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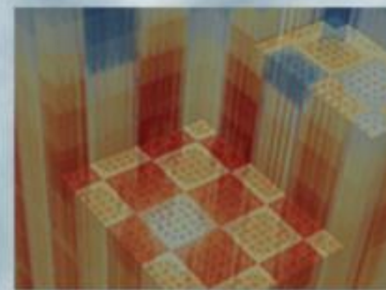
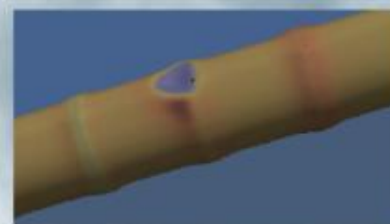


Specification for the VERA Depletion Benchmark Suite



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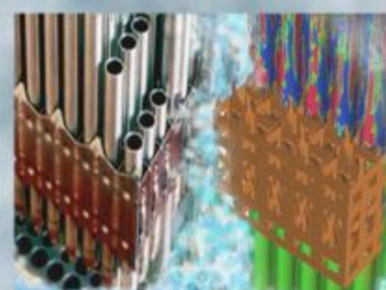

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EXECUTIVE SUMMARY

The CASL neutronics simulator MPACT is under development for the neutronics and T-H coupled simulation for the pressurized water reactor. MPACT includes the ORIGEN-API and internal depletion module to perform depletion calculations based upon neutron-material reaction and radioactive decay. It is a challenge to validate the depletion capability because of the insufficient measured data. One of the detoured methods to validate it is to perform a code-to-code comparison for benchmark problems. In this study a depletion benchmark suite has been developed and a detailed guideline has been provided to obtain meaningful computational outcomes which can be used in the validation of the MPACT depletion capability.

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TABLES

ACRONYMS

2D	Two-Dimensional
CASL	Consortium for Advanced Simulation of Light Water Reactors
FPY	Fission Product Yield
MOC	Method of Characteristics
MG	Multi-group (as in cross sections)
ORNL	Oak Ridge National Laboratory
PND	Particle (Atomic) Number Density
PWR	Pressurized water reactor
T-H	Thermal Hydraulic
UM	University of Michigan
VERA	Virtual Environment for Reactor Applications

1. INTRODUCTION

The CASL neutronics simulator MPACT is under development for the neutronics and T-H coupled simulation for the pressurized water reactor. MPACT includes the ORIGEN-API and internal depletion module to perform depletion calculations based upon neutron-material reaction and radioactive decay. It is a challenge to validate the depletion capability because of the insufficient measured data. One of the detoured methods to validate it is to perform a code-to-code comparison for depletion benchmark problems. In this study a depletion benchmark suite has been developed and a detailed guideline has been provided to obtain meaningful computational outcomes which can be used in the validation of the MPACT depletion capability.

The benchmark problems have been developed based on "The VERA Core Physics Benchmark Progression Problems" [God14]. This document provides the detailed design data and guide lines to obtain meaningful and valuable outcomes for the validation of the MPACT depletion capability.

- Geometry and composition data required in preparing user input files for the engaged simulation codes in Chapter 2,
- Recoverable energies per fission to exclude a difference of neutron flux level due to code specific recoverable energies per fission in Chapter 3,
- Burnup chains of the ORIGEN-API to figure out the differences of burnup chains with the engaged simulation programs in Chapter 4,
- Detailed description for the benchmark problems, user options and nuclear parameters to be edited and compared in Chapter 5.

2. GEOMETRY AND MATERIAL DATA

The depletion benchmark problems have been developed based on the VERA progression problems [God14]. Table 2.1 provides the geometrical and material data for the benchmark problems which come from the VERA progression problems #1 and #2.

Table 2.2 provides density and atomic number densities for each material which should be utilized in depletion calculation to exclude a bias due to the difference in initial atomic number densities.

Table 2.1 Geometry and material data (1/2)

Material	Parameter	Value	Remark
Core	Pressure (bar)	155.13	2250 psia
	Power Density (w/gU)	40.00	
	Fuel assembly power (MW)/cm	0.050324728	Variable
	Assembly Pitch (cm)	21.5000	
	Pin Pitch (cm)	1.2600	
Fuel	Pellet Radius (cm)	0.4096	
	Material	UO_2	Various ^{235}U w/o
	Density (g/cm^3)	10.2570	
Gadolinia Rod	Pellet Radius (cm)	0.4096	
	Material	UO_2+Gd_2O_3	1.8w/o ^{235}U, 5% Gd_2O_3
	Density (g/cm^3)	10.1110	
Clad	Inner Radius (cm)	0.4180	
	Outer Radius (cm)	0.4750	
	Material	Zircaloy-4	
	Density (g/cm^3)	6.5600	
Guide Tube	Inner Radius (cm)	0.5610	
	Outer Radius (cm)	0.6020	
	Material	Zircaloy-4	
	Density (g/cm^3)	6.5600	
Instrumentation Tube	Inner Radius (cm)	0.5590	
	Outer Radius (cm)	0.6050	
	Material	Zircaloy-4	
	Density (g/cm^3)	6.5600	
Thimble inside Instrumentation Tube	Inner Radius of thimble (cm)	0.2580	
	Outer Radius of thimble (cm)	0.3820	
	Material	SS304	
	Internal material	^4He	
	Material between thimble and IT	Moderator	

Table 2.1 Geometrical and material data (2/2)

Material	Parameter	Value	Remark
Control Rod (AgInCd & B_4C)	AgInCd Radius (cm)	0.3820	
	AgInCd Density (g/cm^3)	10.2000	
	B_4C Radius (cm)	0.3730	
	B_4C Density (g/cm^3)	1.7600	
	Clad Inner Radius (cm)	0.3860	
	Clad Outer Radius (cm)	0.4840	
	SS304 Clad Density (g/cm^3)	7.8000	
IFBA	Coating Thickness (μm)	10.0000	
	Material	ZrB_2	
	^{10}B enrichment (w/o)	50.0	
	Density (g/cm^3)	3.8500	
WABA	Material	$B_4C+Al_2O_3$	
	Density (g/cm^3)	3.6500	
	Inner Clad Inner Radius (cm)	0.2860	
	Inner Clad Outer Radius (cm)	0.3390	
	Inner/Outer Clad Material	Zircaloy-4	
	Poison Inner Radius (cm)	0.3530	
	Poison Outer Radius (cm)	0.4040	
	Outer Clad Inner Radius (cm)	0.4180	
	Outer Clad Outer Radius (cm)	0.4840	
Pyrex	Material	$B_2O_3+SiO_2$	12.5 w/o B_2O_3
	Density (g/cm^3)	2.2500	
	Inner Clad Inner Radius (cm)	0.2140	
	Inner Clad Outer Radius (cm)	0.2310	
	Inner/Outer Clad Material	SS-304	
	Poison Inner Radius (cm)	0.2410	
	Poison Outer Radius (cm)	0.4270	
	Outer Clad Inner Radius (cm)	0.4370	
	Outer Clad Outer Radius (cm)	0.4840	

Table 2.2 Density and atomic number density for each material (1/2)

Material	Density(g/cm^3)	Isotope ID	PND (/barn-cm)	Isotope ID	PND (/barn-cm)
Fuel (2.1%)	10.257	92234	4.02487E-06	92238	2.23868E-02
		92235	4.86484E-04	8016	4.57590E-02
		92236	2.23756E-06		
Fuel (3.1%)	10.257	92234	6.11864E-06	92238	2.21546E-02
		92235	7.18132E-04	8016	4.57642E-02
		92236	3.29861E-06		
Fuel (3.6%)	10.257	92234	7.21203E-06	92238	2.20384E-02
		92235	8.33952E-04	8016	4.57669E-02
		92236	3.82913E-06		
Fuel (4.6%)	10.257	92234	9.39876E-06	92238	2.18062E-02
		92235	1.06559E-03	8016	4.57721E-02
		92236	4.89014E-06		
Gap	1.79E-04	2004	2.68714E-05		
Cladding (Zirc-4)	6.56	40090	2.18865E-02	26054	8.68307E-06
		40091	4.77292E-03	26056	1.36306E-04
		40092	7.29551E-03	26057	3.14789E-06
		40094	7.39335E-03	26058	4.18926E-07
		40096	1.19110E-03	24050	3.30121E-06
		50112	4.68066E-06	24052	6.36606E-05
		50114	3.18478E-06	24053	7.21860E-06
		50115	1.64064E-06	24054	1.79686E-06
		50116	7.01616E-05	72174	3.54138E-09
		50117	3.70592E-05	72176	1.16423E-07
		50118	1.16872E-04	72177	4.11686E-07
		50119	4.14504E-05	72178	6.03806E-07
		50120	1.57212E-04	72179	3.01460E-07
		50122	2.23417E-05	72180	7.76449E-07
		50124	2.79392E-05		
Moderator 565 K 1300 ppm	0.743	8016	2.48112E-02	5010	1.07070E-05
		1001	4.96224E-02	5011	4.30971E-05
Moderator 600 K 1300 ppm	0.700	8016	2.33753E-02	5010	1.00874E-05
		1001	4.67505E-02	5011	4.06030E-05
IFBA	3.85	5010	2.16410E-02	40092	3.54348E-03
		5011	1.96824E-02	40094	3.59100E-03
		40090	1.06304E-02	40096	5.78528E-04
		40091	2.31824E-03		
Pyrex	2.25	5010	9.63266E-04	14028	1.81980E-02
		5011	3.90172E-03	14029	9.24474E-04
		8016	4.67761E-02	14030	6.10133E-04
Gadolinia 5% Gd_2O_3 95% UO_2 1.8% ^{235}U Fuel	10.111	92234	3.18096E-06	64155	2.48606E-04
		92235	3.90500E-04	64156	3.43849E-04
		92236	1.79300E-06	64157	2.62884E-04
		92238	2.10299E-02	64158	4.17255E-04
		64152	3.35960E-06	64160	3.67198E-04
		64154	3.66190E-05	8016	4.53705E-02

Table 2.2 Density and atomic number density for each material (2/2)

Material	Density(g/cm^3)	Isotope ID	PND (/barn-cm)	Isotope ID	PND (/barn-cm)
SS304	7.8	6000	3.20895E-04	26054	3.44776E-03
		14028	1.58197E-03	26056	5.41225E-02
		14029	8.03653E-05	26057	1.24992E-03
		14030	5.30394E-05	26058	1.66342E-04
		15031	6.99938E-05	28058	5.30854E-03
		24050	7.64915E-04	28060	2.04484E-03
		24052	1.47506E-02	28061	8.88879E-05
		24053	1.67260E-03	28062	2.83413E-04
		24054	4.16346E-04	28064	7.21770E-05
		25055	1.75387E-03		
AgInCd	10.2	47107	2.36159E-02	48112	6.59276E-04
		47109	2.19403E-02	48113	3.33873E-04
		48106	3.41523E-05	48114	7.84957E-04
		48108	2.43165E-05	48116	2.04641E-04
		48110	3.41250E-04	49113	3.44262E-04
		48111	3.49720E-04	49115	7.68050E-03
B_4C	1.76	5010	1.52689E-02	6000	1.91820E-02
		5011	6.14591E-02		
WABA B_4C-Al_2O_3	3.65	5010	2.98553E-03	8016	5.85563E-02
		5011	1.21192E-02	13027	3.90223E-02
		6000	3.77001E-03		

3. RECOVERABLE ENERGY PER FISSION

The neutron flux level would impact on predicting isotopic inventories at burnup calculation which is estimated by using the code specific recoverable energies per fission. Therefore, it is recommended to utilize the common recoverable energy per fission provided in Table 3.1.

Table 3.1 Recoverable energy per fission

No	ID	Nuclide	ENDF/B-7.0		ENDF/B-7.1	
			Kappa(w-s)	Kappa0(w-s)	Kappa(w-s)	Kappa0(w-s)
1	90230	^{230}Th	3.24352E-11	3.05372E-11	3.22841E-11	2.89031E-11
2	90232	^{232}Th	3.22345E-11	3.01965E-11	3.22345E-11	3.01965E-11
3	91231	^{231}Pa	3.38655E-11	3.06082E-11	3.38655E-11	2.97356E-11
4	91233	^{233}Pa	3.27020E-11	3.06082E-11	3.26046E-11	2.97452E-11
5	92232	^{232}U	3.40754E-11	3.06082E-11	3.40754E-11	2.95739E-11
6	92233	^{233}U	3.20712E-11	3.06082E-11	3.20712E-11	3.06082E-11
7	92234	^{234}U	3.26494E-11	3.07364E-11	3.26494E-11	3.07364E-11
8	92235	^{235}U	3.24187E-11	3.09997E-11	3.24187E-11	3.09872E-11
9	92236	^{236}U	3.30019E-11	3.11610E-11	3.30019E-11	3.11610E-11
10	92237	^{237}U	3.36652E-11	3.14446E-11	3.36652E-11	3.00925E-11
11	92238	^{238}U	3.40626E-11	3.17285E-11	3.40626E-11	3.16891E-11
12	92240	^{240}U	3.33592E-11	3.17330E-11	3.33592E-11	3.17330E-11
13	93237	^{237}Np	3.37405E-11	3.14622E-11	3.37405E-11	3.14622E-11
14	93238	^{238}Np	3.37181E-11	3.18579E-11	3.37181E-11	3.19722E-11
15	93239	^{239}Np	3.42660E-11	3.18579E-11	3.42660E-11	3.04126E-11
16	94236	^{236}Pu	3.29971E-11	3.11610E-11	3.34433E-11	3.19691E-11
17	94237	^{237}Pu	3.30131E-11	3.13869E-11	3.38885E-11	3.22623E-11
18	94238	^{238}Pu	3.36748E-11	3.16240E-11	3.41258E-11	3.21010E-11
19	94239	^{239}Pu	3.43312E-11	3.18586E-11	3.43312E-11	3.18679E-11
20	94240	^{240}Pu	3.43157E-11	3.19589E-11	3.43157E-11	3.19589E-11
21	94241	^{241}Pu	3.47426E-11	3.23611E-11	3.47426E-11	3.23611E-11
22	94242	^{242}Pu	3.47643E-11	3.22969E-11	3.49302E-11	3.24889E-11
23	94244	^{244}Pu	3.41266E-11	3.25004E-11	3.35567E-11	3.19305E-11
24	95241	^{241}Am	3.48348E-11	3.23578E-11	3.48348E-11	3.23578E-11
25	95242	^{242}Am	3.45085E-11	3.22969E-11	3.51714E-11	3.29599E-11
26	95243	^{243}Am	3.56147E-11	3.26238E-11	3.56147E-11	3.26238E-11
27	95242m	^{242m}Am	3.56147E-11	3.26238E-11	3.56147E-11	3.26238E-11
28	96241	^{241}Cm	3.40465E-11	3.24203E-11	3.51880E-11	3.35618E-11
29	96242	^{242}Cm	3.54821E-11	3.24524E-11	3.54821E-11	3.25983E-11
30	96243	^{243}Cm	3.50159E-11	3.24764E-11	3.50159E-11	3.26885E-11
31	96244	^{244}Cm	3.54308E-11	3.25004E-11	3.54308E-11	3.33858E-11
32	96245	^{245}Cm	3.45048E-11	3.27359E-11	3.45060E-11	3.28798E-11
33	96246	^{246}Cm	3.51248E-11	3.29731E-11	3.54721E-11	3.37309E-11
34	96247	^{247}Cm	3.48348E-11	3.32086E-11	3.51698E-11	3.35436E-11
35	96248	^{248}Cm	3.50703E-11	3.34441E-11	3.55936E-11	3.39674E-11
36	97249	^{249}Bk	3.50703E-11	3.34441E-11	3.60559E-11	3.44297E-11
37	98249	^{249}Cf	3.50703E-11	3.34441E-11	3.55494E-11	3.39232E-11
38	98250	^{250}Cf	3.50703E-11	3.34441E-11	3.68134E-11	3.51872E-11
39	98251	^{251}Cf	3.50703E-11	3.34441E-11	3.58147E-11	3.41885E-11
40	98252	^{252}Cf	3.50703E-11	3.34441E-11	3.68984E-11	3.52721E-11

4. BURNUP CHAIN

Typically deterministic/Monte Carlo programs include their own burnup chains and libraries. The SCALE-ORIGEN and CASL-ORIEGN include two different burnup chains which are full and simplified ones. The simplified burnup chain has been developed to include 255 nuclides and to have very good agreement with the full burnup chain especially for the multiplication factor. Since the latest SCALE-ORIGEN burnup chains and libraries reflect the most up-to-date data and methodology, it is recommended to utilize the ORIGEN-API burnup chains and libraries for benchmark calculations. The SCALE-ORIGEN libraries will be provided upon request for which the SCALE license should be acquired at first. If the program is not ready yet to handle the SCALE-ORIGEN libraries, it is required to include its own burnup chain and libraries in the report.

Appendices A and B provide constituent 255 nuclides for the simplified burnup chain and each column includes the following indicators.

- CAT: Category of nuclides
  - 1 : Activation nuclides
  - 2 : Heavy metal nuclides
  - 3 : Fission product nuclides

- ID: Numeric nuclide ID in ORIGEN = ZZZAAAI
  - ZZZ : Atomic number
  - AAA : Atomic mass number
  - I : Stable or meta-stable (0: stable; 1: meta)

- IFPY: Indicator for fission product yield
  - 0 : Non FPY
  - 1 : Direct FPY
  - 2 : Cumulative FPY
  - 3 : Special treatment with weight fractions (W_i)

5. DEPLETION BENCHMARK PROBLEMS

5.1 Benchmark problems

The depletion benchmark suite includes 9 single pin and 16 fuel assembly problems with various fuel temperatures, ^{235}U enrichments, control rods and burnable poisons as shown in Table 5.1. The pin configurations of fuel rods, guide/instrument tubes and burnable poisons are shown in Figure 5.1. The geometrical and material data for the benchmark problems are provided in Chapter 2. In order to verify the input data prepared by participant Table 5.2 provides the multiplication factors obtained by KENO-CE with ENDF/B-7.0 at 0.0 MWD/kgU.

Table 5.1 Single pin and assembly depletion benchmark problems

Problem	Description	Temperature (K)			Moderator Density	^{235}U w/o	Power density (w/gU)
		Moderator	Clad	Fuel			
1A	Pin 3.1w/o T_F=565K	565	565	565	0.743	3.1	40.0
1B	Pin 3.1w/o T_F=600K	600	600	600	0.700	3.1	40.0
1C	Pin 3.1w/o T_F=900K	600	600	900	0.700	3.1	40.0
1D	Pin 3.1w/o T_F=1200K	600	600	1200	0.700	3.1	40.0
1E	Pin IFBA 3.1w/o T_F=600K	600	600	900	0.700	3.1	40.0
1F	Pin 2.1w/o T_F=900K	600	600	900	0.700	2.1	40.0
1G	Pin 3.6w/o T_F=900K	600	600	900	0.700	3.6	40.0
1H	Pin 4.6w/o T_F=900K	600	600	900	0.700	4.6	40.0
1I	Pin Gadolinia rod (5% Gd_2O_3)	600	600	900	0.700	1.8	40.0
1J	Pin 3.1w/o T_F=600/900/1200K	600	600	600/900/1200	0.700	3.1	40.0
2A	FA No Poisons T_F=565K	565	565	565	0.743	3.1	40.0
2B	FA No Poisons T_F=600K	600	600	600	0.700	3.1	40.0
2C	FA No Poisons T_F=900K	600	600	900	0.700	3.1	40.0
2D	FA No Poisons T_F=1200K	600	600	1200	0.700	3.1	40.0
2E	FA 12 Pyrex	600	600	900	0.700	3.1	40.0
2F	FA 24 Pyrex	600	600	900	0.700	3.1	40.0
2G	FA 24 AIC	600	600	900	0.700	3.1	40.0
2H	FA 24 B4C	600	600	900	0.700	3.1	40.0
2I	FA Instrument Thimble	600	600	900	0.700	3.1	40.0
2J	FA Instrument + 24 Pyrex	600	600	900	0.700	3.1	40.0
2K	FA Zoned + 24 Pyrex	600	600	900	0.700	3.1/3.6	40.0
2L	FA 80 IFBA	600	600	900	0.700	3.1	40.0
2M	FA 128 IFBA	600	600	900	0.700	3.1	40.0
2N	FA 104 IFBA + 20 WABA	600	600	900	0.700	3.1	40.0
2O	FA 12 Gadolinia	600	600	900	0.700	3.1/1.8	40.0
2P	FA 24 Gadolinia	600	600	900	0.700	3.1/1.8	40.0

Table 5.2 Multiplication factors at 0.0 MWD/kgU burnup

Problem	Description	Temperature (K)			KENO-CE k_{eff}
		Moderator	Clad	Fuel	
1A	Pin 3.1w/o T_F=565K	565	565	565	1.18704 ± 0.00005
1B	Pin 3.1w/o T_F=600K	600	600	600	1.18428 ± 0.00017
1C	Pin 3.1w/o T_F=900K	600	600	900	1.17393 ± 0.00016
1D	Pin 3.1w/o T_F=1200K	600	600	1200	1.16516 ± 0.00013
1E	Pin IFBA 3.1w/o T_F=600K	600	600	900	0.76521 ± 0.00022
1F	Pin 2.1w/o T_F=900K	600	600	900	1.05835 ± 0.00017
1G	Pin 3.6w/o T_F=900K	600	600	900	1.21335 ± 0.00018
1H	Pin 4.6w/o T_F=900K	600	600	900	1.27094 ± 0.00018
1I	Pin Gadolinia rod (5% Gd_2O_3)	600	600	900	0.21820 ± 0.00010
1J	Pin 3.1w/o T_F=600/900/1200K	600	600	600/900/1200	1.17451 ± 0.00014
2A	FA No Poisons T_F=565K	565	565	565	1.18218 ± 0.00002
2B	FA No Poisons T_F=600K	600	600	600	1.18240 ± 0.00012
2C	FA No Poisons T_F=900K	600	600	900	1.17354 ± 0.00014
2D	FA No Poisons T_F=1200K	600	600	1200	1.16543 ± 0.00015
2E	FA 12 Pyrex	600	600	900	1.06072 ± 0.00016
2F	FA 24 Pyrex	600	600	900	0.96541 ± 0.00017
2G	FA 24 AIC	600	600	900	0.83443 ± 0.00017
2H	FA 24 B4C	600	600	900	0.77337 ± 0.00021
2I	FA Instrument Thimble	600	600	900	1.17256 ± 0.00012
2J	FA Instrument + 24 Pyrex	600	600	900	0.96476 ± 0.00017
2K	FA Zoned + 24 Pyrex	600	600	900	1.00886 ± 0.00019
2L	FA 80 IFBA	600	600	900	1.01133 ± 0.00018
2M	FA 128 IFBA	600	600	900	0.93205 ± 0.00017
2N	FA 104 IFBA + 20 WABA	600	600	900	0.86123 ± 0.00020
2O	FA 12 Gadolinia	600	600	900	1.04004 ± 0.00017
2P	FA 24 Gadolinia	600	600	900	0.91993 ± 0.00016

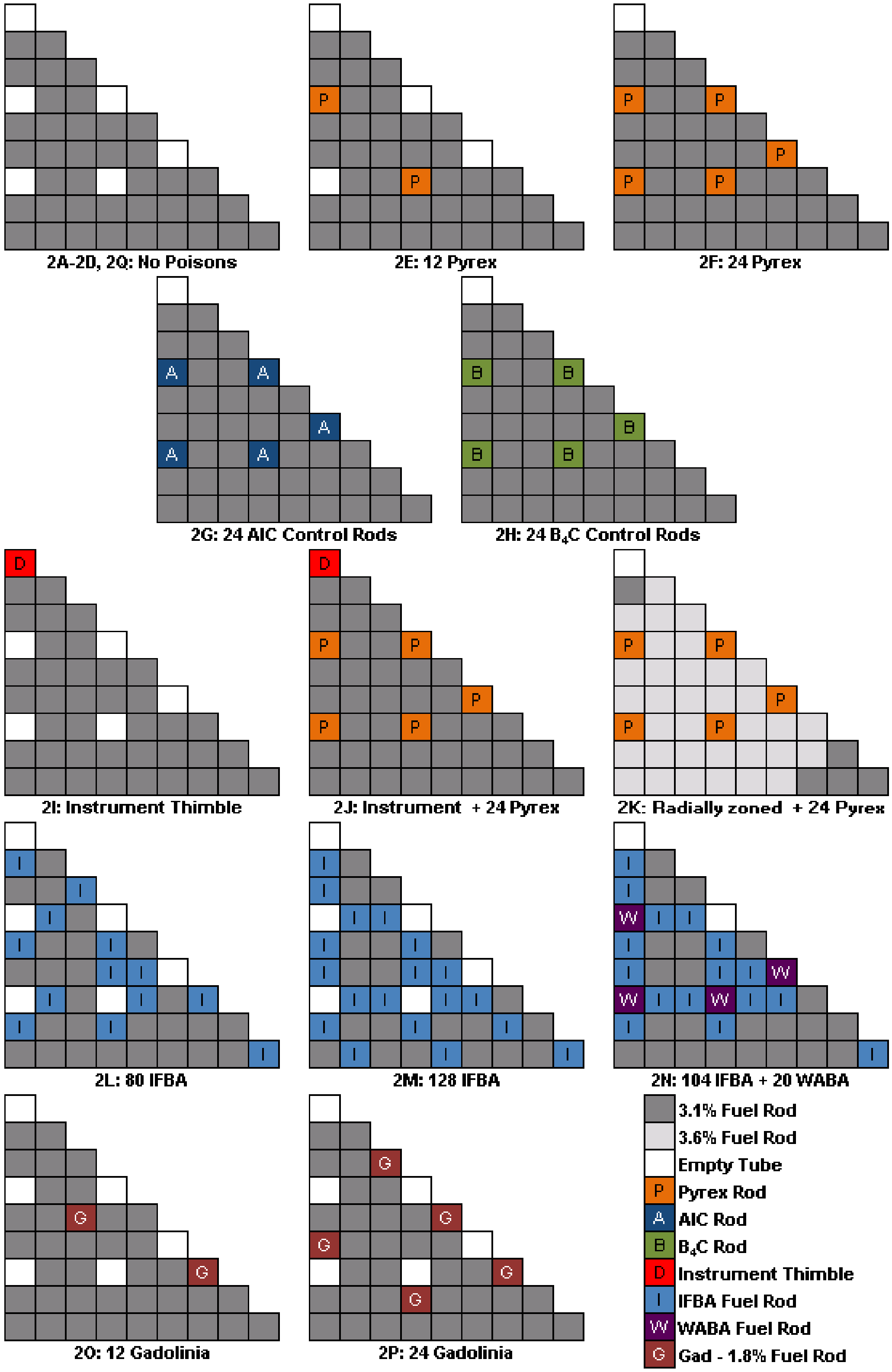

Figure 5.1 Lattice pin cell configuration

5.2 Calculation options

The computational results of the depletion calculations would be dependent upon user options and libraries. Therefore, in order not to have any difference due to the differences of user option and library the following user options and library should be utilized in the calculations.

- Xenon option
  - Non-equilibrium for all cases
  - Equilibrium for the specified cases in Table 5.4 (**1C** and **2C**)
- Power density
  - Table 5.1 provides the specific power density for each case (40.0 w/gU).
- Burnup points
  - Table 5.3 provides the burnup points.
- Library
  - ENDF/B-7.0 or ENDF/B-7.1 (7.0 is more recommended.)
- The number of depletion zones
  - UO_2 pellet: 3 equi-volumetric zones
  - UO_2+Gd_2O_3 Gadolinia rod: 5 equi-volumetric zones
  - WABA & PYREX: 3 equi-volumetric zones

Table 5.3 Burnup points and editing options

Step	Burnup		Edit			Step	Burnup		Edit		
	MWD/kgU	EFPD	P.D.	R.R.	Flux		MWD/kgU	EFPD	P.D.	R.R.	Flux
1	0.00	0.00	O	O	O	21	17.00	425.00			
2	0.01	0.25				22	18.00	450.00			
3	0.25	6.25				23	19.00	475.00			
4	0.50	12.50				24	20.00	500.00	O	O	O
5	1.00	25.00				25	22.50	562.50			
6	2.00	50.00				26	25.00	625.00			
7	3.00	75.00				27	27.50	687.50			
8	4.00	100.00				28	30.00	750.00	O	O	O
9	5.00	125.00	O	O	O	29	32.50	812.50			
10	6.00	150.00				30	35.00	875.00			
11	7.00	175.00				31	37.50	937.50			
12	8.00	200.00				32	40.00	1000.00	O	O	O
13	9.00	225.00				33	42.50	1062.50			
14	10.00	250.00	O	O	O	34	45.00	1125.00			
15	11.00	275.00				35	47.50	1187.50			
16	12.00	300.00				36	50.00	1250.00	O	O	O
17	13.00	325.00				37	52.50	1312.50			
18	14.00	350.00				38	55.00	1375.00			
19	15.00	375.00	O	O	O	39	57.50	1437.50			
20	16.00	400.00				40	60.00	1500.00			

P.D. : Power Distribution
R.R. : Reaction Rate

5.3 Edition of reactor physics parameters

In order to complete the code-to-code comparison the following parameters need to be edited which are also provided in Table 5.3.

- Multiplication factors (keff) vs. burnup
  - All cases
  - All burnup points

- Pin power distribution
  - For the problems: **2C**, **2F**, **2N** and **2P**
  - For the burnup points: 1, 8, 13, 18, 23, 27, 31 and 35

- Particle(atomic) number densities (PND)
  - For the problems: **1C, 1E** and **1H**
  - PND should be edited for each depletion zone. (e.g. UO2 pellet=3 zones)
  - PND needs to be edited for the nuclides in Table 4.1.
  - All burnup points

- Multigroup scalar fluxes
  - For the problems: **1C** and **1H**
  - For the burnup points: 1, 8, 13, 18, 23, 27, 31 and 35
  - Power scaled 1-group scalar flux for each depletion zone
  - Monte Carlo codes: Multi-group (47-group) normalized scalar flux per unit lethargy. (The 47-g structure is provided on Table 5.5.)
  - Deterministic codes: Multi-group normalized scalar flux per unit lethargy with their own group structure.

- Reaction rates
  - For the problems: **1C** and **1H**
  - For the burnup points: 1, 8, 13, 18, 23, 27, 31 and 35
  - 1-group absorption and fission reaction rates for each depletion zone
  - For nuclides: Table 5.6 provides the list of nuclides

5.4 Sensitivities

Sensitivity calculations need to be performed fot the following parameters.

- Xenon
  - For the problems: **1C** and **2C**
  - All burnup points
  - Equilibrium xenon option

- Xenon
  - For the problems: **1C** and **2C**

- All burnup points
- Equilibrium xenon option

- <u>Burnup intervals</u>
    - For the problems: **1C**
    - All burnup points
    - Ver fine burnup points: up to participants

- <u>Number of intra depletion zones for gadolinia rod</u>
    - For the problems: **1H**
    - All burnup points
    - 10 intra depletion zones

Table 5.4 Xenon option and editing parameters

No	Problem	Description	Xenon		Special option	Edit				
			Tran-sient	Equi-librium		k_{eff}	Pin power	PND	Reaction rate	Flux
1	1A	Pin 3.1w/o T_F=565K	O			O				
2	1B	Pin 3.1w/o T_F=600K	O			O				
3	1C	Pin 3.1w/o T_F=900K	O	O	*A	O		O	O	O
4	1D	Pin 3.1w/o T_F=1200K	O			O				
5	1E	Pin IFBA 3.1w/o T_F=565K	O			O		O		
6	1F	Pin 3.6w/o T_F=900K	O			O				
7	1G	Pin 3.6w/o T_F=900K	O			O				
8	1H	Pin Gadolinia rod (5% Gd_2O_3)	O		*B	O		O	O	O
9	1I	Pin 3.1w/o T_F=600/900/1200K	O			O				
10	2A	FA No Poisons T_F=565K	O			O				
11	2B	FA No Poisons T_F=600K	O			O				
12	2C	FA No Poisons T_F=900K	O	O		O	O			
13	2D	FA No Poisons T_F=1200K	O			O				
14	2E	FA 12 Pyrex	O			O				
15	2F	FA 24 Pyrex	O			O	O			
16	2G	FA 24 AIC	O			O				
17	2H	FA 24 B4C	O			O				
18	2I	FA Instrument Thimble	O			O				
19	2J	FA Instrument + 24 Pyrex	O			O				
20	2K	FA Zoned + 24 Pyrex	O			O				
21	2L	FA 80 IFBA	O			O				
22	2M	FA 128 IFBA	O			O				
23	2N	FA 104 IFBA + 20 WABA	O			O	O			
24	2O	FA 12 Gadolinia	O			O				
25	2P	FA 24 Gadolinia	O			O	O			

*A: Burnup interval sensitivy calculation
*B: 10 intra pin subzones for gadolinia rod

Table 5.5 The 47-group boundaries

Gr	Upper (eV)	Gr	Upper (eV)	Gr	Upper (eV)	Gr	Upper (eV)	Gr	Upper (eV)
1	2.00000E+07	11	2.03470E+03	21	5.71501E+00	31	1.07220E+00	41	1.45721E-01
2	6.06530E+06	12	1.30070E+02	22	5.04348E+00	32	1.01370E+00	42	1.11570E-01
3	3.67880E+06	13	7.88933E+01	23	4.45090E+00	33	9.71004E-01	43	8.19682E-02
4	2.23130E+06	14	4.78512E+01	24	3.92790E+00	34	9.09997E-01	44	5.69219E-02
5	1.35340E+06	15	2.90229E+01	25	2.38239E+00	35	7.82083E-01	45	4.27552E-02
6	8.20850E+05	16	1.37100E+01	26	1.85539E+00	36	6.25062E-01	46	3.06129E-02
7	4.97870E+05	17	1.20990E+01	27	1.45740E+00	37	5.03232E-01	47	1.23960E-02
8	1.83160E+05	18	8.31529E+00	28	1.23511E+00	38	3.57670E-01		1.00000E-05
9	6.73790E+04	19	7.33822E+00	29	1.16640E+00	39	2.70521E-01		
10	9.11880E+03	20	6.47602E+00	30	1.12540E+00	40	1.84430E-01		

Table 5.6 Nuclides for editing reaction rates

ID	Nuclide	ID	Nuclide	ID	Nuclide	ID	Nuclide
42095	^{95}Mo	54135	^{135}Xe	61148	^{148}Pm	94238	^{238}Pu
43099	^{99}Tc	55133	^{133}Cs	62149	^{149}Sm	94239	^{239}Pu
44101	^{101}Ru	55134	^{133}Cs	63155	^{155}Eu	94240	^{240}Pu
45103	^{103}Rh	60143	^{143}Nd	92235	^{235}U	94241	^{241}Pu
46105	^{105}Pd	60145	^{145}Nd	92236	^{236}U	94242	^{242}Pu
46107	^{107}Pd	62150	^{150}Sm	92238	^{238}U	95243	^{243}Am
46108	^{108}Pd	62151	^{150}Sm	93237	^{237}Np		

6. DISCUSSION

Currently the programs in Table 6.1 are supposed to be engaged in this code-to-code comparison for the depletion benchmark calculations.

Table 6.1 Transport depletion codes

Code	Solver			Developer	Group
	Transport	Depletion	Resonance		
MPACT	MOC	ORIGEN	Subgroup	CASL	47/51
SHIFT	Monte Carlo	ORIGEN		ORNL	CE
POLARIS	MOC	ORIGEN	ESSM	ORNL	252/56
TRITON	Monte Carlo	ORIGEN	CENTRM	ORNL	252/56
nTRACER	MOC	Krylov	Subgroup	SNU	47
McCARD	Monte Carlo	ORIGEN		SNU	CE
STREAM	MOC		Equivalence	UNIST	MG
SERPENT	Monte Carlo	CRAM		VTT	CE
MCNP6	Monte Carlo			LANL	CE

*ORIGEN: Exponential matrix + Bateman

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REFERENCE

[God14] Andrew T. Godfrey, "VERA Core Physics Benchmark Progression Problem Specifications," CASL-U-2012-0131-004, Rev. 4 (8/29/2014).

[Wie14] W. Wieselquist, K. S. Kim , "Simplified Burnup Chain Development," CASL PHI Ticket#3432 (9/10/2014).

Appendix A. Constituent nuclides for the simplified burnup chain

No	Nuclide	CAT	ID	IFPY	Special Yield Definition ($ID_i/W_i/IFPY_i$)
1	5-B-0	1	50100	0	
2	5-B-10	1	50110	0	
3	8-O-16	1	80160	0	
4	47-Ag-107	1	471070	0	
5	47-Ag-109	1	471090	0	
6	47-Ag-110	1	471100	0	
7	48-Cd-110	1	481100	0	
8	48-Cd-111	1	481110	0	
9	48-Cd-112	1	481120	0	
10	48-Cd-113	1	481130	0	
11	48-Cd-114	1	481140	0	
12	48-Cd-115	1	481150	0	
13	49-In-113	1	491130	0	
14	49-In-115	1	491150	0	
15	62-Sm-152	1	621520	0	
16	62-Sm-153	1	621530	0	
17	63-Eu-151	1	631510	0	
18	63-Eu-152	1	631520	0	
19	63-Eu-152m	1	631521	0	
20	63-Eu-153	1	631530	0	
21	63-Eu-154	1	631540	0	
22	63-Eu-155	1	631550	0	
23	63-Eu-156	1	631560	0	
24	63-Eu-157	1	631570	0	
25	64-Gd-152	1	641520	0	
26	64-Gd-154	1	641540	0	
27	64-Gd-155	1	641550	0	
28	64-Gd-156	1	641560	0	
29	64-Gd-157	1	641570	0	
30	64-Gd-158	1	641580	0	
31	64-Gd-159	1	641590	0	
32	64-Gd-160	1	641600	0	
33	64-Gd-161	1	641610	0	
34	65-Tb-159	1	651590	0	
35	65-Tb-160	1	651600	0	
36	65-Tb-161	1	651610	0	
37	66-Dy-160	1	661600	0	
38	66-Dy-161	1	661610	0	
39	66-Dy-162	1	661620	0	
40	66-Dy-163	1	661630	0	
41	66-Dy-164	1	661640	0	
42	66-Dy-165	1	661650	0	
43	67-Ho-165	1	671650	0	
44	68-Er-162	1	681620	0	
45	68-Er-164	1	681640	0	
46	68-Er-166	1	681660	0	
47	68-Er-167	1	681670	0	
48	68-Er-168	1	681680	0	
49	68-Er-169	1	681690	0	
50	68-Er-170	1	681700	0	

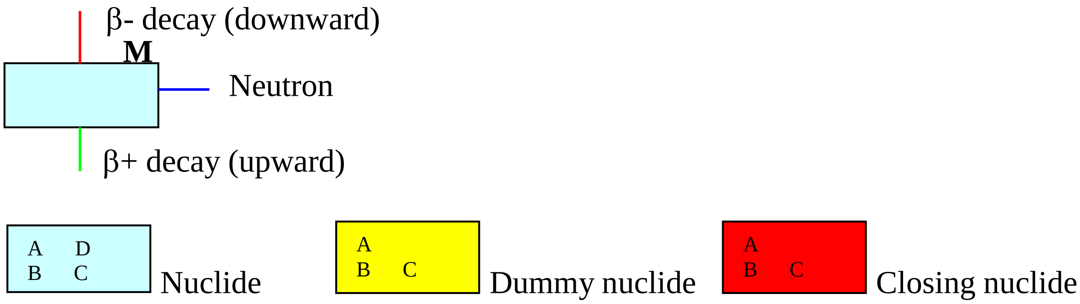
51	68-Er-171	1	681710	0	
52	69-Tm-169	1	691690	0	
53	69-Tm-170	1	691700	0	
54	69-Tm-171	1	691710	0	
55	72-Hf-174	1	721740	0	
56	72-Hf-176	1	721760	0	
57	72-Hf-177	1	721770	0	
58	72-Hf-178	1	721780	0	
59	72-Hf-179	1	721790	0	
60	72-Hf-180	1	721800	0	
61	72-Hf-181	1	721810	0	
62	73-Ta-181	1	731810	0	
63	73-Ta-182	1	731820	0	
64	90-Th-230	2	902300	0	
65	90-Th-231	2	902310	0	
66	90-Th-232	2	902320	0	
67	90-Th-233	2	902330	0	
68	90-Th-234	2	902340	0	
69	91-Pa-231	2	912310	0	
70	91-Pa-232	2	912320	0	
71	91-Pa-233	2	912330	0	
72	91-Pa-234	2	912340	0	
73	92-U-232	2	922320	0	
74	92-U-233	2	922330	0	
75	92-U-234	2	922340	0	
76	92-U-235	2	922350	0	
77	92-U-236	2	922360	0	
78	92-U-237	2	922370	0	
79	92-U-238	2	922380	0	
80	92-U-239	2	922390	0	
81	93-Np-236	2	932360	0	
82	93-Np-237	2	932370	0	
83	93-Np-238	2	932380	0	
84	93-Np-239	2	932390	0	
85	93-Np-240	2	932400	0	
86	93-Np-240m	2	932401	0	
87	94-Pu-236	2	942360	0	
88	94-Pu-237	2	942370	0	
89	94-Pu-238	2	942380	0	
90	94-Pu-239	2	942390	0	
91	94-Pu-240	2	942400	0	
92	94-Pu-241	2	942410	0	
93	94-Pu-242	2	942420	0	
94	94-Pu-243	2	942430	0	
95	95-Am-241	2	952410	0	
96	95-Am-242	2	952420	0	
97	95-Am-42m	2	952421	0	
98	95-Am-243	2	952430	0	
99	95-Am-244	2	952440	0	
100	95-Am-44m	2	952441	0	
101	96-Cm-242	2	962420	0	
102	96-Cm-243	2	962430	0	
103	96-Cm-244	2	962440	0	

104	96-Cm-245	2	962450	0	
105	96-Cm-246	2	962460	0	
106	35-BR-81	3	350810	2	
107	35-BR-82	3	350820	2	
108	36-KR-82	3	360820	3	350821/0.024/1, 360820/1.000/1
109	36-KR-83	3	360830	2	
110	36-KR-84	3	360840	2	
111	36-KR-85	3	360850	2	
112	36-KR-86	3	360860	2	
113	38-SR-89	3	380890	2	
114	38-SR-90	3	380900	2	
115	39-Y-89	3	390890	1	
116	39-Y-90	3	390900	1	
117	39-Y-91	3	390910	2	
118	40-ZR-91	3	400910	1	
119	40-ZR-93	3	400930	2	
120	40-ZR-95	3	400950	2	
121	40-ZR-96	3	400960	2	
122	41-NB-95	3	410950	3	410950/1.000/1, 410951/0.944/1
123	42-MO-95	3	420950	3	410951/0.056/1, 420950/1.000/1
124	42-MO-96	3	420960	3	410960/1.000/1, 420960/1.000/1
125	42-MO-97	3	420970	2	
126	42-MO-98	3	420980	2	
127	42-MO-99	3	420990	2	
128	42-MO-100	3	421000	2	
129	43-TC-99	3	430990	1	
130	43-TC-99m	3	430991	1	
131	43-TC-100	3	431000	1	
132	44-RU-100	3	441000	1	
133	44-RU-101	3	441010	2	
134	44-RU-102	3	441020	2	
135	44-RU-103	3	441030	2	
136	44-RU-104	3	441040	2	
137	44-RU-105	3	441050	2	
138	44-RU-106	3	441060	2	
139	45-RH-102	3	451020	1	
140	45-RH-102m	3	451021	1	
141	45-RH-103	3	451030	1	
142	45-RH-103m	3	451031	1	
143	45-RH-104	3	451040	1	
144	45-RH-105	3	451050	1	
145	45-RH-105m	3	451051	1	
146	45-RH-106	3	451060	1	
147	45-RH-106m	3	451061	1	
148	46-PD-104	3	461040	1	
149	46-PD-105	3	461050	1	
150	46-PD-106	3	461060	1	
151	46-PD-107	3	461070	2	
152	46-PD-108	3	461080	2	
153	46-PD-109	3	461090	2	
154	47-AG-109	3	471090	1	
155	47-AG-109m	3	471091	1	
156	47-AG-110	3	471100	2	

157	47-AG-110m	3	471101	2	
158	47-AG-111	3	471110	2	
159	48-CD-110	3	481100	1	
160	48-CD-111	3	481110	3	471110 /-1.000/2, 481110/1.000/2, 481111/1.000/1
161	48-CD-113	3	481130	2	
162	49-IN-115	3	491150	2	
163	51-SB-121	3	511210	2	
164	51-SB-123	3	511230	2	
165	51-SB-125	3	511250	2	
166	51-SB-127	3	511270	2	
167	52-TE-127	3	521270	-1	
168	52-TE-127m	3	521271	-1	
169	52-TE-129m	3	521291	2	
170	52-TE-132	3	521320	2	
171	53-I-127	3	531270	1	
172	53-I-128	3	531280	3	531280/0.931/2
173	53-I-129	3	531290	3	531290/1.000/2, 521291/-1.000/2
174	53-I-130	3	531300	2	
175	53-I-131	3	531310	2	
176	53-I-132	3	531320	1	
177	53-I-135	3	531350	2	
178	54-XE-128	3	541280	1	
179	54-XE-130	3	541300	1	
180	54-XE-131	3	541310	1	
181	54-XE-132	3	541320	1	
182	54-XE-133	3	541330	2	
183	54-XE-134	3	541340	2	
184	54-XE-135	3	541350	1	
185	54-XE-135m	3	541351	1	
186	54-XE-136	3	541360	2	
187	54-XE-137	3	541370	2	
188	55-CS-133	3	551330	1	
189	55-CS-134	3	551340	1	
190	55-CS-135	3	551350	1	
191	55-CS-136	3	551360	1	
192	55-CS-137	3	551370	1	
193	56-BA-134	3	561340	1	
194	56-BA-137	3	561370	1	
195	56-BA-140	3	561400	2	
196	57-LA-139	3	571390	2	
197	57-LA-140	3	571400	1	
198	58-CE-140	3	581400	1	
199	58-CE-141	3	581410	2	
200	58-CE-142	3	581420	2	
201	58-CE-143	3	581430	2	
202	58-CE-144	3	581440	2	
203	59-PR-141	3	591410	1	
204	59-PR-142	3	591420	1	
205	59-PR-143	3	591430	1	
206	59-PR-144	3	591440	1	
207	60-ND-142	3	601420	1	
208	60-ND-143	3	601430	1	
209	60-ND-144	3	601440	1	

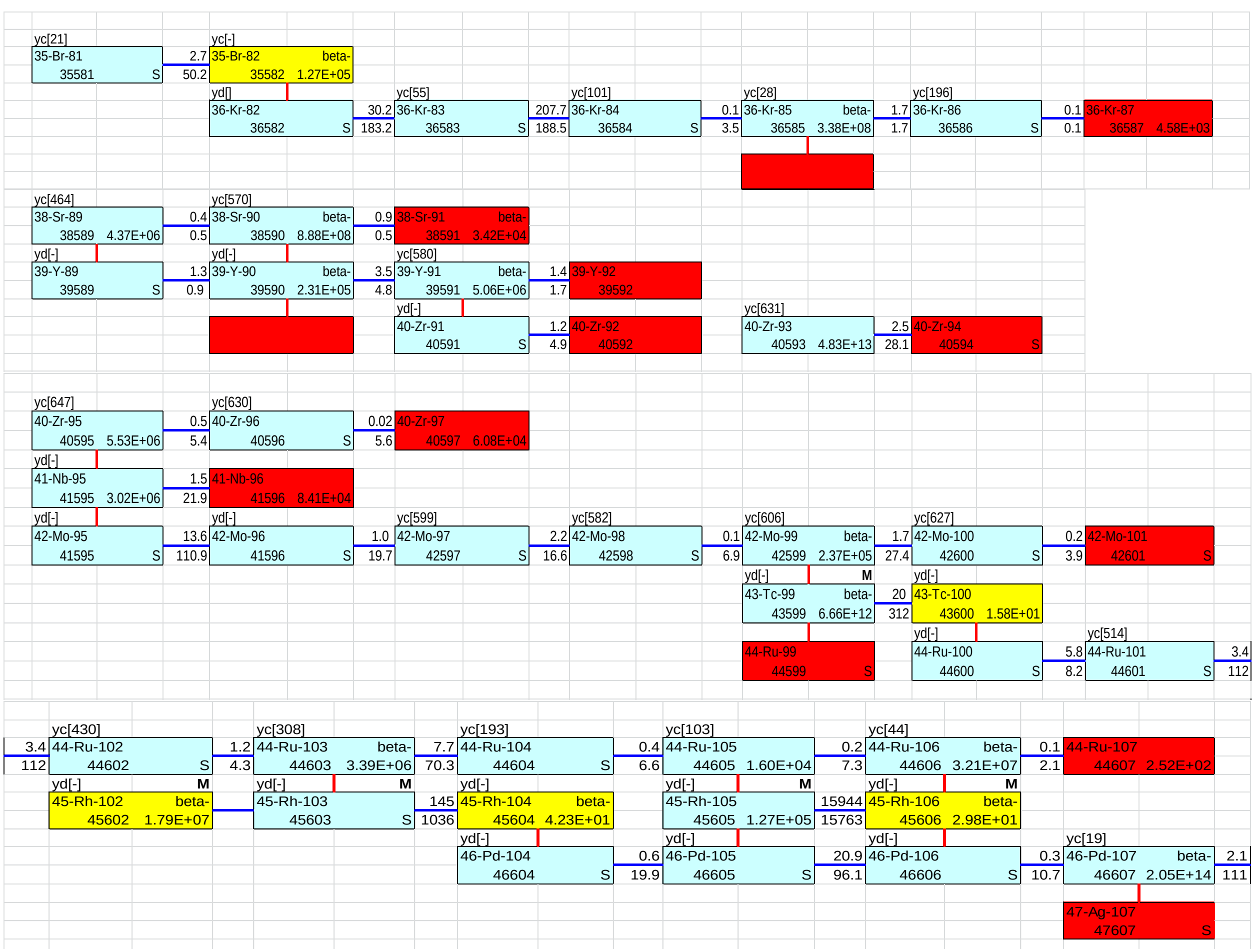
210	60-ND-145	3	601450	2	
211	60-ND-146	3	601460	2	
212	60-ND-147	3	601470	2	
213	60-ND-148	3	601480	2	
214	60-ND-149	3	601490	2	
215	60-ND-150	3	601500	2	
216	60-ND-151	3	601510	2	
217	61-PM-147	3	611470	1	
218	61-PM-148	3	611480	-1	
219	61-PM-148m	3	611481	-1	
220	61-PM-149	3	611490	1	
221	61-PM-150	3	611500	1	
222	61-PM-151	3	611510	1	
223	62-SM-147	3	621470	1	
224	62-SM-148	3	621480	1	
225	62-SM-149	3	621490	1	
226	62-SM-150	3	621500	1	
227	62-SM-151	3	621510	1	
228	62-SM-152	3	621520	2	
229	62-SM-153	3	621530	2	
230	62-SM-154	3	621540	2	
231	62-SM-155	3	621550	2	
232	63-EU-151	3	631510	1	
233	63-EU-153	3	631530	1	
234	63-EU-154	3	631540	1	
235	63-EU-155	3	631550	1	
236	63-EU-156	3	631560	2	
237	63-EU-157	3	631570	2	
238	64-GD-154	3	641540	1	
239	64-GD-155	3	641550	1	
240	64-GD-156	3	641560	1	
241	64-GD-157	3	641570	1	
242	64-GD-158	3	641580	2	
243	64-GD-159	3	641590	2	
244	64-GD-160	3	641600	2	
245	64-GD-161	3	641610	2	
246	65-TB-159	3	651590	1	
247	65-TB-160	3	651600	1	
248	65-TB-161	3	651610	1	
249	66-DY-160	3	661600	1	
250	66-DY-161	3	661610	1	
251	66-DY-162	3	661620	2	
252	66-DY-163	3	661630	2	
253	66-DY-164	3	661640	2	
254	66-DY-165	3	661650	2	
255	67-HO-165	3	671650	3	661651/0.022/2, 671650/1.000 /1

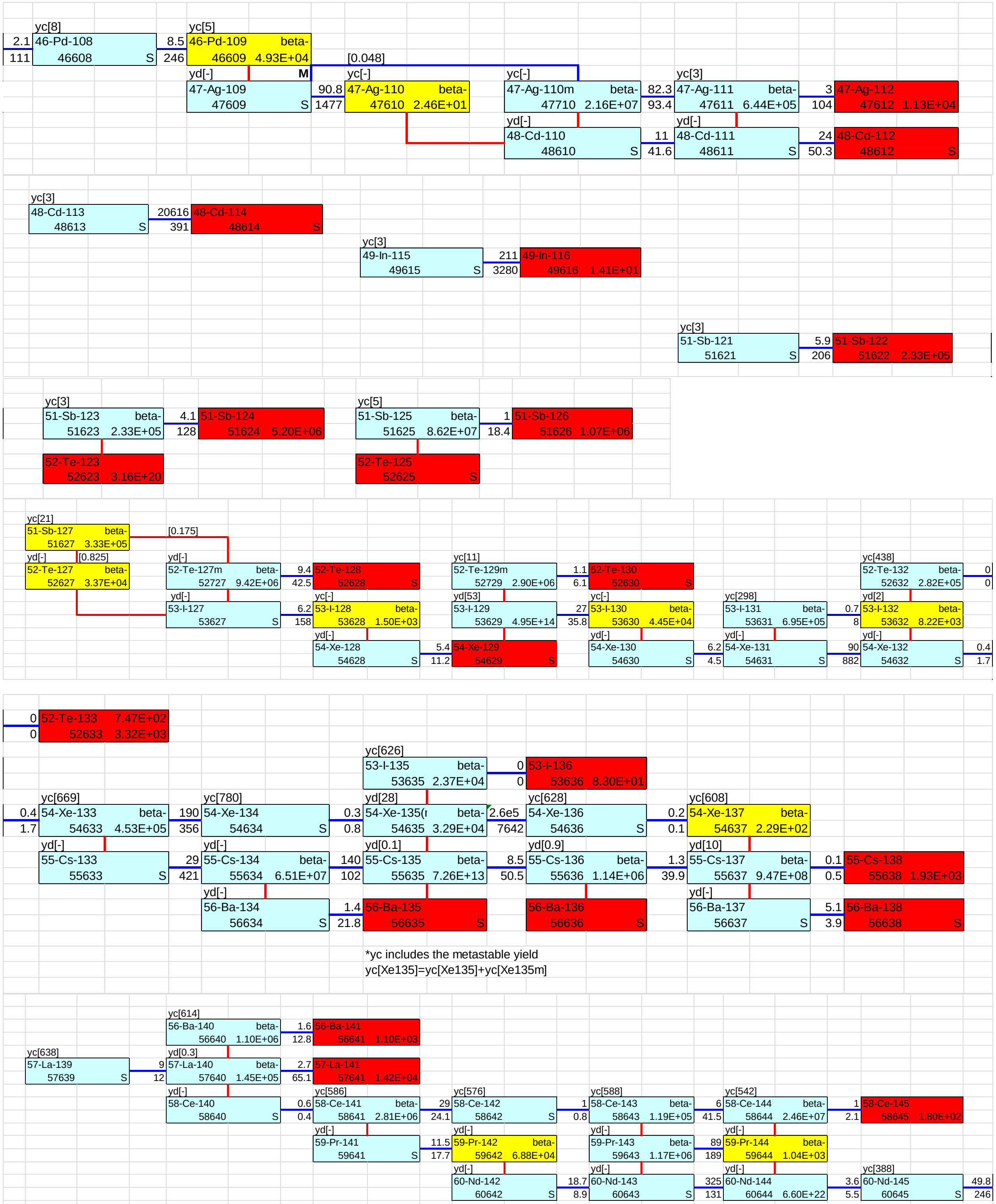
Appendix B. Depletion chain



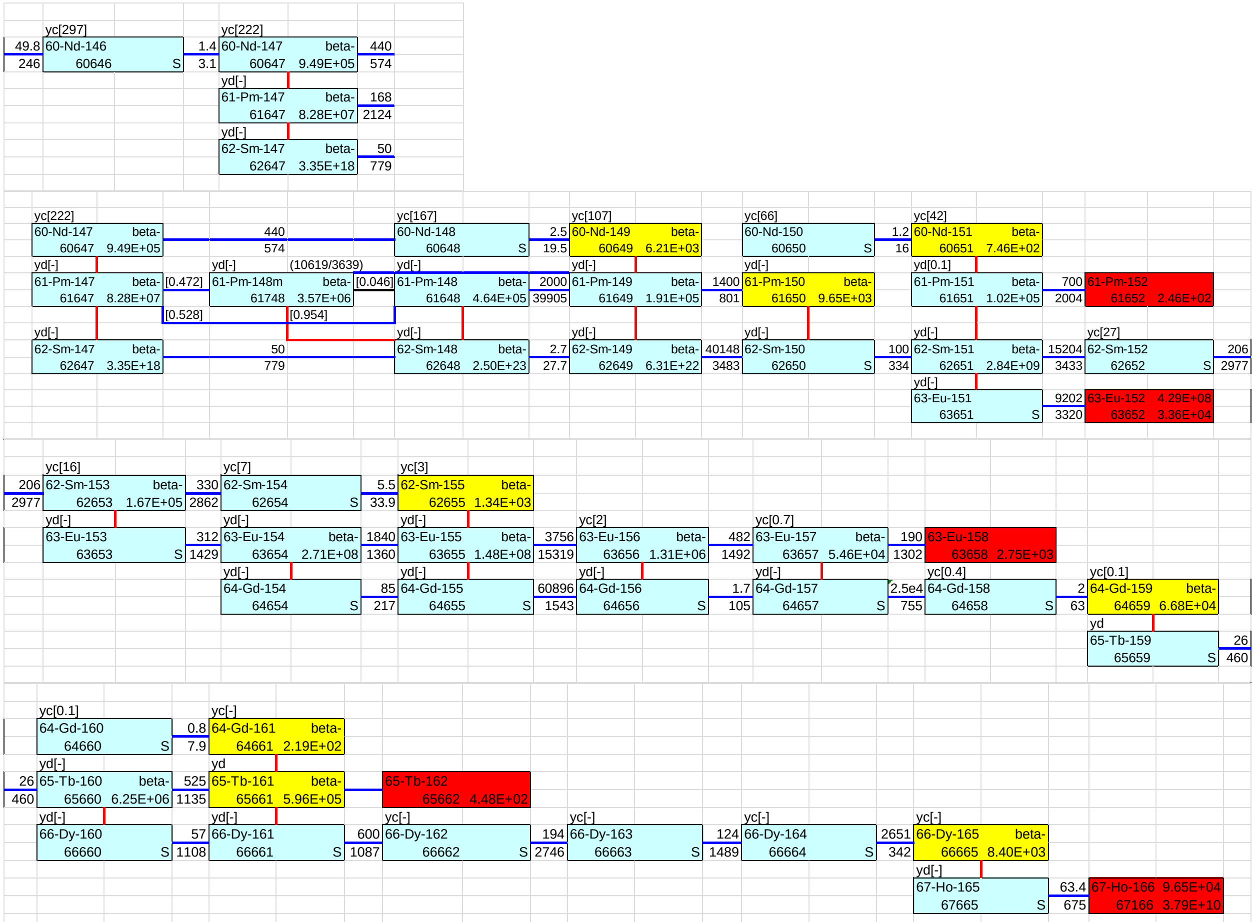
A : Nuclide
B : Nuclide Id. in library
C : Decay half life (s)
D : Decay type
M : Both stable and meta-stable

[Depletion chain of fission product nuclides]

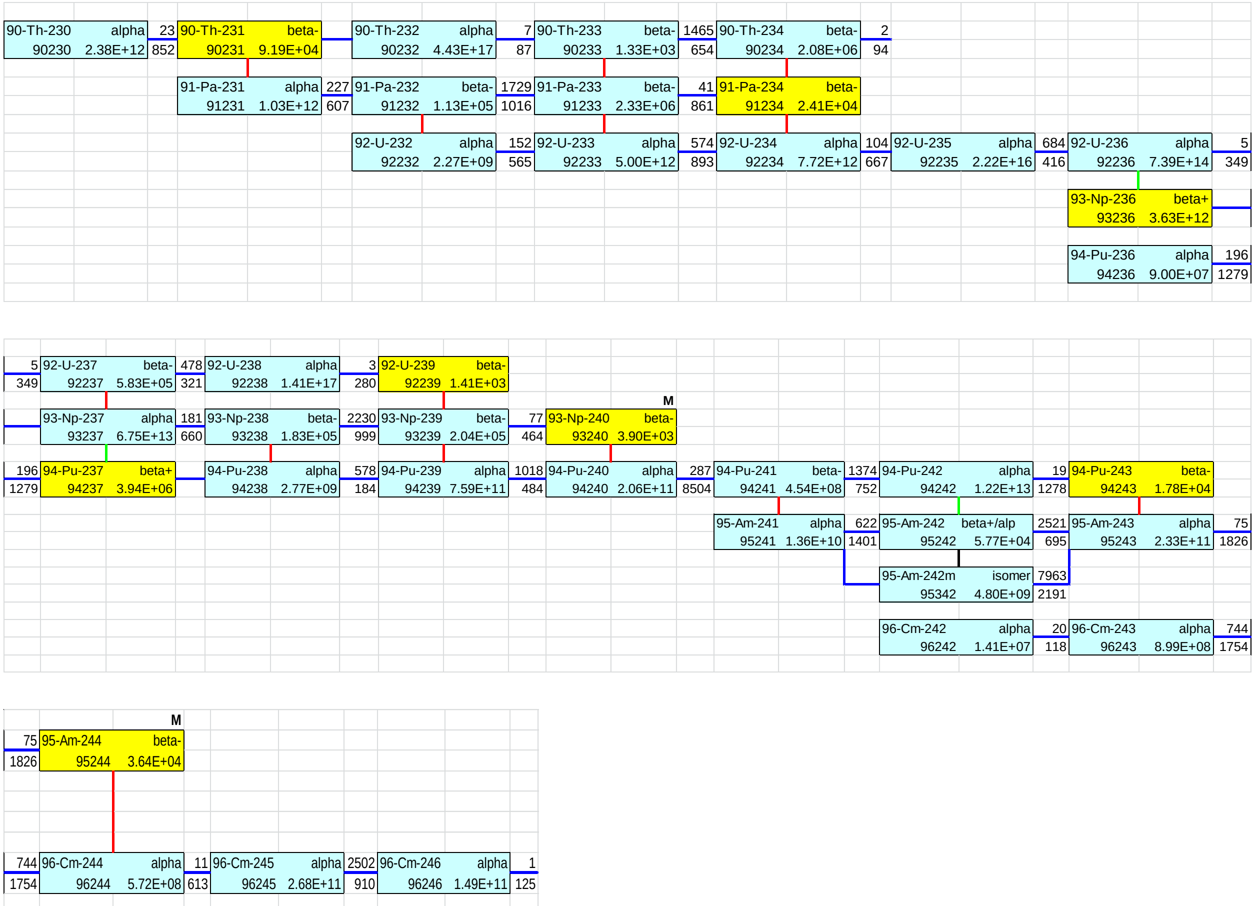




yc[8]
46-Pd-108 46608 S
yc[5]
46-Pd-109 beta- 46609 4.93E+04
[0.048]
47-Ag-109 47609 S
47-Ag-110 beta- 47610 2.46E+01
47-Ag-110m beta- 47710 2.16E+07
47-Ag-111 beta- 47611 6.44E+05
47-Ag-112 47612 1.13E+04
48-Cd-110 48610 S
48-Cd-111 48611 S
48-Cd-112 48612 S
48-Cd-113 48613 S
48-Cd-114 48614 S
49-In-115 49615 S
49-In-116 49616 1.41E+01
51-Sb-121 51621 S
51-Sb-122 51622 2.33E+05
51-Sb-123 beta- 51623 2.33E+05
51-Sb-124 51624 5.20E+06
52-Te-123 52623 3.16E+20
51-Sb-125 beta- 51625 8.62E+07
51-Sb-126 51626 1.07E+06
52-Te-125 52625 S
yc[21]
51-Sb-127 beta- 51627 3.33E+05
[0.175]
[0.825]
52-Te-127 beta- 52627 3.37E+04
52-Te-127m beta- 52727 9.42E+06
52-Te-128 52628 S
52-Te-129m 52729 2.90E+06
52-Te-130 52630 S
52-Te-132 beta- 52632 2.82E+05
53-I-127 53627 S
53-I-128 beta- 53628 1.50E+03
53-I-129 53629 4.95E+14
53-I-130 beta- 53630 4.45E+04
53-I-131 beta- 53631 6.95E+05
53-I-132 beta- 53632 8.22E+03
54-Xe-128 54628 S
54-Xe-129 54629 S
54-Xe-130 54630 S
54-Xe-131 54631 S
54-Xe-132 54632 S
52-Te-133 7.47E+02 52633 3.32E+03
yc[626]
53-I-135 beta- 53635 2.37E+04
53-I-136 53636 8.30E+01
54-Xe-133 beta- 54633 4.53E+05
54-Xe-134 54634 S
54-Xe-135(m) beta- 54635 3.29E+04
54-Xe-136 54636 S
54-Xe-137 beta- 54637 2.29E+02
55-Cs-133 55633 S
55-Cs-134 beta- 55634 6.51E+07
55-Cs-135 beta- 55635 7.26E+13
55-Cs-136 beta- 55636 1.14E+06
55-Cs-137 beta- 55637 9.47E+08
55-Cs-138 55638 1.93E+03
56-Ba-134 56634 S
56-Ba-135 56635 S
56-Ba-136 56636 S
56-Ba-137 56637 S
56-Ba-138 56638 S
*yc includes the metastable yield
yc[Xe135]=yc[Xe135]+yc[Xe135m]
56-Ba-140 beta- 56640 1.10E+06
56-Ba-141 56641 1.10E+03
57-La-139 57639 S
57-La-140 beta- 57640 1.45E+05
57-La-141 57641 1.42E+04
58-Ce-140 58640 S
58-Ce-141 beta- 58641 2.81E+06
58-Ce-142 58642 S
58-Ce-143 beta- 58643 1.19E+05
58-Ce-144 beta- 58644 2.46E+07
58-Ce-145 58645 1.80E+02
59-Pr-141 59641 S
59-Pr-142 beta- 59642 6.88E+04
59-Pr-143 beta- 59643 1.17E+06
59-Pr-144 beta- 59644 1.04E+03
60-Nd-142 60642 S
60-Nd-143 60643 S
60-Nd-144 60644 6.60E+22
60-Nd-145 60645 S


yc[297]
49.8 60-Nd-146
246 60646 S
yc[222]
1.4 60-Nd-147 beta- 440
3.1 60647 9.49E+05 574
yd[-]
61-Pm-147 beta- 168
61647 8.28E+07 2124
yd[-]
62-Sm-147 beta- 50
62647 3.35E+18 779
yc[222]
60-Nd-147 beta- 440
60647 9.49E+05 574
yc[167]
60-Nd-148
60648 S
yc[107]
2.5 60-Nd-149 beta-
19.5 60649 6.21E+03
yc[66]
60-Nd-150
60650 S
yc[42]
1.2 60-Nd-151 beta-
16 60651 7.46E+02
yd[-]
61-Pm-147 beta- [0.472]
61647 8.28E+07
yd[-] (10619/3639)
61-Pm-148m beta- [0.046]
61748 3.57E+06
[0.528] [0.954]
yd[-]
61-Pm-148 beta- 2000
61648 4.64E+05 39905
yd[-]
61-Pm-149 beta- 1400
61649 1.91E+05 801
yd[-]
61-Pm-150 beta-
61650 9.65E+03
yd[0.1]
61-Pm-151 beta- 700
61651 1.02E+05 2004
61-Pm-152
61652 2.46E+02
yd[-]
62-Sm-147 beta- 50
62647 3.35E+18 779
yd[-]
62-Sm-148 beta- 2.7
62648 2.50E+23 27.7
yd[-]
62-Sm-149 beta- 40148
62649 6.31E+22 3483
yd[-]
62-Sm-150 100
62650 S 334
yd[-]
62-Sm-151 beta- 15204
62651 2.84E+09 3433
yc[27]
62-Sm-152 206
62652 S 2977
yd[-]
63-Eu-151 9202
63651 S 3320
63-Eu-152 4.29E+08
63652 3.36E+04
yc[16]
206 62-Sm-153 beta- 330
2977 62653 1.67E+05 2862
yc[7]
62-Sm-154 5.5
62654 S 33.9
yc[3]
62-Sm-155 beta-
62655 1.34E+03
yd[-]
63-Eu-153 312
63653 S 1429
yd[-]
63-Eu-154 beta- 1840
63654 2.71E+08 1360
yd[-]
63-Eu-155 beta- 3756
63655 1.48E+08 15319
yc[2]
63-Eu-156 beta- 482
63656 1.31E+06 1492
yc[0.7]
63-Eu-157 beta- 190
63657 5.46E+04 1302
63-Eu-158
63658 2.75E+03
yd[-]
64-Gd-154 85
64654 S 217
yd[-]
64-Gd-155 60896
64655 S 1543
yd[-]
64-Gd-156 1.7
64656 S 105
yd[-]
64-Gd-157 2.5e4
64657 S 755
yc[0.4]
64-Gd-158 2
64658 S 63
yc[0.1]
64-Gd-159 beta-
64659 6.68E+04
yd
65-Tb-159 26
65659 S 460
yc[0.1]
64-Gd-160 0.8
64660 S 7.9
yc[-]
64-Gd-161 beta-
64661 2.19E+02
yd[-]
26 65-Tb-160 beta- 525
460 65660 6.25E+06 1135
yd
65-Tb-161 beta-
65661 5.96E+05
65-Tb-162
65662 4.48E+02
yd[-]
66-Dy-160 57
66660 S 1108
yd[-]
66-Dy-161 600
66661 S 1087
yc[-]
66-Dy-162 194
66662 S 2746
yc[-]
66-Dy-163 124
66663 S 1489
yc[-]
66-Dy-164 2651
66664 S 342
yc[-]
66-Dy-165 beta-
66665 8.40E+03
yd[-]
67-Ho-165 63.4
67665 S 675
67-Ho-166 9.65E+04
67166 3.79E+10

[Depletion chain of heavy metal nuclides]



[Depletion chain of activation nuclides]