

SEP 27 2001

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CSER 00-007

Addendum 1:

Criticality Safety Evaluation of the Shippingport PWR Core 2 Blanket Fuel Assemblies at Lower Exposures

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management
Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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CSER 00-007

Addendum 1:

Criticality Safety Evaluation of the Shippingport PWR Core 2 Blanket

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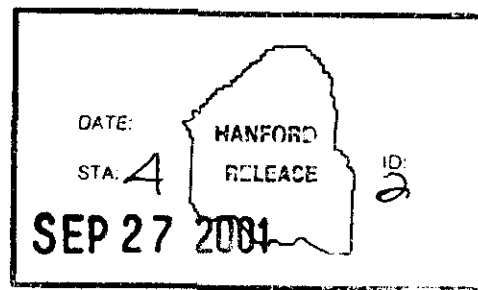
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**CSER 00-007 Addendum 1:
Criticality Safety Evaluation of the
Shippingport PWR Core 2 Blanket Fuel Assemblies
at Lower Exposures**

September 2001

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Executive Summary

This criticality safety evaluation report documents the analyses performed to support the incredibility of a nuclear criticality involving Shippingport PWR Core 2 blanket fuel assemblies by extending the range of applicability to include 6,500 MW_td/MTU and lower fuel exposures.

This addendum supports the given limits for Shippingport PWR Core 2 blanket fuel of:

Fissile Mass Limits

- For each blanket assembly None
- For assembly in the storage pool None
- For assembly in canister storage None

Spacing Limits

- For assemblies in the storage pool None
- For assemblies stored in a canister None

Other Limits

- No other limits or restrictions for criticality safety exist at T Plant for this set of 72 blanket assemblies during the loading/unloading and drying process in preparation for shipping to the Canister Storage Building (CSB).

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LIST OF TERMS

ANS	American Nuclear Society
CPS	Criticality Prevention Specifications
CSB	Canister Storage Building
CSER	Criticality Safety Evaluation Report
DOE	United States Department of Energy
EFPH	Effective Full Power Hours (electrical)
FGE	Fissile Gram Equivalent
FH	Fluor Hanford
H/Pu	Hydrogen to Plutonium atomic ratio
H/X	Hydrogen to Fissionable atomic ratio
MTIHM	Metric Tons Initial Heavy Metal
MTU	Metric Tons Uranium
MW _t d	MegaWatt (thermal) Days
ORIGEN2	Oak Ridge Isotope Generation 2, a code for isotopic buildup and decay
PWR	Pressurized Water Reactor

2.0 METHODOLOGY

2.1 ANALYSIS PHILOSOPHY

The statement of work for this safety evaluation requested to extend the previously calculated range of applicability (13,800 MW_d/MTU to 24,600 MW_d/MTU) down from 13,800 MW_d/MTU to 6,500 MW_d/MTU. The original analysis (Greenborg and Eberle 2000) was reviewed. It was noted that the analysis performed depended on the isotopic analysis calculated by ORIGEN2 (Wittekind 1999). Additional ORIGEN2 calculations performed for this addendum allowed for a lower range of exposures, to include 6,500 MW_d/MTU, and to demonstrate criticality incredibility on the basis of the effective ²³⁵U enrichment of the fissionable material.

2.2 SUBCRITICALITY LIMIT

For the purposes of this report, the criticality prevention criterion is the incredibility principle based on the effective ²³⁵U enrichment of the Shippingport PWR Core 2 blanket assemblies. Reference is made to handbooks that demonstrate the ²³⁵U enrichment is adequate to show incredibility of criticality irrespective of mass, geometry, or neutron reflection. This incredibility criterion is based on implementing the applicable DOE Orders, ANS standards, and HNF-7098. The subcriticality enrichment is used to judge the incredibility of criticality for the Shippingport PWR Core 2 blanket assembly fissionable material.

2.3 ORIGEN2 CODE

The isotopic generation and depletion code ORIGEN2 Version S.2, is under software configuration control and was certified (Roblyer and Schwinkendorf 2001). The validation, or demonstration of applicability to the isotopic calculation of Shippingport PWR Core 2 blanket assemblies, is contained in this document.

2.4 APPLICATION OF THE INCREDIBILITY DETERMINATION

This analysis must meet the requirements of HNF-7098, *Criticality Safety Program*, (FH 2001a). HNF-7098 states that before starting a new operation with fissile material or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions. To demonstrate the Incredibility Determination is satisfied, this CSER must show that by form or distribution of the fissionable material that a nuclear criticality is incredible.

3.0 SHIPPINGPORT PWR CORE 2 MODELING

The modeling of Shippingport PWR Core 2 blanket assemblies requires data on:

- Initial isotopic and elemental composition,
- Irradiation and/or exposure history,
- Decay times, and
- Desired composition quantities.

3.1 INITIAL ISOTOPIC COMPOSITION

The isotopic composition of the blanket assemblies is initially natural uranium. Documentation from Shippingport (Sphar, Leonard, and Lacy 1961) assumed 0.7117 wt% ^{235}U at the start of irradiation. The ORIGEN2 input file was derived from previous ORIGEN2 calculations (Wittekind 1999) and used those initial uranium compositions (0.711 wt% ^{235}U) and impurities.

3.2 IRRADIATION AND EXPOSURE HISTORY

The ten incremental Shippingport exposures to cover the range up to 13,800 MW_d/MTU are shown in Table 3.1.

Table 3.1 Blanket Power Fractions for Desired Assembly Exposures

Shippingport Blanket Power Fractions for Desired Assembly Exposures		
Increment	Blanket Power Fraction	Assembly Exposure (MW _d /MTU)
0.1	0.0472	1380
0.2	0.0944	2760
0.3	0.1416	4140
0.4	0.1888	5520
0.5	0.2360	6900
0.6	0.2832	8280
0.7	0.3304	9660
0.8	0.3776	11040
0.9	0.4248	12420
1	0.4720	13800

These blanket power fraction values are inserted into the spreadsheet calculation, Shippingport Reactor ORIGEN2 Chronology, shown in Table 3.2.

Table 3.2 Shippingport Reactor ORIGEN2 Chronology

Shippingport Reactor ORIGEN2 Chronology						
Date	EFPH	Days	MWt	MWtd	Comment	
30-Apr-65					Core 2 Seed 1 Initial Power	
31-Dec-65	2466.4	245	1.3155	322.31		
31-Dec-66	6543.1	610	1.4596	532.74		
31-Dec-67	10532.6	975	1.4283	521.35	Interpolated Seed 1 Average Power	
31-Dec-68	13256.3	1341	0.9725	355.93		
1-Mar-69	13652	1401	0.8618	51.71	Core 2 Seed 2 Refueling Began	
6-Jul-69	0	1528		0.00	Core 2 Seed 2 Initial Power	
31-Dec-69	1931.9	1706	1.4183	252.46		
31-Dec-70	4515.5	2071	0.9250	337.62		
31-Dec-71	6495.2	2436	0.7088	258.71		
31-Dec-72	8192.7	2802	0.6061	221.83		
31-Dec-73	9957.7	3167	0.6319	230.65		
4-Feb-74	10160	3202	0.7553	26.44	Core 3 PWR-LMBR Refueling	
1-Dec-74		3502			Decay Date	
1-Mar-75		3653			Decay Date	
1-Mar-77		4323			Decay Date	
1-Jan-79		4994			Decay Date	
MWtd Sum			0.4720	3111.75	13799.32	1.000049

The first column, "Date," details blanket fuel assembly power history in simplified steps.

The second column, "EFPH," is the effective full power hours (electrical) of Shippingport PWR operation, entered from Shippingport data (Wittekind 1999).

The third column, "Days," is the increment in days from the date listed in the row above.

The fourth column, "MWt," is the average heat generated in one blanket assembly during an irradiation period. The 0.4720 blanket power share was used in the Table 3.2 calculations. This is the result of calculation:

$$(EFPH(2)-EFPH(1)) / ((Days(2)-Days(1)) * 24) * 505 * 0.4720 / 76 = MWt(2)$$

or in numbers: $(2466.4 - 0.0) / ((245 - 0) * 24) * 505 * 0.4720 / 76 = 1.3155$

The "EFPH" column is effective full power hours (EFPH), so this difference is calculated and divided by 24 hours per day to convert to effective full power days. The result is divided by the increment of days in the "Days" column to give the fraction of full power that the reactor generated during that irradiation period.

The 505 MW_t multiplication converts full power (electrical) into Megawatts thermal, a more useful fuel exposure quantity (WAPD-294 1968, WAPD-332 1973, and WAPD-335 1983). The 0.4720 factor is the blanket power fraction to core total. This factor was calculated to yield 13,800 MW_t/MTU total blanket assembly exposure over the entire irradiation exposure history. The 76 is the number of power generating blanket fueled assemblies in the whole Shippingport Core 2 blanket.

The fifth column, "MWtd," is the product of the power level, "MWt" column, and the increment in days of the irradiation cycle, "Days" column.

The sum of the fifth column, 3111.75 MWtd, is the MW_td generated in one blanket assembly. Division by 0.2255 MTU, the metric tons of initial heavy metal in one blanket assembly, yields 13,799.32 MW_t/MTU total exposure. For the 0.4720 power fraction, this is the desired 13,800 MW_t/MTU blanket fuel exposure.

3.3 DECAY DATE

The decay date to be calculated from ORIGEN2 was chosen to be 1 January 2001. This is conservative because later decay times would have more ²⁴¹Pu decay into ²⁴¹Am, reducing the reactivity.

3.4 DESIRED ORIGEN2 OUTPUT

The desired ORIGEN2 results, for 1 January 2001, are:

- Composition by isotope (grams) for the Actinides and Daughters,
- Composition by isotope (grams) for ¹³⁷Cs,
- Total Burnup (MW_t), and
- Initial mass of heavy metal (MTU).

4.0 SHIPPINGPORT ORIGEN2 CALCULATIONS

4.1 METHODS VALIDATION

The ORIGEN2 code has long been used throughout the nuclear industry for isotope generation calculations (Croff 1980) for a number of different reactor types and for reprocessing facilities.

The ORIGEN2 code used for this calculation is under configuration control (Roblyer and Schwinkendorf 2001) on the Advanced Computer Center (ACC) system at Fluor Federal Services. These machines are 933 MHz Dell Precision 620 workstations, running the Microsoft Windows NT 4.0 operating system.

The ORIGEN2 executable used was located at:

E:\data\snf\cser0007\main.exe

and is dated 2:48 p.m. on December 22, 1998 and used 827,904 units of memory

This was copied from the ORIGEN2 executable located at:

P:\origen2\warren\debug\main.exe

and is dated 2:48 p.m. on December 22, 1998 and used 827,904 units of memory

The libraries used for the output included in this document were:

orig21 [Decay Library] dated 1:06 p.m. on December 21, 1998,
orig22 [PWRU Cross Section Library] dated 1:06 p.m. on December 21, 1998, and
orig61 [Photon Library] dated 1:07 p.m. on December 21, 1998.

These files were used in E:\data\snf\cser0007 but copied from the directory:

P:\origen2\libraries

Different ORIGEN2 cases were run and stored at different times:

- E:\data\snf\cser0007\ship00.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 0,000 MW_td/MTU stored at 4:15 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship01.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 1,380 MW_td/MTU stored at 1:09 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship02.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 2,760 MW_td/MTU stored at 1:10 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship03.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 4,140 MW_td/MTU stored at 1:10 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship04.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 5,520 MW_td/MTU stored at 1:11 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship05.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 6,900 MW_td/MTU stored at 1:11 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship06.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 8,280 MW_td/MTU stored at 1:11 p.m. on September 10, 2001.

- E:\data\snf\cser0007\ship07.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 9,660 MW_td/MTU stored at 1:12 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship08.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 11,040 MW_td/MTU stored at 1:12 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship09.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 12,420 MW_td/MTU stored at 1:12 p.m. on September 10, 2001.
- E:\data\snf\cser0007\ship10.out UO₂ Fuel, Zirc-4, Pyrolytic Carbon 13,800 MW_td/MTU stored at 1:16 p.m. on September 10, 2001.

4.2 ORIGEN2 RESULTS

Table 4.1 tabulated the ORIGEN2 results for decay to 1 January 2001 for all ten exposures (0 MW_td/MTU was only listed out) or eleven columns altogether.

The ORIGEN2 output is assembled into the top 36 rows (1-Jan-01 through MTIHM). There is a blank line, then the MW_td/MT is calculated from the “TOTburn” line divided by the “MTIHM” line.

The “²³⁵U wt%” and “²⁴⁰Pu wt%” lines are calculated from the grams of different isotopes above in this same table. The uranium, following the Shippingport convention (Sphar, Leonard, and Lacy 1961), only considered ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U. The plutonium, following the Shippingport convention (Sphar, Leonard, and Lacy 1961), only considered ²³⁹Pu, ²⁴⁰Pu, ²⁴¹Pu and ²⁴²Pu. These wt% calculations are more explicitly demonstrated in the next ten non-blank lines below.

The highlighted column in Table 4.1 is the ORIGEN2 exposure closest to the 6,500 MW_td/MTU desired for the criticality incredibility study. The shaded horizontal lines are the exposure range of the Shippingport analytical measurements for uranium isotopics and plutonium isotopics. It can be clearly seen that the available Shippingport PWR blanket assembly analytical measurements cover both sides of the range desired as the low exposure, 6,500 MW_td/MTU, for the criticality incredibility study.

These ORIGEN2 results, particularly the uranium isotopes and plutonium isotopes, form the basis for the criticality incredibility study that follows.

The ORIGEN2 input that generated one of these outputs is included in Appendix C, ORIGEN2 Computer Code Input and Output, along with a representative page of output.

The ORIGEN2 cross section library is actually from a different reactor, burnup, and ²³⁵U enrichment, than the Shippingport PWR. There is a detailed comparison between Shippingport PWR isotopic measurements and the ORIGEN2 predictions, and this is documented in Appendix D Shippingport Measurements and ORIGEN2 Calculations.

This comparison between measurement and calculation bounds the Shippingport PWR blanket assembly isotopic composition reactivity, for criticality purposes, by multiplying the ORIGEN2 ²³⁹Pu calculated result by 1.065.

Table 4.1 Shippingport PWR Blanket Assembly ORIGEN2 Results and Calculations

	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01
	13800	12,420	11,040	9,660	8,280	6,900	5,520	4,140	2,760	1,380		0
	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MT	MWd/MT	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU
HE 4	5.232E-01	4.426E-01	3.623E-01	2.873E-01	2.192E-01	1.589E-01	1.071E-01	6.500E-02	3.332E-02	1.232E-02		0.000E+01
PB206	1.423E-10	1.451E-10	1.481E-10	1.514E-10	1.551E-10	1.593E-10	1.640E-10	1.693E-10	1.755E-10	1.829E-10		0.000E+01
PB207	7.208E-09	7.195E-09	7.167E-09	7.119E-09	7.046E-09	6.943E-09	6.807E-09	6.627E-09	6.387E-09	6.050E-09		0.000E+01
BI209	3.144E-10	2.559E-10	2.055E-10	1.617E-10	1.239E-10	9.180E-11	6.499E-11	4.310E-11	2.564E-11			
RA226	1.451E-07	1.465E-07	1.481E-07	1.502E-07	1.527E-07	1.558E-07	1.596E-07	1.643E-07	1.699E-07	1.770E-07		0.000E+01
TH229	1.343E-07	1.114E-07	9.137E-08	7.371E-08	5.820E-08	4.468E-08	3.304E-08	2.310E-08	1.463E-08	7.270E-09		0.000E+01
TH230	1.011E-03	1.005E-03	1.001E-03	1.001E-03	1.006E-03	1.016E-03	1.032E-03	1.055E-03	1.086E-03	1.129E-03		0.000E+01
TH232	1.723E-04	1.641E-04	1.552E-04	1.452E-04	1.337E-04	1.207E-04	1.056E-04	8.781E-05	6.642E-05	3.931E-05		0.000E+01
PA231	4.484E-05	4.668E-05	4.761E-05	4.855E-05	4.955E-05	5.055E-05	5.163E-05	5.280E-05	5.411E-05	5.555E-05		0.000E+01
U233	3.775E-04	3.492E-04	3.183E-04	2.860E-04	2.523E-04	2.171E-04	1.802E-04	1.414E-04	1.000E-04	5.485E-05		0.000E+01
U234	1.283E+01	1.232E-01	1.186E+01	1.146E+01	1.115E+01	1.093E+01	1.084E+01	1.087E-01	1.105E-01	1.139E-01		1.197E-01
U235	5.559E+02	6.122E+02	6.718E+02	7.372E+02	8.098E+02	8.912E+02	9.837E+02	1.090E+03	1.217E+03	1.375E+03		1.603E-03
U236	1.790E+02	1.708E+02	1.619E+02	1.517E+02	1.401E+02	1.267E+02	1.111E+02	9.267E+01	7.031E+01	4.179E+01		0.000E-01
U238	2.197E+05	2.200E+05	2.204E+05	2.208E+05	2.212E+05	2.215E+05	2.219E+05	2.223E+05	2.228E+05	2.233E+05		2.239E+05
NP237	3.597E+01	3.308E+01	2.973E+01	2.621E+01	2.258E+01	1.887E+01	1.509E+01	1.129E+01	7.511E-00	3.801E-00		0.000E+01
PU238	1.786E+01	1.480E+01	1.186E+01	9.160E-00	6.733E-00	4.629E-00	2.891E-00	1.559E-00	6.516E-01	1.536E-01		0.000E+01
PU239	1.080E+03	1.058E+03	1.040E+03	1.016E+03	9.844E+02	9.398E+02	8.770E+02	7.864E+02	6.504E+02	4.311E+02		0.000E+01
PU240	3.641E+02	3.285E+02	3.066E+02	2.837E+02	2.567E+02	2.243E+02	1.858E+02	1.407E+02	8.940E+01	3.558E+01		0.000E+01
PU241	6.306E+01	6.147E+01	5.506E+01	4.720E+01	3.876E+01	3.007E+01	2.134E+01	1.312E+01	6.126E-00	1.395E-00		0.000E+01
PU242	7.268E-01	5.925E+01	4.624E+01	3.453E+01	2.430E-01	1.575E+01	9.027E-00	4.237E-00	1.363E-00	1.651E-01		0.000E+01
PU244	1.104E-03	7.096E-04	4.372E-04	2.521E-04								
AM241	1.992E+02	1.927E+02	1.726E+02	1.482E+02	1.219E+02	9.469E+01	6.727E+01	4.137E+01	1.929E+01	4.376E-00		0.000E+01
AM242M	6.509E-01	5.854E-01	5.021E-01	4.124E-01	3.205E-01	2.307E-01	1.478E-01	7.821E-02	2.868E-02	4.034E-03		0.000E+01
AM243	1.052E+01	7.704E-00	5.380E-00	3.544E-00	2.165E-00	1.188E-00	5.577E-01	2.028E-01	4.568E-02	3.002E-03		0.000E+01
CM242	1.577E-03	1.418E-03	1.217E-03	9.991E-04	7.766E-04	5.590E-04	3.580E-04	1.895E-04	6.948E-05	9.775E-06		0.000E+01
CM243	2.741E-02	2.061E-02	1.482E-02	1.007E-02	6.346E-03	3.597E-03	1.745E-03	6.578E-04	1.543E-04			
CM244	6.939E-01	4.470E-01	2.768E-01	1.606E-01	8.481E-02	3.939E-02	1.509E-02	4.254E-03	6.694E-04			
CM245	5.683E-02	3.430E-02	1.968E-02	1.042E-02	4.950E-03	2.020E-03	6.599E-04					
CM246	4.923E-03	2.672E-03	1.362E-03	6.323E-04	2.591E-04							
SUMTOT	2.223E+05	2.226E+05	2.229E+05	2.233E+05	2.236E+05	2.239E+05	2.242E+05	2.245E+05	2.249E+05	2.252E+05		2.255E+05
TOTAL	2.223E+05	2.226E+05	2.229E+05	2.233E+05	2.236E+05	2.239E+05	2.242E+05	2.245E+05	2.249E+05	2.252E+05		2.255E+05
CS137	5.633E+01	5.048E+01	4.470E+01	3.897E+01	3.330E+01	2.767E+01	2.207E+01	1.650E+01	1.096E+01	5.453E+00		0.000E+01
TO1burn	3.112E+03	2.801E+03	2.489E+03	2.178E+03	1.867E+03	1.556E+03	1.245E+03	9.335E+02	6.224E+02	3.112E+02		0.000E-01
MTHM	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01	2.255E-01		2.255E-01
MWd/MT	1.380E+04	1.242E+04	1.104E+04	9.659E+03	8.280E+03	6.900E+03	5.520E+03	4.140E+03	2.760E+03	1.380E+03		0.000E-01
²³⁵ U wt%	0.252	0.277	0.304	0.333	0.365	0.400	0.441	0.488	0.543	0.612		0.711
²⁴⁰ Pu wt%	23.047	21.795	21.175	20.537	19.683	18.538	16.996	14.897	11.963	7.599		0.000
U234	0.0058	0.0056	0.0054	0.0052	0.0050	0.0049	0.0049	0.0049	0.0049	0.0051		0.0053
U235	0.2522	0.2773	0.3036	0.3325	0.3645	0.4005	0.4411	0.4877	0.5431	0.6119		0.7108
U236	0.0812	0.0774	0.0732	0.0684	0.0631	0.0569	0.0498	0.0415	0.0314	0.0186		0.0000
U238	99.6608	99.6398	99.6178	99.5939	99.5674	99.5377	99.5042	99.4660	99.4206	99.3645		99.2839
	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000		100.0000
PU239	68.3614	70.1955	71.8282	73.5470	75.4815	77.6746	80.2256	83.2648	87.0346	92.0682		100.0000
PU240	23.0466	21.7951	21.1755	20.5367	19.6832	18.5384	16.9965	14.8974	11.9632	7.5987		0.0000
PU241	3.9915	4.0784	3.8027	3.4167	2.9720	2.4853	1.9521	1.3892	0.8198	0.2979		0.0000
PU242	4.6005	3.9311	3.1936	2.4996	1.8633	1.3017	0.8258	0.4486	0.1824	0.0353		0.0000
	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000		0.0000

5.0 EVALUATION AND RESULTS

This criticality incredibility study performs several steps before justifying the conclusion:

- Conversion of all isotopes, except ^{235}U , to ^{239}Pu fissile gram equivalent (FGE),
- Summation of the all the ^{239}Pu fissile gram equivalents,
- Calculation of the effective ^{240}Pu wt%,
- Calculation of the plutonium critical mass for this effective ^{240}Pu wt%,
- Converting the ^{239}Pu FGE at this ^{240}Pu wt% to ^{235}U FGE.
- Adding the ^{235}U FGE to the remaining ^{235}U for an effective ^{235}U wt%,
- Comparing the effective ^{235}U wt% on the ^{235}U critical mass vs. ^{235}U enrichment plot.

5.1 FISSILE GRAM EQUIVALENT CONVERSION

The fissile gram equivalent calculation was performed using the spreadsheet shown in Table 5.1 Shippingport PWR Assembly Fissile Gram Equivalent and Burnup Enrichment.

The ^{239}Pu fissile gram equivalent was calculated using tabulated values (Bushore and Miller 2000). These tabulated conversion factors are listed in the leftmost column of Table 5.1. These equivalents are multiplied times the eleven columns of ORIGEN2 results for actinides decayed to 1 January 2001, as shown in Table 4.1, to give the eleven columns of ^{239}Pu FGE shown in Table 5.1.

The “Pu239 FGE” row is the sum of all ^{239}Pu FGE, except for ^{235}U .

The “Pu239 FGE adj” row is the sum of all ^{239}Pu FGE, except for ^{235}U , except with an additional 0.065 times the ^{239}Pu mass. This bounds the Shippingport PWR blanket assembly isotopic composition, for criticality purposes, as explained in Appendix D Shippingport Measurements and ORIGEN2 Calculations.

The “U235 wt%” and “Pu240 wt%” rows are the ORIGEN2 calculations for these quantities, according to the Shippingport convention. These are the same values as in Table 4.1.

The “Pu240 eff wt%” row is calculated by $100 * ^{240}\text{Pu} / (^{240}\text{Pu} + ^{239}\text{Pu FGE adj})$. This ^{240}Pu effective wt% is lower than the previous directly calculated ^{240}Pu wt% row just above.

Some values were read off Figure B.1 in Appendix B (Paxton and Pruvost 1987) for the calculated effect of ^{240}Pu content on the minimum critical mass of plutonium. Minimum critical mass values as a function of ^{240}Pu content are taken to be:

- 0 ^{240}Pu wt%, 520 g Pu;
- 5 ^{240}Pu wt%, 610 g Pu;
- 10 ^{240}Pu wt%, 750 g Pu;
- 15 ^{240}Pu wt%, 900 g Pu;
- 20 ^{240}Pu wt%, 1120 g Pu.

These values are used in a five point Lagrangian Interpolation for the minimum critical mass for the particular “Pu240 eff wt%” in the same column. The five individual terms in the five point Lagrangian Interpolation are calculated individually for spreadsheet simplicity. The resulting plutonium minimum critical masses are shown in the row “Pu Critical mass (g).”

The “U235 Crit. Mass (g)” row is 700 grams ²³⁵U minimum critical mass.

Table 5.1 Shippingport Blanket Assembly Fissile Gram Equivalent and ²³⁵U Enrichment

		1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01	1-Jan-01
		13800 MWd/MT	12,420 MWd/MT	11,040 MWd/MT	9,660 MWd/MT	8,280 MWd/MT	6,900 MWd/MT	5,520 MWd/MT	4,140 MWd/MT	2,760 MWd/MT	1,380 MWd/MT	0 MWd/MT	0
HE 4		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
PB206		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
PB207		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
B1209		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
RA226		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
TH229		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
TH230		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
TH232		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
PA231		0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
1.00E-00	U233	3.775E-04	3.492E-04	3.183E-04	2.860E-04	2.523E-04	2.171E-04	1.802E-04	1.414E-04	1.000E-04	5.485E-05	0.000E+01	0.000E+01
	U234	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
	U235	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
	U236	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
	U238	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
0.015	NP237	5.396E-01	4.962E-01	4.460E-01	3.932E-01	3.387E-01	2.831E-01	2.264E-01	1.694E-01	1.127E-01	5.702E-02	0.000E+01	0.000E+01
0.1125	PU238	2.009E-00	1.665E-00	1.334E-00	1.031E-00	7.575E-01	5.208E-01	3.252E-01	1.754E-01	7.331E-02	1.728E-02	0.000E+01	0.000E+01
1.00E-00	PU239	1.080E-03	1.058E+03	1.040E-03	1.016E+03	9.844E+02	9.398E+02	8.770E+02	7.864E+02	6.504E+02	4.311E+02	0.000E+01	0.000E+01
0.0225	PU240	8.192E-00	7.391E-00	6.899E-00	6.383E-00	5.776E-00	5.047E-00	4.181E-00	3.166E-00	2.012E-00	8.006E-01	0.000E+01	0.000E+01
2.25	PU241	1.419E+02	1.383E+02	1.239E+02	1.062E+02	8.721E+01	6.766E+01	4.802E+01	2.952E+01	1.378E+01	3.139E+00	0.000E+01	0.000E+01
0.0075	PU242	5.451E-01	4.444E-01	3.468E-01	2.590E-01	1.823E-01	1.181E-01	6.770E-02	3.178E-02	1.022E-02	1.238E-03	0.000E+01	0.000E+01
	PU244	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
0.01875	AM241	3.735E-00	3.613E-00	3.236E-00	2.779E-00	2.286E-00	1.775E-00	1.261E-00	7.757E-01	3.617E-01	8.205E-02	0.000E+01	0.000E+01
34.61538	AM242m	2.253E+01	2.026E+01	1.738E+01	1.428E+01	1.109E+01	7.986E+00	5.116E+00	2.707E+00	9.928E-01	1.396E-01	0.000E+01	0.000E+01
0.012857	AM243	1.353E-01	9.905E-02	6.917E-02	4.557E-02	2.784E-02	1.527E-02	7.170E-03	2.607E-03	5.873E-04	3.860E-05	0.000E+01	0.000E+01
	CM242	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
5.00E-00	CM243	1.371E-01	1.031E-01	7.410E-02	5.035E-02	3.173E-02	1.799E-02	8.725E-03	3.289E-03	7.715E-04	0.000E+01	0.000E+01	0.000E+01
0.09	CM244	6.245E-02	4.023E-02	2.491E-02	1.445E-02	7.633E-03	3.545E-03	1.358E-03	3.829E-04	6.025E-05	0.000E+01	0.000E+01	0.000E+01
1.50E+01	CM245	8.525E-01	5.145E-01	2.952E-01	1.563E-01	7.425E-02	3.030E-02	9.899E-03	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
	CM246	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01	0.000E+01
	Pu239 FGE	1.261E+03	1.231E+03	1.194E+03	1.148E+03	1.092E+03	1.023E+03	9.362E+02	8.230E+02	6.677E+02	4.353E+02	0.000E+01	0.000E+01
	Pu239 FGE adj	1.331E+03	1.300E+03	1.262E+03	1.214E+03	1.156E+03	1.084E+03	9.932E+02	8.741E+02	7.100E+02	4.634E+02	0.000E+01	0.000E+01
	U235 FGE	7.638E+02	8.047E+02	8.073E+02	8.004E+02	7.909E+02	7.757E+02	7.508E+02	7.085E+02	6.340E+02	4.854E+02	0.000E+01	0.000E+01
	Del U235 wt%	0.346	0.364	0.365	0.361	0.356	0.349	0.337	0.317	0.283	0.216	0.000	0.000
	U235 eff wt%	0.599	0.642	0.669	0.694	0.720	0.749	0.778	0.805	0.826	0.828	0.711	0.711
	U235 wt%	0.252	0.277	0.304	0.333	0.365	0.400	0.441	0.488	0.543	0.612	0.711	0.711
	Pu240 wt%	22.789	21.583	21.003	20.401	19.582	18.468	16.952	14.873	11.953	7.596	0.000	0.000
	Pu240 eff wt%	21.482	20.176	19.551	18.947	18.169	17.140	15.759	13.865	11.183	7.131	0.000	0.000
0	520	63	5	-10	-18	-22	-18	-7	8	9	-21	520	520
5	610	-385	-30	62	115	140	122	48	-61	-72	337	0	0
10	750	1020	83	-174	-329	-417	-382	-164	257	698	462	0	0
15	900	-1446	-131	293	597	859	1020	994	700	173	-135	0	0
20	1120	1967	1204	923	697	462	237	55	-40	-23	26	0	0
	Pu Critical Mass (g)	1220	1131	1094	1061	1023	979	926	864	784	668	520	520
	U235 Crit. Mass (g)	700	700	700	700	700	700	700	700	700	700	700	700

The “U235 FGE” row is calculated from:

$$\text{“Pu239 FGE”} * (\text{“U235 Crit. Mass (g)”} / \text{“Pu Critical Mass (g)”})$$

This ^{235}U FGE is mostly lower than the ^{239}Pu FGE because of the ^{240}Pu content.

The “Del U235 wt%” row is the effective increase in the ^{235}U enrichment due to the ^{239}Pu FGE. Note that this contribution from the ^{239}Pu FGE reaches a maximum at 11,040 MW_t/MTU and decreases as the exposure increases.

The “U235 eff wt%” row is the total effective ^{235}U enrichment, given what is left from the initial ^{235}U enrichment, and the ^{239}Pu FGE after taking into account the effect of ^{240}Pu content. Note that this effective ^{235}U wt% actually increases to a maximum at 1,380 MW_t/MTU , and then decreases at higher exposures.

The significant ORIGEN2 results are shown in the highlighted line “U235 eff wt%.”

5.2 EFFECTIVE ^{235}U ENRICHMENT

The ORIGEN2 results shown highlighted in Table 5.1 indicate the effective ^{235}U wt%. At 0 MW_t/MTU is the original 0.711 ^{235}U wt%. At 1,380 MW_t/MTU , there is an increase to 0.828 effective ^{235}U wt%. At 4,140 MW_t/MTU , there is a decrease to 0.805 effective ^{235}U wt%, and this decrease continues with the increasing exposure.

5.3 MINIMUM CRITICAL ^{235}U ENRICHMENT EVALUATION

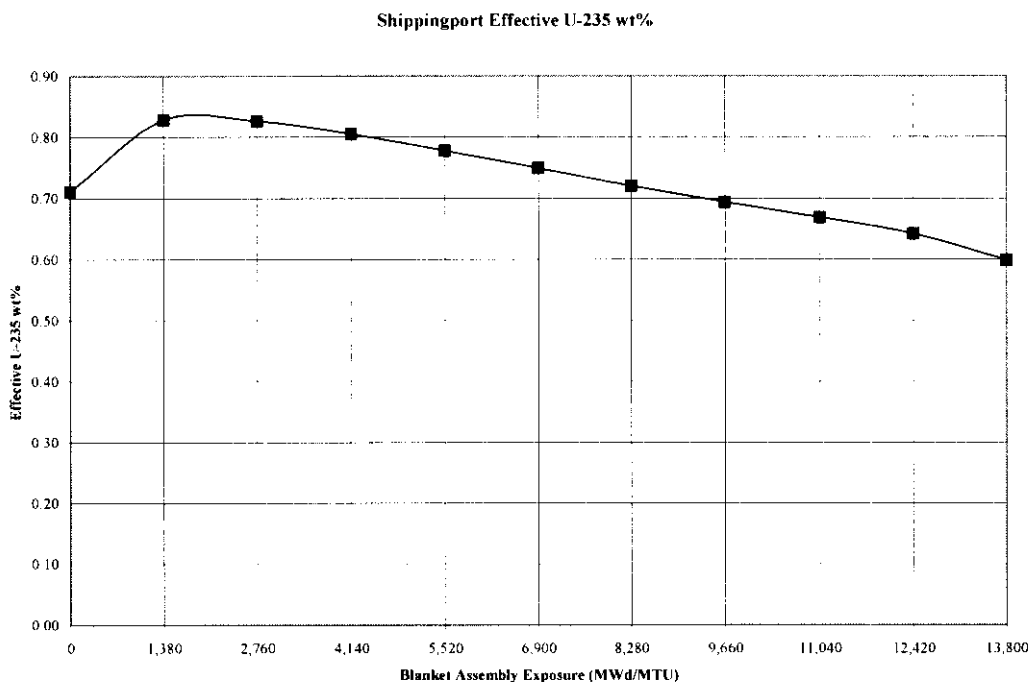
The chart for minimum critical mass for uranium metal in water, Figure B.2 in Appendix B (Paxton and Pruvost 1987), shows the critical homogeneous limit as a ^{235}U wt% about 1.03%, while the heterogeneous limit is about 0.72 wt% ^{235}U . The Shippingport fuel is uranium dioxide. The uranium oxide enrichment limit is higher than the uranium metal limit. The chart for uranium metal and uranium oxide ^{235}U enrichment and mass, Figure B.3 in Appendix B (ANS 1998), shows the uranium oxide ^{235}U enrichment limit for criticality safety versus ^{235}U mass.

The total Shippingport special nuclear materials inventory (Johnson 2001) shows approximately 120 kg Pu, 84.7 kg ^{239}Pu , and 32 kg ^{235}U . Using 100 kg mass for all the ^{235}U FGE in the 76 Shippingport blanket fuel assemblies, read from Mass Limits for Uranium Water Lattices, Figure B.4 in Appendix B (ANS 1998), gives the minimum critical enrichment of 0.80 wt% ^{235}U .

5.4 SHIPPINGPORT EXPOSURE FOR EFFECTIVE ^{235}U ENRICHMENT

The Shippingport PWR blanket assembly exposure will now be calculated as a function of the effective ^{235}U enrichment. Figure 5.1 shows the effective ^{235}U wt% in the Shippingport blanket fuel versus exposure.

Figure 5.1 Shippingport Effective ²³⁵U wt%



Observe the linear relationship from 2,760 MW_td/MTU to 12,420 MW_td/MTU. Interpolation performed between 0.8 and 0.7 wt% ²³⁵U, will use the points (4,140 MW_td/MTU, 0.8047 ²³⁵U wt%) and (9,660 MW_td/MTU, 0.6935 ²³⁵U wt%). The equation is:

$$((x - 4140)/(9660-4140))*0.6935 + ((x-9660)/(4140-9660))*0.8047 = y$$
 where x is exposure (MW_td/MTU) and y is eff. ²³⁵U wt%. Results are shown in Table 5.2.

Table 5.2 Effective ²³⁵U Interpolated to Blanket Assembly Exposure

Effective ²³⁵ U wt % Interpolated to Blanket Assembly Exposure Linear Interpolation Used	
Eff. ²³⁵ U wt%	MW _t d/MTU
0.82	3380
0.81	3877
0.80	4373
0.79	4869
0.78	5366
0.77	5862
0.76	6359
0.75	6855
0.74	7351
0.73	7848
0.72	8344
0.70	9337

Table 5.2 shows that for a limiting ^{235}U enrichment of 0.80 wt%, the minimum blanket assembly exposure is 4,375 MW_td/MTU. This fulfills the Incredibility Determination safety criterion.

5.5 CONSERVATIVE ASSUMPTIONS

- Conversion to ^{239}Pu fissile gram equivalents by the logic of minimum critical mass is conservative because not all of the minimum critical masses occur at the same neutron energy, some are fast neutron systems, while others are thermal neutrons systems. A mixture is not as reactive as a single isotope (Bushore and Miller 2000).
- ORIGEN2 results are scaled to be conservative by scaling up the non-conservative isotopes and not adjusting the isotopes where ORIGEN2 is conservative with respect to Shippingport measurements. This occurred when ^{239}Pu FGE is adjusted to ^{239}Pu FGE adj.
- The ^{239}Pu FGE adj is also used as the basis for conservative change from the ^{240}Pu wt% to ^{240}Pu eff wt% which is used to infer the plutonium critical mass.
- Comparison with the UO_2 curve from Figure B.3 (ANS 1998) for uranium in water lattices is conservative because an ideal arrangement for ^{235}U and ^{235}U FGE safe enrichment would be optimally moderated in spherical geometry with full H_2O reflection, not Shippingport blanket fuel assembly geometry.
- Calculation of the minimum exposure for 100 kg ^{235}U requires the total inventory of all the Shippingport blanket assemblies be at this ^{235}U effective wt%. Many of the Shippingport blanket assemblies are much more exposed than this maximum ^{235}U effective wt% (Johnson 2001).
- Neutron absorption due to fission products, cladding, and blanket assembly structural members is ignored.
- ^{241}Pu decay continues to decrease reactivity for times later than 1 January 2001.

These conservative assumptions fully justify the determination of an incredible risk of criticality for the 76 Shippingport PWR Core 2 blanket assemblies.

5.6 CONCLUSIONS

This analysis meets the requirements of HNF-7098, *Criticality Safety Program*, (FH 2001a). HNF-7098 states that before starting a new operation with fissile material or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions. To demonstrate the Incredibility Principle is satisfied, this CSER shows that the form or distribution is such that criticality is impossible. This evaluation demonstrated, that on the basis of effective ^{235}U enrichment, criticality is not possible.

The minimum blanket assembly exposure is 4,375 MW_td/MTU for fissile material that is shown to fulfill the Incredibility Principle safety criterion on the basis of enrichment

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APPENDIX A REVIEWERS COMMENTS

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Reviewer Comments from J. Greenborg – 9/21/2001

CSER 00-007, Addendum 1, was independently peer reviewed by J. Greenborg, a qualified Criticality Safety Specialist in the Criticality And Shielding group of Fluor Federal Services in accordance with Fluor Hanford's Technical Safety Programs Desk Instruction 2.0, Rev 1, *Technical Peer Review* (dated June 15, 2001). This technical review covered all aspects of this report. As shown in the Independent Review Checklist, this report was reviewed with no gaps.

The reviewer concurs that this CSER correctly evaluates the safety of the Shippingport core 2 blanket fuel assemblies at the lower exposures. Editorial comments were incorporated. The reviewer concurs with the conservative assumptions and the conclusions of the analysis.

S. R. Gedeon reviewed the hand calculations, spreadsheets and computer input and outputs. Items checked identically in the attached checklists indicate Mr. Gedeon and Mr. Greenborg concur.

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed - HNF-8853 Rev 0

Title: CSER 00-007 Addendum 1 Criticality Safety Evaluation of the Shippingport PWR Core 2 Blanket Fuel Assessment at Lower Exposures

Author: W. D. Wittekind

Date: September 21, 2001

Scope of Review: Entire Document Except Computer Codes and Spreadsheets

<u>Yes</u>	<u>No*</u>	<u>NA</u>	
[✓]	[]	[]	Referenced analyses appropriate.
[✓]	[]	[]	Problem completely defined and all potential configurations considered.
[]	[]	[✓]	Accident scenarios developed in a clear and logical manner.
[✓]	[]	[]	Necessary assumptions explicitly stated and supported.
[✓]	[]	[]	Computer codes and data files documented.
[✓]	[]	[]	Data used in calculations explicitly stated in document.
[✓]	[]	[]	Data checked for consistency with original source information as applicable.
[✓]	[]	[]	Mathematical derivations checked including dimensional consistency of results
[✓]	[]	[]	Models appropriate and used within range of validity, or use outside range of established validity justified.
[✓]	[]	[]	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
[✓]	[]	[]	Software input correct and consistent with document reviewed.
[✓]	[]	[]	Software output consistent with input and with results reported in document reviewed.
[✓]	[]	[]	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
[✓]	[]	[]	Safety margins consistent with good engineering practices.
[✓]	[]	[]	Conclusions consistent with analytical results and applicable limits.
[✓]	[]	[]	Results and conclusions address all points required in the problem statement.
[✓]	[]	[]	Format consistent with applicable guides or other standards.
[✓]	[]	[]	** Review calculations, comments, and/or notes are attached.
[✓]	[]	[]	Document approved (for example, the reviewer affirms the technical accuracy of the document).

J. Greenberg
 Technical Peer Reviewer (printed name and signature)

9/21/01
 Date

- * All "no" responses must be explained below or on an additional sheet.
- ** Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. The material should be labeled and recorded in such a manner as to be understandable to a technically qualified third party.

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed - HNF-8853 Rev 0

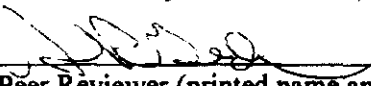
Title: CSER 00-007 Addendum 1: Criticality Safety Evaluation of the Shippingport PWR Core 2 Blanket Fuel Assessment at Lower Exposures

Author: W. D. Wittekind

Date: September 21, 2001

Scope of Review: Computer Codes and Spreadsheets

<u>Yes</u>	<u>No*</u>	<u>NA</u>	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Referenced analyses appropriate.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Problem completely defined and all potential configurations considered.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Accident scenarios developed in a clear and logical manner.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Necessary assumptions explicitly stated and supported.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Computer codes and data files documented.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Data used in calculations explicitly stated in document.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Data checked for consistency with original source information as applicable.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Mathematical derivations checked including dimensional consistency of results
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Models appropriate and used within range of validity, or use outside range of established validity justified.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Software input correct and consistent with document reviewed.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Software output consistent with input and with results reported in document reviewed.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Safety margins consistent with good engineering practices.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Conclusions consistent with analytical results and applicable limits.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Results and conclusions address all points required in the problem statement.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Format consistent with applicable guides or other standards.
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	** Review calculations, comments, and/or notes are attached.
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Document approved (for example, the reviewer affirms the technical accuracy of the document).

S. R. Gedeon 
 Technical Peer Reviewer (printed name and signature)

21 Sep 2001
 Date

- * All "no" responses must be explained below or on an additional sheet.
- ** Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. The material should be labeled and recorded in such a manner as to be understandable to a technically qualified third party.

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APPENDIX B HANDBOOK FIGURES

Figure B.1. Calculated effect of ^{240}Pu content on Pu Spherical Critical Mass versus Density of Pu, from LA-10860-MS, Figure 35 page 73.

Figure B.2. Uranium Spherical Critical Mass versus ^{235}U Enrichment, from LA-10860-MS, Figure 22 page 52

Figure B.3 Mass limit for uranium water lattices versus ^{235}U enrichment, from ANSI/ANS-8.1-1998, Figure 1 page 10.

Figure B.4 Detail of mass limit for uranium water lattices versus ^{235}U enrichment, from ANSI/ANS-8.1-1998, Figure 1 page 10. Detail is 0 to 1.0 wt% and 60 kg ^{235}U to 100 kg ^{235}U .

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Figure B.1. Calculated effect of ^{240}Pu content on Pu Spherical Critical Mass versus Density of Pu, from LA-10860-MS, Figure 35 page 73.

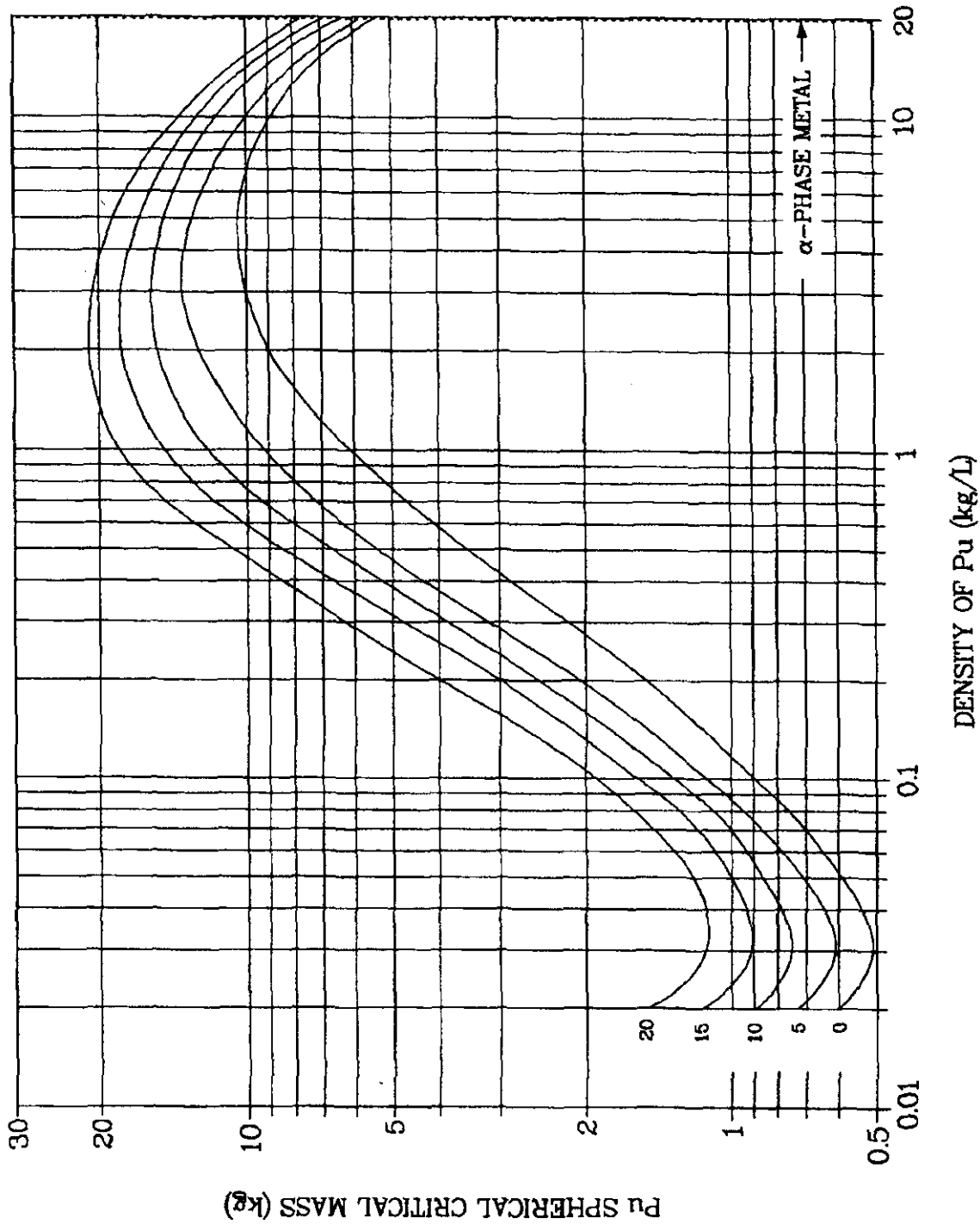


Fig. 35. Calculated effect of ^{240}Pu content on the critical mass of water-reflected homogeneous plutonium metal-water spheres. The ^{240}Pu content, in wt%, is indicated for each curve.

Figure B.2. Uranium Spherical Critical Mass versus ^{235}U Enrichment, from LA-10860-MS, Figure 22 page 52

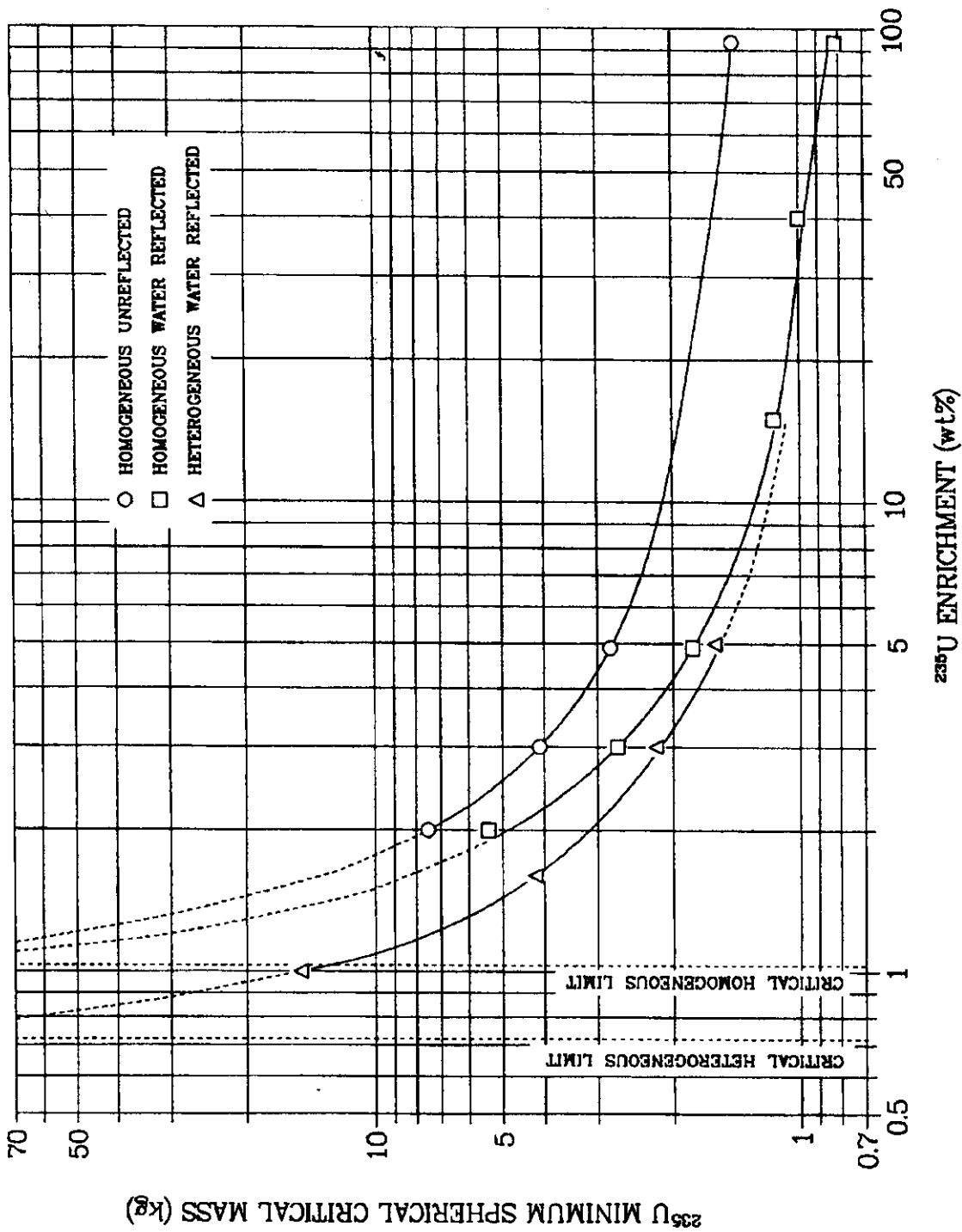


Fig. 22. Minimum spherical critical masses as functions of ^{235}U enrichment in homogeneous and heterogeneous hydrogen-moderated systems.

Figure B.3 Mass limit for uranium water lattices versus ^{235}U enrichment, from ANSI/ANS-8.1-1998, Figure 1 page 10.

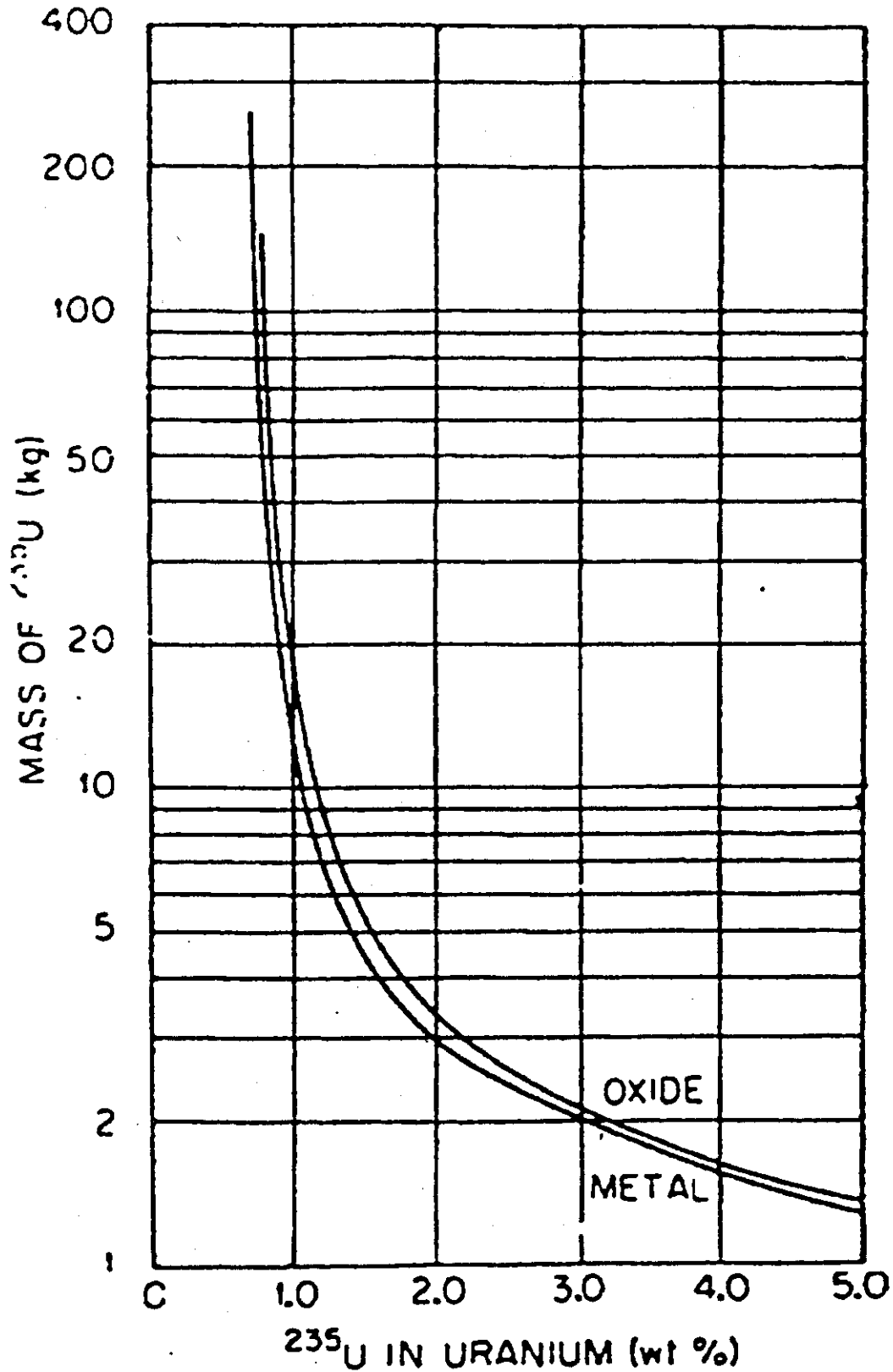
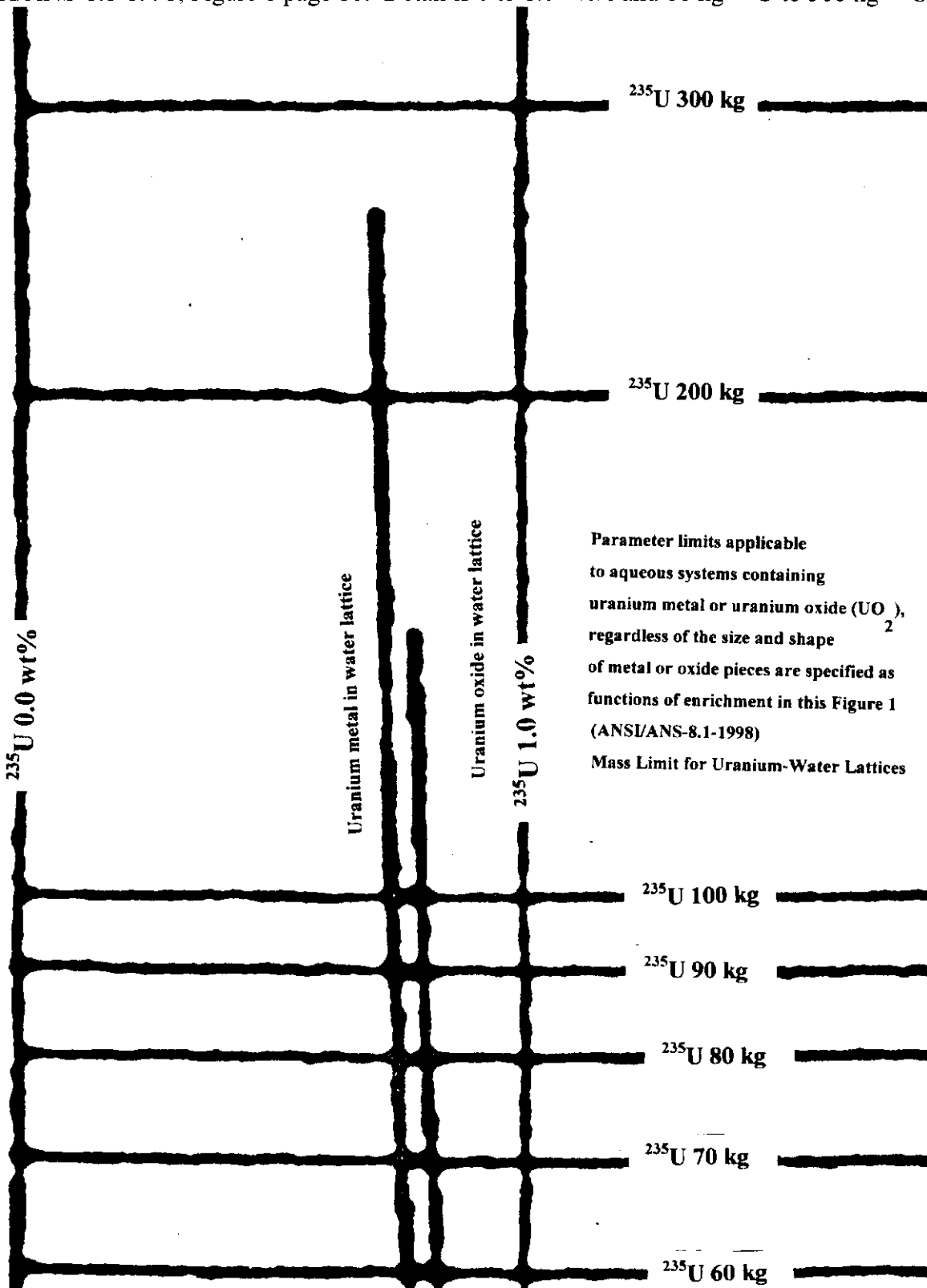


Figure B.4 Detail of mass limit for uranium water lattices versus ^{235}U enrichment, from ANSI/ANS-8.1-1998, Figure 1 page 10. Detail is 0 to 1.0 wt% and 60 kg ^{235}U to 300 kg ^{235}U .



APPENDIX C ORIGEN2 COMPUTER CODE INPUT AND OUTPUT

ORIGEN2 Input for case 1,380 MW_t/MTU

ORIGEN2 Representative page (Actinide mass) of Output for case 1,380 MW_t/MTU

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APPENDIX D SHIPPINGPORT MEASUREMENTS AND ORIGEN2 CALCULATIONS

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The Shippingport PWR was an experimental reactor, and tests and measurements were made that are documented. One very useful measurement was on the burnup isotopics of uranium and plutonium. These results are included as the next two pages (reproduced from Sphar, C. D., J. H. Leonard and P. S. Lacey, 1961, *Isotopic Analysis of Irradiated Natural Uranium Dioxide Fuel Rods from PWR Core 1 – Preliminary Results*, WAPD-TM-280, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania).

The isotopic data measurements include:

- Total uranium,
- Total plutonium,
- ¹³⁷Cs quantity,
- Uranium isotopics, and
- Plutonium isotopics.

The ORIGEN2 calculations were converted to the same quantities as were used in the Shippingport PWR isotopic data measurements. The main difference is that the quantity of uranium that was analyzed. The ORIGEN2 quantity is scaled to 134.096 grams of uranium

Table D.1 ORIGEN2 Scaled to Pin Uranium Mass in Grams

Pin Uranium Mass (grams)	
135.30	
134.06	
133.00	
133.97	
135.21	
134.41	
134.15	
134.06	
133.18	
133.62	
134.096	Average
0.751	Std. Dev.
0.2375	Std. Dev. of the Mean

The total measured uranium differs so much from the initial uranium loading manufacturing data that it was not taken seriously in the original documentation.

There is no exposure indicated, so the ²³⁵U will be used as the exposure tracking quantity. Actually the burnout of ²³⁵U could also be used here, but the choice is to use ²³⁵U wt%. Detailed discussion of individual Shippingport measurements to ORIGEN2 calculations is made with Figure D.1 through D.8. The Shippingport PWR measurements are plotted with the ORIGEN2 calculations on the same graphs for visual comparison purposes. There is a discussion with each graph.

Table I
Measured Compositions of UO₂ Rods

	Assembly 6E Rod Number				
	1	2	3	4	5
Total Uranium (gm)	133.67 ± 0.12	115.12 ± 0.11	127.34 ± 0.35	135.8 ± 1.2	132.34 ± 0.14
Isotopic Weight Percent					
Uranium-234	0.0051 ± 0.0004	0.0047 ± 0.0002	0.0055 ± 0.0003	0.0050 ± 0.0004	0.0046 ± 0.0001
Uranium-235	0.3059 ± 0.0008	0.2822 ± 0.0047	0.3538 ± 0.0043	0.3159 ± 0.0025	0.4397 ± 0.0004
Uranium-236	0.0667 ± 0.0007	0.0734 ± 0.0007	0.0627 ± 0.0005	0.0696 ± 0.0009	0.0479 ± 0.0003
Uranium-238	99.622 ± 0.0008	99.639 ± 0.005	99.582 ± 0.006	99.610 ± 0.003	99.512 ± 0.0005
Total Plutonium (gm)	0.617 ± 0.012	0.278 ± 0.006	0.1428 ± 0.0015	0.222 ± 0.011	0.506 ± 0.01
Isotopic Weight Percent					
Plutonium-239	69.71 ± 0.04	65.023 ± 0.038	71.098 ± 0.230	67.889 ± 0.074	79.84 ± 0.06
Plutonium-240	22.20 ± 0.02	24.882 ± 0.029	21.049 ± 0.130	23.218 ± 0.062	15.2 ± 0.05
Plutonium-241	6.68 ± 0.02	7.889 ± 0.023	6.521 ± 0.100	7.151 ± 0.024	4.45 ± 0.03
Plutonium-242	1.41 ± 0.02	2.206 ± 0.007	1.332 ± 0.021	1.735 ± 0.017	0.51 ± 0.02
Cesium-137 (gm)	3.18 x 10 ⁻²	3.02 x 10 ⁻²	2.63 x 10 ⁻²	3.21 x 10 ⁻²	1.90 x 10 ⁻²
Initial Uranium Loading-(Materials Bal.)	135.28	116.34	128.30	137.20	133.43
Initial Uranium Loading Manufacturing Data	135.30	134.06	133.0	133.97	135.21

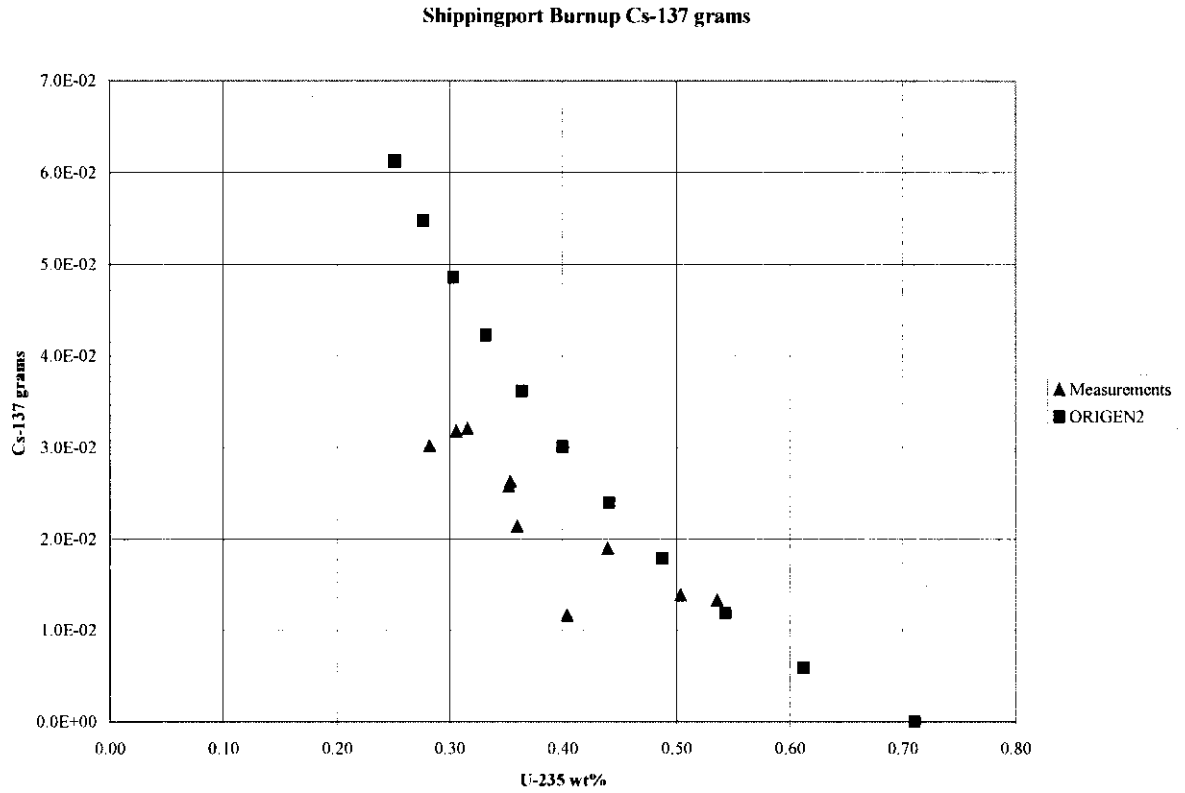
Table I continued
Measured Compositions of UO₂ Rods

	Assembly 6E Rod Number				
	6	7	8	9	10
Total Uranium (gm)	77.60 ± 0.75	22.34 ± 0.04	134.85 ± 1.05	137.45 ± 0.12	131.44 ± 0.61
Isotopic Weight Percent					
Uranium-234	0.0059 ± 0.0007	0.0058 ± 0.0004	0.0059 ± 0.0007	0.0056 ± 0.0003	0.0063 ± 0.0004
Uranium-235	0.36 ± 0.0031	0.404 ± 0.007	0.3526 ± 0.0036	0.5036 ± 0.0065	0.5357 ± 0.0125
Uranium-236	0.0636 ± 0.0039	0.0539 ± 0.0004	0.0551 ± 0.0044	0.0382 ± 0.0003	0.0380 ± 0.0007
Uranium-238	99.571 ± 0.025	99.536 ± 0.007	99.582 ± 0.004	99.451 ± 0.005	99.420 ± 0.012
Total Plutonium (gm)	0.0295 ± 0.0005	0.00715 ± 0.00013	0.466 ± 0.012	0.1172 ± 0.0008	0.0711 ± 0.0009
Isotopic Weight Percent					
Plutonium-239	70.528 ± 0.345	75.223 ± 0.063	72.107 ± 0.095	83.754 ± 0.245	84.143 ± 0.038
Plutonium-240	21.616 ± 0.267	18.269 ± 0.059	20.637 ± 0.094	12.734 ± 0.134	12.856 ± 0.023
Plutonium-241	6.434 ± 0.067	5.597 ± 0.12	6.12 ± 0.032	3.204 ± 0.081	2.771 ± 0.015
Plutonium-242	1.422 ± 0.097	0.91 ± 0.021	1.136 ± 0.007	0.308 ± 0.037	0.23 ± 0.003
Cesium-137 (gm)	2.14 × 10 ⁻²	1.17 × 10 ⁻²	2.58 × 10 ⁻²	1.39 × 10 ⁻²	1.33 × 10 ⁻²
Initial Uranium Loading-(Materials Bal.)	78.29	22.71	136.12	138.00	131.92
Initial Uranium Loading Manufacturing Data	134.41	134.15	134.06	133.18	133.62

Table D.2 ORIGEN2 Results One Year After Discharge

	0 MWd/MTU	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74	1-Dec-74
	0 MWd/MTU	1,380	2,760	4,140	5,520	6,900	8,280	9,660	11,040	12,420	13,800
	0 MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU	MWd/MTU
HF 4	0.00E+01	2.46E-03	8.75E-03	2.14E-02	4.12E-02	6.83E-02	1.02E-01	1.43E-01	1.89E-01	2.40E-01	2.94E-01
PB206	0.00E+01	9.39E-13	9.16E-13	9.01E-13	8.91E-13	8.88E-13	8.90E-13	8.98E-13	9.11E-13	9.32E-13	9.59E-13
PB207	0.00E+01	1.56E-10	1.75E-10	1.89E-10	2.00E-10	2.09E-10	2.16E-10	2.21E-10	2.25E-10	2.29E-10	2.31E-10
BI209			2.78E-12	5.15E-12	8.31E-12	1.23E-11	1.73E-11	2.32E-11	3.02E-11	3.83E-11	4.78E-11
RA226	0.00E+01	1.29E-08	1.24E-08	1.19E-08	1.15E-08	1.12E-08	1.08E-08	1.05E-08	1.02E-08	9.91E-09	9.62E-09
TH229	0.00E+01	2.89F-09	6.85E-09	1.23E-08	1.96E-08	2.87E-08	3.99E-08	5.32E-08	6.88E-08	8.69E-08	1.08E-07
TH230	0.00E+01	3.02E-04	2.89E-04	2.77E-04	2.67E-04	2.58E-04	2.49E-04	2.41E-04	2.33E-04	2.26E-04	2.19E-04
TH232	0.00E+01	7.62E-06	1.31E-05	1.76E-05	2.14E-05	2.47E-05	2.76E-05	3.03E-05	3.26E-05	3.48E-05	3.68E-05
PA231	0.00E+01	1.94E-05	2.21E-05	2.41E-05	2.57E-05	2.70E-05	2.81E-05	2.90E-05	2.97E-05	3.03E-05	3.08E-05
U233	0.00E+01	2.34E-05	3.94E-05	5.21E-05	6.25E-05	7.15E-05	7.93E-05	8.61E-05	9.22E-05	9.77E-05	1.03E-04
U234	1.20E+01	1.14E+01	1.09E+01	1.05E+01	1.02E+01	9.90E-00	9.64E-00	9.40E-00	9.19E-00	9.00E-00	8.83E-00
U235	1.60E+03	1.38E+03	1.22E+03	1.09E+03	9.83E+02	8.91E+02	8.09E+02	7.36E+02	6.71E+02	6.11E+02	5.55E+02
U236	0.00E+01	4.17E+01	7.01E+01	9.23E+01	1.11E+02	1.26E+02	1.39E+02	1.51E+02	1.61E+02	1.70E+02	1.78E+02
U238	2.24E+05	2.23E+05	2.23E+05	2.22E+05	2.22E+05	2.22E+05	2.21E+05	2.21E+05	2.20E+05	2.20E+05	2.20E+05
NP237	0.00E+01	3.68E-00	6.96E-00	1.01E+01	1.32E+01	1.61E+01	1.91E+01	2.19E+01	2.48E+01	2.75E+01	3.02E+01
PU238	0.00E+01	1.86E-01	7.81E-01	1.86E-00	3.43E-00	5.49E-00	7.97E-00	1.08E+01	1.40E+01	1.75E+01	2.12E+01
PU239	0.00E+01	4.32E+02	6.51E+02	7.87E+02	8.78E+02	9.41E+02	9.85E+02	1.02E+03	1.04E+03	1.06E+03	1.08E+03
PU240	0.00E+01	3.57E+01	8.97E+01	1.41E+02	1.86E+02	2.25E+02	2.57E+02	2.84E+02	3.07E+02	3.29E+02	3.64E+02
PU241	0.00E+01	4.90E-00	2.15E+01	4.61E+01	7.49E+01	1.06E+02	1.36E+02	1.66E+02	1.93E+02	2.16E+02	2.21E+02
PU242	0.00E+01	1.65E-01	1.36E-00	4.24E-00	9.03E-00	1.58E+01	2.43E+01	3.45E+01	4.62E+01	5.92E+01	7.27E+01
PU244								2.52E-04	4.37E-04	7.10E-04	1.10E-03
AM241	0.00E+01	1.00E-00	4.48E-00	9.64E-00	1.57E+01	2.20E+01	2.82E+01	3.41E+01	3.94E+01	4.41E+01	4.68E+01
AM242m	0.00E+01	4.54E-03	3.23E-02	8.81E-02	1.66E-01	2.60E-01	3.61E-01	4.64E-01	5.66E-01	6.59E-01	7.33E-01
AM243	0.00E+01	3.01E-03	4.58E-02	2.03E-01	5.59E-01	1.19E-00	2.17E-00	3.55E-00	5.39E-00	7.72E-00	1.06E+01
CM242	0.00E+01	2.17E-03	1.71E-02	5.12E-02	1.06E-01	1.79E-01	2.69E-01	3.71E-01	4.84E-01	6.02E-01	7.16E-01
CM243			2.91E-04	1.24E-03	3.29E-03	6.78E-03	1.20E-02	1.90E-02	2.80E-02	3.89E-02	5.17E-02
CM244			1.82E-03	1.15E-02	4.10E-02	1.07E-01	2.30E-01	4.36E-01	7.51E-01	1.21E-00	1.88E-00
CM245					6.61E-04	2.03E-03	4.96E-03	1.04E-02	1.97E-02	3.44E-02	5.70E-02
CM246							2.60E-04	6.35E-04	1.37E-03	2.68E-03	4.94E-03
SUMTOT	2.26E+05	2.25E+05	2.25E+05	2.25E+05	2.24E+05	2.24E+05	2.24E+05	2.23E+05	2.23E+05	2.23E+05	2.22E+05
OTOTAL	2.26E+05	2.25E+05	2.25E+05	2.25E+05	2.24E+05	2.24E+05	2.24E+05	2.23E+05	2.23E+05	2.23E+05	2.22E+05
CS137	0.00E+01	9.96E-00	2.00E+01	3.02E+01	4.03E+01	5.06E+01	6.08E+01	7.12E+01	8.17E+01	9.22E+01	1.03E+02
BURNUP	0	3.11E+02	6.22E+02	9.34E+02	1.24E+03	1.56E+03	1.87E+03	2.18E+03	2.49E+03	2.80E+03	3.11E+03
MTU	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05	2.26E+05
MWd/MTU	0.00E+01	1.38E-03	2.76E-03	4.14E-03	5.52E-03	6.90E-03	8.28E-03	9.66E-03	1.10E-02	1.24E-02	1.38E-02
U234	0.0053	0.0051	0.0049	0.0047	0.0046	0.0044	0.0043	0.0042	0.0042	0.0041	0.0040
U235	0.7108	0.6119	0.5431	0.4877	0.4408	0.4002	0.3642	0.3322	0.3033	0.2769	0.2518
U236	0.0000	0.0186	0.0313	0.0413	0.0496	0.0567	0.0627	0.0681	0.0728	0.0770	0.0808
U238	99.2839	99.3645	99.4208	99.4663	99.5050	99.5387	99.5687	99.5955	99.6197	99.6421	99.6634
	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
PU239	100.0000	91.3728	85.2620	80.4370	76.4584	73.0968	70.2260	67.7359	65.5556	63.6939	62.1415
PU240	0.0000	7.5555	11.7433	14.4214	16.2290	17.4717	18.3406	18.9287	19.3452	19.7637	20.9382
PU241	0.0000	1.0368	2.8163	4.7087	6.5264	8.2074	9.7013	11.0362	12.1845	12.9794	12.7390
PU242	0.0000	0.0349	0.1784	0.4329	0.7862	1.2241	1.7321	2.2992	2.9147	3.5630	4.1813
	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
Pin data											
U grams	134.096	133.637	133.262	132.902	132.612	132.328	132.109	131.834	131.564	131.295	131.088
Pu grams	0.000	0.281	0.454	0.583	0.685	0.768	0.839	0.899	0.952	0.999	1.046
Cs137 g	0.00E+01	5.92E-03	1.19E-02	1.79E-02	2.40E-02	3.01E-02	3.62E-02	4.23E-02	4.86E-02	5.48E-02	6.12E-02

Highlighted column is the ORIGEN2 exposure closest to 6,500 MW_d/MTU. The horizontal highlighted areas are the low exposure to high exposure range of Shippingport measurements. Only exposures at or below 13,800 MW_d/MTU are considered in this report. The ORIGEN2 results in Table D.2 are for comparison to Shippingport measurements.

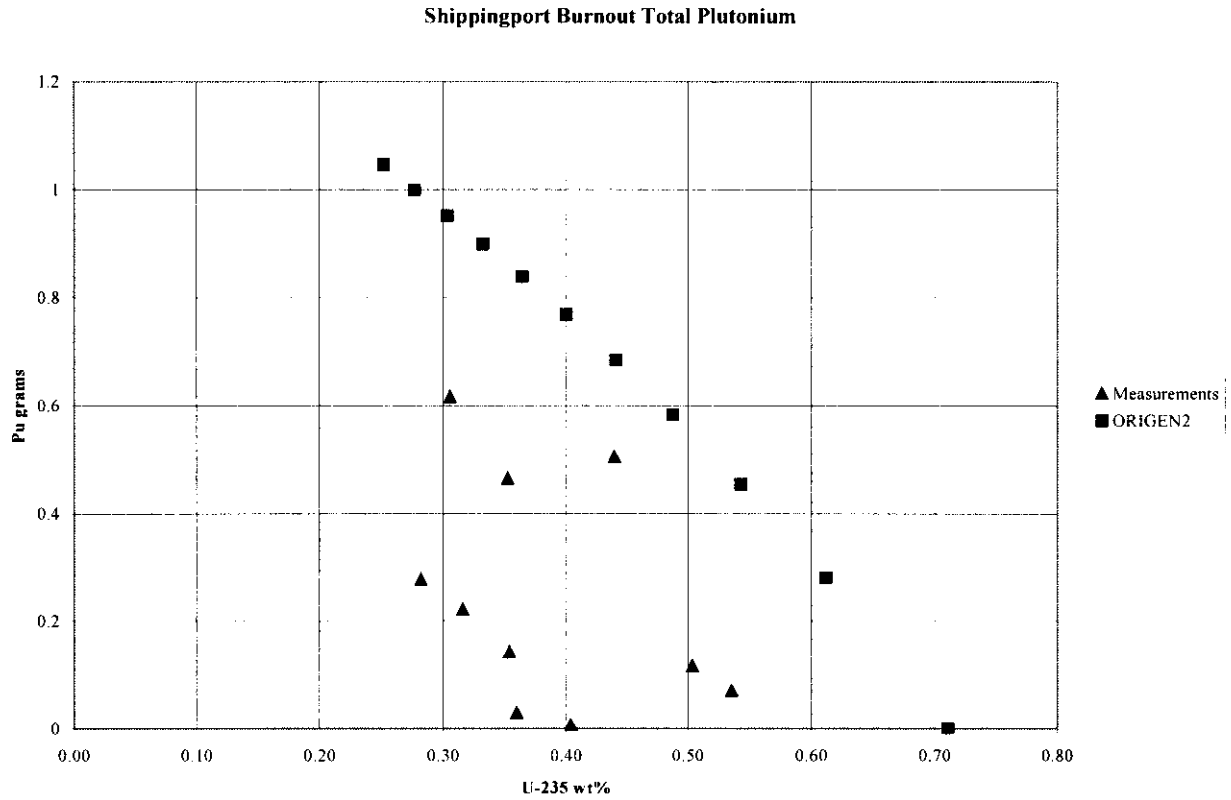
Figure D.1 Shippingport Burnup ^{137}Cs Quantity

This graph demonstrates the inconsistency of the measured ^{137}Cs quantity with the ORIGEN2 calculation, and with itself. Absolute measurements, such as total quantity ^{137}Cs , are difficult measurements to make. It is noteworthy that all of the ^{137}Cs quantities fell on or below the ORIGEN2 calculated values. It appears that the ^{137}Cs quantity measurements, except for one, are inconsistent with ORIGEN2 and with other Shippingport data. ^{137}Cs is a fission product which increases with MW_t/MTU exposure.

The ^{137}Cs quantity would form the basis for exposure determination. Without reliable Shippingport measurements for MW_t/MTU exposure, the Shippingport measurements can only be plotted relative to ^{235}U wt%, which will suffice for exposure tracking. ORIGEN2 results will be plotted on the same graphs for a comparison. The lowest exposure is at 0.7108 wt% ^{235}U and increasing exposure toward lower wt% ^{235}U .

No other conclusions can be drawn from this graph of ^{137}Cs quantity.

Figure D.2 Shippingport Burnup Total Plutonium

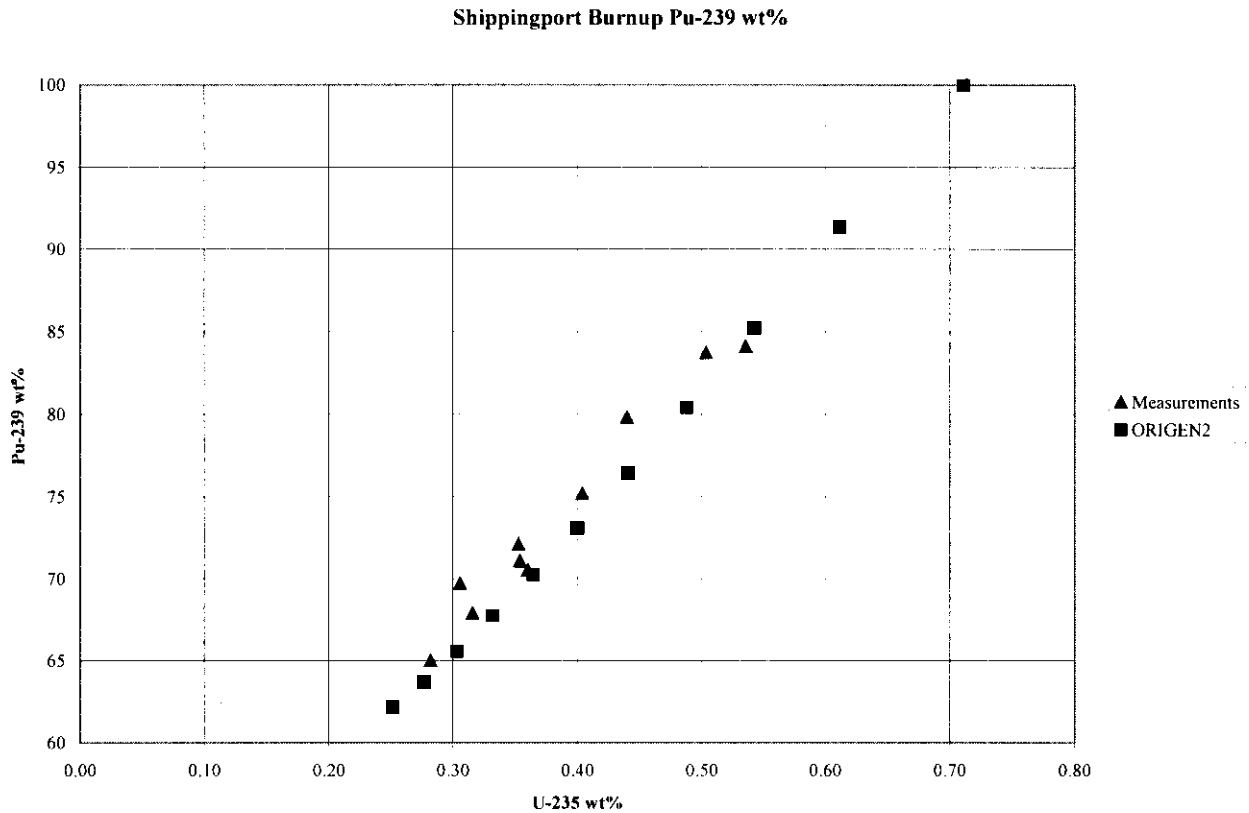


This graph demonstrates the inconsistency of the measured plutonium quantity with the ORIGEN2 calculation, and with itself. Absolute measurements, such as total quantity plutonium, are difficult measurements to make. It is noteworthy that all of the plutonium quantities fell below the ORIGEN2 calculated values.

There is no reliable standard from Shippingport measurements for the total quantity of plutonium as a function of exposure. Reliance will have to be placed on the relative wt% of ²³⁵U to the relative wt% of plutonium isotopes to infer Shippingport absolute plutonium mass.

No other conclusions can be drawn from this graph of total plutonium quantity.

Figure D.3 Shippingport Burnup ^{239}Pu wt%



This comparison demonstrates reasonable agreement between ORIGEN2 calculated ^{239}Pu wt% and the Shippingport measured ^{239}Pu wt%. Two points help set bounds on how much more ^{239}Pu is in the Shippingport PWR blanket fuel assemblies.

Shippingport measurements:

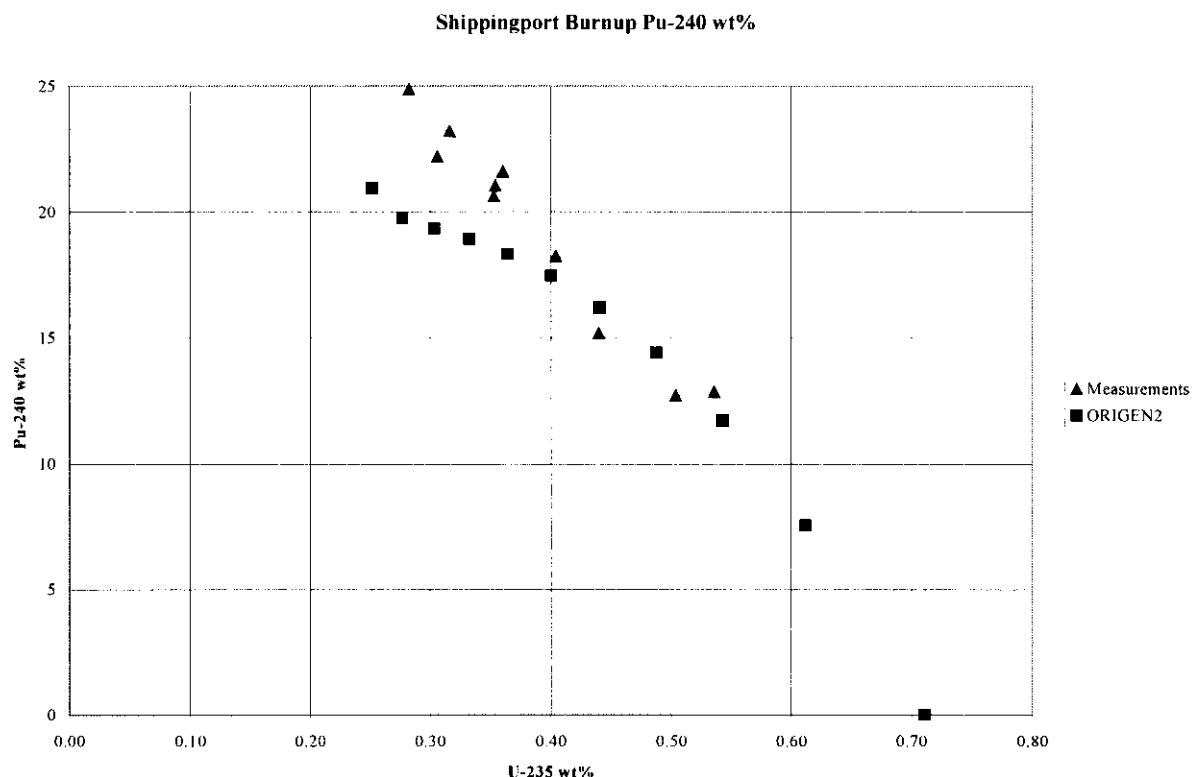
- 0.4397 wt% ^{235}U , 79.84 wt% ^{239}Pu , and
- 0.3059 wt% ^{235}U , 69.71 wt% ^{239}Pu .

ORIGEN2 calculations:

- 0.4408 wt% ^{235}U , 76.4584 wt% ^{239}Pu , and
- 0.3033 wt% ^{235}U , 65.5556 wt% ^{239}Pu .

At 0.45 wt% ^{235}U , the measured ^{239}Pu is +3.816 wt% ^{239}Pu higher, or a factor of 1.0442. At 0.31 wt% ^{235}U , the measured ^{239}Pu is +4.154 wt% ^{239}Pu higher, or a factor of 1.0634.

We bound the Shippingport ^{239}Pu by multiplying the ORIGEN2 ^{239}Pu results by 1.065. Then all of the Shippingport wt% ^{239}Pu is bounded by 1.065 times the ORIGEN2 ^{239}Pu results.

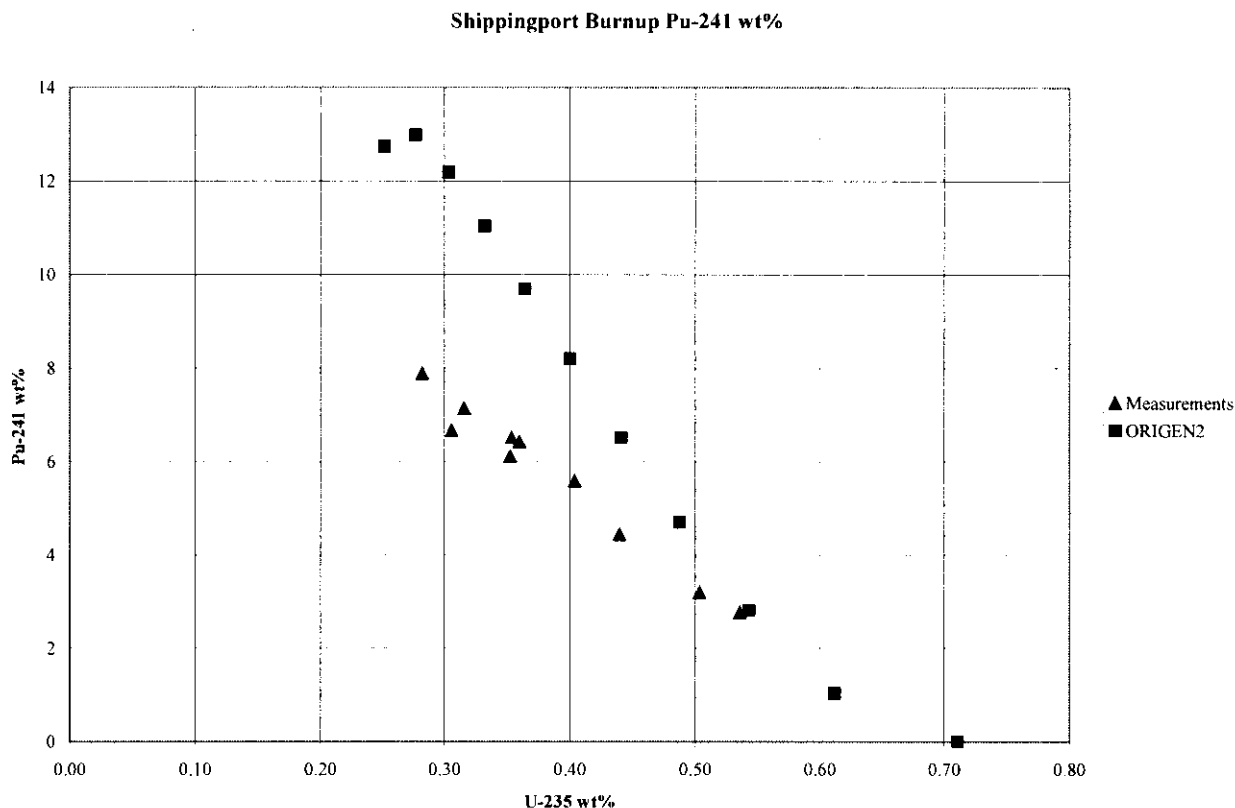
Figure D.4 Shippingport Burnup ^{240}Pu wt%

This graph demonstrates a reasonable consistency of the ^{240}Pu wt% versus the ^{235}U wt% between Shippingport measured data and the ORIGEN2 calculation. Relative measurements, such as uranium and plutonium isotopic ratios are more reliable measurements to make. The ORIGEN2 calculation at 6,900 MW_d/MTU (0.400 wt% ^{235}U , 18.537 wt% ^{240}Pu) is the closest to the desired 6,500 MW_d/MTU lower exposure for the criticality incredibility study.

It is noteworthy that, between 0.40 wt% ^{235}U (17.5 wt% ^{240}Pu) and 0.7108 wt% ^{235}U (0 wt% ^{240}Pu), there is scatter among the Shippingport measurements, some are below and some are above the ORIGEN2 calculation. This may be due to neutron spectrum changes between the different analyzed pin locations.

The dominant isotopes contributing to fission are ^{235}U , ^{239}Pu , and ^{241}Pu . Because of a difference in the neutron spectrum between Shippingport PWR and the ORIGEN2 modeled PWR, there could be a difference between the relative burnout rates of ^{235}U and ^{239}Pu . This comparison demonstrates that below 17.5 wt% ^{240}Pu , there is consistency between ^{235}U and ^{240}Pu for Shippingport measurements and ORIGEN2. Above 17.5 wt% ^{240}Pu , there is an increase in ^{240}Pu for Shippingport compared to ORIGEN2.

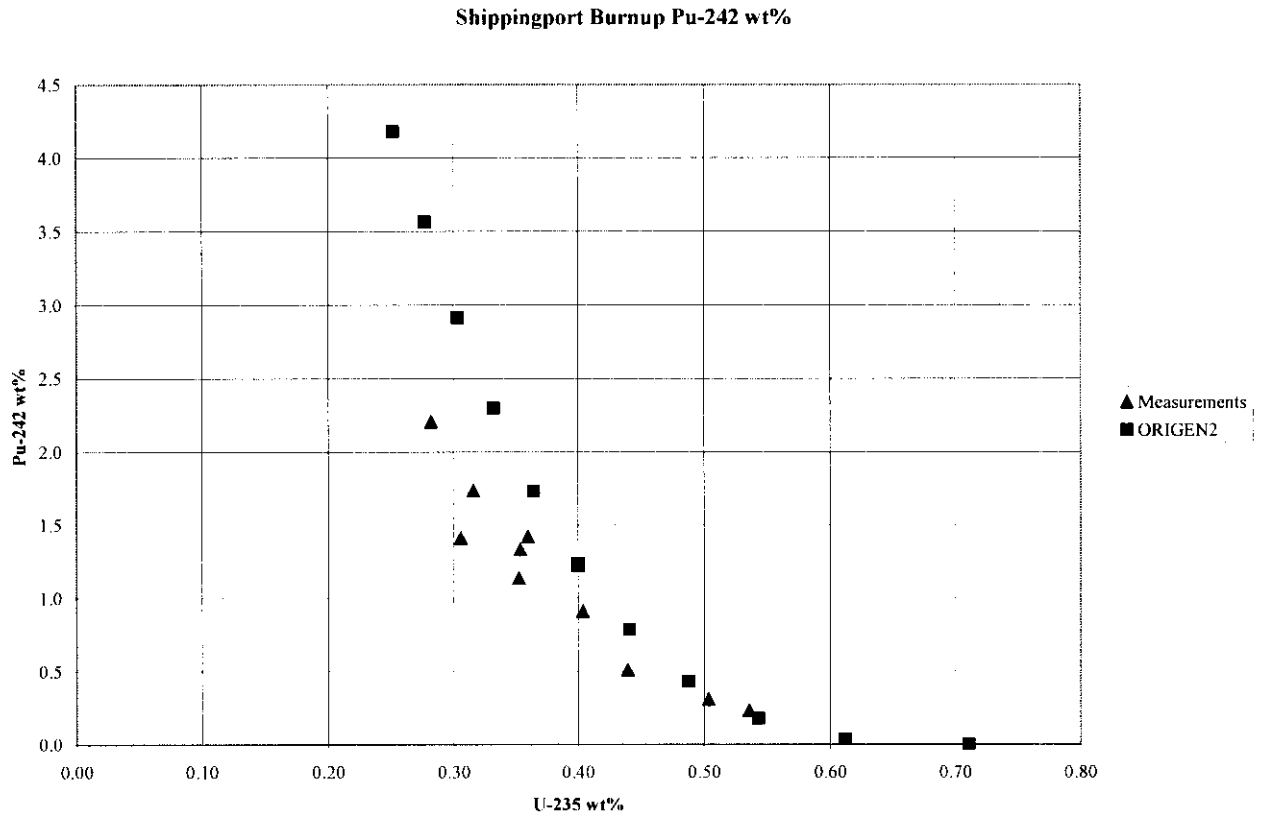
Below 17.5 wt% ^{240}Pu , the ORIGEN2 calculations are a very reasonable prediction for ^{240}Pu in Shippingport PWR blanket assemblies. At higher exposures, Shippingport will have more ^{240}Pu than calculated by ORIGEN2. It is conservative to ignore any increase in ^{240}Pu for Shippingport PWR blanket assemblies compared to ORIGEN2.

Figure D.5 Shippingport Burnup ^{241}Pu wt%

This graph demonstrates a reasonable consistency of the ^{241}Pu wt% versus the ^{235}U wt% between Shippingport measured data and the ORIGEN2 calculation up to only about 2,760 MW_d/MTU (0.5431 wt% ^{235}U , 2.8163 wt% ^{241}Pu). At higher exposures, the ORIGEN2 predictions for ^{241}Pu are higher than the Shippingport measurements. The ^{241}Pu isotope is counted as 9/4 times the ^{239}Pu isotope for FGE calculations. It is conservative to ignore the overprediction of ^{241}Pu by ORIGEN2 compared to Shippingport measurements.

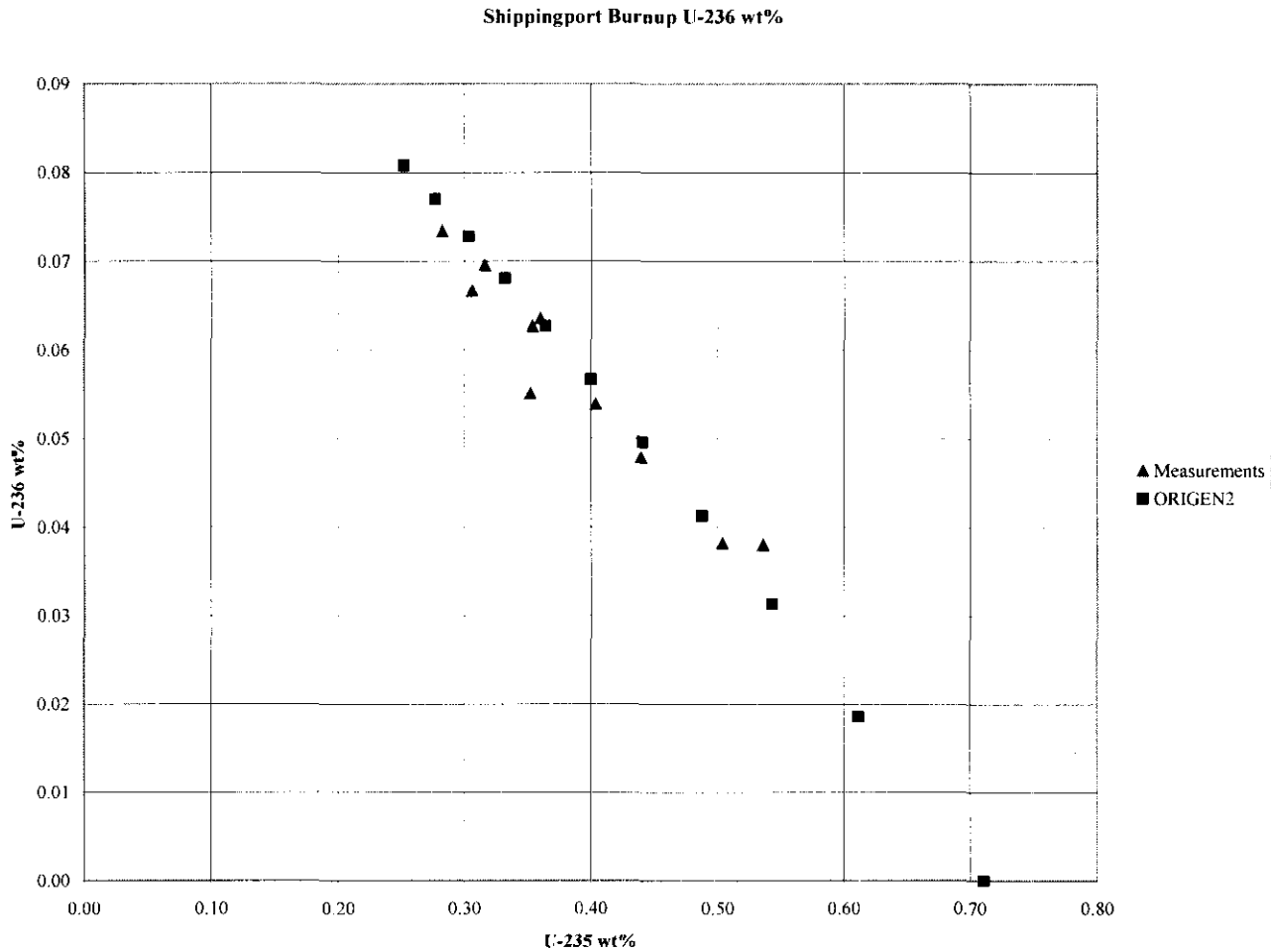
There is decay of ^{241}Pu that needs to be taken into account. The Shippingport measurements were approximately one year after the blanket fuel rods were removed from the core (page 18 in Sphar, C. D., J. H. Leonard and P. S. Lacey, 1961, *Isotopic Analysis of Irradiated Natural Uranium Dioxide Fuel Rods from PWR Core 1 – Preliminary Results*, WAPD-TM-280, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania). The ORIGEN2 calculations were decayed from 4 February 1974 to 1 December 1974 (300 days or 0.821 years). This shorter decay time would have increased the ORIGEN2 result for ^{241}Pu quantity by $\text{EXP}(\ln(2) \cdot (65/365)/14.15) = 1.00876$, or less than 1%. This is not enough by itself to explain the ORIGEN2 overprediction of ^{241}Pu for the Shippingport PWR. This effect is reduced because approximately 26 years have passed since 4 February 1974, reducing all ^{241}Pu by a factor of $\text{EXP}(-\ln(2) \cdot (2001-1974)/14.15) = 0.2798$.

Conservatively, the overprediction of ^{241}Pu by ORIGEN2 compared to Shippingport measurements will be ignored.

Figure D.6 Shippingport Burnup ^{242}Pu wt%

This graph demonstrates a reasonable consistency of the ^{242}Pu wt% versus the ^{235}U wt% between Shippingport measured data and the ORIGEN2 calculation up to only about 4,140 MW_td/MTU (0.4877 wt% ^{235}U , 0.4329 wt% ^{242}Pu). At higher exposures, the ORIGEN2 predictions for ^{242}Pu are higher than the Shippingport measurements. The ^{242}Pu isotope is counted as 9/1200 times the ^{239}Pu isotope for FGE calculations.

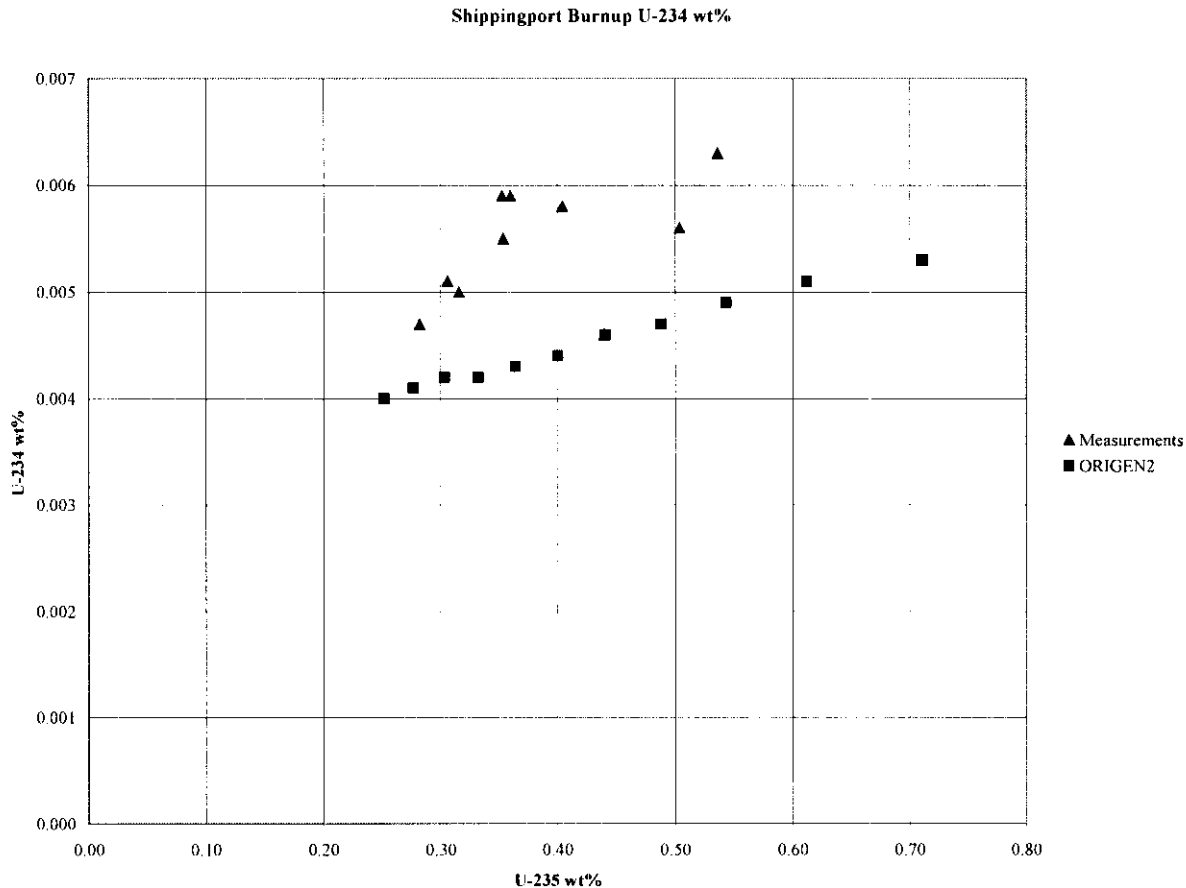
It is conservative, and insignificant, to ignore the overprediction of ^{242}Pu by ORIGEN2 compared to Shippingport measurements.

Figure D.7 Shippingport Burnup ^{236}U wt%

This graph demonstrates a reasonable consistency of the ^{236}U wt% versus the ^{235}U wt% between Shippingport measured data and the ORIGEN2 calculation with the measurements falling above and below the ORIGEN2 calculations.

The ^{236}U isotope is not counted as ^{239}Pu for FGE calculations. This does show that the $^{235}\text{U}(n,\gamma)^{236}\text{U}$ absorption cross section in ORIGEN2 is reasonable for Shippingport PWR blanket assemblies. This increases confidence in the ^{235}U fission cross section from ORIGEN2 being applied to the Shippingport PWR.

It is insignificant to ignore any differences in the ORIGEN2 calculation of ^{236}U compared to Shippingport measurements.

Figure D.8 Shippingport Burnup ^{234}U wt%

This graph demonstrates a reasonable consistency, on an absolute ^{234}U wt% basis, of ^{234}U wt% versus ^{235}U wt% between Shippingport measurements and ORIGEN2 calculations.

^{234}U is a minor uranium isotope and is not counted as ^{239}Pu for FGE calculations. This shows that ^{235}U (n,2n) ^{234}U cross section in ORIGEN2 are reasonable for Shippingport PWR blanket assemblies. This increases confidence in the ^{235}U fission cross section from ORIGEN2 being applied to the Shippingport PWR. The difference between ORIGEN2 and measurements would be between burnout of ^{239}Pu and ^{241}Pu . This is compensated by scaling the ^{239}Pu mass by 1.065.

It is insignificant, to ignore the any differences in the ORIGEN2 calculation of ^{234}U compared to Shippingport measurements.

CONCLUSIONS

ORIGEN2 calculations bound the Shippingport PWR blanket assembly isotopic composition reactivity for criticality purposes by multiplying the ORIGEN2 ^{239}Pu calculated result by 1.065.