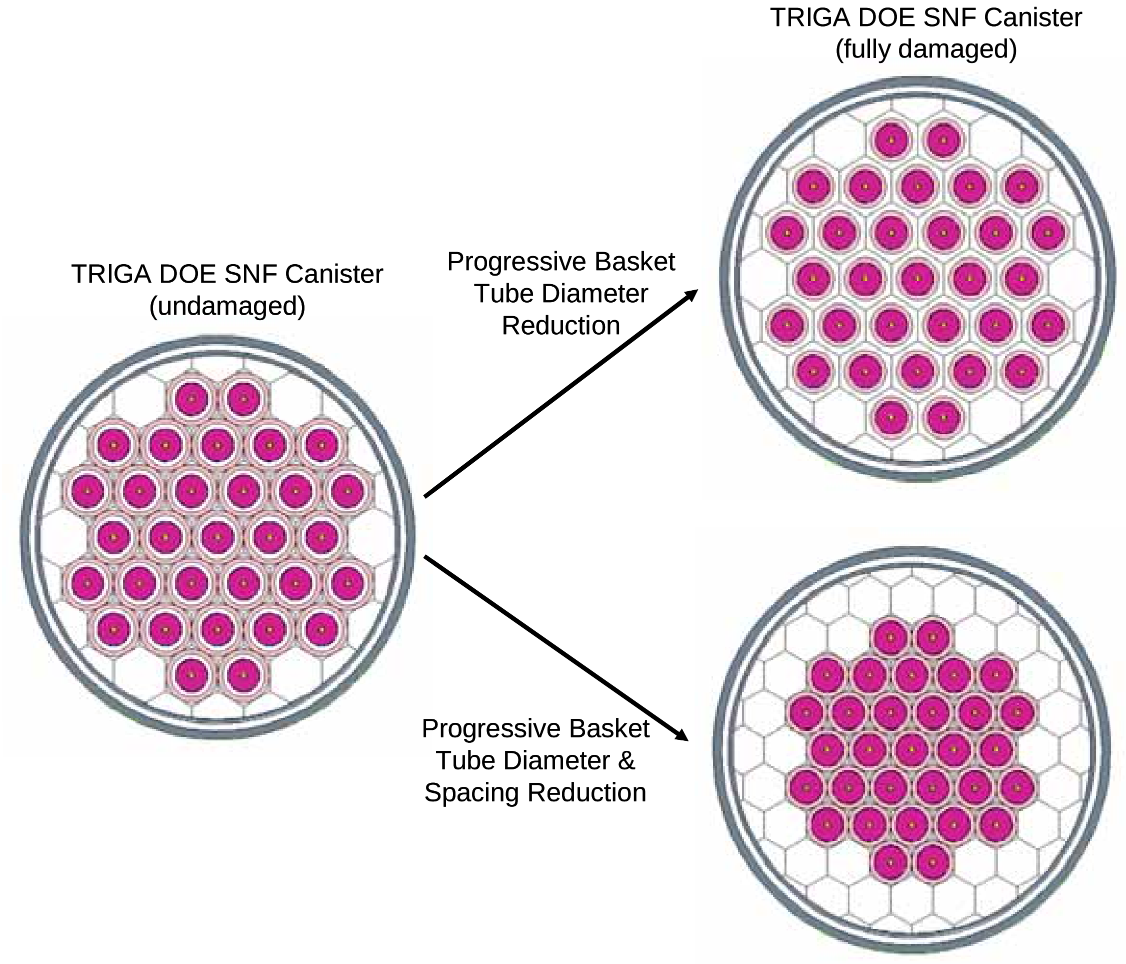

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Figure 6-89: Radial Cross-Section Views of the TRIGA DOE SNF Canister Depicting the Configurations Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.1.8 No Basket Present Models – EF, FFTF and TRIGA DOE SNF Canisters

The EF, FFTF and TRIGA DOE SNF canisters are separately examined without the presence of a basket structure. The absence of a basket structure allows for a more acute conglomeration of SNF than would otherwise be possible. Consequently, the configuration of SNF in the *no basket present* calculations differs from the SNF configuration in the basket present calculations described in Sections 6.2.2.1.2.1.2, 6.2.2.1.2.1.3, and 6.2.2.1.2.1.7.

The *no basket present* calculations are based on maximum SNF damage, as described in detail in Sections 6.2.2.1.2.1.2, 6.2.2.1.2.1.3, and 6.2.2.1.2.1.7. Cross-section views of the EF, FFTF and TRIGA DOE SNF canister MCNP models under the described *no basket present* scenario are provided in Figure 6-90, Figure 6-91, and Figure 6-92, respectively.

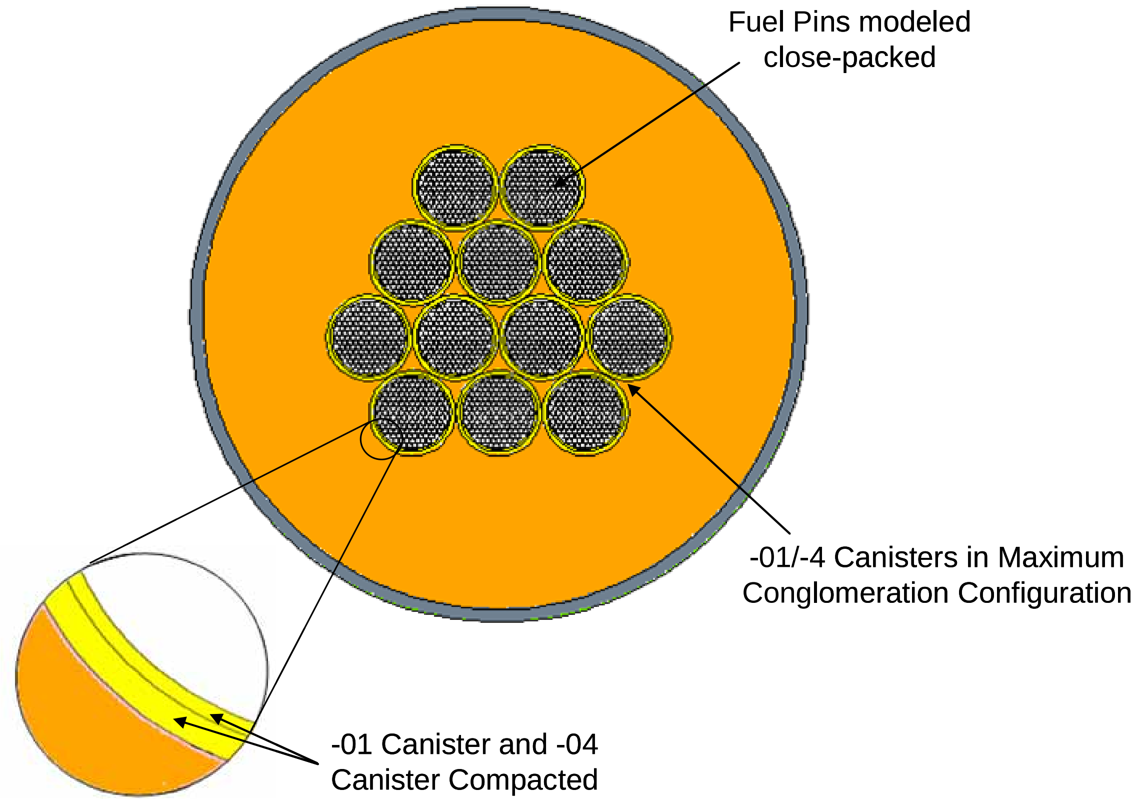

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Figure 6-90: Radial Cross-Section View of the EF DOE SNF Canister Depicting the *No Basket Present* Configuration Examined in the Dry Damaged Intact Condition MCNP Calculations

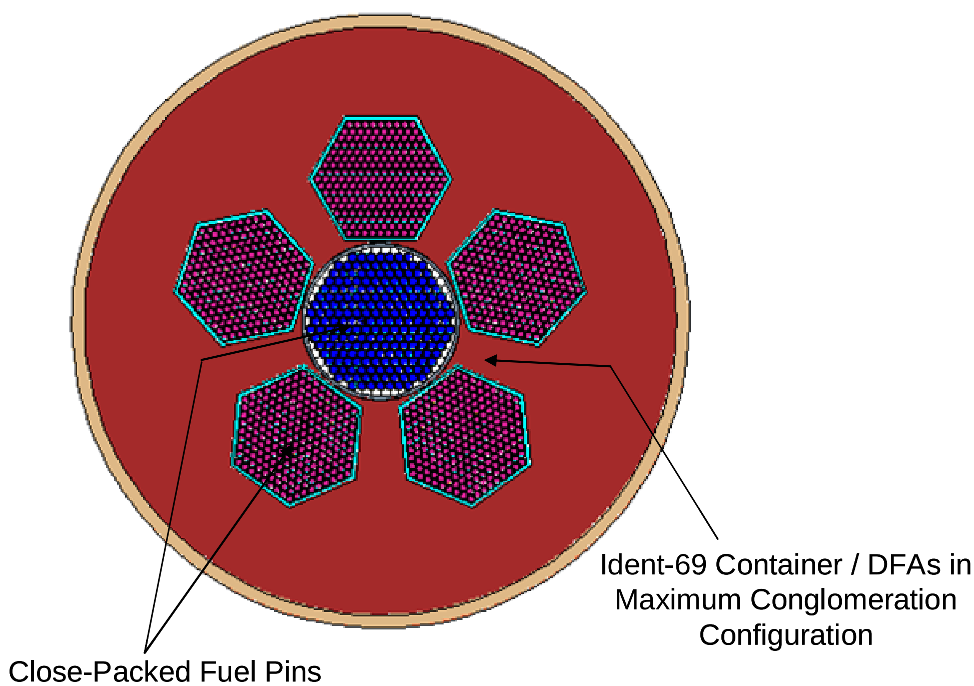

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Figure 6-91: Radial Cross-Section View of the FFTF DOE SNF Canister Depicting the *No Basket Present* Configuration Examined in the Dry Damaged Intact Condition MCNP Calculations

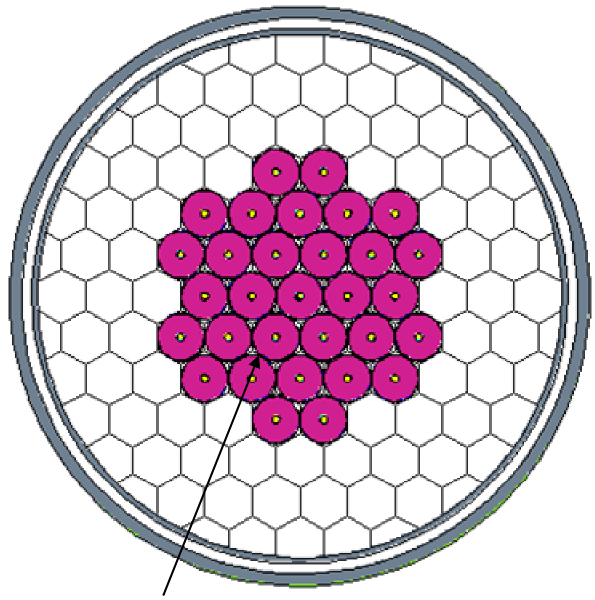

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Figure 6-92: Radial Cross-Section View of the TRIGA DOE SNF Canister Depicting the *No Basket Present* Configuration Examined in the Dry Damaged Intact Condition MCNP Calculations

6.2.2.1.2.2 Dry Damaged Degraded Configurations

The *dry damaged degraded* configuration calculations are based on complete or partial release of SNF, SNF clad, basket structure and basket filler material (where applicable) forming a homogeneous mixture of material.

The *dry damaged degraded* configuration calculations are based on homogeneous mixtures only. Heterogeneous mixtures are not considered based on the fissile enrichment of the SNF examined, which is inherently more reactive in a homogeneous form.

The degree of degradation examined in the calculations (i.e. the quantity of SNF, clad, basket and basket filler material that is considered released) is expressed as a percentage of the total inventory for the respective canister. For example, canister debris with a basket filler content of 40% means that 40% of the total mass of basket filler material associated with the respective canister is modeled in the canister debris.

The inventory of each DOE SNF canister is provided in Table 6-32, together with the range of material release fractions considered in the MCNP calculations. The explicit material compositions for each MCNP calculation are computed using the material compositions provided in Attachment 1, in conjunction with the material release fractions specific to the calculation, allowing for the selected void fraction. Cross-section views of the MCNP models are provided in Figure 6-93.

For all calculations, any clad, basket structure or basket filler material not represented in the modeled debris is not explicitly modeled in the calculation. For example canister debris with a basket filler content of 40% means that 60% of the total mass of basket filler material associated with the respective canister is not modeled in the canister debris. The residual 60% is not modeled external to the canister debris because the effect of the presence of any material external to the canister debris is accounted for in the wide variety of reflection conditions considered (which also includes reflector materials specific to the canister examined). Given that all *dry damaged degraded* configuration calculations consider a fixed 100% release of SNF, this treatment is conservative.

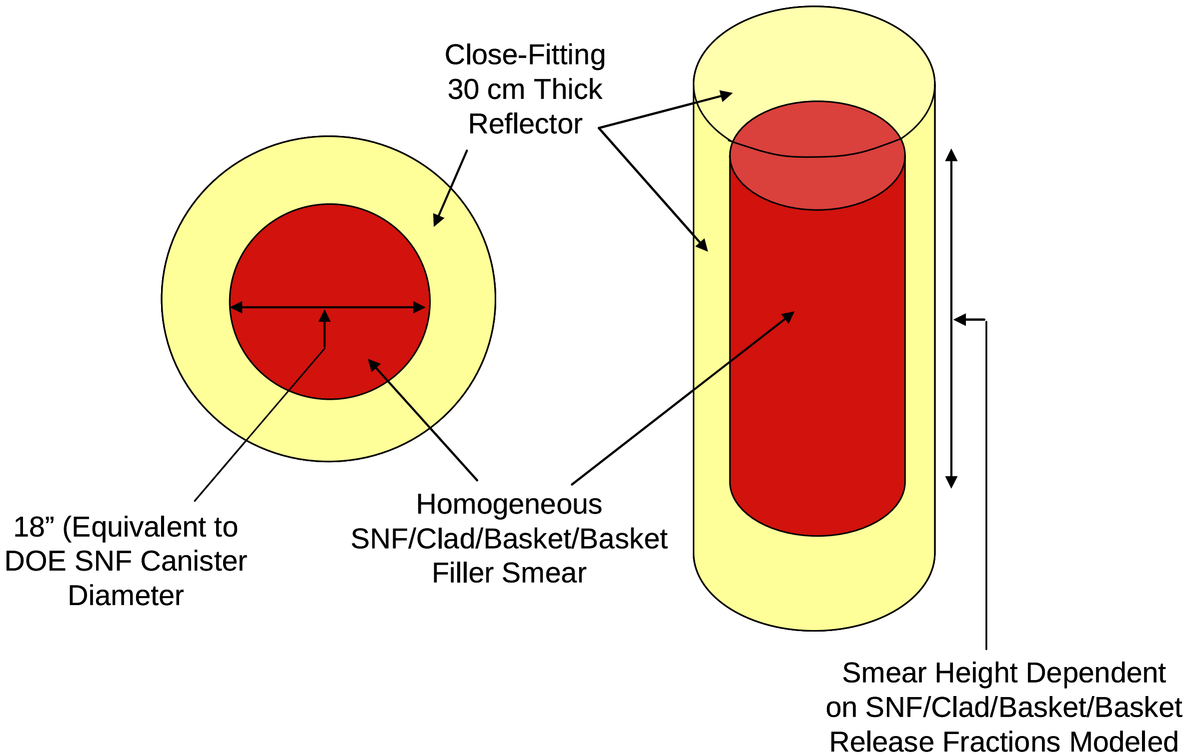

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Figure 6-93: Radial and Axial Cross-Section View of the Degraded DOE SNF Canister MCNP Models

Table 6-32. DOE SNF Canister Inventory and Material Release Fractions Examined in the Degraded Configuration MCNP Calculations

DOE SNF Canister	Mass per DOE SNF Canister (kg)			
	SNF	SNF Clad	Basket Structure	Basket Filler Material
ATR	90.6 [a] 92.975 [2]	132.61 [b]	555.06 [p]	N/A
EF	503.392 [c] 506.28 [2]	30.912 [d]	383.52 [q]	800 [o]
FFTF	244.44 [e] 246.87 [2]	166.24 [f]	426.78 [r]	760 [o]
FSV	210.04 [g] 215.23 [2]	0.0 [h]	425.0 [s]	N/A
SLWBR	337.44 [i] 340.92 [2]	136.8 [j]	402.14 [t]	400 [o]
SPWR	59.78 [k] 60.805 [2]	103.0 [l]	501.71 [u]	N/A
TRIGA	214.5 [m] 217.75 [2]	23.6 [n]	626.82 [v]	N/A

Source:

[a] Ref. 2.2.13, Pg. 40 (based on 30 elements x 3.02 kg per element).
[b] Ref. 2.2.13, Pg. 40 (based on 30 elements x 4.42 kg (clad and frame mass) per element).
[c] Ref. 2.2.14, Pg. 7 (based on 24 -01/-04 cans x 140 pins/can x 149.82 g(fuel matrix) per pin).
[d] Ref. 2.2.14, Pg. 7 (based on 24 -01/-04 cans x 140 pins/can x 9.2 g(Zr) per pin).
[e] Ref. 2.2.15, Table 1 (based on 153 g(U+Pu) per pin, 217 Type 4.1 pins per DFA, 5 DFAs, and 217 Ident-69 Container pins (with a pin mass 1.48 x greater than a Type 4.1 pin).
[f] Based on 15.5cc and 18.5cc of clad per pin for the DFA Type 4.1 pins and the Ident-69 Container pins, respectively. Clad volume estimates calculated from FFTF MCNP model parameters contained in Attachment 3, *MCNP inputs.zip.*
[g] Ref. 2.2.16, Table 2-7, (based on 3130 fuel compacts per assembly and 5 element blocks per canister).
[h] Note that the FSV clad is integrated with the fuel matrix and therefore is accounted for in the SNF material composition and mass.
[i] Ref. 2.2.20, Table 3-4.
[j] Based on 33.7cc of clad per pin and 619 pins per canister. Clad volume estimates calculated from SLWBR MCNP model parameters contained in Attachment 3, *MCNP inputs.zip.*
[k] Ref. 2.2.19, Table 3-3.
[l] Estimated from SPWR MCNP model parameters contained in Attachment 3, *MCNP inputs.zip.*
[m] Ref. 2.2.22, Table 3-7.
[n] Estimated from TRIGA MCNP model parameters contained in Attachment 3, *MCNP inputs.zip.*
[o] Estimated based on available volume and filler density from EF, FFTF and SLWBR MCNP model parameters contained in Attachment 3, *MCNP inputs.zip.*
[p] Ref. 2.2.27, Table A-1.
[q] Ref. 2.2.27, Table D-1.
[r] Ref. 2.2.27, estimated from dimensions portrayed in Figure C-1.
[s] Ref. 2.2.16, Table 2-1.
[t] Ref. 2.2.27, Table G-1.
[u] Ref. 2.2.27, Table F-1.
[v] Ref. 2.2.27, Table E-1.

NOTES:
[2] Based on given SNF mass with allowance for 10 vol % moisture content.

6.2.2.1.3 Single Canister Damage with Breach

Under normal conditions DOE SNF canisters are handled individually. In the event of a process upset resulting in inadvertent release of a DOE SNF canister during handling, it is possible that the canister (and its content) could be damaged.

This section describes the MCNP calculations performed for off-normal conditions consisting of damage to an individual DOE SNF canister, with actual breach of the canister shell and coincident flooding of the canister content. The key aspects of this off-normal conditions analysis involve postulated damage to the DOE SNF canister resulting in:

1. a rearrangement of its internal structure (e.g. repositioning of SNF and basket structure), but not resulting in a physical release of material (i.e. creation of fuel debris). This configuration is referred to as a *flooded damaged intact* configuration.
2. complete or partial release of its internal structure, forming 'debris' (i.e. a mixture of SNF, basket structure and basket filler material). This configuration is referred to as a *flooded damaged degraded* configuration.

Similar to the evaluation of normal conditions, the single canister *flooded damage* models incorporate close fitting full-thickness (30 cm) reflection adjacent all surfaces of the canister. A series of reflector materials (Attachment 1) are examined to determine the limiting reflection condition for each DOE SNF canister. Examination of alternate reflectors is performed for the *dry damage* off-normal conditions analysis (rather than using the worst-case reflector established from the normal conditions analysis) in recognition of softening of the neutron spectrum resultant for moderation of the canister contents examined in the calculations.

6.2.2.1.3.1 Flooded Damaged Intact Configurations

The *flooded damaged intact* configuration calculations are based on progressive degrees of canister basket and SNF damage that result in a gradual rearrangement of basket structure and SNF that would be expected to result in an increase in k_{eff} under moderated conditions. Under moderated conditions this type of damage is characterized by a separation of SNF, which typically results in an increase in k_{eff} due to an increase in the atom ratio of hydrogen to fissile material in the fuel region. Since this analysis is focused on examining geometric perturbations that result in an increase in k_{eff}, rather than examining geometric perturbations that would realistically characterize the canister contents under canister impact scenarios, the damage conditions examined are considered conservative approximations of potential damage.

Given that the seven fuel basket/waste forms examined in this calculation have unique designs (i.e. are entirely different from each other), the damage conditions examined for each DOE SNF canister are also unique, and generally dissimilar to the damage conditions examined under *dry damaged intact* conditions. The explicit *flooded damaged intact* configurations examined for each DOE SNF canister are described in detail in the following sub-sections. Cross-sectional views of the MCNP models are provided to depict the progressive levels of damage examined for each canister. The degree of damage is generally expressed as a percentage of the maximum potential damage for which k_{eff} would be maximized. In addition, each damage condition examined in the calculations is quantified (in a tabulated numeric form) in terms of the actual change in dimensions or positions of SNF and basket structure in the MCNP models.

In addition to geometric perturbations, for each *flooded damaged intact* configuration calculation described in the following sub-sections, the neutron absorber content of the basket structure (if any) and the basket filler material (if any) is varied to establish the sensitivity of the system to a reduced presence of neutron absorber.

6.2.2.1.3.1.1 ATR

The ATR DOE SNF canister is described in detail in Section 6.1.3.1. The ATR DOE SNF canister comprises thirty ATR fuel elements arranged in a stacked tri-level basket structure that provides ten fuel elements per basket. Each fuel element consists of nineteen curved aluminum clad uranium aluminide (UAl_x) plates containing highly enriched uranium. The plates are held in place by aluminum side plates that serve to provide a fixed separation between each plate. The nominal plate separation is 0.198 cm. Under *flooded damaged intact* conditions the fuel element plate separation is gradually increased from its nominal value until all available space within the fuel compartment is utilized. Refer to Figure 6-94 for an illustration of the fuel element plate spacing parameter examined in the *flooded damaged intact* condition MCNP calculations.

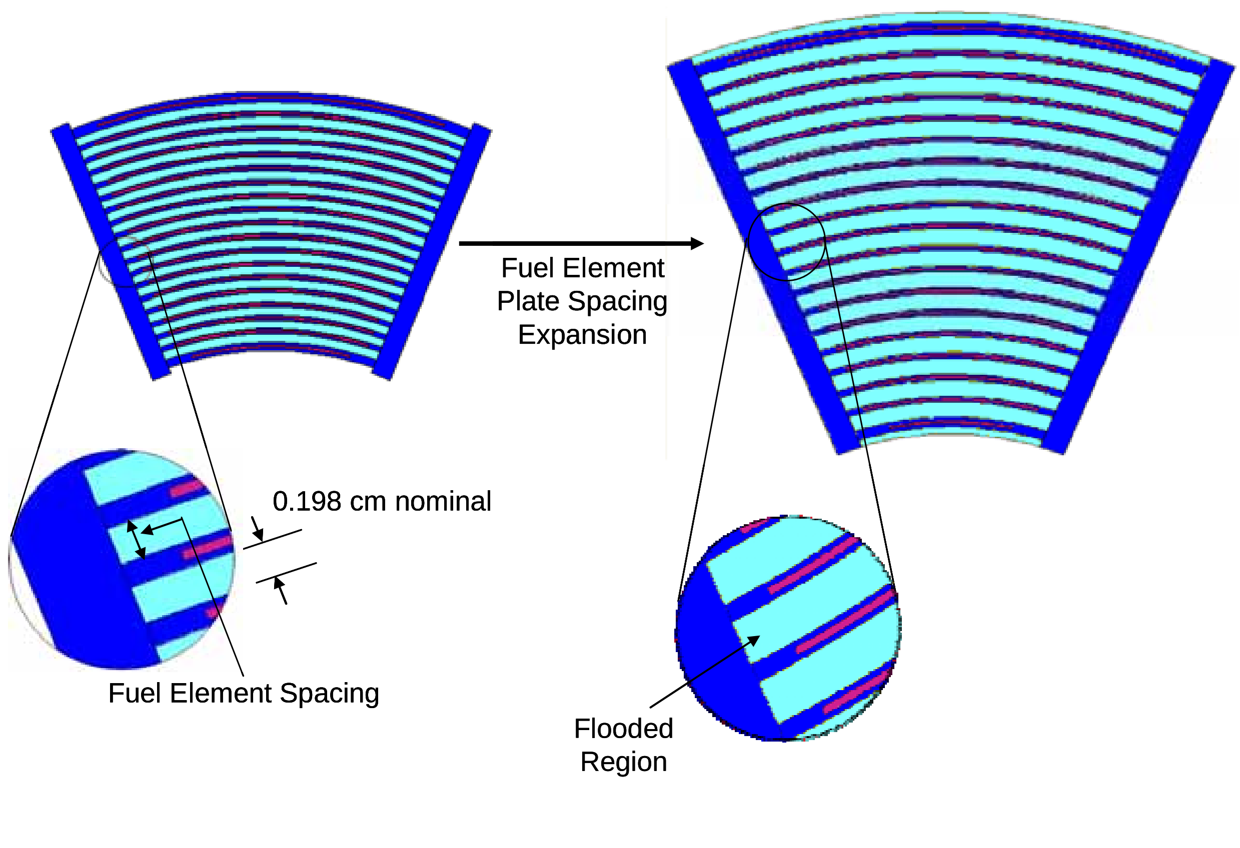

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Figure 6-94: Horizontal Cross-section of the ATR Fuel Element Depicting the Fuel Element Plate Separation Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The ATR DOE SNF canister fuel basket consists of a series of a perpendicularly arranged plates conforming to a symmetric pattern. The compartments formed by the arrangement of basket plates accommodate the ATR fuel elements, and ensure spacing between adjacent fuel elements.

The nominal fuel basket plate separation is 9.049 cm. Under *flooded damaged intact* conditions the basket plate separation is unchanged from its nominal value to maximize the fuel element plate expansion achievable.

In addition to geometric perturbations, the ATR DOE SNF Canister *flooded damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the ATR DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-33. Note that all permutations of the parameters detailed in Table 6-33 are examined. Cross-section views of the ATR DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-95.

Table 6-33. Geometry and Neutron Absorber Perturbations Examined for the ATR DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
ATR Fuel Element	Fuel Element Plate Separation	Fuel Element Plate Spacing Expansion	0 %	0.198 cm	0.198 cm
			20 %	0.220 cm	
			40 %	0.242 cm	
			60 %	0.265 cm	
			80 %	0.287 cm	
			100 %	0.309 cm	
ATR Fuel Basket	Fuel Basket Plate Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
Total Permutations (Number of Cases Examined): 36					

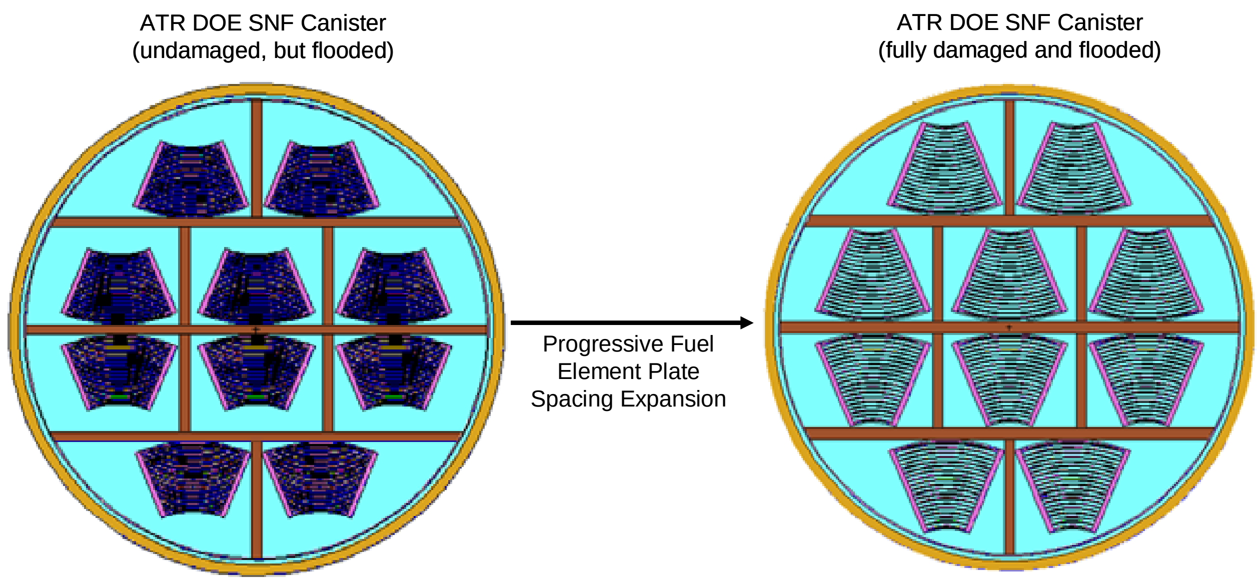

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Figure 6-95: Radial Cross-Section Views of the ATR DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact MCNP Calculations

6.2.2.1.3.1.2 EF

The EF DOE SNF canister is described in detail in Section 6.1.3.2. The EF DOE SNF canister comprises twenty four basket tubes arranged in a stacked bi-level structure that provides twelve basket tubes, or compartments, per basket. Each basket tube position accommodates 140 fuel pins, which are sealed in a -04 canister, that is enclosed in an -01 canister. The 140 fuel pins positioned in each -04 canister are loaded loose, and have no supporting or spacing mechanism. Under *flooded damaged intact* conditions the fuel pin pitch is progressively increased from a close-packed condition to a maximum possible pitch (constrained by the -04 canister inner diameter). Refer to Figure 6-96 for an illustration of the fuel pin pitch parameter examined in the *flooded damaged intact* condition MCNP calculations.

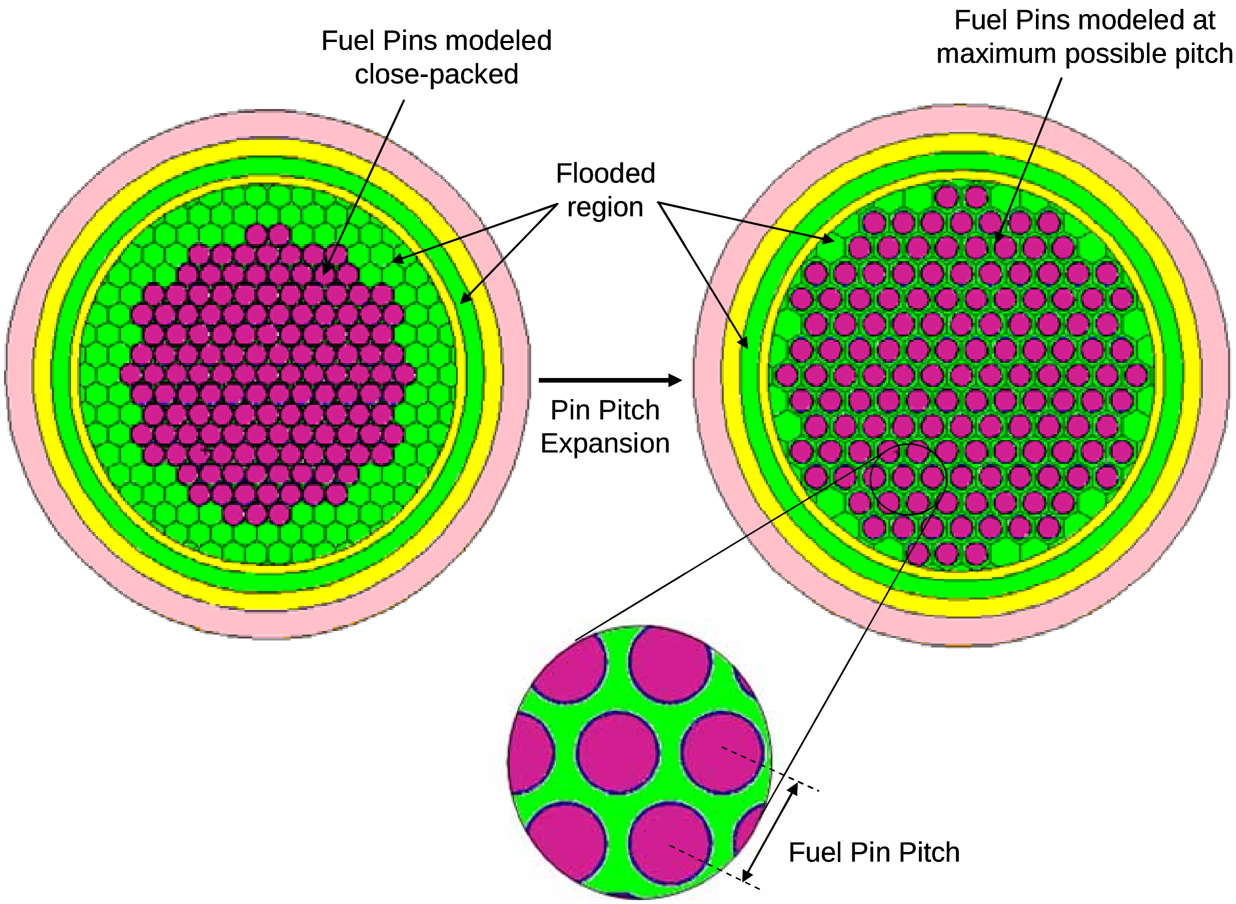

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Figure 6-96: Horizontal Cross-section of the EF -04 Canister Depicting the *Fuel Pin Pitch* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The EF DOE SNF canister basket assembly consists of twelve nickel-gadolinium alloy tubes attached to a stainless steel base plate. The void space between the twelve tubes is filled with iron shot (Fe) containing gadolinium phosphate ($GdPO_4$). Under flooded conditions, the void space within this basket filler material is flooded.

Similar to the *dry damaged intact* condition calculations, the basket tube separation is gradually reduced from its nominal value to the smallest achievable separation distance (equivalent to a bunched basket tube configuration), to minimize the effectiveness of the neutron absorber contained in the basket filler material. Refer to Figure 6-97 for an illustration of the basket tube spacing parameter examined in the *flooded damaged intact* condition MCNP calculations. Note that for conservatism the basket tube diameter is modeled fully contracted for all *flooded damaged intact* condition MCNP calculations. This treatment minimizes the effectiveness of the neutron absorber contained in the basket tubes.

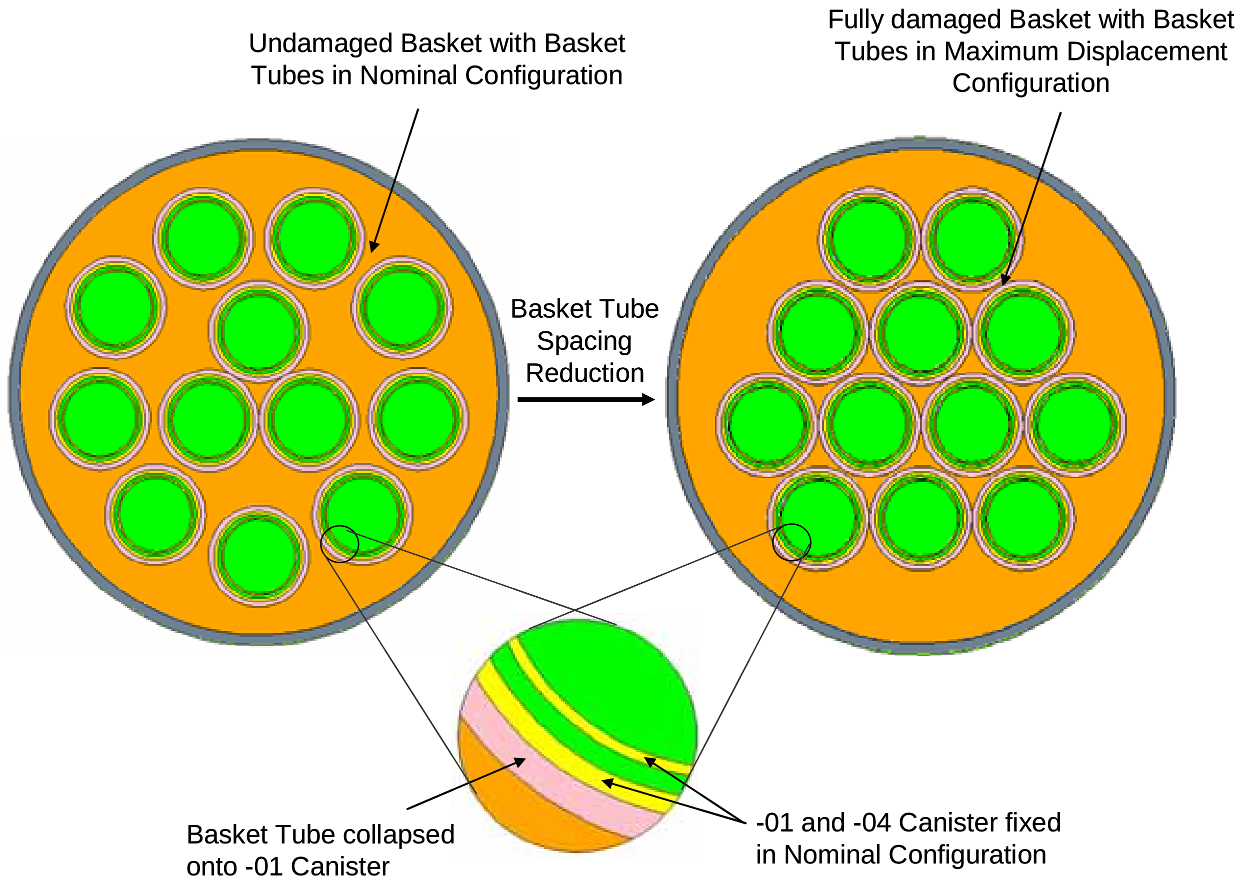

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Figure 6-97: Horizontal Cross-section of the EF DOE SNF Canister Depicting the *Basket Tube Separation* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the EF DOE SNF Canister *flooded damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure, and independently the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the EF DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-34. Note that all permutations of the parameters detailed in Table 6-34 are examined. Cross-section views of the EF DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-98.

Table 6-34. Geometry and Neutron Absorber Perturbations Examined for the EF DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
EF Fuel Pin	Pin Pitch	Pin Pitch Expansion	0 %	0.401 cm	0.401 cm[1]
			20 %	0.421 cm	
			40 %	0.441 cm	
			60 %	0.460 cm	
			80 %	0.480 cm	
			100 %	0.5 cm	
EF Fuel Basket Tube	Basket Tube Separation	Basket Tube Spacing Reduction	0 %	4.164 cm	4.164 cm[2]
			20 %	3.331 cm	
			40 %	2.498 cm	
			60 %	1.666 cm	
			80 %	0.833 cm	
			100 %	0.0 cm	
EF Fuel Basket Tube	Basket Tube Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
EF Basket Filler Material	Basket Filler Neutron Absorber ($GdPO_4$) Content	Basket Filler Gd content	0 %	0.0 vol% $GdPO_4$	3.0 vol% $GdPO_4$
			20 %	0.6 vol% $GdPO_4$	
			40 %	1.2 vol% $GdPO_4$	
			60 %	1.8 vol% $GdPO_4$	
			80 %	2.4 vol% $GdPO_4$	
			100 %	3.0 vol% $GdPO_4$	
Total Permutations (Number of Cases Examined): 1296					

[1] The fuel pins are treated as close-packed within the -04 canister as a nominal condition for the flooded damaged intact MCNP calculations.
[2] The Basket Tube Separation values provided are based on (and therefore apply only to) the Basket Tube positioned the furthest from the center of the canister (i.e. the Basket Tube situated in the “6-oclock’ position).

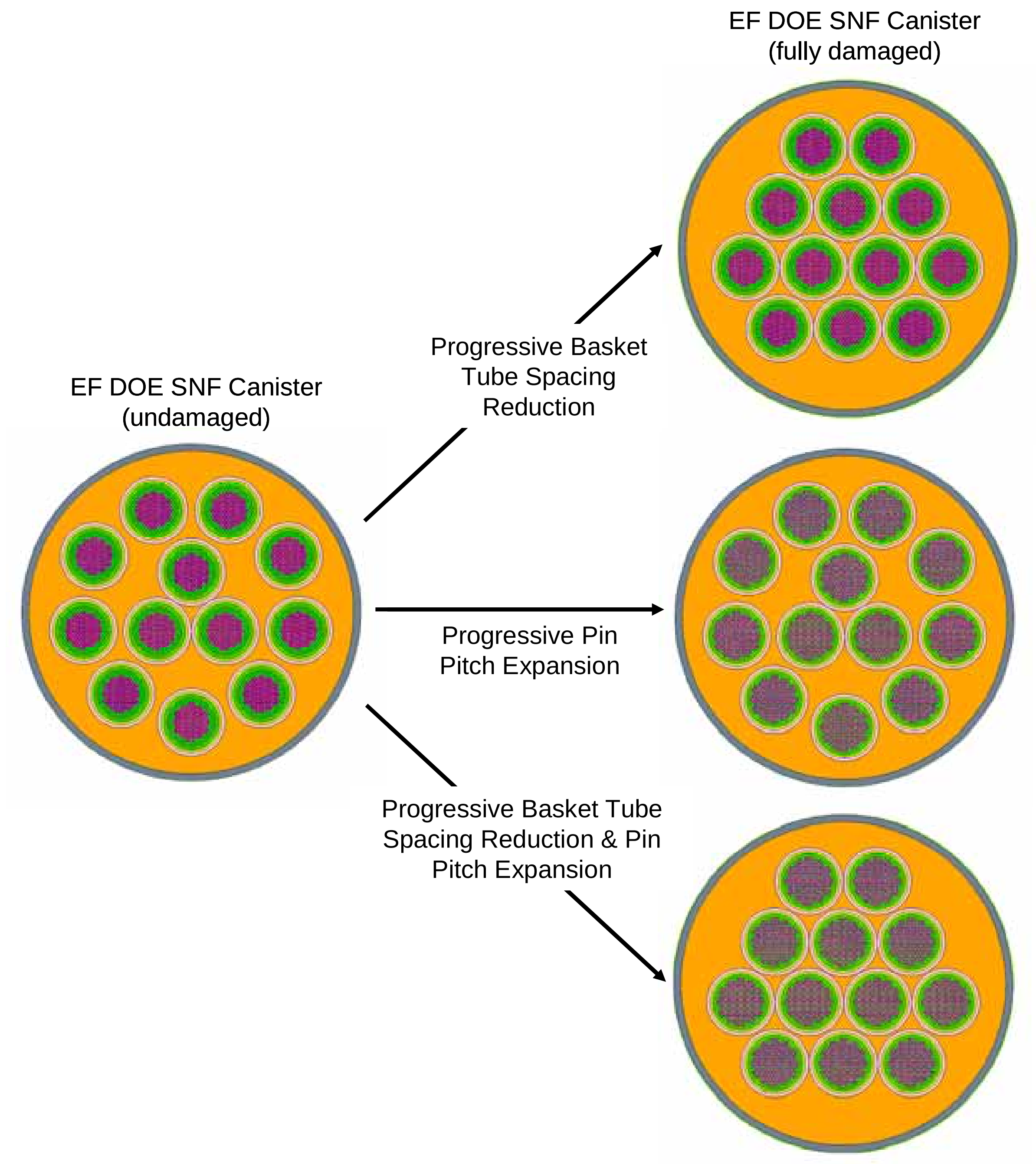

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Figure 6-98: Radial Cross-Section Views of the EF DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact MCNP Calculations

6.2.2.1.3.1.3 FFTF

The FFTF DOE SNF canister is described in detail in Section 6.1.3.3. The FFTF DOE SNF canister comprises five DFAs, with each DFA containing 217 fuel pins, in addition to a centralized Ident-69 container which is used to accommodate loose fuel pins from disassembled DFAs. The Ident-69 container is positioned in the center of the canister within a cylindrical basket center tube. The five DFAs are distributed amongst five compartments created by five basket divider plates, or spokes, that extend radially from the center basket tube to the inside wall of the DOE SNF canister.

Under *flooded damaged intact* conditions the fuel pin pitch associated with the DFAs is progressively increased from its nominal value to a maximum possible pitch, governed by the available space within the basket compartment. Refer to Figure 6-99 for an illustration of the fuel pin pitch parameter examined in the *flooded damaged intact* condition MCNP calculations.

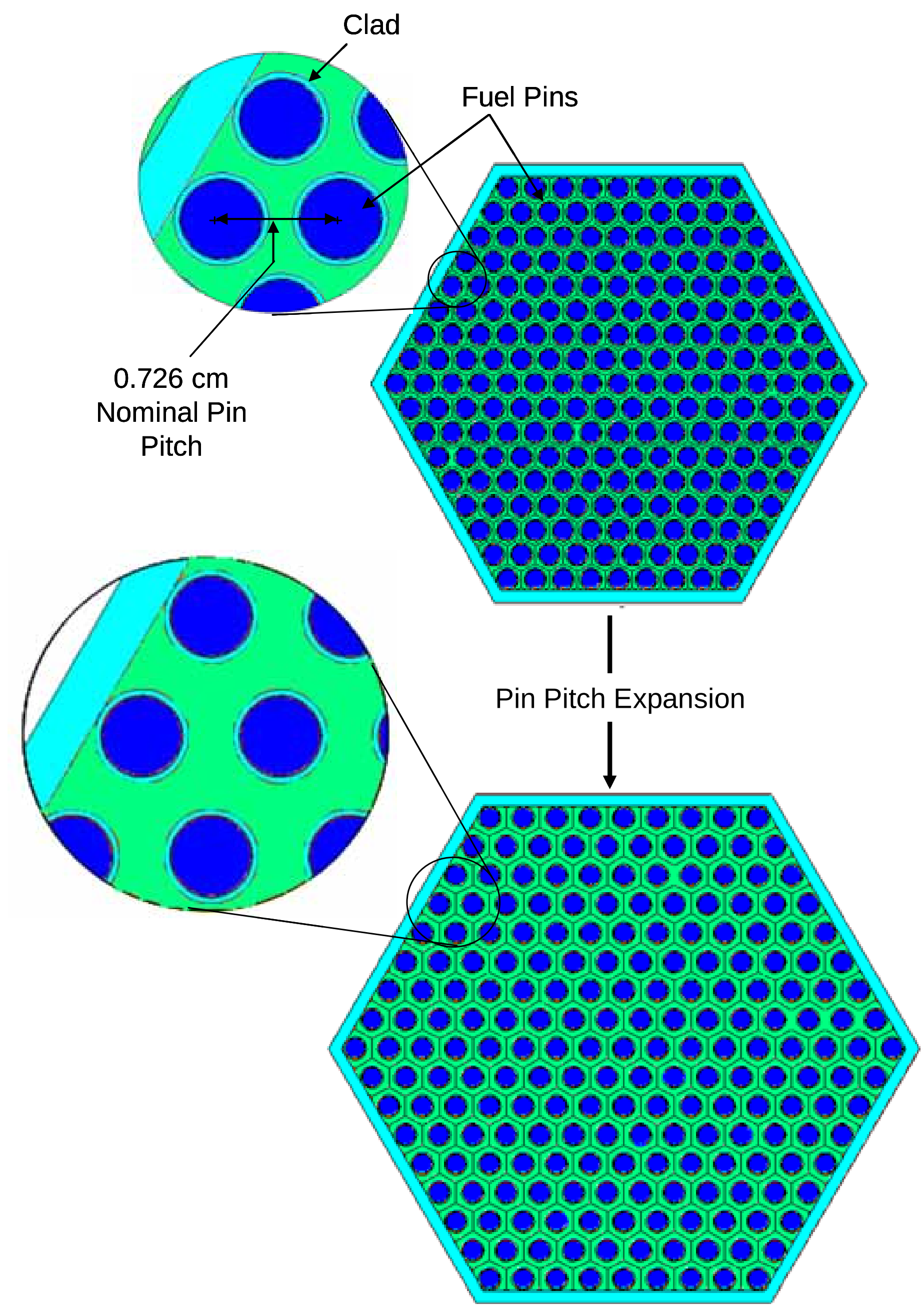

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Figure 6-99: Horizontal Cross-section of the FFTF DFA Depicting the *Fuel Pin Pitch* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

Independent to the DFA pin pitch variation, the pin pitch associated with the fuel pins situated within the Ident-69 container is progressively increased from its nominal value by reducing the number of fuel pins situated within the container. This modeling treatment progressively results in an increase in k_{eff} due to a progressive increase in the thermalization of neutrons, until the point of optimum moderation is achieved. A range of fuel pin pitch values are examined to establish the sensitivity of k_{eff} to pin pitch (and thus the Ident-69 container payload). Refer to Figure 6-100 for an illustration of the fuel pin pitch parameter examined in the *flooded damaged intact* condition MCNP calculations.

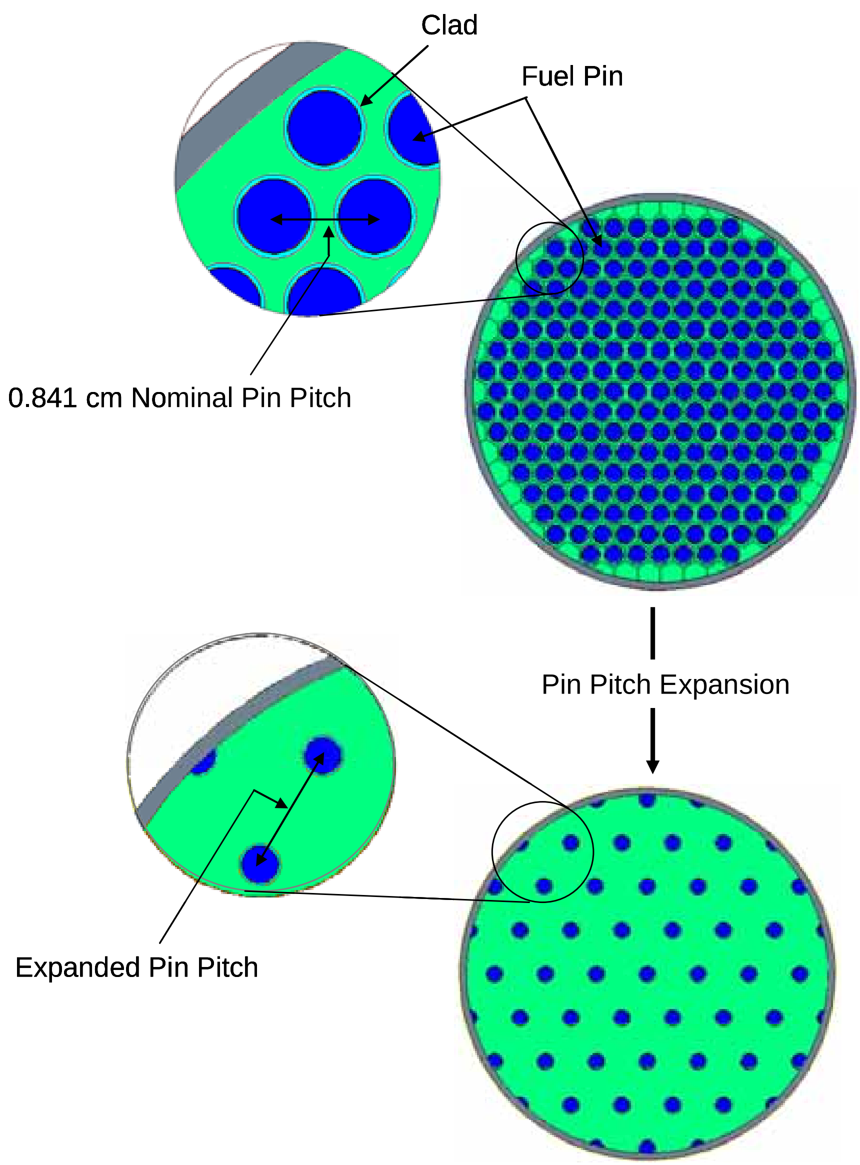

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Figure 6-100: Horizontal Cross-section of the FFTF Ident-69 Container Depicting the *Fuel Pin Pitch* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The FFTF DOE SNF canister basket tube and divider plates consist of nickel-gadolinium alloy tubes and plates. The void space between the tube/divider plates is filled with aluminum gadolinium phosphate (Al-$GdPO_4$) shot (filler material). Under flooded conditions, the void space within this basket filler material is flooded. The nominal basket assembly design is portrayed in Figure 6-101.

Under *flooded damaged intact* conditions the centralized basket tube diameter is maintained at its nominal diameter to allow the Ident-69 container to progressively expand to fill all of the space within the basket center compartment. Refer to Figure 6-101 for an illustration of the basket arrangement examined in the *flooded damaged intact* condition MCNP calculations.

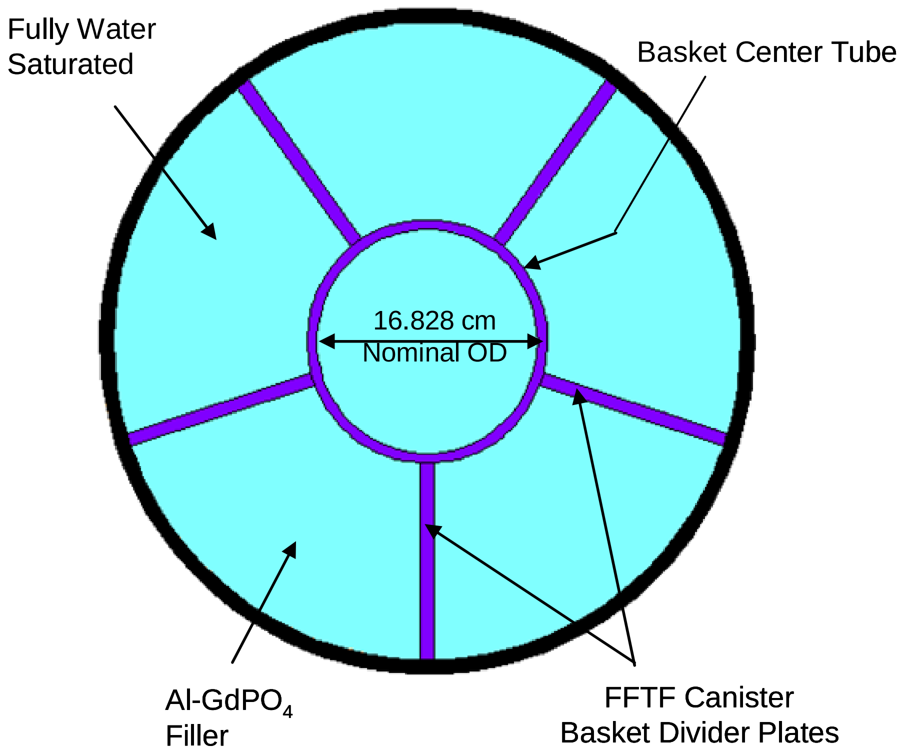

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Figure 6-101: Horizontal Cross-section of the FFTF DOE SNF Canister Depicting the Basket Arrangement Examined in the Flooded Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the FFTF DOE SNF Canister *flooded damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket structure, and independently the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the FFTF DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-35. Note that all permutations of the parameters detailed in Table 6-35 are examined. Cross-section views of the FFTF DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-102.

Table 6-35. Geometry and Neutron Absorber Perturbations Examined for the FFTF DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
FFTF DFA Fuel Pin	DFA Pin Pitch	DFA Pin Pitch Expansion	0 %	0.726 cm	0.726 cm
			20 %	0.752 cm	
			40 %	0.778 cm	
			60 %	0.805 cm	
			80 %	0.831 cm	
			100 %	0.857 cm	
FFTF Ident-69 Container Fuel Pin	Ident-69 Container Pin Pitch	Ident-69 Container Pin Pitch	0.690 cm	0.690 cm	0.690 cm[1]
			0.890 cm	0.890 cm	
			1.090 cm	1.090 cm	
			1.290 cm	1.290 cm	
			1.490 cm	1.490 cm	
			1.690 cm	1.690 cm	
			1.890 cm	1.890 cm	
			2.090 cm	2.090 cm	
FFTF Fuel Basket Tube	Basket Tube Neutron Absorber (Gd) Content	Basket Gd content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
FFTF Basket Filler Material	Basket Filler Neutron Absorber (Gd) Content	Basket Filler Gd content	0 %	0.0 wt% Gd	4.3 wt% Gd
			20 %	0.86 wt% Gd	
			40 %	1.72 wt% Gd	
			60 %	2.58 wt% Gd	
			80 %	3.44 wt% Gd	
			100 %	4.3 wt% Gd	
Total Permutations (Number of Cases Examined): 1728					

[1] Note that the Ident-69 container nominal fuel pin pitch is based on a close-packed (i.e. minimum possible pitch) fuel pin arrangement for the flooded damaged intact MCNP calculations.

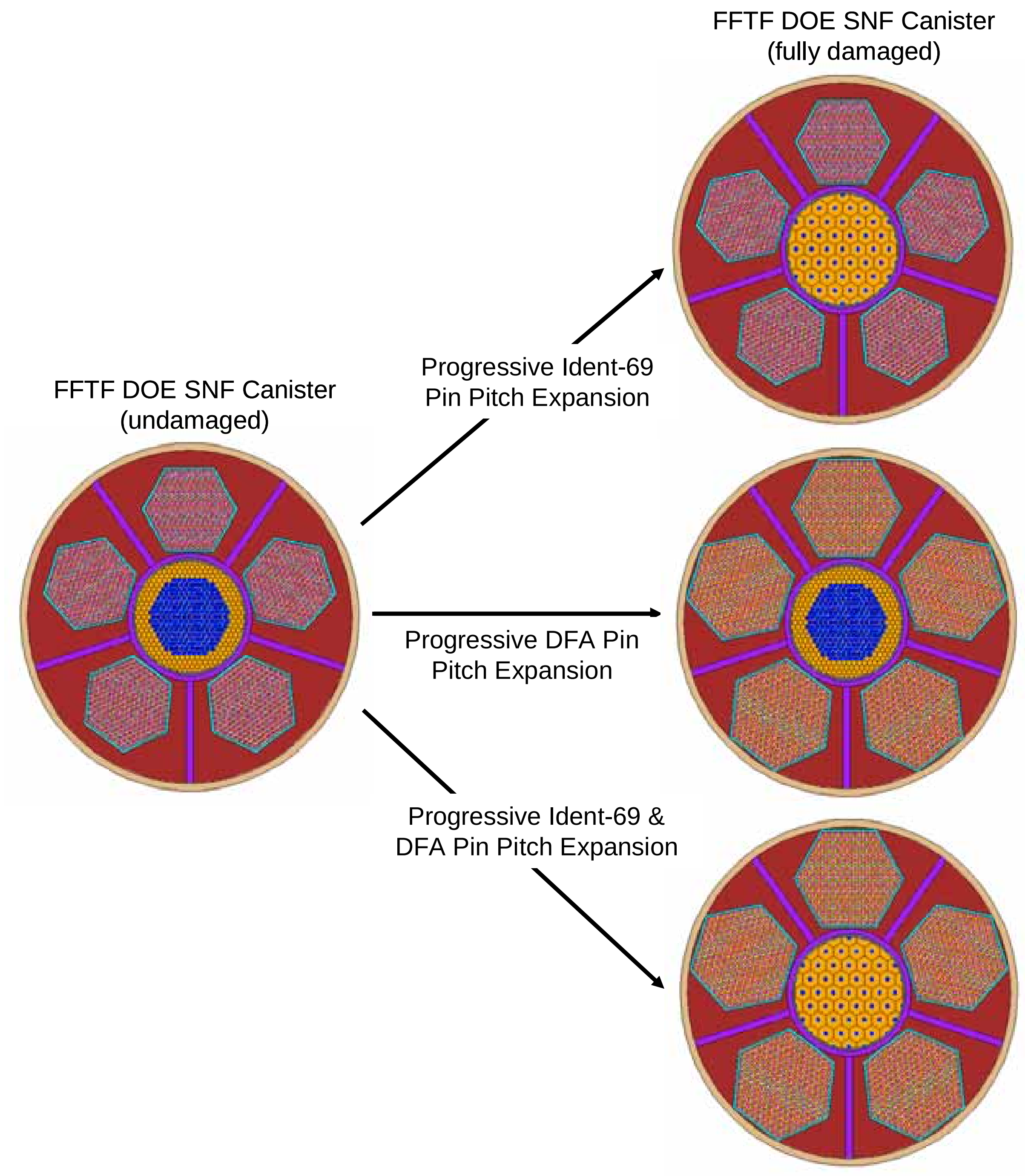

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Figure 6-102: Radial Cross-Section Views of the FFTF DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact Condition MCNP Calculations

6.2.2.1.3.1.4 FSV

The FSV DOE SNF canister is described in detail in Section 6.1.3.4. The FSV DOE SNF canister fuel element consists of a solid, single piece, block of graphite with an array of drilled channels to accommodate fuel compacts. Based on this design no potential damage configurations were identified for *flooded intact damage* conditions, other than flooding the fuel element (including the porus spaces within the block). A cross-section view of the FSV DOE SNF canister MCNP model in the described *flooded damaged intact* configuration is provided in Figure 6-103.

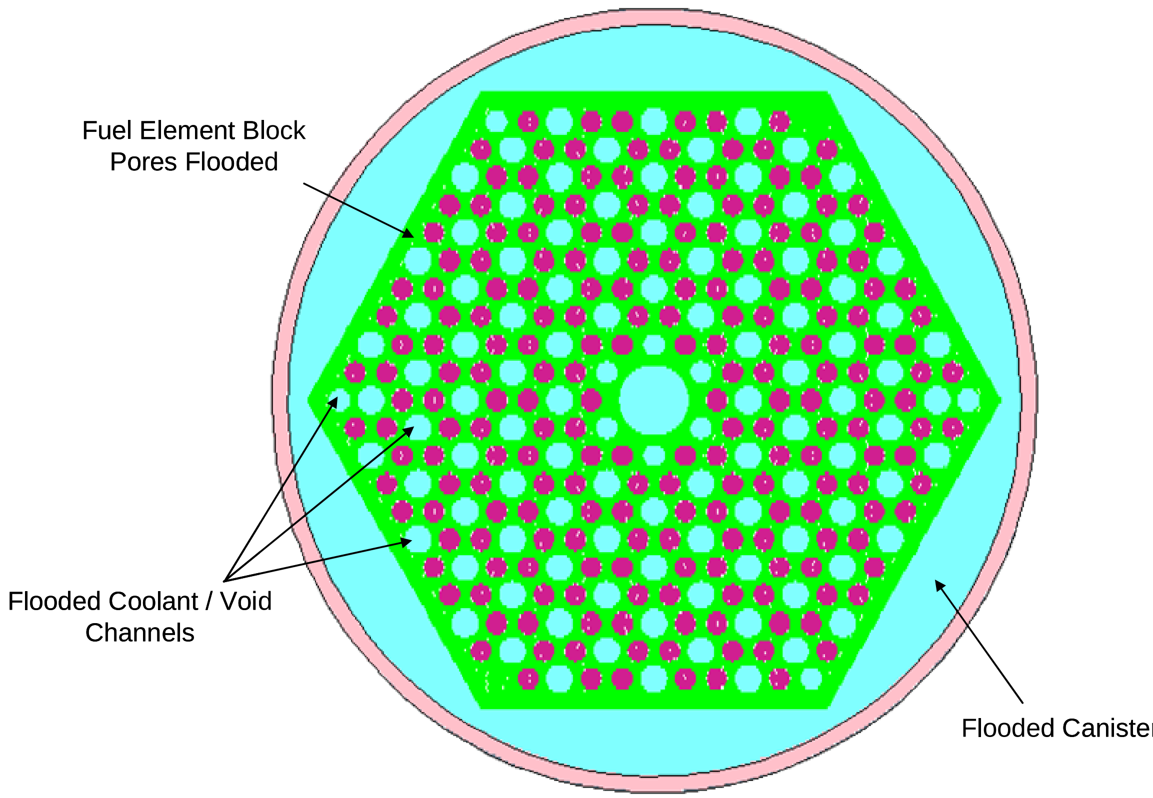

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Figure 6-103: Radial Cross-Section View of the FSV DOE SNF Canister Depicting the Configuration Examined in the Flooded Damaged Intact Condition MCNP Calculations

6.2.2.1.3.1.5 SLWBR

The SLWBR DOE SNF canister is described in detail in Section 6.1.3.5. The SLWBR DOE SNF canister comprises a single hexagonal fuel assembly containing 619 fuel pins positioned on a triangular lattice. Under *flooded damaged intact* conditions the fuel pin pitch is progressively reduced from its nominal value to a minimum possible pitch, equivalent to a close-packed configuration of pins. Refer to Figure 6-104 for an illustration of the fuel pin pitch parameter examined in the *flooded damaged intact* condition MCNP calculations.

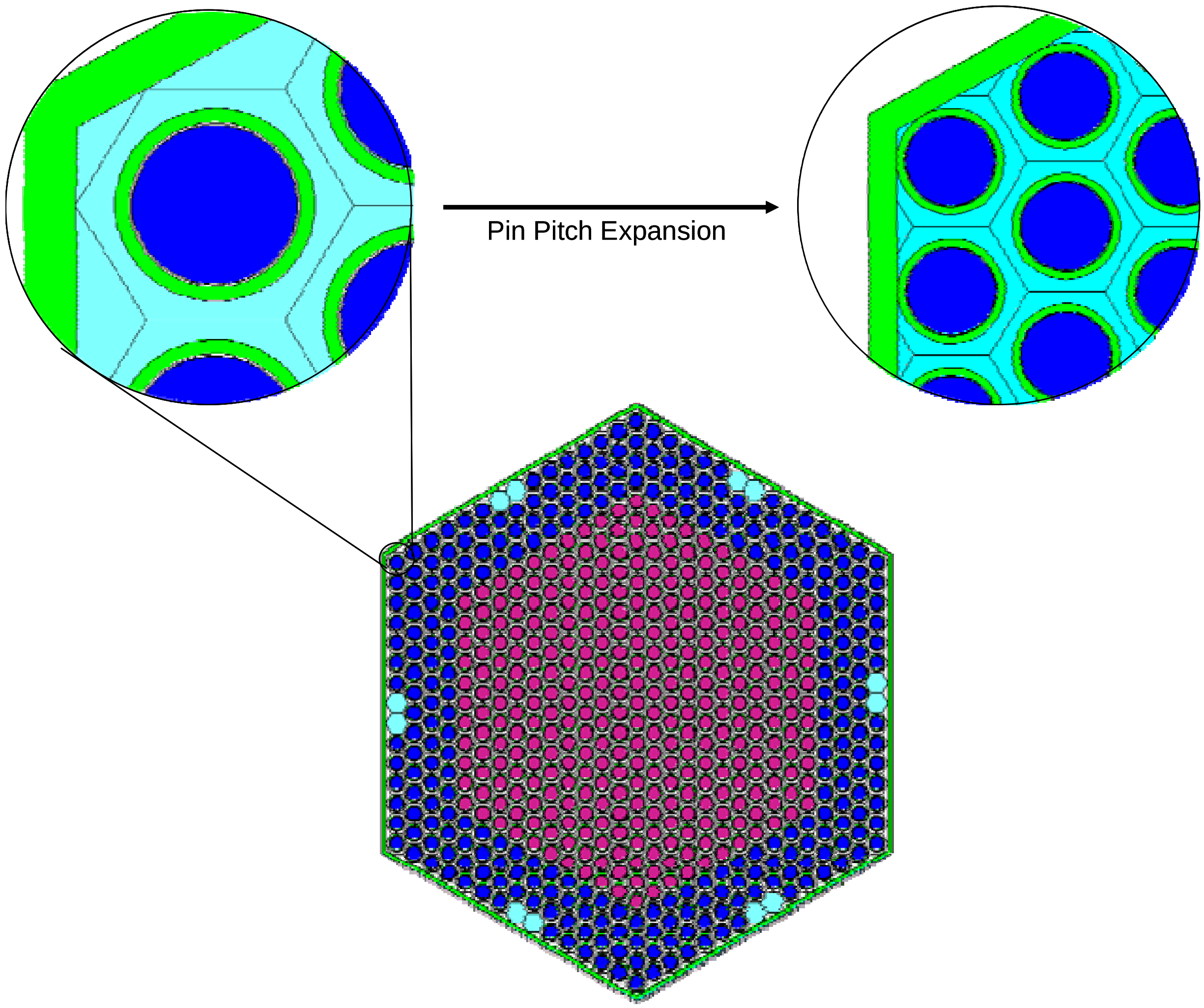

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Figure 6-104: Horizontal Cross-section of the SLWBR Fuel Assembly Depicting the *Fuel Pin Pitch* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The SLWBR DOE SNF canister contains a rectangular stainless steel basket structure within which the fuel assembly is positioned. The void spaces within the canister are filled with aluminum gadolinium phosphate (Al-$GdPO_4$) shot (filler material). Under flooded conditions, the void space within the basket filler material is flooded. The SLWBR DOE SNF Canister *flooded damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket filler material, to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the SLWBR DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-36. Note that all permutations of the parameters detailed in Table 6-36 are examined. Cross-section views of the SLWBR DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-105.

Table 6-36. Geometry and Neutron Absorber Perturbations Examined for the SLWBR DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
SLWBR Fuel Pin	Pin Pitch	Pin Pitch Expansion	0 %	0.936 cm	0.936 cm
			20 %	0.940 cm	
			40 %	0.944 cm	
			60 %	0.948 cm	
			80 %	0.952 cm	
			100 %	0.956 cm	
SLWBR Basket Filler Material	Basket Filler Neutron Absorber (Gd) Content	Basket Filler Gd Content	0 %	0.0 wt% Gd	0.1 wt% Gd
			20 %	0.02 wt% Gd	
			40 %	0.04 wt% Gd	
			60 %	0.06 wt% Gd	
			80 %	0.08 wt% Gd	
			100 %	0.1 wt% Gd	
Total Permutations (Number of Cases Examined): 36					

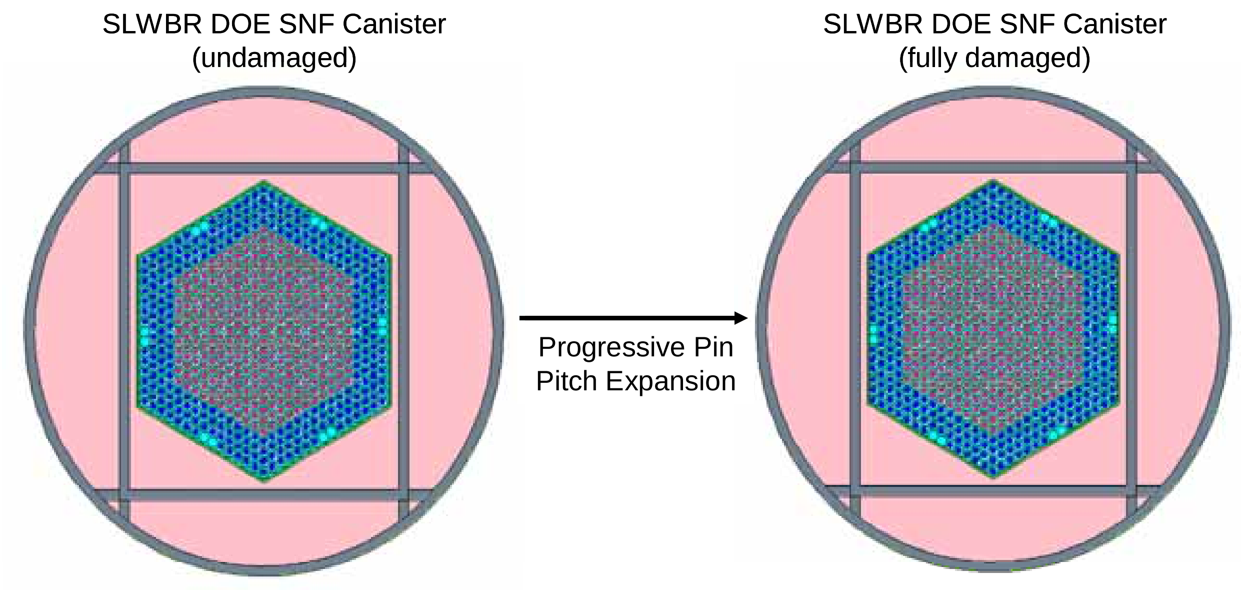

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Figure 6-105: Radial Cross-Section Views of the SLWBR DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact Condition MCNP Calculations

6.2.2.1.3.1.6 SPWR

The SPWR DOE SNF canister is described in detail in Section 6.1.3.6. The SPWR DOE SNF canister comprises a single fuel cluster which is composed of four fuel subclusters arranged in a square array with 1.2 cm spacing between each subclsuter to form a cruciform-shaped channel in the center of the fuel cluster. Each subcluster comprises nineteen fuel and two neutron absorber (end) plates/wafers. Under *flooded damaged intact* conditions the fuel plate/wafer separation is progressively expanded from its nominal value to a maximum value governed by the sizing of the rectangular stainless steel basket structure within which the fuel cluster is positioned. Refer to Figure 6-106 for an illustration of the fuel plate/wafer separation parameter examined in the *flooded damaged intact* condition MCNP calculations.

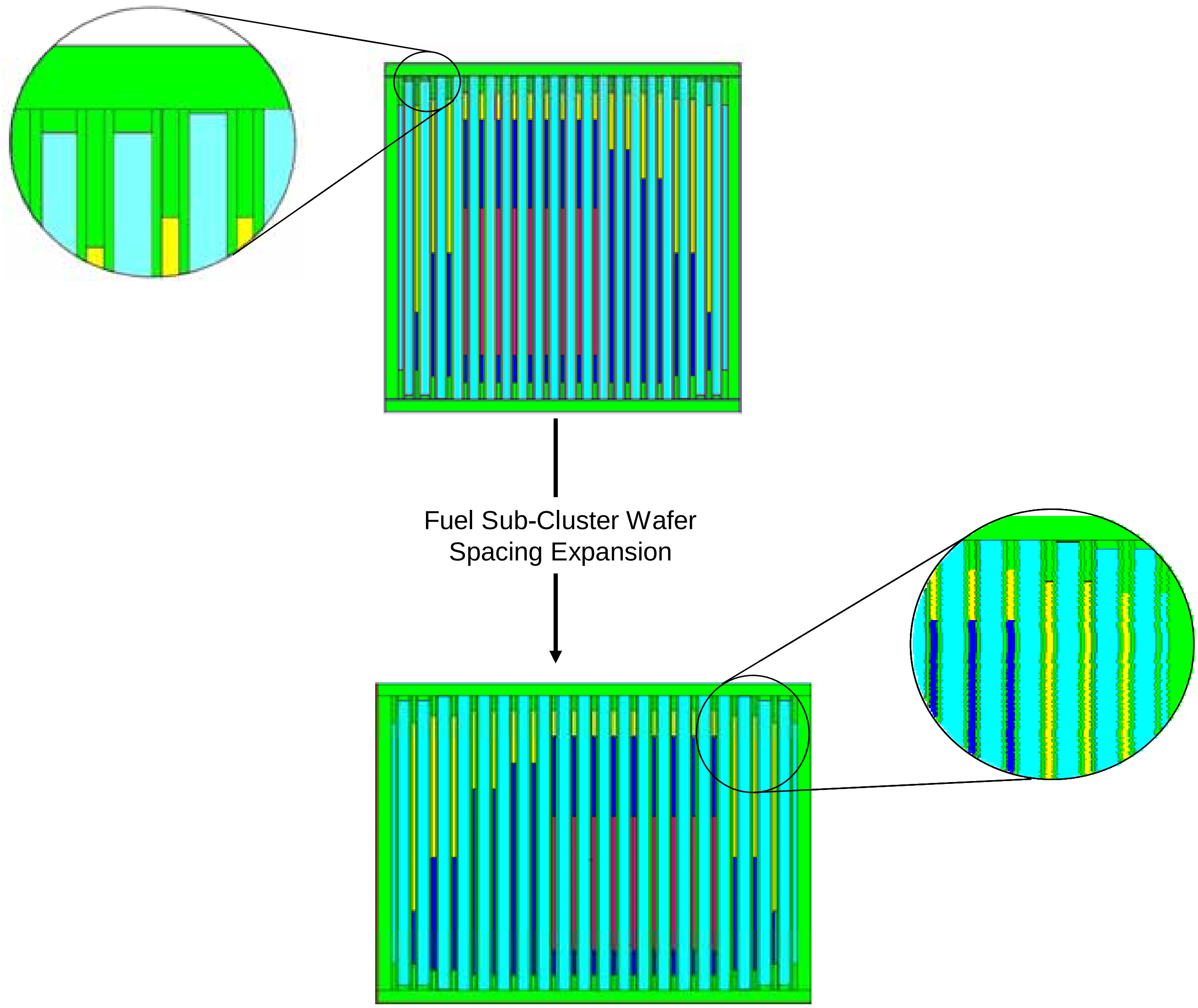

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Figure 6-106: Horizontal Cross-section of the SPWR Fuel Assembly Depicting the *Fuel Wafer Separation* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The fuel subcluster spacing is also examined independently to the fuel subcluster wafer spacing. Under *flooded damaged intact* conditions the fuel subcluster separation is progressively increased from a no separation condition to a maximum possible separation condition (dictated by the dimensions of the surrounding rectangular stainless steel basket structure. Refer to Figure 6-107 for an illustration of the fuel sub-cluster separation parameter examined in the *flooded damaged intact* condition MCNP calculations. Note that a rotated sub-cluster orientation is used for these MCNP calculations to allow a more onerous configuration of SNF under damage conditions.

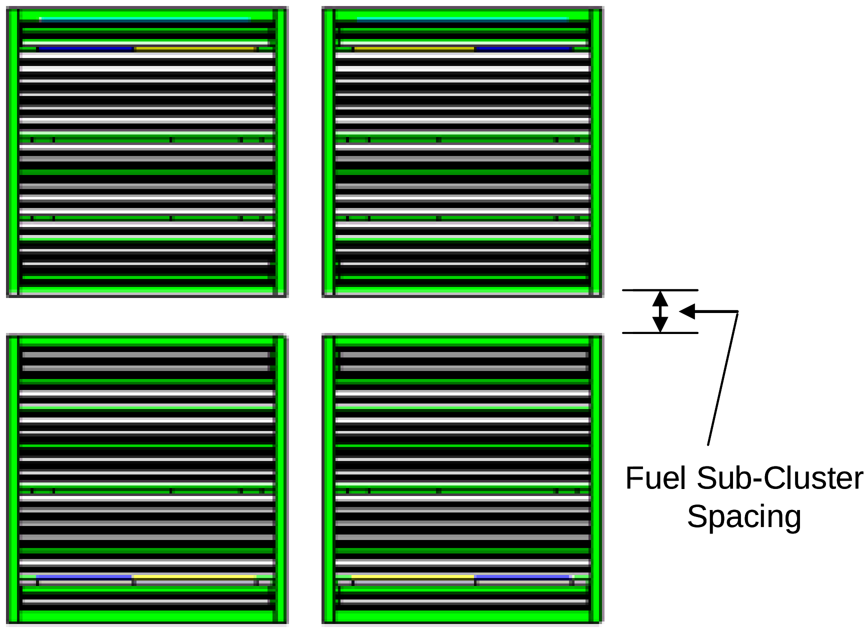

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Figure 6-107: Horizontal Cross-section of the SPWR Fuel Assembly Depicting the *Fuel SubCluster Separation* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

The specific geometry perturbations examined (and described above) for the SPWR DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-37. Note that all permutations of the parameters detailed in Table 6-37 are examined. Cross-section views of the SPWR DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-108.

Table 6-37. Geometry Perturbations Examined for the SPWR DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
SPWR Fuel Cluster	Fuel SubCluster Wafer Separation	Fuel SubCluster Wafer Spacing Expansion	0 %	0.204 cm	0.204 cm[1]
			20 %	0.221 cm	
			40 %	0.238 cm	
			60 %	0.254 cm	
			80 %	0.271 cm	
			100 %	0.288 cm	
SPWR Fuel Cluster	Fuel SubCluster Separation	Fuel SubCluster Spacing in X-Plane	0 %	0.0 cm	1.2 cm[2]
			20 %	0.672 cm	
			40 %	1.344 cm	
			60 %	2.017 cm	
			80 %	2.689 cm	
			100 %	3.361 cm	
SPWR Fuel Cluster	Fuel SubCluster Separation	Fuel SubCluster Spacing in Y-Plane	0 %	0.0 cm	1.2 cm[2]
			20 %	0.672 cm	
			40 %	1.344 cm	
			60 %	2.017 cm	
			80 %	2.689 cm	
			100 %	3.361 cm	
Total Permutations (Number of Cases Examined): 216					

[1] The nominal fuel wafer separation distance provided corresponds to the smallest fuel wafer separation distance.

[2] The range of subcluster separation distances provided corresponds to largest range possible. Note, however, that the fuel subcluster separation distance in the Y-Plane is dependent on the degree of fuel subcluster wafer spacing expansion considered. The maximum value provided for the Y-Plane fuel subcluster separation distance is based on 0% fuel subcluster wafer spacing expansion.

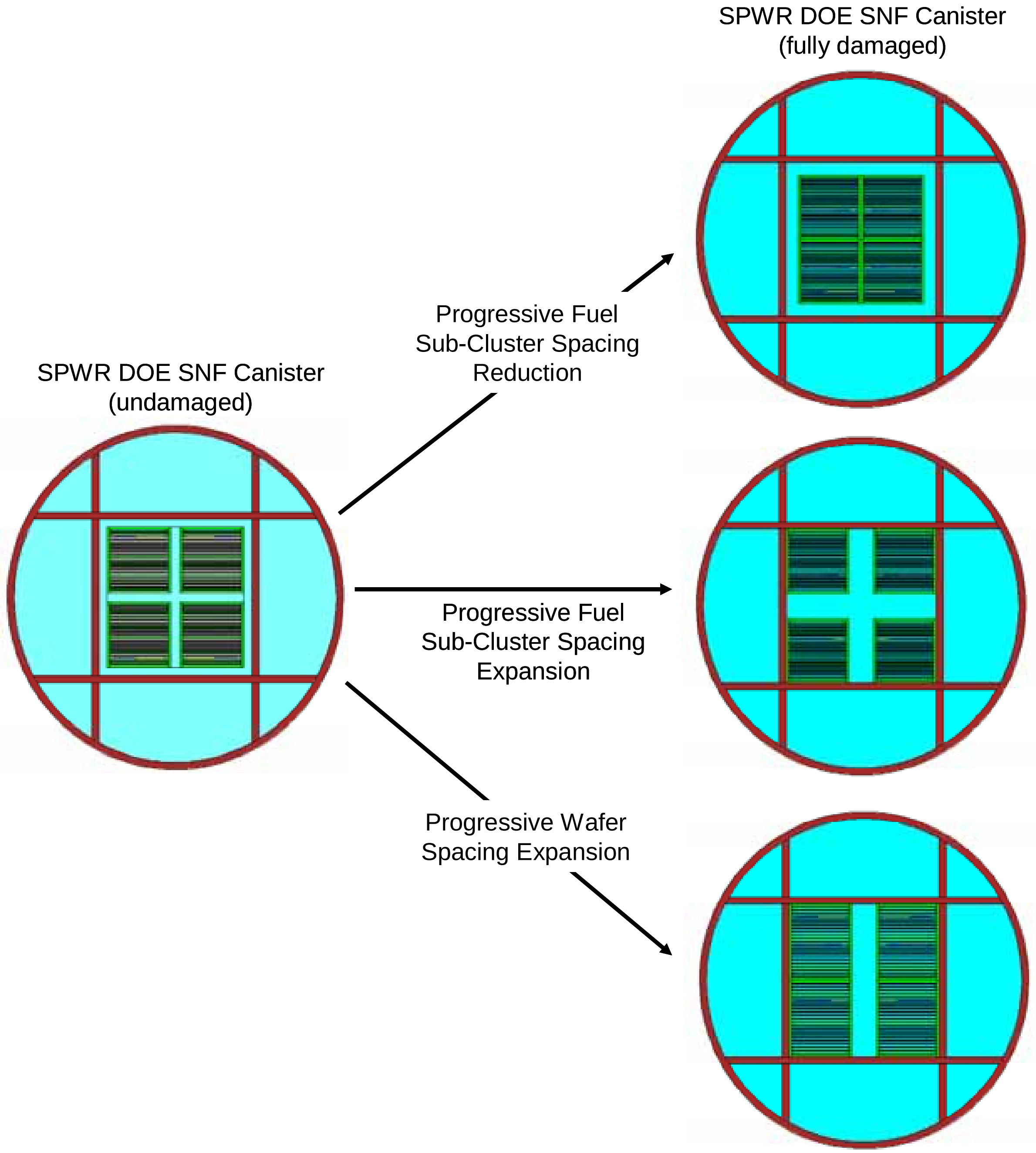

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Figure 6-108: Radial Cross-Section Views of the SPWR DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact Condition MCNP Calculations

6.2.2.1.3.1.7 TRIGA

The TRIGA DOE SNF canister is described in detail in Section 6.1.3.7. The TRIGA DOE SNF canister comprises ninety three TRIGA fuel elements arranged in a stacked tri-level basket structure that provides thirty one fuel elements per basket. Each fuel element is solid uranium-zirconium hydride containing highly enriched uranium. The fuel elements are loaded into basket tubes constructed of nickel-gadolinium alloy. Under *flooded damaged intact* conditions the fuel element-basket tube separation distance is gradually reduced from its nominal value to zero (i.e. a no separation condition). Refer to Figure 6-109 for an illustration of the basket tube diameter parameter examined in the *flooded damaged intact* condition MCNP calculations.

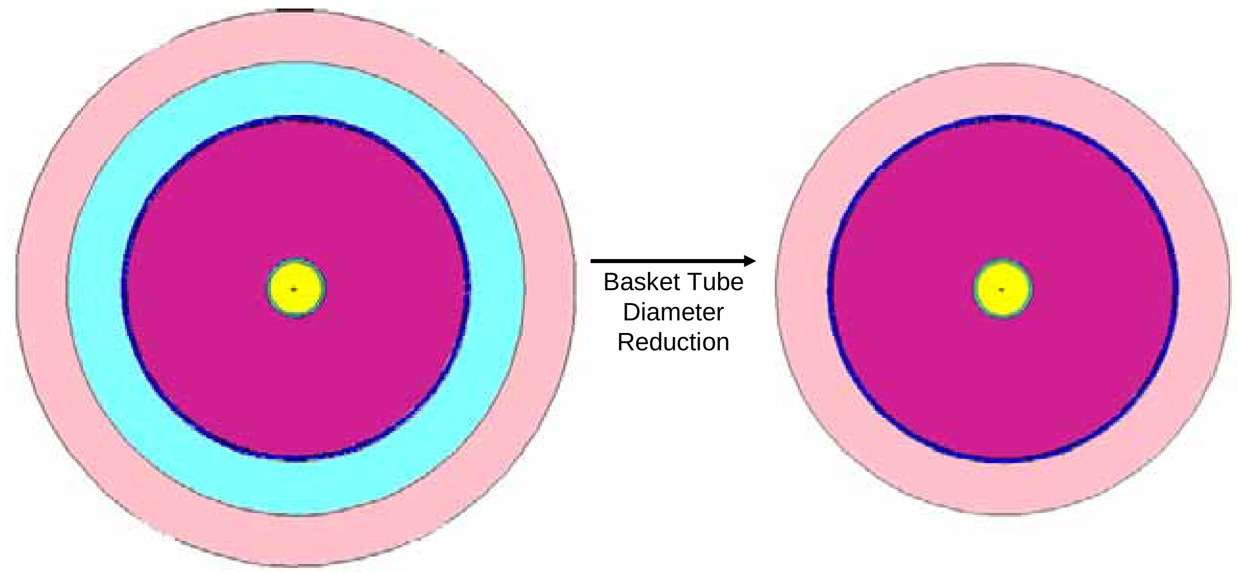

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Figure 6-109: Horizontal Cross-section of the TRIGA Fuel Element Depicting the *Basket Tube Diameter* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

Under nominal, i.e. un-damaged conditions, the TRIGA fuel basket tubes are close-packed (i.e. touching). As the basket tube diameter is varied in the *flooded damaged intact* condition calculations, spacing is introduced between each basket tube. This spacing is independently re-adjusted. Refer to Figure 6-110 for an illustration of the basket tube diameter spacing parameter examined in the *flooded damaged intact* condition MCNP calculations.

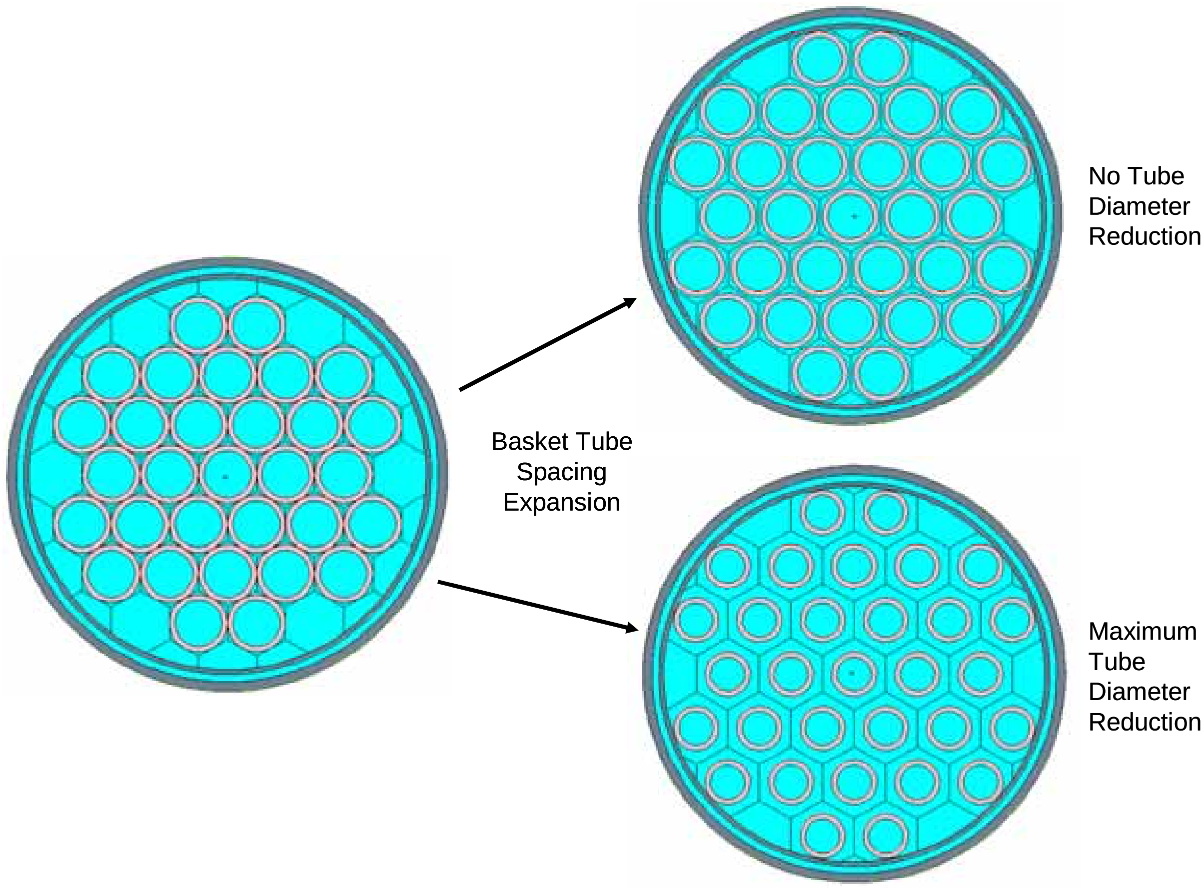

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Figure 6-110: Horizontal Cross-section of the TRIGA DOE SNF Canister Basket Structure Fuel Depicting the *Basket Tube Separation* Parameter Examined in the Flooded Damaged Intact Condition MCNP Calculations

In addition to geometric perturbations, the TRIGA DOE SNF Canister *flooded damaged intact* configuration calculations examine a progressive reduction in neutron absorber content of the basket tubes to establish the sensitivity of the system to reduction of neutron absorber content.

The specific geometry and neutron absorber perturbations examined (and described above) for the TRIGA DOE SNF canister under *flooded damaged intact* conditions are explicitly quantified in Table 6-38. Note that all permutations of the parameters detailed in Table 6-38 are examined. Cross-section views of the TRIGA DOE SNF canister MCNP models under the described *flooded damaged intact* configurations are provided in Figure 6-111.

Table 6-38. Geometry and Neutron Absorber Perturbations Examined for the TRIGA DOE SNF Canister Under Flooded Damaged Intact Conditions

Component	Parameter	MCNP Model Variable Name	MCNP Model Variable Value Used	Model Value Used	Nominal Model Value
TRIGA Fuel Basket Tube	Fuel Basket Tube Inner Diameter	Basket Tube Inner Diameter Reduction	0 %	4.925 cm	4.925 cm
			20 %	4.691 cm	
			40 %	4.457 cm	
			60 %	4.222 cm	
			80 %	3.988 cm	
			100 %	3.754 cm	
TRIGA Fuel Basket	Fuel Basket Tube Separation	Basket Tube Spacing Expansion	0 %	0.0 cm	0.0 cm[1]
			20 %	0.234 cm	
			40 %	0.468 cm	
			60 %	0.703 cm	
			80 %	0.937 cm	
			100 %	1.171 cm	
TRIGA Fuel Basket	Fuel Basket Tube Neutron Absorber (Gd) Content	Basket Gd Content	0 %	0.0 wt% Gd	1.5 wt% Gd
			20 %	0.3 wt% Gd	
			40 %	0.6 wt% Gd	
			60 %	0.9 wt% Gd	
			80 %	1.2 wt% Gd	
			100 %	1.5 wt% Gd	
Total Permutations (Number of Cases Examined): 216					

[1] As the basket tube diameter is varied in the flooded damaged intact condition calculations, spacing is introduced between each basket tube. Normally there is no space between each tube. In the event of complete collapse of the basket tubes onto their respective fuel elements a maximum basket tube separation of 1.171cm is created. This maximum value is reflected in the Table.

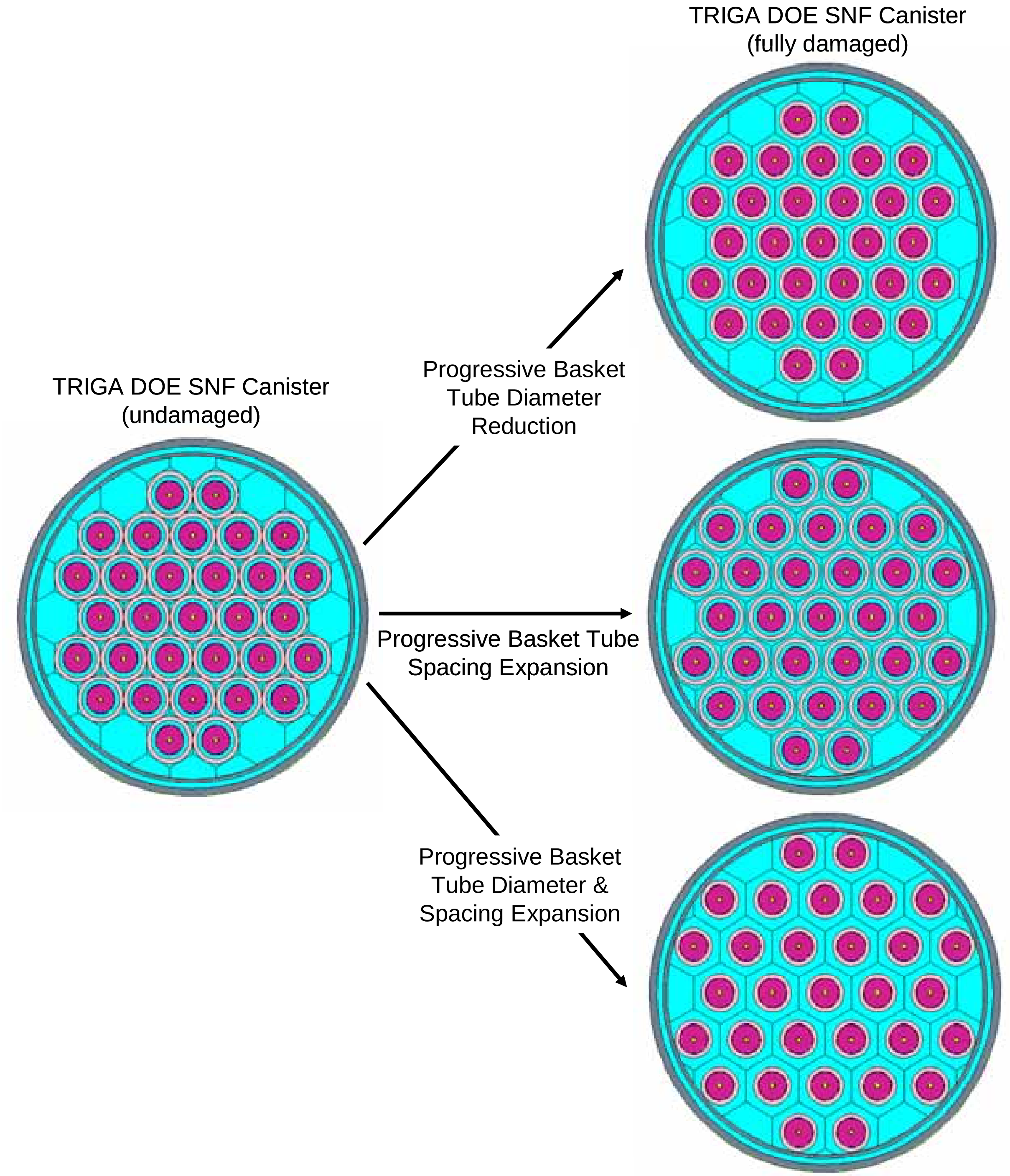

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Figure 6-111: Radial Cross-Section Views of the TRIGA DOE SNF Canister Depicting the Configurations Examined in the Flooded Damaged Intact Condition MCNP Calculations

6.2.2.1.3.2 Flooded Damaged Degraded Configurations

The *flooded damaged degraded* configuration calculations are similar to the *dry damaged degraded* configuration calculations (Section 6.2.2.1.2.2), except that the homogeneous mixture of debris modeled is progressively moderated with the gradual addition of water. Specifically, the *flooded damaged degraded* configuration calculations are based on complete or partial release of SNF, SNF clad, basket structure and basket filler material (where applicable) forming a homogeneous mixture which is progressively diluted with water.

The *flooded damaged degraded* configuration calculations are based on homogeneous mixtures only. Heterogeneous mixtures are not considered based on the fissile enrichment of the SNF examined, which is inherently more reactive in a homogeneous form.

The inventory of each DOE SNF canister is provided in Table 6-32, together with the range of material release fractions considered in the MCNP calculations. The explicit material compositions for each MCNP calculation are computed using the material compositions provided in Attachment 1, in conjunction with the material release fractions specific to the calculation, allowing for the selected moderator content. Cross-section views of the *flooded damaged degraded* MCNP models are provided in Figure 6-93.

The degree of degradation examined in the calculations (i.e. the quantity of SNF, clad, basket and basket filler material that is considered released) is expressed as a percentage of the total inventory for the respective canister. For example, canister debris with a basket filler content of 40% means that 40% of the total mass of basket filler material associated with the respective canister is modeled in the canister debris.

For all calculations, any clad, basket structure or basket filler material not represented in the modeled debris is not explicitly modeled in the calculation. For example canister debris with a basket filler content of 40% means that 60% of the total mass of basket filler material associated with the respective canister is not modeled in the canister debris. The residual 60% is not modeled external to the canister debris because the effect of the presence of any material external to the canister debris is accounted for in the wide variety of reflection conditions considered (which also includes reflector materials specific to the canister examined). Given that all *flooded damaged degraded* configuration calculations consider a fixed 100% release of SNF, this treatment is conservative.

7. RESULTS AND CONCLUSIONS

This section presents the results of, and draws conclusions from, the MCNP criticality safety calculations performed for DOE SNF canisters and loaded, sealed, WPs under both normal conditions and potential off-normal conditions. The following structure is used:

- Section 7.1 presents the results of the MCNP calculations and provides a brief discussion of pertinent data as well as data trends; and
- Section 7.2 draws conclusions from the results of the normal condition and potential off-normal condition calculations, and identifies the limits on system parameters that are necessary to ensure subcriticality.

7.1 RESULTS

7.1.1 Normal Conditions

7.1.1.1 Surface Facilities and Intra-site Operations

The criticality safety process for evaluating DOE SNF canisters and loaded, sealed, WPs under normal conditions in the surface facilities (including intra-site operations) is described in detail in Section 6.2.1.1. The results of the calculations performed based on this process are presented in this section.

7.1.1.1.1 DOE SNF Canisters

This section presents the MCNP k_{eff} results for undamaged and dry DOE SNF canisters with the reflection conditions described in Attachment 1. The following results are presented:

1. k_{eff} values for individual undamaged and dry DOE SNF canisters under a wide variety of close fitting full (30 cm) thickness reflection conditions (presented in Figure 7-1 and Table 7-1).

2. k_{eff} values for changes (increase) in the density and moisture content of the SNF waste forms examined in (1). These additional results are presented in Figure 7-2 through Figure 7-4 and are limited to the study of individual DOE SNF canisters with the limiting reflection condition established in (1).

Refer to Figure 6-51 and Figure 6-52 for a cross-section view of a single DOE SNF canister MCNP model with incorporated close-fitting full thickness reflector. Note that the abovementioned calculations consider only individual DOE SNF canisters because under normal conditions all DOE SNF canisters will be handled individually and will be staged only in the dedicated DOE canister staging racks situated in the CRCF. The subcriticality of DOE SNF canister staging under normal conditions is indirectly demonstrated by the results of the off-normal conditions calculations reported in Section 7.1.2.1.1.1. Therefore, explicit calculations representative of the actual DOE SNF canister staging arrangement (i.e. a precise number of canisters with exact canister separation distances and external structure materials and thicknesses) are not performed.

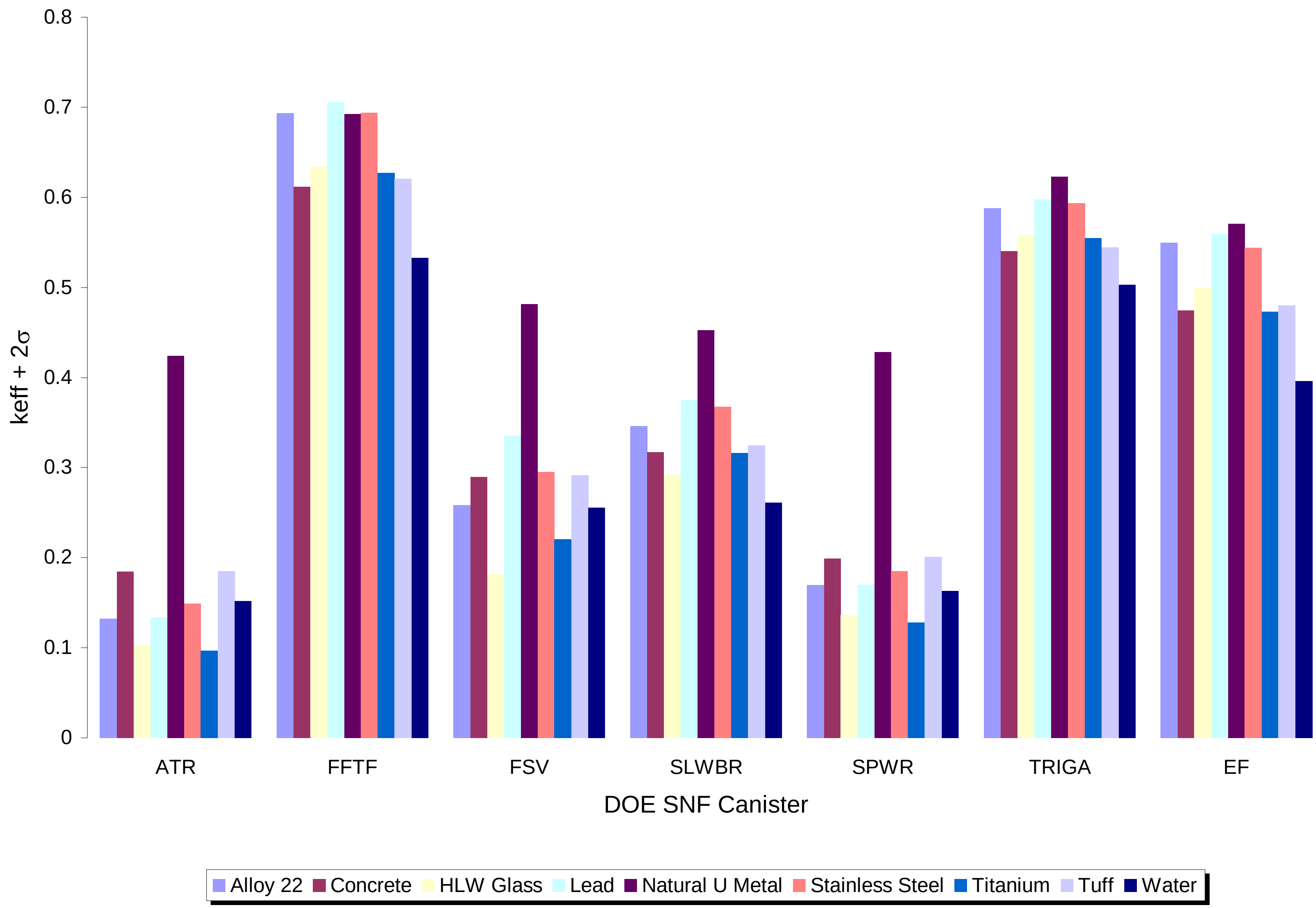

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Figure 7-1: keff+2σ values for individual undamaged and dry DOE SNF canisters under a variety of close fitting full (30 cm) thickness reflection conditions

Table 7-1: keff+2σ values for individual undamaged and dry DOE SNF canisters under a variety of close fitting full (30 cm) thickness reflection conditions

Close Fitting 30cm Thick Reflector	DOE SNF Canister						
	ATR	EF	FFTF	FSV	SLWBR	SPWR	TRIGA
Alloy 22	0.13234	0.54999	0.69337	0.25825	0.3462	0.16936	0.58783
Concrete	0.18435	0.47449	0.61189	0.28939	0.3176	0.19906	0.54038
HLW Glass	0.10337	0.49983	0.63434	0.18174	0.29218	0.13685	0.558
Lead	0.13365	0.55975	0.70597	0.33537	0.37511	0.16998	0.59747
Natural U Metal	0.4239	0.57061	0.69225	0.48149	0.45264	0.4284	0.62276
Stainless Steel	0.14918	0.54412	0.69422	0.29551	0.36746	0.18494	0.59342
Titanium	0.09684	0.47267	0.62753	0.22044	0.31633	0.1282	0.55457
Tuff	0.18497	0.48009	0.62087	0.29139	0.32434	0.20089	0.54468
Water	0.1519	0.39576	0.53241	0.25554	0.26119	0.16287	0.50327

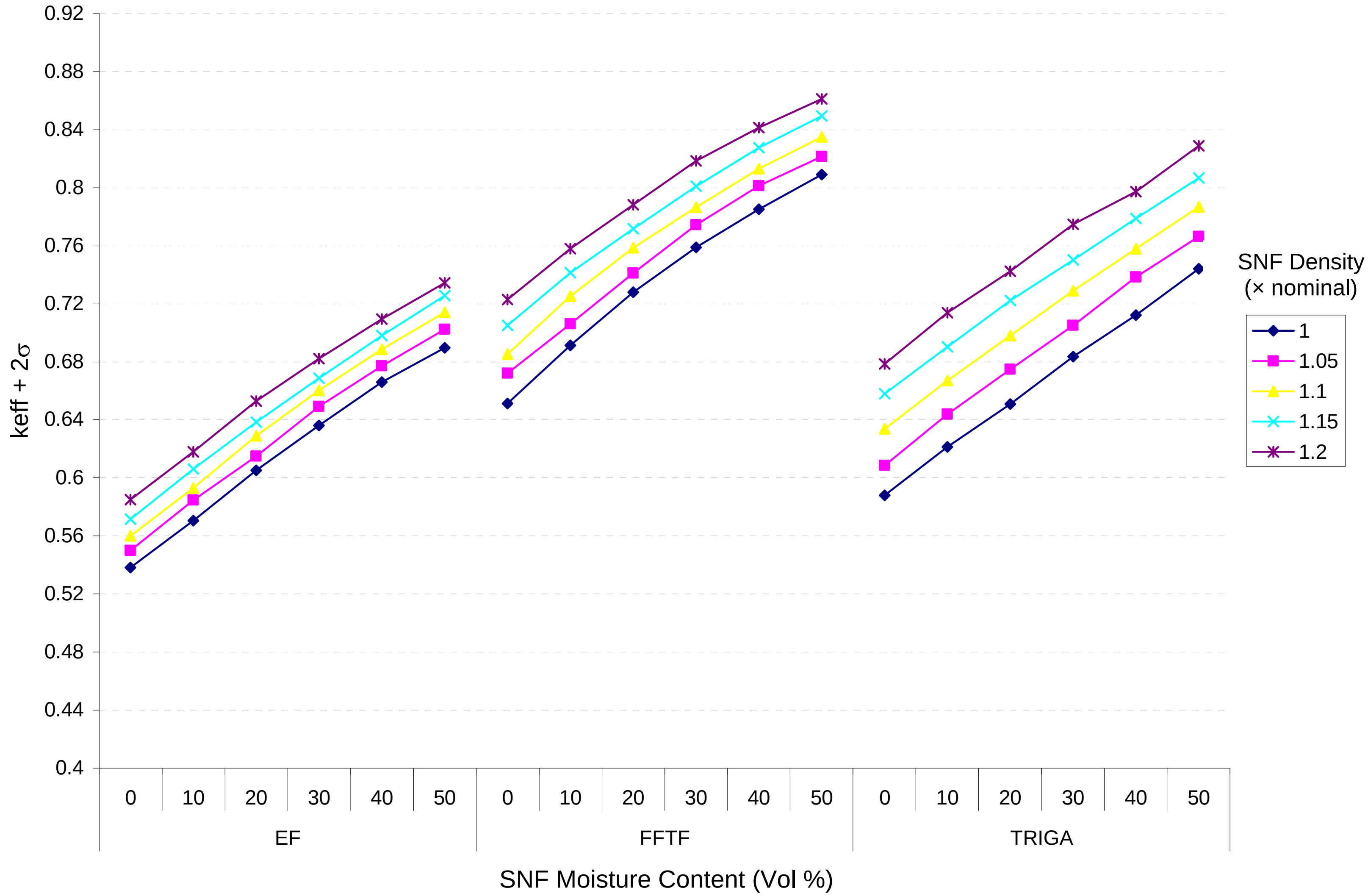

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Figure 7-2: keff+2σ values for individual undamaged and dry EF, FFTF & TRIGA DOE SNF canisters with a variety of SNF density and moisture (water) content, and with close fitting full (30 cm) thickness natural uranium metal reflection

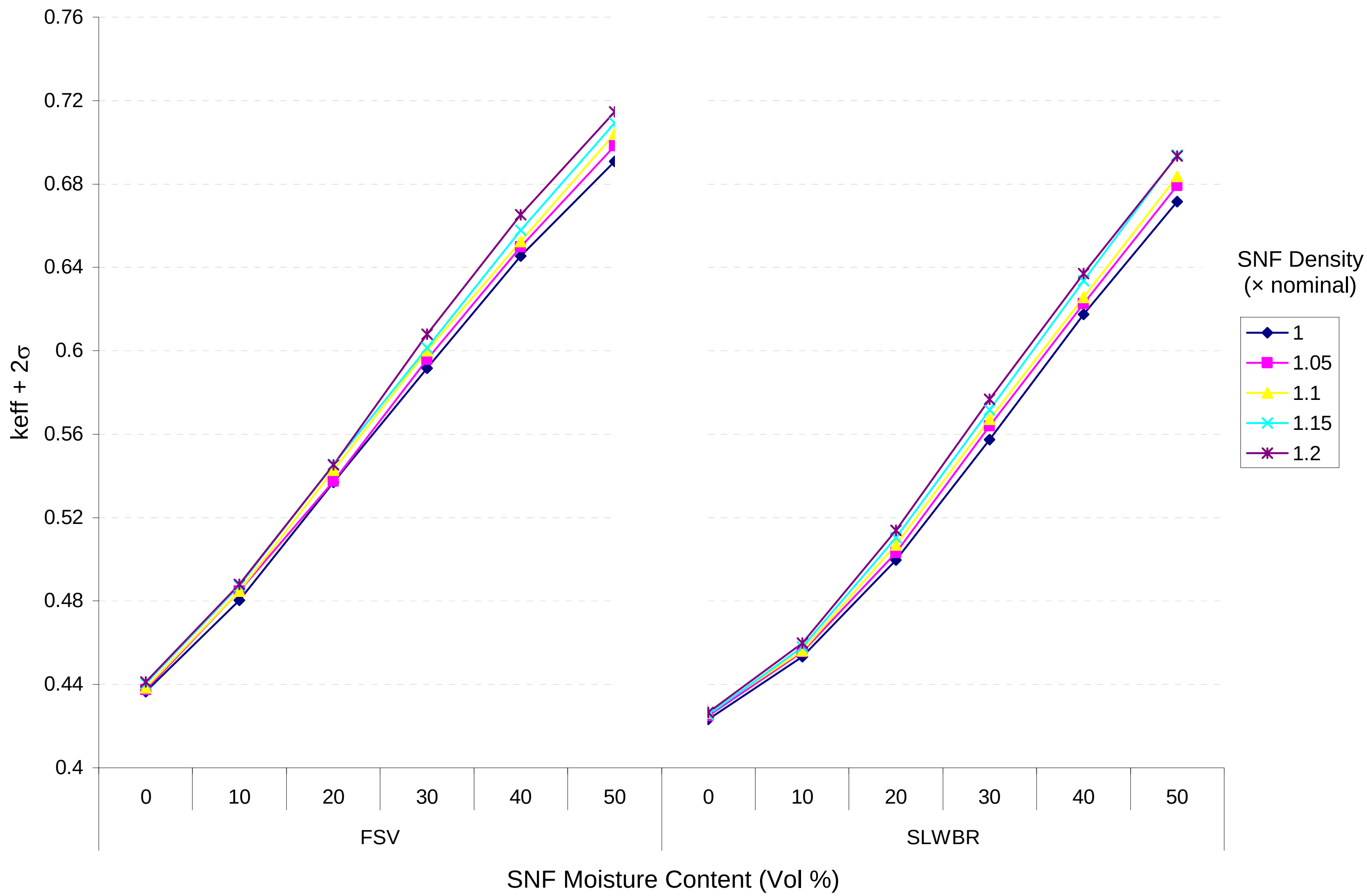

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Figure 7-3: keff+2σ values for individual undamaged and dry FSV $ SLWBR DOE SNF canisters with a variety of SNF density and moisture (water) content, and with close fitting full (30 cm) thickness natural uranium metal reflection

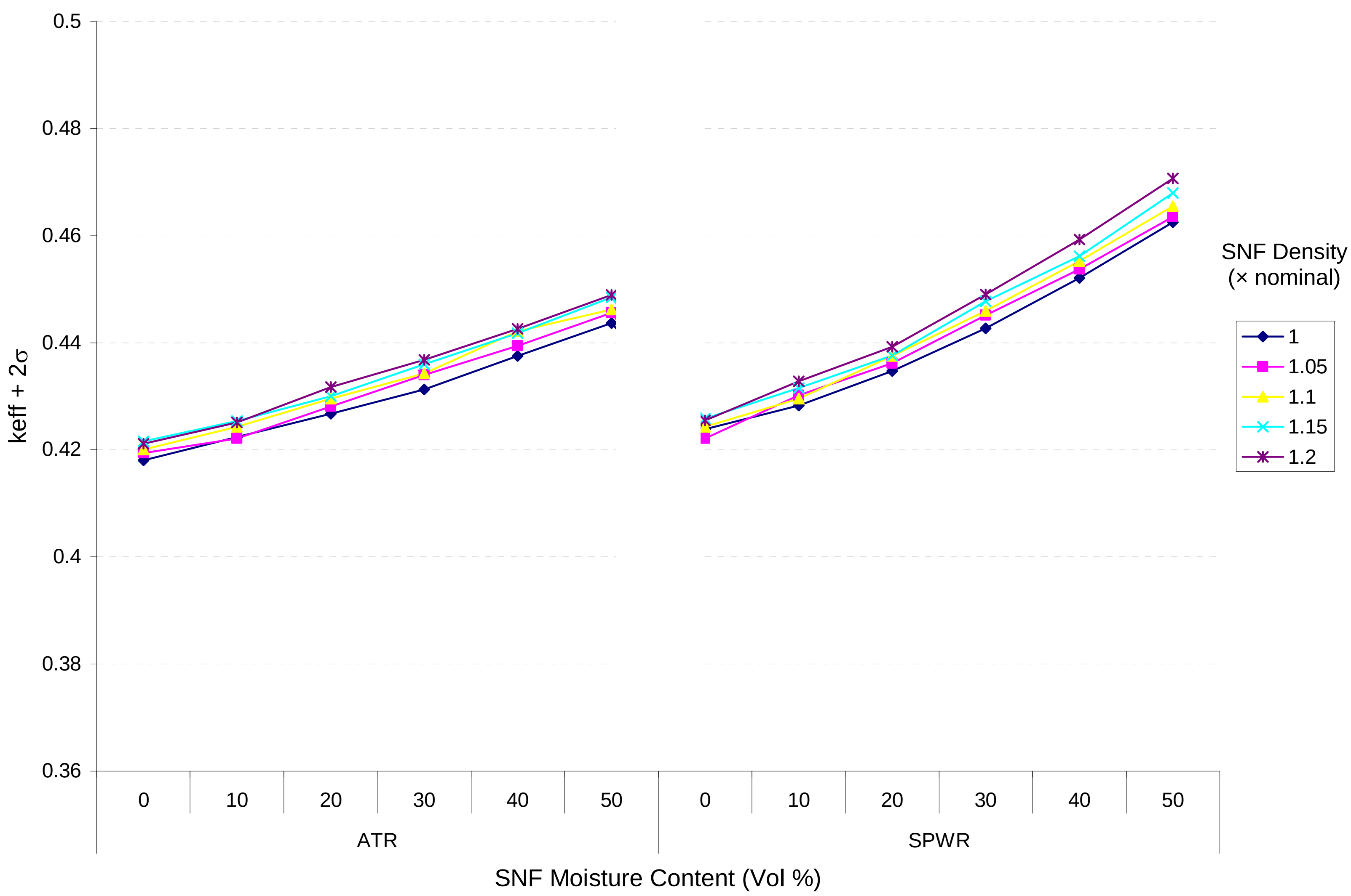

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Figure 7-4: keff+2σ values for individual undamaged and dry ATR & SPWR DOE SNF canisters with a variety of SNF density and moisture (water) content, and with close fitting full (30 cm) thickness natural uranium metal reflection

7.1.1.1.2 5-DHLW/DOE SNF WPs

This section presents the MCNP k_{eff} results for WPs with the reflection conditions described in Attachment 1. The following results are presented:

1. k_{eff} values for individual WPs under a wide variety of close fitting full (30 cm) thickness reflection conditions (presented in Figure 7-5).
2. k_{eff} values for an infinite planar array of WPs under a wide variety of close fitting full (30 cm) thickness axial reflection conditions, separation distances, and under a full range of interstitial moderation conditions (presented in Figure 7-6 through Figure 7-10).

Refer to Figure 6-53 and Figure 6-54 for a cross-section view of a single DOE SNF WP MCNP model with incorporated close-fitting full thickness reflector. Refer to Figure 6-55 and Figure 6-56 for a cross-section view of the WP infinite planar array MCNP model with incorporated periodic boundary condition and close-fitting full-thickness axial reflectors.

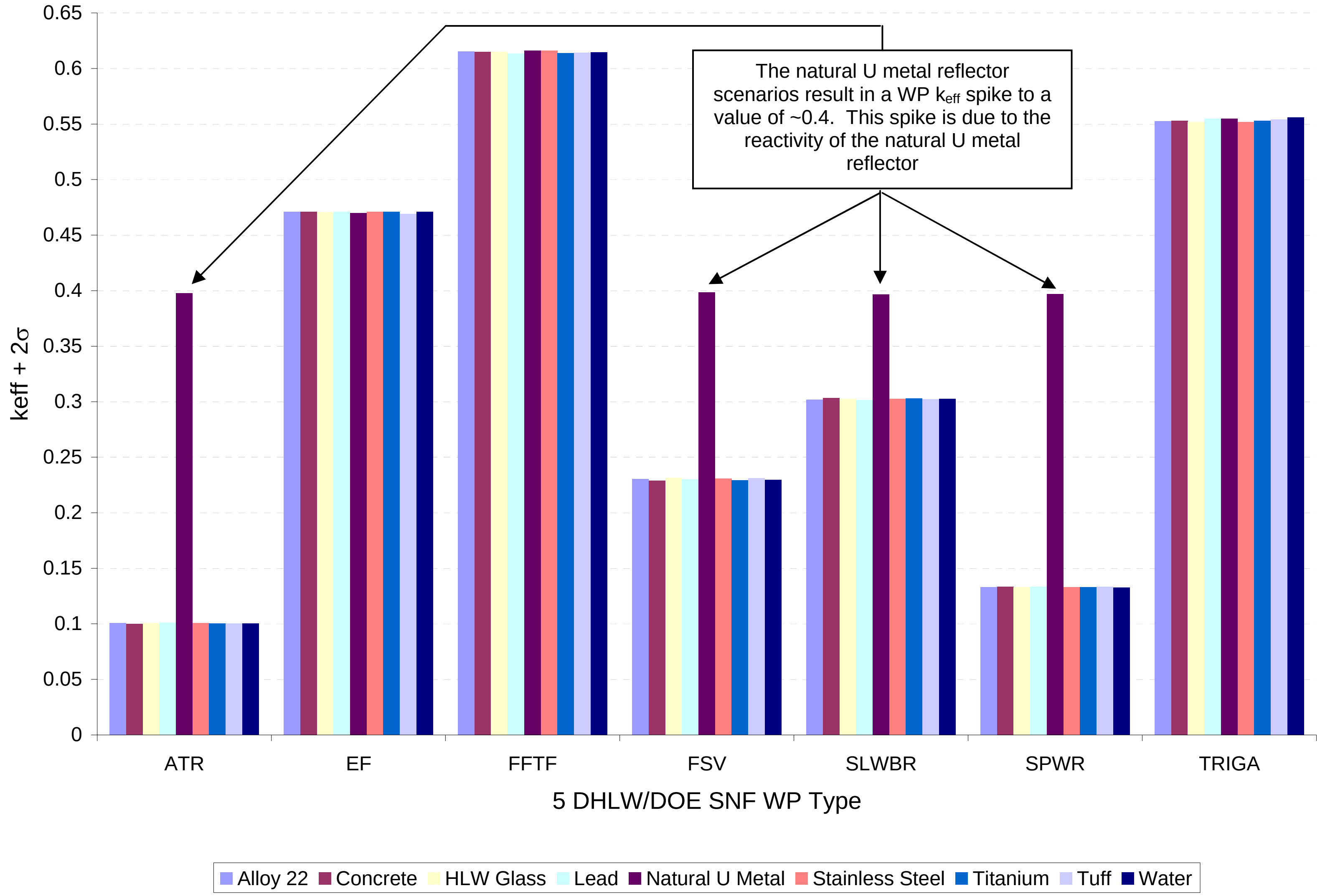

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Figure 7-5: keff+2σ values for individual undamaged, dry and normally loaded 5 DHLW/DOE SNF WPs under a variety of close fitting full (30 cm) thickness reflection conditions

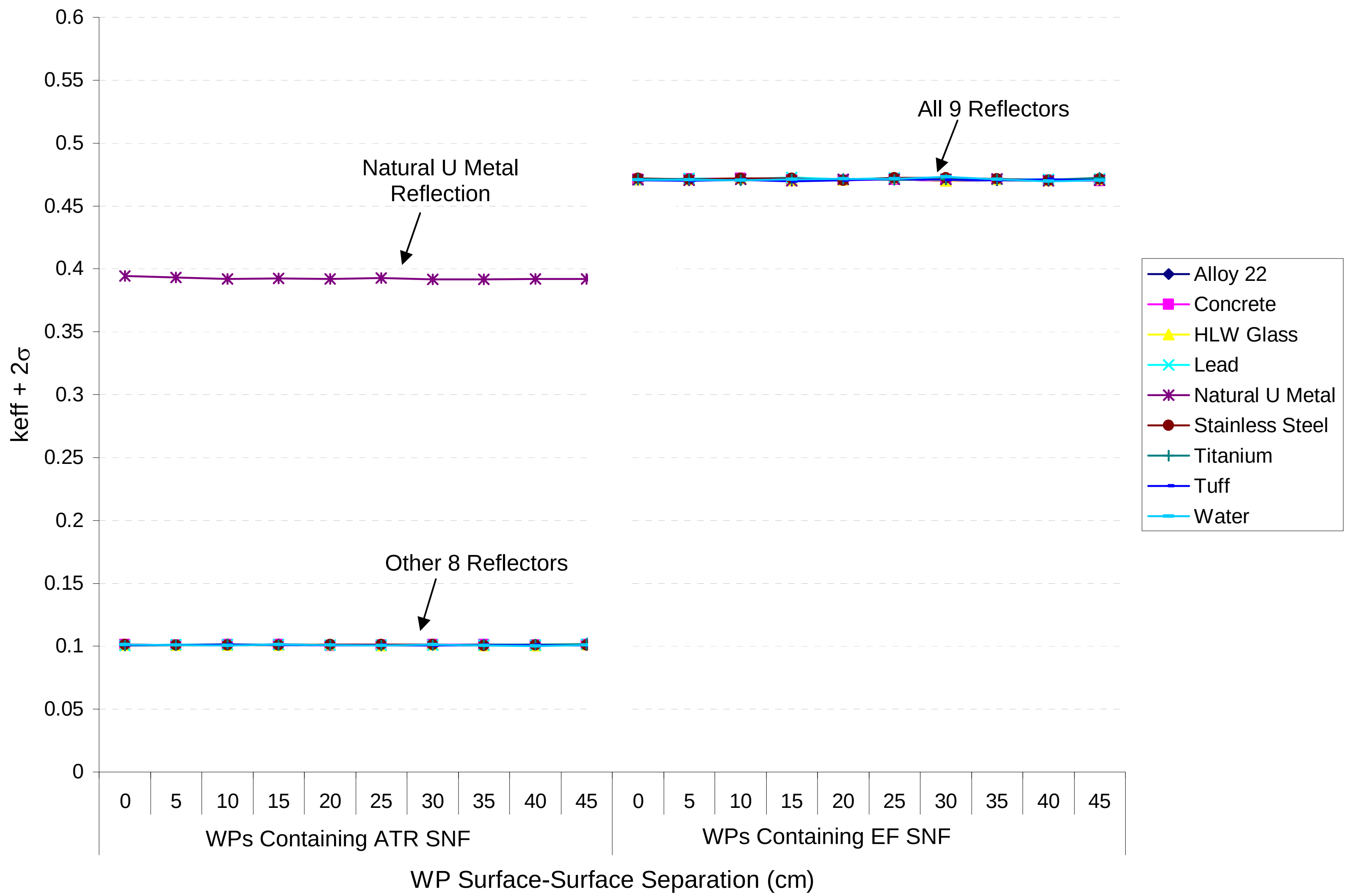

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Figure 7-6: keff+2σ values for an infinite planar array of normally loaded 5 DHLW/DOE SNF WPs (containing ATR/EF DOE SNF Canisters) under a variety of close fitting full (30 cm) thickness axial reflection conditions and with no interstitial moderation

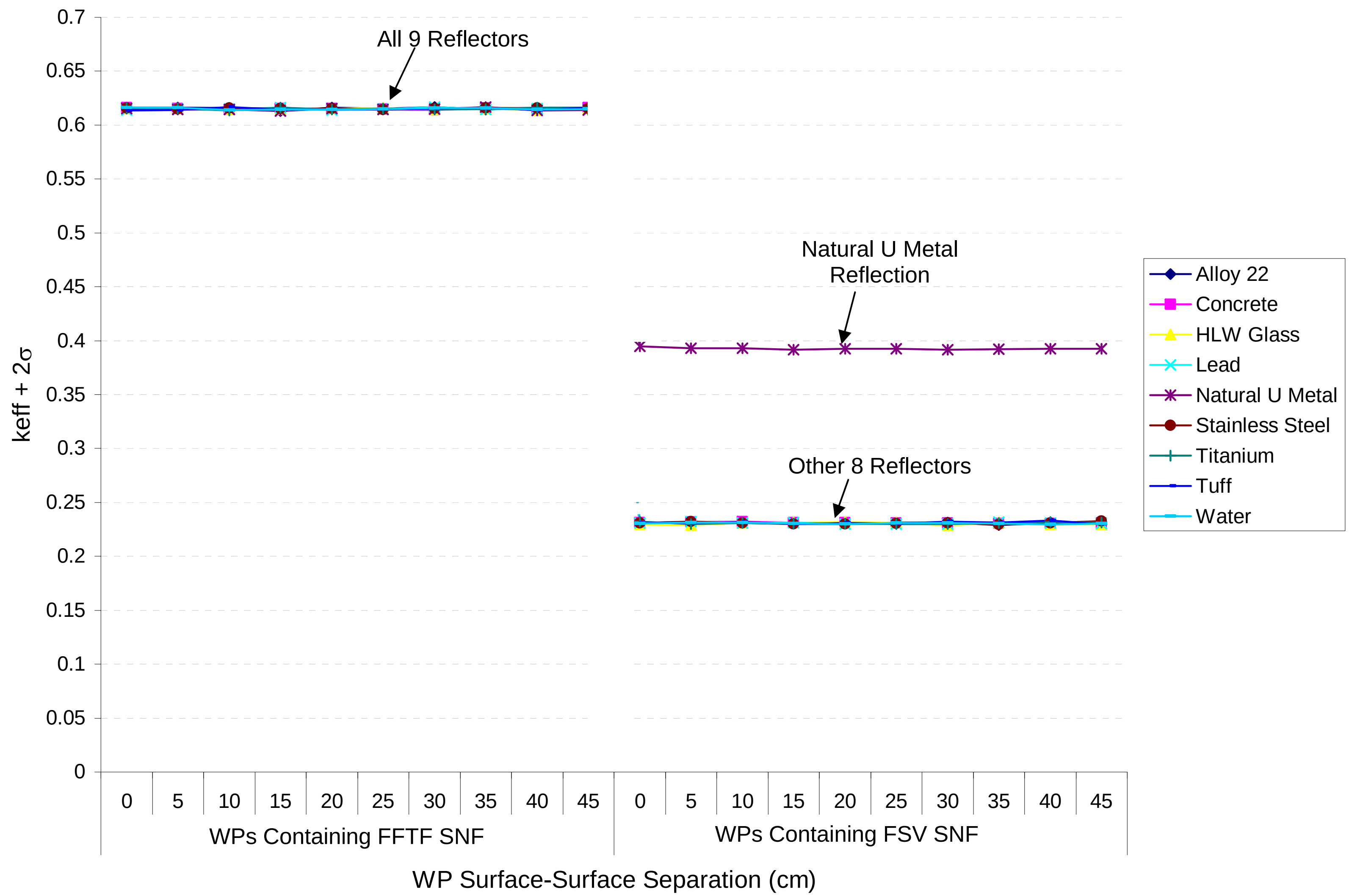

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Figure 7-7: keff+2σ values for an infinite planar array of normally loaded 5 DHLW/DOE SNF WPs (containing FFTF/FSV DOE SNF Canisters) under a variety of close fitting full (30 cm) thickness axial reflection conditions and with no interstitial moderation

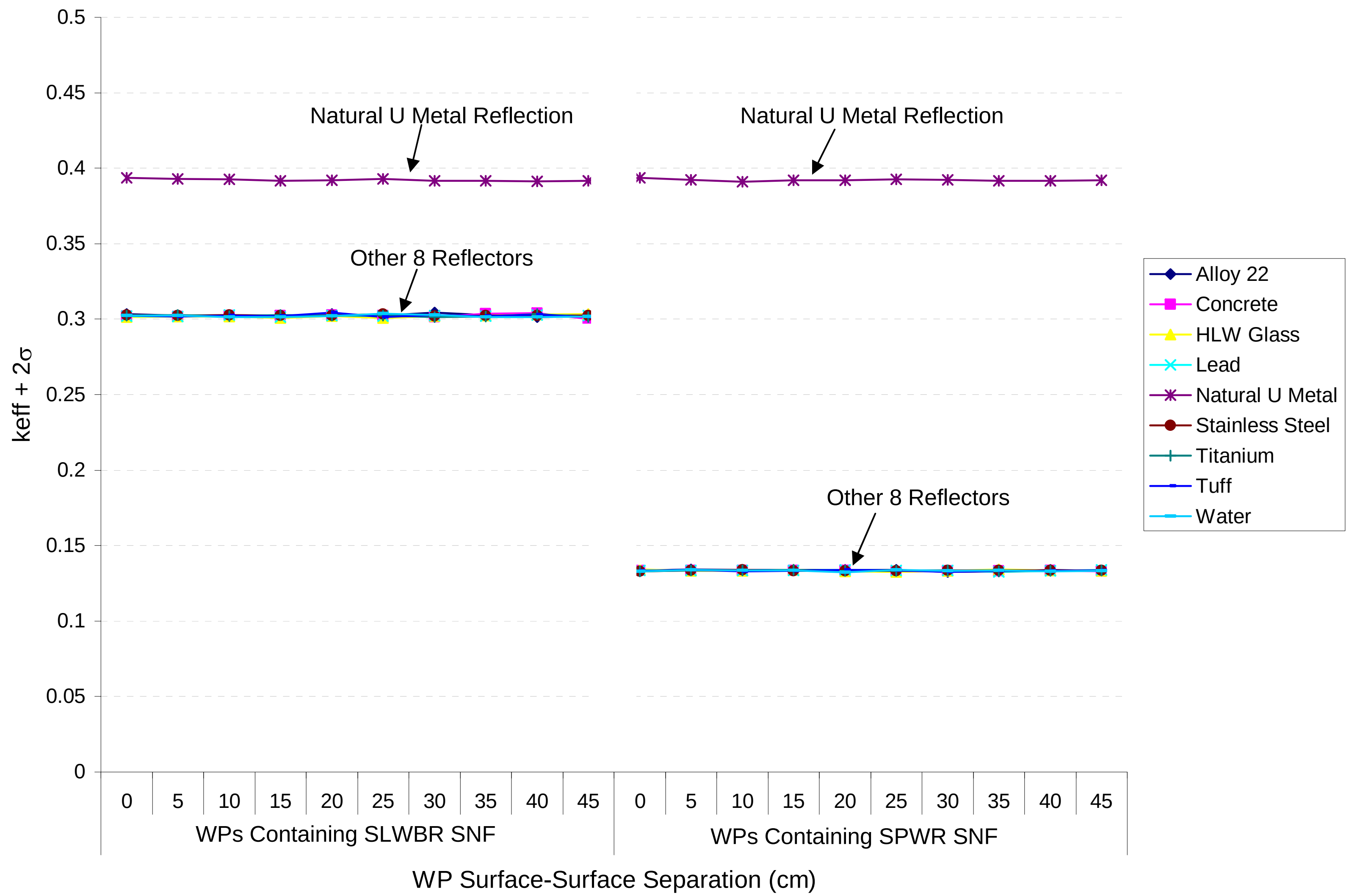

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Figure 7-8: keff+2σ values for an infinite planar array of normally loaded 5 DHLW/DOE SNF WPs (containing SLWBR/SWPR DOE SNF Canisters) under a variety of close fitting full (30 cm) thickness axial reflection conditions and with no interstitial moderation

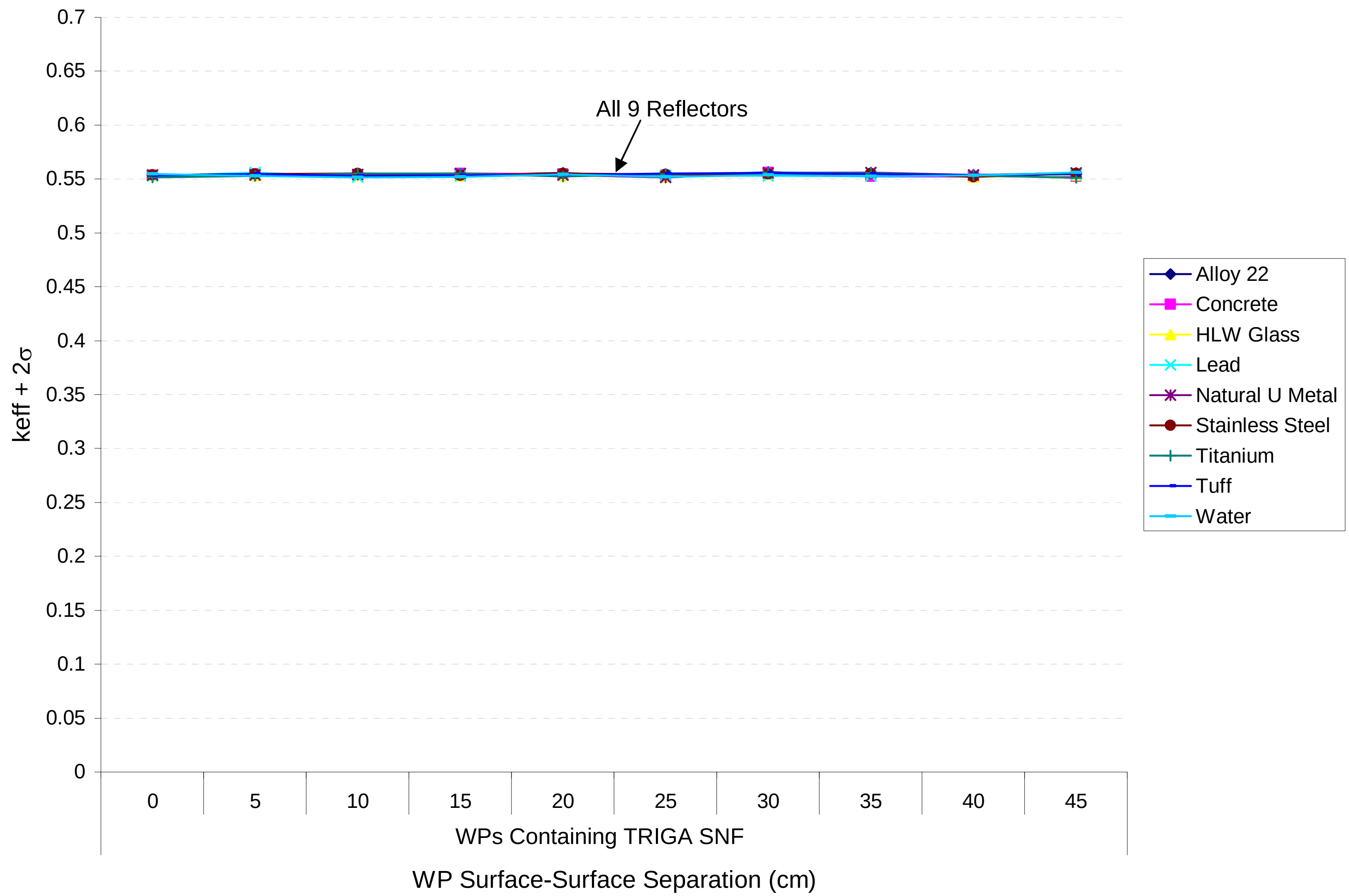

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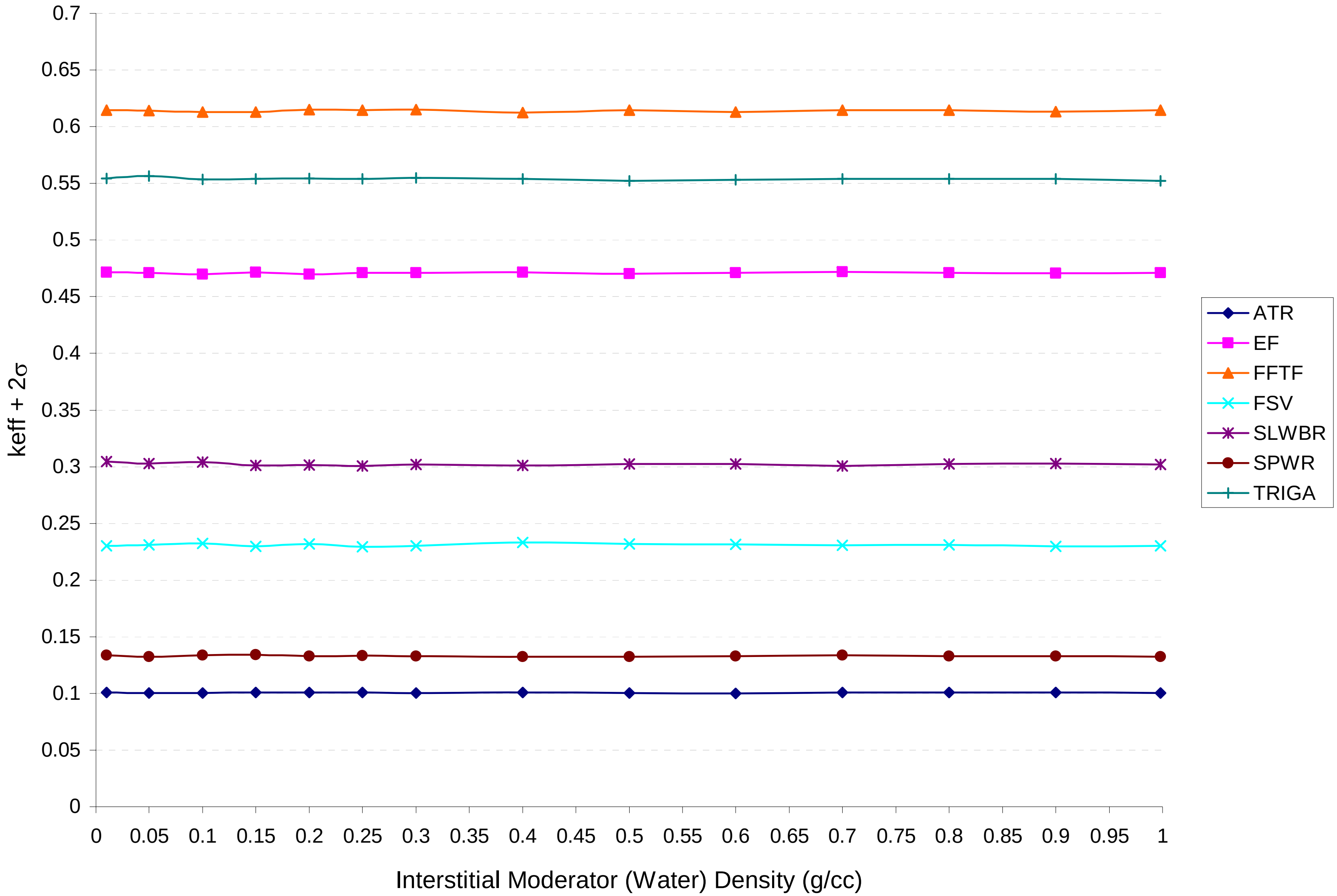
Figure 7-9: keff+2σ values for an infinite planar array of normally loaded 5 DHLW/DOE SNF WPs (containing a TRIGA DOE SNF Canister) under a variety of close fitting full (30 cm) thickness axial reflection conditions and with no interstitial moderation



Source: Original

Figure 7-10: keff+2σ values for an infinite planar array of close-packed and normally loaded 5 DHLW/DOE SNF WPs with close fitting full (30 cm) thickness stainless steel axial reflection and a variety of interstitial water moderation conditions

7.1.1.2 Sub-Surface Facility

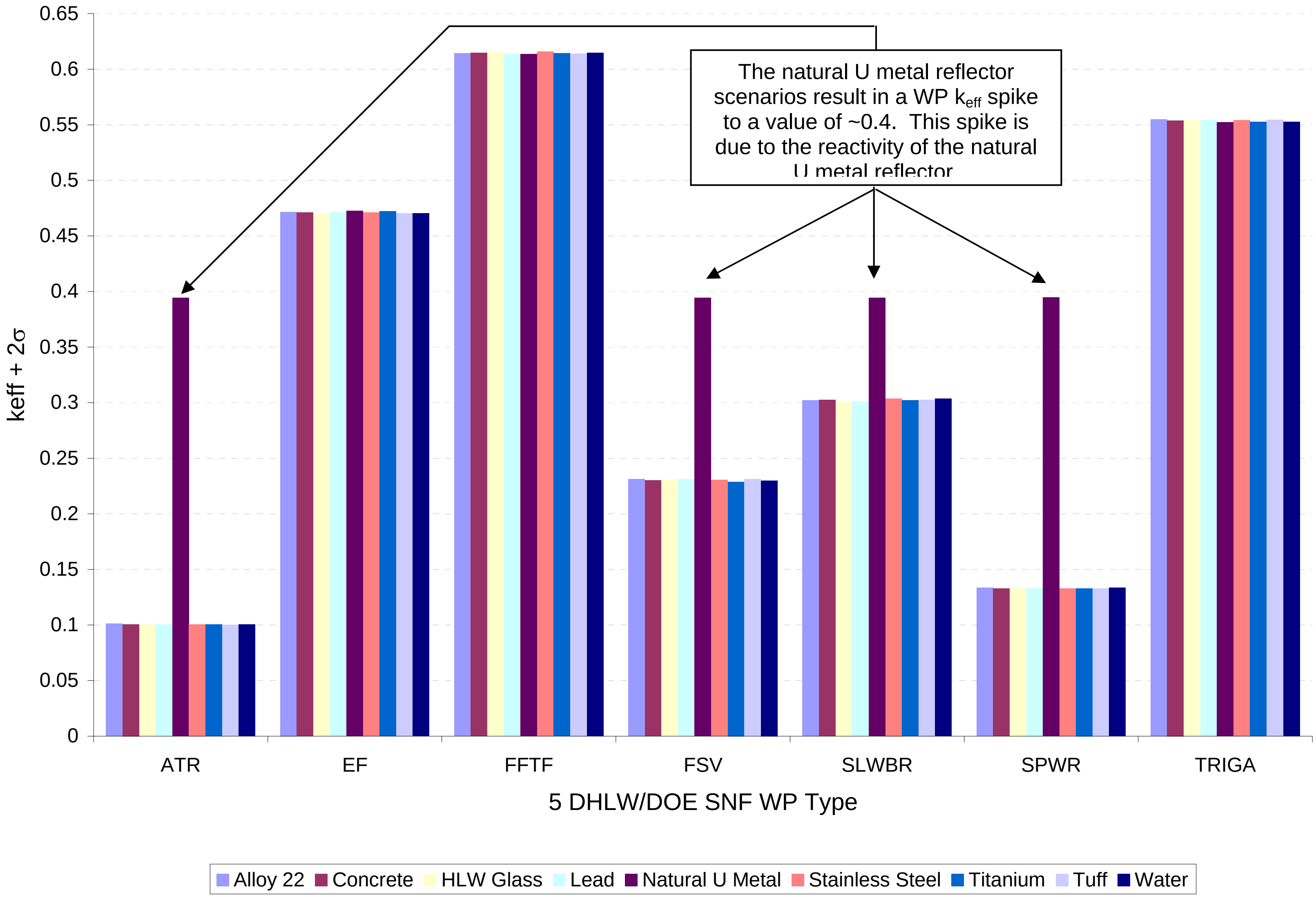
7.1.1.2.1 DOE SNF Canisters

Operations conducted in the sub-surface facility concern the receipt and placement of loaded, sealed, waste packages containing commercial spent nuclear fuel, DOE spent nuclear fuel, naval spent nuclear fuel, and HLW glass. Consequently, DOE SNF canisters are not directly handled in the sub-surface facility.

7.1.1.2.2 5-DHLW/DOE SNF WPs

The subcriticality of loaded and sealed DHLW/DOE SNF WPs positioned in the sub-surface facility emplacement drifts is demonstrated in this section for normal conditions (i.e. for dry WPs containing a single undamaged DOE SNF canister and five HLW Glass Canisters).

The criticality safety process for evaluating loaded, sealed, WPs under normal conditions in the sub-surface facility is described in detail in Section 6.2.1.2. The results of the MCNP k_{eff} calculations performed based on this process are presented in Figure 7-11 and include k_{eff} values for WPs in an emplacement configuration (as described in Section 6.2.1.2), with a wide variety of close fitting full (30 cm) thickness radial reflection conditions. Refer to Figure 6-57 for a cross-section view of the WP emplacement MCNP model with incorporated close-fitting full-thickness radial reflector and axial mirror boundary condition.



Source: Original

Figure 7-11: keff+2σ values for undamaged, dry and normally loaded 5 DHLW/DOE SNF WPs in an emplacement configuration (i.e. mirror axial reflection), with a variety of close fitting full (30 cm) thickness radial reflection conditions

7.1.2 Potential Off-Normal Conditions

7.1.2.1 Surface Facilities and Intra-site Operations

The criticality safety process for evaluating DOE SNF canisters and loaded, sealed, WPs under off-normal conditions in the surface facilities (including intra-site operations) is described in detail in Section 6.2.2.1. The results of the calculations performed based on this process are presented in this section.

7.1.2.1.1 DOE SNF Canisters

This section presents the MCNP k_{eff} results for both individual and groups of DOE SNF canisters. The calculations are structured according to three basic types off-normal conditions, as follows:

1. Incorrect staging of undamaged dry DOE SNF Canisters (refer to Section 7.1.2.1.1.1 for results).
2. Damage to an individual DOE SNF Canister without canister breach (refer to Section 7.1.2.1.1.2 for results).
3. Damage to an individual DOE SNF Canister also resulting in canister breach and coincident entrainment of liquid moderator (refer to Section 7.1.2.1.1.3 for results).

For 'intact damage' off-normal condition calculations, the neutron absorber content of the basket structure (if any), and the basket filler material (if any), is varied to establish the sensitivity of the system to a reduced presence of neutron absorber.

7.1.2.1.1.1 Staging Error

Under normal operating conditions, all DOE SNF canisters are handled individually and staged only in the dedicated CRCF DOE canister staging racks, which ensures a safe configuration. Incorrect staging of DOE SNF canisters in positions outside the dedicated DOE canister staging racks could result in a condition in which k_{eff} would exceed the USL.

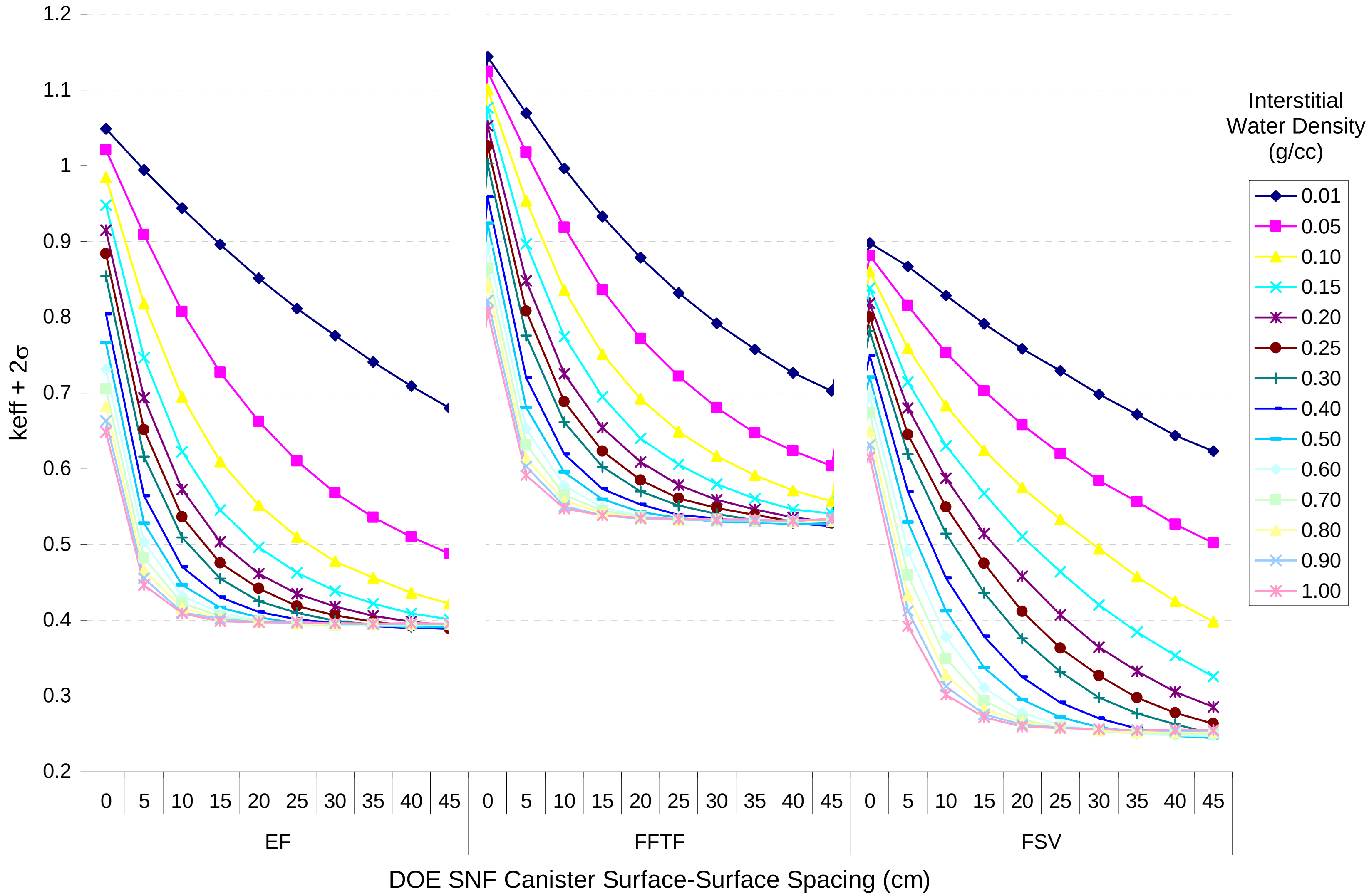
This section presents the MCNP k_{eff} results for an assemblage of multiple undamaged and dry DOE SNF canisters. The following results are presented:

1. k_{eff} values for an infinite planar array of DOE SNF canisters under a wide variety of close fitting full (30 cm) thickness axial reflection conditions, and a full range of interstitial moderation conditions (presented in Figure 7-12 through Figure 7-14).

2. k_{eff} values for a close-packed cluster (variable, limited, quantity) of DOE SNF canisters under a wide variety of close fitting full (30 cm) thickness reflection conditions (presented in Figure 7-15).

Refer to Figure 6-58 and Figure 6-59 for a cross-section view of the DOE SNF canister infinite planar array MCNP model with incorporated periodic boundary condition and close-fitting full-thickness axial reflectors. Refer to Figure 6-60 through Figure 6-64 for cross-section views of the DOE SNF canister cluster MCNP models with close-fitting full-thickness reflector.

In respect of the abovementioned calculations it is noted that canister mixing scenarios are not considered (i.e. each MCNP model comprises only one waste form). Based on the results of the DOE SNF canister infinite planar array calculations (Figure 7-12 through Figure 7-14), it is seen that k_{eff} decreases with the addition of interstitial moderator between canisters. This trend implies that the neutron spectral differences between the various waste forms would not create a condition where a 'mixed' canister array would result in a k_{eff} value greater than the largest k_{eff} value observed for the non-mixed (i.e. single type) canister arrays. This statement is supported by the result of an additional calculation recorded in worksheet *Mixed Can Cluster Data* of workbook *Ancillary Results* (Attachment 3). This additional calculation is based (exactly) on the configuration depicted in Figure 6-64, except that the center FFTF DOE SNF canister is replaced with a FSV DOE SNF canister.



Source: Original

Figure 7-12: keff+2σ values for an infinite planar array of undamaged and dry DOE SNF canisters (EF, FFTF & FSV) with close fitting full (30 cm) thickness stainless steel axial reflection and a variety of interstitial water moderation conditions

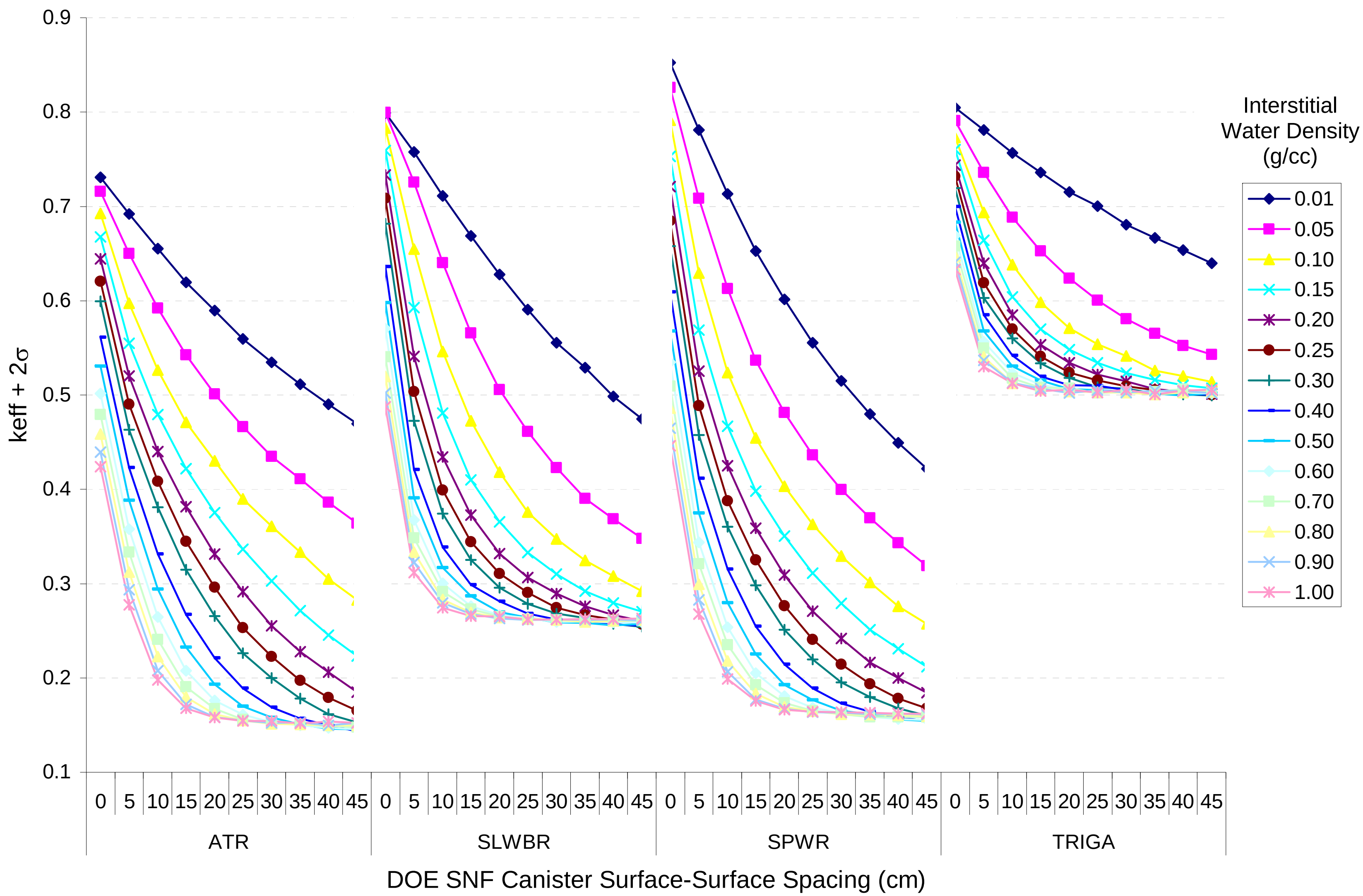


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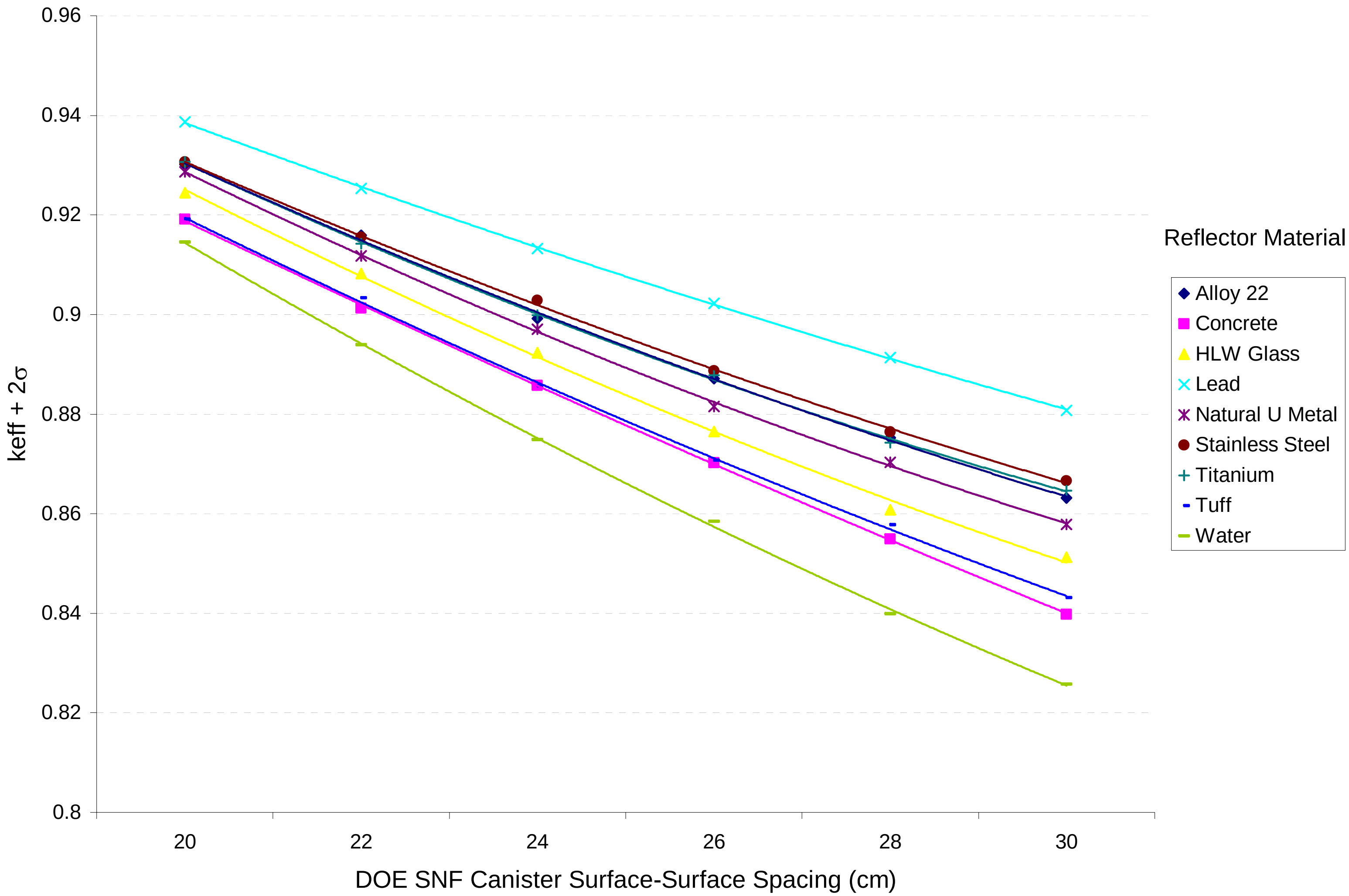
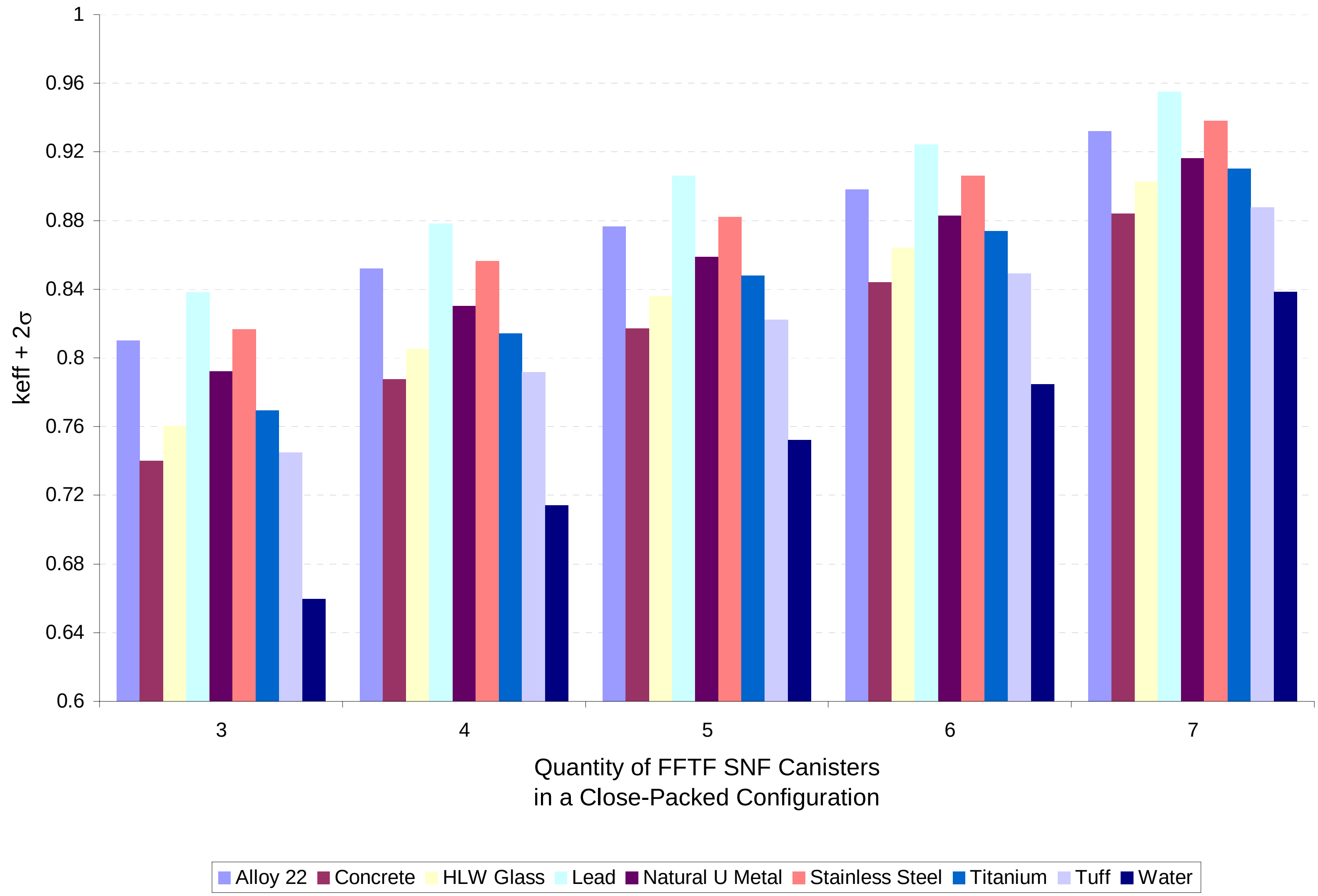
Figure 7-13: keff+2σ values for an infinite planar array of undamaged and dry DOE SNF canisters (ATR, SLWBR, SPWR & TRIGA) with close fitting full (30 cm) thickness stainless steel axial reflection and a variety of interstitial water moderation conditions



Source: Original

Figure 7-14: keff+2σ values for an infinite planar array of undamaged and dry FFTF DOE SNF canisters with no interstitial moderation and a variety of close fitting full (30 cm) thickness axial reflection conditions



Source: Original

Figure 7-15: keff+2σ values for a limited size cluster of undamaged and dry FFTF DOE SNF canisters under a variety of close fitting full (30 cm) thickness reflection conditions

7.1.2.1.1.2 Single Canister Damage without Breach

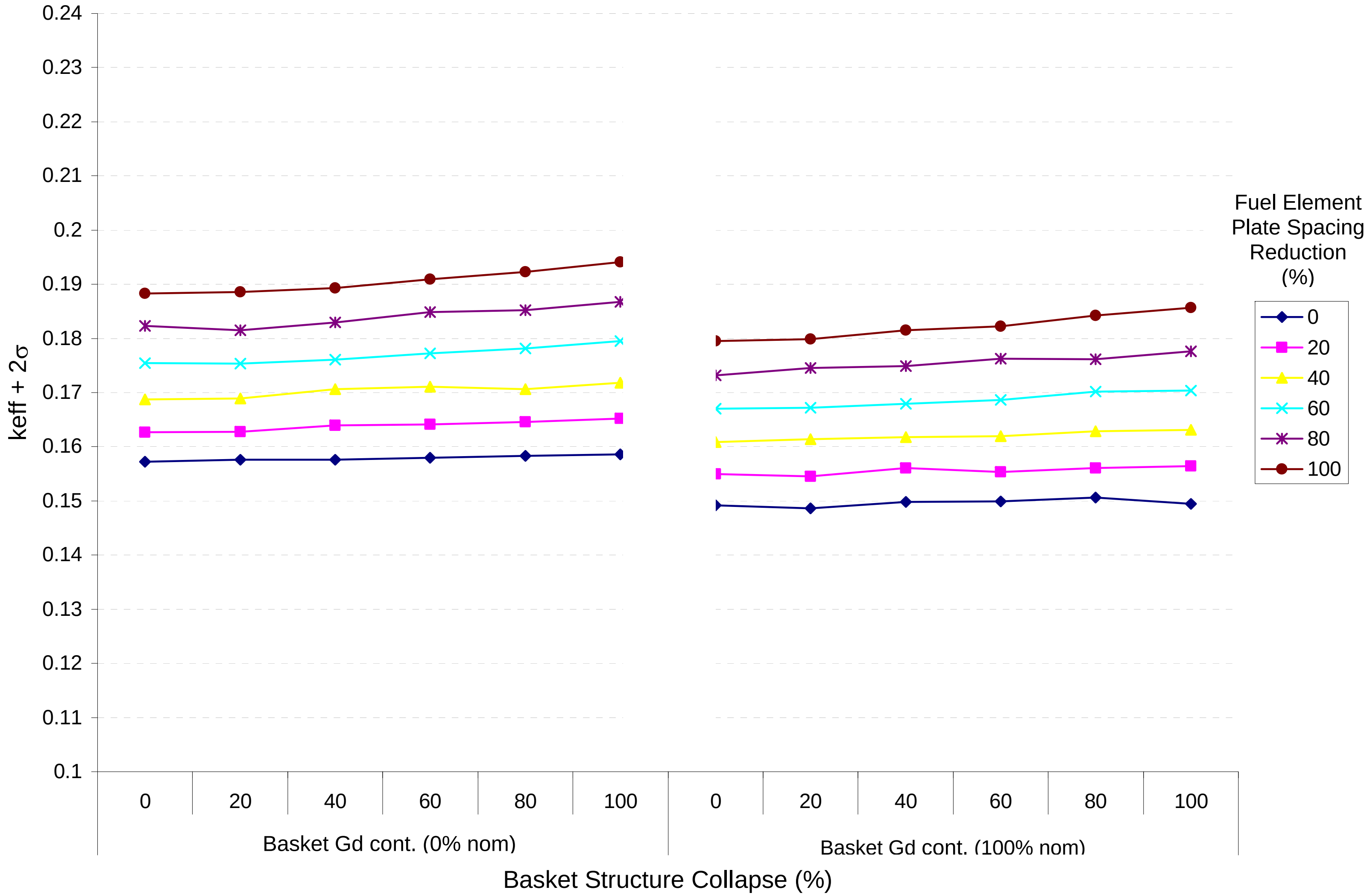
This section presents the MCNP k_{eff} results for off-normal conditions consisting of damage to an individual DOE SNF canister without actual breach of the canister shell, as described in Section 6.2.2.1.2. Within this framework, two basic configurations are examined:

1. Damage to an individual DOE SNF canister resulting in a rearrangement of its internal structure (e.g. repositioning of SNF and basket structure), but not resulting in a physical release of material (i.e. creation of debris). This configuration is referred to as a *dry damaged intact* configuration.
2. Damage to an individual DOE SNF canister resulting in complete or partial release of its internal structure as debris (i.e. SNF, basket structure and basket filler material). This configuration is referred to as a *dry damaged degraded* configuration.

For the *dry damaged intact* calculations, the neutron absorber content of the basket structure (if any) and the basket filler material (if any) is varied to establish the sensitivity of the system to reduction of neutron absorber content. Note that for the EF, FFTF and TRIGA canisters, the effect on k_{eff} due to the absence of a canister basket is examined.

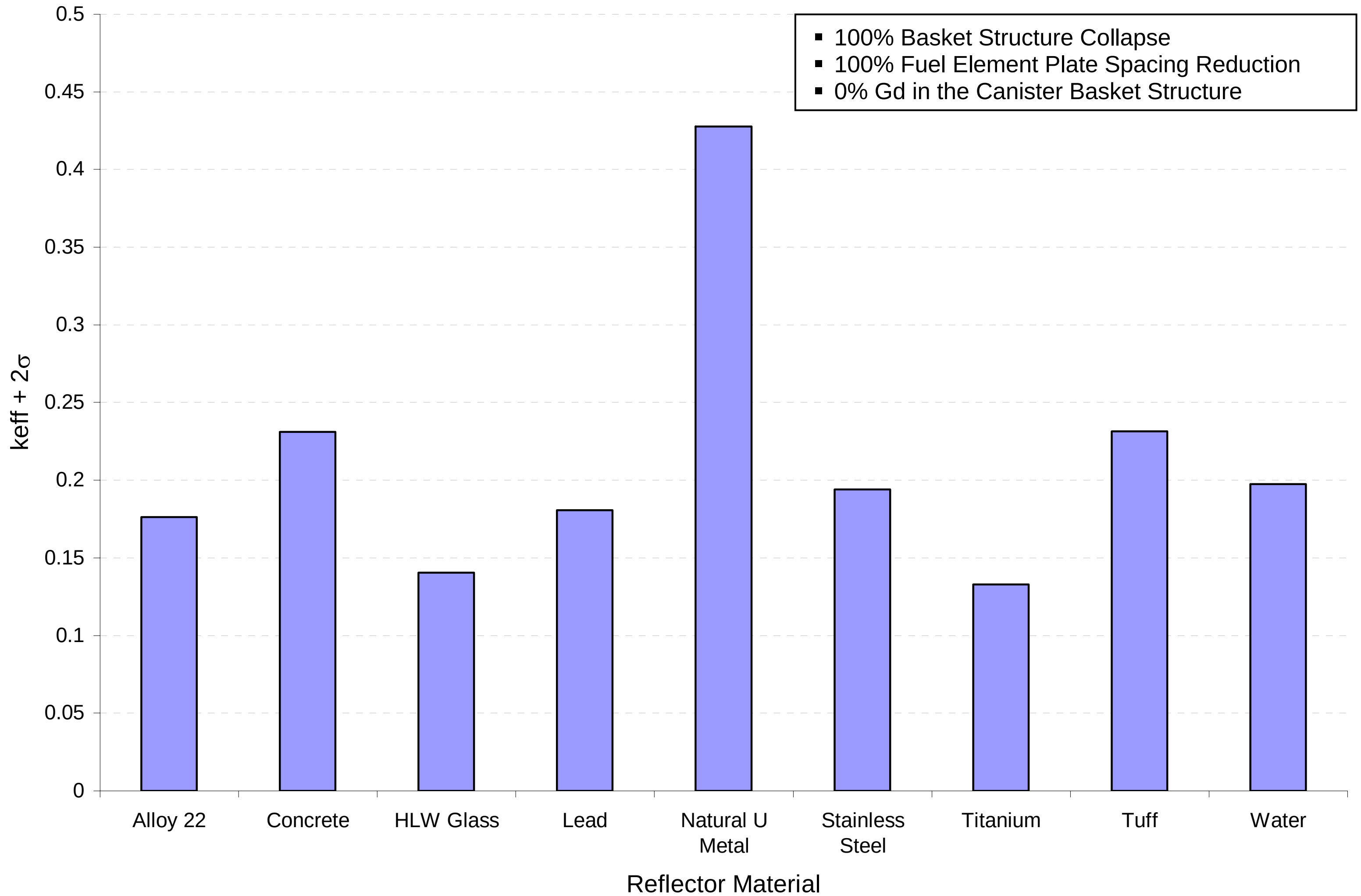
The results of the *dry damaged intact* DOE SNF canister calculations are presented in Figure 7-16 through Figure 7-29, which are categorized according to waste form. The explicit damage configurations (i.e. positioning of SNF, basket structure, etc.) correlate to the configurations explained in detail in Section 6.2.2.1.2.1. The degree of damage is expressed as a percentage of the maximum potential damage for which k_{eff} is expected to be maximized. Refer to Section 6.2.2.1.2.1 and Figure 6-72 through Figure 6-92 (MCNP model cross-section views) for further details. Note that the results of the 'no basket' calculations for the EF, FFTF and TRIGA canisters are presented in Figure 7-19, Figure 7-21, and Figure 7-29.

The results of the dry damaged and degraded DOE SNF canister calculations are presented in Figure 7-30 through Figure 7-48, which are also categorized according to waste form. The explicit damage configurations (i.e. positioning of SNF, basket structure, etc.) correlate to the configurations explained in detail in Section 6.2.2.1.2.2. The degree of degradation (i.e. the quantity of SNF, clad, basket and basket filler material that is considered released) is expressed as a percentage of the total inventory for the respective canister. For example, canister debris with a basket filler content of 40% means that 40% of the total mass of basket filler material associated with the respective canister is modeled in the canister debris. Refer to Section 6.2.2.1.2.2 and Figure 6-93 for further details.



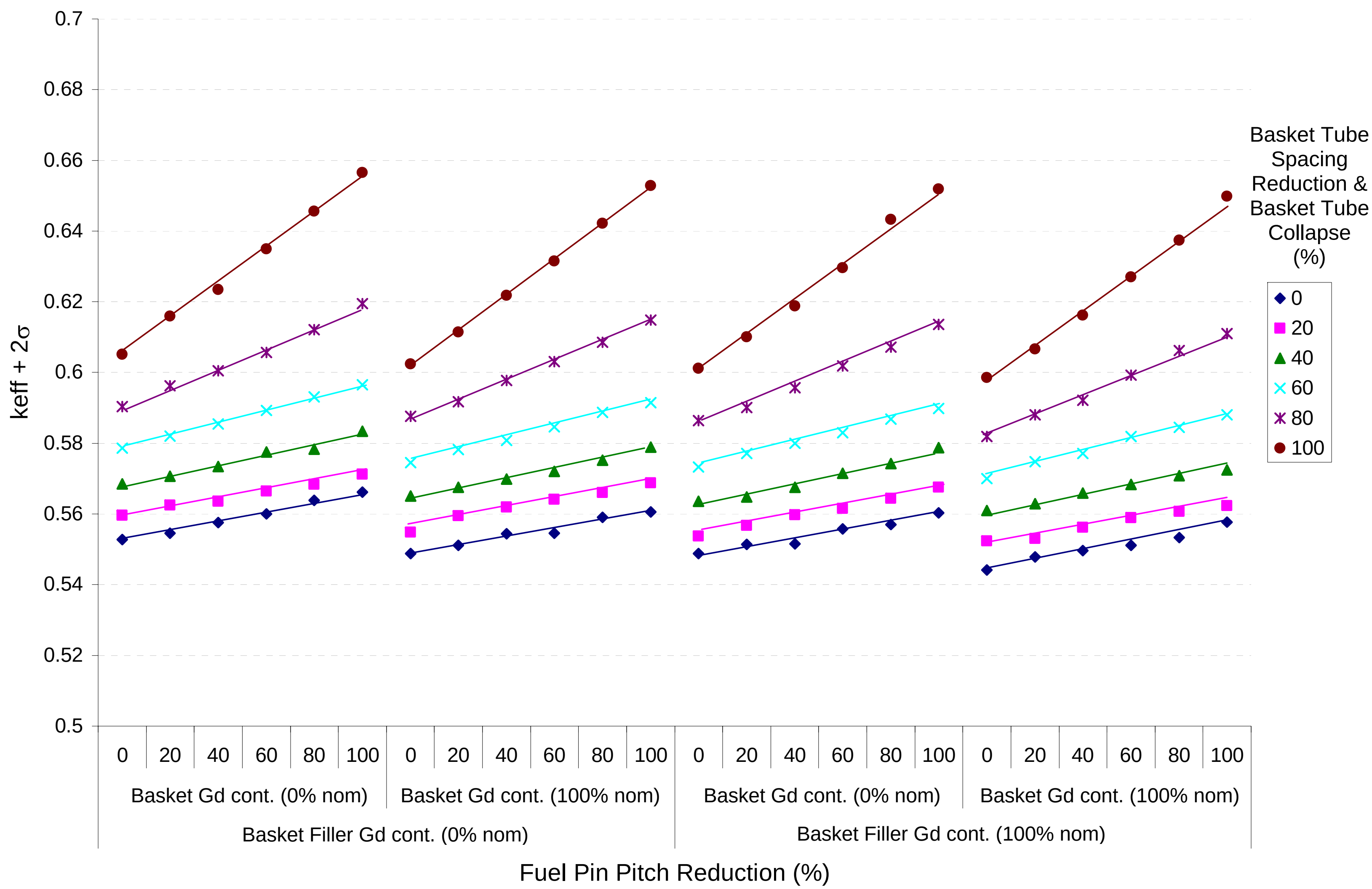
Source: Original

Figure 7-16: keff+2σ values (as a function of basket structure collapse, basket structure Gd content, and fuel element spacing reduction) for an individual dry damaged, but intact, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-17: keff+2σ values for an individual dry damaged, but intact, ATR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-18: keff+2σ values (as a function of pin pitch reduction, basket filler and structure Gd content, basket tube spacing reduction, and basket tube collapse) for an individual dry damaged, but intact, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

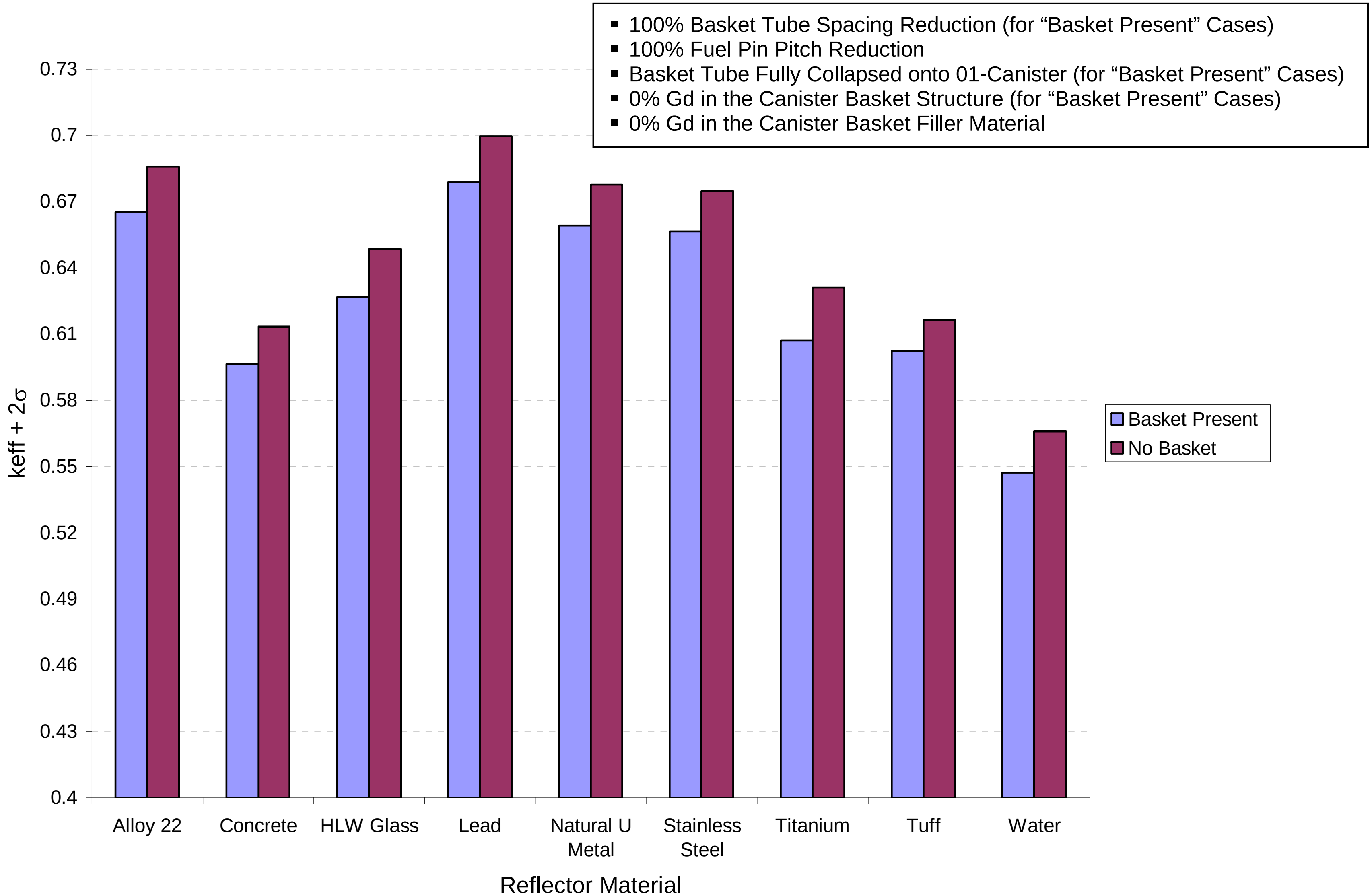


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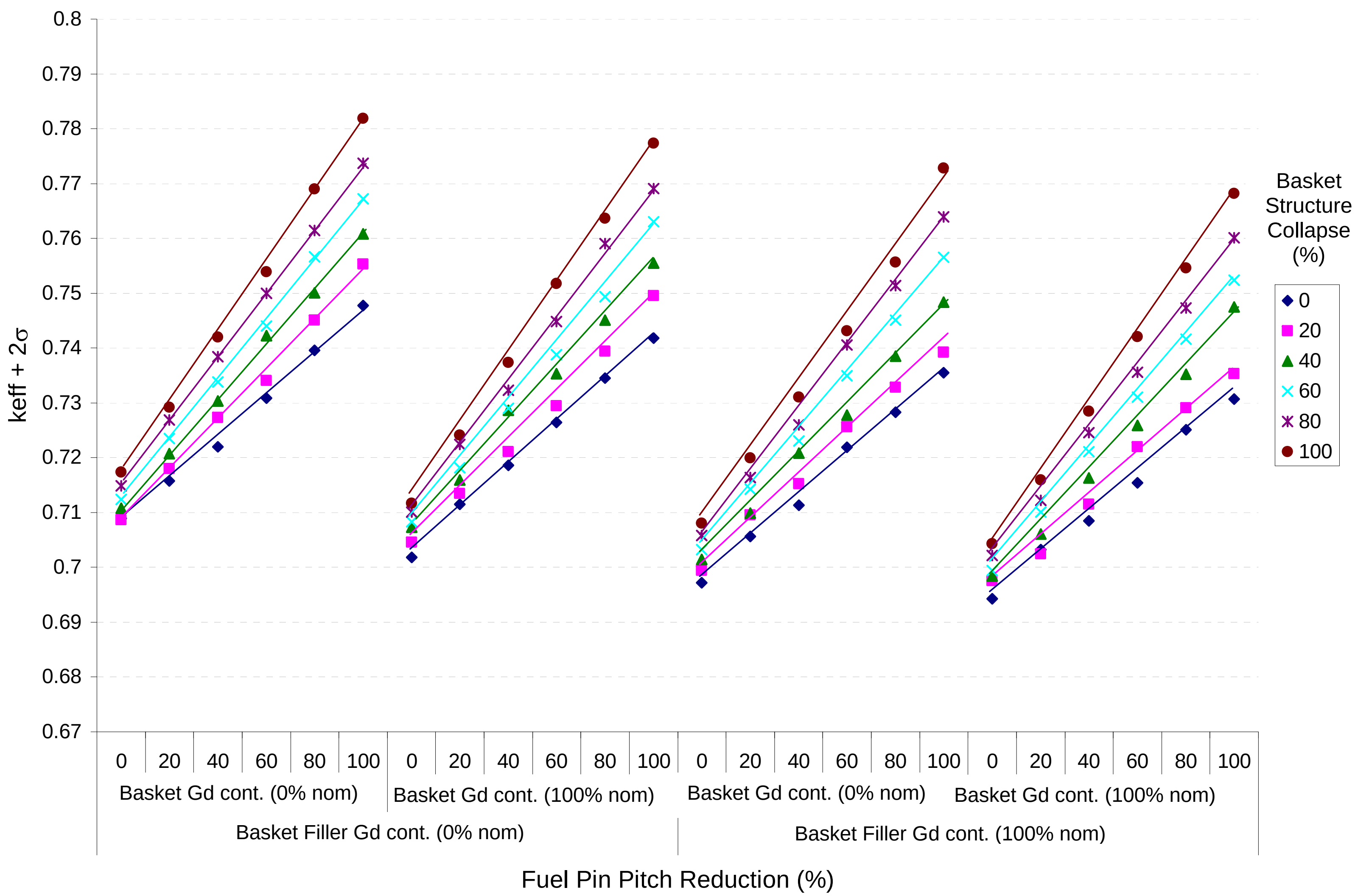
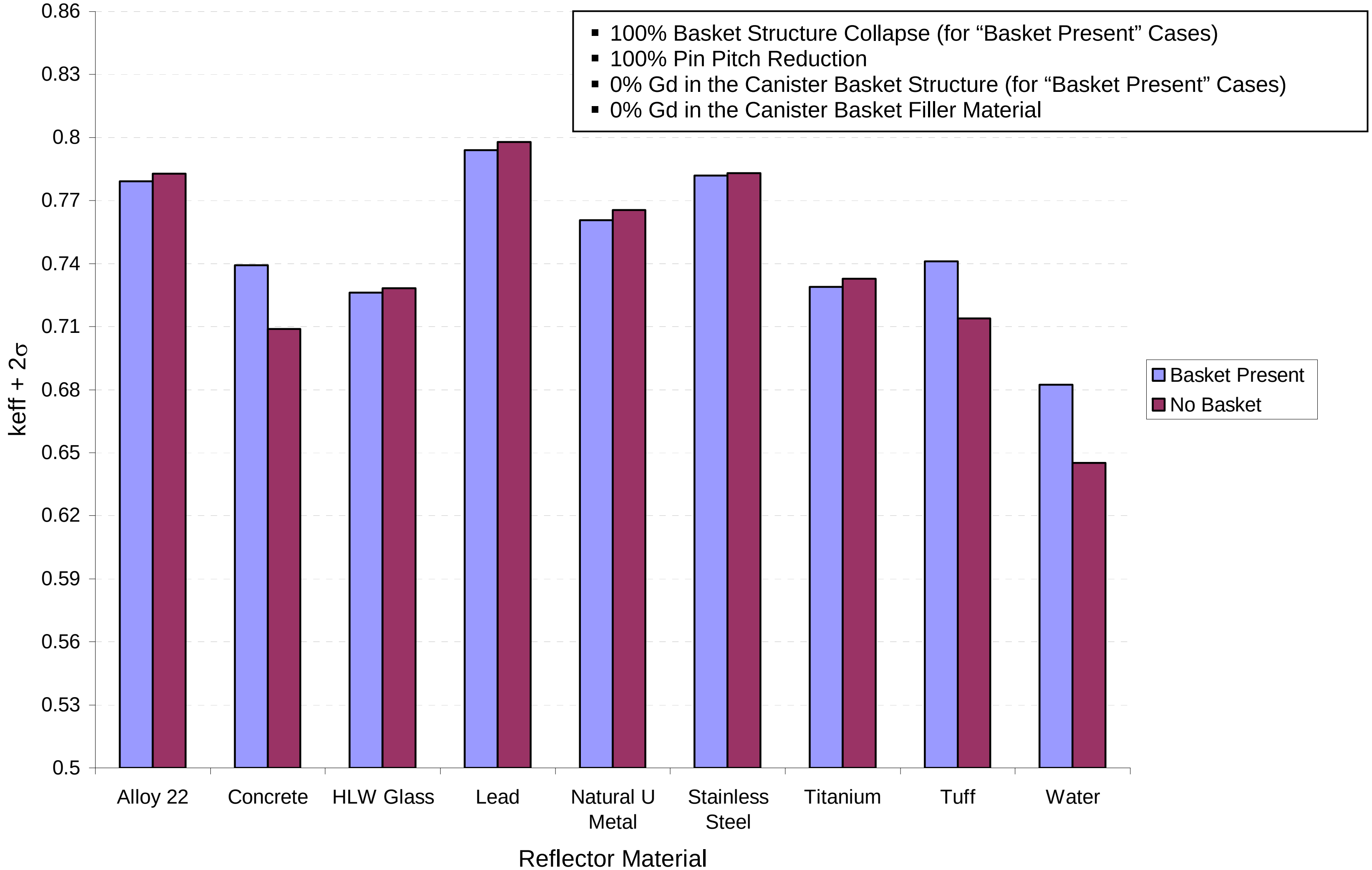
Figure 7-19: keff+2σ values for an individual dry damaged, but intact, EF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



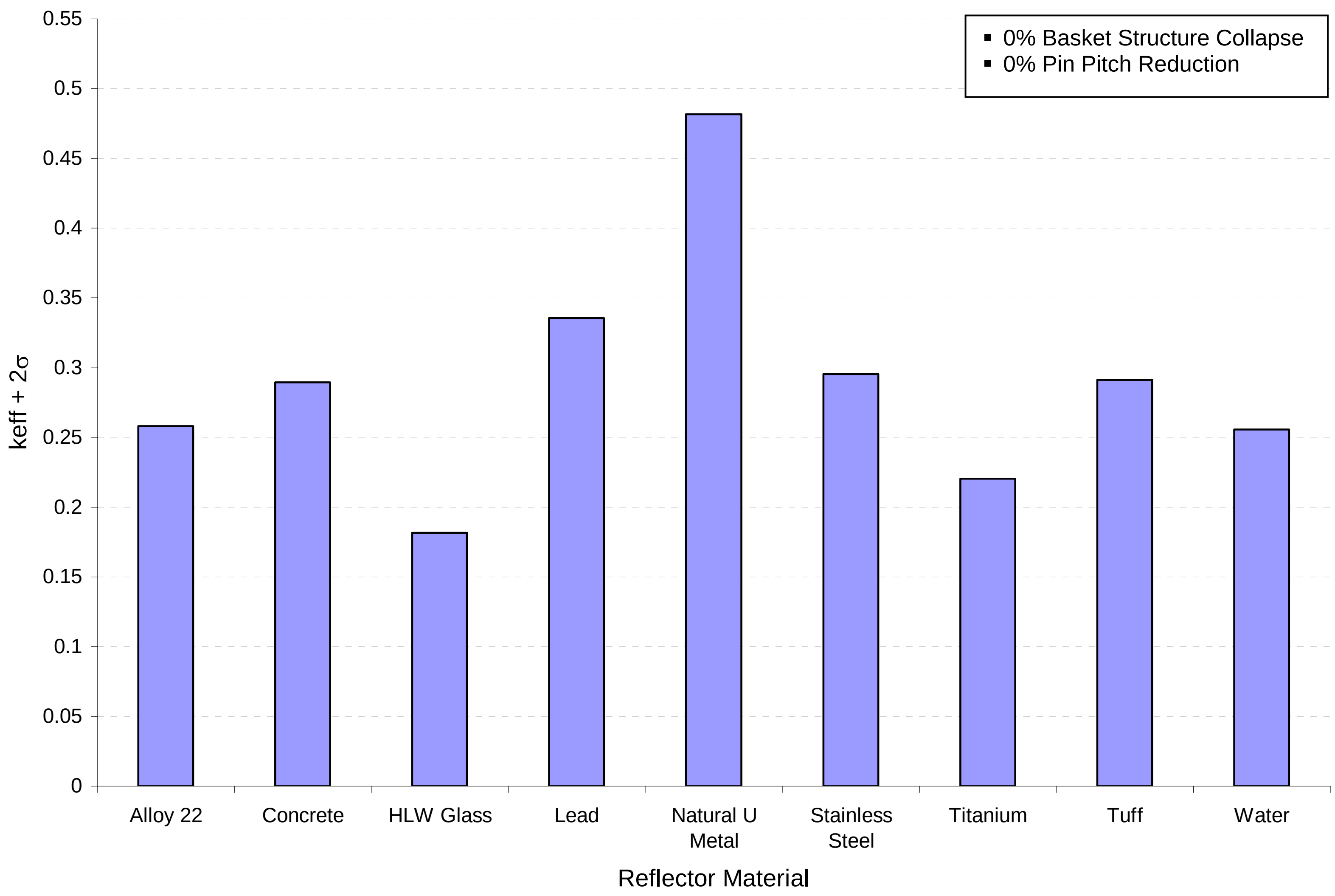
Source: Original

Figure 7-20: keff+2σ values (as a function of DFA and Ident-69 pin pitch reduction, basket filler and structure Gd content, and basket structure collapse) for an individual dry damaged, but intact, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



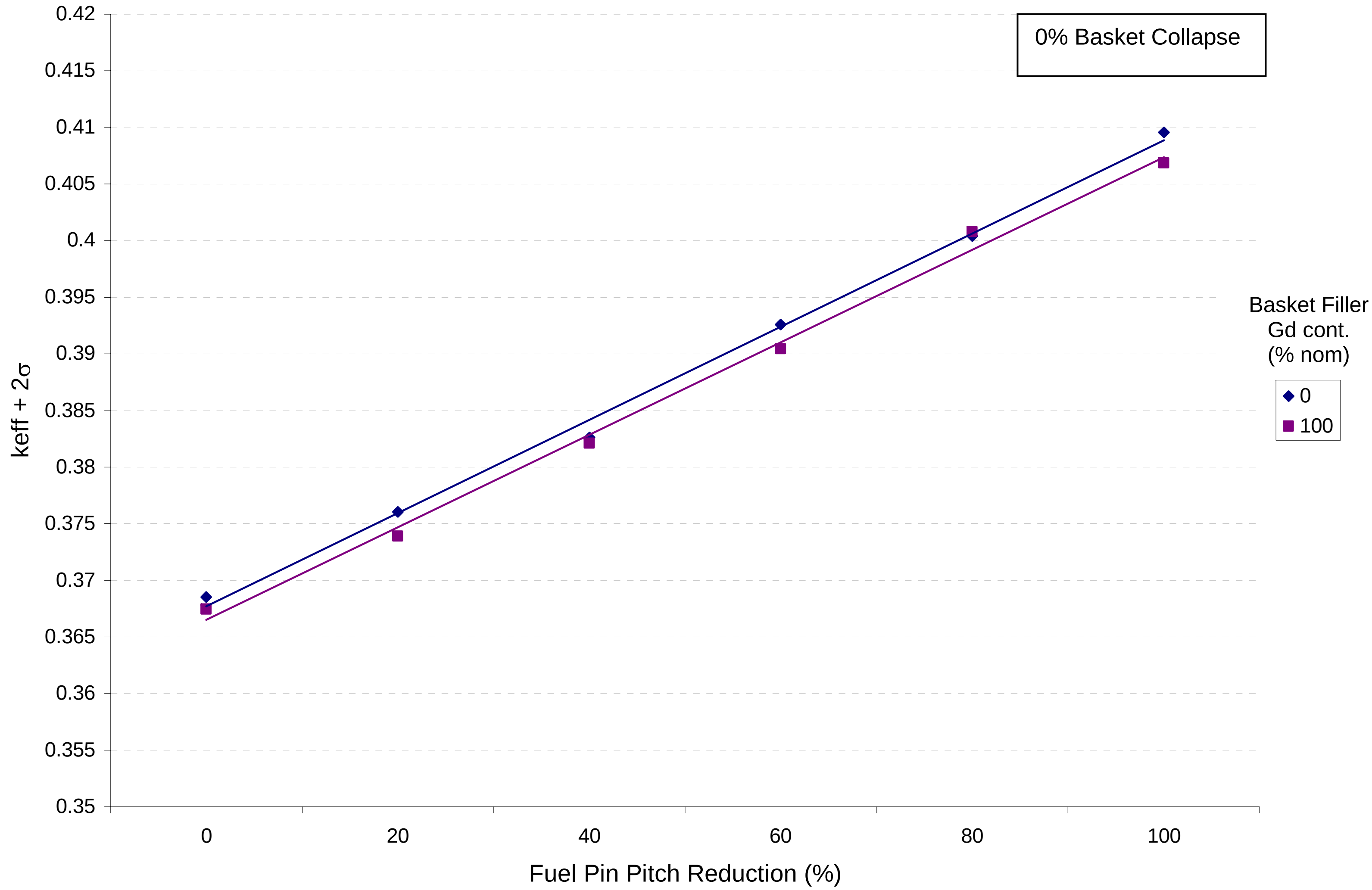
Source: Original

Figure 7-21: keff+2σ values for an individual dry damaged, but intact, FFTF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-22: keff+2σ values for an individual undamaged FSV DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-23: keff+2σ values (as a function of pin pitch, and basket filler Gd content) for an individual dry damaged, but intact, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

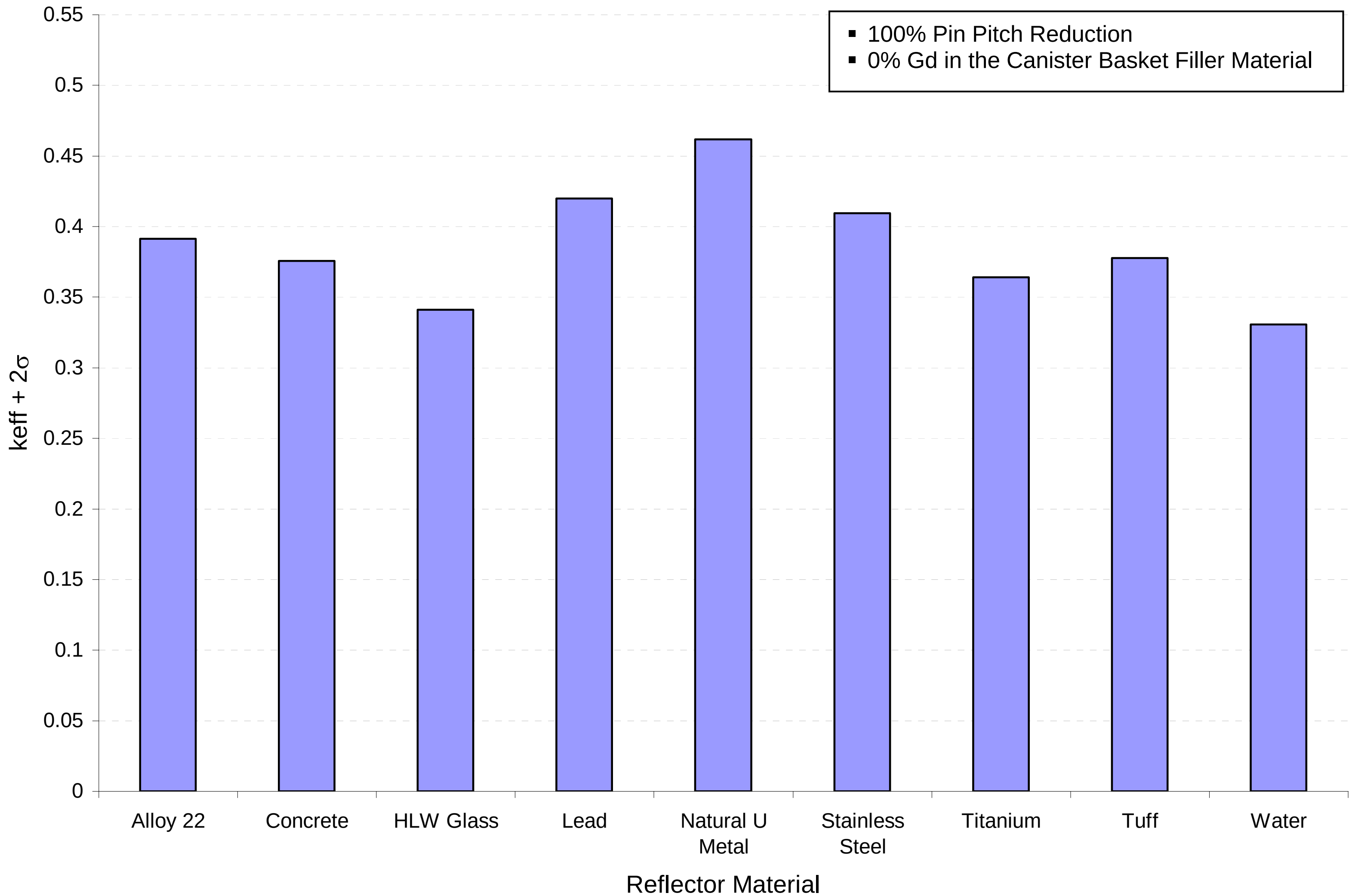


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Figure 7-24: keff+2σ values for an individual dry damaged, but intact, SLWBR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

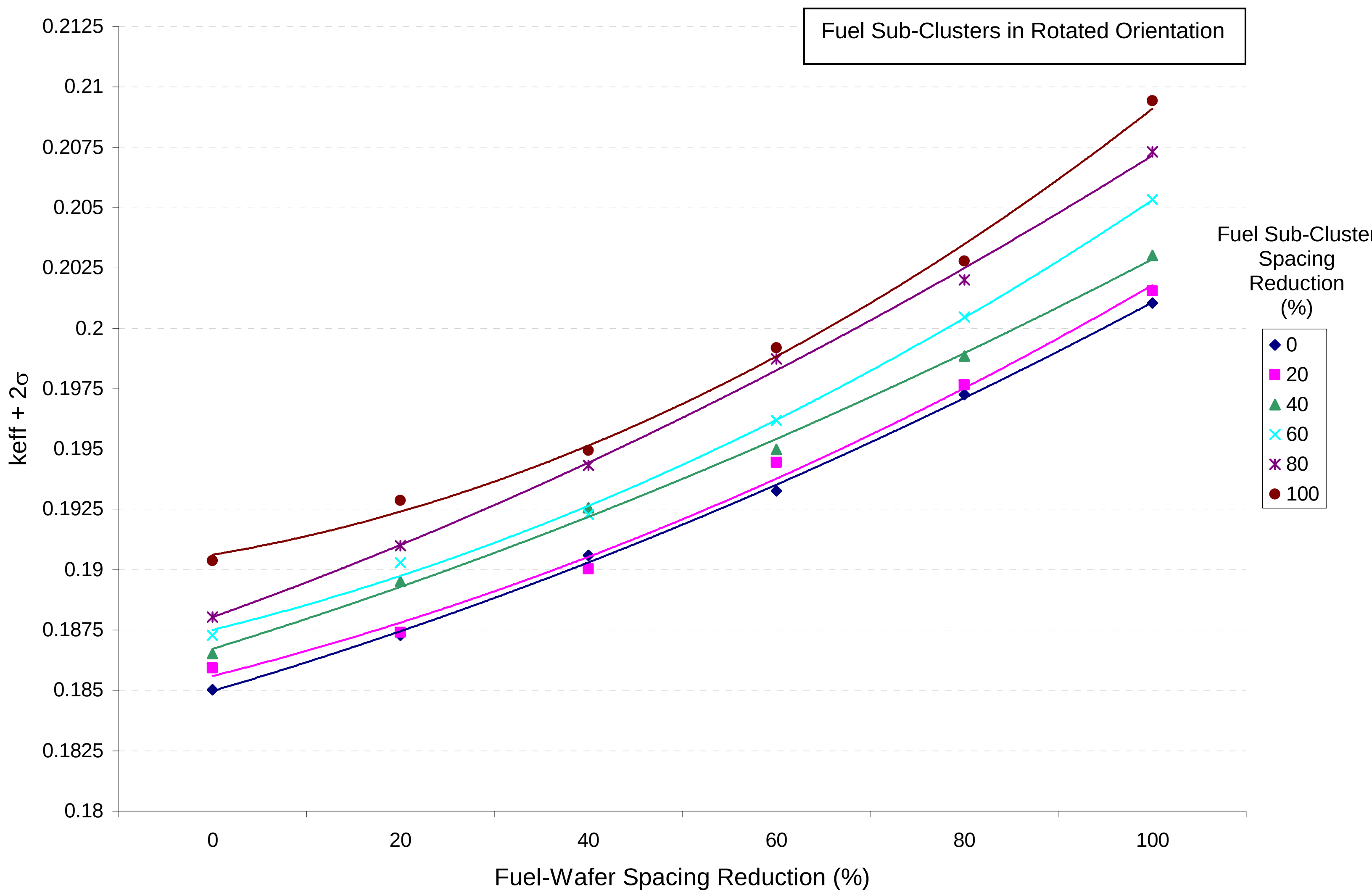

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Figure 7-25: keff+2σ values (as a function of fuel wafer spacing reduction, and fuel sub-cluster spacing reduction) for an individual dry damaged, but intact, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection (fuel sub-clusters in rotated orientation)

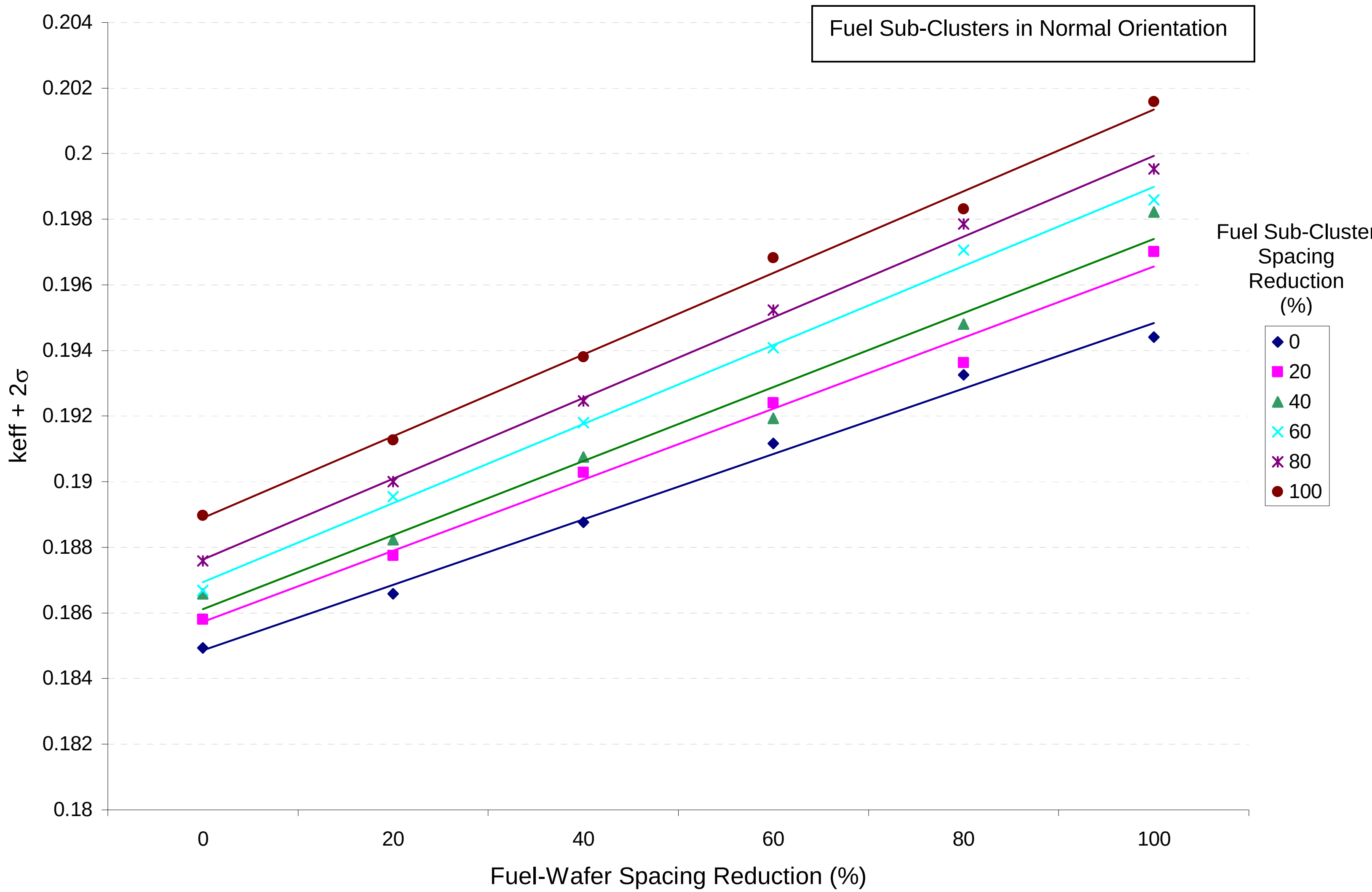

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Figure 7-26: keff+2σ values (as a function of fuel wafer spacing reduction, and fuel sub-cluster spacing reduction) for an individual dry damaged, but intact, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection (fuel sub-clusters in normal orientation)

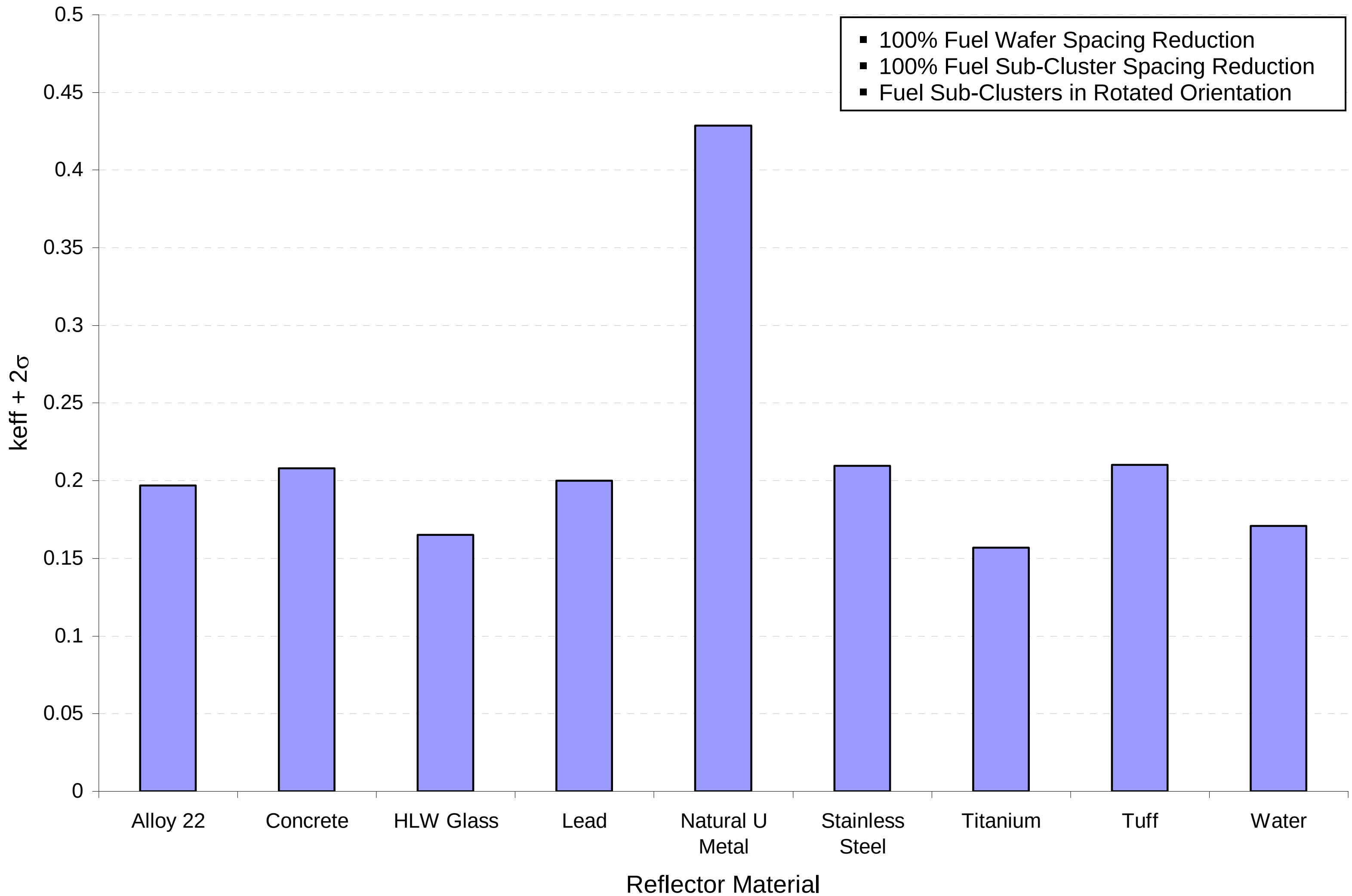

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Figure 7-27: keff+2σ values for an individual dry damaged, but intact, SPWR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions (fuel sub-clusters in rotated orientation)

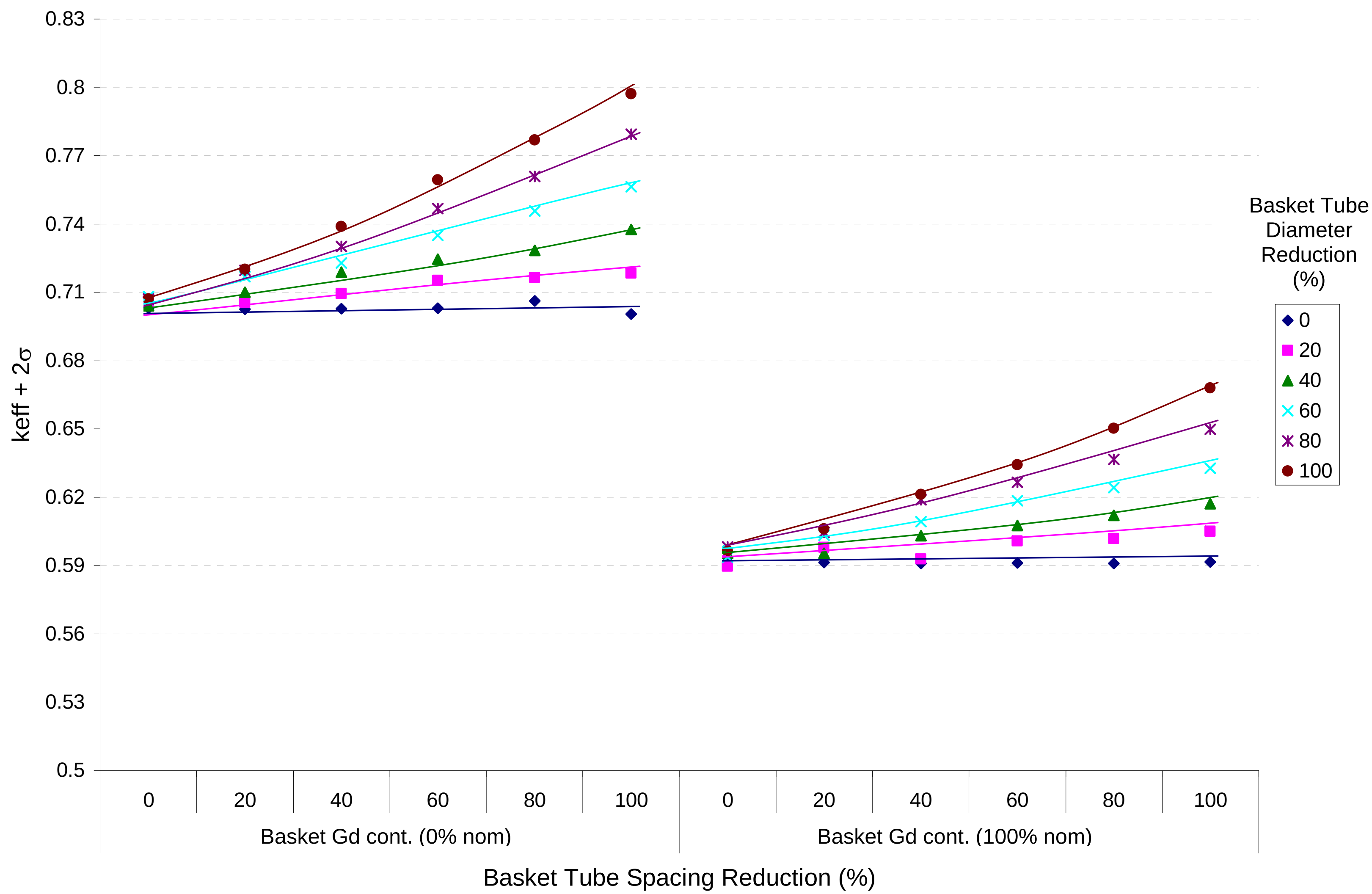

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Figure 7-28: keff+2σ values (as a function of basket tube spacing reduction, basket tube Gd content, and basket tube diameter reduction) for an individual dry damaged, but intact, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

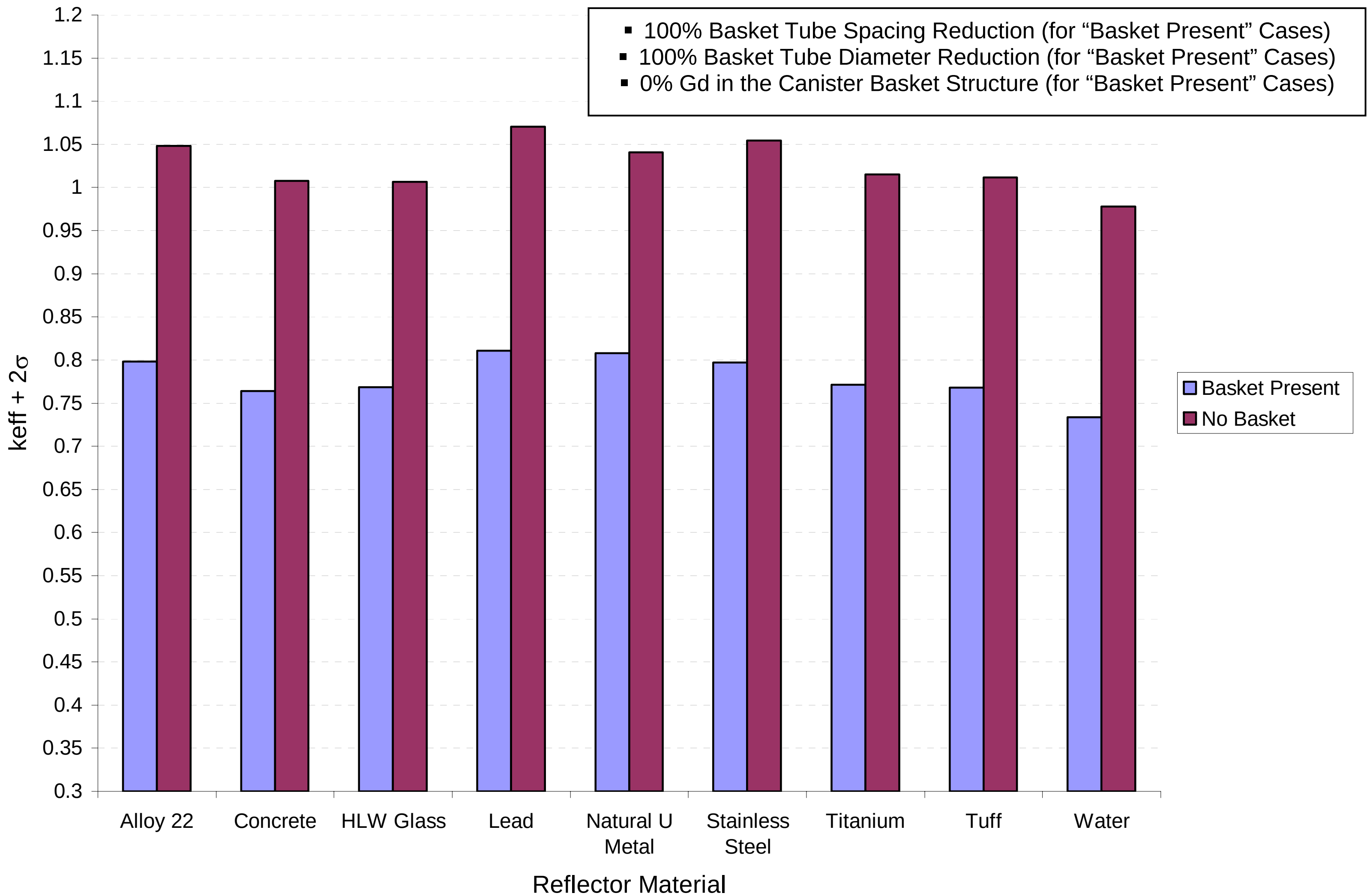

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Figure 7-29: keff+2σ values for an individual dry damaged, but intact, TRIGA DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

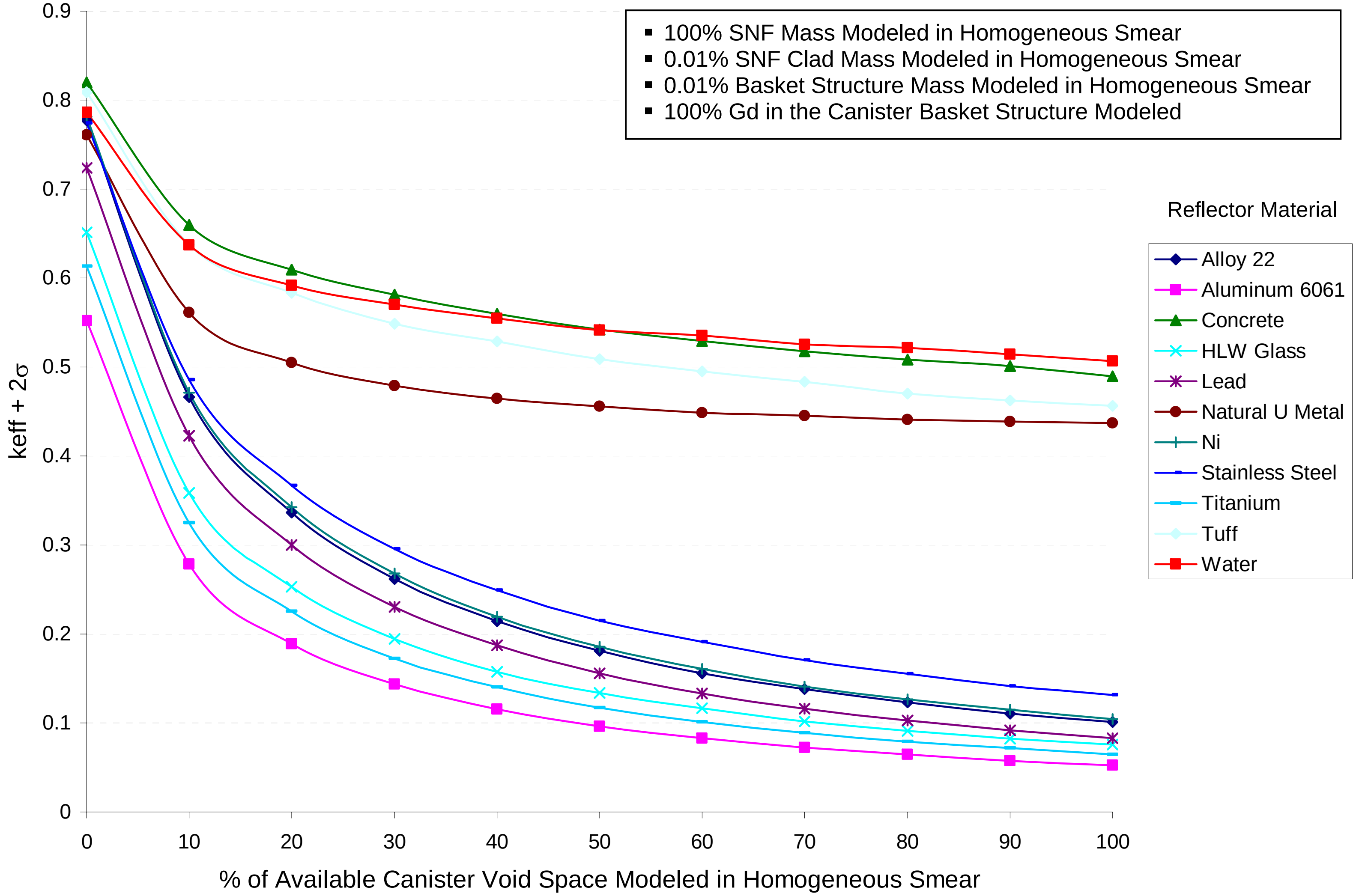

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Figure 7-30: keff+2σ values (as a function of void space modeled) for an individual dry damaged, and degraded, ATR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

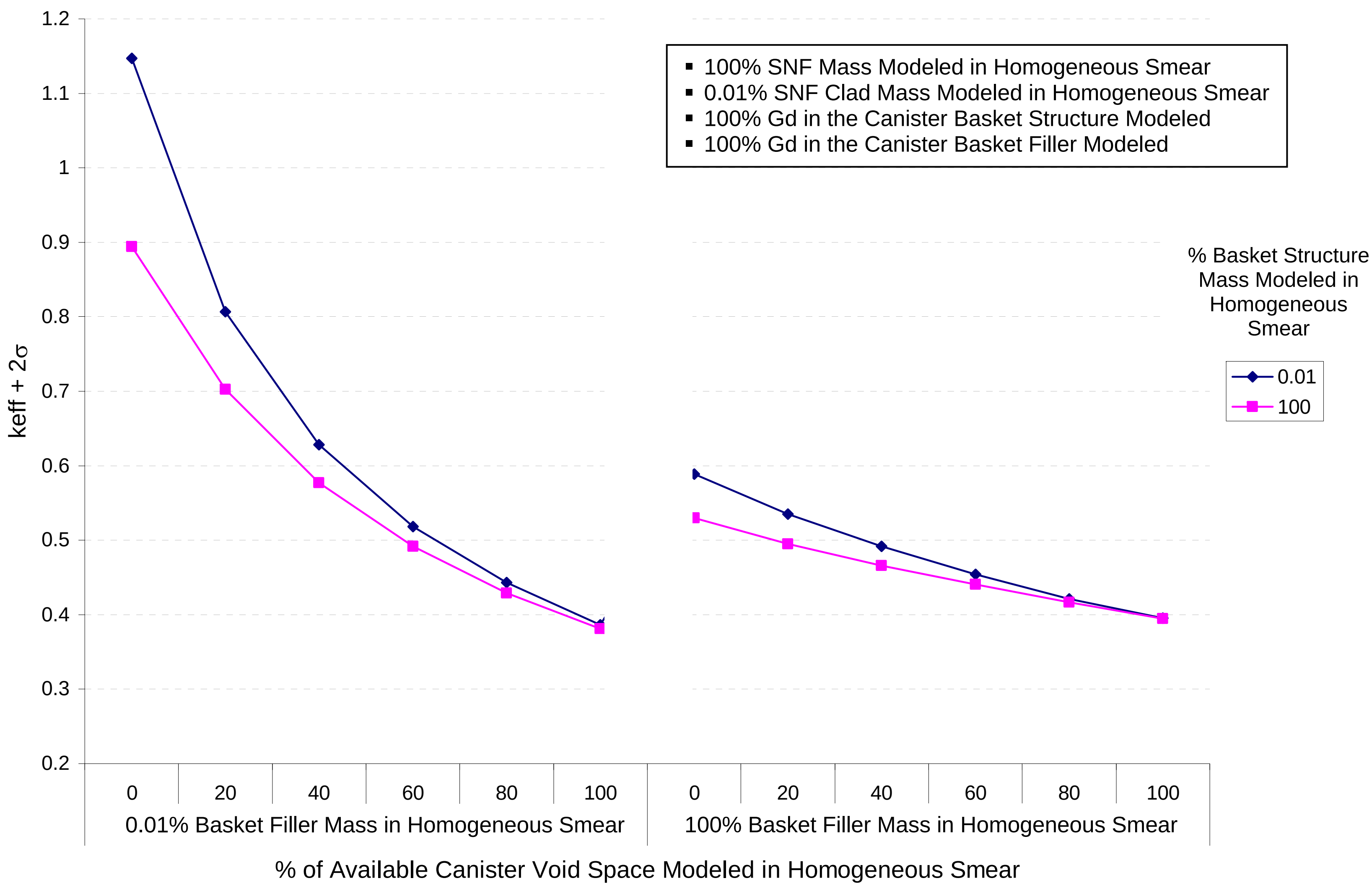

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Figure 7-31: keff+2σ values (as a function of void space, basket filler mass, and basket structure mass modeled) for an individual dry damaged, and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection

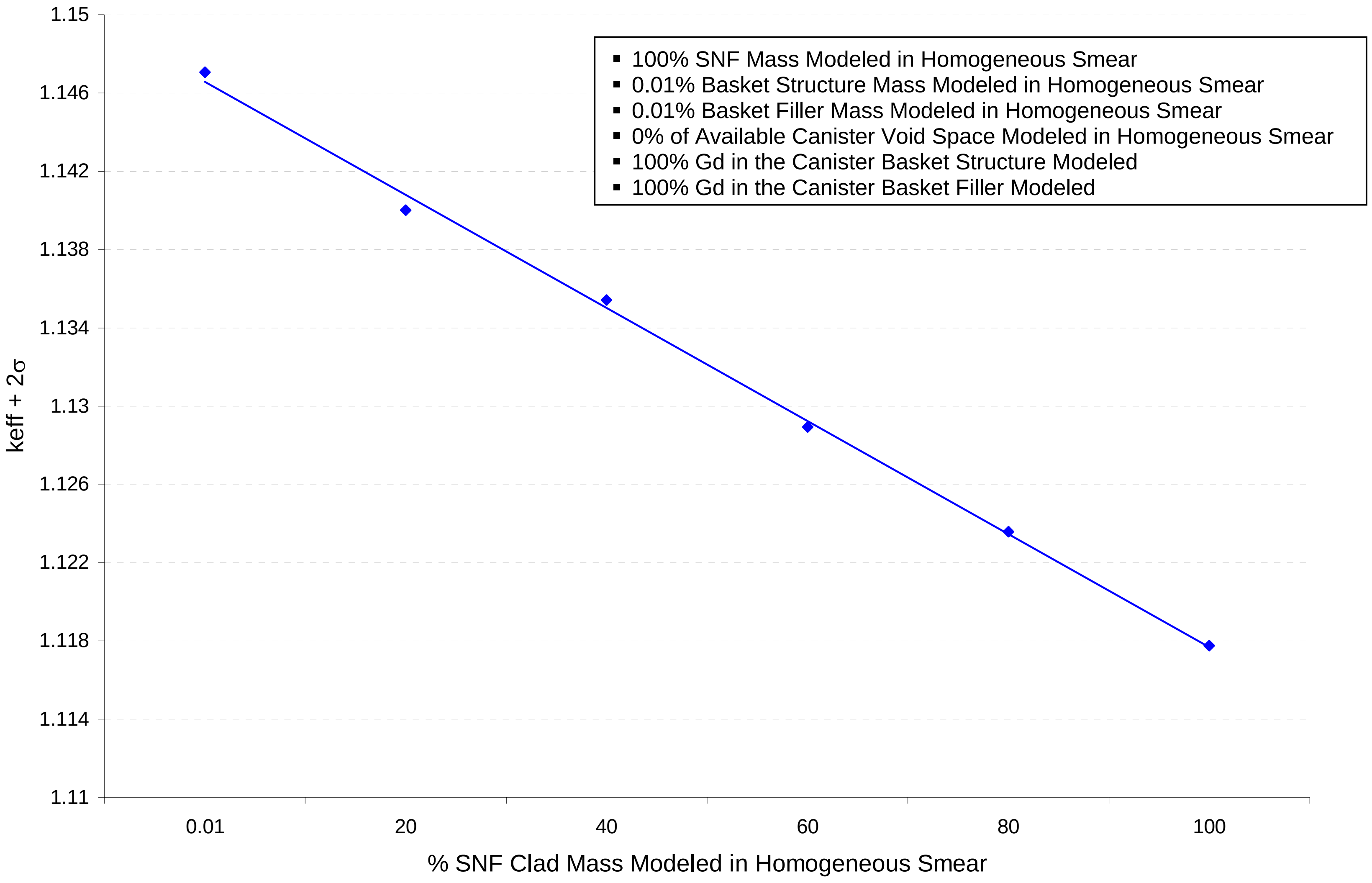

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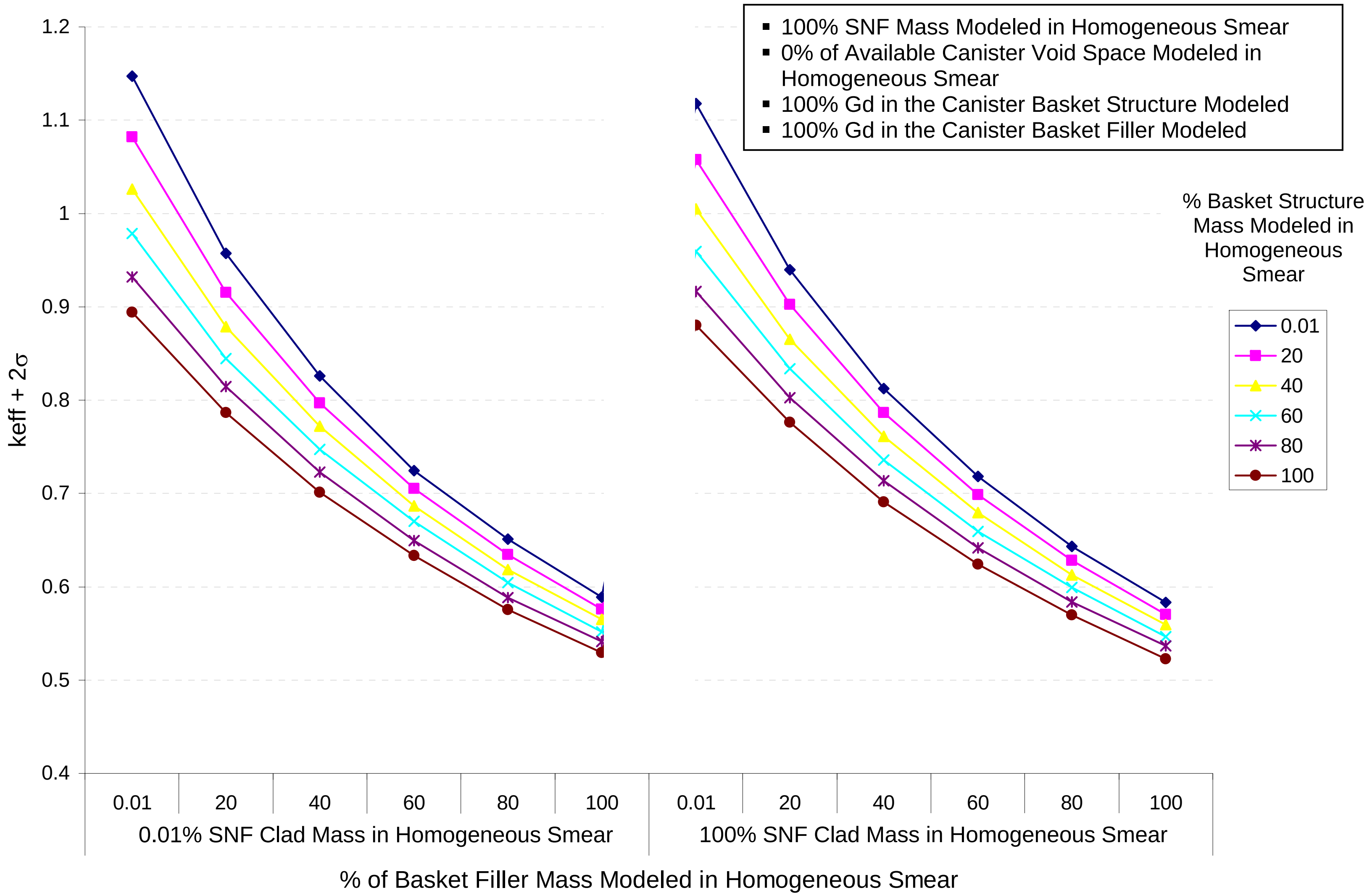
Figure 7-32: keff+2σ values (as a function of SNF clad mass modeled) for an individual dry damaged, and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection



Source: Original

Figure 7-33: keff+2σ values (as a function of basket filler mass, SNF clad mass, and basket structure mass modeled) for an individual dry damaged, and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection

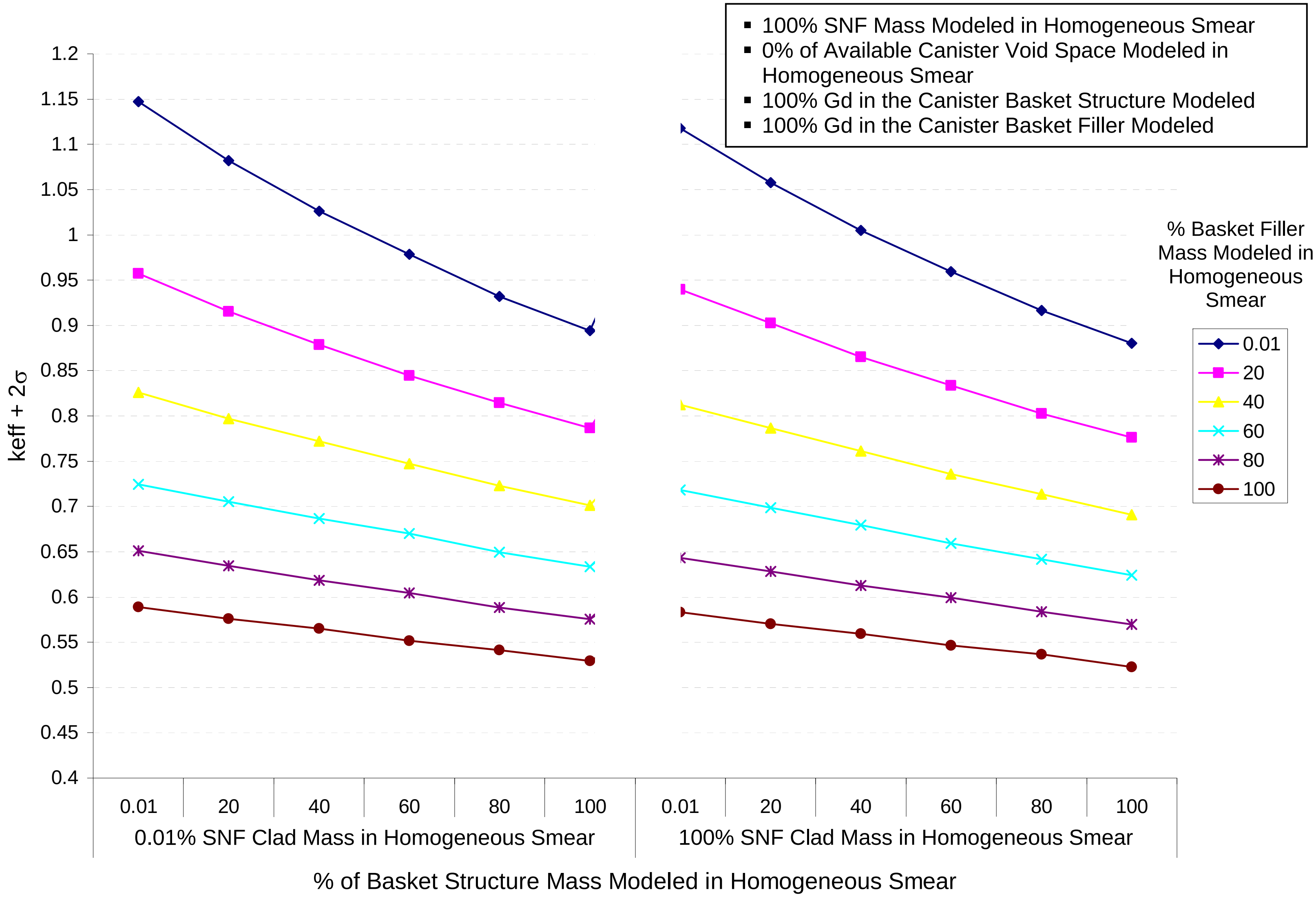


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Figure 7-34: keff+2σ values (as a function of basket structure mass, SNF clad mass, and basket filler mass modeled) for an individual dry damaged, and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection

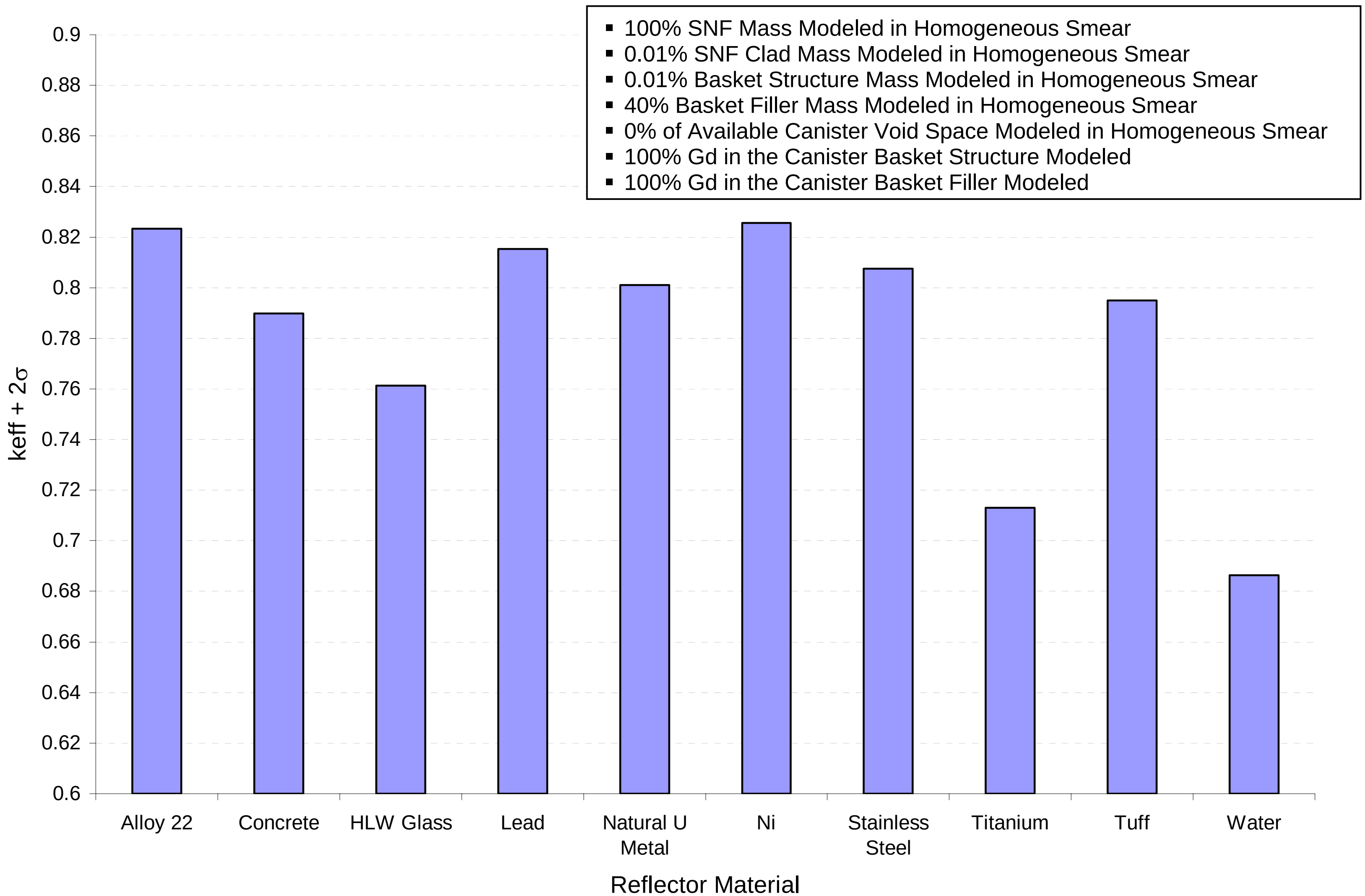

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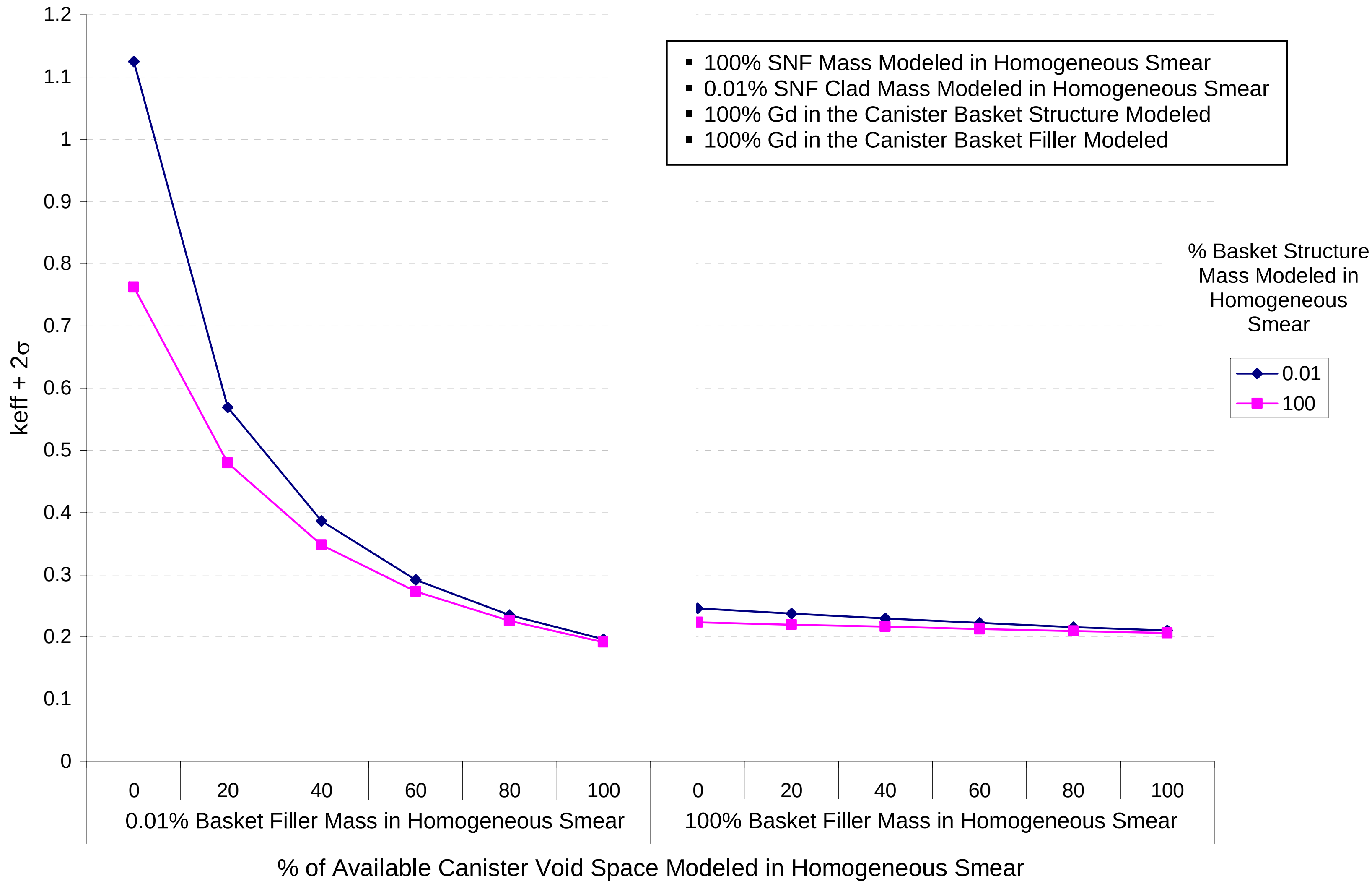
Figure 7-35: keff+2σ values for an individual dry damaged, and degraded, EF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-36: keff+2σ values (as a function of void space, basket filler mass, and basket structure mass modeled) for an individual dry damaged, and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection

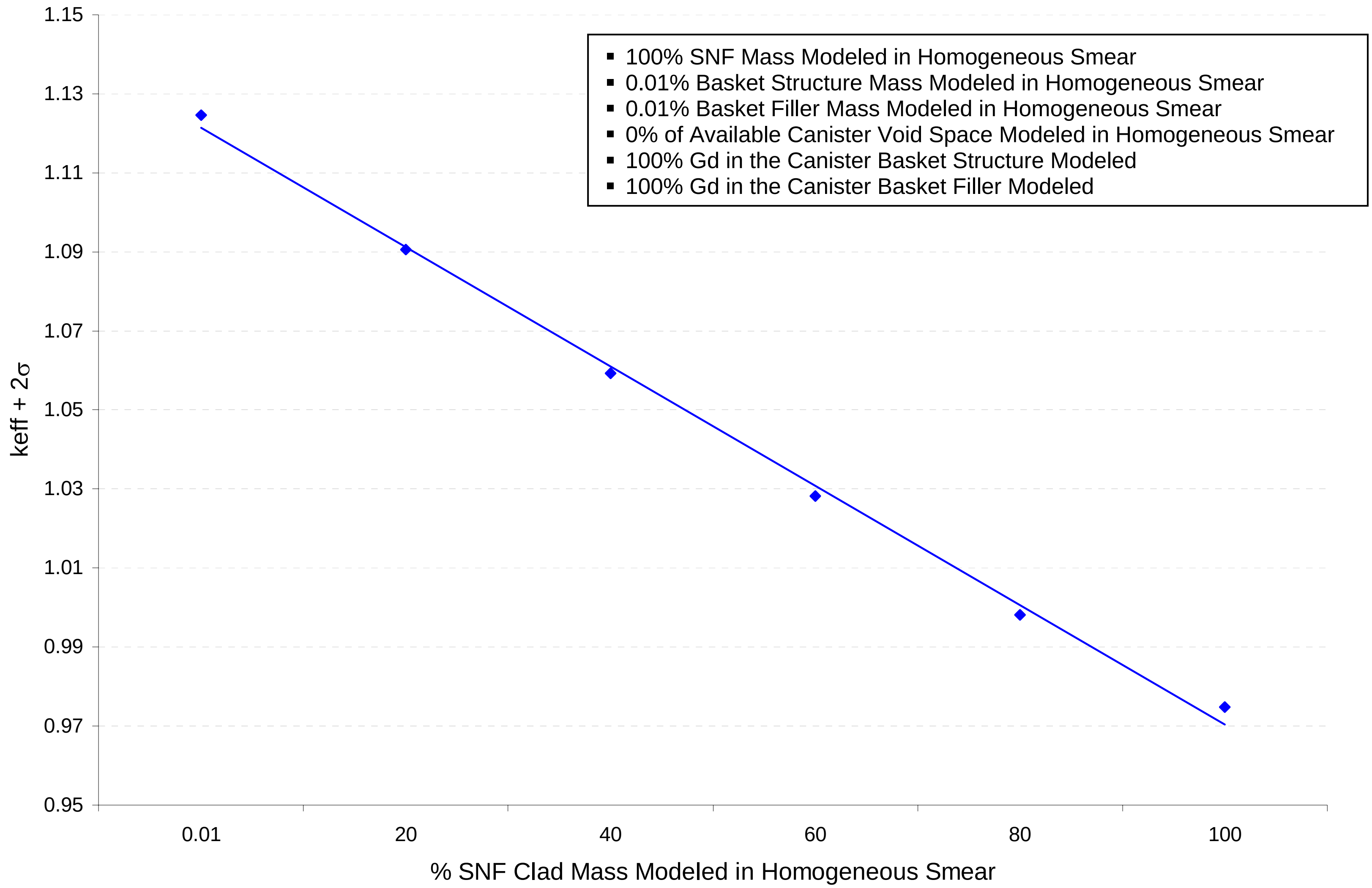


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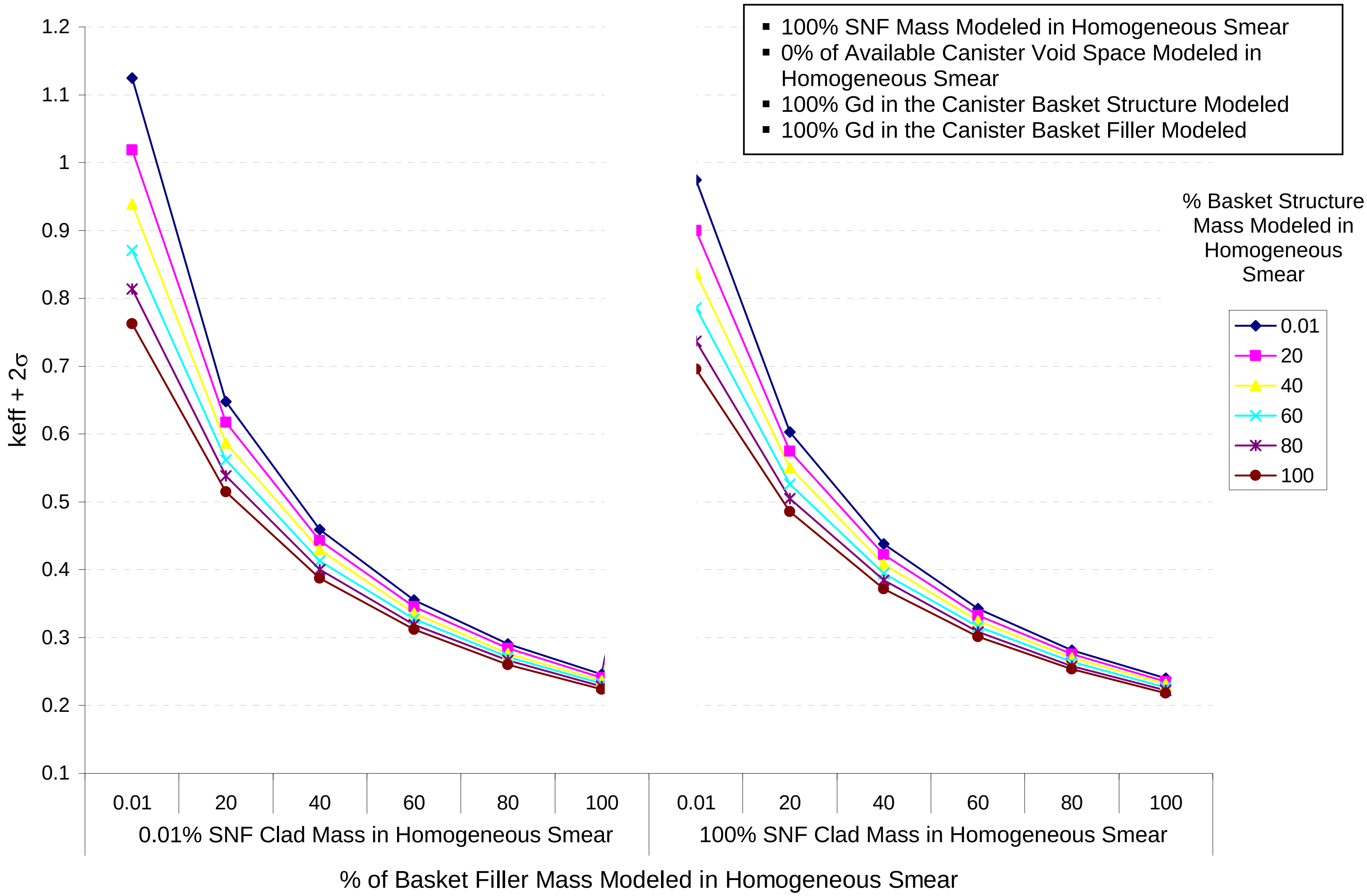
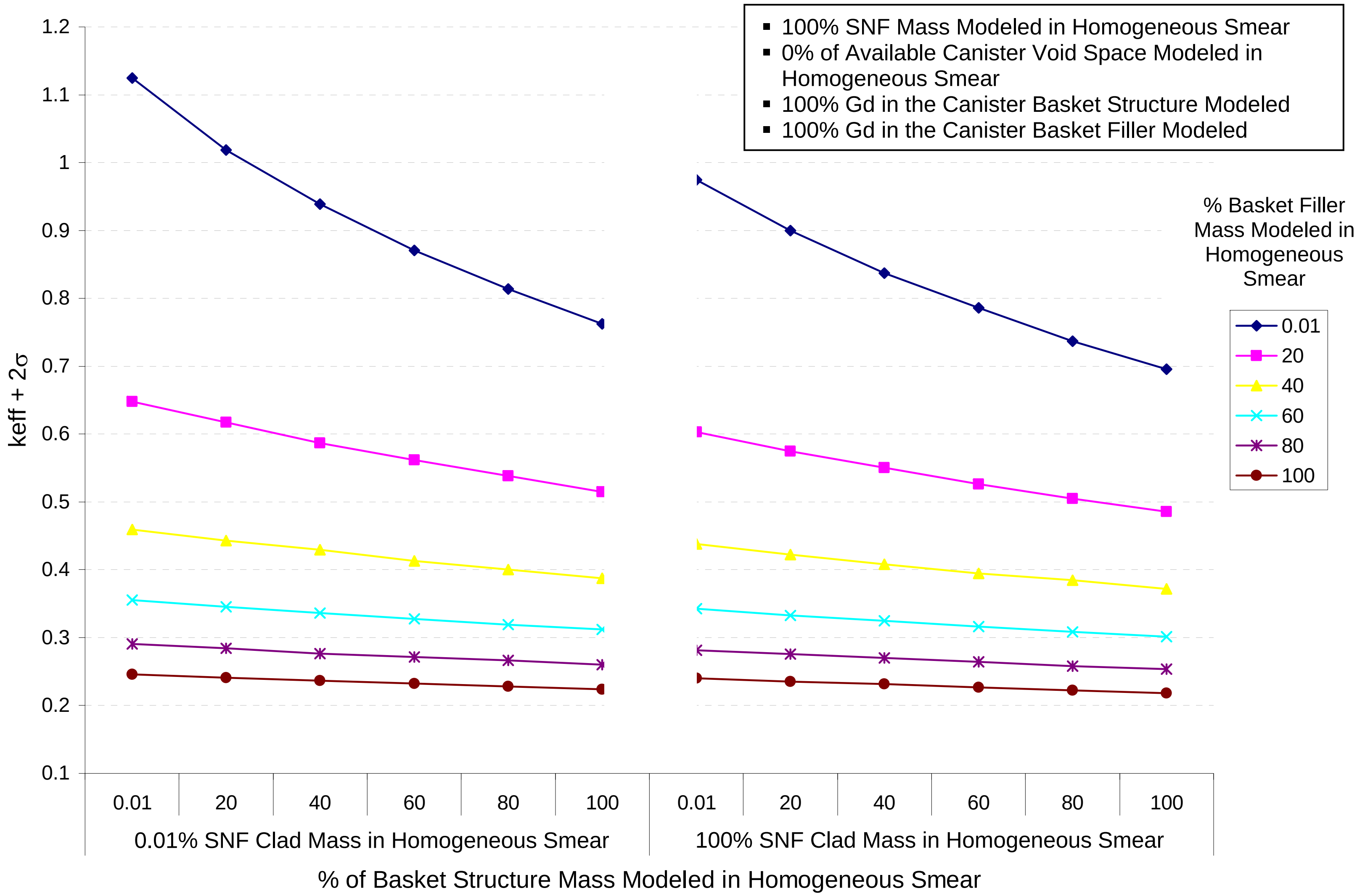
Figure 7-37: keff+2σ values (as a function of SNF clad mass modeled) for an individual dry damaged, and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection



Source: Original

Figure 7-38: keff+2σ values (as a function of basket filler mass, SNF clad mass, and basket structure mass modeled) for an individual dry damaged, and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection



Source: Original

Figure 7-39: keff+2σ values (as a function of basket structure mass, SNF clad mass, and basket filler mass modeled) for an individual dry damaged, and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness nickel reflection

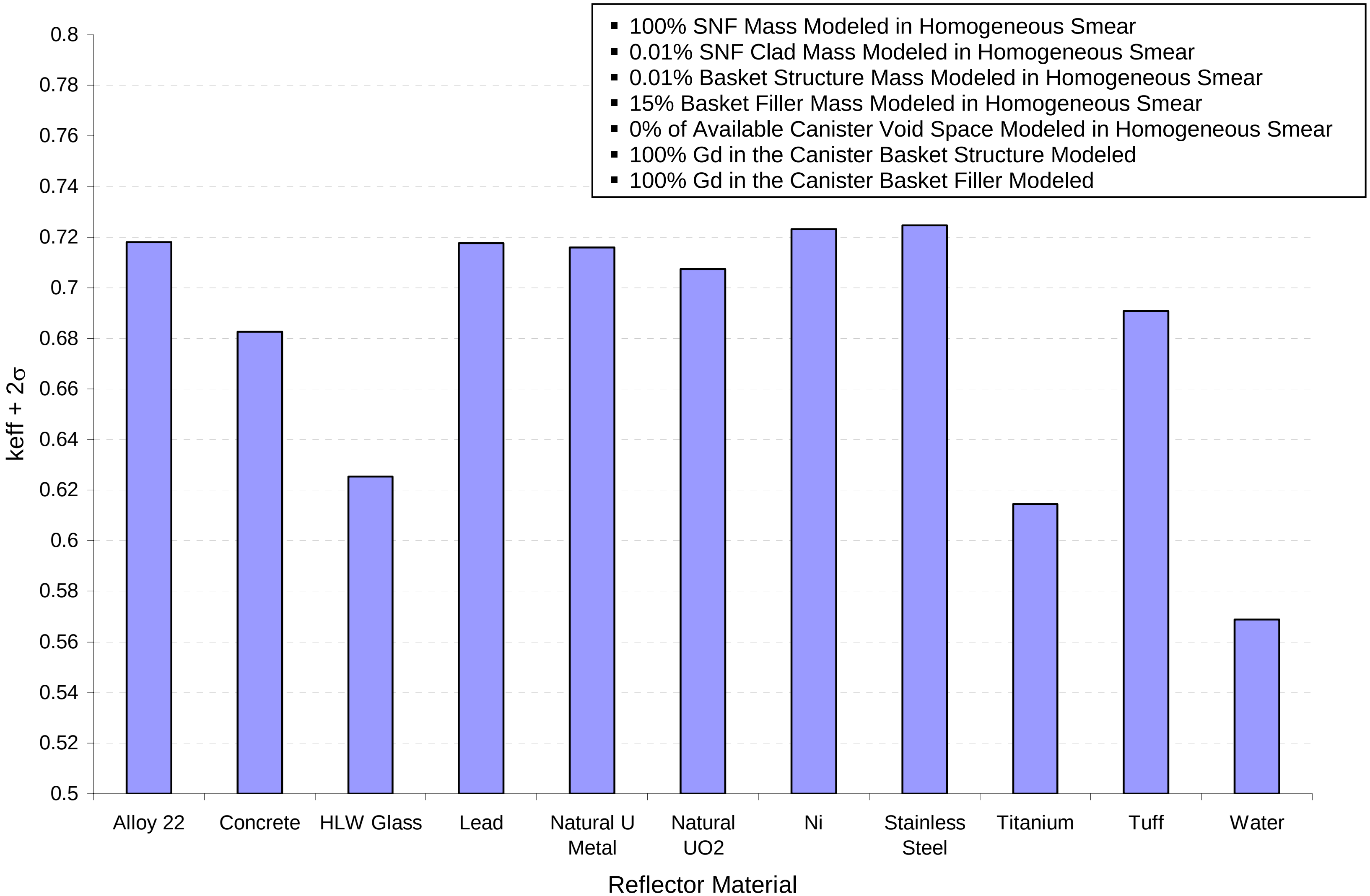


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Figure 7-40: keff+2σ values for an individual dry damaged, and degraded, FFTF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

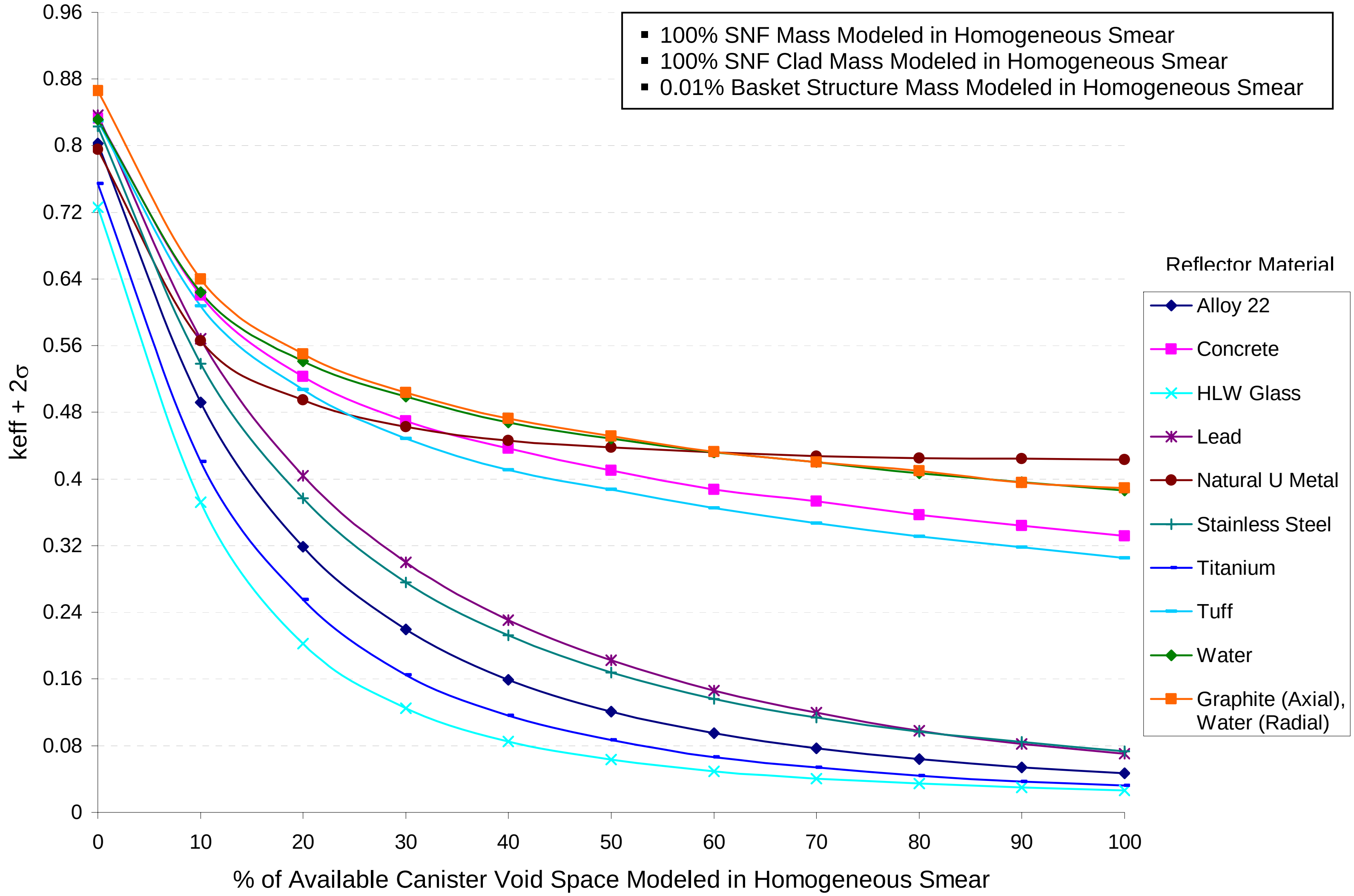

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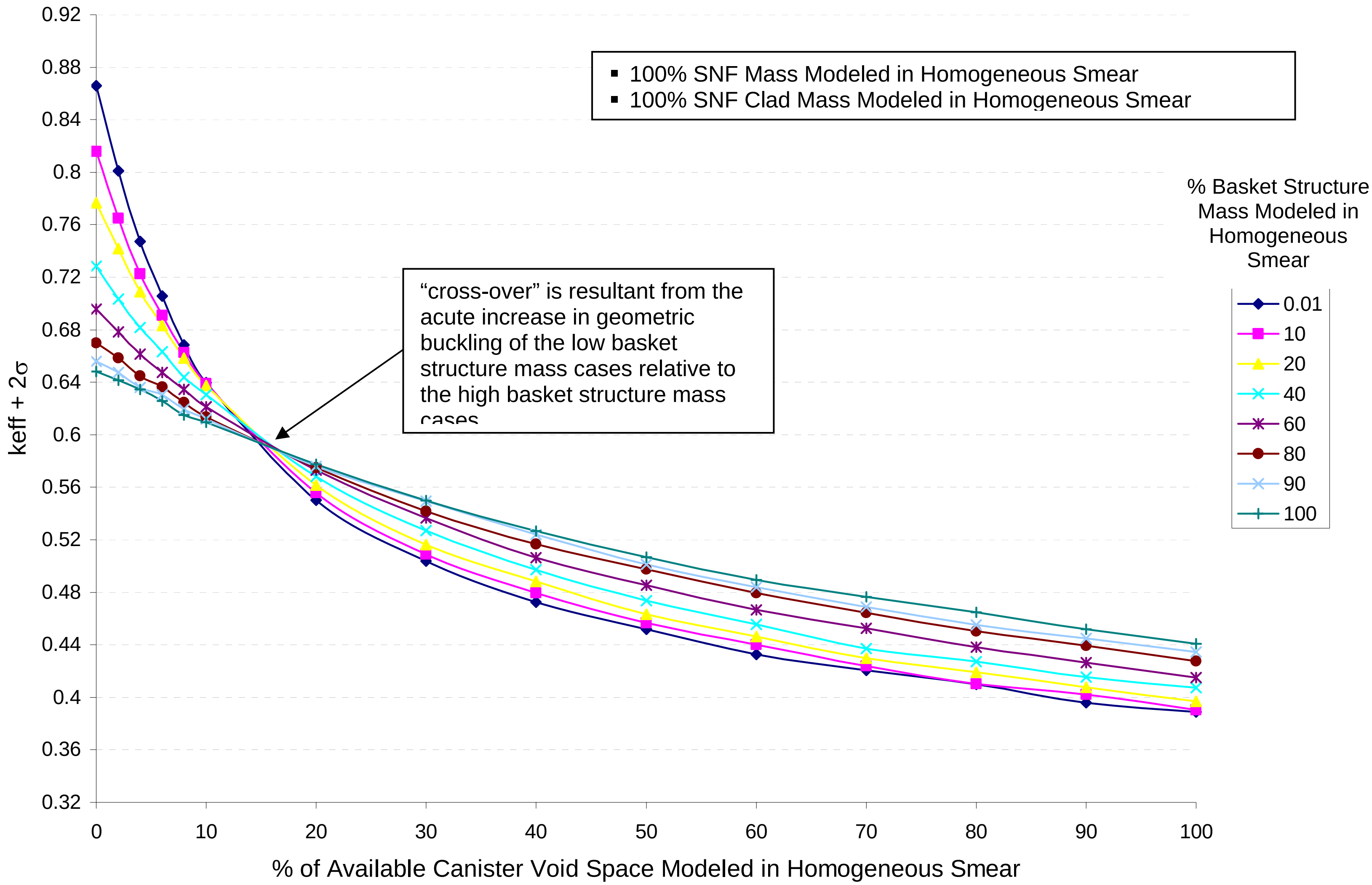
Figure 7-41: keff+2σ values (as a function of void space modeled) for an individual dry damaged, and degraded, FSV DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-42: keff+2σ values (as a function of void space, and basket structure mass modeled) for an individual dry damaged, and degraded, FSV DOE SNF canister with close fitting full (30 cm) thickness graphite reflection (axial) and water reflection (radial)

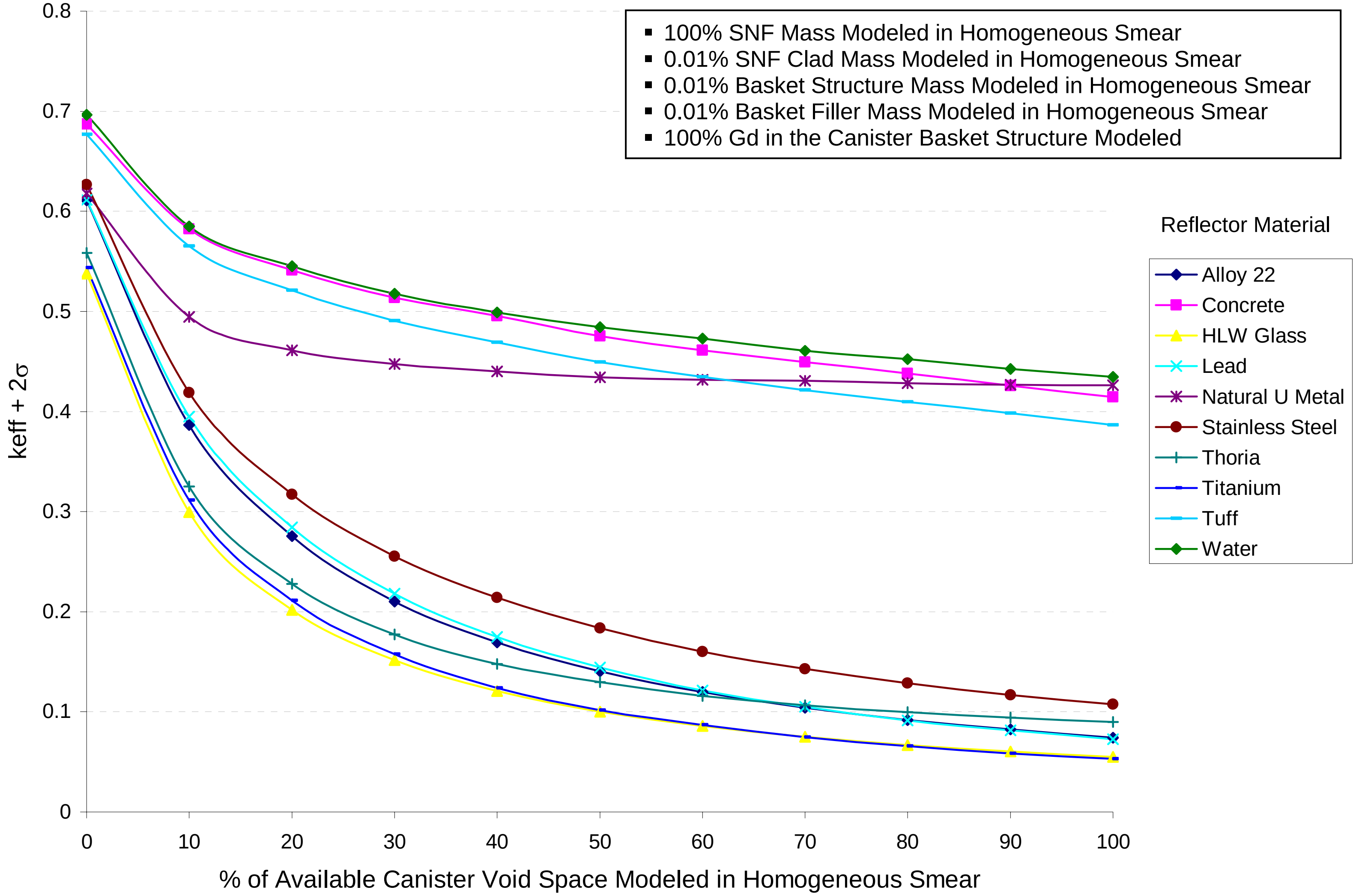


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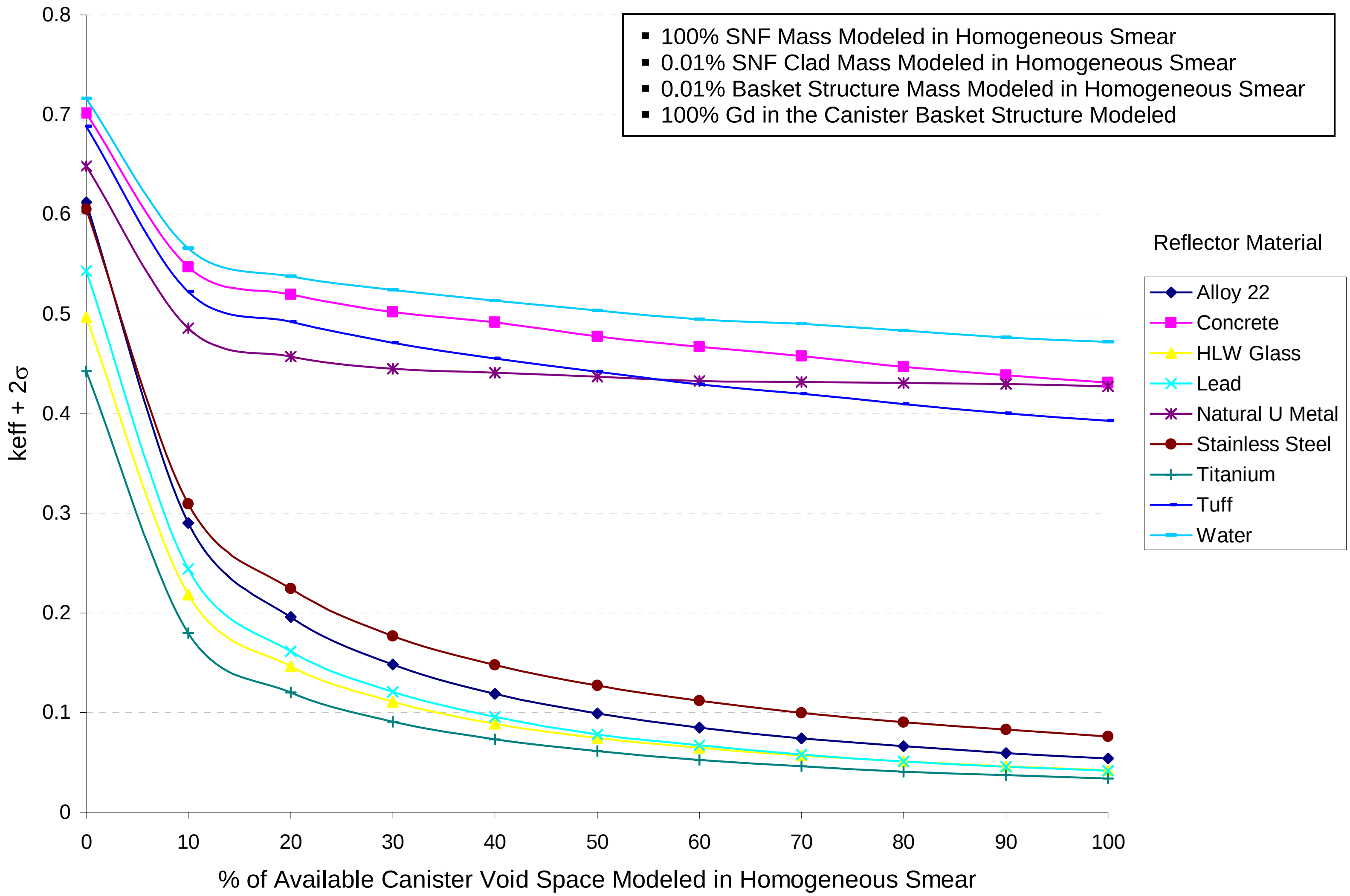
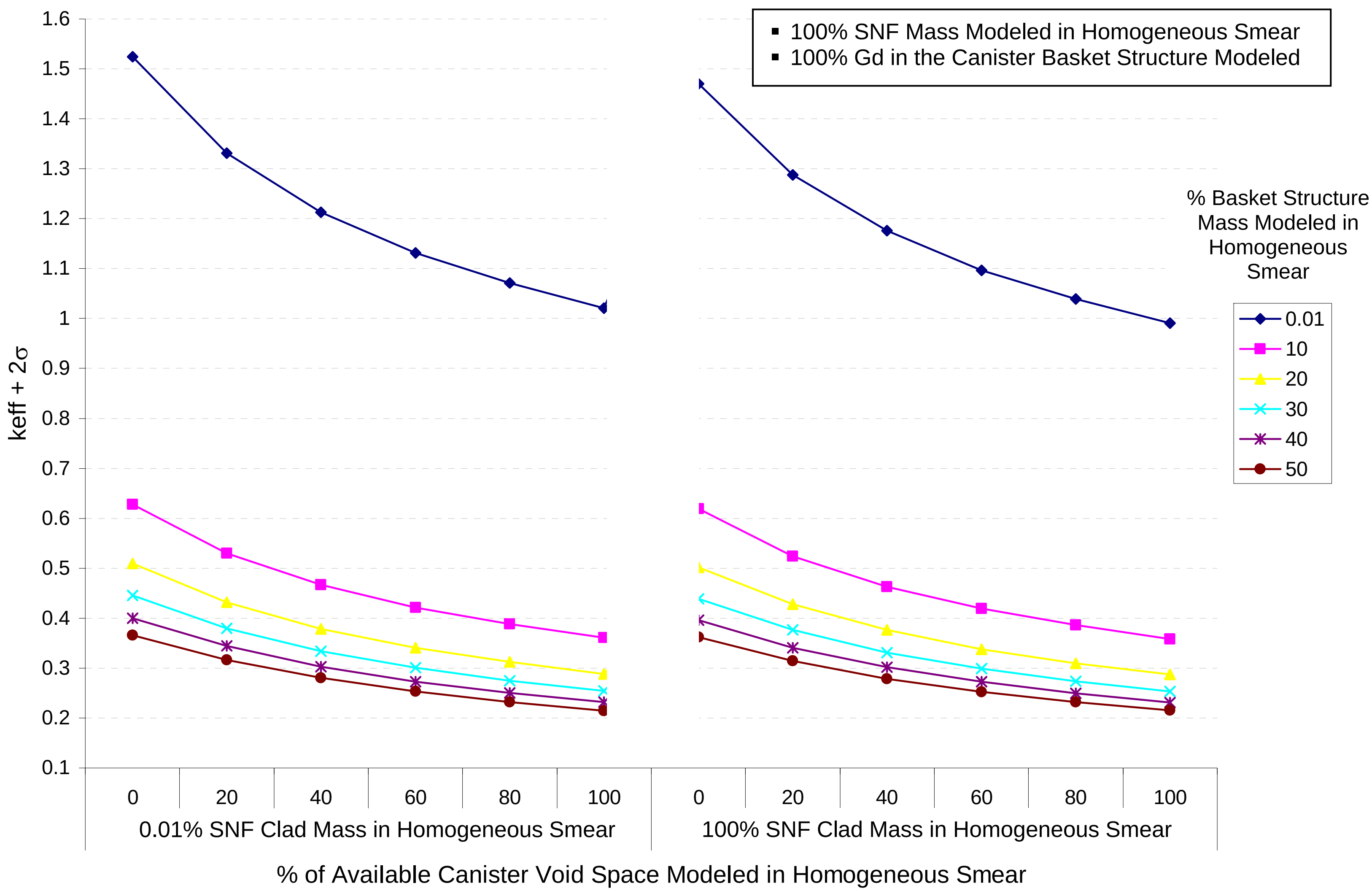
Figure 7-43: keff+2σ values (as a function of void space modeled) for an individual dry damaged, and degraded, SLWBR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



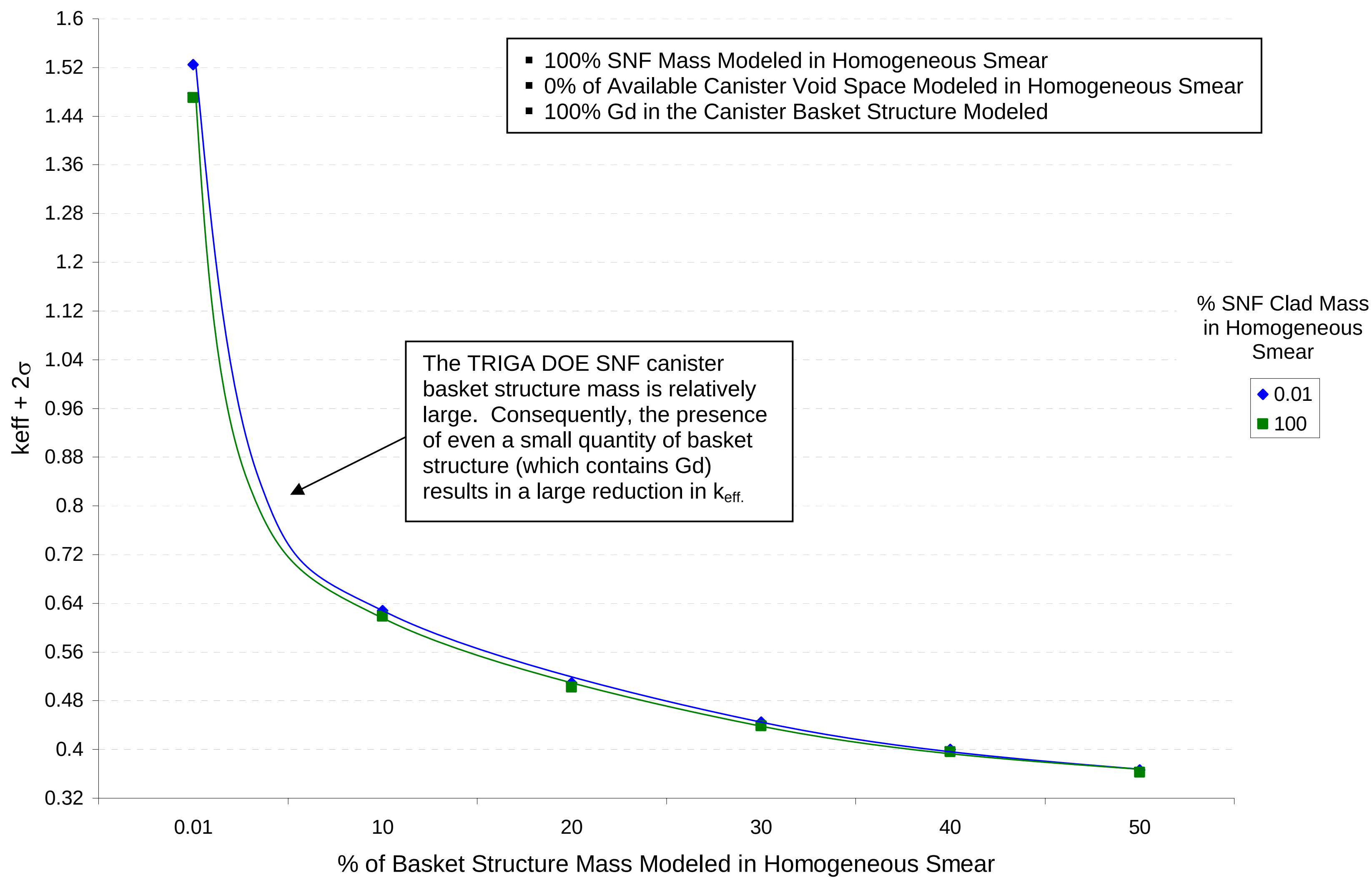
Source: Original

Figure 7-44: keff+2σ values (as a function of void space modeled) for an individual dry damaged, and degraded, SPWR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



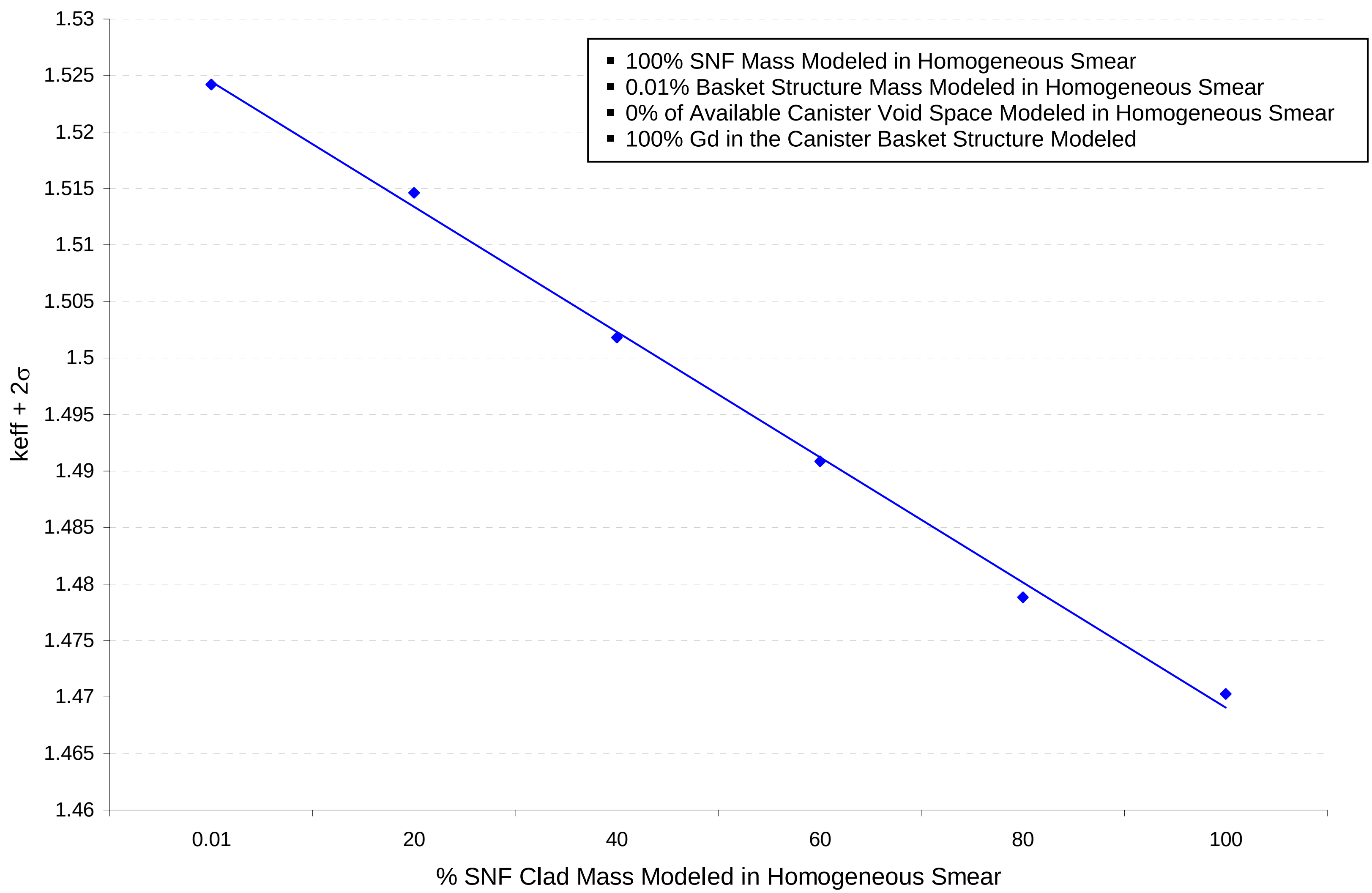
Source: Original

Figure 7-45: keff+2σ values (as a function of void space, SNF clad mass, and basket structure mass modeled) for an individual dry damaged, and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness graphite reflection



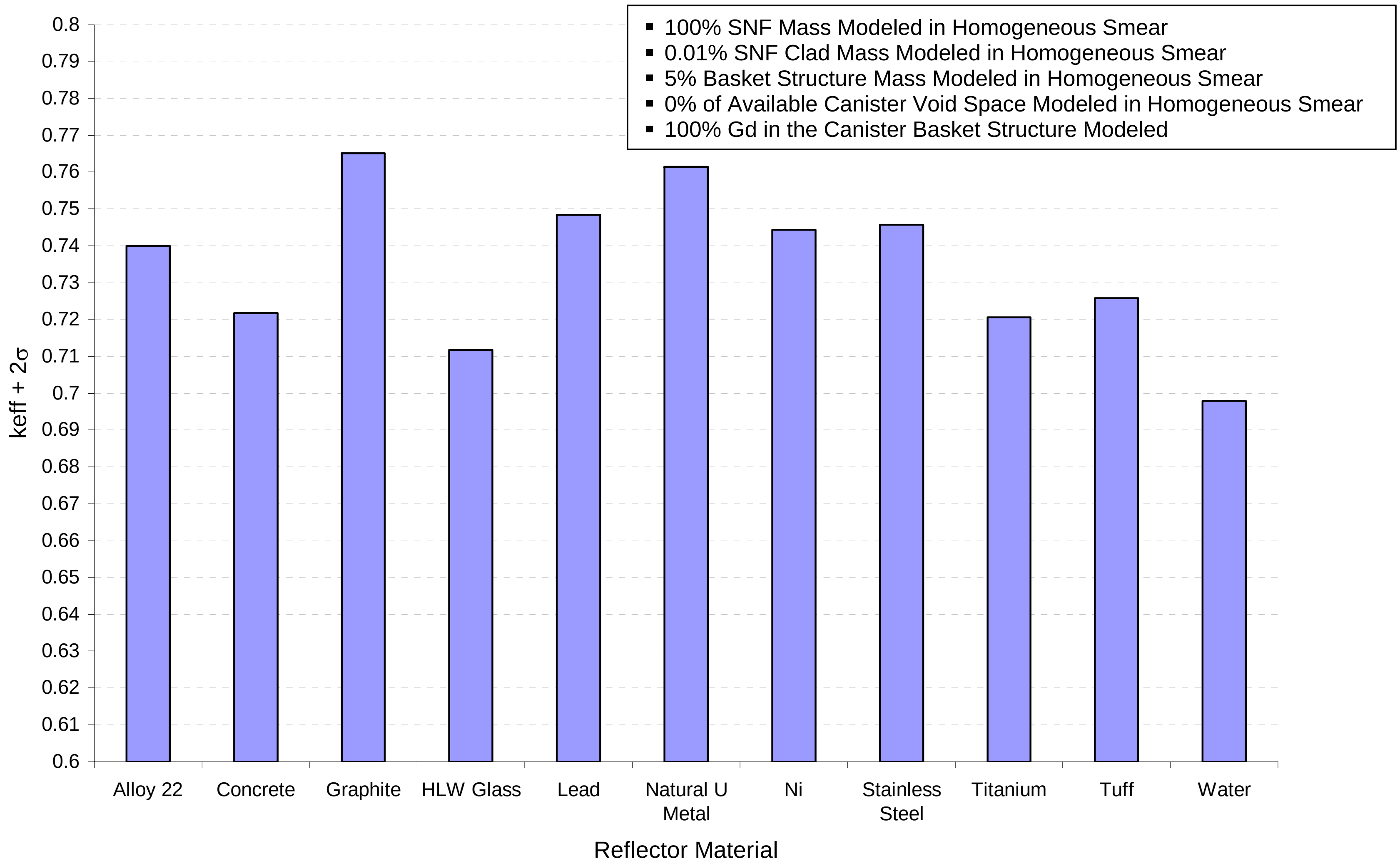
Source: Original

Figure 7-46: keff+2σ values (as a function of basket structure mass, and SNF clad mass modeled) for an individual dry damaged, and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness graphite reflection



Source: Original

Figure 7-47: keff+2σ values (as a function of SNF clad mass modeled) for an individual dry damaged, and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness graphite reflection



Source: Original

Figure 7-48: keff+2σ values for an individual dry damaged, and degraded, TRIGA DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

7.1.2.1.1.3 Single Canister Damage with Breach

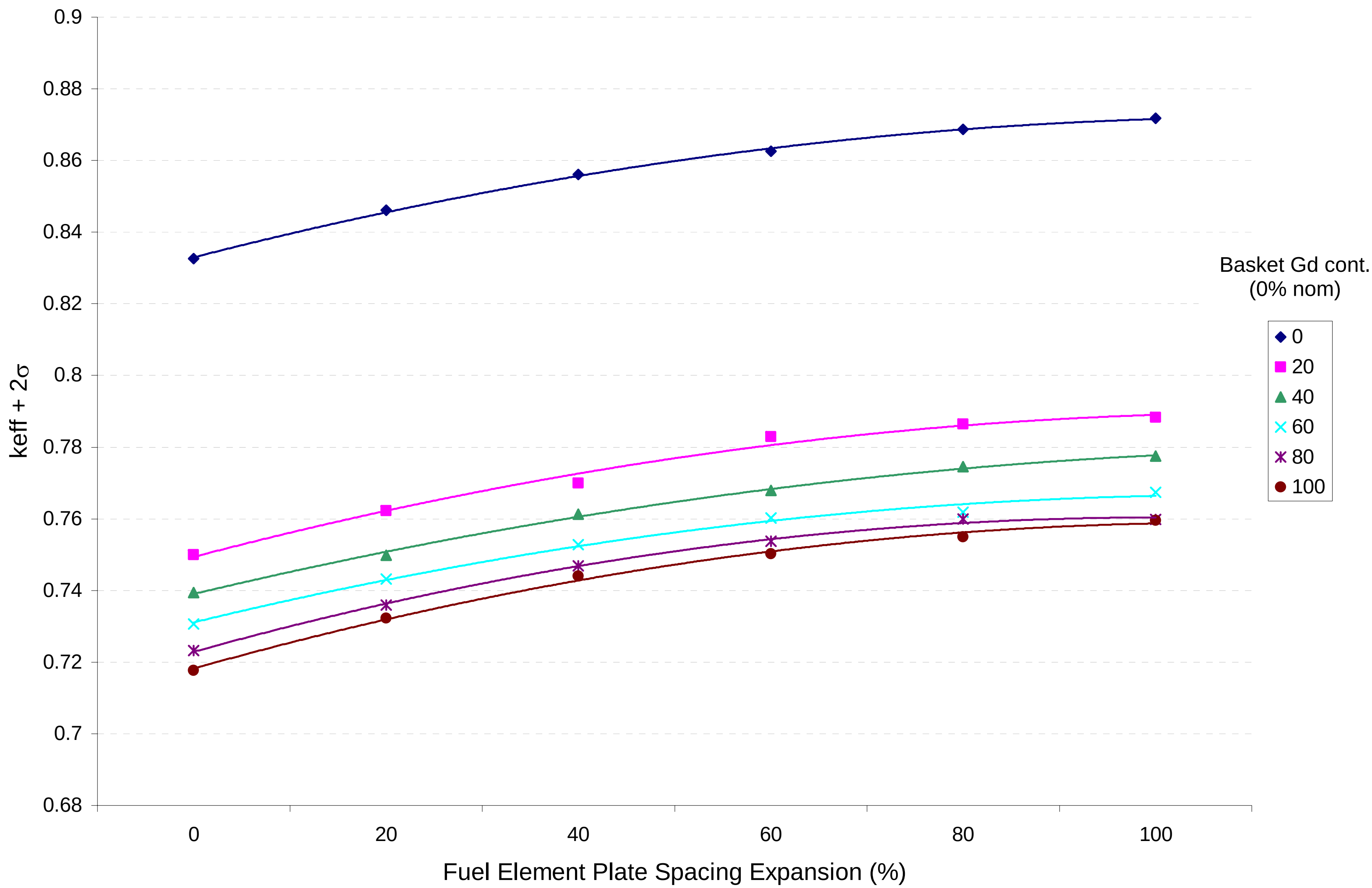
This section presents the MCNP k_{eff} results for off-normal conditions consisting of damage to an individual DOE SNF canister, also resulting in actual breach of the canister shell, coincident with entrainment of liquid moderator. Based on this scenario, two basic configurations are examined:

1. Damage to an individual DOE SNF canister resulting in a rearrangement of its internal structure (e.g. repositioning of SNF and basket structure), but not resulting in a physical release of material (i.e. production of debris). This configuration is referred to as a *flooded damaged intact* configuration.
2. Damage to an individual DOE SNF canister resulting in complete or partial release of its internal structure as debris (i.e. SNF, basket structure and basket filler material). This configuration is referred to as a *flooded damaged degraded* configuration.

For intact off-normal condition calculations, the neutron absorber content of the basket structure (if any) and the basket filler material (if any) is varied to establish the sensitivity of the system to reduction of neutron absorber content.

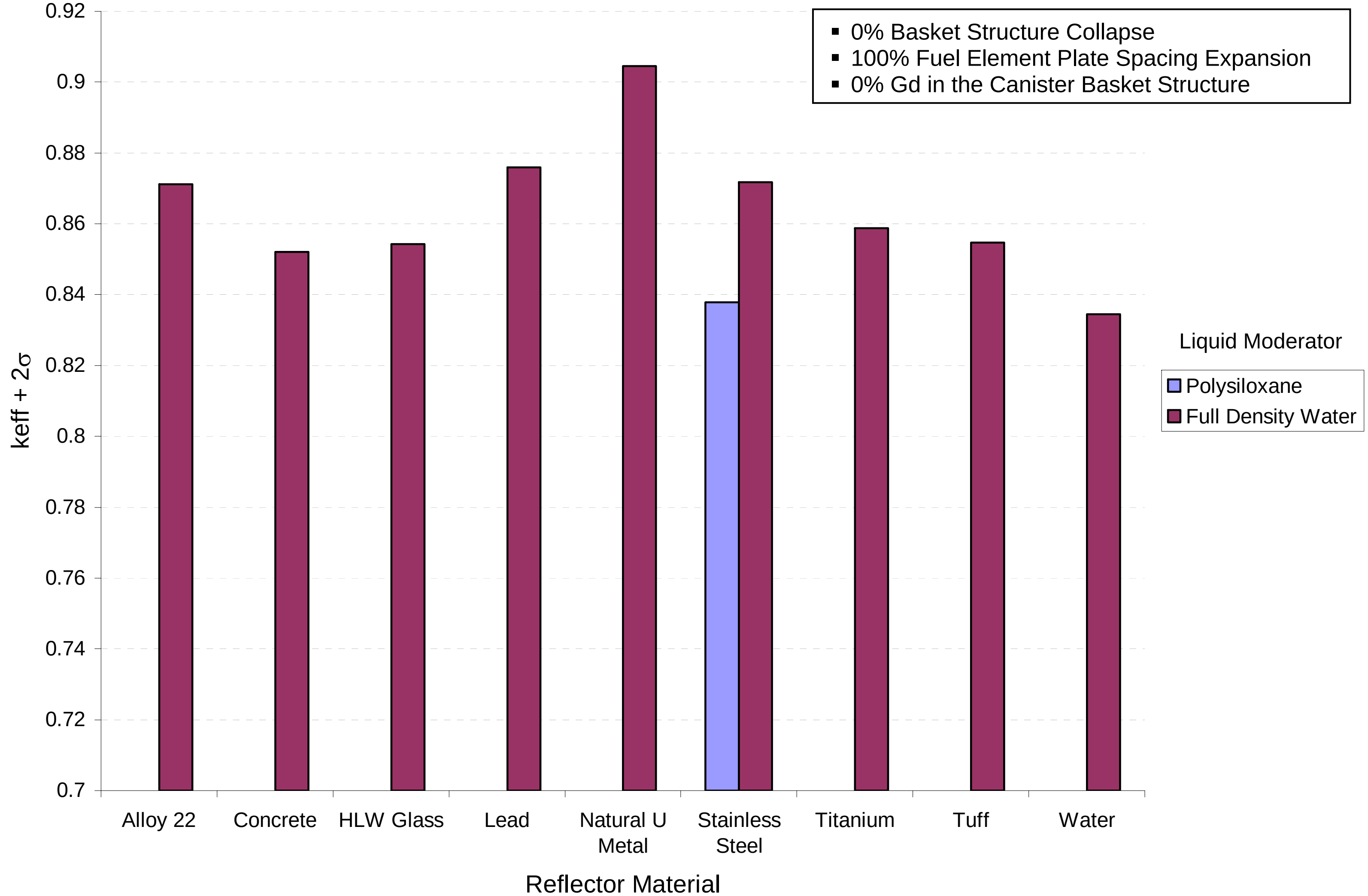
The results of the *flooded damaged intact* DOE SNF canister calculations are presented in Figure 7-49 through Figure 7-62, which are categorized according to waste form. The liquid moderator modeled in the calculations is full density water, however, an isolated case (based on maximum damage, no neutron absorber) is considered with polysiloxane fluid; a common silicone-based hydraulic fluid (refer to Assumption 3.2.3 for details). The explicit damage configurations (i.e. positioning of SNF, basket structure, etc.) correlate to the configurations explained in detail in Section 6.2.2.1.3.1. The degree of damage is expressed as a percentage of the maximum potential damage for which k_{eff} is expected to be maximized. Refer to Section 6.2.2.1.3.1 and Figure 6-94 through Figure 6-111 (MCNP model cross-section views) for further details.

The results of the *flooded damaged degraded* DOE SNF canister calculations are presented in Figure 7-63 through Figure 7-125, which are also categorized according to waste form. The liquid moderator modeled in the calculations is full density water. The explicit damage configurations (i.e. positioning of SNF, basket structure, etc.) correlate to the configurations explained in detail in Section 6.2.2.1.3.2. The degree of degradation (i.e. the quantity of SNF, clad, basket and basket filler material that is considered released) is expressed as a percentage of the total inventory for the respective canister. For example, canister debris with a basket filler content of 40% means that 40% of the total mass of basket filler material associated with the respective canister is modeled in the canister debris. Refer to Section 6.2.2.1.3.2 and Figure 6-93 for further details.



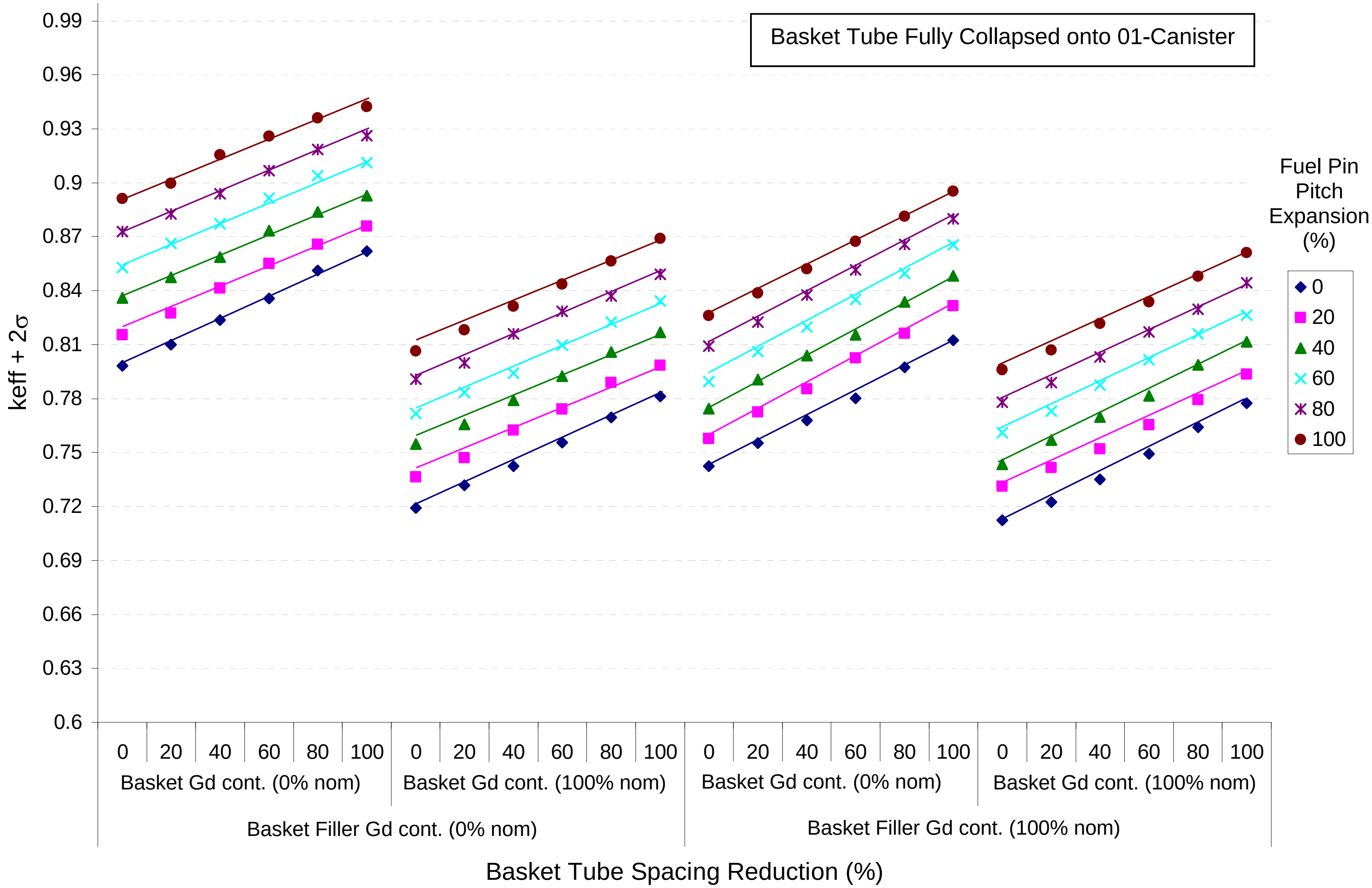
Source: Original

Figure 7-49: keff+2σ values (as a function of fuel element plate spacing expansion, and basket structure Gd content) for an individual fully water flooded and damaged, but intact, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-50: keff+2σ values for an individual fully flooded and damaged, but intact, ATR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



Source: Original

Figure 7-51: keff+2σ values (as a function of basket tube spacing reduction, basket filler and structure Gd content, and fuel pin pitch expansion) for an individual fully water flooded and damaged, but intact, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

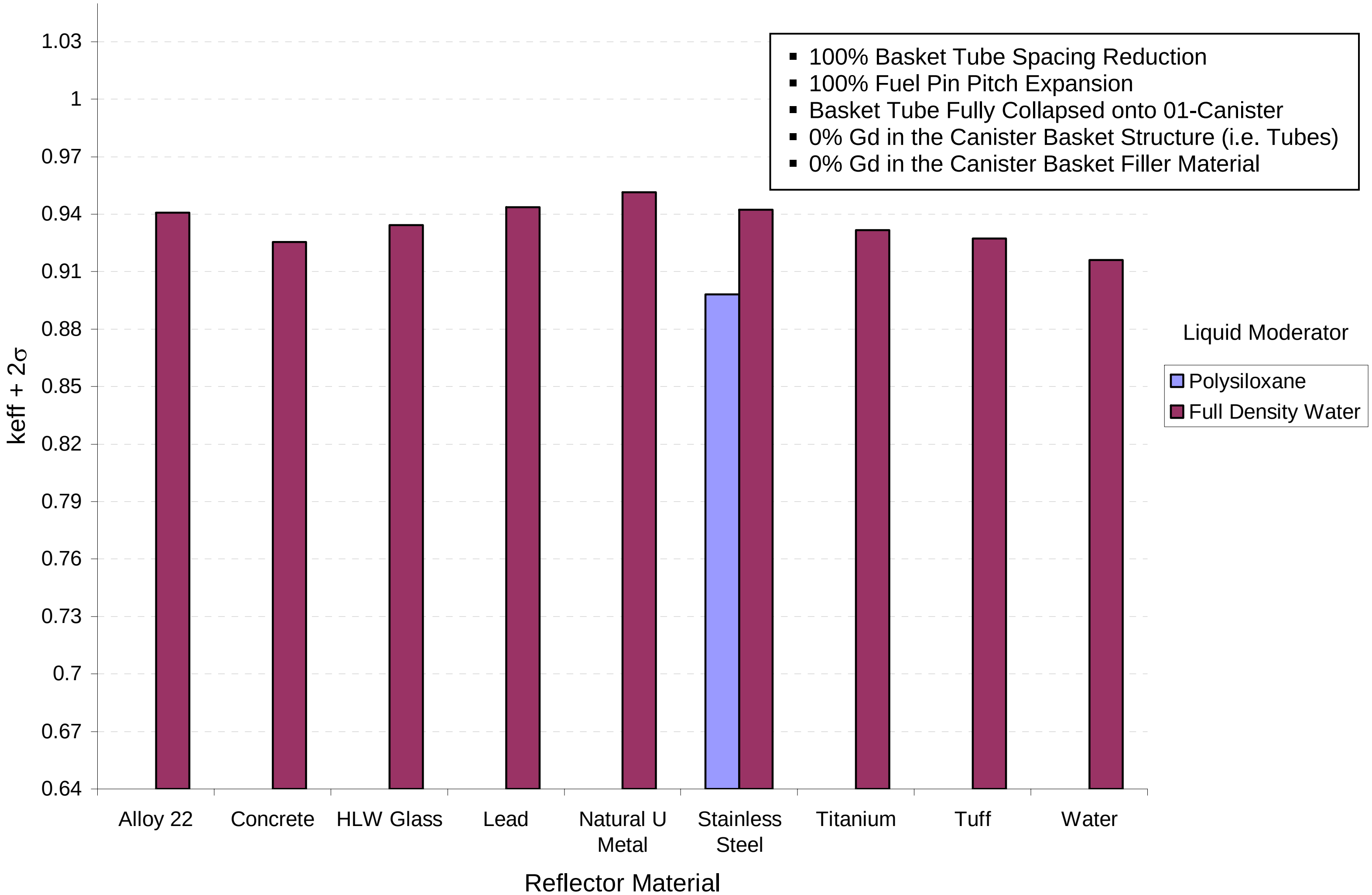


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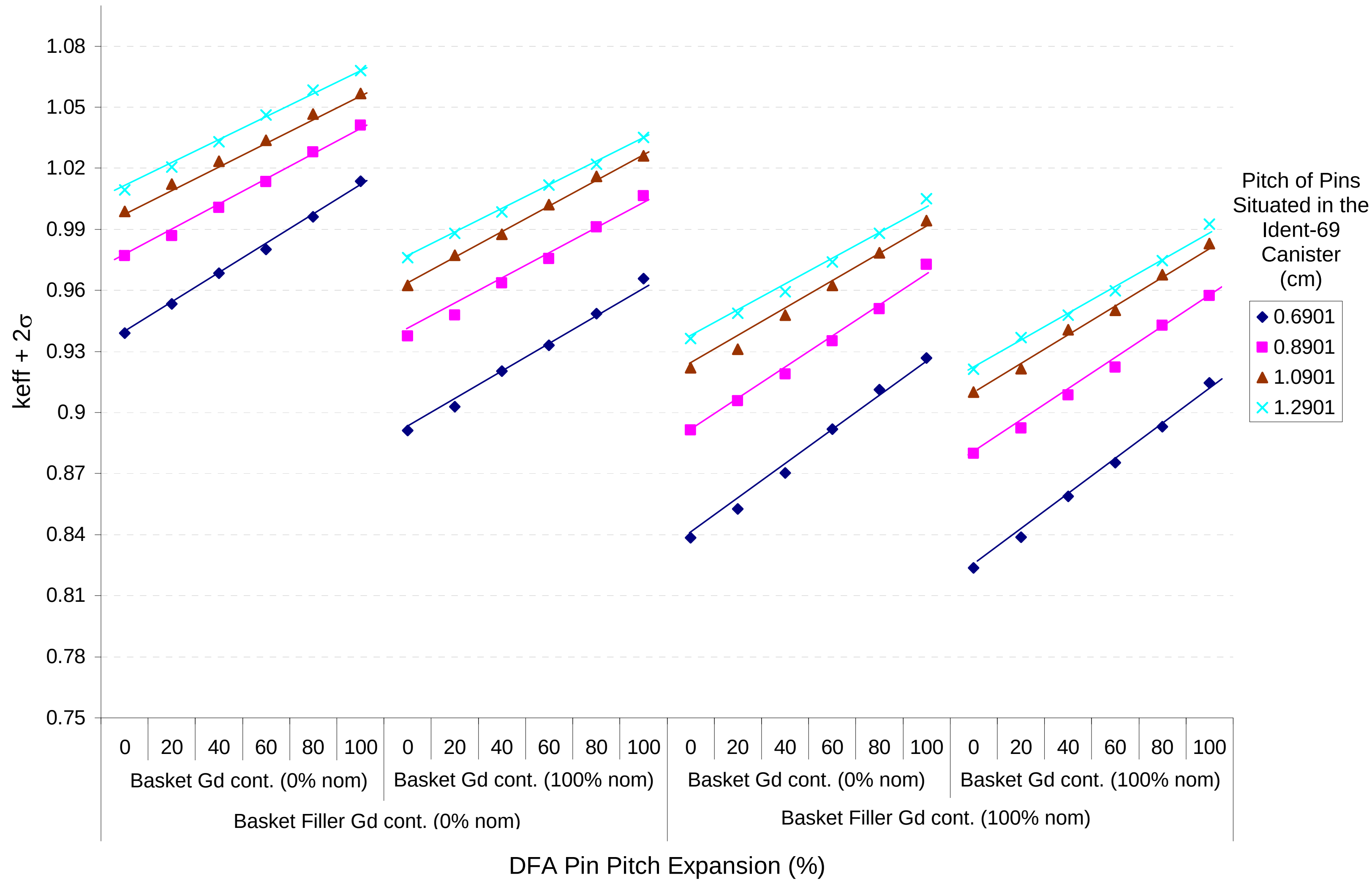
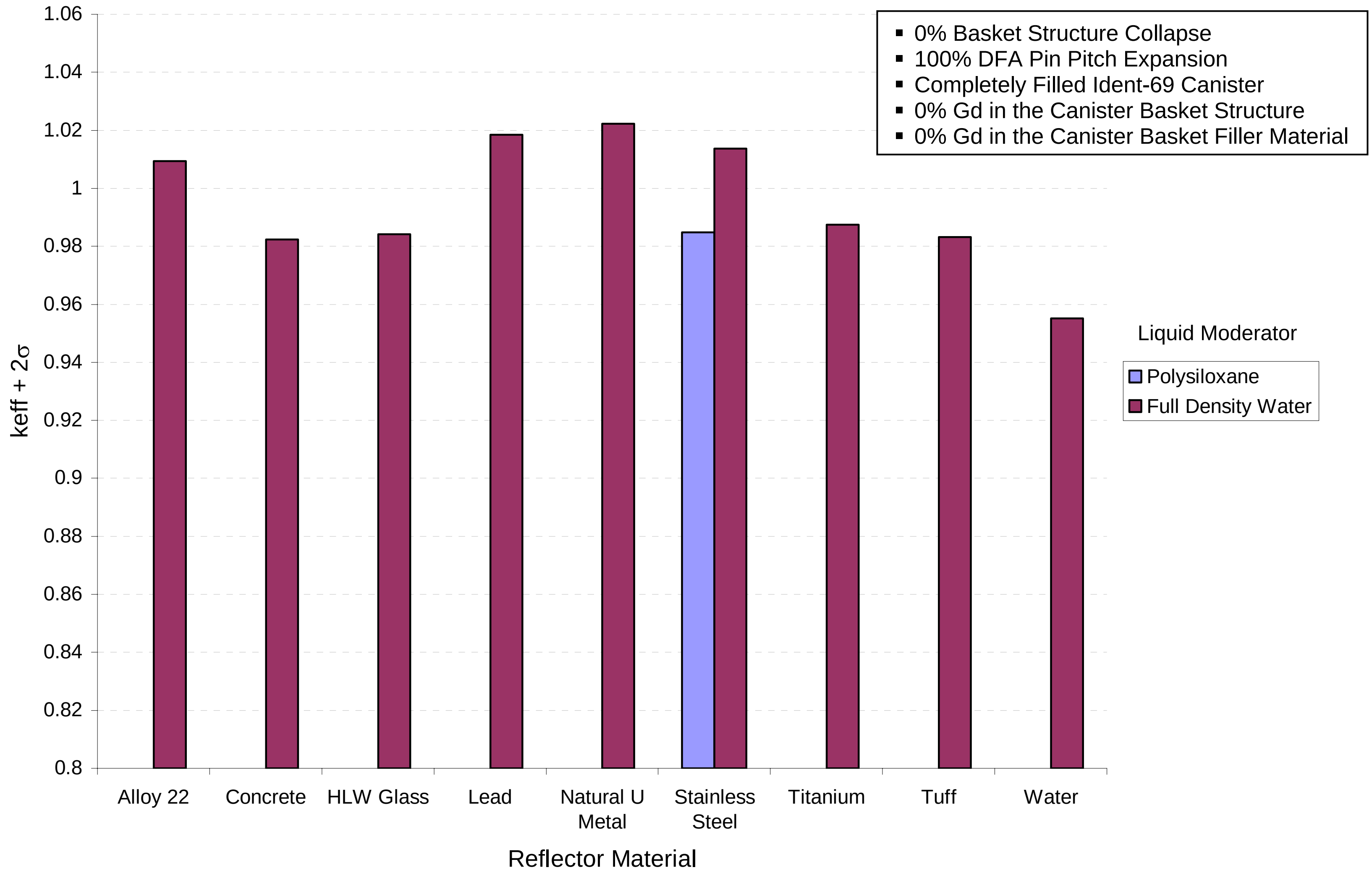
Figure 7-52: keff+2σ values for an individual fully flooded and damaged, but intact, EF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



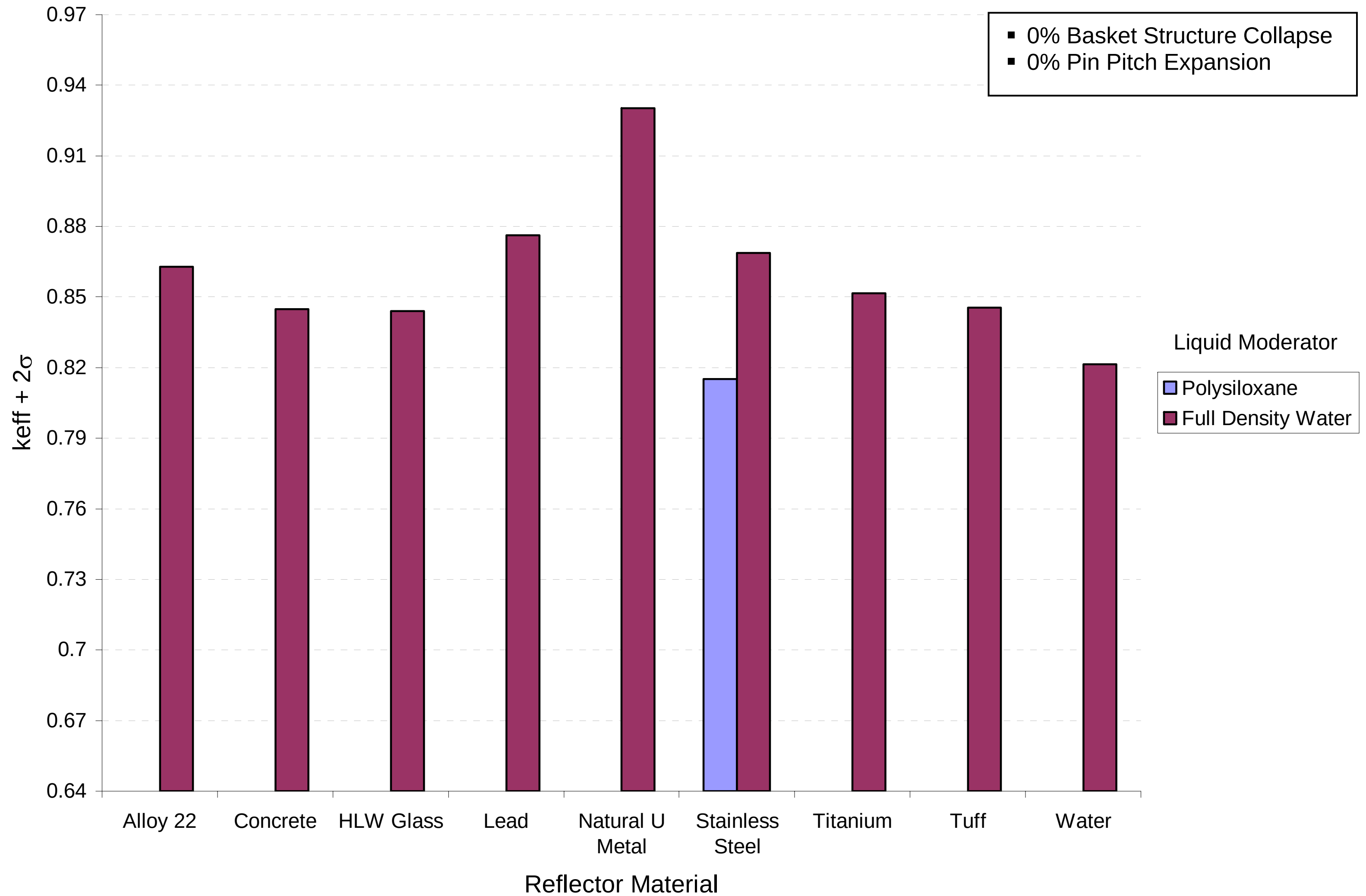
Source: Original

Figure 7-53: keff+2σ values (as a function of DFA pin pitch expansion, basket filler and structure Gd content, and Ident-69 pin pitch) for an individual fully water flooded and damaged, but intact, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



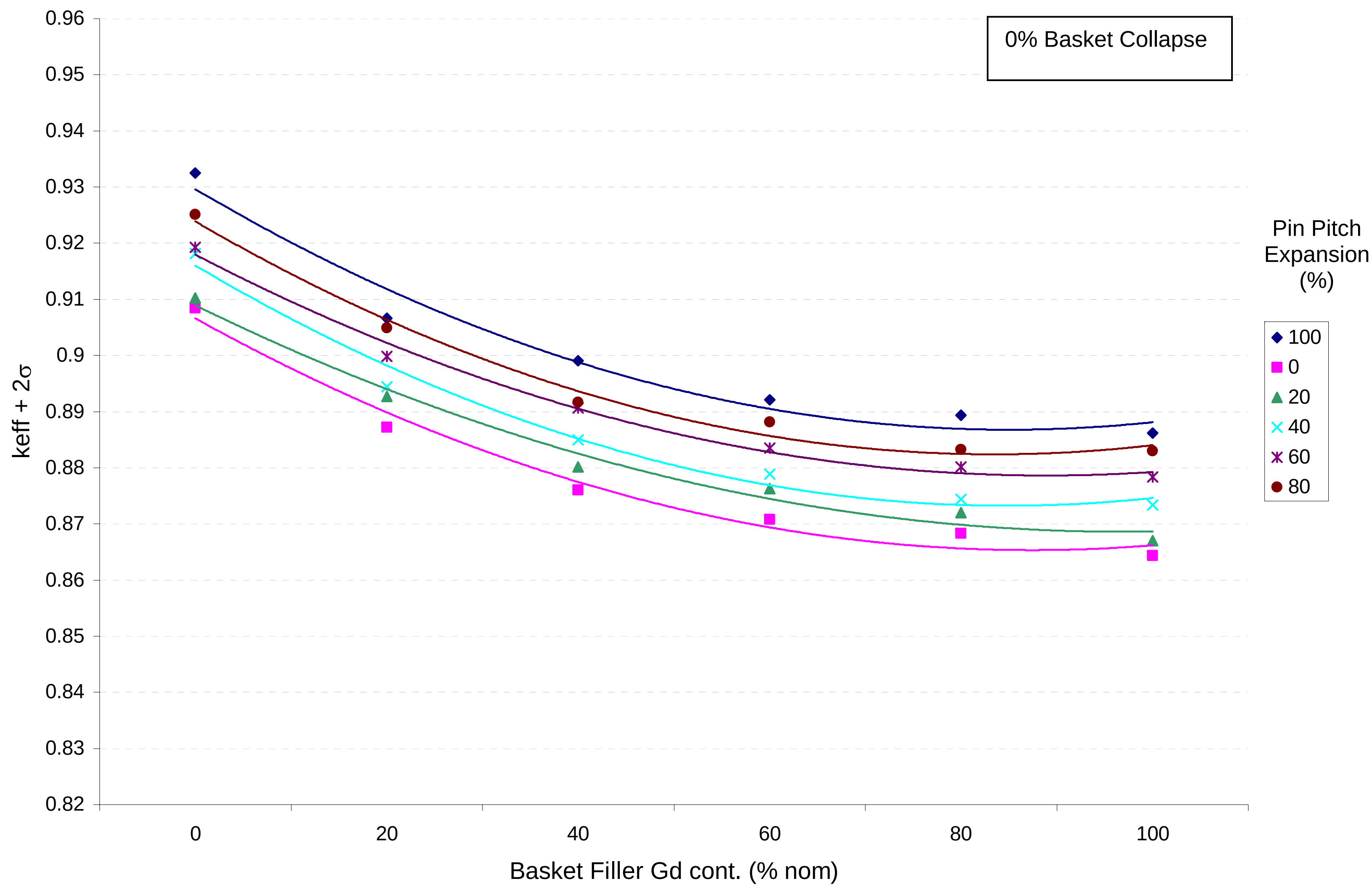
Source: Original

Figure 7-54: keff+2σ values for an individual fully flooded and damaged, but intact, FFTF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



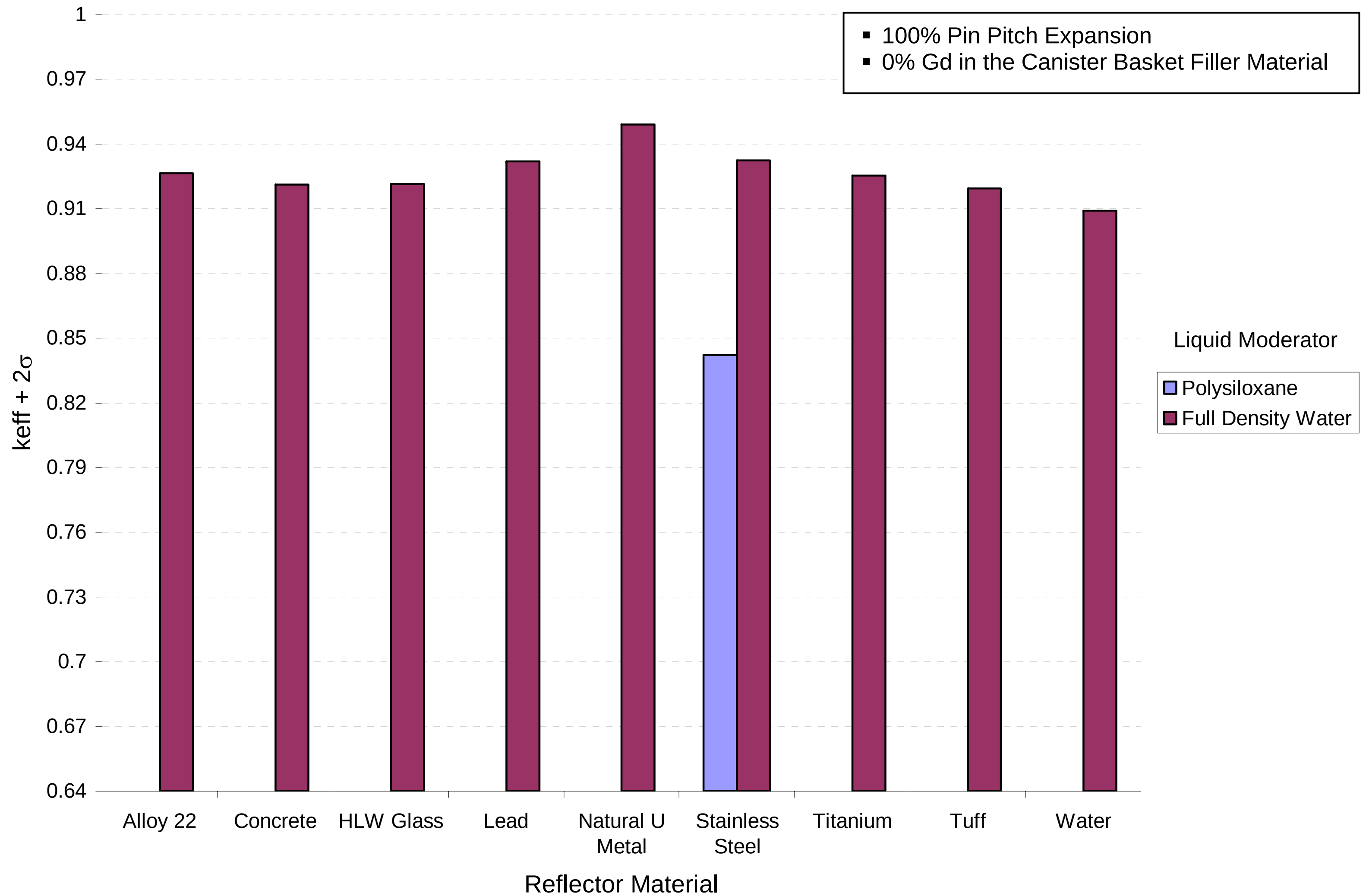
Source: Original

Figure 7-55: keff+2σ values for an individual fully flooded undamaged and intact FSV DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



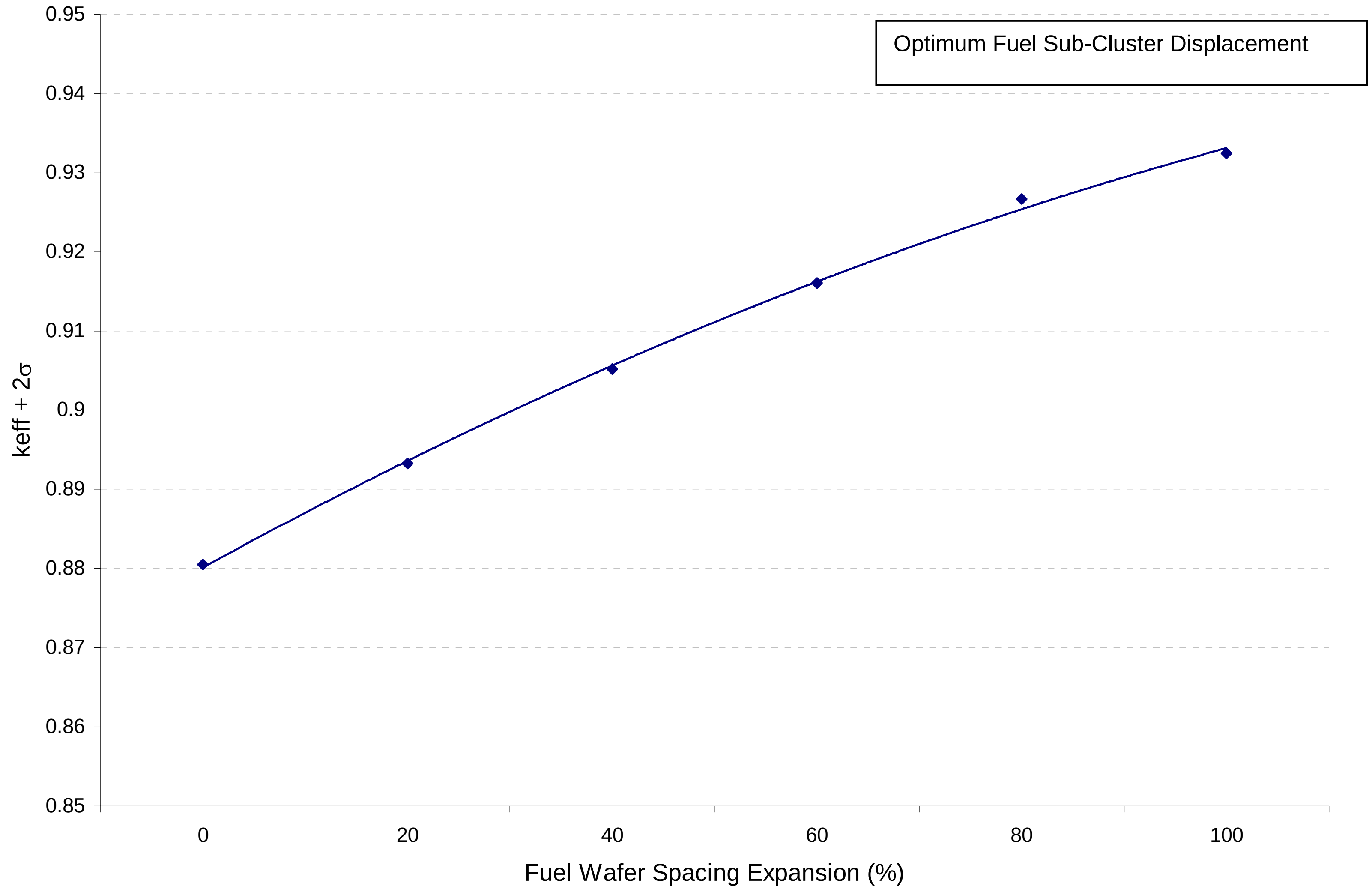
Source: Original

Figure 7-56: keff+2σ values (as a function of basket filler Gd content, and pin pitch expansion) for an individual fully water flooded and damaged, but intact, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



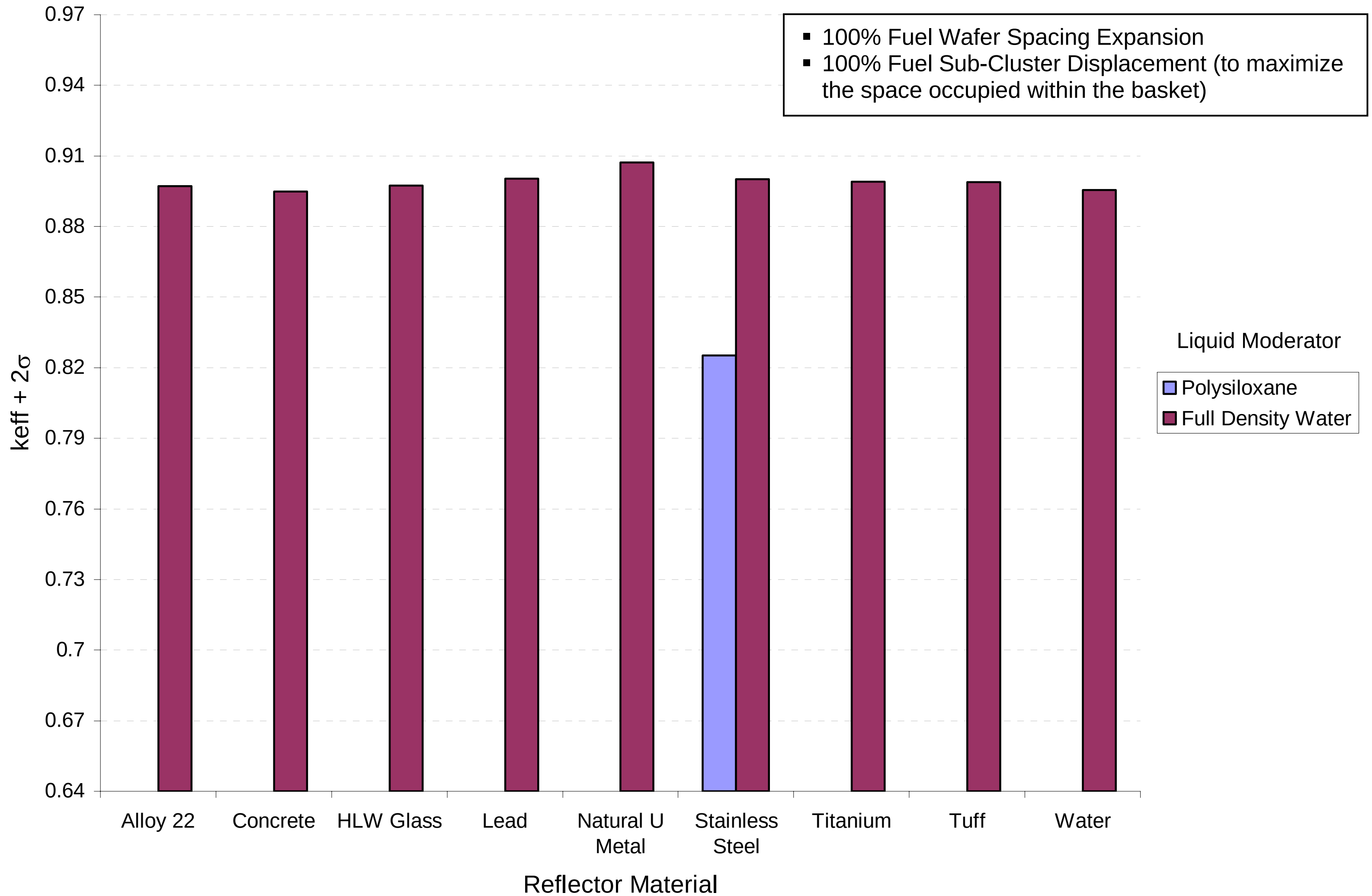
Source: Original

Figure 7-57: keff+2σ values for an individual fully flooded and damaged, but intact, SLWBR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



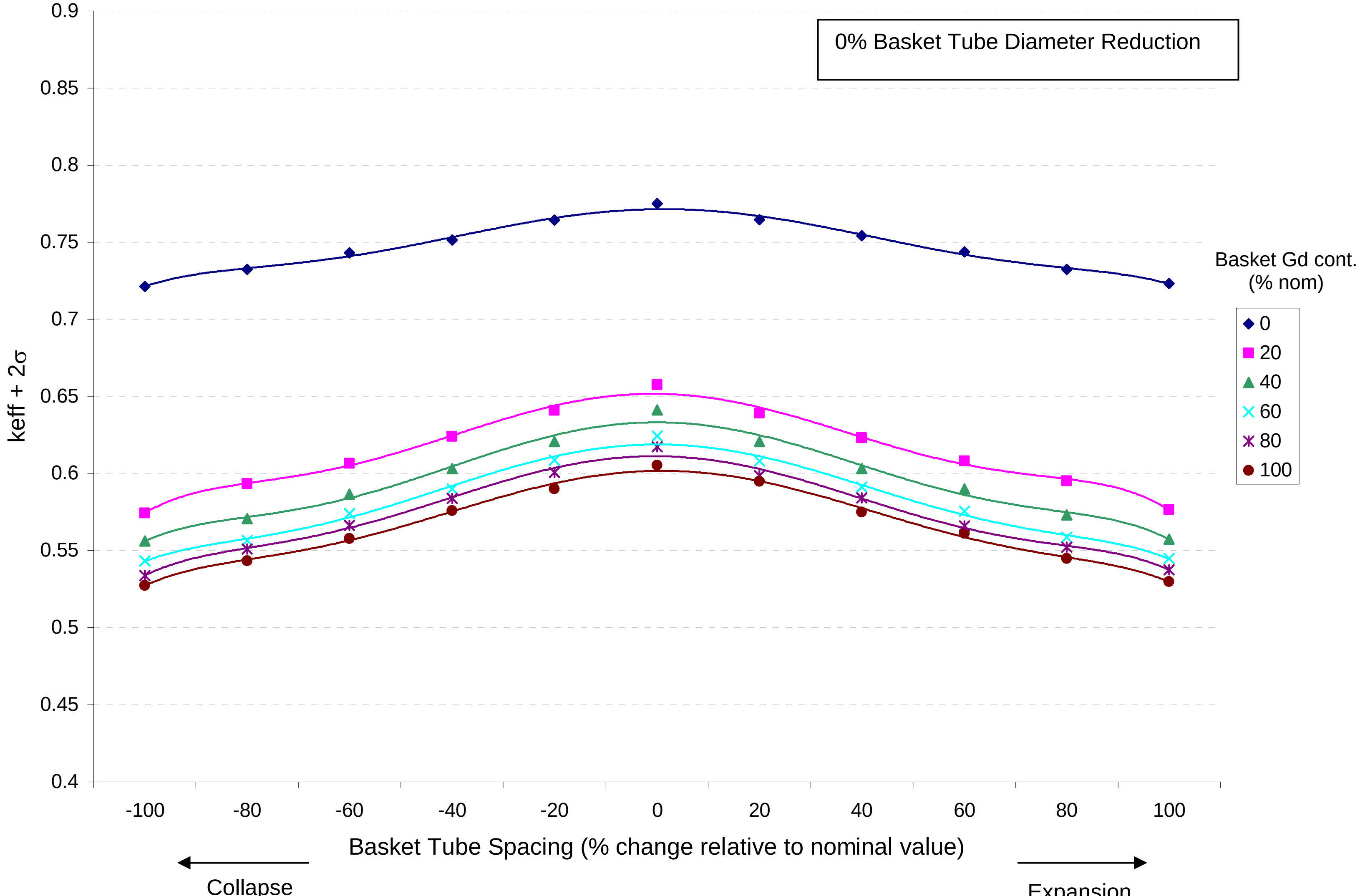
Source: Original

Figure 7-58: keff+2σ values (as a function of fuel wafer spacing expansion) for an individual fully water flooded and damaged, but intact, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



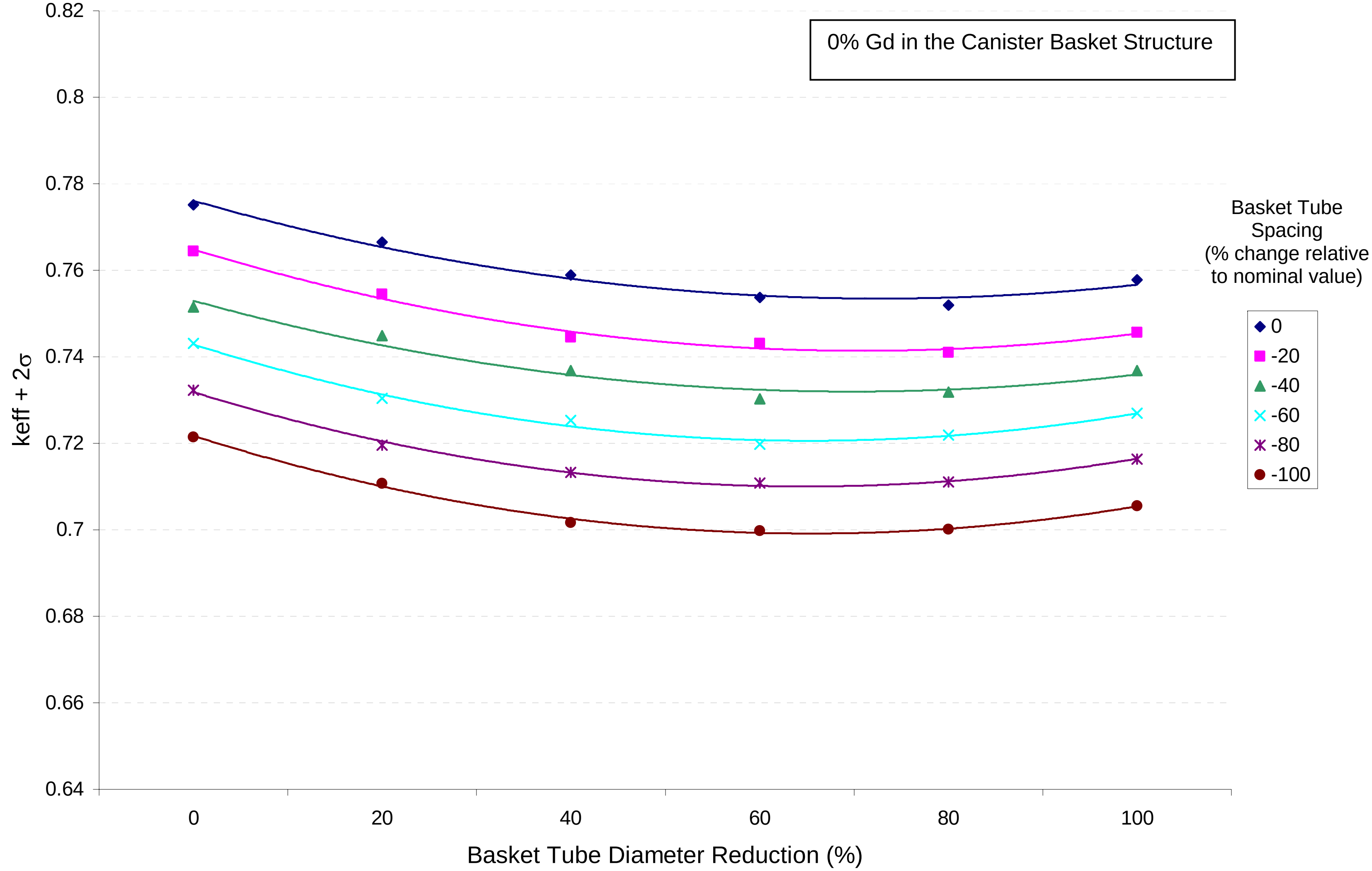
Source: Original

Figure 7-59: keff+2σ values for an individual fully flooded and damaged, but intact, SPWR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



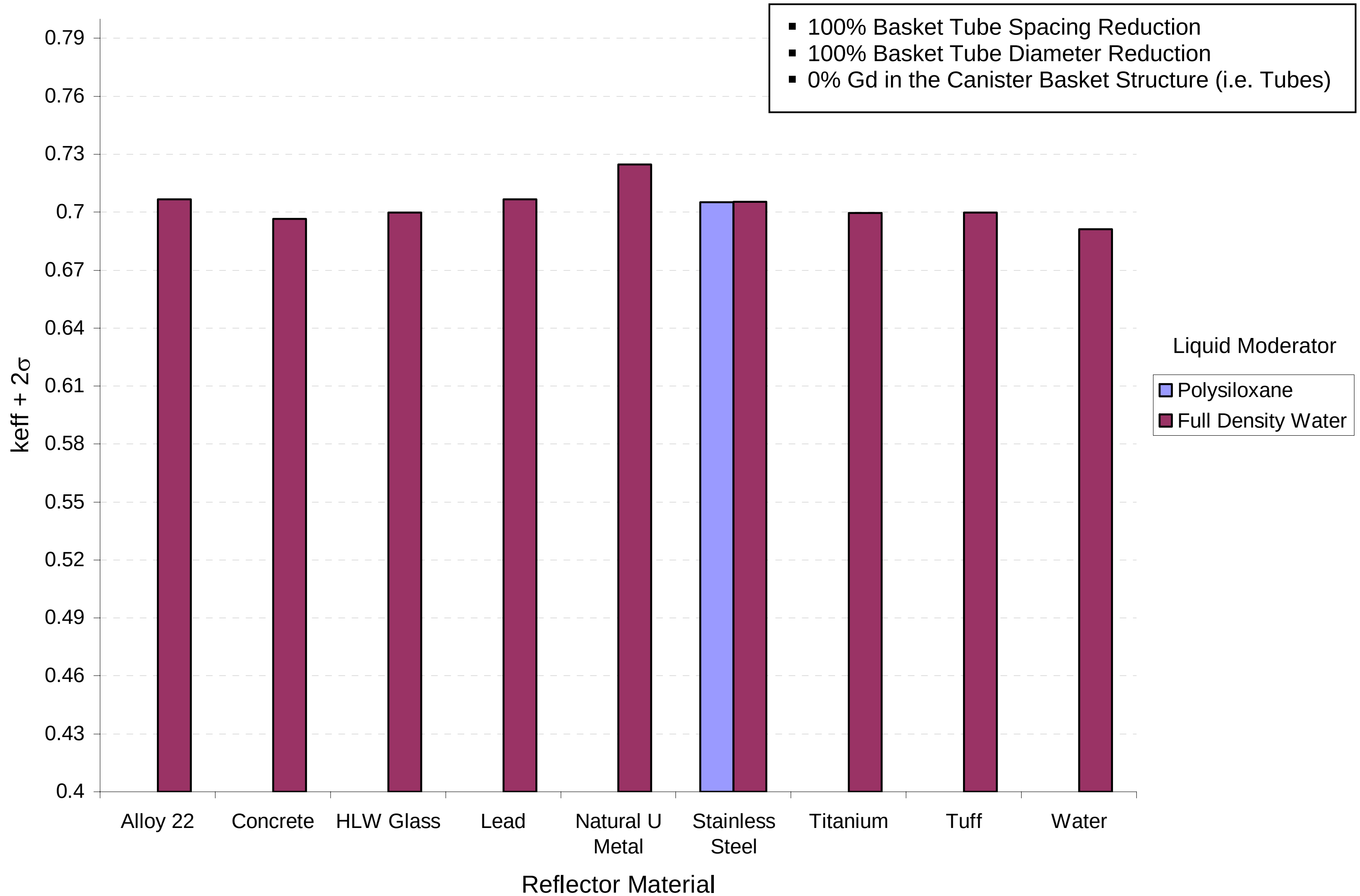
Source: Original

Figure 7-60: keff+2σ values (as a function of basket tube spacing and basket tube Gd content) for an individual fully water flooded and damaged, but intact, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



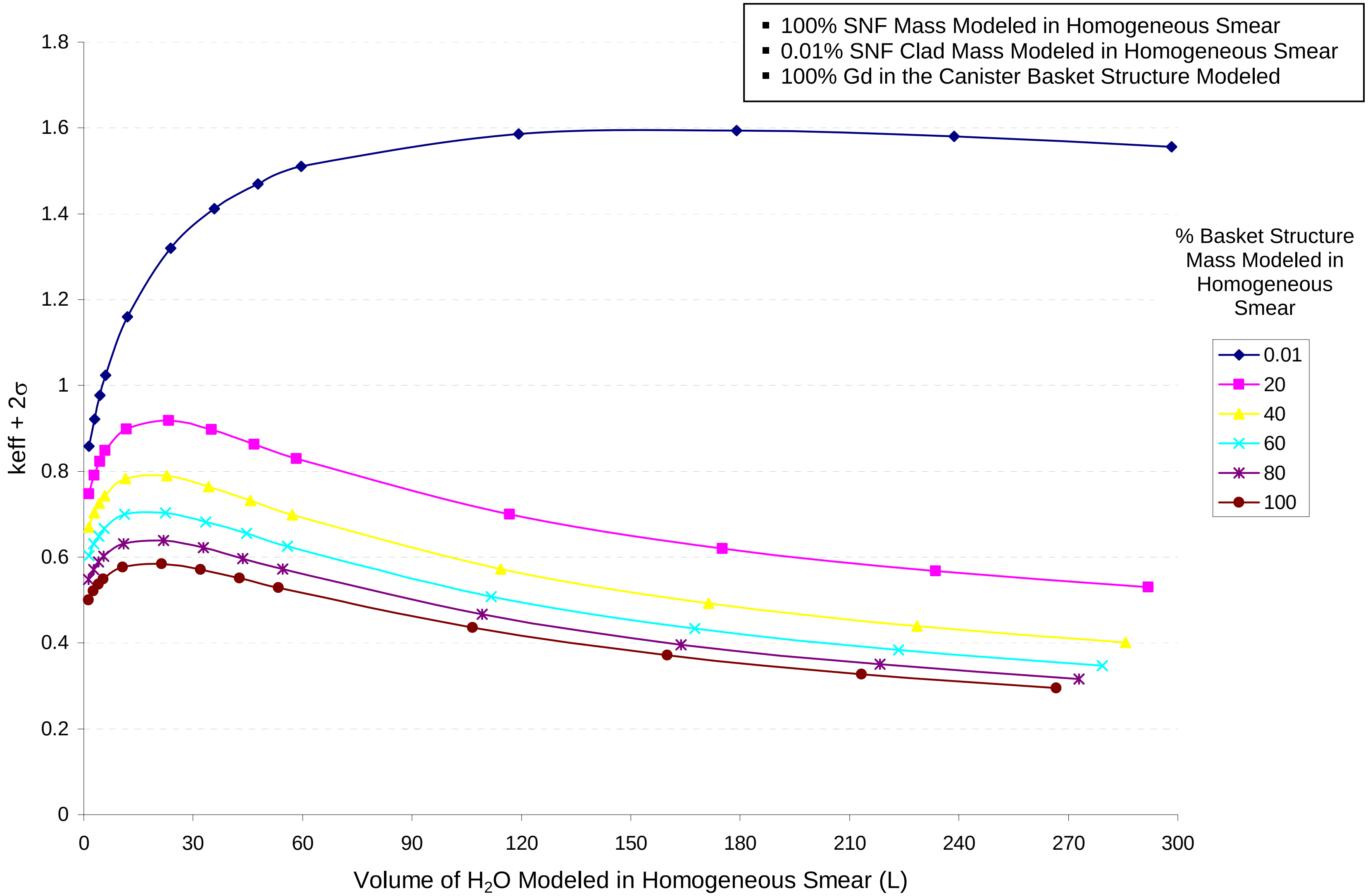
Source: Original

Figure 7-61: keff+2σ values (as a function of basket tube diameter reduction and basket tube spacing) for an individual fully water flooded and damaged, but intact, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



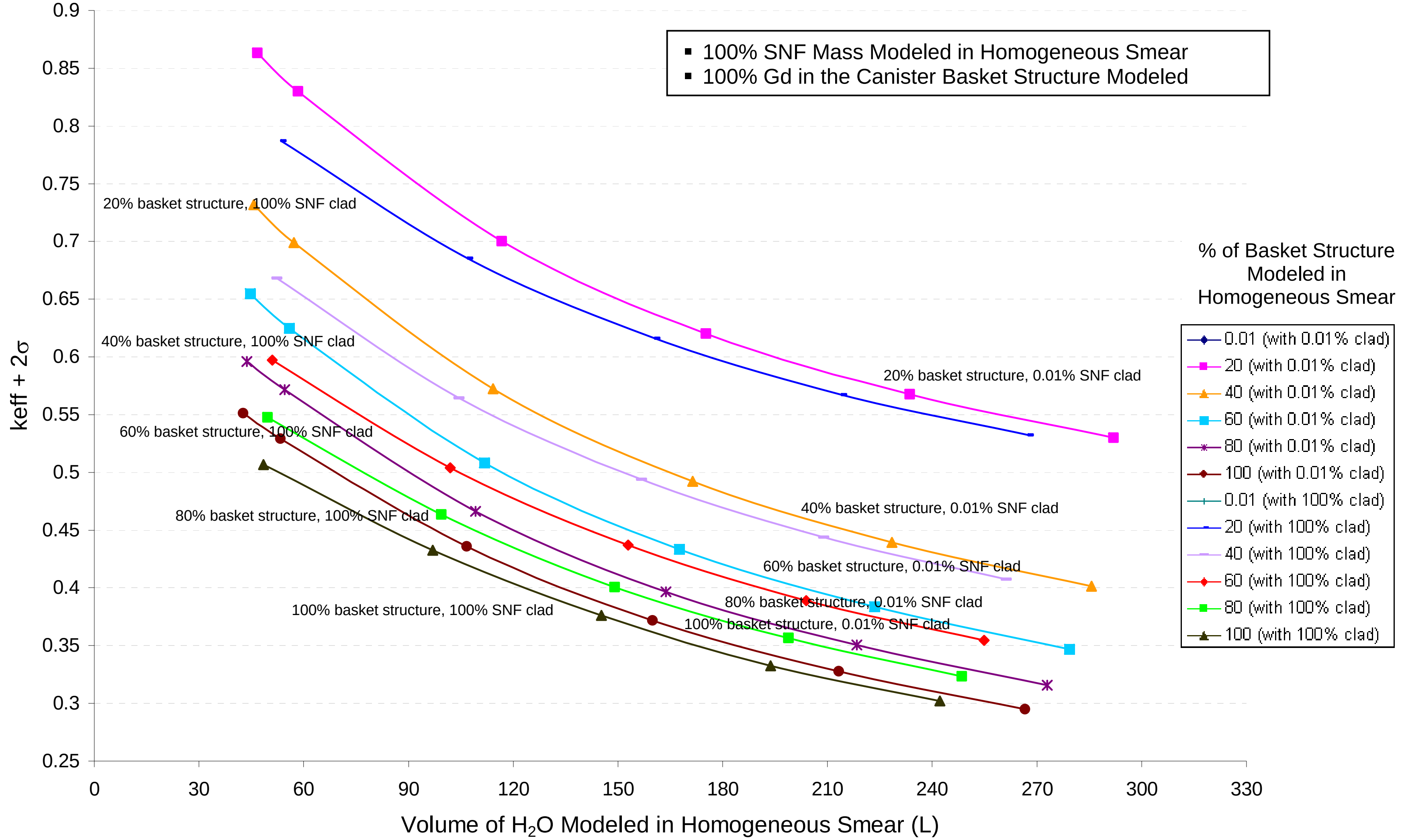
Source: Original

Figure 7-62: keff+2σ values for an individual fully flooded and damaged, but intact, TRIGA DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



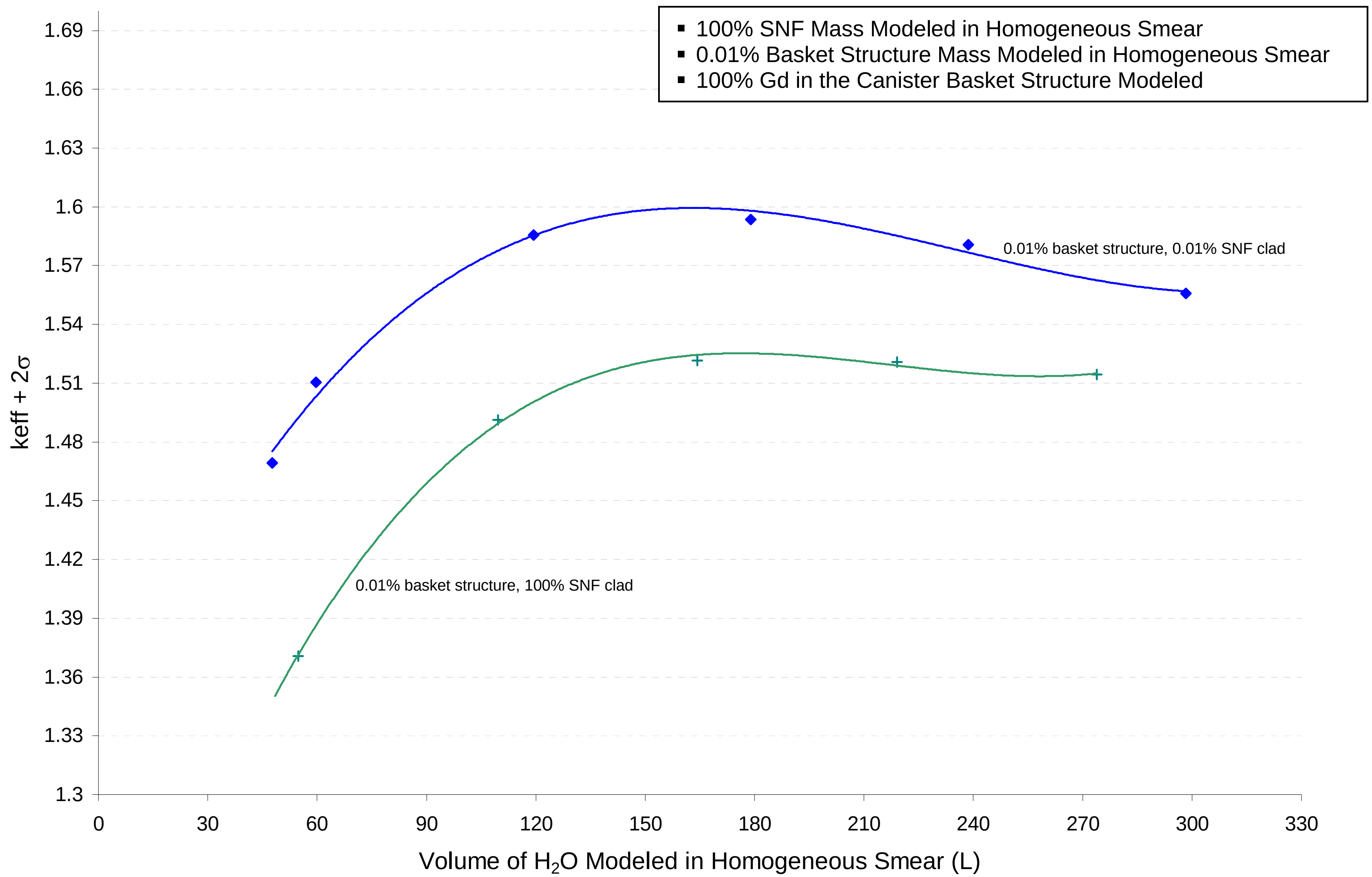
Source: Original

Figure 7-63: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-64: keff+2σ values (as a function of H_2O volume, basket structure mass, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-65: keff+2σ values (as a function of H_2O volume, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

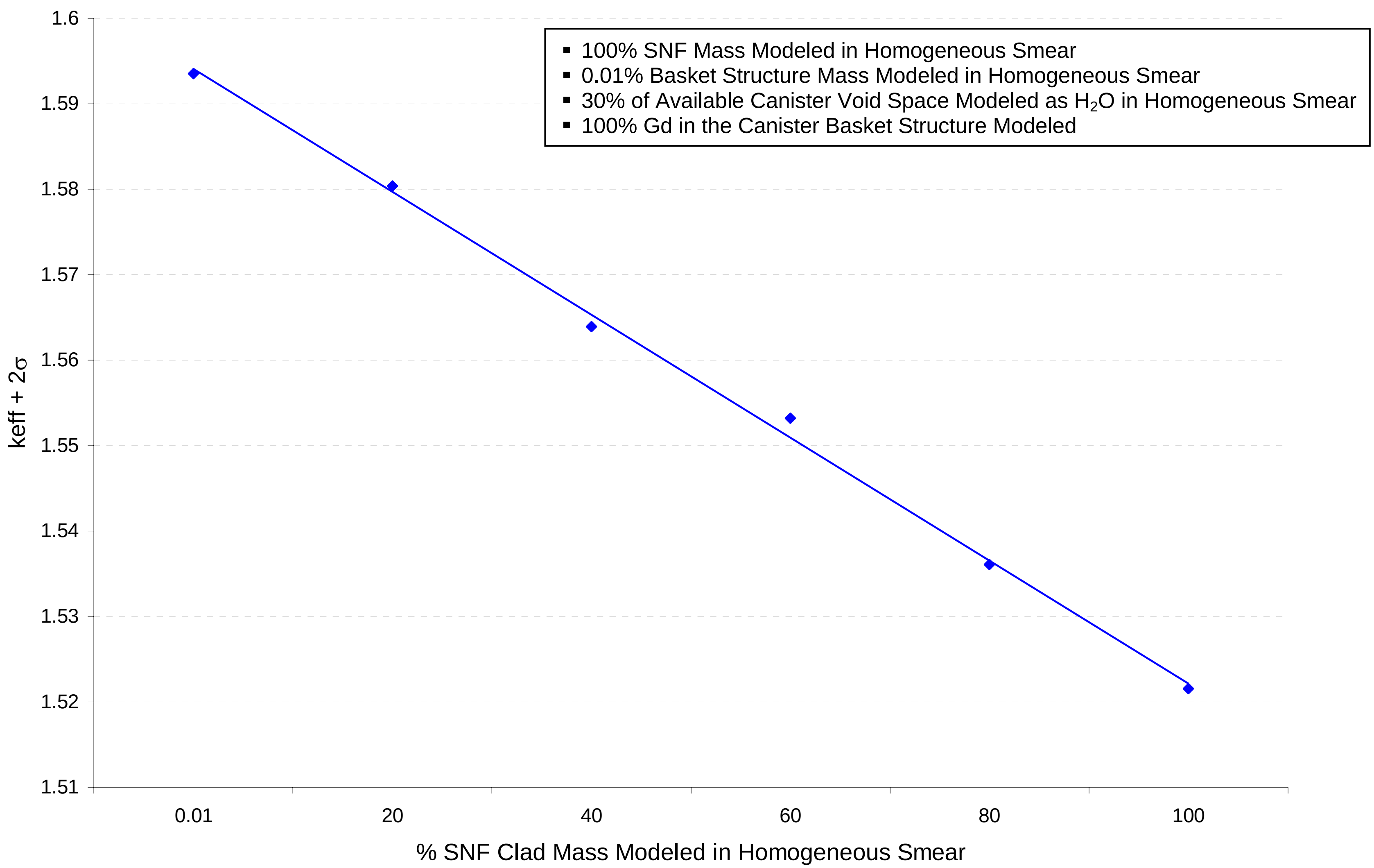


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Figure 7-66: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

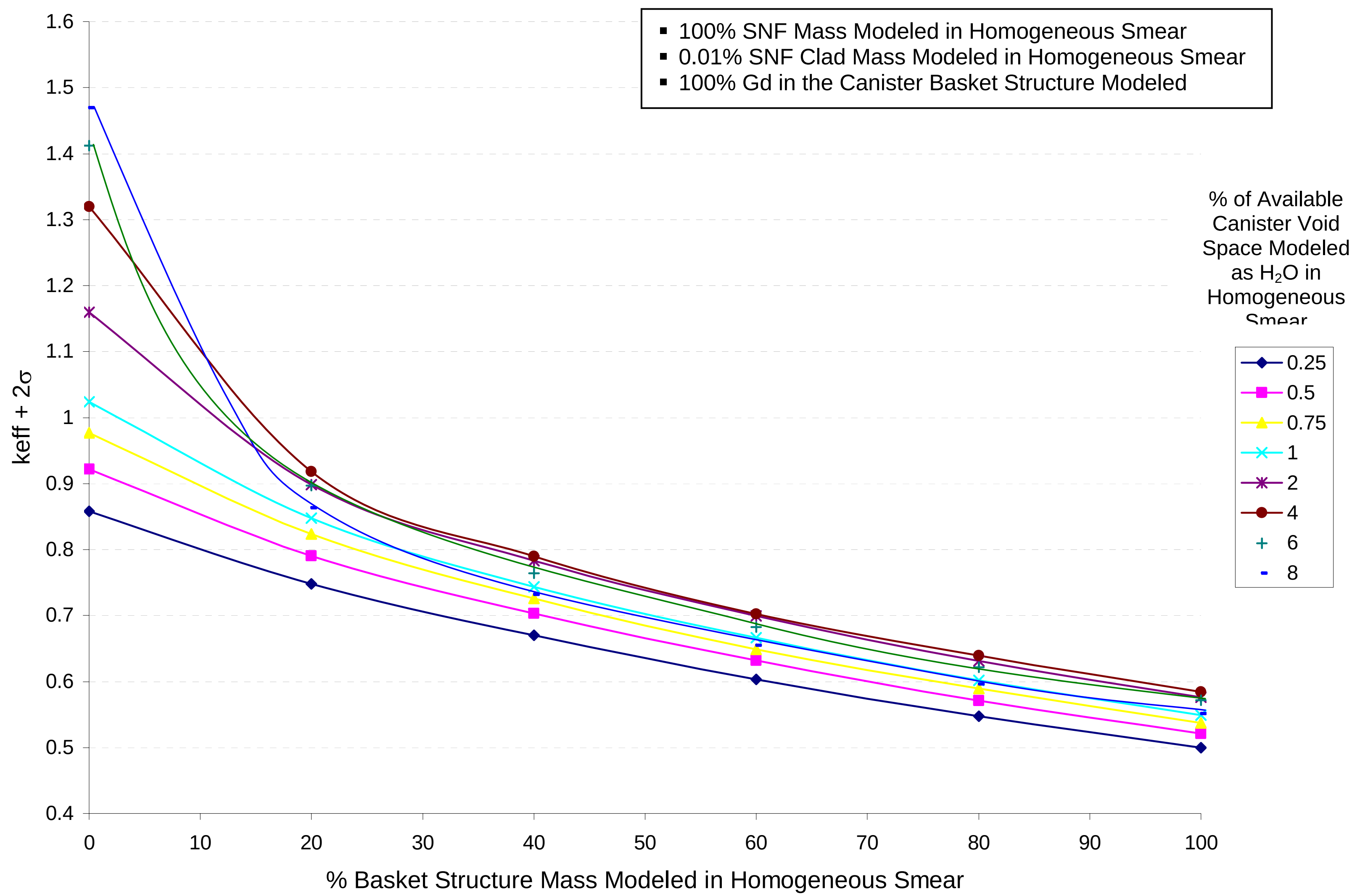

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Figure 7-67: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

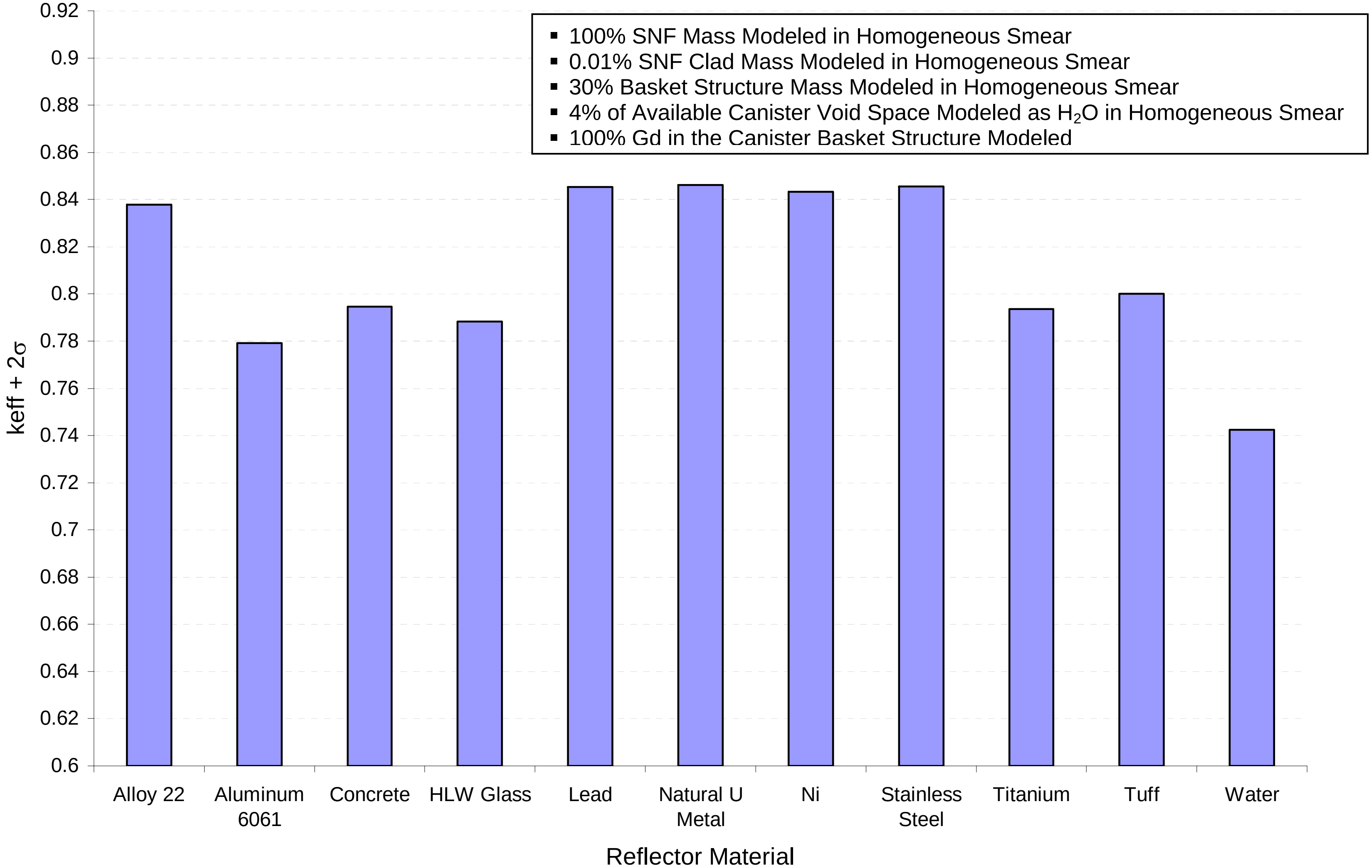

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Figure 7-68: keff+2σ values for an individual fully water flooded, damaged and degraded, ATR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

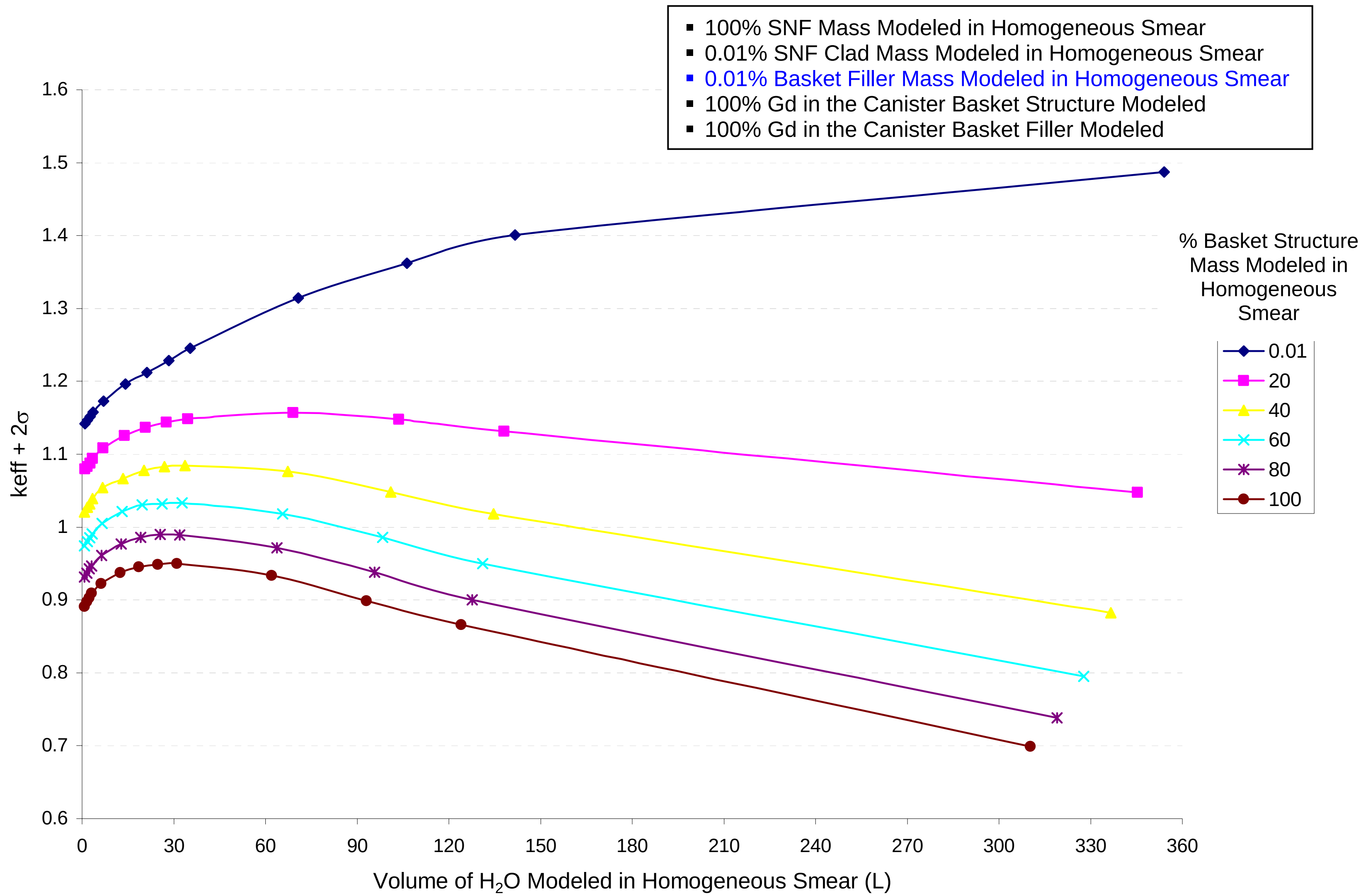

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Figure 7-69: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

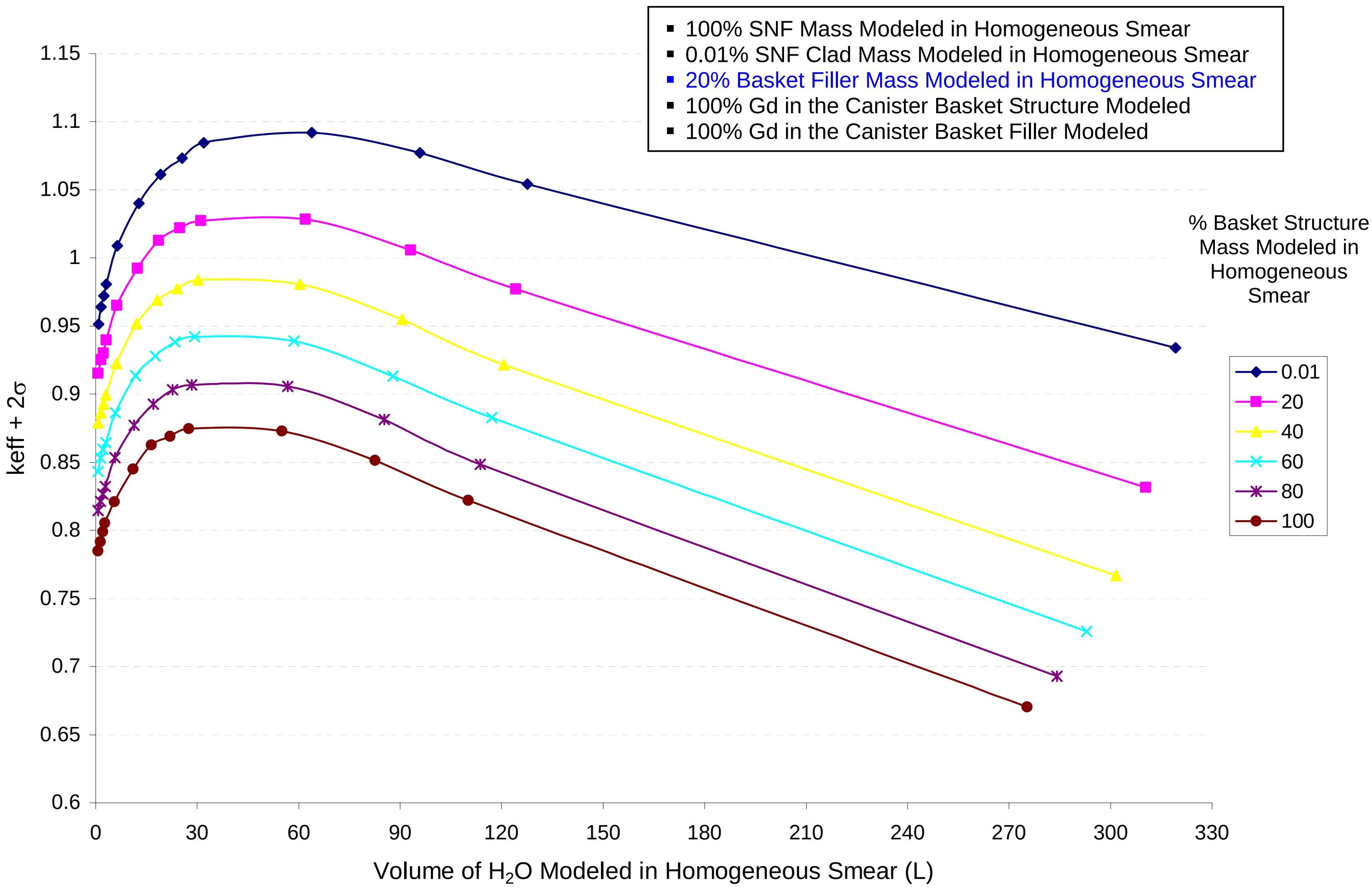

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Figure 7-70: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

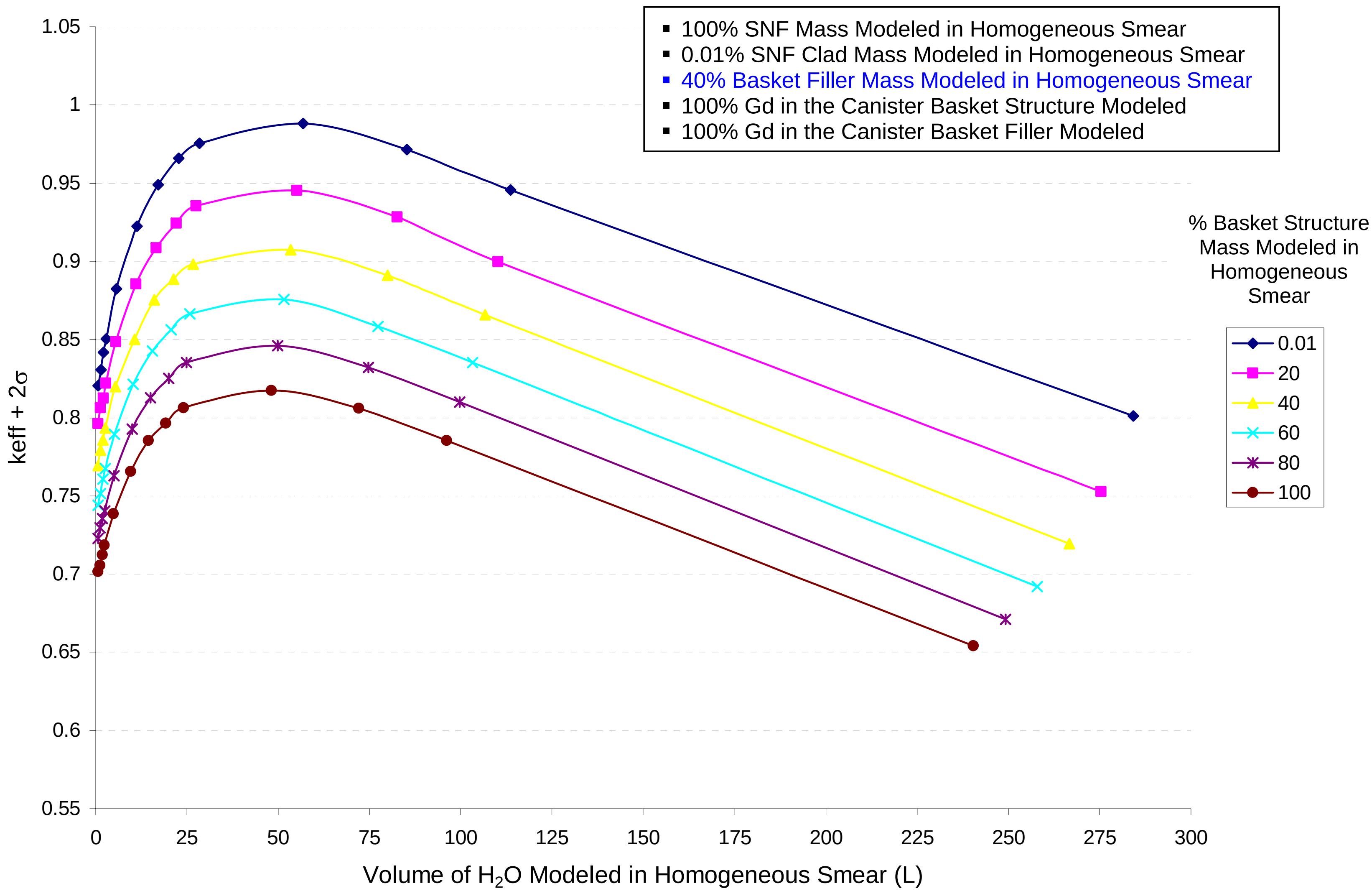

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Figure 7-71: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

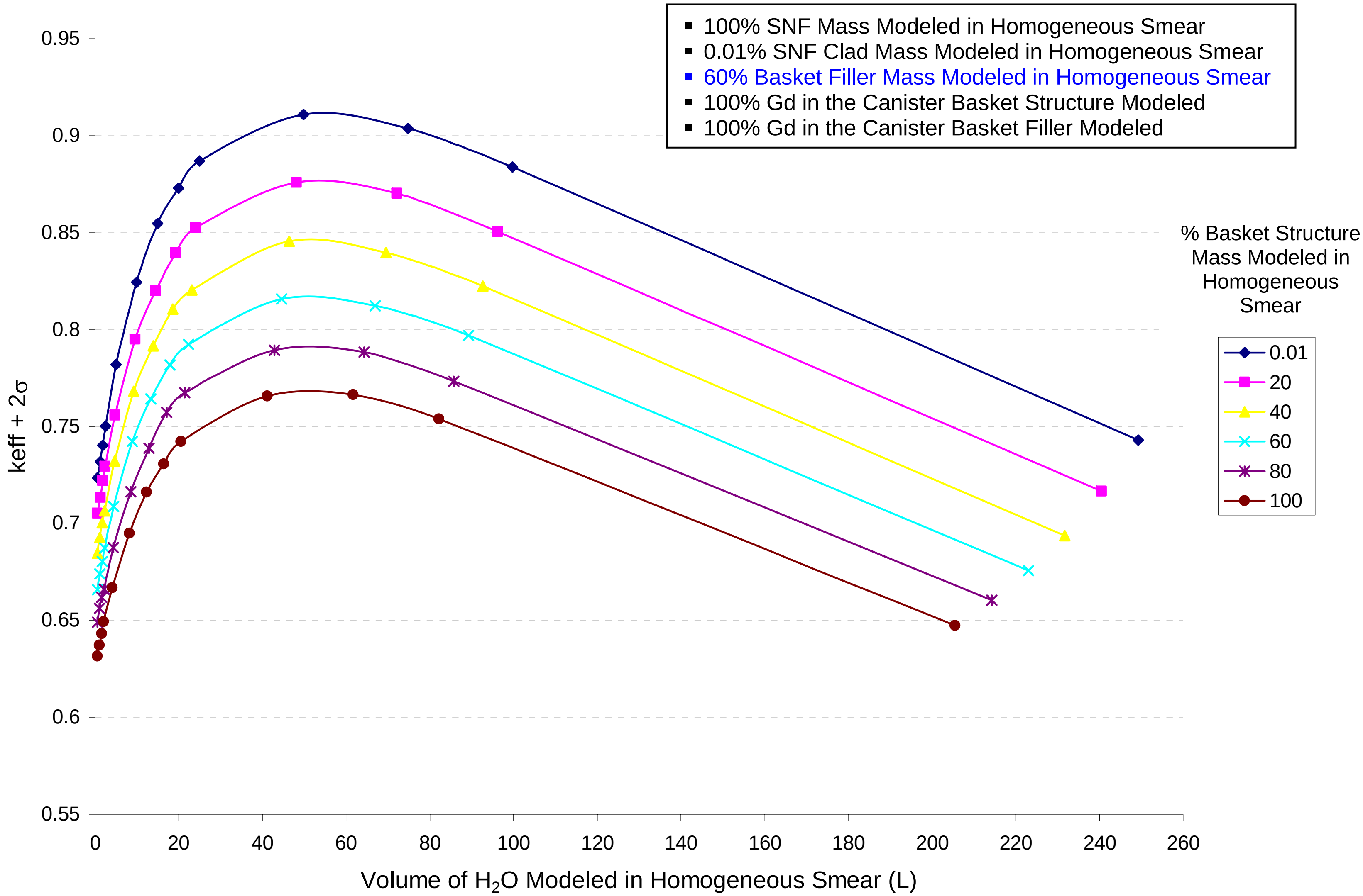

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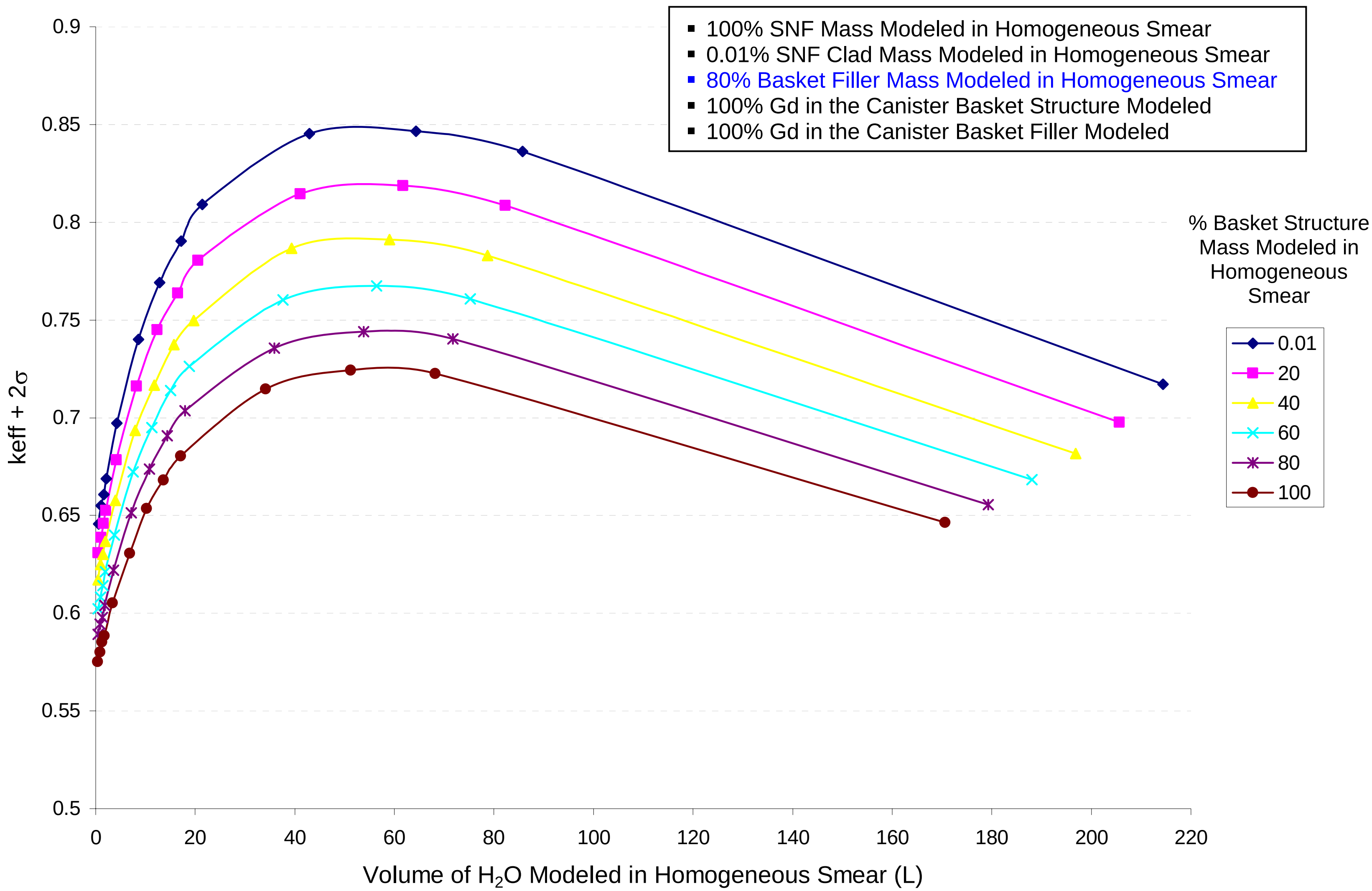
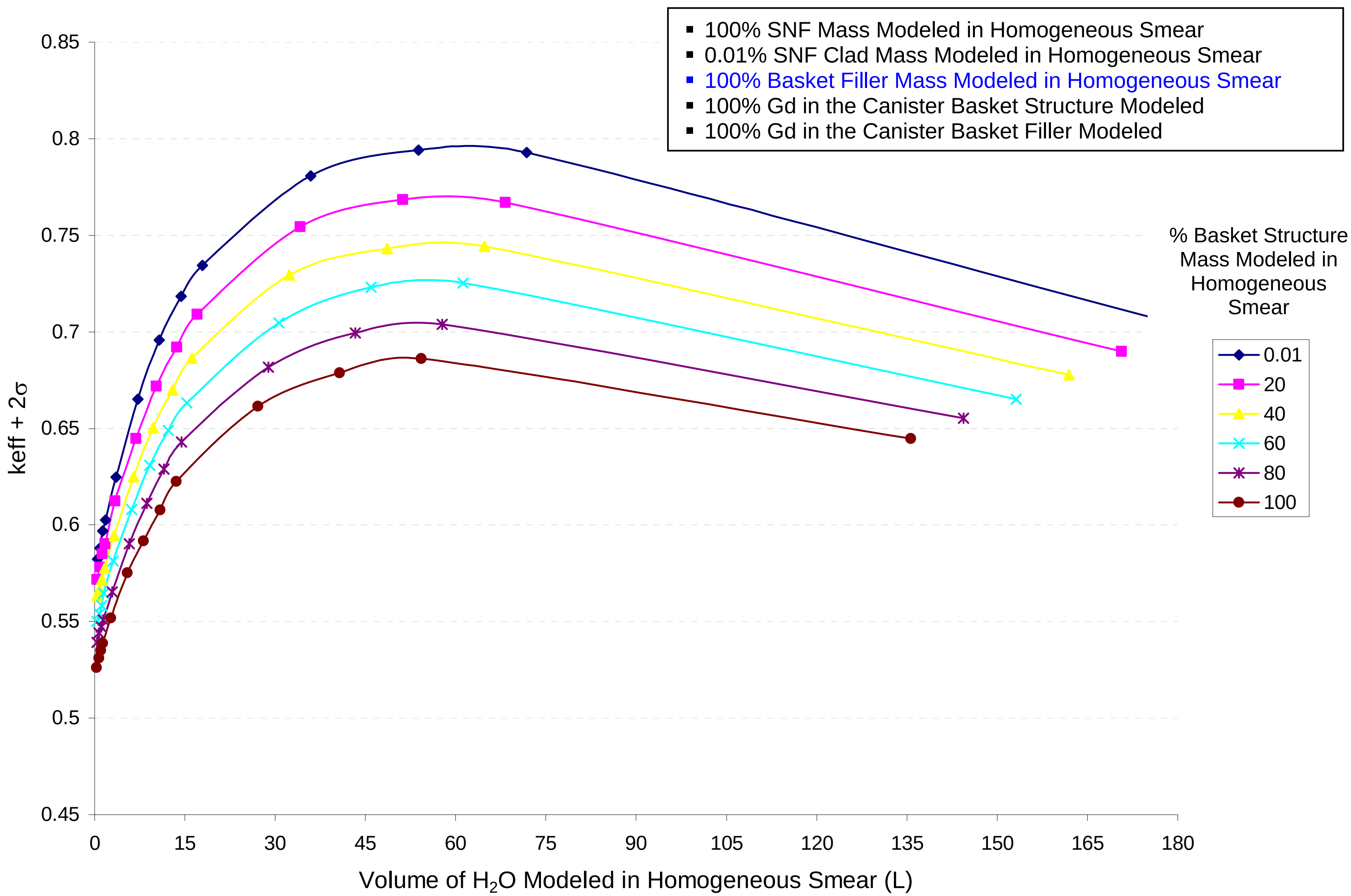
Figure 7-72: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-73: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-74: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

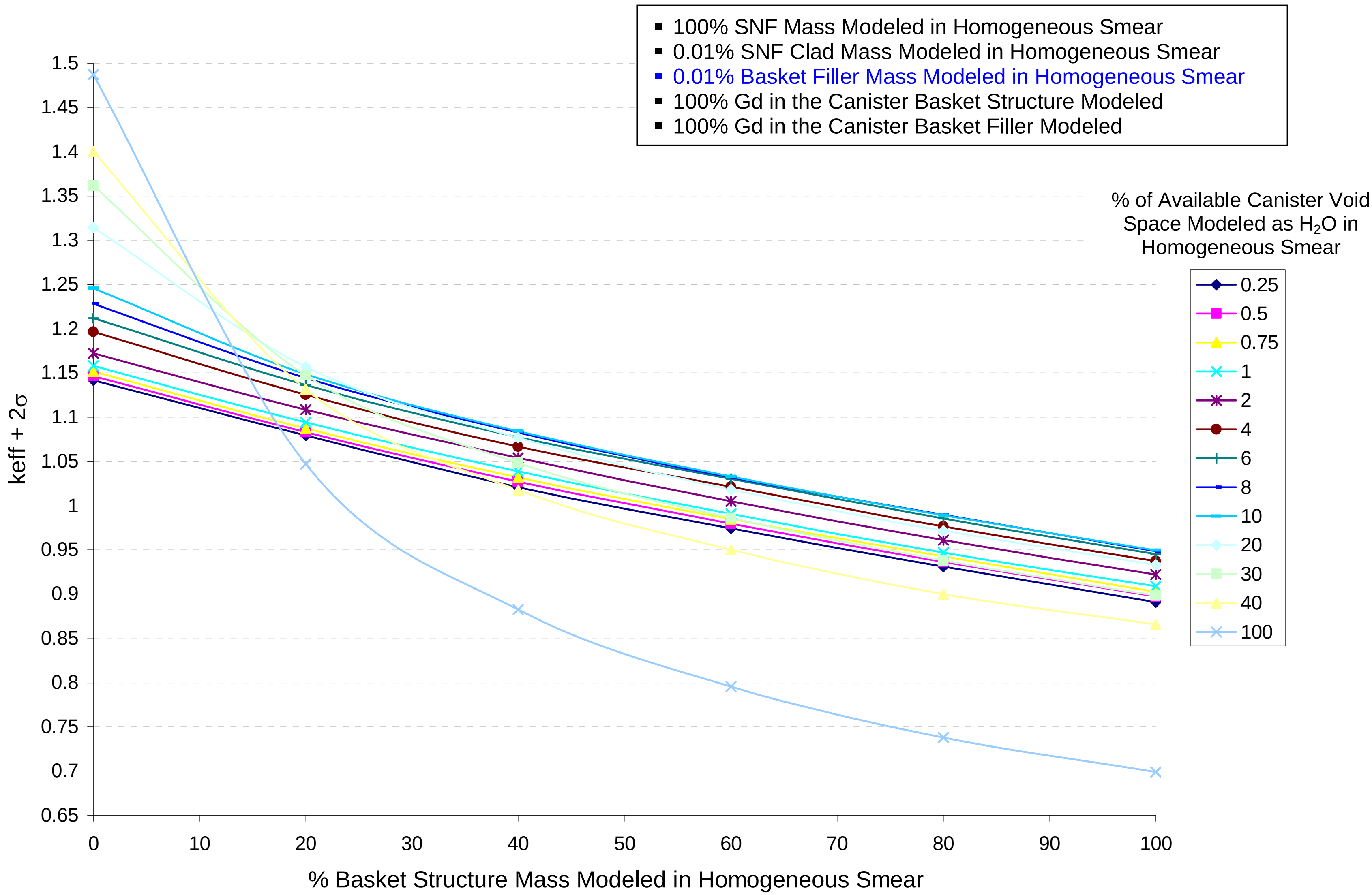


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Figure 7-75: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection

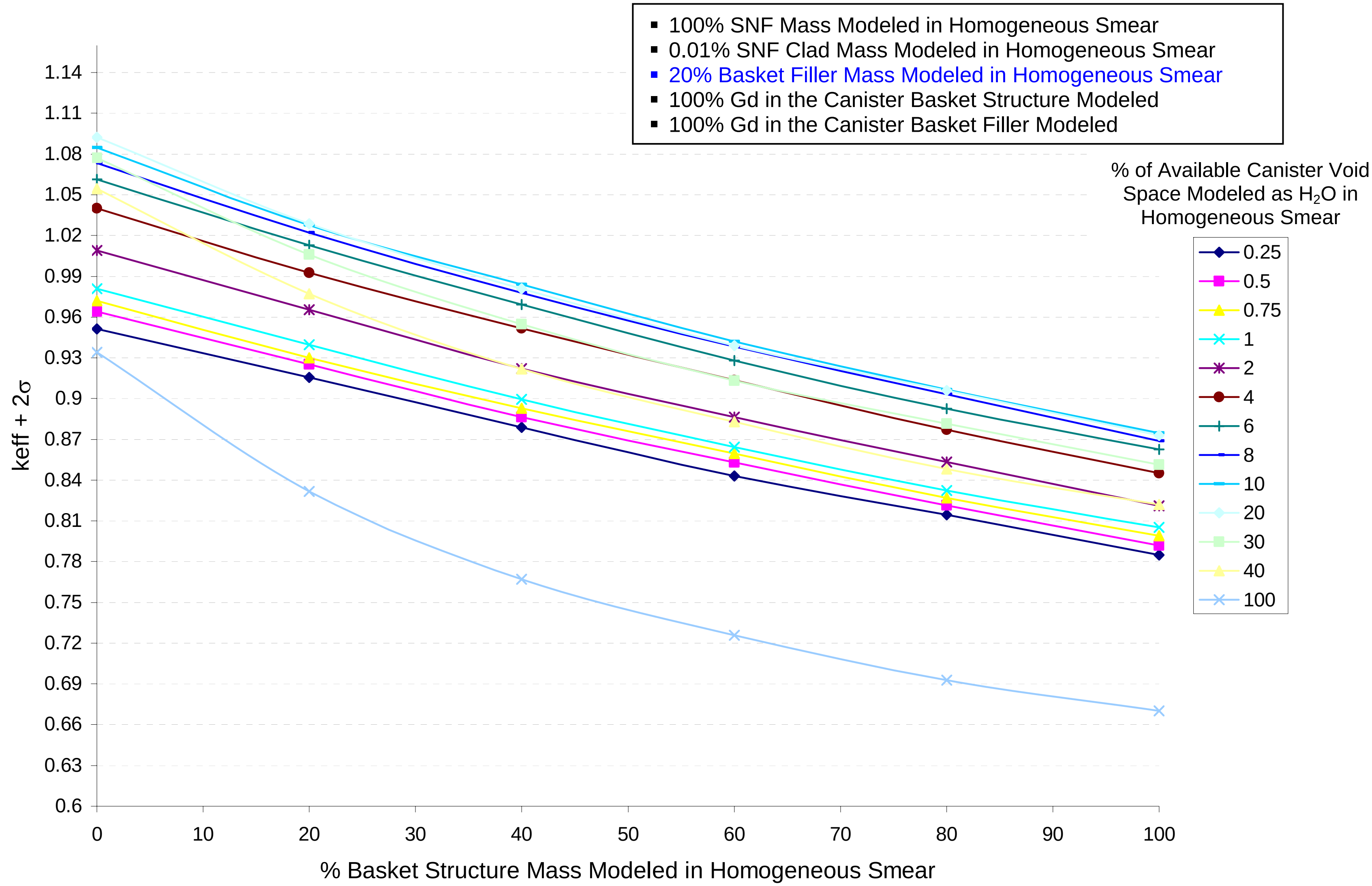

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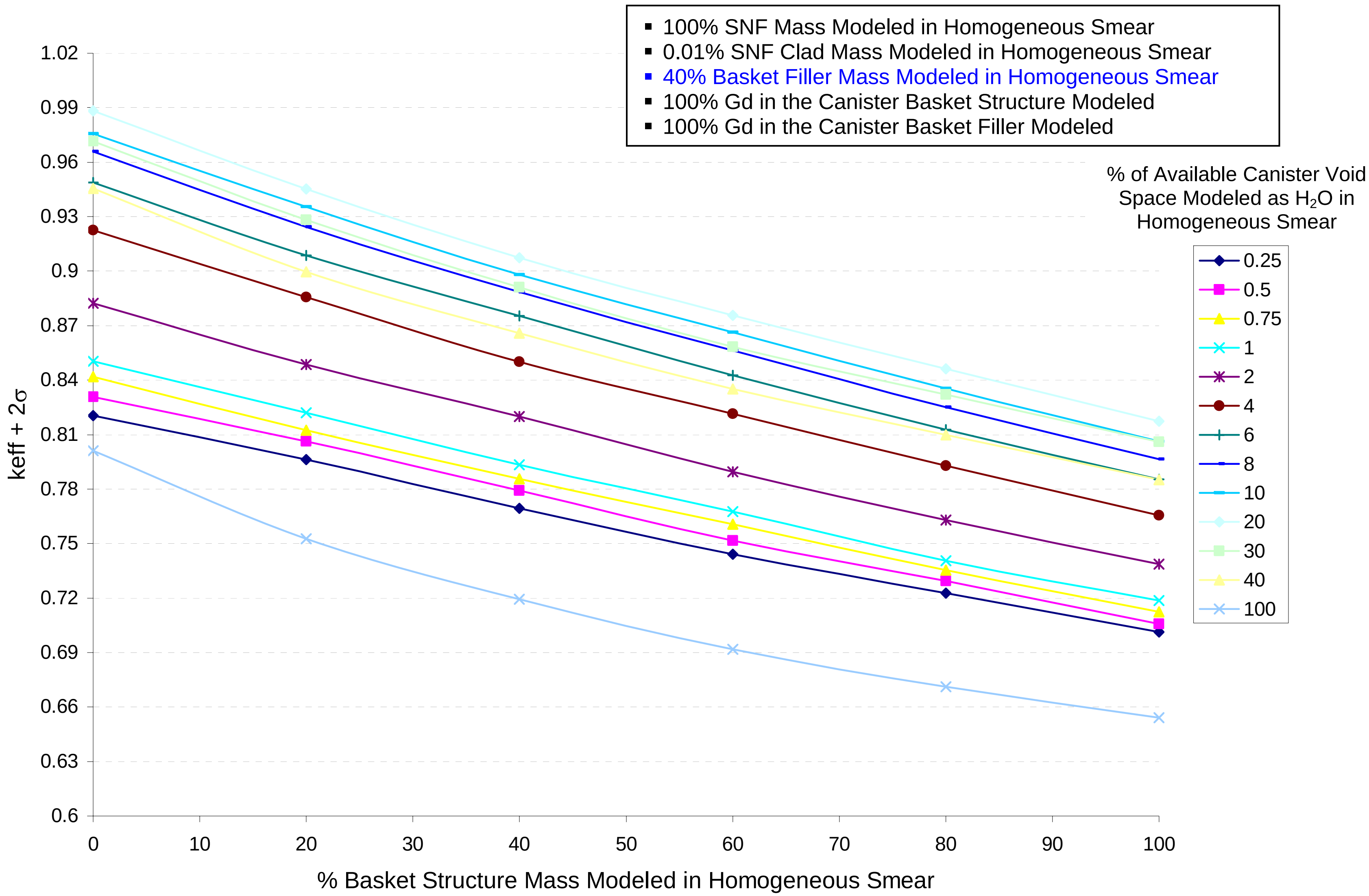
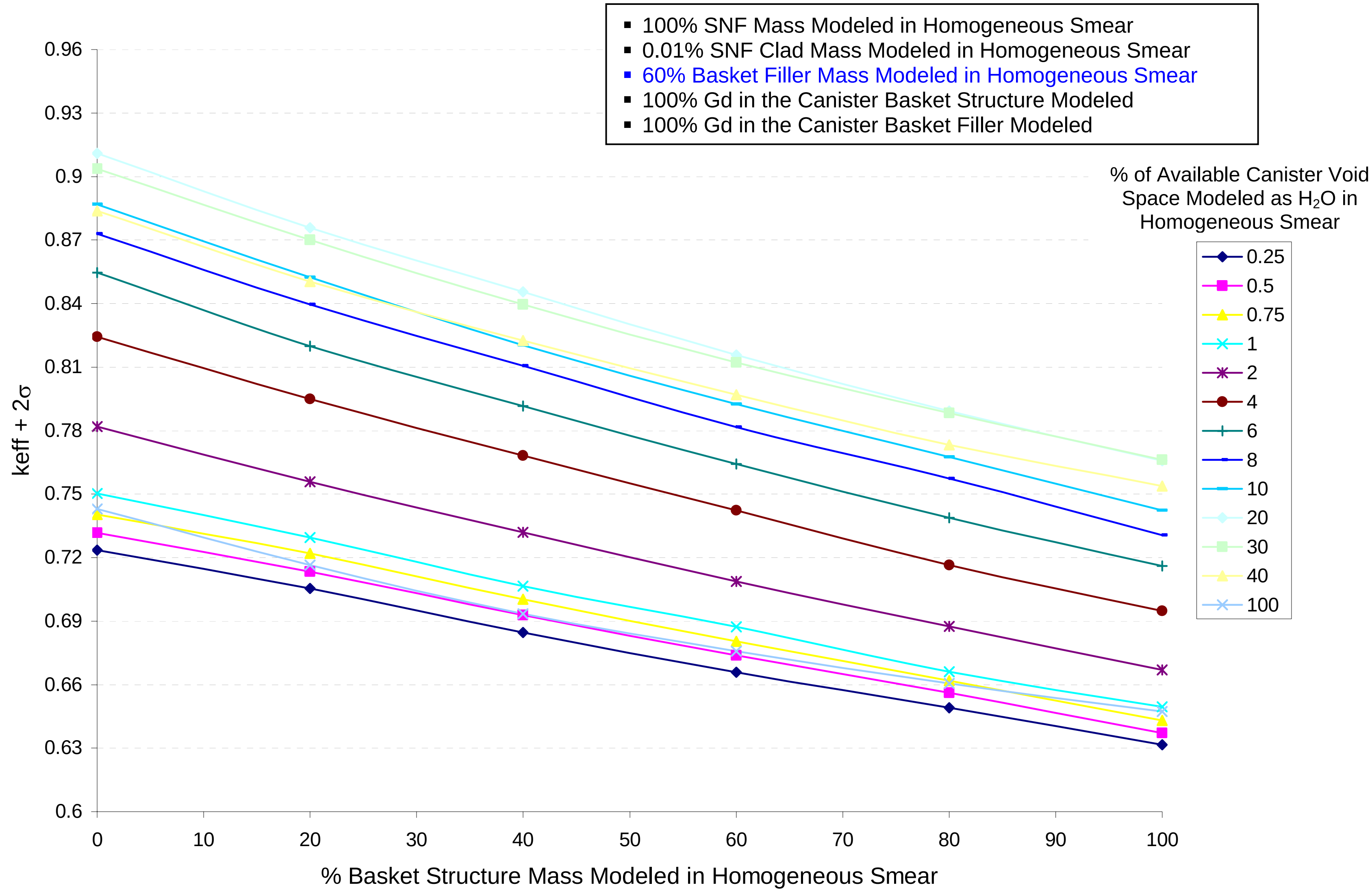
Figure 7-76: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



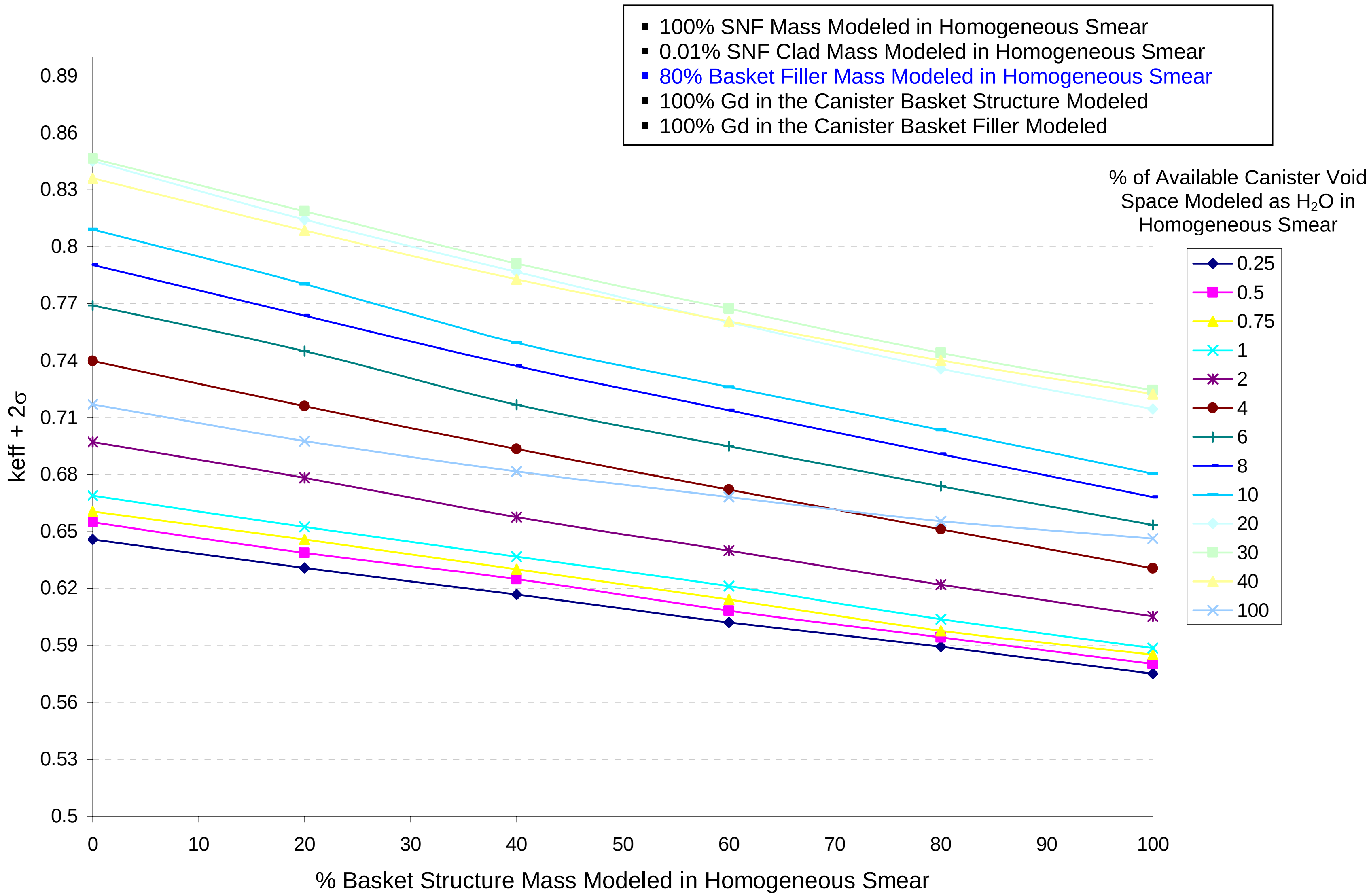
Source: Original

Figure 7-77: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



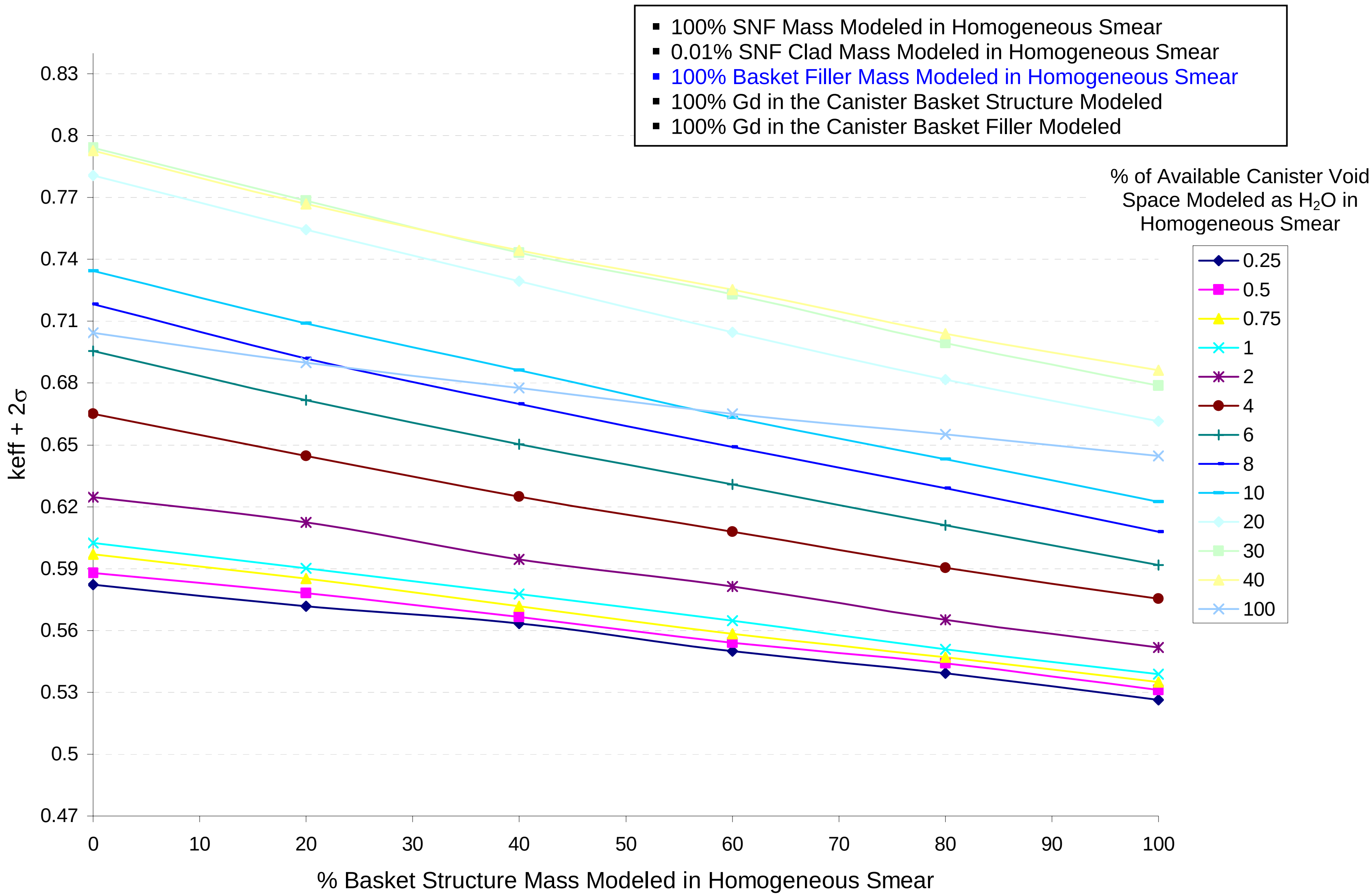
Source: Original

Figure 7-78: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



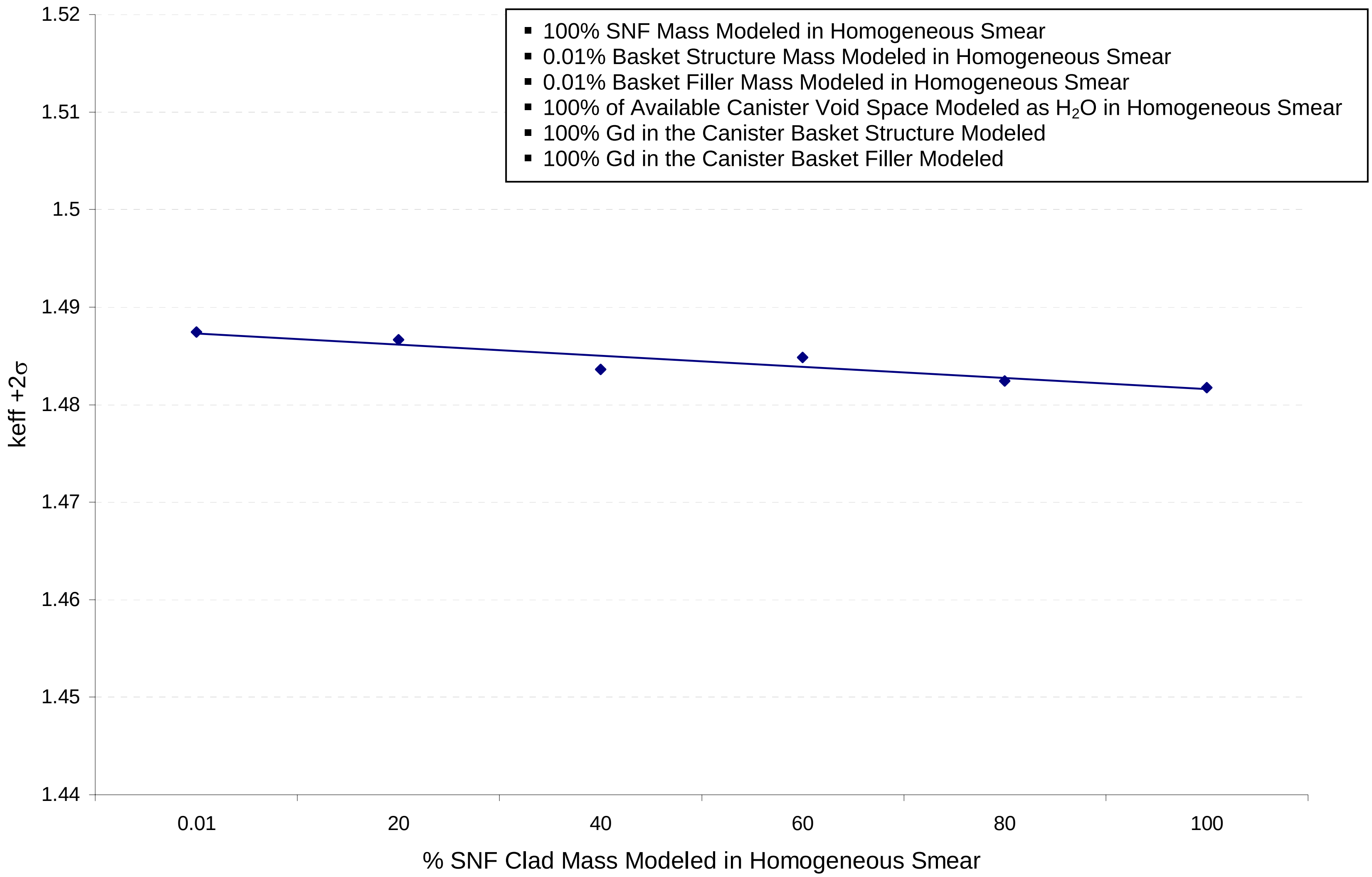
Source: Original

Figure 7-79: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



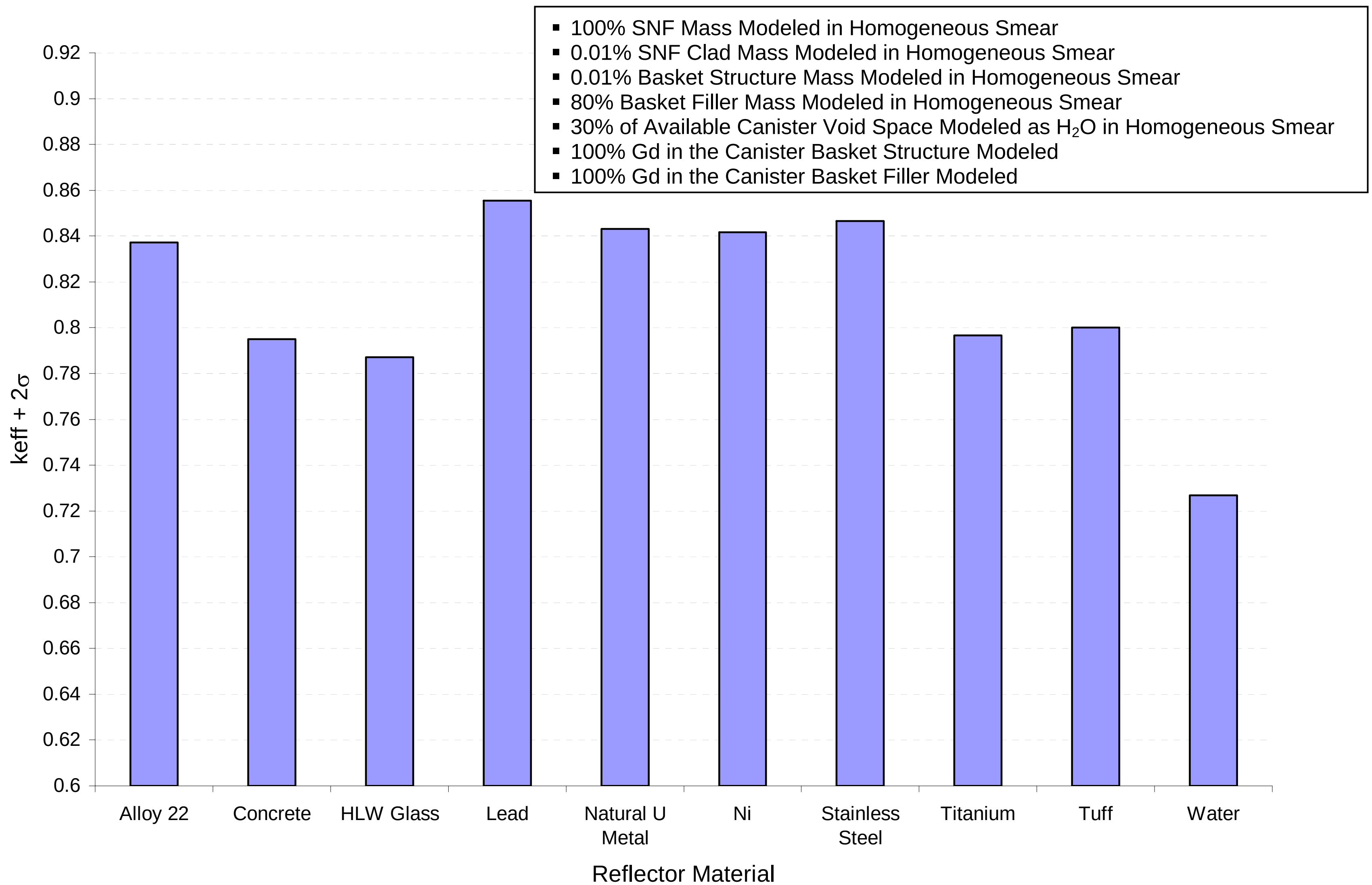
Source: Original

Figure 7-80: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



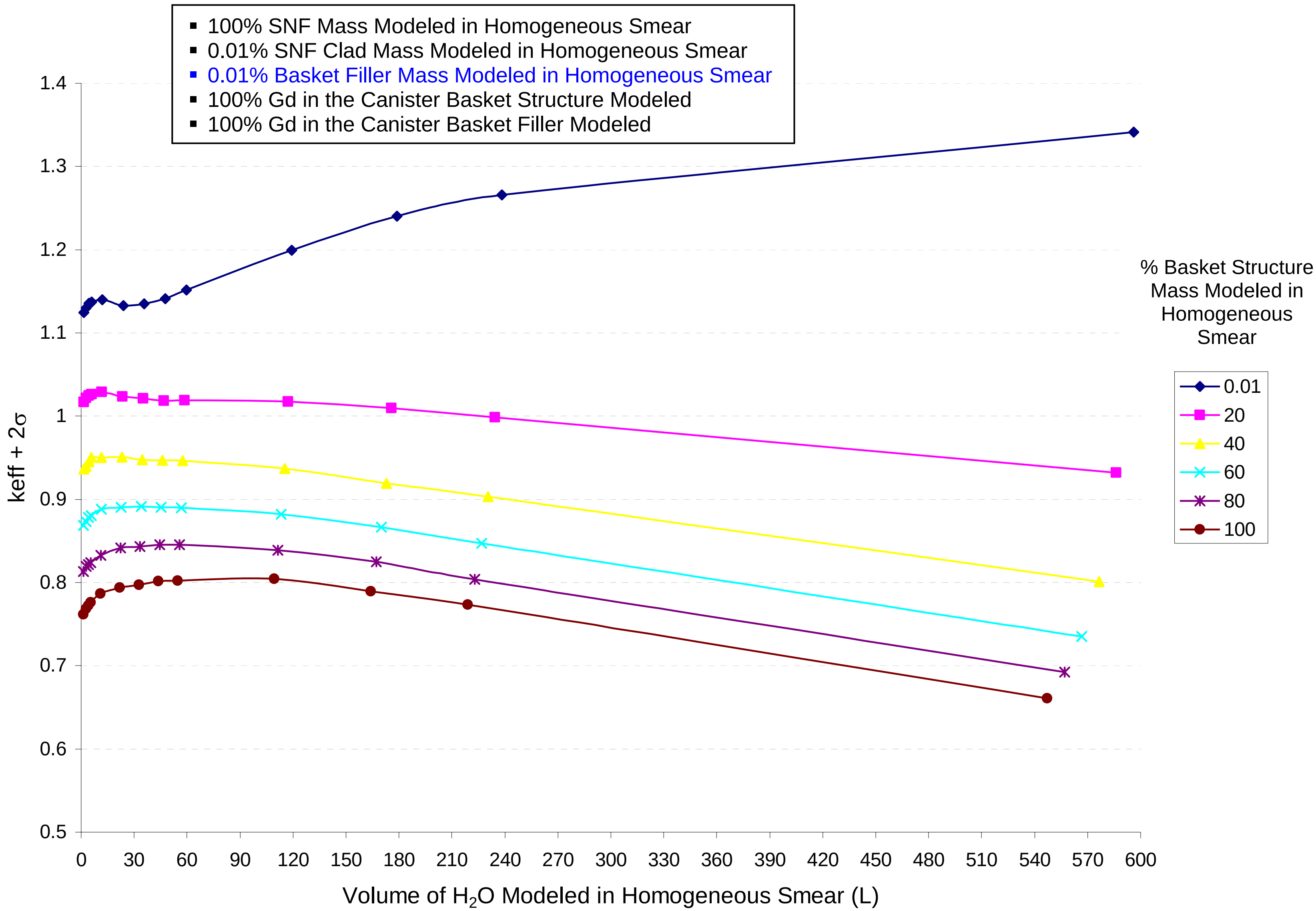
Source: Original

Figure 7-81: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, EF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



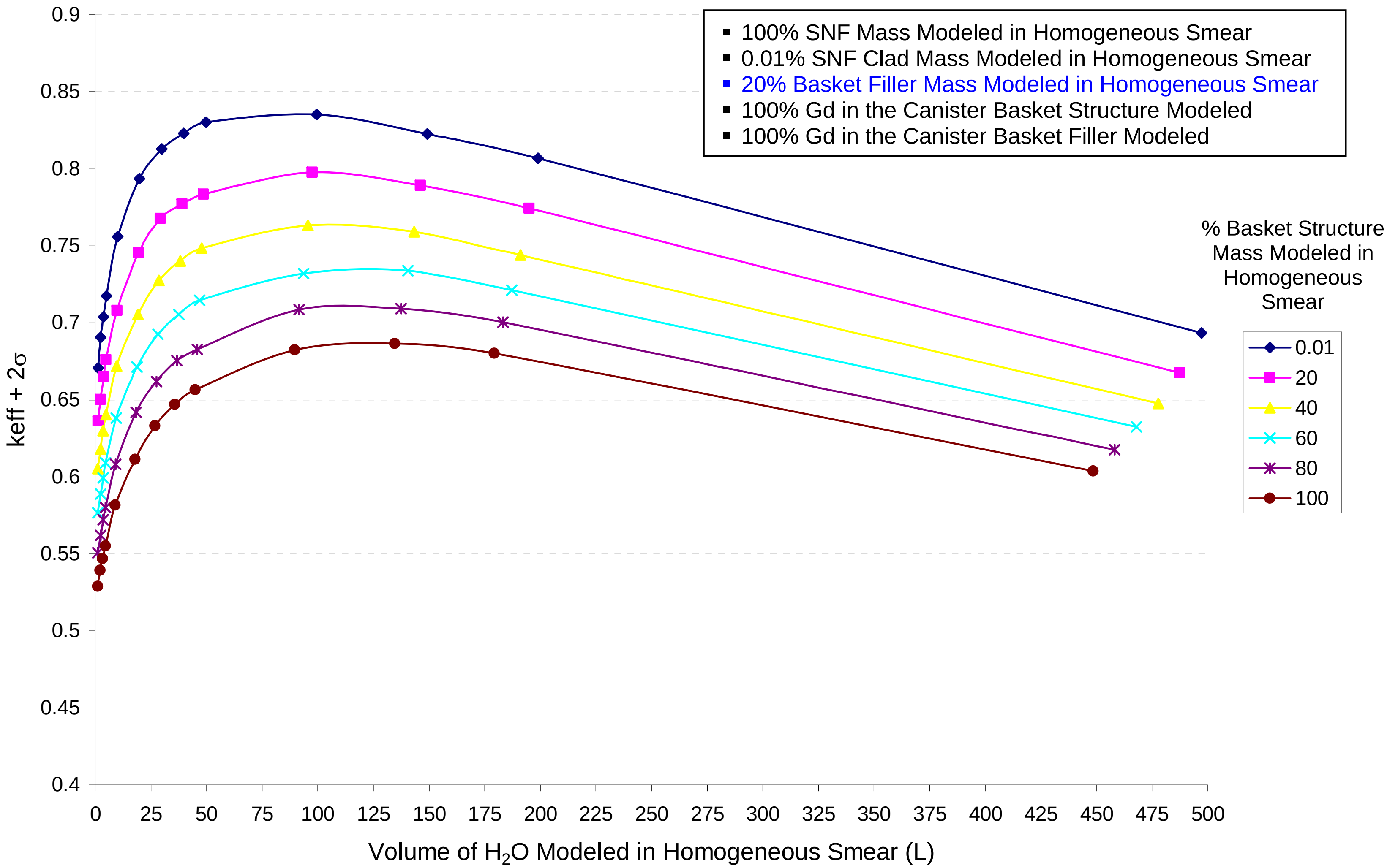
Source: Original

Figure 7-82: keff+2σ values for an individual fully water flooded, damaged and degraded, EF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



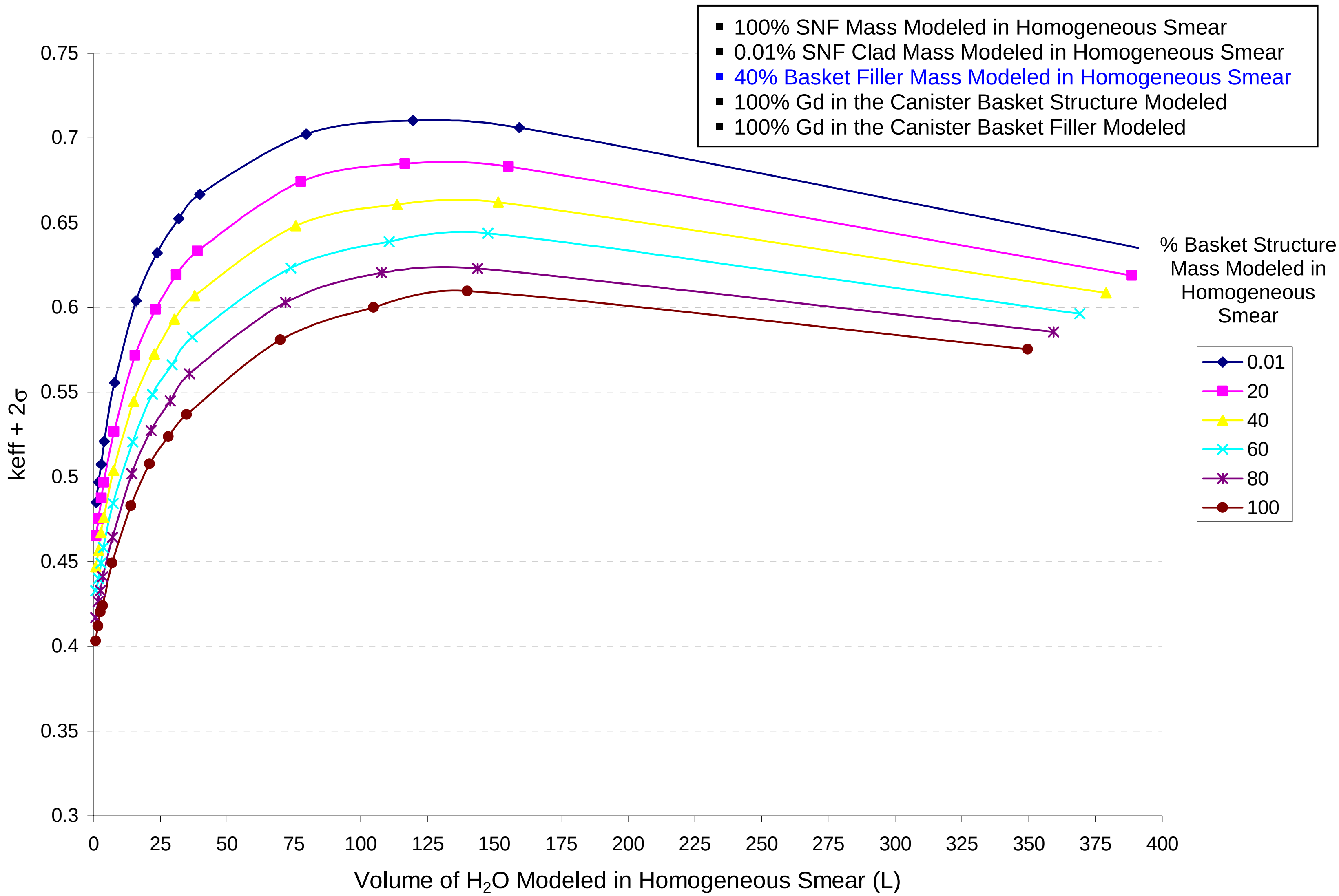
Source: Original

Figure 7-83: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



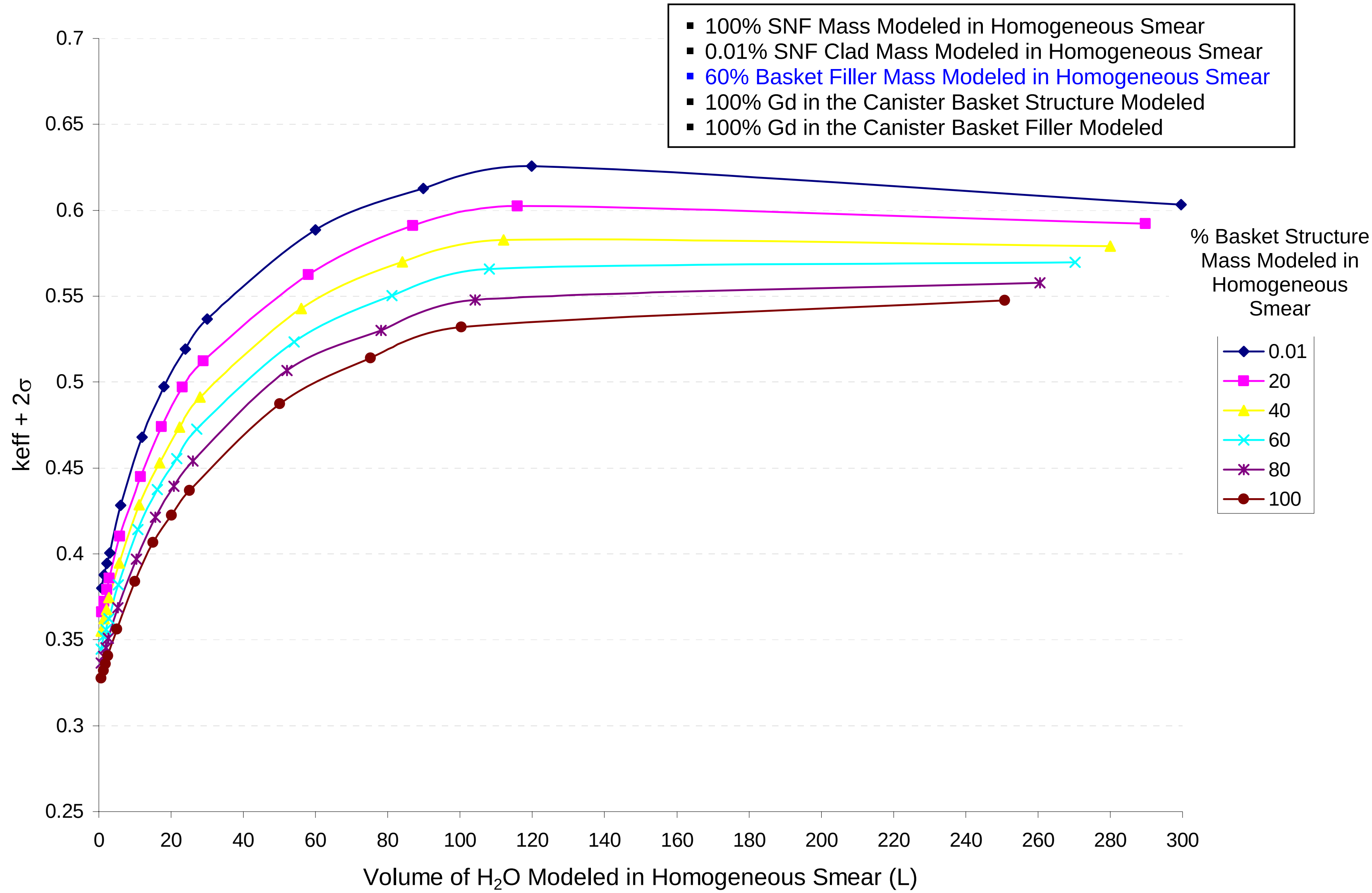
Source: Original

Figure 7-84: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



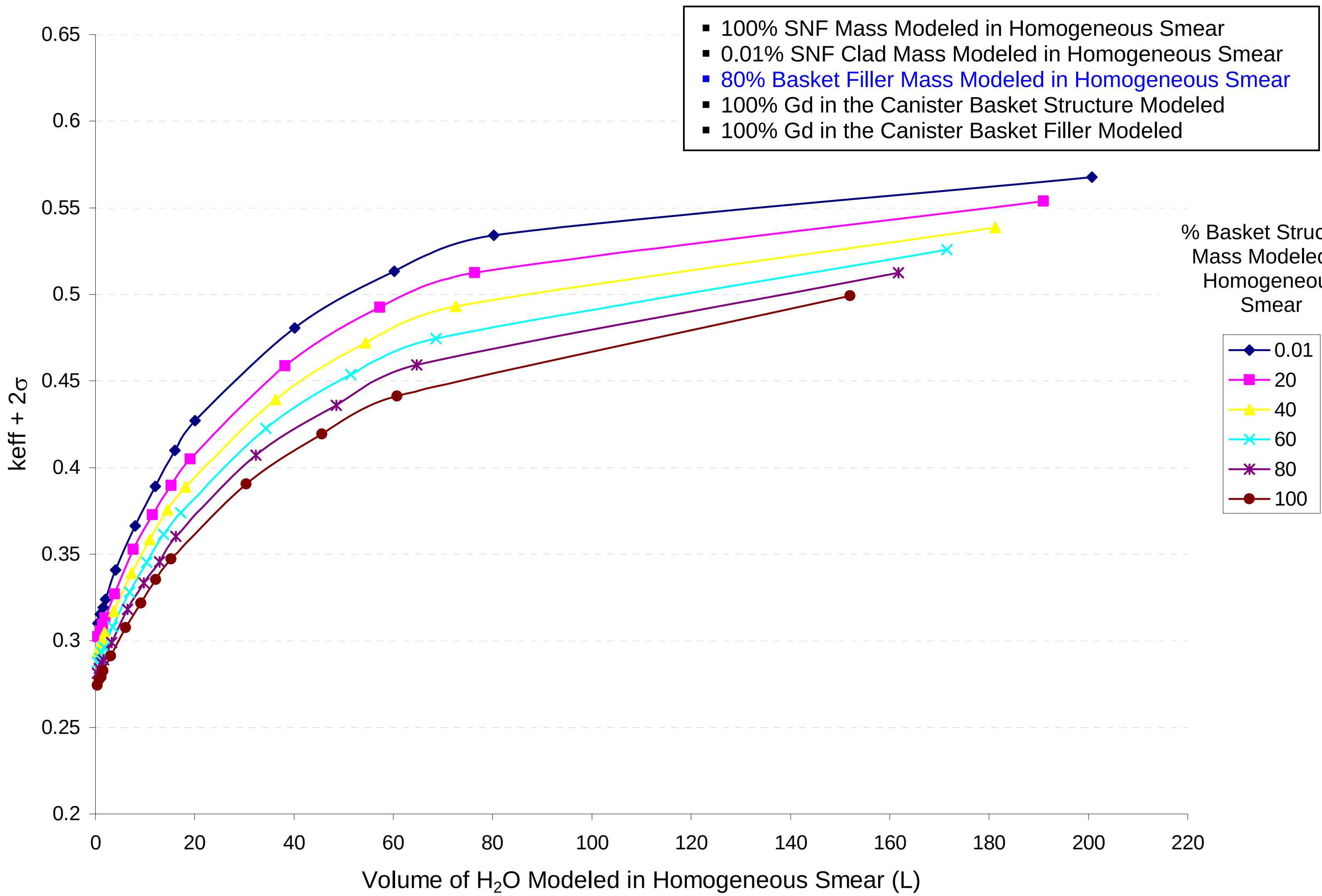
Source: Original

Figure 7-85: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



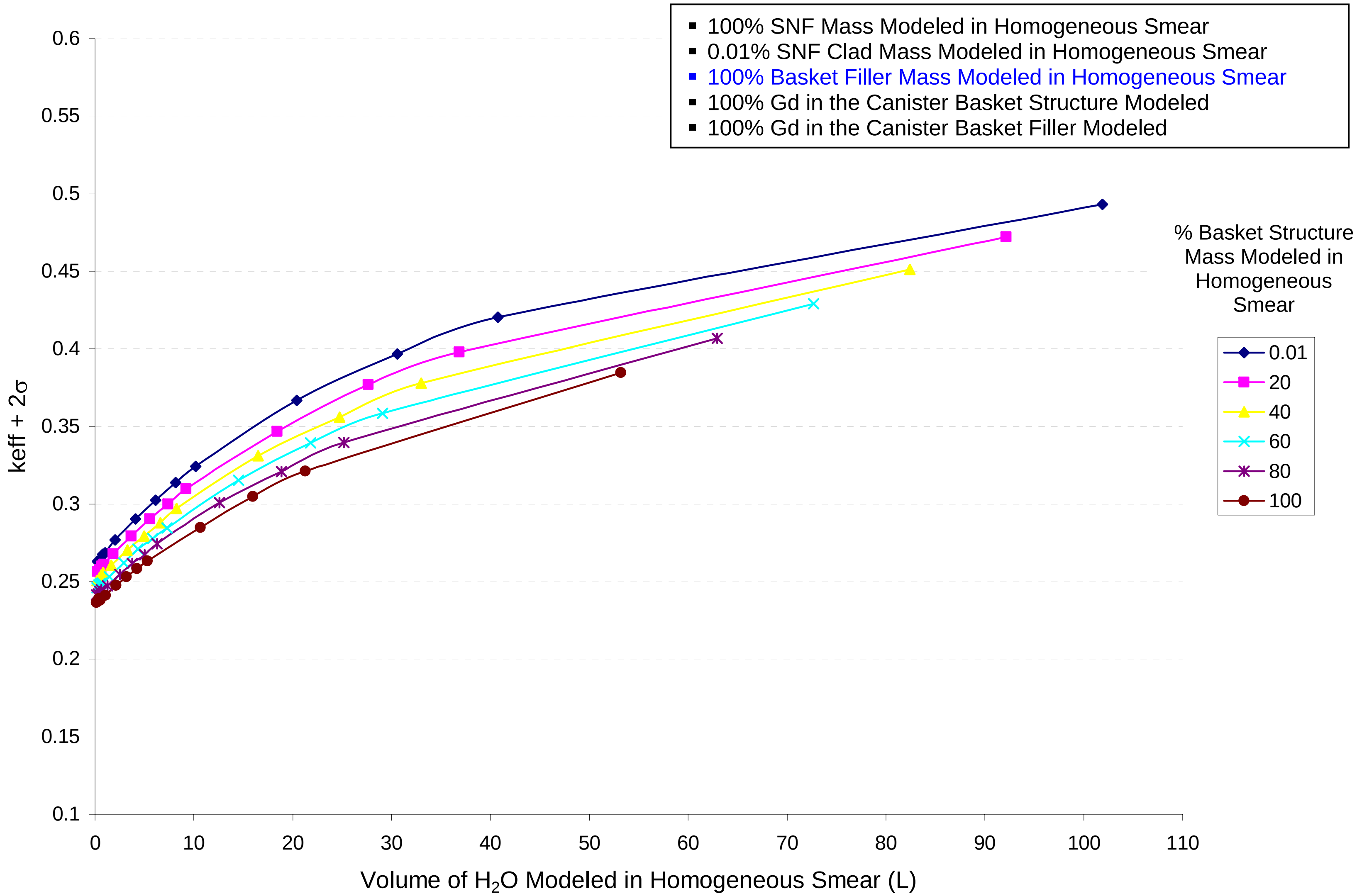
Source: Original

Figure 7-86: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



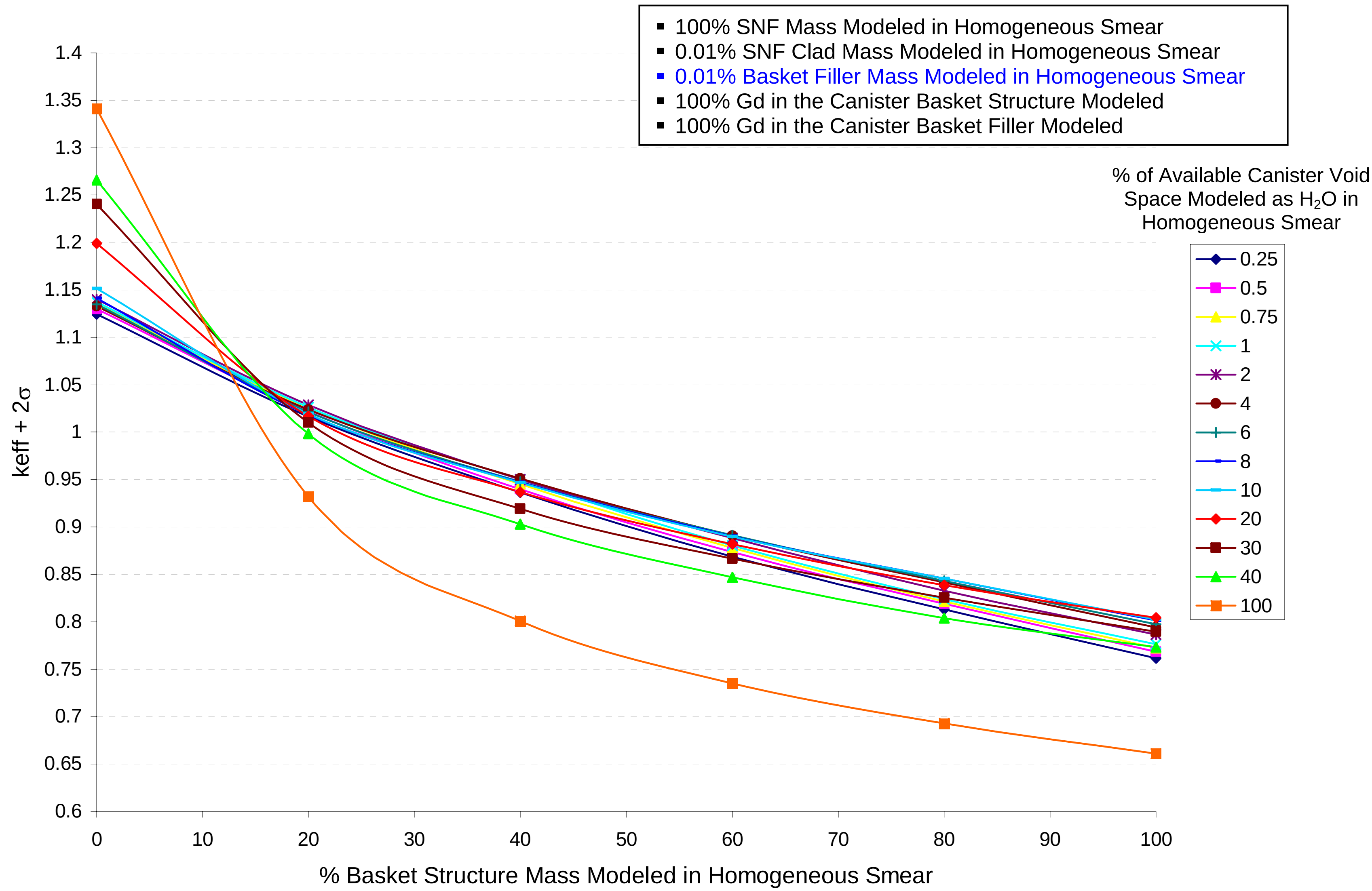
Source: Original

Figure 7-87: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



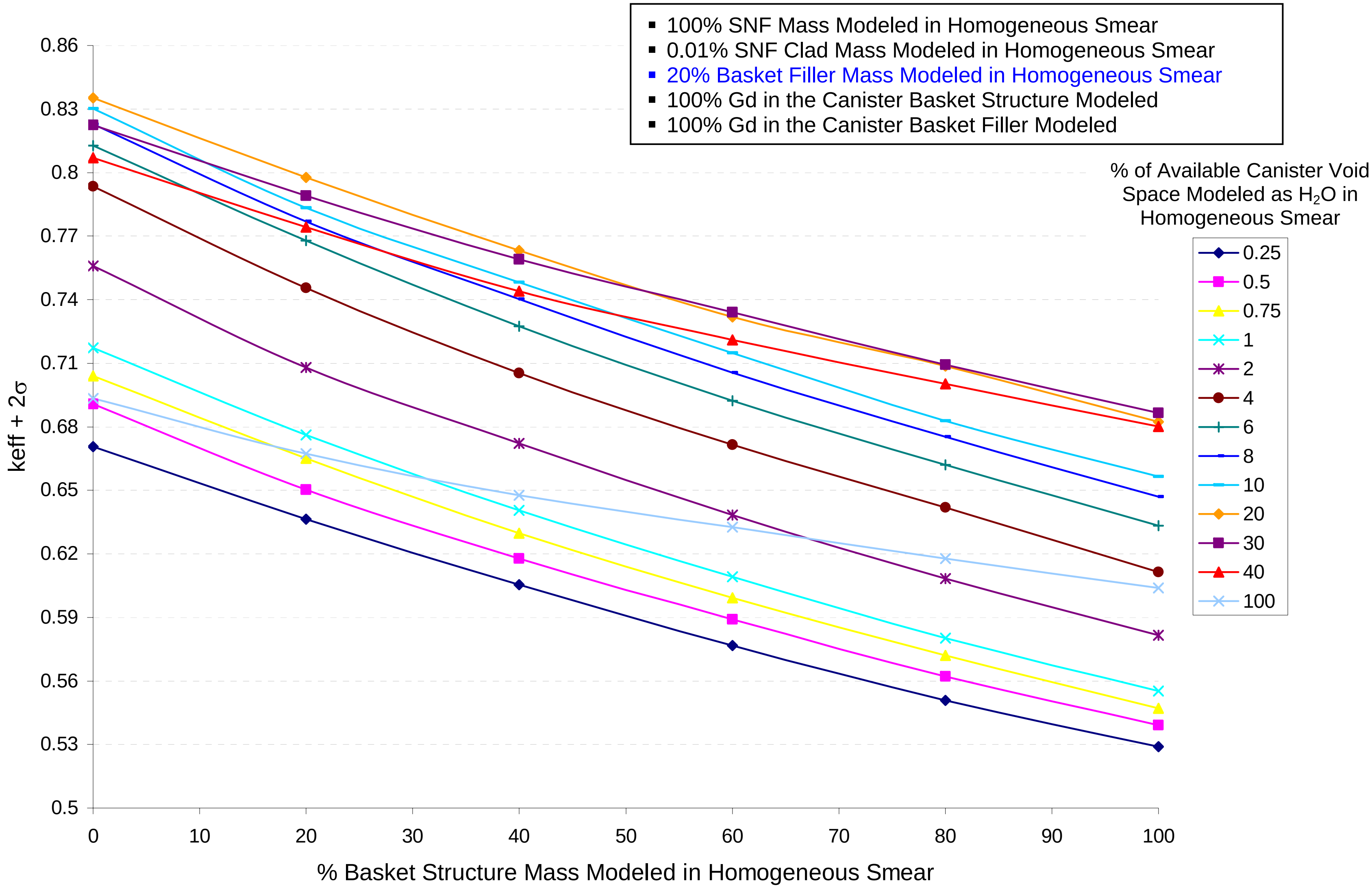
Source: Original

Figure 7-88: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



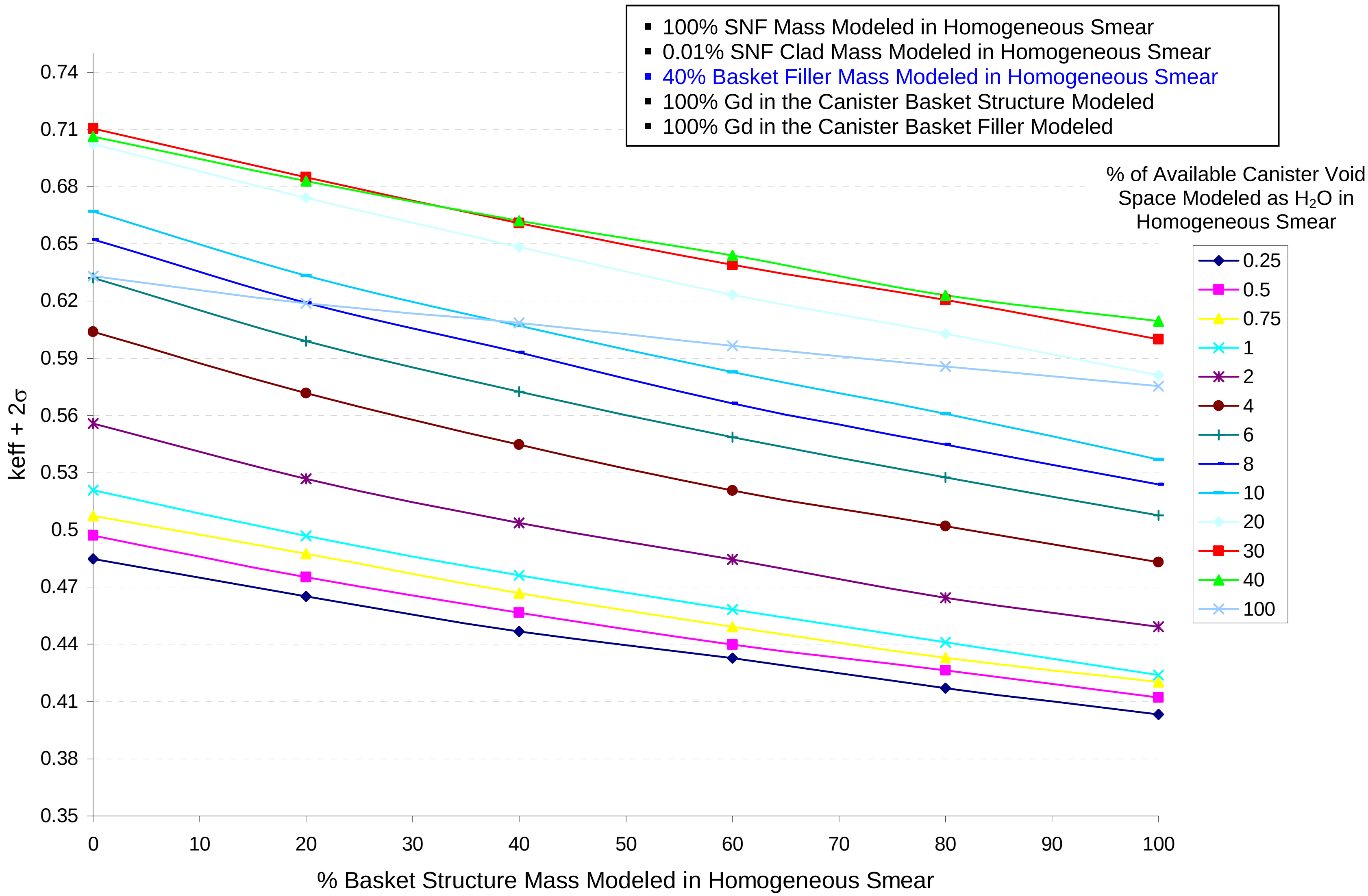
Source: Original

Figure 7-89: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



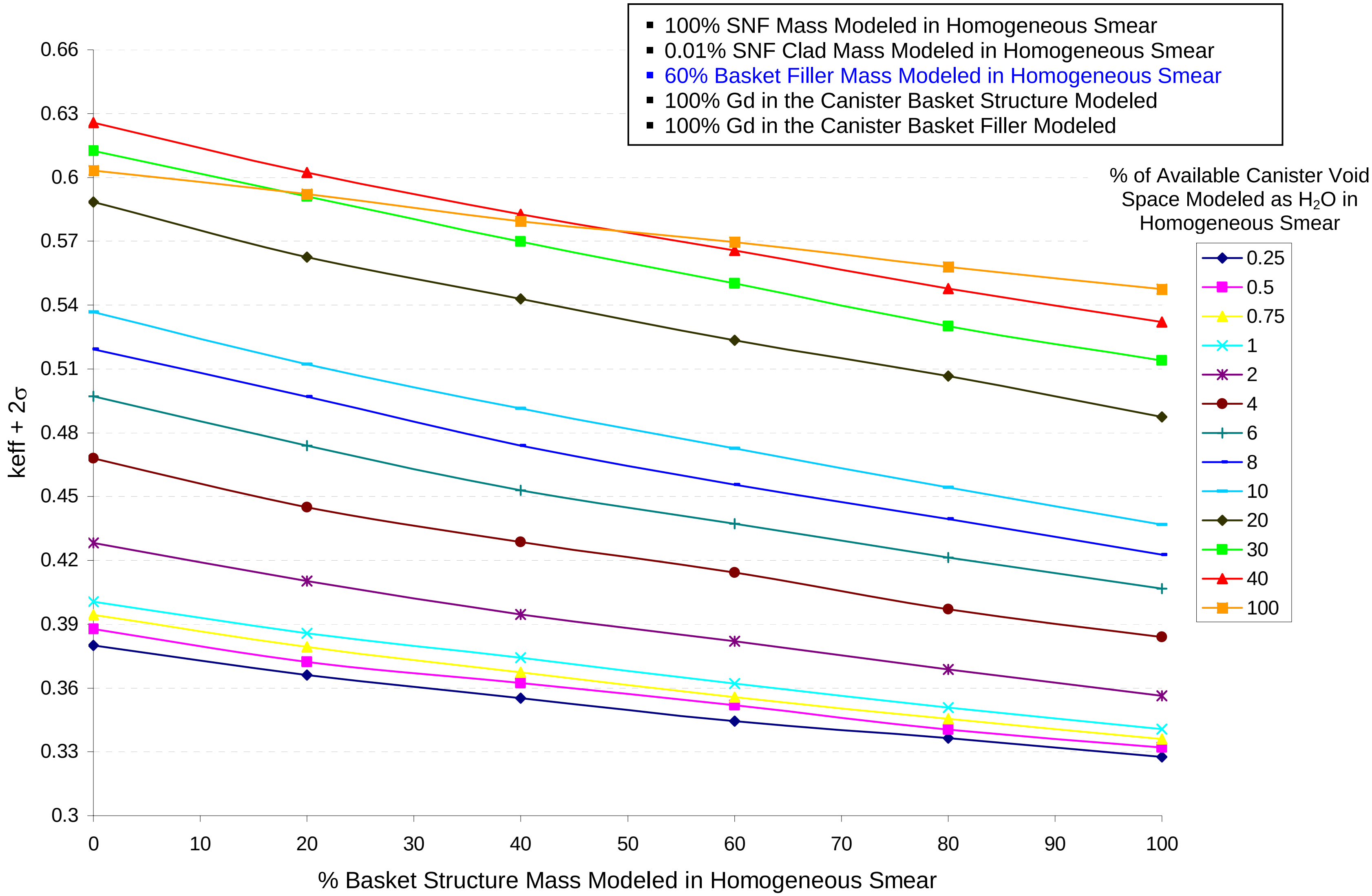
Source: Original

Figure 7-90: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



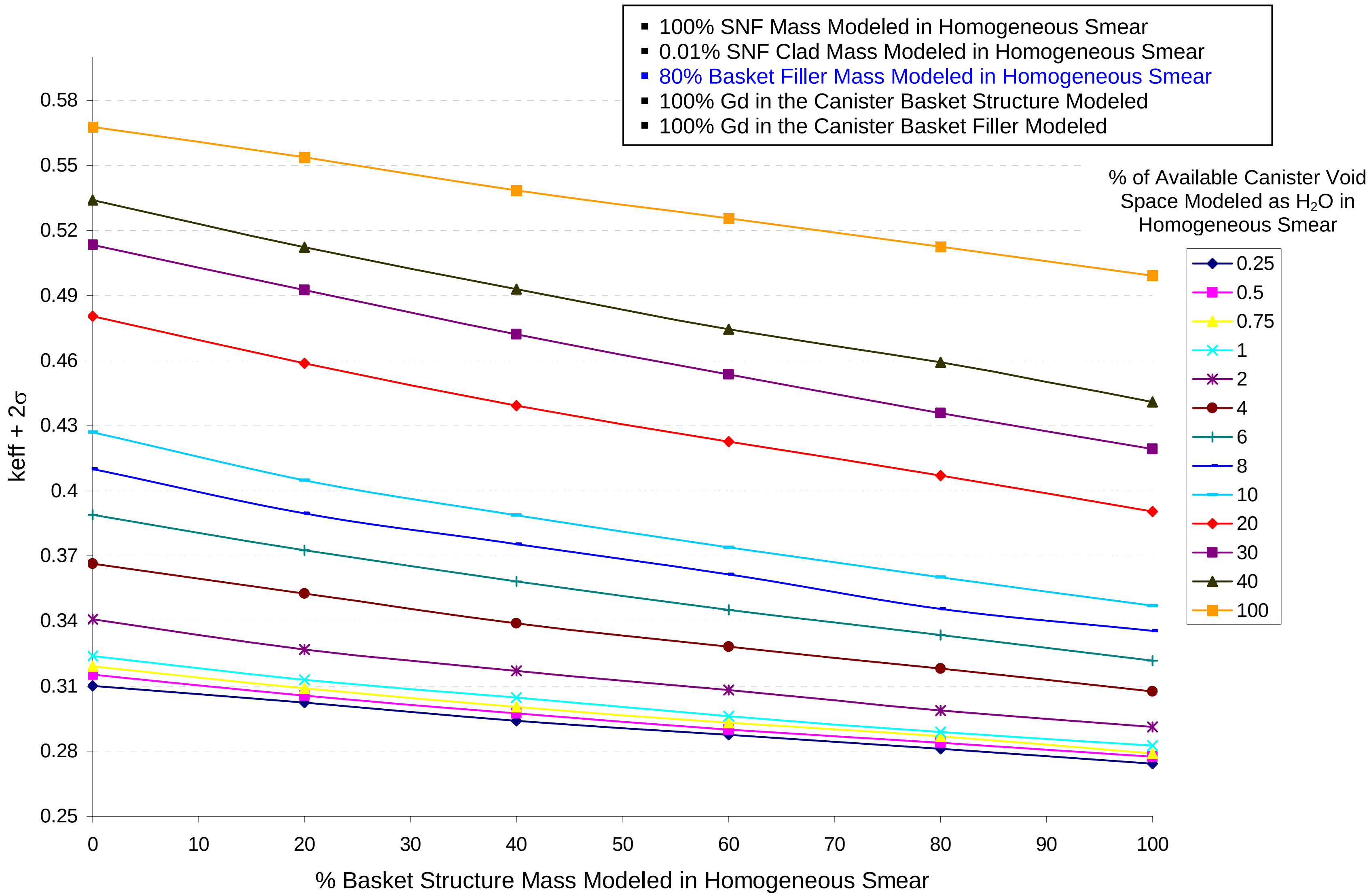
Source: Original

Figure 7-91: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



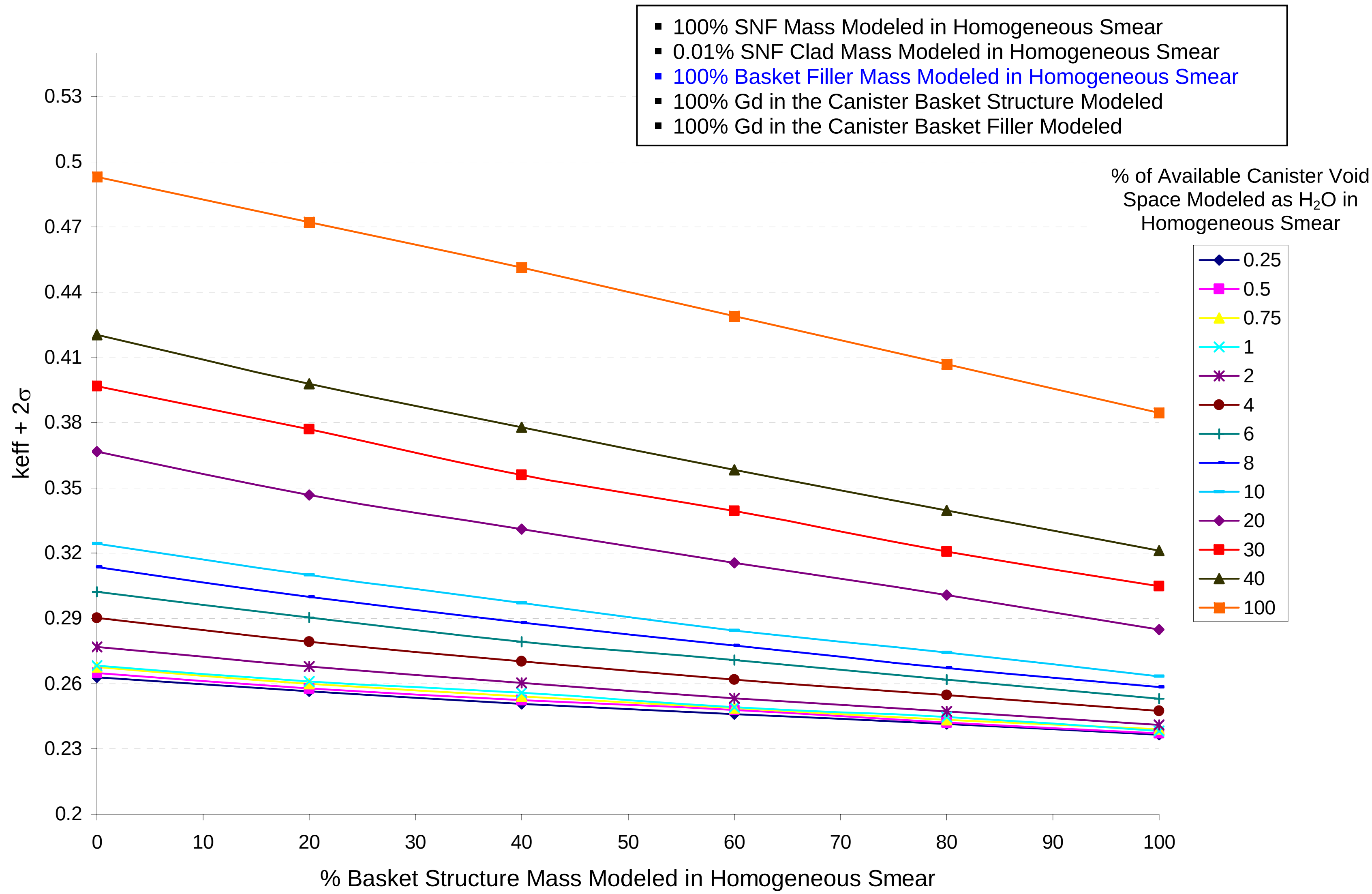
Source: Original

Figure 7-92: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



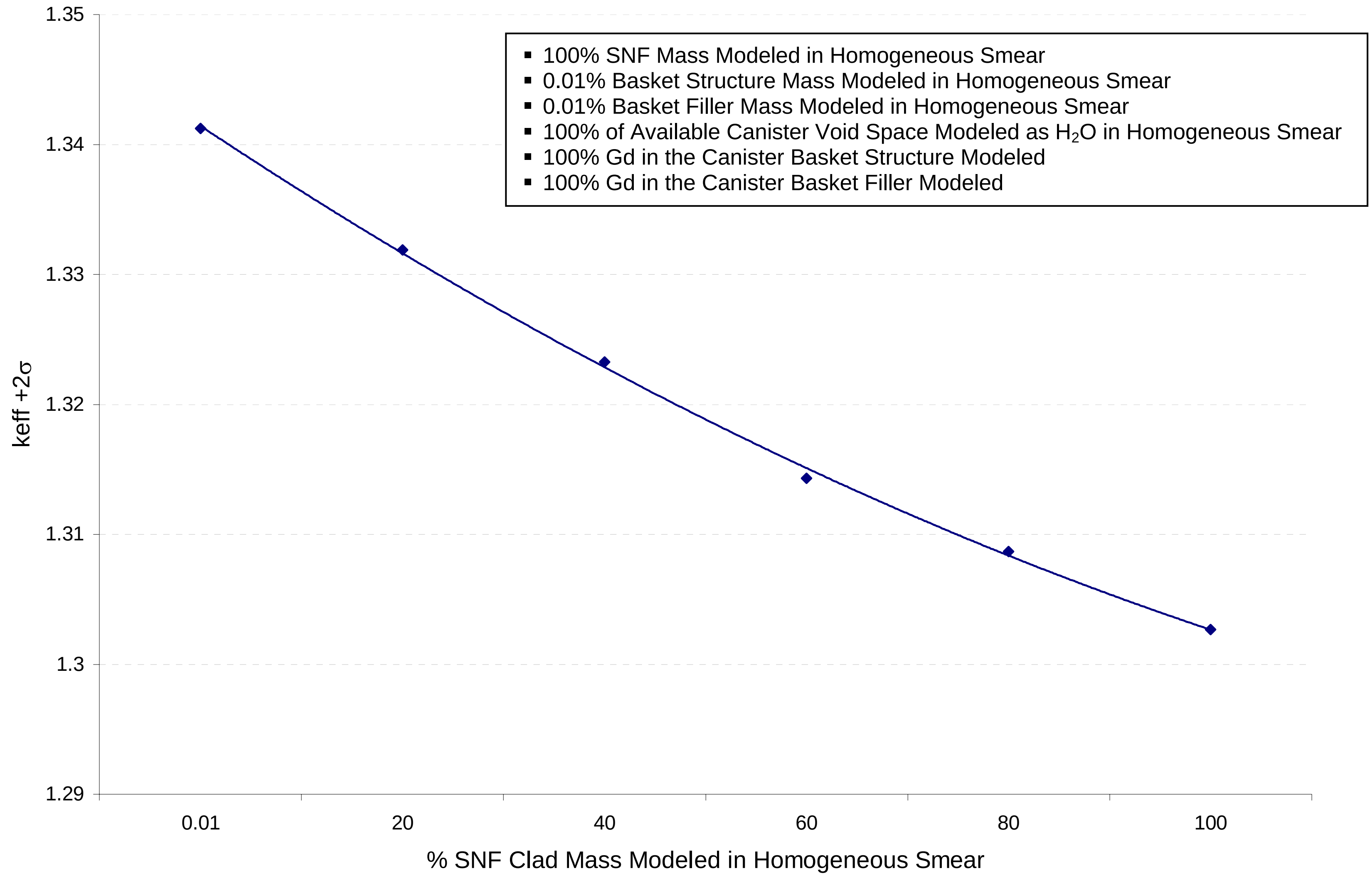
Source: Original

Figure 7-93: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



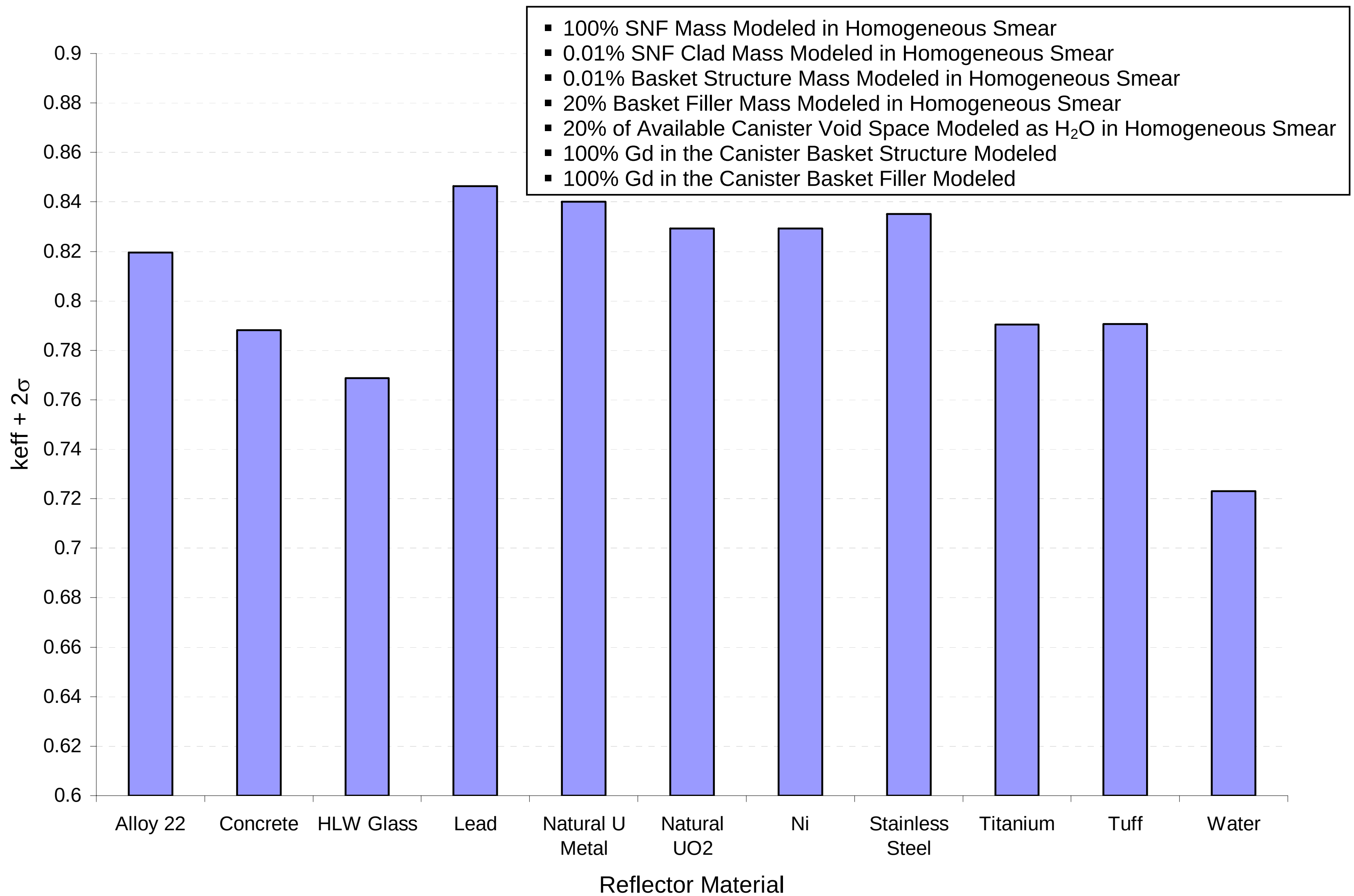
Source: Original

Figure 7-94: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



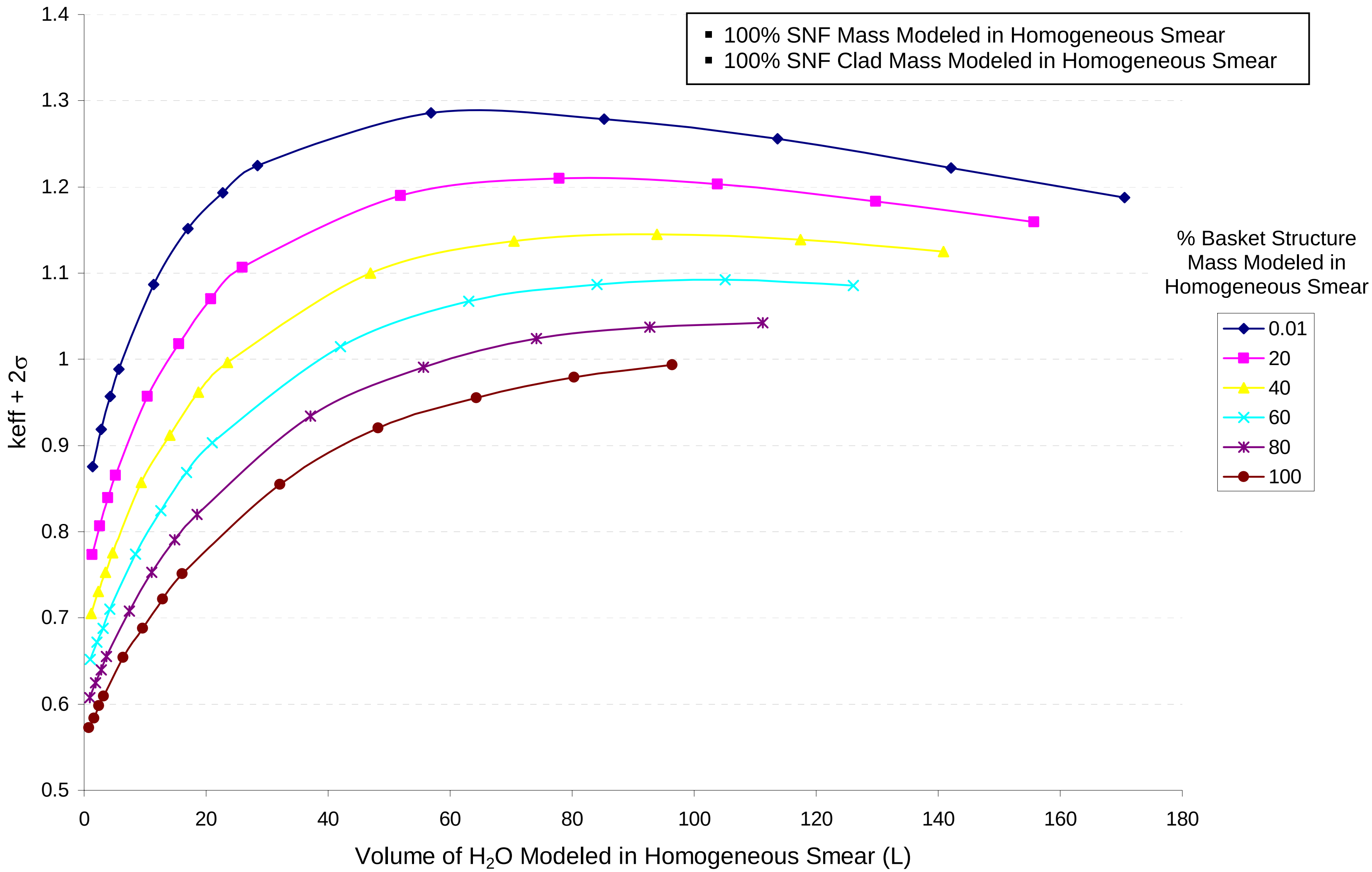
Source: Original

Figure 7-95: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



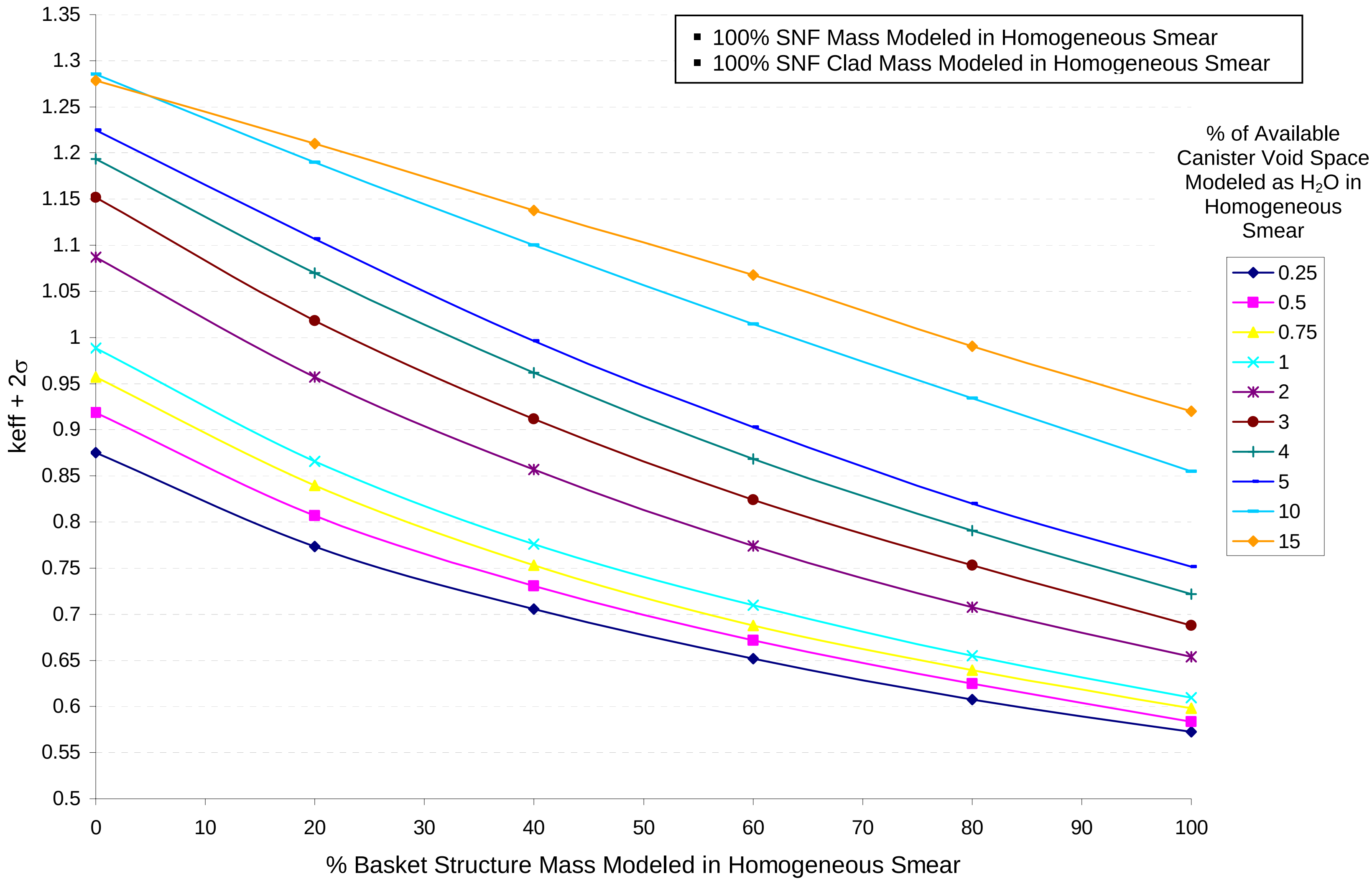
Source: Original

Figure 7-96: keff+2σ values for an individual fully water flooded, damaged and degraded, FFTF DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



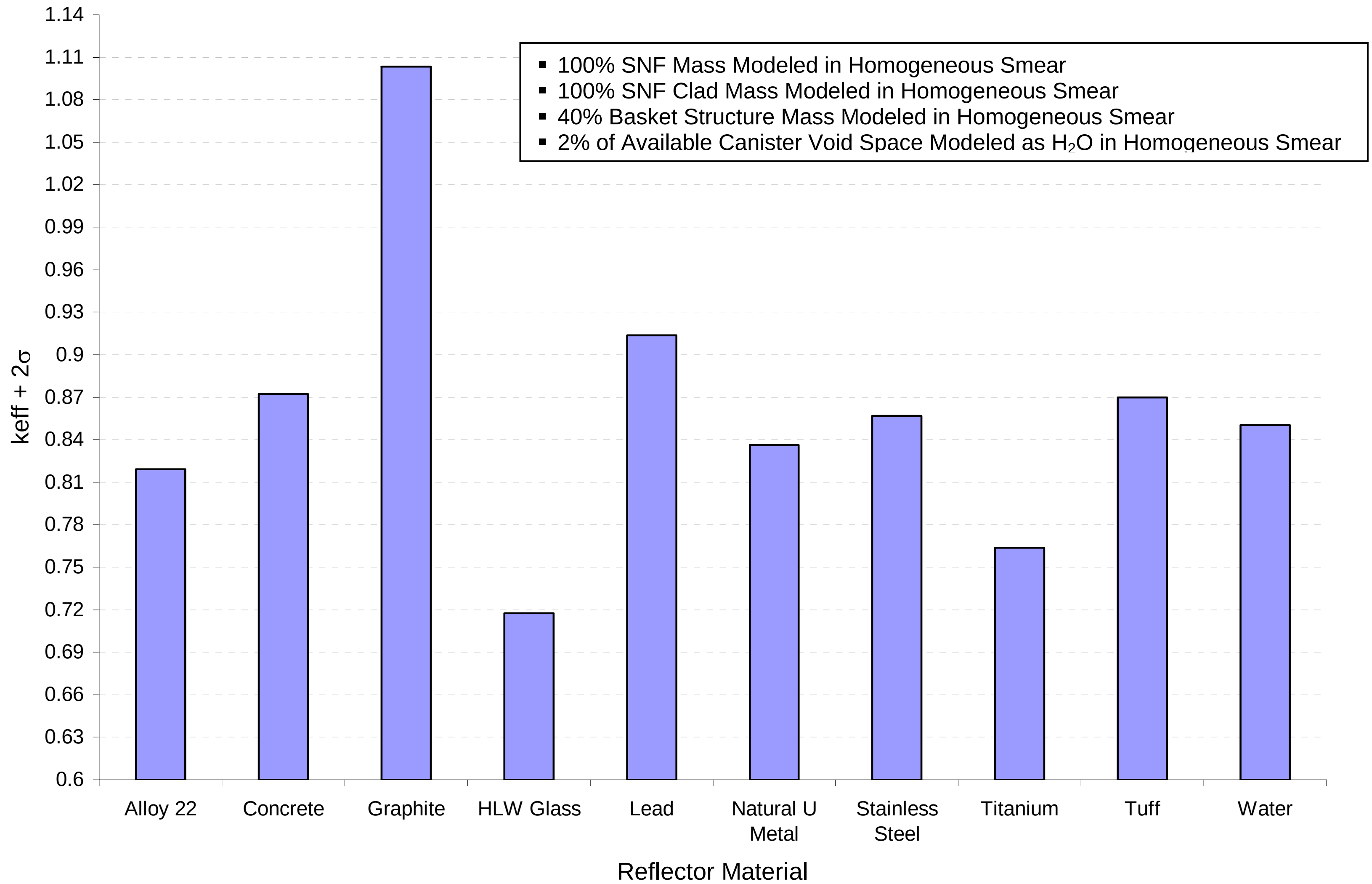
Source: Original

Figure 7-97: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, FSV DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



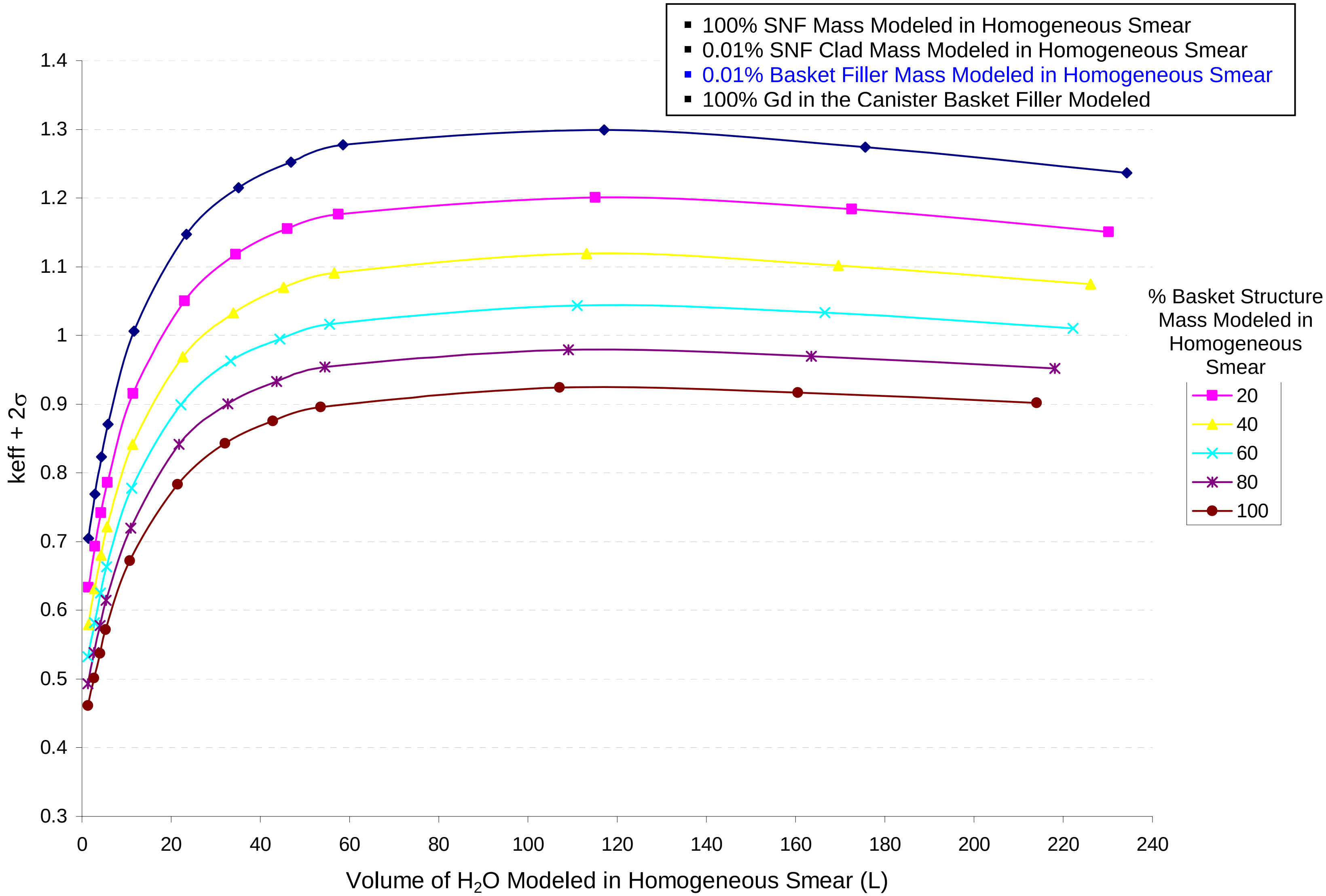
Source: Original

Figure 7-98: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, FSV DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



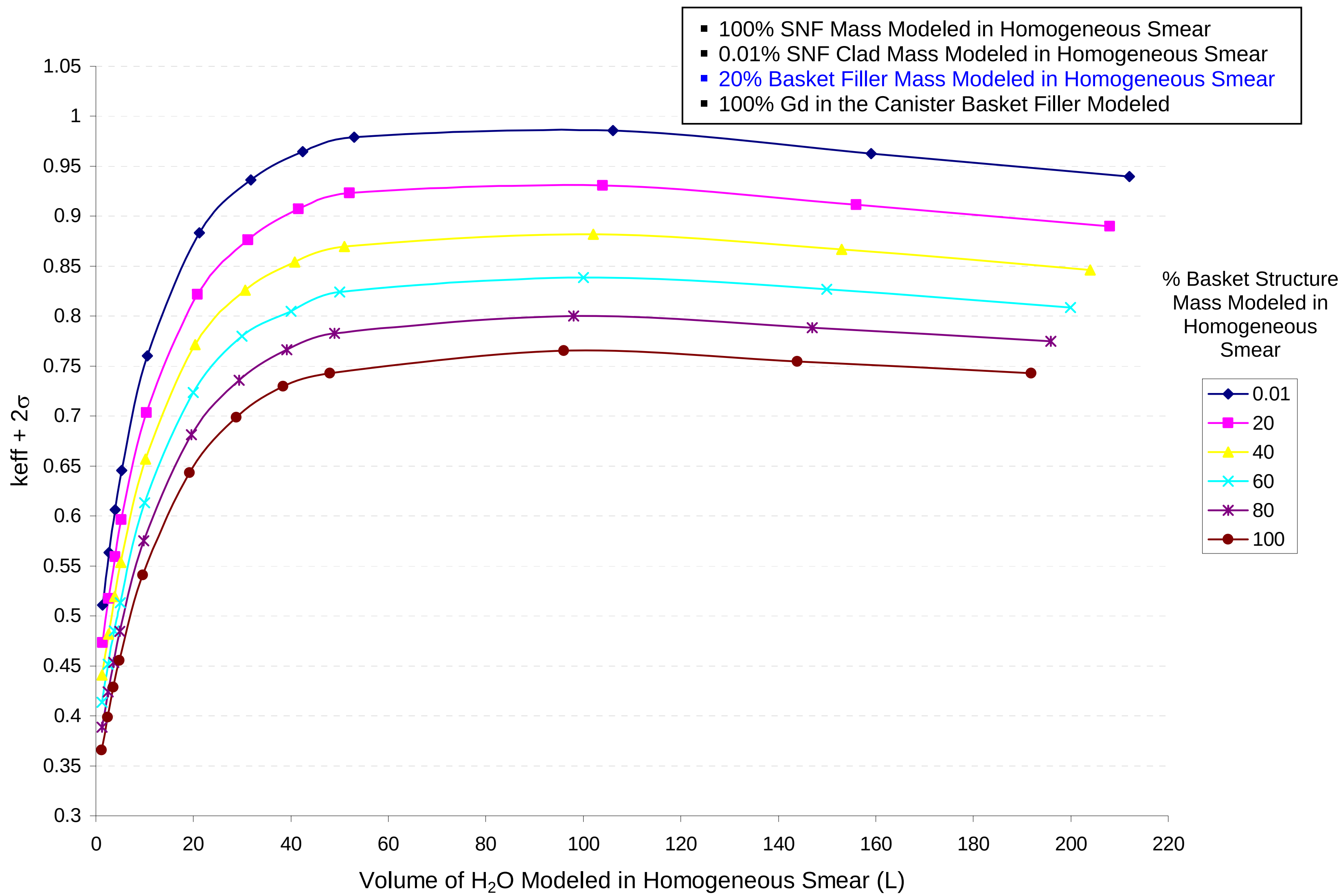
Source: Original

Figure 7-99: keff+2σ values for an individual fully water flooded, damaged and degraded, FSV DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



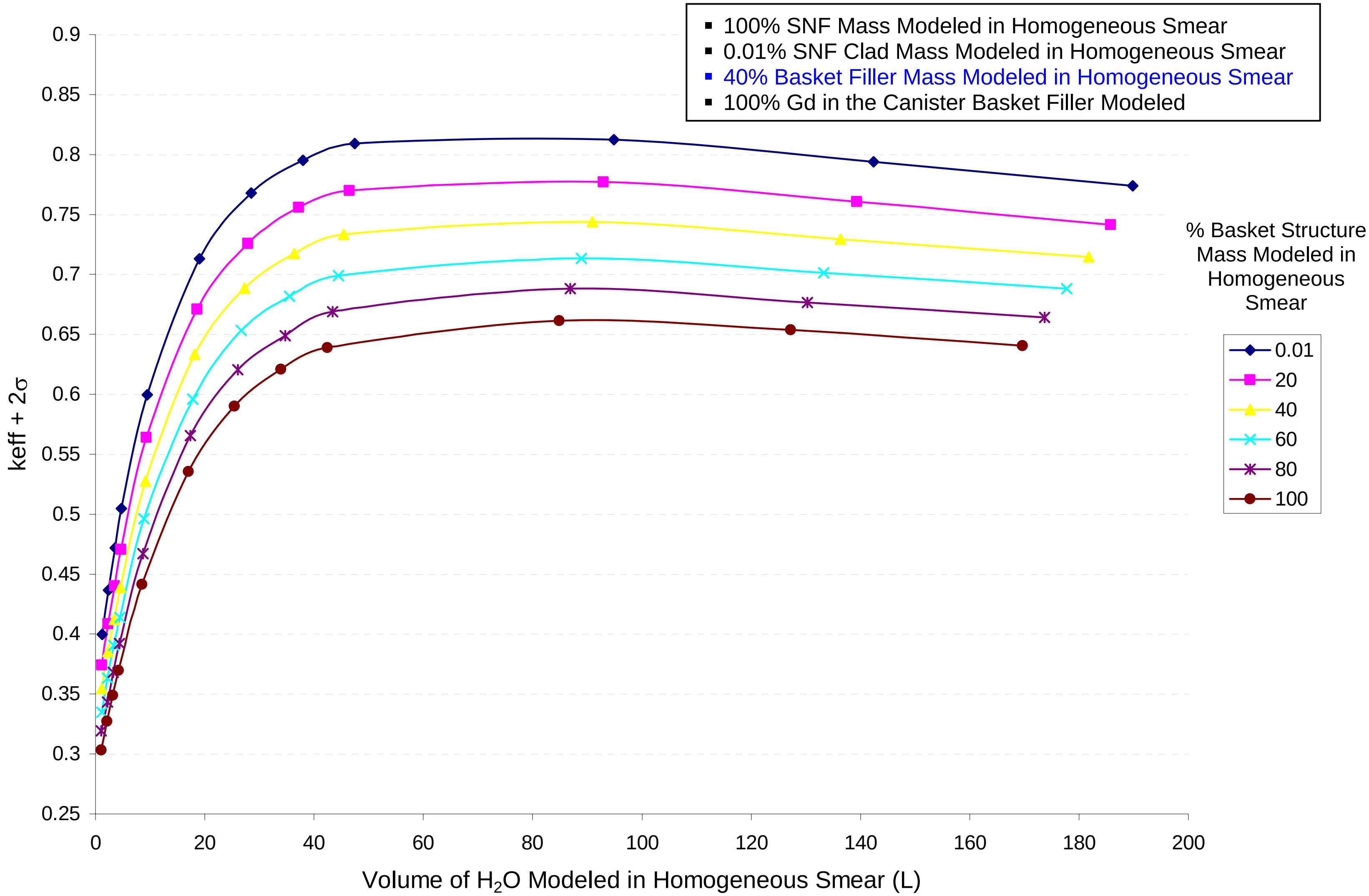
Source: Original

Figure 7-100: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



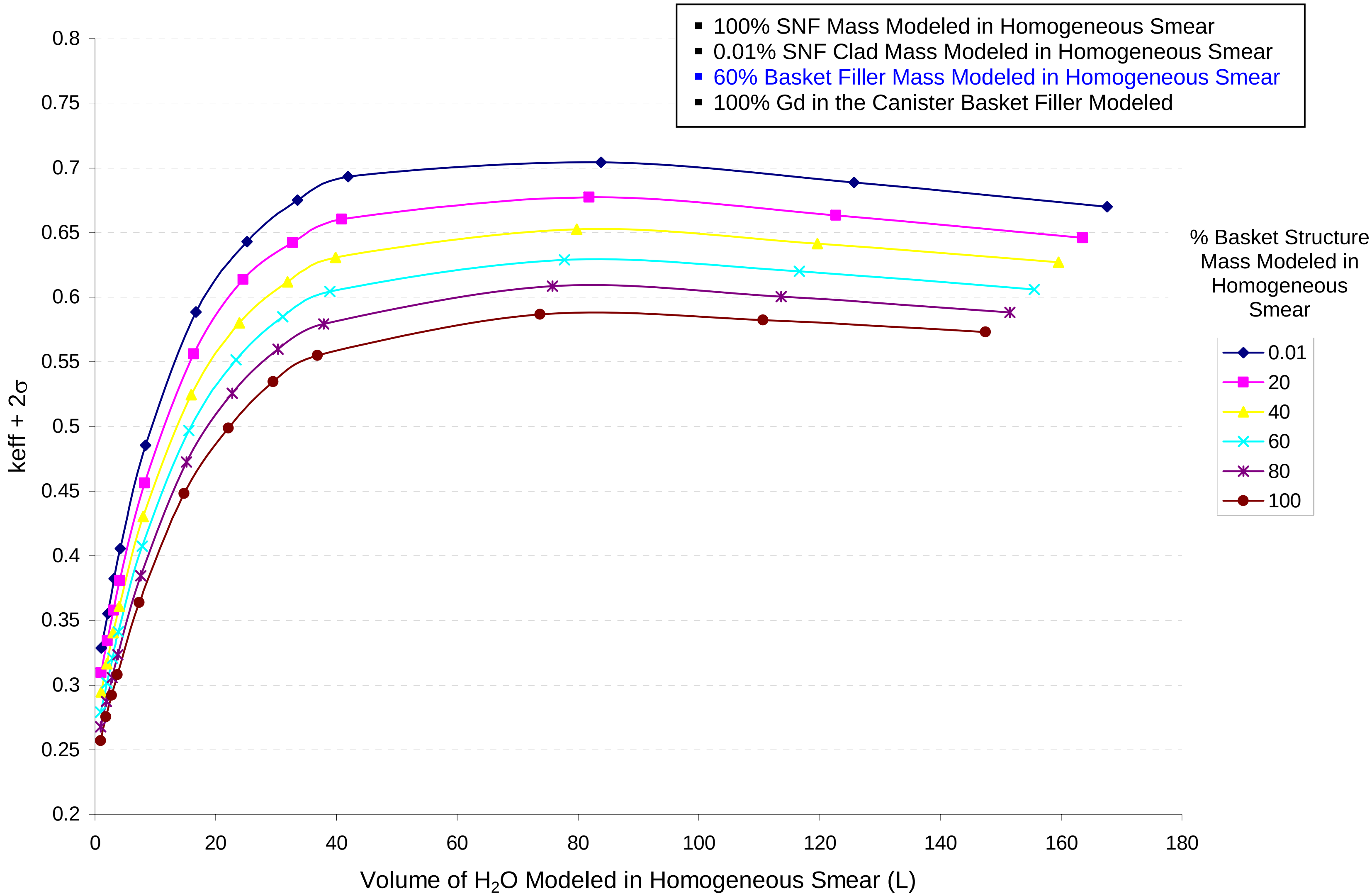
Source: Original

Figure 7-101: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



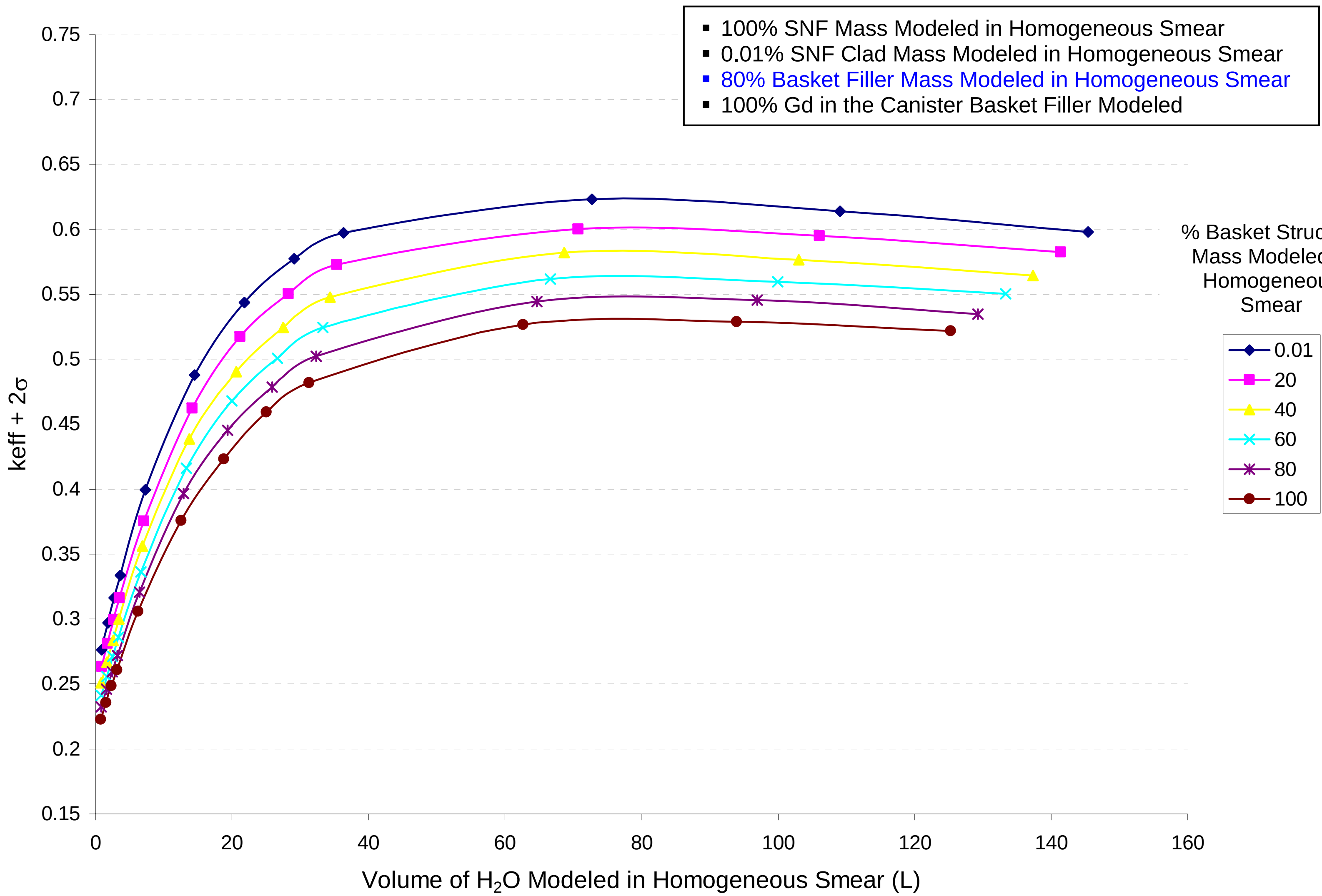
Source: Original

Figure 7-102: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



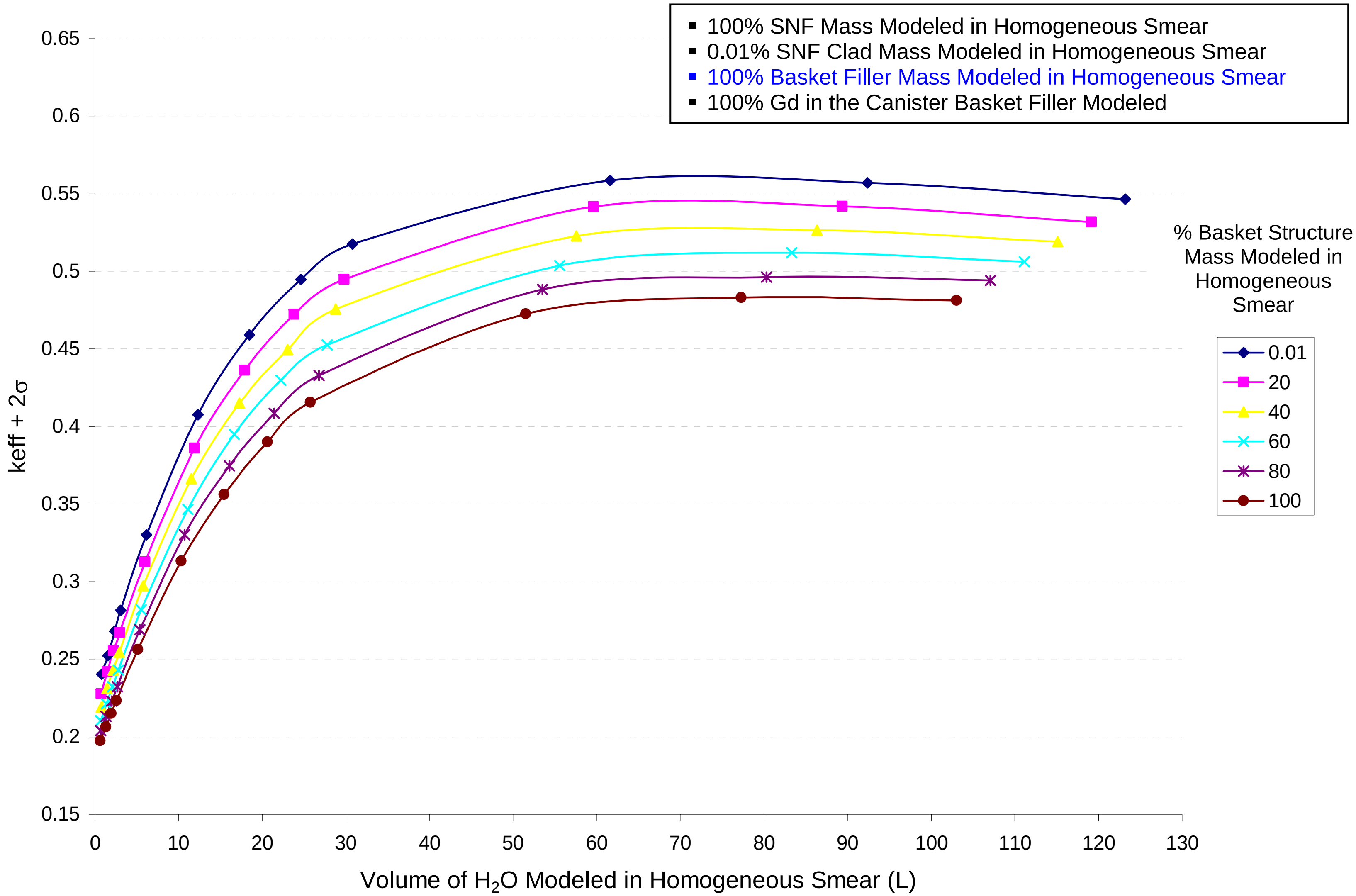
Source: Original

Figure 7-103: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



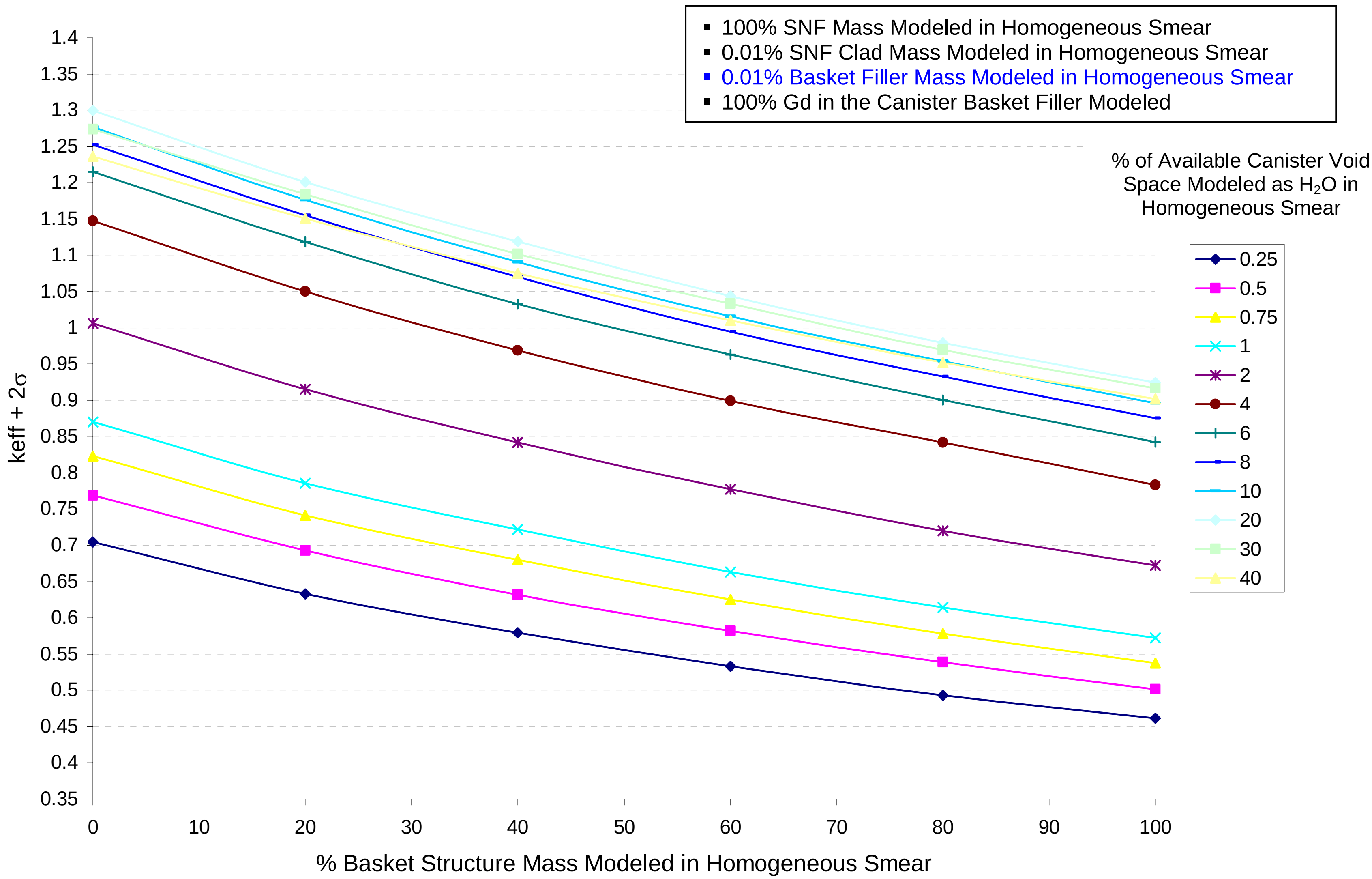
Source: Original

Figure 7-104: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



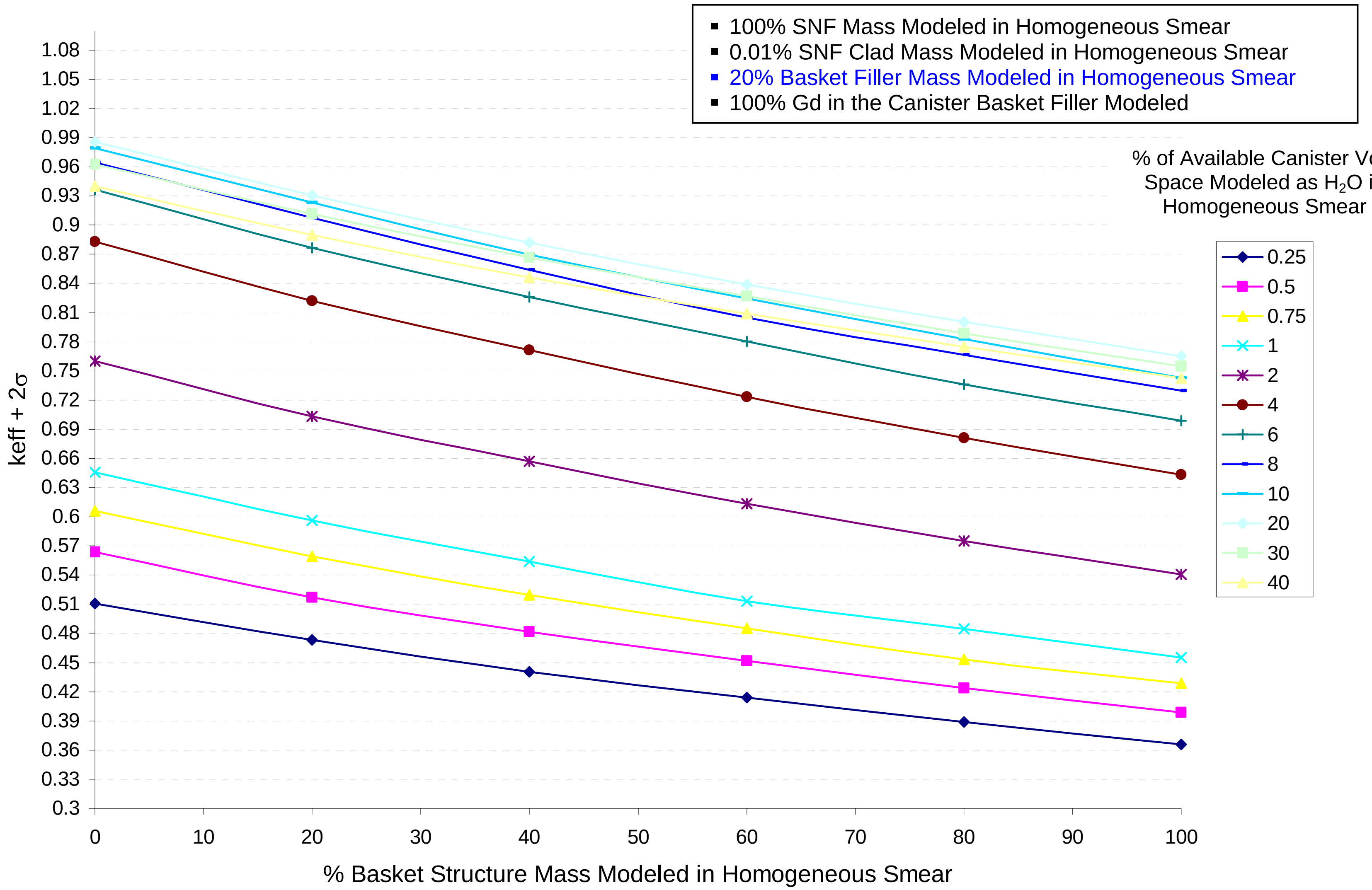
Source: Original

Figure 7-105: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



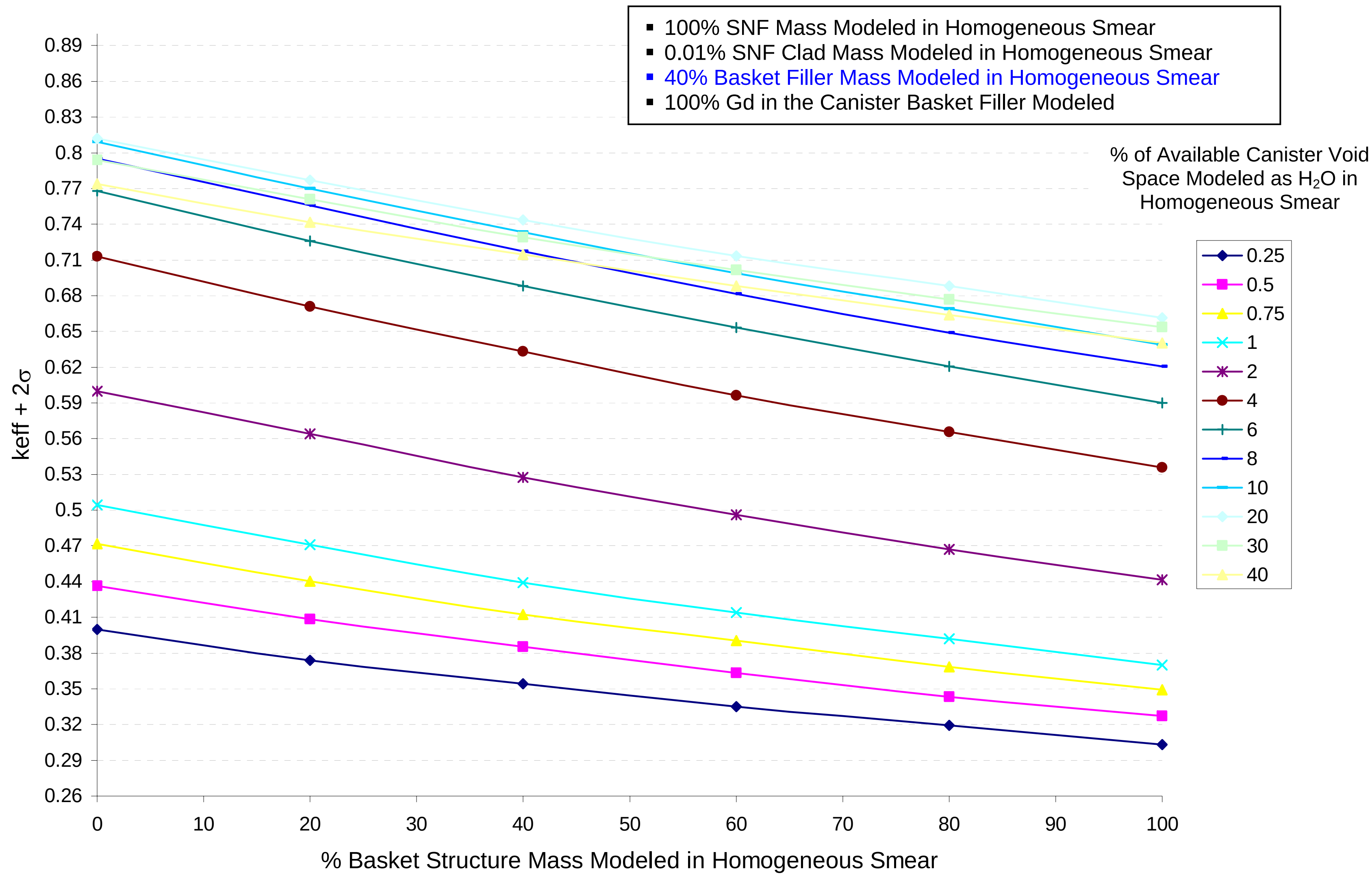
Source: Original

Figure 7-106: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



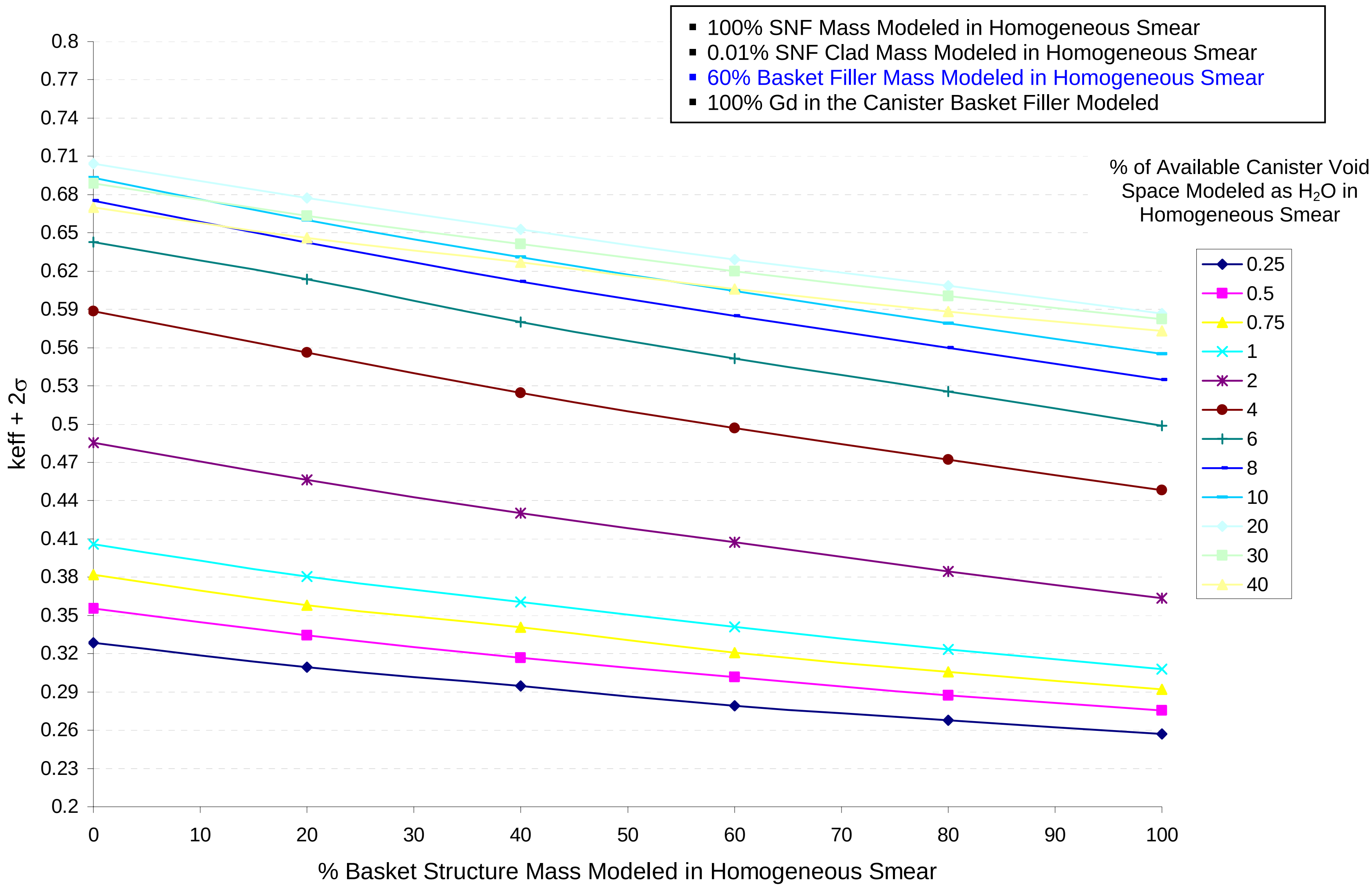
Source: Original

Figure 7-107: keff+2σ values (as a function of basket structure mass and H2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



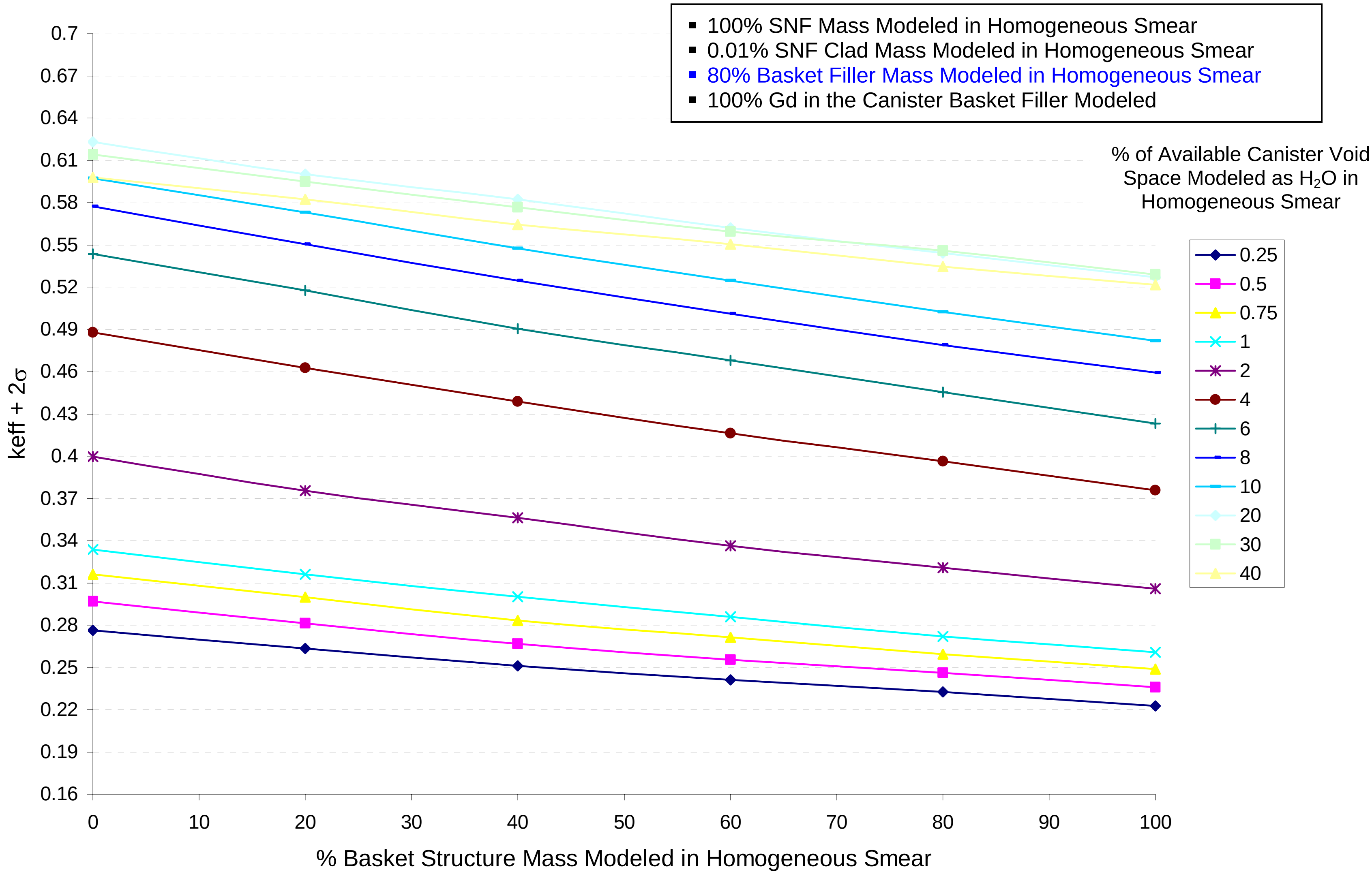
Source: Original

Figure 7-108: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



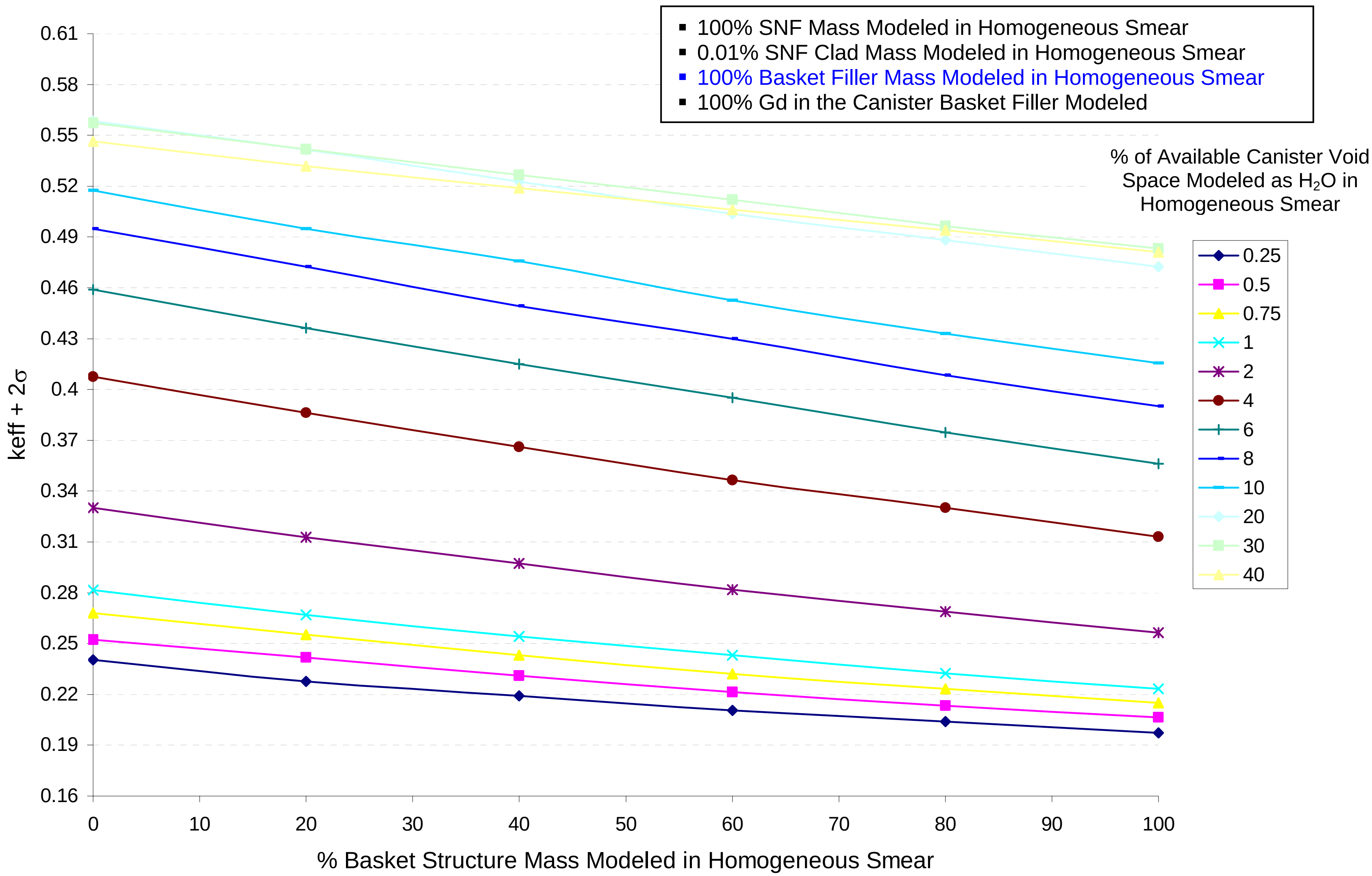
Source: Original

Figure 7-109: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



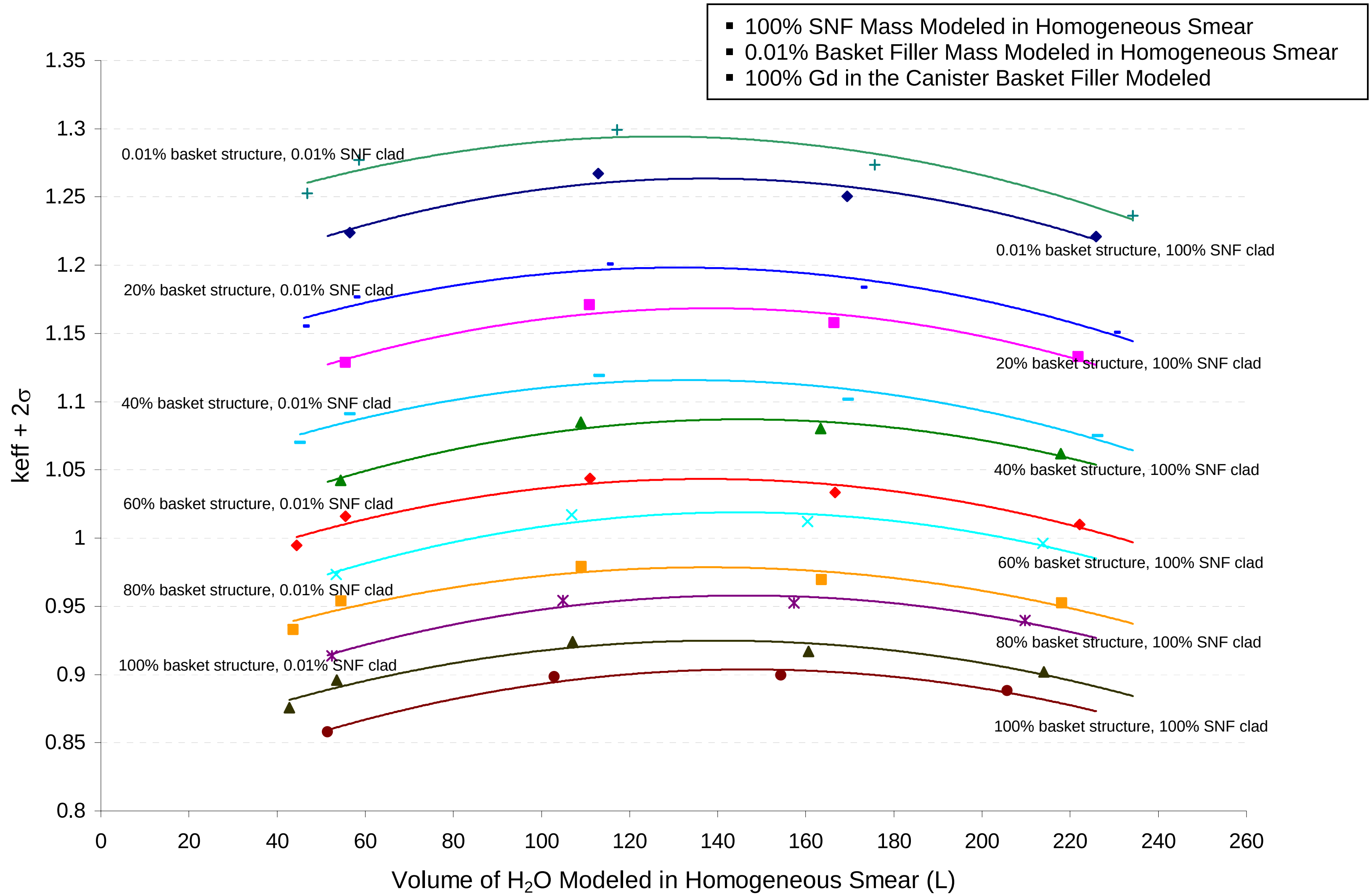
Source: Original

Figure 7-110: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



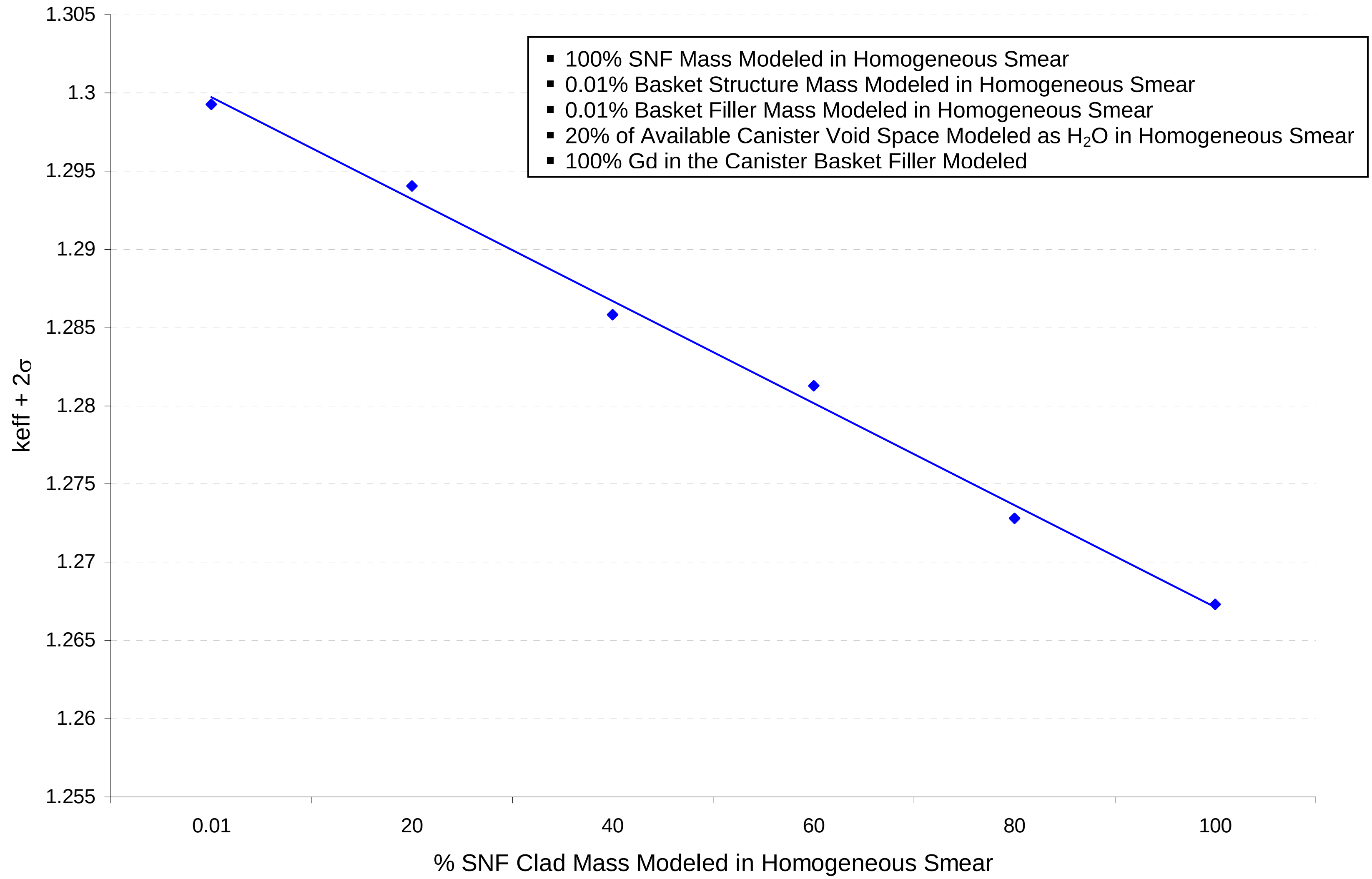
Source: Original

Figure 7-111: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



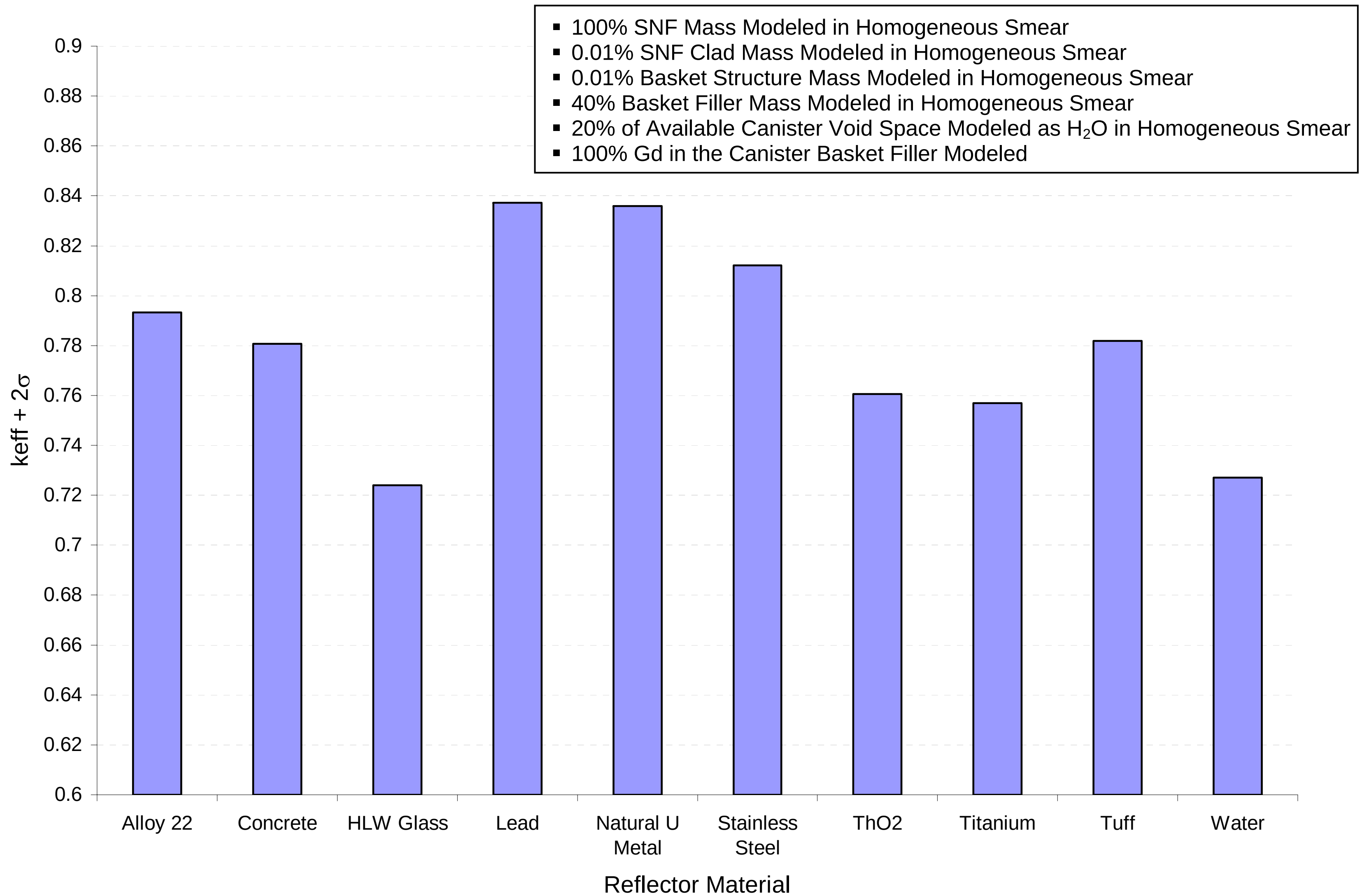
Source: Original

Figure 7-112: keff+2σ values (as a function of H_2O volume, basket structure mass, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



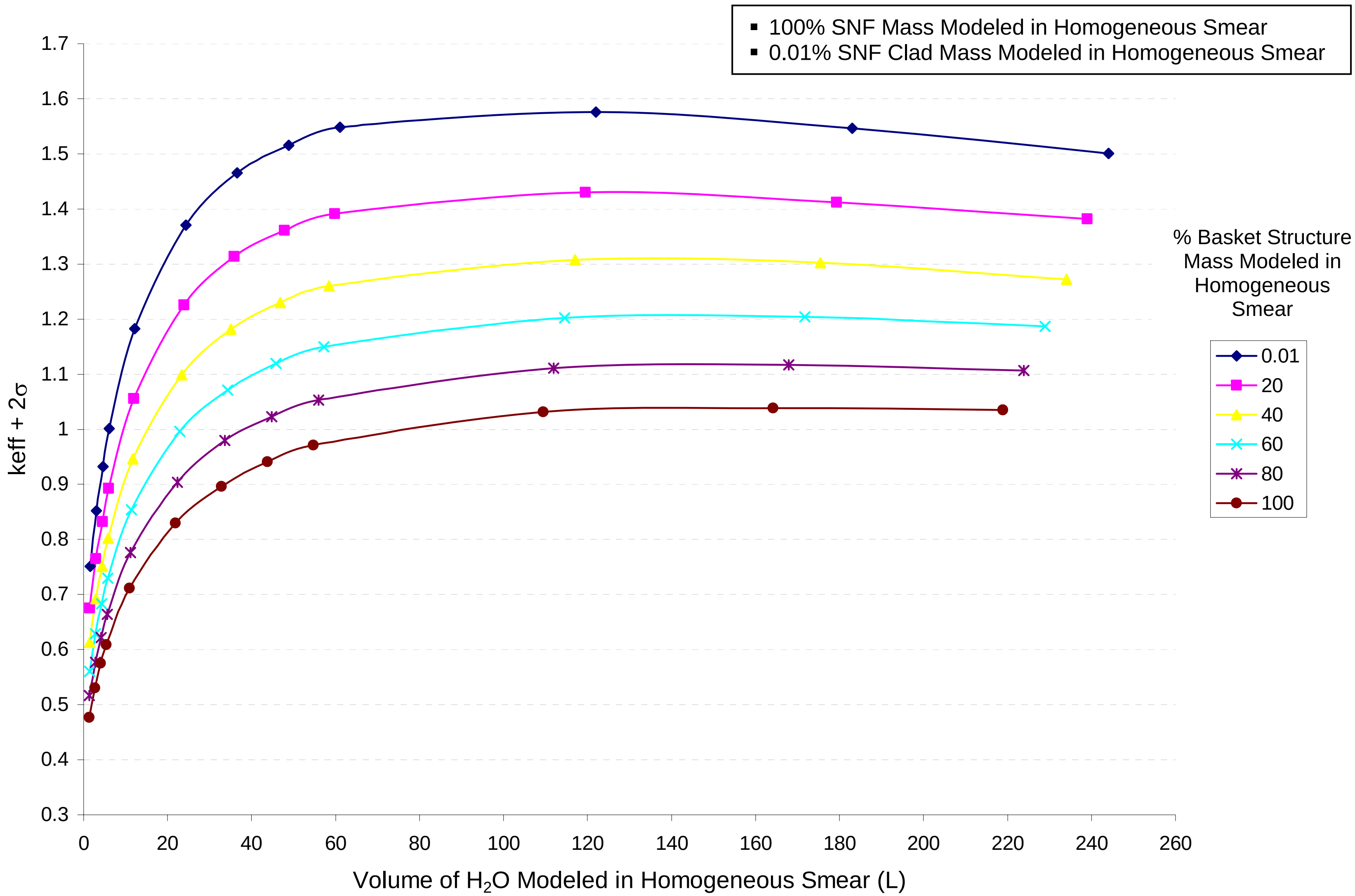
Source: Original

Figure 7-113: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



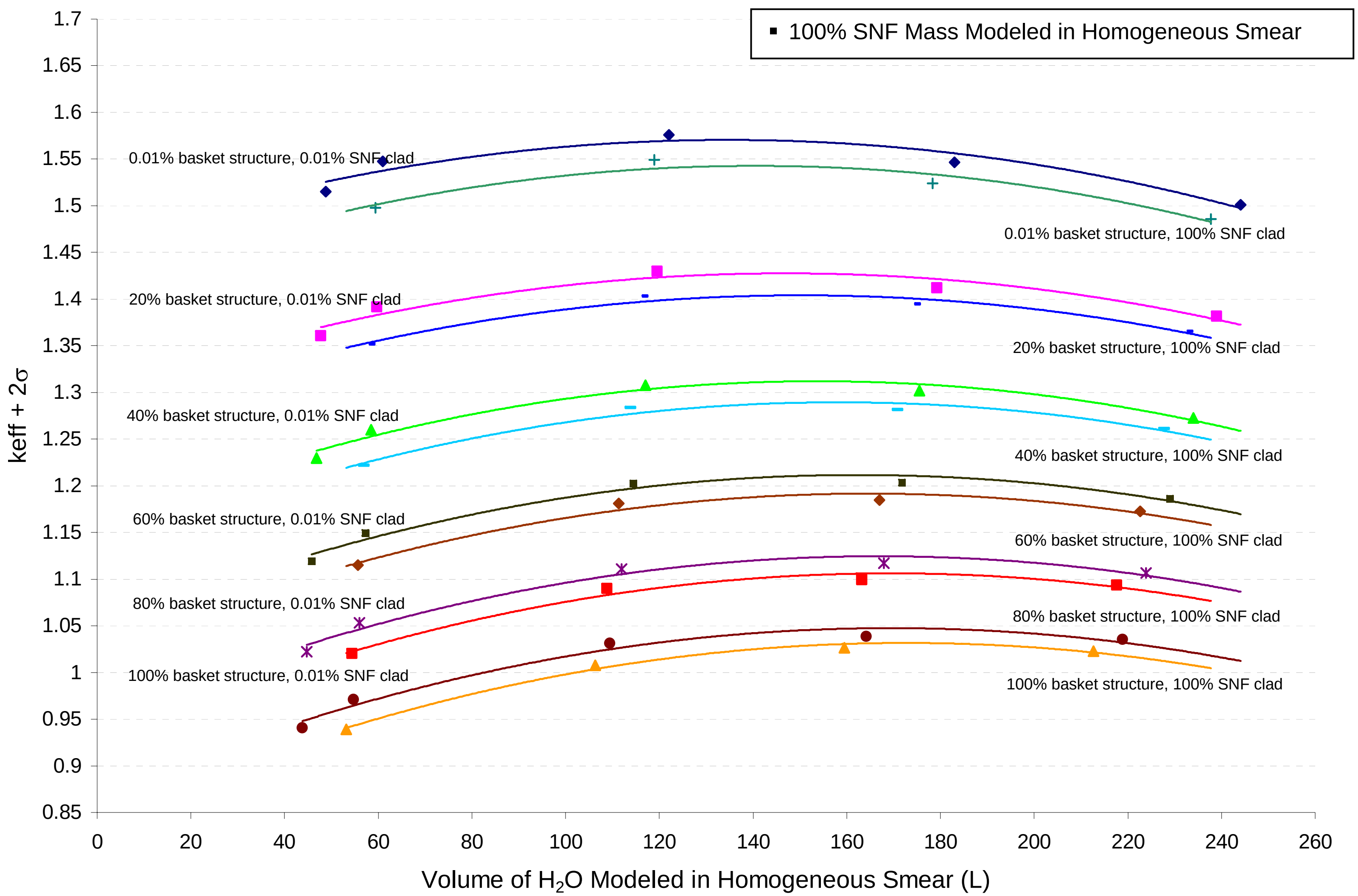
Source: Original

Figure 7-114: keff+2σ values for an individual fully water flooded, damaged and degraded, SLWBR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



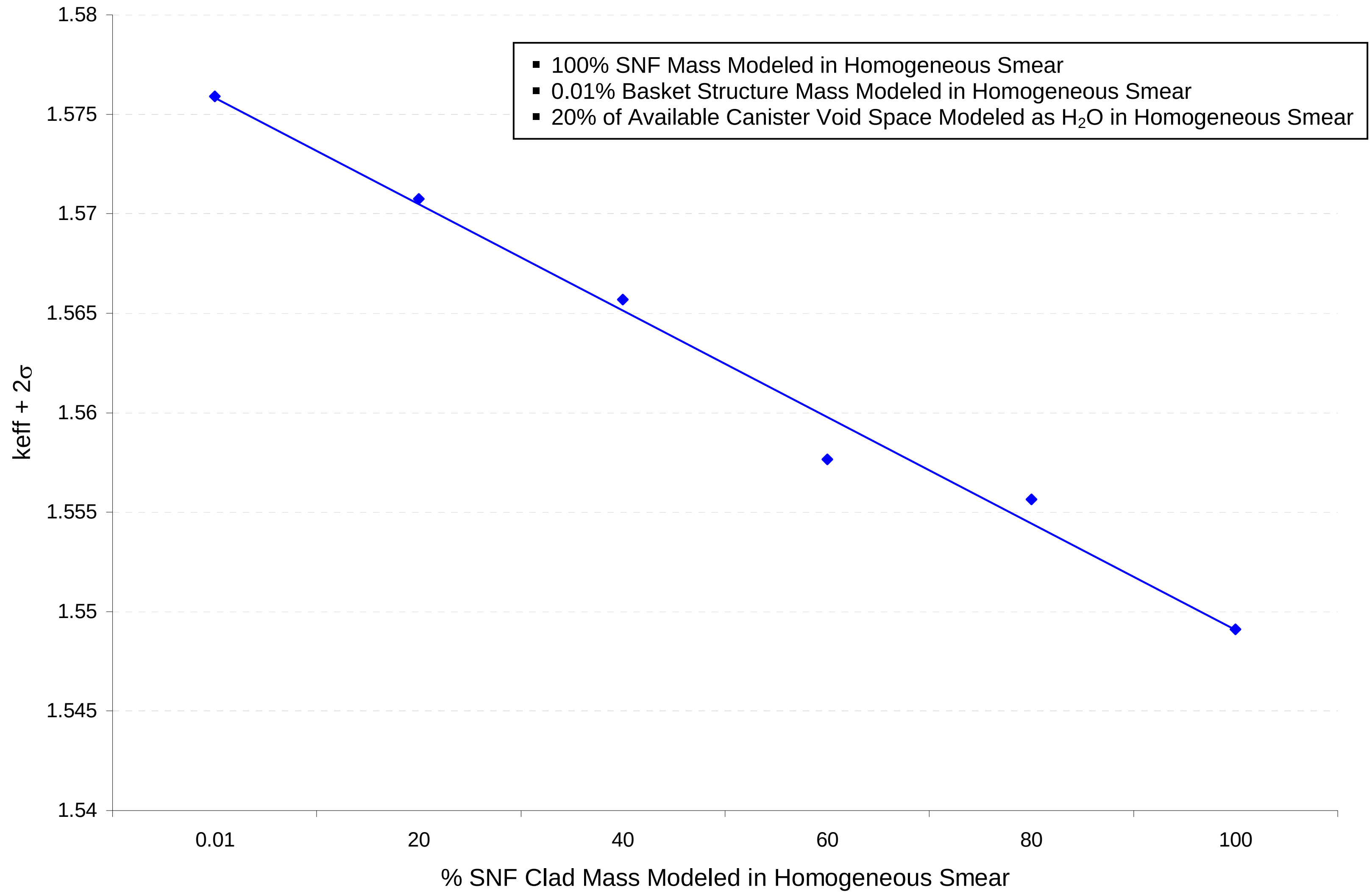
Source: Original

Figure 7-115: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



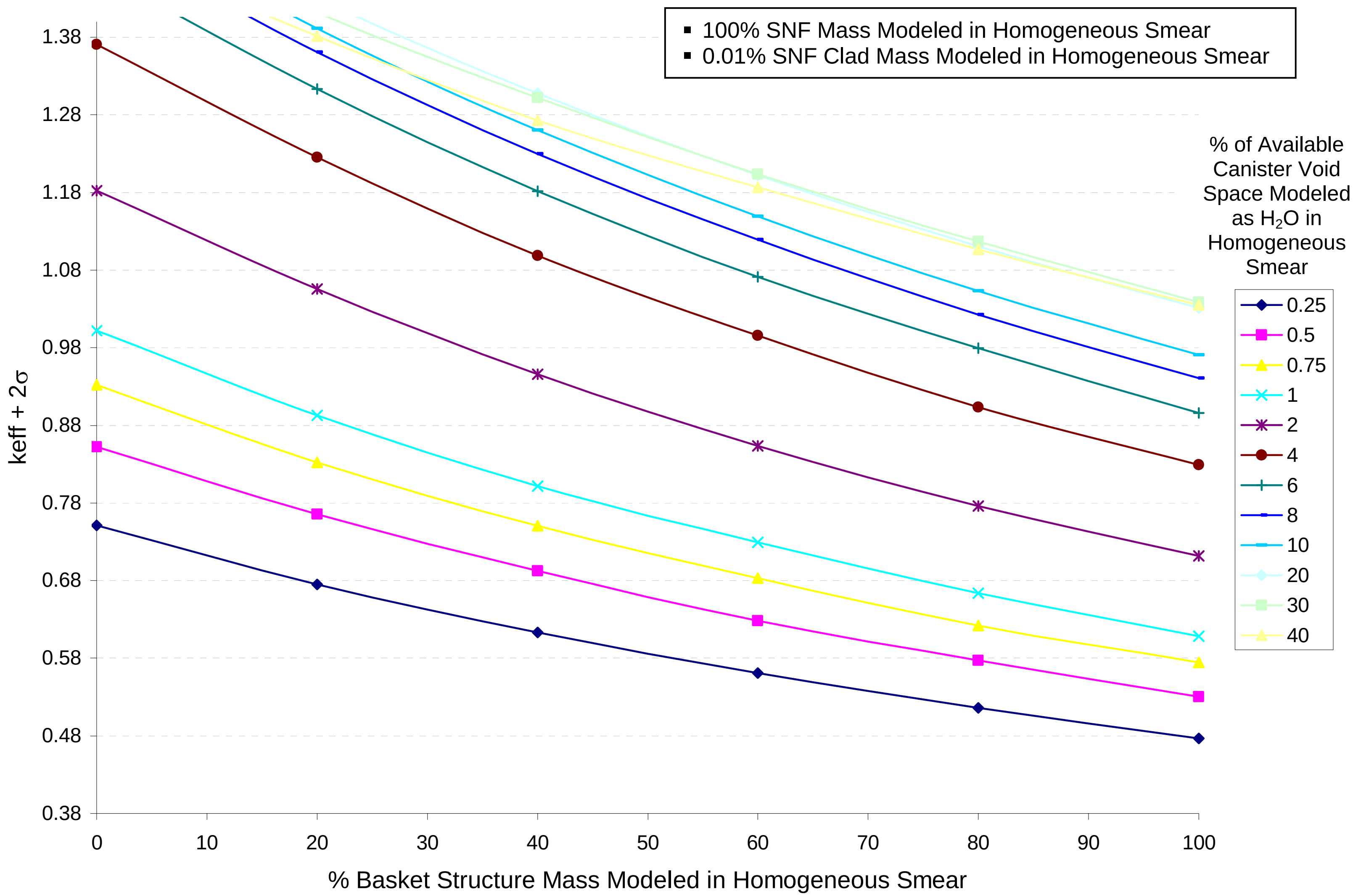
Source: Original

Figure 7-116: keff+2σ values (as a function of H_2O volume, basket structure mass, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



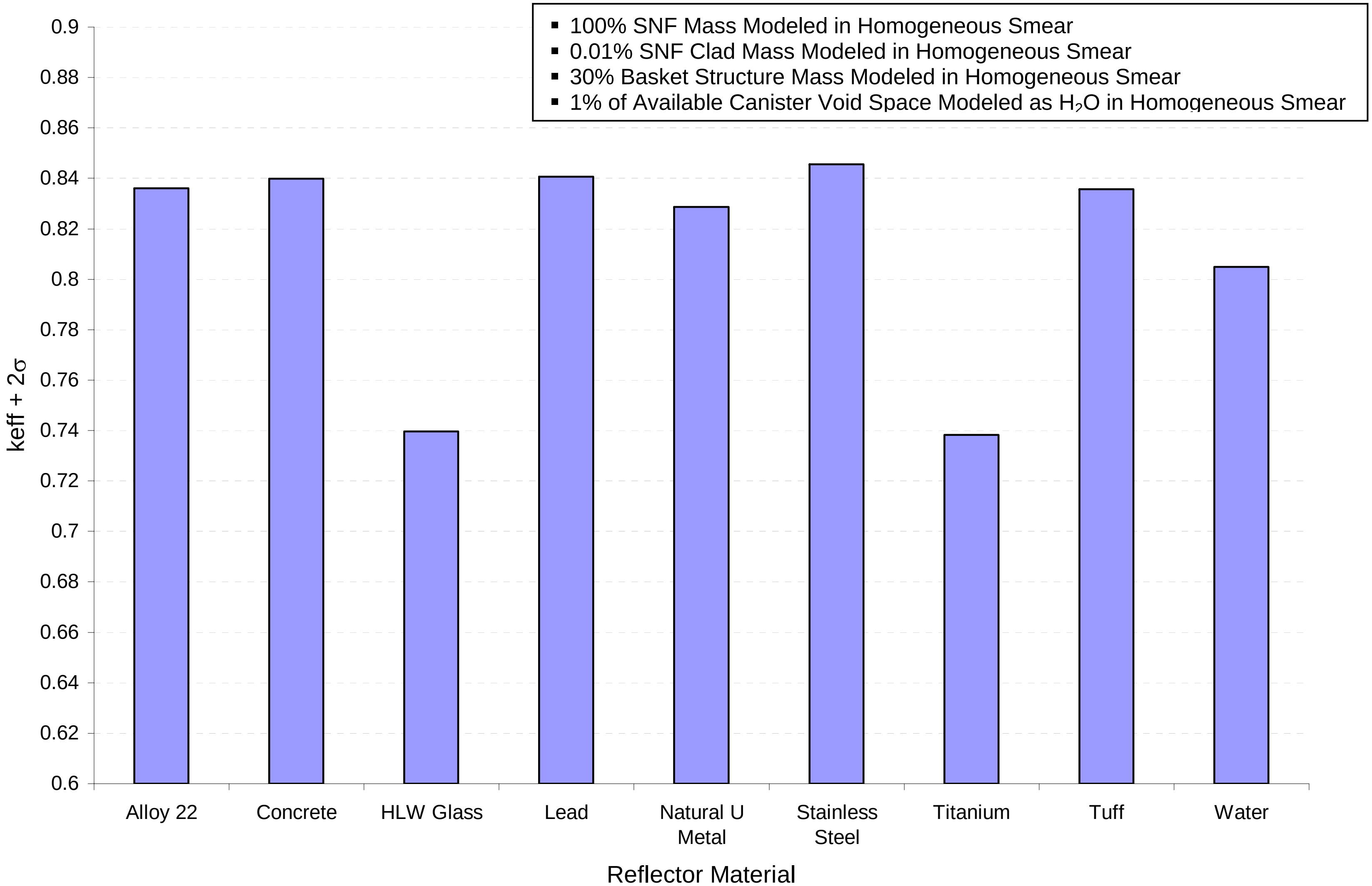
Source: Original

Figure 7-117: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



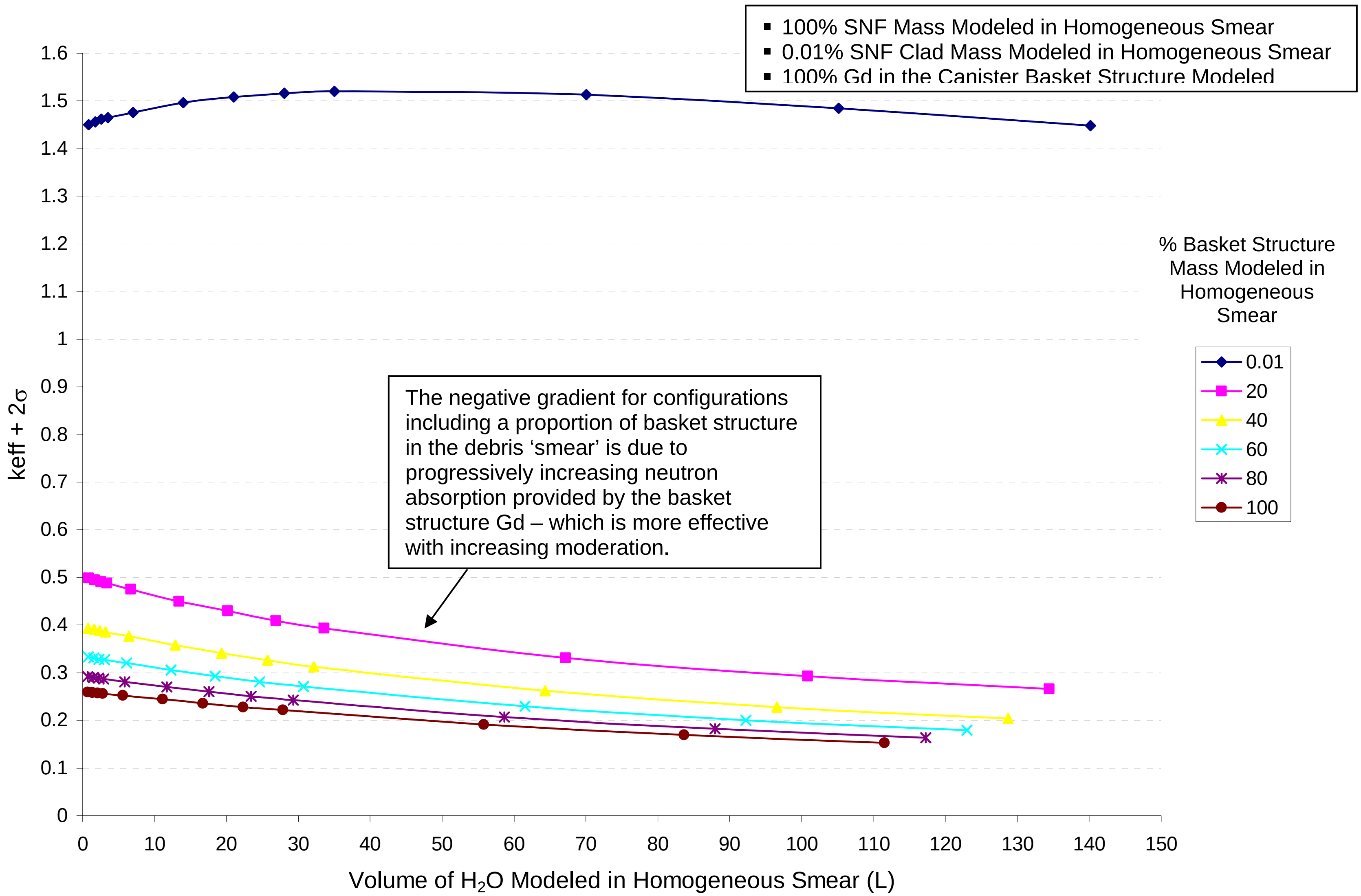
Source: Original

Figure 7-118: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, SPWR DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



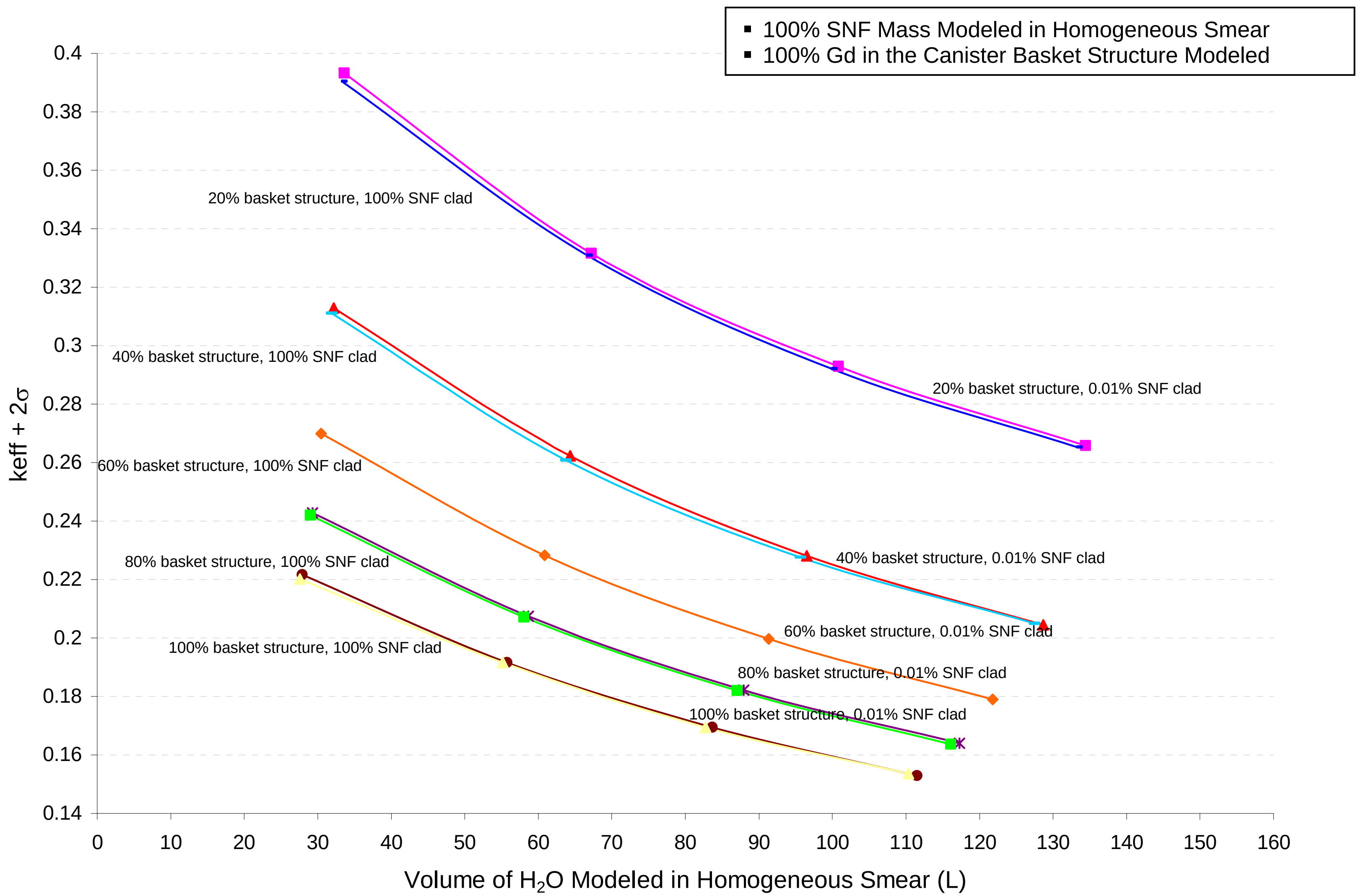
Source: Original

Figure 7-119: keff+2σ values for an individual fully water flooded, damaged and degraded, SPWR DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions



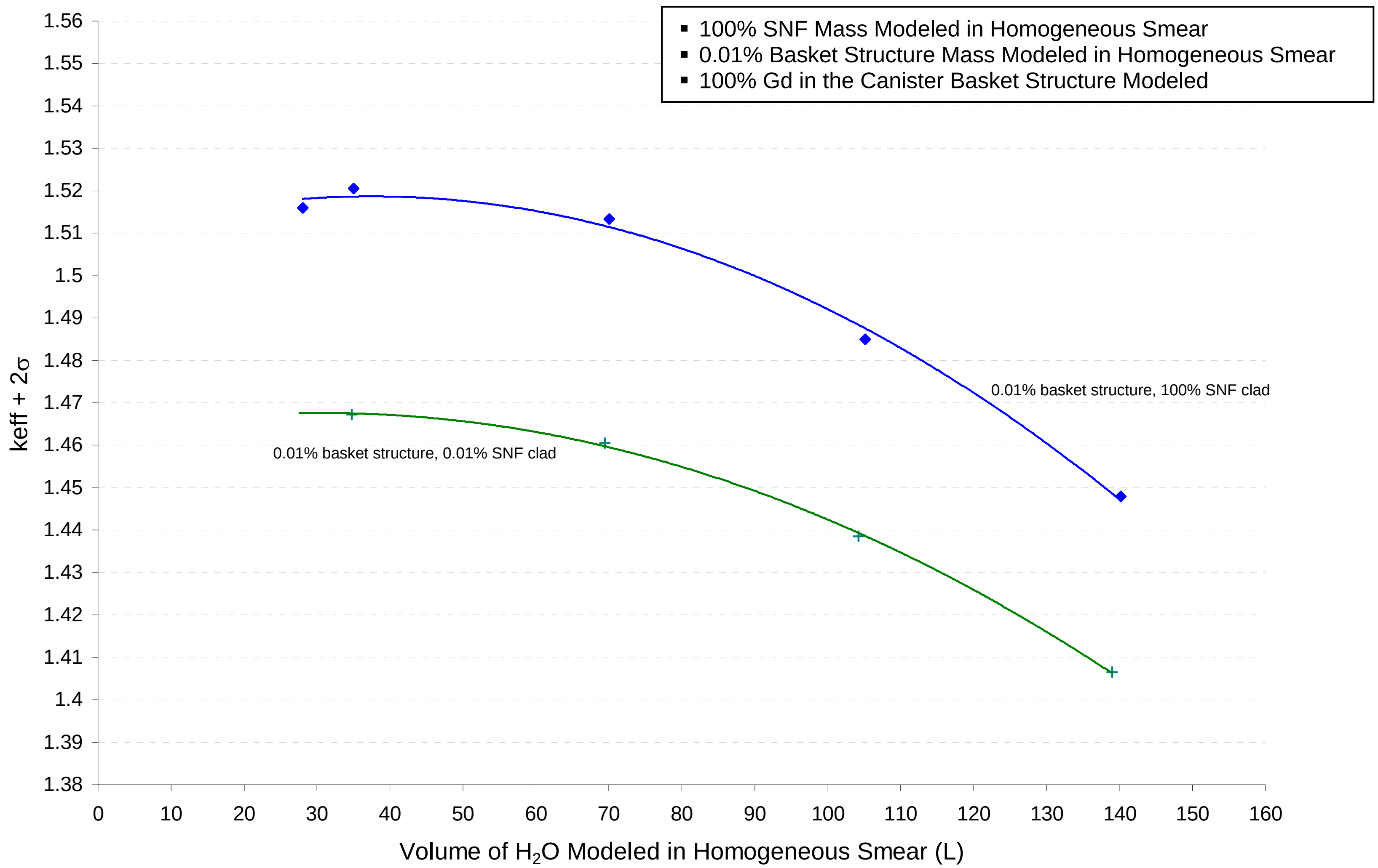
Source: Original

Figure 7-120: keff+2σ values (as a function of H_2O volume and basket structure mass modeled) for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



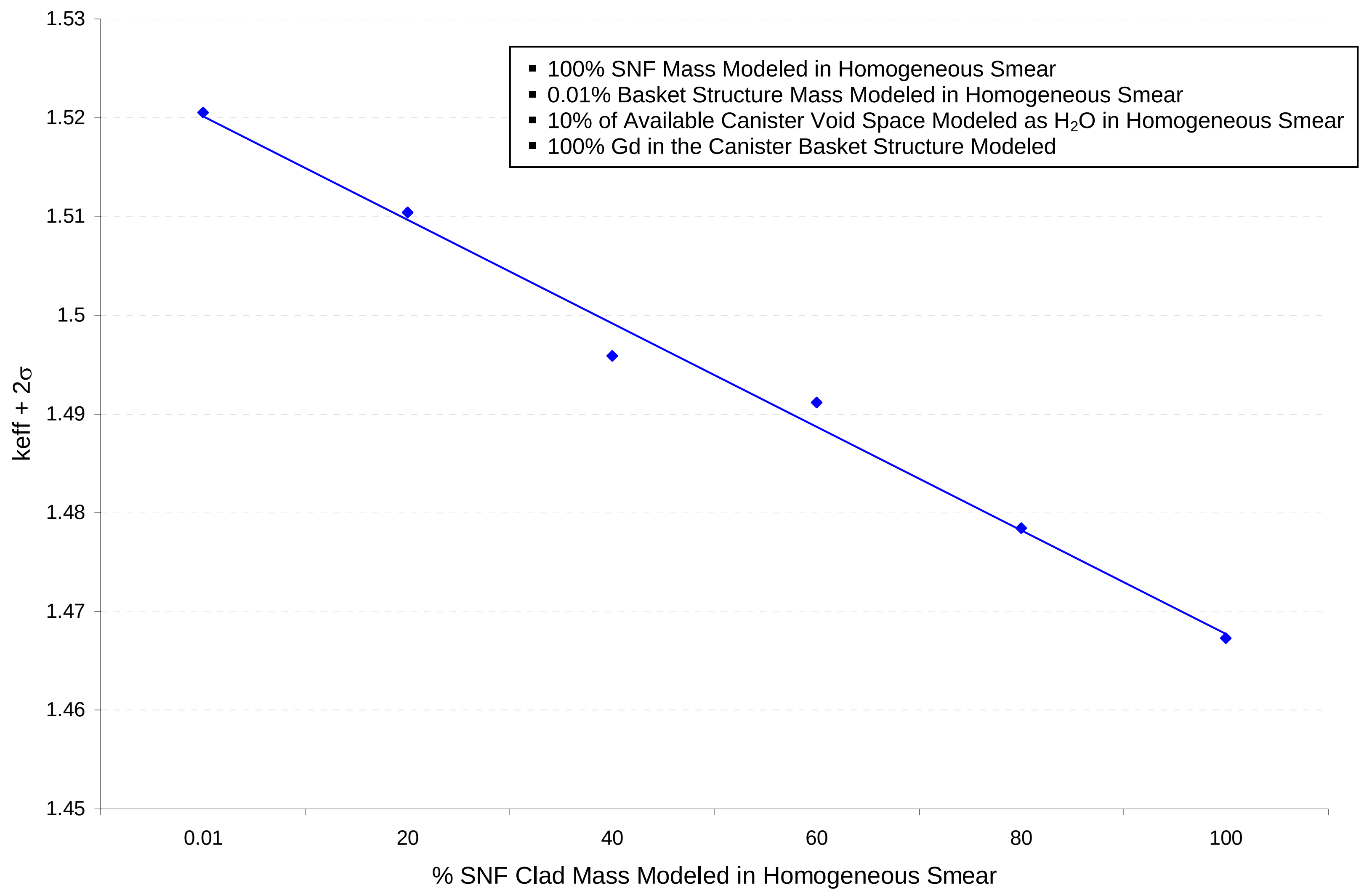
Source: Original

Figure 7-121: keff+2σ values (as a function of H_2O volume, basket structure mass, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



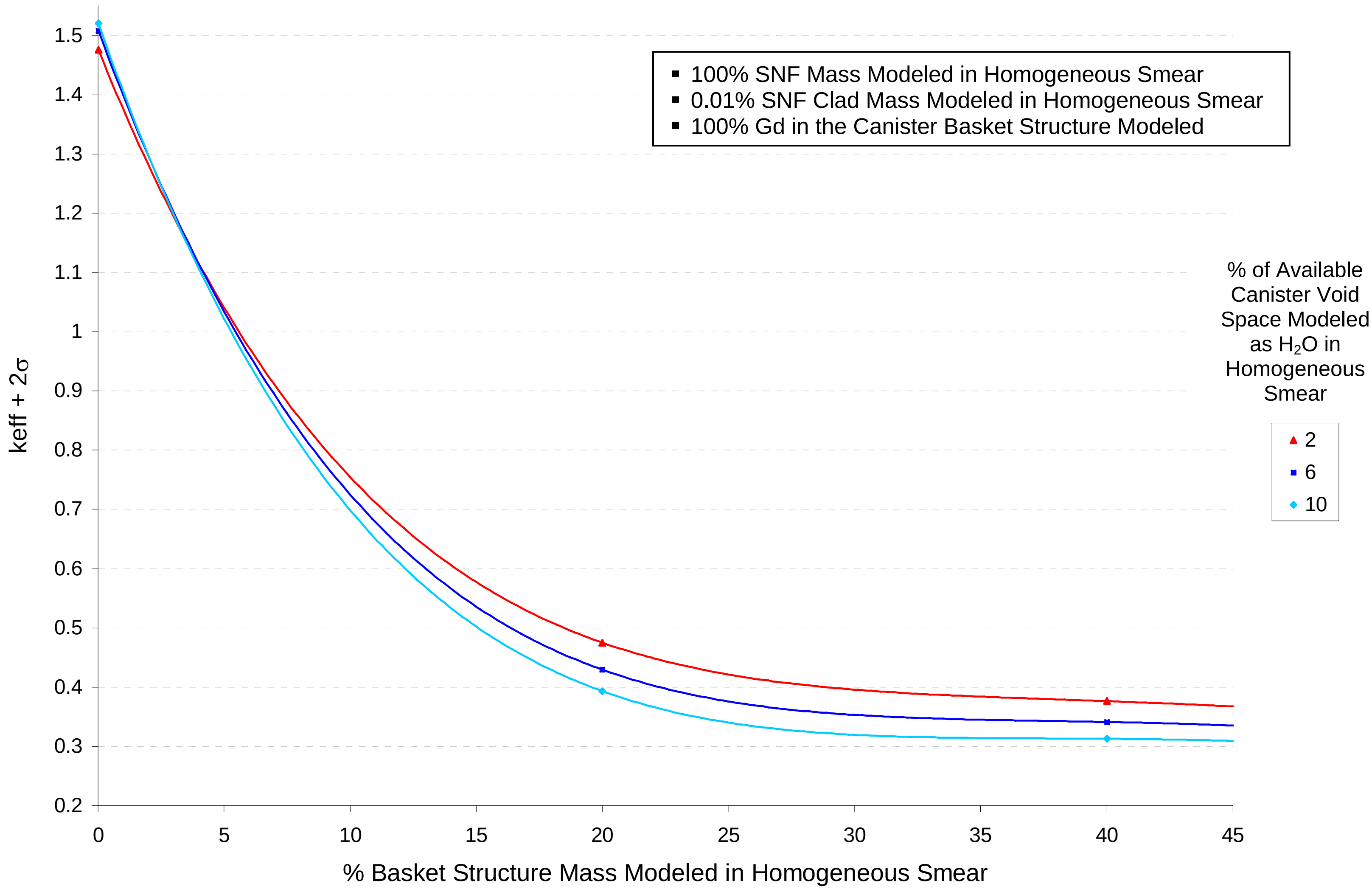
Source: Original

Figure 7-122: keff+2σ values (as a function of H_2O volume, and SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



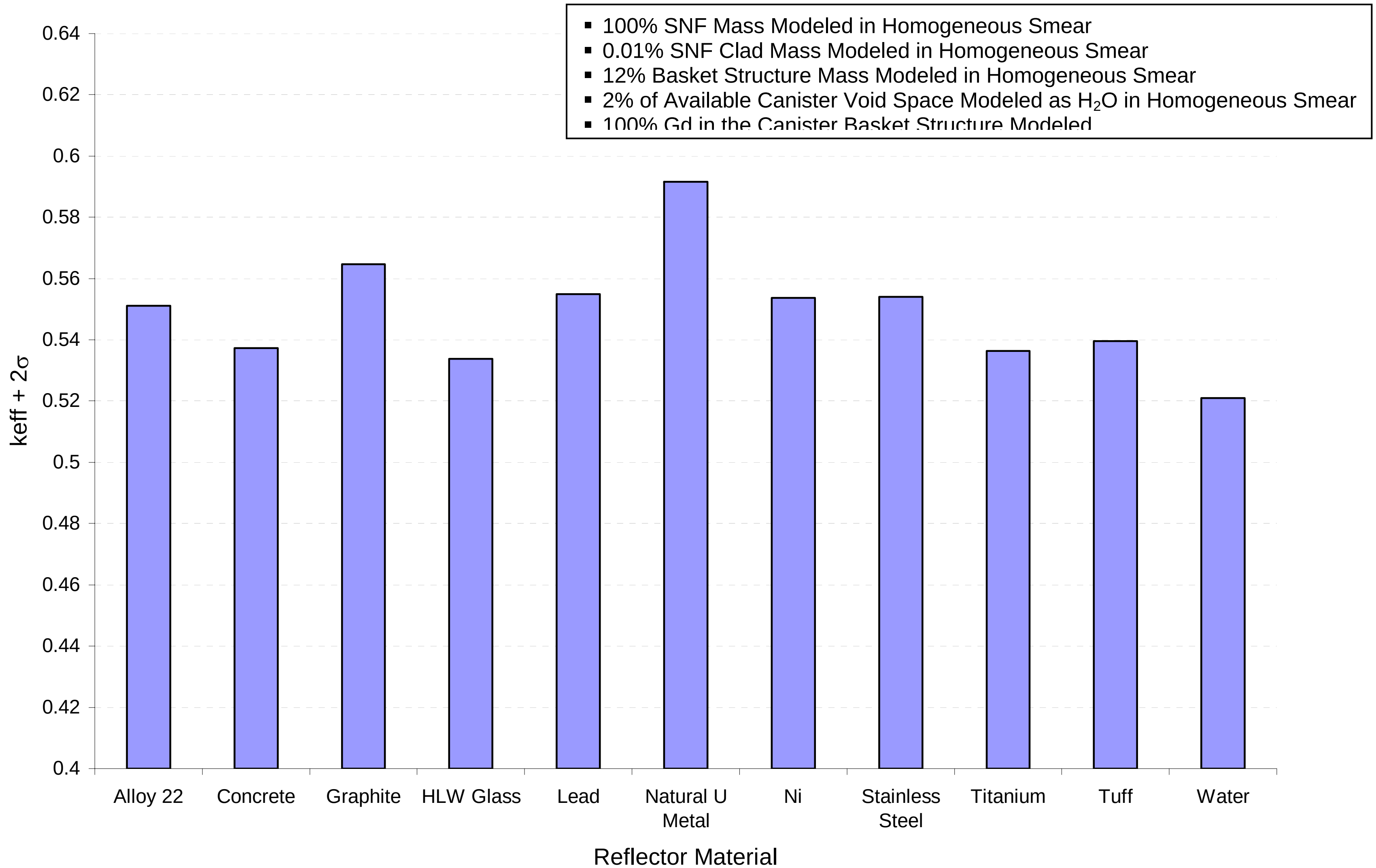
Source: Original

Figure 7-123: keff+2σ values (as a function of SNF clad mass modeled) for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



Source: Original

Figure 7-124: keff+2σ values (as a function of basket structure mass and H_2O volume fraction modeled) for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister with close fitting full (30 cm) thickness stainless steel reflection



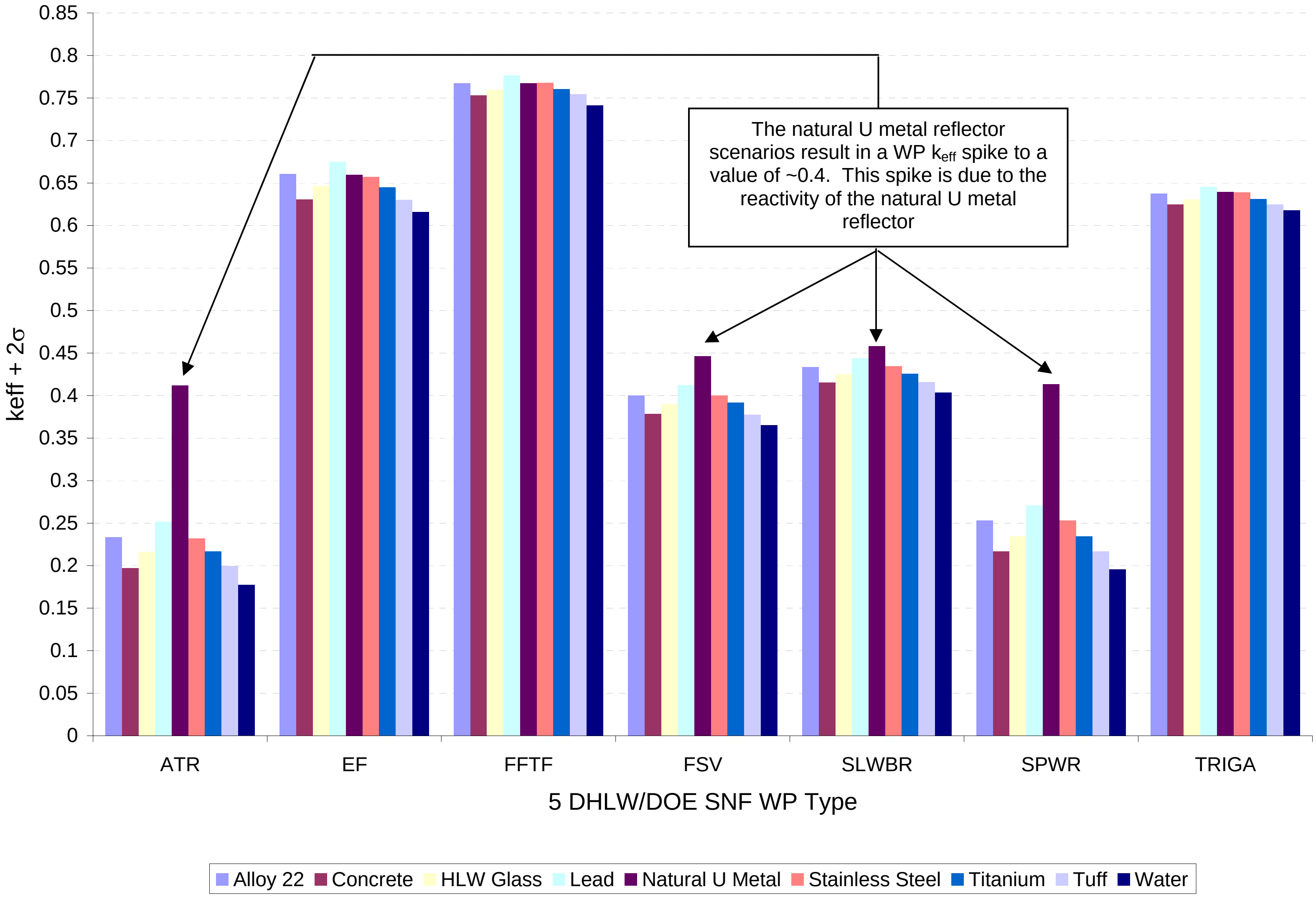
Source: Original

Figure 7-125: keff+2σ values for an individual fully water flooded, damaged and degraded, TRIGA DOE SNF canister under a variety of close fitting full (30 cm) thickness reflection conditions

7.1.2.1.2 5-DHLW/DOE SNF WPs

Under normal operating conditions, all loaded WPs contain only one 18” DOE SNF canister. However, in the event of operating error it is possible that more than one 18” DOE SNF canister could be loaded into the same WP (i.e. a WP could be misloaded). To determine the potential safety consequences of misloading an individual WP, calculations are performed to evaluate k_{eff} for individual WPs containing a maximum possible inventory of six DOE SNF canisters (i.e. one normally loaded DOE SNF canister together with five misloaded DOE SNF canisters). In respect of these misloading calculations it is noted that canister mixing scenarios are not considered (i.e. each misloaded WP considered in the calculations contains only one waste form). Based on the results of the DOE SNF canister infinite planar array calculations (Section 7.1.2.1.1.1), the reduction in k_{eff} with the addition of interstitial moderator between canisters (Figure 7-12 through Figure 7-14) suggests that a ‘mixed’ canister array would not result in a k_{eff} value greater than the largest k_{eff} value observed for the non-mixed (i.e. single type) canister arrays. This statement is supported by the result of an additional calculation recorded in worksheet *Mixed Can Cluster Data* of workbook *Ancillary Results* (Attachment 3). This additional calculation is based (exactly) on the configuration depicted in Figure 6-64, except that the center FFTF DOE SNF canister is replaced with a FSV DOE SNF canister.

The results of the misloaded WP calculations are presented in Figure 7-126, as a function of the waste form (i.e. DOE SNF canister type) and reflection condition. Refer to Figure 6-65 through Figure 6-71 for radial cross-section views of the misloaded DOE SNF WP MCNP models with incorporated close-fitting full thickness reflector.



Source: Original

Figure 7-126: keff+2σ values for individual undamaged, dry but misloaded 5 DHLW/DOE SNF WPs (containing 6 DOE SNF canisters) under a variety of close fitting full (30 cm) thickness reflection conditions

7.1.2.2 Sub-Surface Facility

7.1.2.2.1 DOE SNF Canisters

Operations conducted in the sub-surface facility concern the receipt and placement of loaded, sealed, waste packages containing commercial spent nuclear fuel, DOE spent nuclear fuel, naval spent nuclear fuel, and HLW glass. Consequently, DOE SNF canisters are not directly handled in the sub-surface facility.

7.1.2.2.2 5-DHLW/DOE SNF WPs

The subcriticality of sealed DHLW/DOE SNF WPs positioned in the sub-surface facility emplacement drifts is demonstrated in Section 7.1.1.2.2 for normal conditions (i.e. for dry WPs containing a single undamaged DOE SNF canister and five HLW Glass Canisters).

No specific off-normal condition calculations are performed for DHLW/DOE SNF WPs positioned in the sub-surface facility. However, based on the results of other calculations document herein, it is judged that the safety limits applicable to the single DOE SNF canister calculations (i.e. damage conditions that result in a k_{eff} value equal to the USL) would be bounding of safety limits applicable to damaged WPs situated in the sub-surface facility.

7.2 CONCLUSIONS

The results of the MCNP criticality safety calculations described in this document are presented in Section 7.1. Based on the data presented, key results are identified and detailed in Table 7-2.

Based on the results presented in Section 7.1 and summarized in Table 7-2, attributes of the DOE SNF canisters and WPs that are important to ensuring their subcriticality are established. These attributes can be categorized according to the criticality control parameter that is impacted. Based on the categorization presented below, it is seen that *Moderation, Interaction* and *Geometry* control are the underlying criticality control parameters. However, *Neutron Absorber* control is also important because the design of the canister baskets, including the associated neutron absorber, directly influence the tolerable geometry limits. It is also seen that the *Waste Form Characteristic* need to be controlled.

<u>Geometry</u>

Under all normal conditions the DOE SNF canisters feature dry intact SNF, held within a dry intact basket. Based on these dry (i.e. un-moderated) conditions, each examined canister type is safely subcritical (i.e. has a computed peak keff+2σ value that is below the USL value of 0.88 (Section 3.1.1). Furthermore, each examined canister remains safely subcritical under the most extreme damage conditions resulting in a rearrangement of SNF, basket structure and basket filler material (where one exists), but not resulting in a breakup of material (i.e. formation of debris).

Under process upsets involving damage of a canister including its breach and subsequent introduction of moderator, the geometry of the CSNF and basket material is important. The tolerable geometry limits for each examined canister under flooded damaged conditions are summarized in Table 7-2.

<u>Neutron Absorber</u>

Under normal conditions the DOE SNF canisters and WPs are completely dry, which, for non self moderating waste forms, results in a hard neutron spectrum. Under dry, un-moderated conditions, the neutron absorber (Gd) associated with the Ni-Gd basket structure of the ATR, EF, FFTF, and TRIGA canisters, in addition to the basket filler material associated with the EF, FFTF and SLWBR canisters, provides very limited neutron absorption, to the extent that its complete omission will not result in an unsafe condition. However, under potential off-normal conditions resulting in a break-up of SNF or basket structure, the neutron absorber associated with the ATR, EF, FFTF, SLWBR and TRIGA canisters is important to ensuring their sub-criticality.

Under flooded or partially flooded conditions (and without any SNF or basket damage), the neutron absorber associated with the FFTF and SLWBR canisters is important to ensuring their sub-criticality.

Therefore, neutron absorber control is important to criticality safety, but only in the context of ensuring subcriticality under potential off-normal conditions concerning SNF/basket structure breakup, or, for FFTF and SLWBR, breach and flooding/partial flooding of the DOE SNF canister content.

Moderation

Under all normal conditions the DOE SNF canisters feature dry intact SNF, held within a dry intact basket. Based on these dry (i.e. un-moderated) conditions, each examined canister remains safely subcritical under the most extreme damage conditions resulting in a rearrangement of SNF, basket structure and basket filler material (where one exists), but not resulting in a breakup of material (i.e. formation of debris). However, for potential off-normal conditions involving full moderation (or partial moderation) of the DOE SNF canister cavity, the USL may be exceeded, depending on the geometry (i.e. damage) conditions examined. Consequently, moderation control is essential to preserving the subcriticality of the DOE SNF canisters in the surface and sub-surface facilities examined in this document. The tolerable geometry limits for each examined canister under full flooded conditions are summarized in Table 7-2.

Interaction

The infinite planar array configuration MCNP calculations performed for undamaged DOE SNF canisters demonstrate that spacing (interaction control) is necessary to ensuring the subcriticality of EF, FFTF, FSV and TRIGA DOE SNF canisters, but is not necessary for the ATR, SLWBR and DOE SNF SPWR canisters.

The infinite planar array configuration considered for undamaged DOE SNF WPs in the MCNP calculations bounds foreseen neutron interaction conditions that could be realized in the surface facilities under normal conditions. Furthermore, the 'infinite row' configuration considered for DOE SNF WPs in the criticality safety emplacement models accounts for neutron interaction conditions that could be realized in the sub-surface facility.

Based on the above discussion, interaction control is essential for ensuring the subcriticality of DOE SNF canisters in the surface facilities. However, interaction control is not important to ensuring the subcriticality of DOE SNF WPs in the surface or sub-surface facilities.

Reflection

The effect of reflection on DOE SNF canisters and WPs is accounted for in the configurations examined in this document. For all calculations performed, close fitting full-thickness (i.e. 30 cm) reflection is considered. In addition, a comprehensive range of reflector materials (Attachment 1) are examined to determine the limiting reflection condition. Consequently, the reflection conditions accounted for the MCNP calculations are considered to bound any foreseen reflection conditions that could be realized in the surface and subsurface facilities examined in this document. Therefore, reflection control is not important to ensuring the subcriticality of the DOE SNF canisters and WPs in the surface and sub-surface facilities examined in this document.

Waste Form Characteristics

This calculation is based on the representative DOE SNF fuel types described in Section 1.1.1. Consideration of waste form misload is not appropriate because loading procedures for DOE SNF canisters have not been established at this time.

Table 7-2: Summary of Key Results

DOE SNF Canister	Undamaged Interaction Limit		*Dry Damaged Intact* Conditions Limit	*Dry Damaged Degraded* Conditions Limit	*Flooded Damaged Intact* Conditions Limit	*Flooded Damaged Degraded* Conditions Limit
	Spacing	Accumulation				
ATR	No Limit [Figure 7-13]	Not Evaluated[3]	No Limit[5] [Figure 7-29]	No Limit[4] [Figure 7-30]	No Limit[6] [Figure 7-50] ~40% Fuel Element Expansion[5] [Figure 7-49]	~30% Bkt. Struct. Mass + Any Mod. Vol.[4] [Figure 7-63, 7-68]
EF	25 cm[1,2] [Figure 7-12]	Not Evaluated[3]	No Limit[5] [Figure 7-19]	100% Bkt. Struct. Mass + 0% Bkt. Fill. Mass[4] [Figures 7-34,7-35] or ~32% Bkt. Fill. Mass + 0% Bkt. Struct. Mass[4] [Figure 7-33, 7-35]	~80% Fuel Pin Pitch Expansion + 0% Bkt. Tube Spc. Reduction[5] [Figures 7-51,7-52] or 100% Fuel Pin Pitch Expansion + 100% Bkt. Tube Spc. Reduction[4] [Figures 7-51,7-52]	100% Bkt. Struct. Mass + ~0.5L Mod. Vol. + 0% Bkt. Fill. Mass[4] [Figure 7-69, 7-82] or ~80% Bkt. Fill. Mass + Any Mod. Vol. + 0% Bkt. Struct. Mass[4] [Figure 7-73, 7-82]
FFTF	28 cm[1] [Figure 7-14]	4 canisters[1] [Figure 7-15]	No Limit[5] [Figure 7-21]	~60% Bkt. Struct. Mass + 0% Bkt. Fill. Mass[4] [Figure 7-39, 7-40] or ~10% Bkt. Fill. Mass + 0% Bkt. Struct. Mass[4] [Figure 7-38, 7-40]	~60% DFA Fuel Pin Pitch Expansion + Close-Packed Pins in Ident-69 Container[4] [Figures 7-53,7-54] or ~40% DFA Fuel Pin Pitch Expansion + Close-Packed Pins in Ident-69 Container[7] [Figures 7-53,7-54]	~65% Bkt. Struct. Mass + Any Mod. Vol. + 0% Bkt. Fill. Mass[4] [Figure 7-89, 7-96] or ~20% Bkt. Fill. Mass + Any Mod. Vol. + 0% Bkt. Struct. Mass[4] [Figure 7-84, 7-96]

DOE SNF Canister	Undamaged Interaction Limit		*Dry Damaged Intact* Conditions Limit	*Dry Damaged Degraded* Conditions Limit	*Flooded Damaged Intact* Conditions Limit	*Flooded Damaged Degraded* Conditions Limit
	Spacing	Accumulation				
FSV	10 cm[1,2] [Figure 7-12]	Not evaluated	No Limit[5] [Figure 7-22]	No Limit[9] [Figure 7-42]	No Limit[8] [Figure 7-55]	0% Bkt. Struct. Mass + 1.4L Mod. Vol.[9] [Figure 7-99] or 100% Bkt. Struct. Mass + + ~35L Mod. Vol.[9] [Figure 7-99]
SLWBR	No Limit [Figure 7-13]	Not Evaluated[3]	No Limit[5] [Figure 7-24]	No Limit[4] [Figure 7-43]	No Pin Pitch Expansion[4] [Figure 7-56,7-57]	~60% Bkt. Struct. Mass + Any Mod. Vol. + 20% Bkt. Fill. Mass[4] [Figure 7-101,7-107, 7-114] or ~40% Bkt. Fill. Mass + Any Mod. Vol. + 0% Bkt. Struct. Mass[4] [Figure 7-102, 7-114]
SPWR	No Limit [Figure 7-13]	Not Evaluated[3]	No Limit[5] [Figure 7-27]	No Limit[4] [Figure 7-44]	No Fuel Wafer Spc. Expansion[8] [Figure 7-58,7-59]	0% Bkt. Struct. Mass + 3L Mod. Vol. [4] [Figure 7-115,7-119] or 100% Bkt. Struct. Mass + 25L Mod. Vol. [4] [Figure 7-115,7-119]
TRIGA	No Limit [Figure 7-13]	Not Evaluated[3]	No Limit[5] [Figure 7-29]	~5% Bkt. Struct. Mass[4] [Figures 7-46,48]	No Limit[5] [Figure 7-62]	~10% Bkt. Struct. Mass + Any Mod. Vol. [4] [Figure 7-124,7-125]

DOE SNF Canister	Undamaged Interaction Limit		*Dry Damaged Intact* Conditions Limit	*Dry Damaged Degraded* Conditions Limit	*Flooded Damaged Intact* Conditions Limit	*Flooded Damaged Degraded* Conditions Limit
	Spacing	Accumulation				

[1] The maximum safe spacing limit provided corresponds to a 'void' interstitial moderation condition and close fitting 30cm thickness stainless steel reflection.
[2] The data provided is based on an extrapolation of values provided in the cite Figure(s).
[3] This configuration is not examined because it is bounded by the FFTF configuration, which is the most restrictive canister type.
[4] 100% neutron absorber credit (where exists) and any close-fitting full thickness (30 cm) reflection (Attachment 1) condition.
[5] 0% neutron absorber credit (where exists) and any close-fitting full thickness (30 cm) reflection (Attachment 1) condition.
[6] 0% neutron absorber credit (where exists) and any close-fitting full thickness (30 cm) reflection (Attachment 1) condition, except Natural Uranium Metal reflection.
[7] 100% neutron absorber credit in basket filler material, 0% neutron absorber credit in basket structure material, and any close-fitting full thickness (30 cm) reflection (Attachment 1) condition.
[8] Only safely subcritical flooded when not reflected with 30 cm close fitting Natural Uranium Metal.
[9] Only safely subcritical flooded when not reflected with 30 cm close fitting axial and radial Graphite.

Attachment 1: Materials Description

This attachment provides the explicit composition of materials that are modeled in the MCNP calculations examined and reported in this document. The following structure is used:

- Section A1.1 details the composition of generic materials associated with the DOE SNF WP and the standardized DOE canisters, in addition to the composition of materials associated with the DOE SNF canister contents (i.e. clad, basket structure and basket filler material (where applicable)). The physical arrangement of these materials is described in detail in Section 6.1.
- Section A1.2 details the reflector materials (and their composition) considered when evaluating the effect of structures and components surrounding the DOE SNF WPs and DOE SNF canisters modeled in the calculations described in detail in Section 6.2.
- Section A1.3 details the composition of moderators modeled in the *damaged flooded intact* conditions calculations and the *damaged flooded degraded* conditions calculations.

The majority of the material specifications detailed in this Section are taken directly from *Dimension and Material Specification Selection for Use in Criticality Analyses* (Ref. 2.2.1). With respect to the material specification descriptions, the MCNP unique identifiers called 'ZAIDs', are provided. These identifiers generally contain the atomic number (Z), mass number (A), and data library specifier of the element or isotope of interest.

The material specifications for certain materials (e.g. SAR concrete) utilize the atomic weights, isotopic masses, and isotopic abundances (in atom percent) specified in *Nuclides and Isotopes* (Ref. 2.2.5), to expand the elemental weight percents into their constituent natural isotopic weight percents for use in the MCNP calculations. This expansion is performed by:

1. Calculating a natural weight fraction of each isotope in the elemental state, and
2. Multiplying the elemental weight percent in the material of interest by the natural weight fraction of the isotope in the elemental state, to obtain the weight percent of the isotope in the material of interest.

The abovementioned two step process is described mathematically in equations 1 and 2.

$$WF_i = \frac{A_i\,(At\%_i)}{\sum_{i=1}^{I} A_i\left(At\%_i\right)} \qquad \text{(Equation 1)}$$

where

WF_i = the weight fraction of isotope *i* in the natural element
A_i = the atomic mass of isotope *i*
$At\%_i$ = the atom percent of isotope *i* in the natural element
I = the total number of isotopes in the natural element.

$$Wt\%_i = WF_i\,(E_{wt\%}) \qquad \text{(Equation 2)}$$

where

$Wt\%_i$ = the weight percent of isotope i in the material composition
WF_i = the weight fraction of isotope i from Equation 1
$E_{wt\%}$ = the referenced weight percent of the element in the material composition.

The elements from material specifications that require separation into their constituent isotopes include gadolinium, chromium, iron, and nickel. In most cases determination of the isotopic split is provided in the documentation from which the material specification is taken. In a number of cases (e.g., SAR concrete) determination of the isotopic split of the constituent elements is performed and described in this document. In these limited cases, the atomic weight and natural isotopic abundance (based on the data contained in *Nuclides and Isotopes* (Ref. 2.2.5, pg. 40, 46, 58, 59 & 70)) is used for the isotopic split determination for each element. The relevant data is summarized in Table A1-1.

Table A1-1: Isotopic Abundances and Atomic Weights

Element/ Isotope	Natural Isotopic Abundance (atom %)	Atomic Weight (g/mol)
Gd	--	157.25
^{152}Gd	0.20	151.919788
^{154}Gd	2.18	153.920862
^{155}Gd	14.80	154.922619
^{156}Gd	20.47	155.922120
^{157}Gd	15.65	156.923957
^{158}Gd	24.84	157.924101
^{160}Gd	21.86	159.927051
Cr	--	51.9961
^{50}Cr	4.345	49.946050
^{52}Cr	83.789	51.940512
^{53}Cr	9.501	52.940654
^{54}Cr	2.365	53.938885
Fe	--	55.845
^{54}Fe	5.845	53.939615
^{56}Fe	91.754	55.934942
^{57}Fe	2.119	56.935399
^{58}Fe	0.282	57.933280
Ni	--	58.6934
^{58}Ni	68.0769	57.935348
^{60}Ni	26.2231	59.930791
^{61}Ni	1.1399	60.931060
^{62}Ni	3.6345	61.928349
^{64}Ni	0.9256	63.927970
^{235}U	0.72	235.043923
^{238}U	99.2745	238.050783

Source: Ref. 2.2.5, pg. 40, 46, 58, 59 & 70.

A1.1 DOE SNF Canister and WP Materials

Table A1-2: Material Specification for Alloy 22 (SB-575 N06022)

Element/Isotope	ZAID	wt%	Element/Isotope	ZAID	wt%
C-nat	6000.50c	0.0150	Co-59	27059.50c	2.5000
Mn-55	25055.50c	0.5000	W-182 [a]	74182.55c	0.7877
Si-nat	14000.50c	0.0800	W-183 [a]	74183.55c	0.4278
Cr-50	24050.60c	0.8879	W-184 [a]	74184.55c	0.9209
Cr-52	24052.60c	17.7863	W-186 [a]	74186.55c	0.8636
Cr-53	24053.60c	2.0554	V	23000.50c	0.3500
Cr-54	24054.60c	0.5202	Fe-54	26054.60c	0.2260
Ni-58	28058.60c	36.8024	Fe-56	26056.60c	3.6759
Ni-60	28060.60c	14.6621	Fe-57	26057.60c	0.0865
Ni-61	28061.60c	0.6481	Fe-58	26058.60c	0.0116
Ni-62	28062.60c	2.0975	S-32	16032.50c	0.0200
Ni-64	28064.60c	0.5547	P-31	15031.50c	0.0200
Mo-nat	42000.50c	13.5000	Density = 8.69 g/cm^3		

Source: Ref. 2.2.1, Table 4

NOTES: [a] W-180 cross section libraries are not available, so the atom percents of the remaining isotopes were used to renormalize the elemental weight and derive isotopic weight percents excluding the negligible 0.120 atom percent in nature contribution from W-180.

Table A1-3: Material Specification for Stainless Steel 316L (SA-240 UNS S31600)

Element/Isotope	ZAID	wt%	Element/Isotope	ZAID	wt%
C-nat	6000.50c	0.0200	Fe-54	26054.60c	3.69112
N-14	7014.50c	0.0800	Fe-56	26056.60c	60.0322
Si-nat	14000.50c	1.000	Fe-57	26057.60c	1.41193
P-31	15031.50c	0.0450	Fe-58	26058.60c	0.18975
S-32	16032.50c	0.0300	Ni-58	28058.60c	8.0641
Cr-50	24050.60c	0.71035	Ni-60	28060.60c	3.2127
Cr-52	24052.60c	14.22912	Ni-61	28061.60c	0.1420
Cr-53	24053.60c	1.64434	Ni-62	28062.60c	0.4596
Cr-54	24054.60c	0.41619	Ni-64	28064.60c	0.1216
Mn-55	25055.50c	2.0000	Mo-nat	42000.50c	2.5000
Density = 7.98 g/cm^3					

Source: Ref. 2.2.1, Table 5

Table A1-4: Material Specification for Stainless Steel 316L (SA-240 S31603)

Element/Isotope	ZAID	wt%	Element/Isotope	ZAID	wt%
C-nat	6000.50c	0.0300	Fe-54	26054.60c	3.7036
N-14	7014.50c	0.1000	Fe-56	26056.60c	60.2343
Si-nat	14000.50c	0.7500	Fe-57	26057.60c	1.4167
P-31	15031.50c	0.0450	Fe-58	26058.60c	0.1904
S-32	16032.50c	0.0300	Ni-58	28058.60c	8.0641
Cr-50	24050.60c	0.7103	Ni-60	28060.60c	3.2127
Cr-52	24052.60c	14.2291	Ni-61	28061.60c	0.1420
Cr-53	24053.60c	1.6443	Ni-62	28062.60c	0.4596
Cr-54	24054.60c	0.4162	Ni-64	28064.60c	0.1216
Mn-55	25055.50c	2.0000	Mo-nat	42000.50c	2.5000
Density = 7.98 g/cm^3					

Source: Ref. 2.2.1, Table 6

Table A1-5: Material Specifications for Carbon Steel ASTM A 516 Grade 70 (SA-516 K02700)

Element/Isotope	ZAID	wt%	Element/Isotope	ZAID	wt%
C-nat	6000.50c	0.2700	Fe-54	26054.60c	5.5558
Mn-55	25055.50c	1.0450	Fe-56	26056.60c	90.3584
P-31	15031.50c	0.0350	Fe-57	26057.60c	2.1252
S-32	16032.50c	0.0350	Fe-58	26058.60c	0.2856
Si-nat	14000.50c	0.2900	Density = 7.850 g/cm^3		

Source: Ref. 2.2.1, Table 9

Table A1-6: Material Specifications for Stainless Steel 304L (SA-240 S30403)

Element/Isotope	ZAID	wt%	Element/Isotope	ZAID	wt%
C-nat	6000.50c	0.0300	Fe-54	26054.60c	3.8448
N-14	7014.50c	0.1000	Fe-56	26056.60c	62.5318
Si-nat	14000.50c	0.7500	Fe-57	26057.60c	1.4707
P-31	15031.50c	0.0450	Fe-58	26058.60c	0.1977
S-nat	16032.50c	0.0300	Ni-58	28058.60c	6.7201
Cr-50	24050.60c	0.7939	Ni-60	28060.60c	2.6773
Cr-52	24052.60c	15.9031	Ni-61	28061.60c	0.1183
Cr-53	24053.60c	1.8378	Ni-62	28062.60c	0.3830
Cr-54	24054.60c	0.4652	Ni-64	28064.60c	0.1013
Mn-55	25055.50c	2.0000	Density = 7.94 g/cm^3		

Source: Ref. 2.2.1, Table 13

Table A1-7: Composition and Density of Inconel Alloy 600

Element	ZAID	(wt %)
C	6000.50c	0.15
Mn	25055.50c	1.0
Fe	26000.55c	8.0
S	16032.50c	0.015
Si	14000.50c	0.5
Cu	29000.50c	0.5
Cr	24000.50c	15.5
Ni	28000.50c	73.835
Density[a] = 8.47 g/cm^3		

Source: Ref. 2.2.24, pages 9-11

Table A1-8: Material Specifications for Ni-Gd Alloy (UNS N06464) [a]

Element/ Isotope	ZAID	Weight Percent Gadolinium in Ni-Gd Alloy					
		1.5 wt%	**1.2 wt%**	**0.9 wt%**	**0.6 wt%**	**0.3 wt%**	**0.0 wt%**
C-nat	6000.50c	0.0100	0.010	0.010	0.010	0.010	0.010
Mn-55	25055.50c	0.5000	0.502	0.503	0.505	0.506	0.508
Si-nat	14000.50c	0.0800	0.080	0.080	0.081	0.081	0.081
Cr-50	24050.60c	0.6602	0.662	0.664	0.666	0.668	0.670
Cr-52	24052.60c	13.2247	13.265	13.305	13.346	13.386	13.426
Cr-53	24053.60c	1.5283	1.533	1.538	1.542	1.547	1.552
Cr-54	24054.60c	0.3868	0.388	0.389	0.390	0.392	0.393
Ni-58	28058.60c	43.3679	43.500	43.632	43.764	43.896	44.028
Ni-60	28060.60c	17.2778	17.330	17.383	17.436	17.488	17.541
Ni-61	28061.60c	0.7637	0.766	0.768	0.771	0.773	0.775
Ni-62	28062.60c	2.4717	2.479	2.487	2.494	2.502	2.509
Ni-64	28064.60c	0.6537	0.656	0.658	0.660	0.662	0.664
Mo-nat	42000.50c	14.5500	14.594	14.639	14.683	14.727	14.772
Co-59	27059.50c	2.0000	2.006	2.012	2.018	2.024	2.030
Gd-152	64152.50c	0.0029	0.002	0.002	0.001	0.001	0.0
Gd-154	64154.50c	0.0320	0.026	0.019	0.013	0.006	0.0
Gd-155	64155.50c	0.2187	0.175	0.131	0.087	0.044	0.0
Gd-156	64156.50c	0.3045	0.244	0.183	0.122	0.061	0.0
Gd-157	64157.50c	0.2343	0.187	0.141	0.094	0.047	0.0
Gd-158	64158.50c	0.3742	0.299	0.225	0.150	0.075	0.0
Gd-160	64160.50c	0.3335	0.267	0.200	0.133	0.067	0.0
Fe-54	26054.60c	0.0565	0.057	0.057	0.057	0.057	0.057
Fe-56	26056.60c	0.9190	0.922	0.925	0.927	0.930	0.933
Fe-57	26057.60c	0.0216	0.022	0.022	0.022	0.022	0.022
Fe-58	26058.60c	0.0029	0.003	0.003	0.003	0.003	0.003
S-32	16032.50c	0.0050	0.005	0.005	0.005	0.005	0.005
P-31	15031.50c	0.0050	0.005	0.005	0.005	0.005	0.005
O-16	8016.50c	0.0050	0.005	0.005	0.005	0.005	0.005
N-14	7014.50c	0.0100	0.010	0.010	0.010	0.010	0.010
density, g/cm^3		8.76	8.7337	8.7074	8.6812	8.6549	8.6286

Source: Ref. 2.2.1, Table 7 (with adjustment for Gd content reduction).

NOTE: [a] 1.5wt% nominal gadolinium amount is based on typical value of 75% credit (Ref. 2.2.6, p. 8-4) allowed for fixed neutron absorbers and a nominal gadolinium loading of 2.0 wt% for Ni-Gd Alloy.

Table A1-9: Compositions for Dry and Water Saturated EF Iron Shot Filler Material

Element	ZAID	Vol Percent Gadolinium Phosphate in Iron Shot					
		3.0%	2.4%	1.8%	1.2%	0.6%	0.0%
Dry (no water) Shot Filler Material							
^{16}O	8016.50c	0.489	0.391	0.293	0.196	0.098	0.0
Fe-nat	26000.55c	98.074	98.463	98.849	99.235	99.618	100.0
Gd-152	64152.50c	0.002	0.002	0.001	0.001	0.000	0.0
Gd-154	64154.50c	0.026	0.021	0.016	0.010	0.005	0.0
Gd-155	64155.50c	0.175	0.140	0.105	0.070	0.035	0.0
Gd-156	64156.50c	0.244	0.195	0.146	0.098	0.049	0.0
Gd-157	64157.50c	0.188	0.150	0.113	0.075	0.038	0.0
Gd-158	64158.50c	0.300	0.240	0.180	0.120	0.060	0.0
Gd-160	64160.50c	0.267	0.214	0.160	0.107	0.053	0.0
^{31}P	15031.50c	0.237	0.190	0.142	0.095	0.047	0.0
density, g/cm^3		4.5808	4.5634	4.5458	4.5282	4.5104	4.4925
Fully Water Saturated Shot Filler Material							
^{1}H	1001.50c	0.921	0.932	0.942	0.953	0.964	0.975
^{16}O	8016.50c	7.762	7.755	7.749	7.744	7.739	7.736
Fe-nat	26000.55c	89.998	90.262	90.524	90.782	91.037	91.289
Gd-152	64152.50c	0.002	0.001	0.001	0.001	0.000	0.0
Gd-154	64154.50c	0.024	0.019	0.014	0.010	0.005	0.0
Gd-155	64155.50c	0.161	0.128	0.096	0.064	0.032	0.0
Gd-156	64156.50c	0.224	0.179	0.134	0.089	0.045	0.0
Gd-157	64157.50c	0.173	0.138	0.103	0.069	0.034	0.0
Gd-158	64158.50c	0.275	0.220	0.165	0.110	0.055	0.0
Gd-160	64160.50c	0.245	0.196	0.147	0.098	0.049	0.0
^{31}P	15031.50c	0.217	0.174	0.130	0.087	0.043	0.0
density, g/cm^3		4.9918	4.9780	4.9639	4.9498	4.9356	4.9212

Source: calculated from data contained in Fermi.xls from Ref. 2.2.14

Table A1-10: Compositions for Dry and Water Saturated FFTF Aluminum Shot Filler Material

Element	Weight Percent Gadolinium in Aluminum-Gadolinium Phosphate Shot						
	ZAID	4.3%	3.44%	2.58%	1.72%	0.86%	0.0%
Dry (no water) Shot Filler Material							
^{16}O	8016.50c	1.750	1.400	1.050	0.700	0.350	0.0
^{27}Al	13027.50c	93.103	94.482	95.862	97.241	98.621	100.0
Gd-152	64152.50c	0.008	0.007	0.005	0.003	0.002	0.0
Gd-154	64154.50c	0.092	0.073	0.055	0.037	0.018	0.0
Gd-155	64155.50c	0.627	0.502	0.376	0.251	0.125	0.0
Gd-156	64156.50c	0.873	0.698	0.524	0.349	0.175	0.0
Gd-157	64157.50c	0.672	0.537	0.403	0.269	0.134	0.0
Gd-158	64158.50c	1.073	0.858	0.644	0.429	0.215	0.0
Gd-160	64160.50c	0.956	0.765	0.574	0.382	0.191	0.0
^{31}P	15031.50c	0.847	0.678	0.508	0.339	0.169	0.0
density, g/cm^3		1.5381	1.5169	1.4956	1.4744	1.4532	1.4320
Fully Water Saturated Shot Filler Material							
^{1}H	1001.50c	2.601	2.661	2.721	2.782	2.844	2.907
^{16}O	8016.50c	21.989	22.185	22.390	22.607	22.834	23.072
^{27}Al	13027.50c	71.459	72.016	72.551	73.064	73.554	74.021
Gd-152	64152.50c	0.006	0.005	0.004	0.002	0.001	0.0
Gd-154	64154.50c	0.070	0.056	0.042	0.028	0.014	0.0
Gd-155	64155.50c	0.481	0.382	0.285	0.188	0.094	0.0
Gd-156	64156.50c	0.670	0.532	0.396	0.262	0.130	0.0
Gd-157	64157.50c	0.515	0.410	0.305	0.202	0.100	0.0
Gd-158	64158.50c	0.823	0.654	0.487	0.322	0.160	0.0
Gd-160	64160.50c	0.734	0.583	0.434	0.287	0.143	0.0
^{31}P	15031.50c	0.650	0.516	0.385	0.255	0.126	0.0
density, g/cm^3		2.0039	1.9901	1.9762	1.9623	1.9484	1.9346

Source: Ref. 2.2.18, Table 5-12 (with adjustment for Gd content reduction).

Table A1-11: Compositions for Dry and Water Saturated SLWBR Aluminum Shot Filler Material

Element	Weight Percent Gadolinium in Aluminum-Gadolinium Phosphate Shot						
	ZAID	0.1%	0.08%	0.06%	0.04%	0.02%	0.0%
Dry (no water) Shot Filler Material							
^{16}O	8016.50c	0.041	0.033	0.024	0.016	0.008	0.0
^{27}Al	13027.50c	99.840	99.872	99.904	99.936	99.968	100.0
Gd-152	64152.50c	0.000	0.000	0.000	0.000	0.000	0.0
Gd-154	64154.50c	0.002	0.002	0.001	0.001	0.000	0.0
Gd-155	64155.50c	0.015	0.012	0.009	0.006	0.003	0.0
Gd-156	64156.50c	0.020	0.016	0.012	0.008	0.004	0.0
Gd-157	64157.50c	0.016	0.012	0.009	0.006	0.003	0.0
Gd-158	64158.50c	0.025	0.020	0.015	0.010	0.005	0.0
Gd-160	64160.50c	0.022	0.018	0.013	0.009	0.004	0.0
^{31}P	15031.50c	0.020	0.016	0.012	0.008	0.004	0.0
density, g/cm^3		1.4410	1.4405	1.4401	1.4396	1.4392	1.4387
Fully Water Saturated Shot Filler Material							
^{1}H	1001.50c	2.734	2.735	2.737	2.738	2.739	2.741
^{16}O	8016.50c	21.728	21.733	21.738	21.743	21.748	21.753
^{27}Al	13027.50c	75.448	75.460	75.471	75.483	75.494	75.506
Gd-152	64152.50c	0.000	0.000	0.000	0.000	0.000	0.0
Gd-154	64154.50c	0.002	0.001	0.001	0.001	0.000	0.0
Gd-155	64155.50c	0.011	0.009	0.007	0.004	0.002	0.0
Gd-156	64156.50c	0.015	0.012	0.009	0.006	0.003	0.0
Gd-157	64157.50c	0.012	0.009	0.007	0.005	0.002	0.0
Gd-158	64158.50c	0.019	0.015	0.011	0.008	0.004	0.0
Gd-160	64160.50c	0.017	0.013	0.010	0.007	0.003	0.0
^{31}P	15031.50c	0.015	0.012	0.009	0.006	0.003	0.0
density, g/cm^3		1.9069	1.9066	1.9063	1.9060	1.9057	1.9054

Source: Ref. 2.2.18, Table 5-12 (with adjustment for Gd content reduction).

A1.2 Reflector Materials

DOE SNF Canister and WP operations in the surface and sub-surface facilities result in the positioning of Canisters and WPs within close proximity to, or in contact with, a wide variety of structures and components, such as transportation casks, the facility floor and walls, the volcanic tuff associated with the emplacement drifts, etc. To bound the wide range of reflection conditions that could credibly exist, the MCNP models described in Section 6.2 feature a variety of close fitting full-thickness (i.e. 30 cm) reflectors.

The reflector materials examined in the MCNP calculations are described in the following sub-sections. The reflector materials provided have been selected cognizant of the materials that could be present under foreseen normal and potential off-normal conditions. The reflector materials selected have been limited to those materials that possess atomic characteristics, and exist in significant quantities, to provide a meaningful degree of neutron reflection.

Water

Water (H2O), when modeled as a neutron reflector, is treated at full theoretical density (0.99821 gcm^{-3}) in the MCNP calculations. The specification for water, based on water at 20˚ C (*Handbook of Chemistry and Physics* (Ref. 2.2.7, page 6-2)), is provided in Table A1-12.

Table A1-12: Water Material Specification

Element/ Isotope	ZAID	Atoms per Molecule
^{1}H	1001.50c	2
^{16}O	8016.50c	1
Density: 0.99821 g/cm^3		

Source: Ref. 2.2.7, pg. 6-2

Concrete

Numerous detailed concrete compositions are available and some of the most common were evaluated in *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.1) The results demonstrate that the differing compositions have a statistically insignificant effect on the calculated neutron multiplication factor when evaluated for similar systems. Therefore, a single concrete material specification is used in the MCNP calculations. The material specification selected is *SAR concrete*, which has a material composition defined in *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.1).

Table A1-13: Material Specifications for SAR Concrete

Element/ Isotope	ZAID	Wt%	Element/ Isotope	ZAID	Wt%
^{1}H	1001.50c	0.6	Fe-nat	N/A	1.2
^{16}O	8016.50c	50.0	54Fe	26054.60c	0.0316
^{23}Na	11023.50c	1.7	56Fe	26056.60c	0.5142
^{27}Al	13027.50c	0.480	57Fe	26057.60c	0.0121
Si-nat	14000.50c	31.5	58Fe	26058.60c	0.0016
K-nat	19000.50c	1.90	Density = 2.35 g/cm3		
Ca-nat	20000.50c	8.30			

Source: Ref. 2.2.1, Table 56

Steel

Steel, when modeled as a neutron reflector, is treated as *304 Stainless Steel* in the MCNP calculations. The specification for 304 Stainless Steel is based on the specification provided in *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.1), where it is designated as *SA-240 S30400*. The specification for 304 Stainless Steel used in the MCNP calculations is detailed in Table A1-14.

Table A1-14: Material Specification for 304 Stainless Steel

Element/Isotope	ZAID	Wt%	Element/Isotope	ZAID	Wt%
C-nat	6000.50c	0.0800	^{54}Fe	26054.60c	3.8844
^{14}N	7014.50c	0.1000	^{56}Fe	26056.60c	63.1751
Si-nat	14000.50c	0.7500	^{57}Fe	26057.60c	1.4859
^{31}P	15031.50c	0.0450	^{58}Fe	26058.60c	0.1997
S-nat	16032.50c	0.0300	^{58}Ni	28058.60c	6.2161
^{50}Cr	24050.60c	0.7939	^{60}Ni	28060.60c	2.4765
^{52}Cr	24052.60c	15.9031	^{61}Ni	28061.60c	0.1095
^{53}Cr	24053.60c	1.8378	^{62}Ni	28062.60c	0.3543
^{54}Cr	24054.60c	0.4652	^{64}Ni	28064.60c	0.0937
^{55}Mn	25055.50c	2.0000	Density = 7.94 g/cm^3		

Source: Ref. 2.2.1, Table 12

Depleted Uranium

Depleted uranium is uranium that has a reduced proportion of the fissile isotope ^{235}U, relative to the proportion found in nature. When modeled as a neutron reflector in the MCNP calculations, depleted uranium is treated as uranium metal at full theoretical density (18.95 g/cm^3, *Nuclides and Isotopes*, Ref. 2.2.5, back cover). The isotopic distribution of the depleted uranium is conservatively based on a two-isotope natural uranium specification, i.e. [0.72 atom percent ^{235}U, 99.28 atom percent ^{238}U], to conservatively account for variations in source material depletion (refer to Assumption 3.2.1). The material specification for uranium used in the MCNP calculations is provided in Table A1-15.

Table A1-15: Natural Uranium Metal Specification

Element/ Isotope	ZAID	Atom Weight Fraction
^{235}U	92235.50c	0.0072
^{238}U	92238.50c	0.9928
Density: 18.95 g/cm^3		

Source: Ref. 2.2.5 (pg. 70 and back-cover) and Assumption 3.2.1

Lead

Lead, when modeled as a neutron reflector, is treated at full theoretical density (11.35 g/cm^3) in the MCNP calculations. The specification for lead, based on the material data provided in Ref. 2.2.5 (back cover)), is detailed in Table A1-16.

Table A1-16: Lead Material Specification

Element/ Isotope	ZAID	Wt%
^{82}Pb	82000.50c	100
Density: 11.35 g/cm^3		

Source: Ref. 2.2.5, back-cover

High-Level Radioactive Waste (HLW) Glass

High-Level Radioactive Waste (HLW) glass, when modeled as a neutron reflector in the MCNP calculations, is defined using the Savannah River Site (SRS) HLW glass specification. Therefore, the isotopic distribution for HLW glass in the MCNP calculations is established, based on the SRS HLW glass nuclide composition and concentrations. The HLW glass material specification is provided in Table A1-17.

Table A1-17: Material Specifications for Savannah River Site High-Level Waste Glass

Element/Isotope	ZAID	Wt%	Element/Isotope	ZAID	Wt%
Li-6	3006.50c	0.0960	P	15031.50c	0.0141
Li-7	3007.55c	1.3804	Cr-50	24050.60c	0.0035
B-10	5010.50c	0.5918	Cr-52	24052.60c	0.0691
B-11	5011.56c	2.6189	Cr-53	24053.60c	0.0080
O	8016.50c	44.7700	Cr-54	24054.60c	0.0020
F	9019.50c	0.0319	Cu	29000.50c	0.1526
Na	11023.50c	8.6284	Ag	47000.55c	0.0503
Mg	12000.50c	0.8248	Ba-137 [a]	56138.50c	0.1127
Al[b]	13027.50c	2.3318	Pb	82000.50c	0.0610
Si	14000.50c	21.8880	Cl	17000.50c	0.1159
S	16000.60c	0.1295	Th-232	90232.50c	0.1856
K	19000.50c	2.9887	Cs-133	55133.50c	0.0409
Ca	20000.50c	0.6619	Cs-135	55135.50c	0.0052
Ti	22000.50c	0.5968	U-234	92234.50c	0.0003
Mn	25055.50c	1.5577	U-235	92235.50c	0.0044
Fe-54	26054.60c	0.4176	U-236	92236.50c	0.0010
Fe-56	26056.60c	6.7919	U-238	92238.50c	1.8666
Fe-57	26057.60c	0.1597	Zn	N/A [b]	0.0646
Fe-58	26058.60c	0.0215	Pu-238	94238.50c	0.0052
Ni-58	28058.60c	0.4939	Pu-239	94239.55c	0.0124
Ni-60	28060.60c	0.1968	Pu-240	94240.50c	0.0023
Ni-61	28061.60c	0.0087	Pu-241	94241.50c	0.0010
Ni-62	28062.60c	0.0281	Pu-242	94242.50c	0.0002
Ni-64	28064.60c	0.0074	Density = 2.85 g/cm^3 at 25 $^\circ$C, 2.69 g/cm^3 at 825 $^\circ$C		

NOTES: [a] Ba-137 cross-section data unavailable; therefore substituted as Ba-138 (See Assumption 3.2.2).
[b] Zn cross-section data unavailable; therefore *substituted as Al-27 (See Assumption 3.2.4).*

Source: DOE SRS HLW Glass Chemical Composition (Ref. 2.2.1, Table 19); Preliminary Waste Form Characteristics Report (Ref. 2.2.9, p. 2.2.1.1-4).

Tuff

Tuff, when modeled as a neutron reflector, is modeled 100% saturated and treated at full density (2.359 g/cm^3) in the MCNP calculations. The specification for Tuff is detailed in Table A1-18.

Table A1-18: Tuff Material Specification

Element/Isotope	ZAID	100% Saturated Atom Density (a/b-cm)
Si	14000.50c	1.7281E-02
Al-27	13027.50c	3.3505E-03
Fe-54	26054.60c	1.1224E-05
Fe-56	26056.60c	1.7604E-04
Fe-57	26057.60c	4.0676E-06
Fe-58	26058.60c	5.3724E-07
Mg	12000.50c	4.3900E-05
Ca	20000.50c	1.2135E-04
Na-23	11023.50c	1.5460E-03
K	19000.50c	1.3958E-03
Ti	22000.50c	1.8746E-05
P-31	15031.50c	9.5885E-06
Mn-55	25055.50c	1.3431E-05
O-16	8016.50c	4.5507E-02
H-1	1001.50c	7.8665E-03
Density = 2.359 g/cm^3		

NOTE: [a] Derivations are provided in Attachment II, Homog_Mats.xls, sheet Tuff, of *Dimension and Material Specification for Use in Criticality Analyses* (Ref. 2.2.1).
[b] The listed materials account for 99.16 wt% of the tuff material composition. Trace impurities (e.g., Cl, F, S, etc.) that are in quantities of 0.05 wt% and less are omitted from the representative composition since they are too sparse in concentration to have any appreciable difference on the reflective properties of the tuff

Source: *Geochemistry of Repository Block* (Ref. 2.2.10), mean values (called out by *IED Geotechnical and Thermal Parameters* (Ref. 2.2.12))

Titanium

Titanium, when modeled as a neutron reflector, is treated at full theoretical density (4.54 g/cm^3) in the MCNP calculations. The specification for Titanium, based on the material data provided in Ref. 2.2.5 (back cover), is detailed in Table A1-19.

Table A1-19: Titanium Material Specification

Element/ Isotope	ZAID	Wt%
^{22}Ti	22000.60c	100
Density: 4.54 g/cm^3		

Source: Ref. 2.2.5, back cover

Alloy 22

Alloy 22, when modeled as a neutron reflector, is treated at full density (8.69 g/cm^3) in the MCNP calculations. The specification for Alloy 22 is based on the specification provided in Table A1-2.

Natural UO_2

Natural UO_2 associated with FFTF insulator end pellets is modeled at density 10.42 g/cm^3 [Ref. 2.2.15, Section 3] in the MCNP calculations when treated as a neutron reflector in the degraded FFTF MCNP calculations. The specification for Natural UO_2 is based on the material data provided in Ref. 2.2.15, workbook *FFTF.xls*.

Table A1-20: Natural Uranium Oxide Material Specification

Element/ Isotope	ZAID	Wt%
^{235}U	92235.50c	0.640
^{238}U	92238.50c	87.510
^{16}O	8016.50c	11.850
Density: 10.42 g/cm^3		

Source: Ref. 2.2.15, workbook *FFTF.xls*

ThO_2

ThO_2 associated with SLWBR end reflectors is modeled at density 9.678 g/cm^3 [Ref. 2.2.18, Table 5-2] in the MCNP calculations when treated as a neutron reflector in the degraded SLWBR MCNP calculations. The specification for ThO_2 is based on the material data provided in Ref. 2.2.17, p. 10.

Table A1-21: Thorium Oxide Material Specification

Element/ Isotope	ZAID	Atom Proportion
^{232}Th	90232.50c	1
^{16}O	8016.50c	2
Density: 9.678 g/cm^3		
Source: Ref. 2.2.18, Table 5-2, and Ref. 2.2.17, p. 10		

Graphite

Graphite associated with TRIGA end reflectors is modeled at density 2.25 g/cm^3 [Ref. 2.2.25, p. 44] in the MCNP calculations when treated as a neutron reflector in the degraded TRIGA MCNP calculations. The specification for Graphite is based on the material data provided in [Ref. 2.2.22, Sections 3.2 and 3.2.1].

Table A1-22: Graphite Material Specification

Element/ Isotope	ZAID	Atom Proportion
C-nat	6000.50c	1
Density: 2.25 g/cm^3		

Source: Ref. 2.2.25, p. 44, and Ref. 2.2.22, Sections 3.2, 3.2.1

Aluminum 6061

Aluminum 6061 associated with ATR canister materials is modeled at density 2.713 g/cm^3 in the MCNP calculations when treated as a neutron reflector in the degraded ATR MCNP calculations. The specification for Aluminum 6061 is based on the material data provided in [Ref. 2.2.26, p. 102].

Table A1-23: Aluminum 6061 Material Specification

Element/ Isotope	ZAID	Wt%
Si-nat	14000.50c	0.600
^{54}Fe	26054.60c	0.040
^{56}Fe	26056.60c	0.643
^{57}Fe	26057.60c	0.015
^{58}Fe	26058.60c	0.002
^{63}Cu	29063.60c	0.188
^{65}Cu	29065.60c	0.087
^{55}Mn	25055.50c	0.150
Mg-nat	12000.50c	1.000
^{50}Cr	24050.60c	0.008
^{52}Cr	24052.60c	0.163
^{53}Cr	24053.60c	0.019
^{54}Cr	24054.60c	0.005
Ti-nat	22000.50c	0.150
^{27}Al	13027.50c	96.930
Density: 2.713 g/cm^3		

Source: Ref. 2.2.26, p. 102

Nickel

Nickel associated with the Ni-Gd Alloy in the ATR, EF, FFTF and TRIGA canister basket structure is modeled at density 8.6286 g/cm^3 in the MCNP calculations when treated as a neutron reflector in the degraded ATR, EF, FFTF and TRIGA MCNP calculations. The specification for Nickel is based on the material data provided in Reference 2.2.1, with adjustment to discount Gd content.

Table A1-24: Nickel Material Specification

Element/ Isotope	ZAID	Wt%
C-nat	6000.50c	0.010
Mn-55	25055.50c	0.508
Si-nat	14000.50c	0.081
Cr-50	24050.60c	0.670
Cr-52	24052.60c	13.426
Cr-53	24053.60c	1.552
Cr-54	24054.60c	0.393
Ni-58	28058.60c	44.028
Ni-60	28060.60c	17.541
Ni-61	28061.60c	0.775
Ni-62	28062.60c	2.509
Ni-64	28064.60c	0.664
Mo-nat	42000.50c	14.772
Co-59	27059.50c	2.030
Fe-54	26054.60c	0.057
Fe-56	26056.60c	0.933
Fe-57	26057.60c	0.022
Fe-58	26058.60c	0.003
S-32	16032.50c	0.005
P-31	15031.50c	0.005
O-16	8016.50c	0.005
N-14	7014.50c	0.010
Density: 8.6286 g/cm^3		

Source: Ref. 2.2.1, Table 7 (with adjustment to discount Gd content)

A1.3 Moderator Materials

Water

Water (H2O), when modeled as a neutron moderator is modeled at full theoretical density (0.99821 gcm^{-3}) in the MCNP calculations. The specification for water, based on water at 20˚ C (*Handbook of Chemistry and Physics* (Ref. 2.2.7, page 6-2)), is provided in Table A1-25.

Polysiloxane

Polysiloxane fluid (a common silicone-based hydraulic fluid), when modeled as a neutron moderator is modeled with a viscosity of 10cSt with a degree of polymerization of four (which is necessary for a viscosity of 10cSt at 25°C (Gelest Silicone Fluids: Stable, Inert Media (Ref. 2.2.8, p.11)). Refer to Assumption 3.2.3. The specification for polysiloxane is provided in Table A1-25.

Table A1-25: Polysiloxane Material Specification

Element/ Isotope	ZAID	Atoms per Molecule
^{1}H	1001.50c	42
Si	6000.50c	14
^{16}O	8016.50c	5
C	14000.50c	6
Density: 0.9 g/cm^3		

Source: Ref. 2.2.8, p.11, Assumption 3.2.3

Attachment 2: Digital Video Disc Listing

This attachment contains a listing and description of the files contained on the attachment Digital Video Disc (DVD) of this report (Attachment 3). The zip archives were created using WINZIP 9.0. The file attributes on the DVD are as follows:

Filename	File Size (bytes)	File Date	File Time	Description
MCNP inputs.zip	138,939,000	12/21/07	12:04	WinZip file containing all MCNP input files relevant to this document
MCNP outputs.zip	1,702,080,000	12/21/07	13:08	WinZip file containing all MCNP output files relevant to this document
Undamaged Canister & WP Results (Fig 7-1 to Fig 7-15 & Fig 7-126).xls	1,108,000	1/02/08	14:32	Microsoft Excel workbook containing results and data analysis relevant to Figures 7-1 through 7-15 and Figure 7-126 in this document
Dry Damaged Intact Canister Results (Fig 7-16 to Fig 7-29).xls	1,919,000	12/20/07	11:59	Microsoft Excel workbook containing results and data analysis relevant to Figures 7-16 through 7-29 in this document
Dry Damaged Degraded Canister Results (Fig 7-30 to 7-48).xls	2,891,000	11/29/07	18:07	Microsoft Excel workbook containing results and data analysis relevant to Figures 7-30 through 7-48 in this document
Flooded Damaged Intact Canister Results (Fig 7-49 to Fig 7-62).xls	1,850,000	12/04/07	10:18	Microsoft Excel workbook containing results and data analysis relevant to Figures 7-49 through 7-62 in this document
Flooded Damaged Degraded Canister Results (Fig 7-63 to Fig 7-125).xls	3,689,000	1/02/08	16:05	Microsoft Excel workbook containing results and data analysis relevant to Figures 7-63 through 7-125 in this document
Ancillary Results.xls	387,000	12/26/07	08:59	Microsoft Excel workbook containing results calculations related to increased reflector thicknesses and canister mixing scenarios discussed in this document

There are 19286 total files contained in the zip archive file *MCNP inputs.zip*, and 19286 total files contained in the zip archive file *MCNP outputs.zip*. Files suffixed "_in" are input files, whereas files suffixed "_ino" denote output files. Including six Microsoft Excel workbooks, the DVD contains a total of 38578 files.