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Engineering Design File

Engineering Test Reactor Radionuclides and the Radionuclide Relative Ratios

Idaho Cleanup Project

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5. **Summary:**
The purpose of this EDF is to document the radionuclides and the scaling factors between the radionuclides of the activated materials inside of the Engineering Test Reactor (ETR). These radionuclides and scaling factors may then be used in MicroShield models to estimate the source term values (activity) of the reactor and activated components based on dose rate measurements.

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1. PURPOSE

The purpose of this EDF is to document the radionuclides and the scaling factors between the radionuclides of the activated materials inside of the Engineering Test Reactor (ETR). These radionuclides and scaling factors may then be used in MicroShield models to estimate the source term values (activity) of the reactor and activated components based on dose rate measurements. This EDF is based on research and calculations performed by Glen R. Longhurst, James R. Parry and Michael L. Carboneau of the Idaho National Laboratory.

2. INTRODUCTION

The ETR operated from 1957 until 1981 at the Reactor Technology Complex (RTC). The ETR was designed to have high neutron flux levels and large internal test spaces. Various fuel and plug configurations were used at different times to accommodate testing. Figure 1 presents a vertical cross section of the reactor and shows the relative location of the various reactor components.

The ETR core had an active core length of 36” and consisted of 3” × 3” fuel elements/control rod positions/experiment positions arranged in a 10 × 10 array surrounded by a beryllium reflector. The region outside the beryllium reflector is the aluminum reflector, also arranged in the same 3” × 3” grid spacing[1]. Figure 2 below shows those locations that were used for experiments. Numbered circles were control rod locations. Those numbered 1 through 4 are “black” control rods initially using cadmium then later using hafnium as the neutron absorber[2]. The remainder are “gray” control rods. These rods are not totally opaque (absorptive) to neutrons and used Type-A nickel as the neutron absorber. Aluminum filler pieces occupied the region between the aluminum reflector pieces and the inner tank wall. Holes in the beryllium reflector were for capsule experiments, but they were filled with aluminum plugs when not in use for experiments.

Full power operation of the ETR was achieved in 1958. From then through 1972, the ETR produced approximately 487,728 megawatt-days[3].

Starting in 1973, the ETR was modified to support testing for the Department of Energy's breeder reactor safety program. The reactor was fitted with a new top closure, a helium coolant system, and a sodium handling system to support these tests. Testing in the reactor began again in October 1975. For the period 1975 to 1981 the reactor produced approximately 12,376 megawatt-days[3].

Starting in December 1981, deactivation commenced, which included removing the neutron source and all fuel from the reactor, draining the primary coolant system (and all other liquid systems in the facility), and all major equipment was prepared for long-term storage.

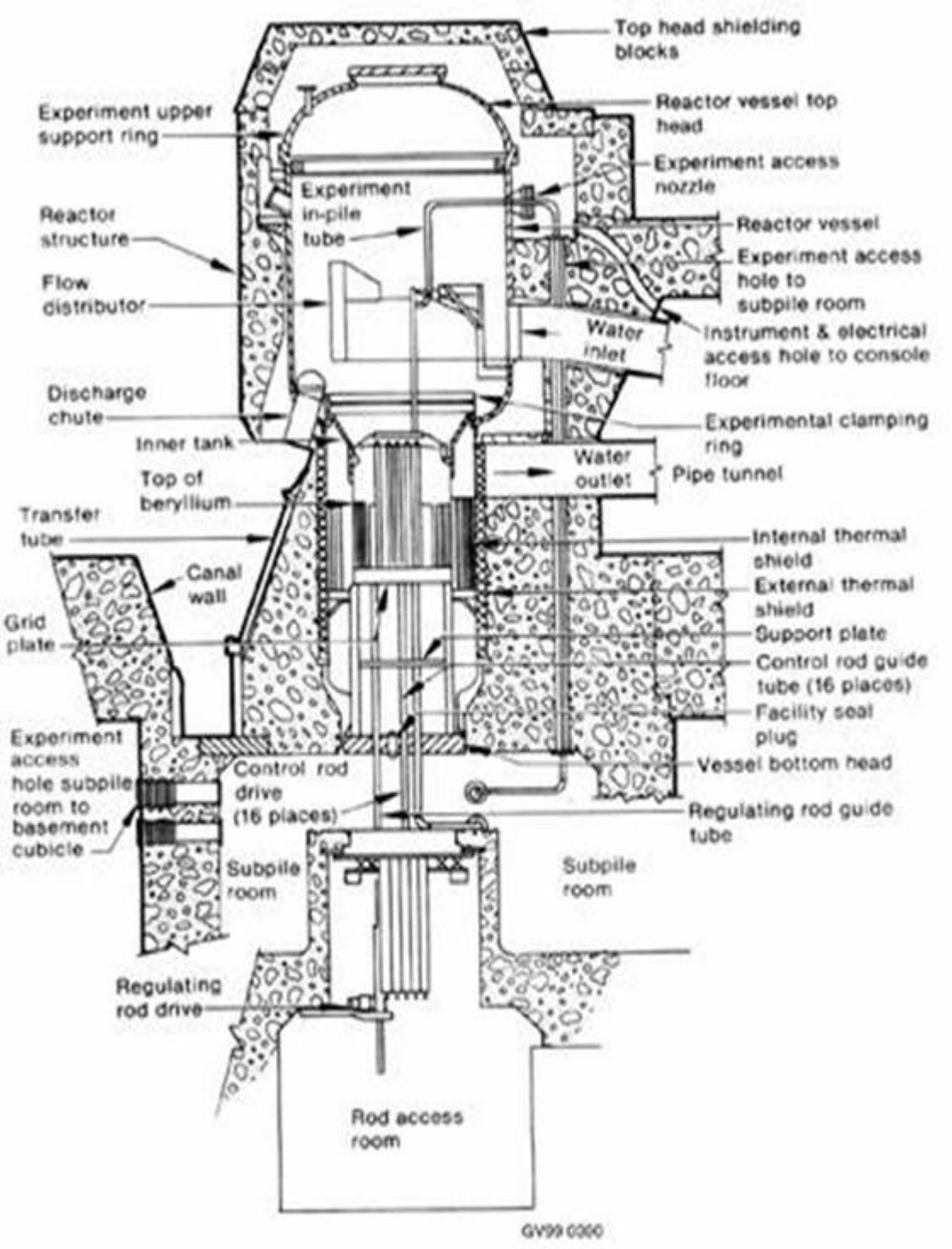

Figure 1. Vertical Cross Section of the ETR.

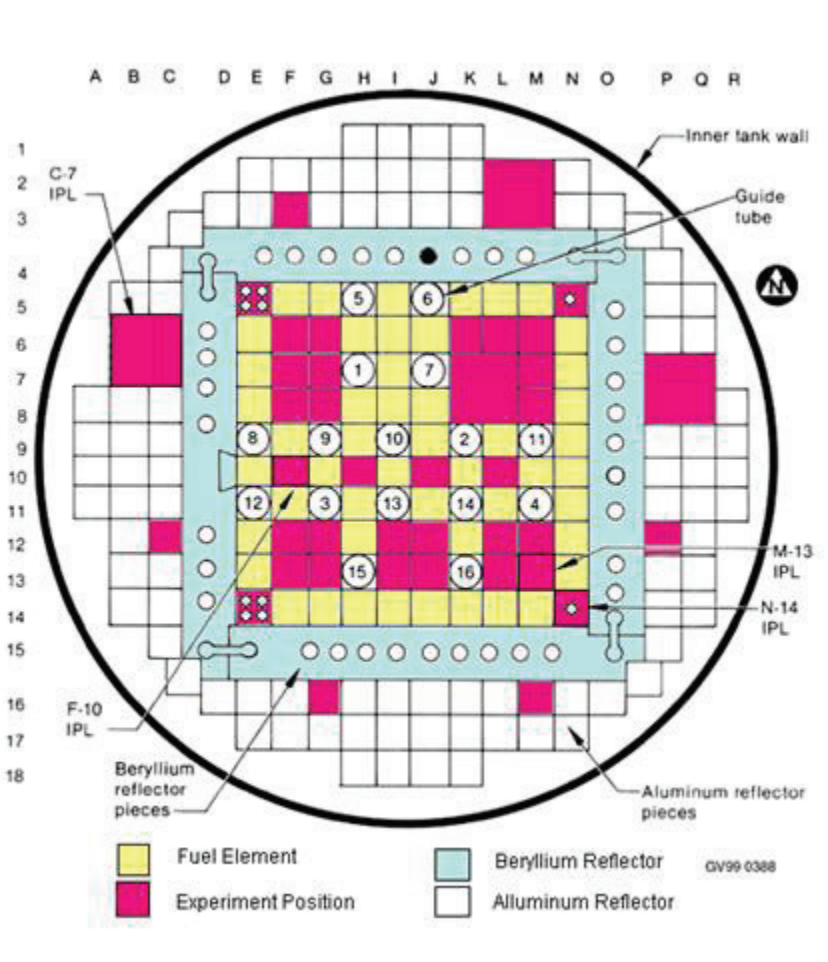

Figure 2. Cross Section View of the ETR Core

3. ACTIVATED STRUCTURES IN THE ETR

Experience with other reactors has shown that only structures within about 1 m from the core edge experience any significant (in terms of contribution to total inventory) activation from neutrons[4]. The activated structures positioned within this 1 m area include the various in-pile tubes still in the core, the beryllium reflector, the internal and external thermal shields, the grid plate, the support plate, the inner tank, and the control rod guide tube support structure. The control rod drive assemblies have been removed from the reactor vessel however, the control rod guide tubes, poison sections, control rod shafts and shock assemblies remain[5]. The control rod drive tubes and shafts are made of aluminum and, like other aluminum structures, do not contain activation products of consequence. The shock assemblies, though stainless steel, were outside the high-flux region during reactor operation.

Table 1 lists the structures within the reactor vessel and surrounding area that underwent significant activation during ETR operation. Some of the components listed, for example the beryllium reflector and the black control rod poison assemblies, experienced different irradiation histories due to different installation times[8,9]. These differing irradiation histories were accounted for in the activity determinations.

Table 1. ETR core structures with significant activation.

Component	Main Materials
External Thermal Shield	Pb, SS
External Tank	304-SS, Steel
Gray Control Rod Poison	Type A Ni
Black Control Rod Poison	Cd changed to Hf
Internal Thermal Shields	304-SS
Inner Tank	304-SS, Steel
Grid Plate	347-SS
Upper Support Frame	304 SS
Beryllium Reflector	Be
C-7 In-Pile Tube	304-SS
F-10 In-Pile Tube	304-SS
M-13 In-Pile Tube	304-SS
N-14 In-Pile Tube	304-SS
Core and Shield Support Beams	304-SS

A number of small pieces, including spacers, adapters, and plugs were placed on the top of the ETR core at the time of shutdown[5]. So far as could be determined, the items placed there were low activity aluminum. There appear to be no highly activated stainless steel components on the core top that have not been accounted for.

4. METHODOLOGY

For activated material within the reactor vessel and nearby locations, calculations were performed using the MCNP-4C[6] code to estimate neutron fluxes at various locations in the vessel. A paper, written by Dr. Parry discussing the MCNP-4C modeling of the ETR vessel is presented in Appendix D. Once the neutron flux values were determined, the ORIGEN2[7] code was used to calculate activation and fission products based on an average neutron flux acting on the significantly activated section of the reactor component. Impurities and alloy materials that were assumed to exist in the materials forming the various reactor components are shown in Attachment 1 and are based on the letter presented in Attachment 3. The significantly activated component neutron flux, mass, and volume are shown in Appendix D.

Drawings for the in-pile tubes could not be located. For convenience, the activation characteristics of the in-pile tubes were represented in the calculations by those of their nuclear mockups. The nuclear mockups were designed to provide the same neutronic response in the core as the actual test trains. Even though the actual test trains are more complex and contain small components of materials other than those of the mockups, the basic contribution to radionuclide inventories was judged to be given with sufficient accuracy by the mockup parameters. The main material forming both the mock-up and the in-pile tubes was 304 SS. Impurities and alloying materials that were used in the model for 304 SS are presented in Appendixes A and C. Any experiments in the IPTs would have a negligible effect on the IPT or other components activation.

The activities values for each component in the vessel, determined by ORIGEN2 and presented in Appendix E, were then normalized to Co-60 for use in MicroShield[10] models. Activity values are normalized to Co-60 by dividing the radionuclides activity value by the components Co-60 activity value. (Note: When developing a MicroShield model to determine a source term value based on a measured dose rates, a standard practice is to use activity values normalized to a dominate high energy gamma emitter. The radionuclide to which the other activity values are normalized to does not influence the calculation as long as the relative ratios of the activity values between the radionuclides remain unchanged).

Co-60 normalized activity values for the reactor as a whole were also determined by summing each radionuclide activity in each component and dividing this value by the summed Co-60 activity. Additionally, the percent contribution of each component to the total reactor source term was determined from the Appendix E values by summing the radionuclide activity values in the component and dividing this value by the sum of the radionuclide activity values from every component.

5. UNCERTAINTIES

The total uncertainty associated with the estimated neutron activation product inventory in the significantly activated section is due to a combination of various assumptions used in the models to account for unknown data:

- There is uncertainty in the alloy composition for the precursor element that neutron activates to the isotope of concern (e.g., Mo is in stainless steel and Mo98 + n transmutes to Tc99; so Mo is the precursor for Tc99). Often, reported assay data indicate upper limits on impurities, and these were usually used. However, there is no guarantee that the impurities included in that process really are there.
- The uncertainty in the computer code to accurately predict the isotope inventory (due to uncertainties in decay or cross-section data and mathematical models in the code).
- The way the power history data were modeled.

5.1 Computer Code Usage

The two computer codes formed the basis for the activation calculations, MCNP4C and ORIGEN2.

The MCNP4C code is maintained under INEEL configuration control tracking number 64573. The code was implemented and used by Dr. James R. Parry.

ORIGEN2 calculations were performed by Michael L. Carboneau. Mr. Carboneau is the INEEL custodian for the ORIGEN2 code, which is maintained under configuration control tracking number 64556.

Normalization calculations were performed using an EXCEL spreadsheet.

Results

Table 2 below presents the scaling factors, normalized to Co-60, for use in the ETR MicroShield models and the percent contribution each component adds to the total reactor source term.

Table 2. Scaling factors, normalized to Co-60.

Isotope	Be Reflector (Be) (Ci/Ci)	Grid Plate (304-SS) (Ci/Ci)	I-Beams (all 6, 304-SS) (Ci/Ci)	C-7 In-Pile Tube (304-SS) (Ci/Ci)	F-10 In-Pile Tube (304-SS) (Ci/Ci)	M-13 In-Pile Tube (304-SS)	N-14 In-Pile Tube (304-SS) (Ci/Ci)	Upper Support Frame (304-SS) (Ci/Ci)	Inner Tank (304-SS, Steel) (Ci/Ci)	Internal Thermal Shields (304-SS) (Ci/Ci)	External Thermal Shield (304-SS. Pb) (Ci/Ci)	External Tank (304-SS, Steel) (Ci/Ci)	Black Rod Poison (Cd) (Ci/Ci)	Gray Rod Poison (Ni) (Ci/Ci)	Reactor Totals (Ci/Ci)
H-3	2.97E+04	8.63E-03	7.57E-03	4.94E-03	1.38E-03	1.93E-03	3.20E-03	7.54E-03	6.46E-03	7.56E-03	1.44E-01	9.36E-02	8.55E-04	2.42E-07	1.67E+01
Be-10	3.36E-01	1.56E-09	1.32E-09	1.01E-09	1.04E-09	6.54E-10	6.88E-10	1.31E-09	1.18E-09	1.31E-09	3.19E-08	2.06E-08	1.40E-09	2.18E-09	1.89E-04
C-14	2.67E+00	8.55E-03	6.31E-03	5.93E-03	6.68E-03	4.13E-03	4.15E-03	6.29E-03	6.42E-03	6.32E-03	1.26E-02	1.03E-02	9.00E-03	6.93E-07	6.74E-03
Cl-36	3.27E-02	8.78E-05	5.01E-05	4.65E-05	4.82E-05	3.14E-05	3.23E-05	5.00E-05	5.06E-05	5.02E-05	2.83E-05	3.63E-05	5.71E-05	2.33E-08	6.40E-05
Mn-54	8.26E-09	2.95E-09	1.50E-09	1.62E-09	2.02E-09	2.51E-09	2.23E-09	1.50E-09	1.53E-09	1.50E-09	1.80E-08	1.19E-08	2.69E-09	1.05E-11	1.63E-09
Ni-59	2.42E-02	1.01E-02	3.53E-02	3.03E-02	2.15E-02	1.79E-02	2.04E-02	3.52E-02	3.43E-02	3.55E-02	1.99E-02	2.56E-02	1.56E-02	1.79E-01	6.72E-02
Co-60	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Ni-63	3.50E+00	1.15E+00	3.73E+00	3.45E+00	3.41E+00	2.36E+00	2.46E+00	3.73E+00	3.75E+00	3.75E+00	2.21E+00	2.72E+00	3.66E+00	3.57E+01	1.23E+01
Zn-65	3.86E-11	6.98E-14	3.71E-14	4.39E-14	8.24E-14	7.97E-14	6.28E-14	3.69E-14	3.94E-14	3.71E-14	4.85E-13	6.78E-14	1.69E-13	5.59E-14	8.68E-14
Sr-90	6.78E-01	8.85E-05	1.66E-05	4.56E-05	7.67E-05	4.68E-05	3.87E-05	1.65E-05	3.59E-05	1.68E-05	1.46E-04	9.86E-05	9.34E-05	5.67E-09	4.29E-04
Nb-94	7.39E-03	8.63E-03	8.58E-05	7.89E-05	7.82E-05	5.25E-05	5.46E-05	8.51E-05	8.64E-05	8.56E-05	2.77E-04	2.06E-04	8.67E-05	5.64E-09	2.45E-03
Tc-99	4.96E-04	5.84E-06	3.41E-06	3.03E-06	2.78E-06	1.94E-06	2.08E-06	3.39E-06	3.33E-06	3.38E-06	1.97E-06	2.49E-06	2.73E-06	1.85E-10	3.22E-06
Ru-106	2.77E-07	7.00E-12	8.40E-14	4.06E-12	5.70E-12	7.97E-12	6.37E-12	8.35E-14	2.58E-12	1.15E-13	7.24E-13	4.89E-13	5.35E-12	2.91E-16	1.59E-10
Ag-108m	3.16E-02	1.18E-04	6.84E-05	6.32E-05	6.37E-05	4.33E-05	4.48E-05	6.81E-05	6.87E-05	6.82E-05	7.35E-01	3.94E-04	6.65E-04	4.59E-09	1.23E-04
Ag-110m	2.35E-11	2.23E-14	1.69E-14	1.40E-14	4.02E-15	1.32E-14	1.73E-14	1.69E-14	1.52E-14	1.69E-14	1.83E-10	9.77E-14	1.77E-13	6.79E-20	3.75E-14
Sb-125	6.21E-04	5.18E-06	2.92E-06	3.13E-06	4.04E-06	4.28E-06	3.84E-06	2.92E-06	2.96E-06	2.92E-06	2.38E-05	2.12E-06	5.65E-06	2.63E-10	3.35E-06
I-129	3.69E-06	1.73E-10	1.05E-11	8.61E-11	1.47E-10	8.70E-11	7.05E-11	1.05E-11	6.12E-11	1.10E-11	9.04E-11	6.10E-11	1.59E-10	1.06E-14	2.15E-09
Cs-134	2.10E-03	5.94E-07	3.65E-07	3.62E-07	3.07E-07	4.40E-07	4.51E-07	3.63E-07	3.55E-07	3.65E-07	2.05E-07	2.64E-07	2.32E-07	1.45E-11	1.49E-06
Cs-137	2.27E+00	1.83E-04	1.80E-05	9.35E-05	1.68E-04	1.02E-04	8.14E-05	1.79E-05	6.76E-05	1.85E-05	1.58E-04	1.06E-04	2.00E-04	1.23E-08	1.37E-03
Ce-144	1.98E-09	6.74E-14	6.86E-15	3.94E-14	5.39E-14	7.46E-14	6.06E-14	6.83E-15	2.74E-14	7.09E-15	6.07E-14	4.08E-14	5.29E-14	2.82E-18	1.15E-12
Eu-152	1.38E-02	6.80E-05	1.33E-03	5.25E-05	8.34E-08	1.63E-06	1.99E-05	1.32E-03	2.19E-04	1.30E-03	1.07E-01	6.80E-02	3.81E-08	3.05E-12	9.23E-05
Eu-154	8.11E-01	1.64E-04	7.59E-05	9.21E-05	2.58E-05	5.48E-05	7.54E-05	7.56E-05	8.90E-05	7.59E-05	6.11E-03	3.90E-03	7.10E-06	6.42E-10	5.31E-04
Pb-210	1.45E-11	3.02E-14	2.11E-10	1.38E-14	5.60E-14	1.60E-14	9.27E-15	1.74E-09	1.18E-14	2.68E-13	1.95E-10	1.09E-10	1.25E-13	6.57E-18	3.50E-14
Ra-226	2.02E-11	7.41E-14	6.09E-10	3.48E-14	4.83E-14	2.43E-14	2.13E-14	5.03E-09	3.14E-14	7.73E-13	5.63E-10	3.15E-10	4.35E-14	3.50E-18	5.65E-14
Ac-227	1.14E-07	9.24E-10	3.81E-09	4.97E-10	1.96E-10	2.20E-10	3.02E-10	2.66E-08	6.14E-10	6.79E-10	2.51E-08	1.59E-08	8.91E-11	8.03E-15	5.14E-10
Th-228	5.68E-05	1.15E-07	2.39E-05	5.58E-08	1.42E-07	7.83E-08	5.19E-08	1.98E-04	3.22E-08	3.03E-08	8.38E-05	4.47E-05	1.16E-07	8.83E-12	9.10E-08

Table 2. (continued).

Isotope	Be Reflector (Be) (Ci/Ci)	Grid Plate (304-SS) (Ci/Ci)	I-Beams (all 6, 304-SS) (Ci/Ci)	C-7 In-Pile Tube (304-SS) (Ci/Ci)	F-10 In-Pile Tube (304-SS) (Ci/Ci)	M-13 In-Pile Tube (304-SS)	N-14 In-Pile Tube (304-SS) (Ci/Ci)	Upper Support Frame (304-SS) (Ci/Ci)	Inner Tank (304-SS, Steel) (Ci/Ci)	Internal Thermal Shields (304-SS) (Ci/Ci)	External Thermal Shield (304-SS. Pb) (Ci/Ci)	External Tank (304-SS, Steel) (Ci/Ci)	Black Rod Poison (Cd) (Ci/Ci)	Gray Rod Poison (Ni) (Ci/Ci)	Reactor Totals (Ci/Ci)
Th-229	9.51E-08	1.11E-09	1.10E-09	6.00E-10	1.56E-10	1.96E-10	3.23E-10	1.10E-09	8.31E-10	1.02E-09	3.60E-08	2.31E-08	7.70E-11	6.77E-15	6.10E-10
Th-230	2.95E-09	6.88E-12	6.15E-08	3.31E-12	4.72E-12	2.80E-12	2.32E-12	5.08E-07	2.81E-12	7.76E-11	5.69E-08	3.18E-08	3.96E-12	3.07E-16	5.95E-12
Th-232	1.17E-08	1.85E-10	2.41E-05	1.11E-10	1.64E-11	2.53E-11	5.40E-11	1.99E-04	2.54E-10	3.03E-08	8.46E-05	4.52E-05	7.19E-12	6.35E-16	1.04E-09
Pa-231	1.82E-07	1.34E-09	7.57E-09	7.27E-10	2.95E-10	3.41E-10	4.64E-10	5.55E-08	8.81E-10	9.77E-10	3.79E-08	2.39E-08	1.39E-10	1.22E-14	7.53E-10
U-232	5.53E-05	1.11E-07	1.21E-12	5.42E-08	1.38E-07	7.61E-08	5.04E-08	8.84E-13	3.11E-08	2.85E-10	1.15E-10	8.91E-11	1.13E-07	8.61E-12	8.76E-08
U-233	3.15E-05	3.07E-07	3.08E-07	1.72E-07	4.36E-08	6.26E-08	1.03E-07	3.07E-07	2.32E-07	2.85E-07	1.01E-05	6.45E-06	2.00E-08	1.73E-12	1.73E-07
U-234	1.24E-05	1.31E-08	1.48E-04	6.49E-09	9.59E-09	7.32E-09	5.63E-09	1.23E-03	4.99E-09	1.86E-07	1.38E-04	7.69E-05	6.83E-09	5.01E-13	1.56E-08
U-235	3.44E-09	1.83E-11	6.75E-06	1.23E-11	7.51E-13	8.70E-13	4.17E-12	5.59E-05	4.55E-11	8.46E-09	6.25E-06	3.48E-06	6.10E-13	4.31E-17	1.29E-10
U-236	4.96E-07	1.71E-10	1.60E-10	9.55E-11	2.78E-11	3.30E-11	5.58E-11	1.60E-10	1.31E-10	1.60E-10	1.38E-09	9.26E-10	2.72E-11	1.69E-15	3.67E-10
U-238	2.17E-06	1.09E-09	1.47E-04	6.55E-10	8.19E-11	1.41E-10	3.15E-10	1.21E-03	1.53E-09	1.84E-07	1.36E-04	7.59E-05	2.72E-11	2.72E-15	4.33E-09
Np-237	1.70E-06	3.25E-10	2.92E-11	1.59E-10	8.76E-11	9.93E-11	1.17E-10	2.91E-11	1.04E-10	2.88E-11	2.50E-10	1.68E-10	6.19E-11	4.32E-15	1.09E-09
Pu-238	7.01E-02	7.86E-06	5.80E-13	3.11E-06	4.30E-06	3.54E-06	2.35E-06	6.98E-14	8.36E-07	4.41E-10	4.58E-11	3.73E-11	1.66E-06	1.51E-10	4.24E-05
Pu-239	1.14E-02	5.07E-06	7.79E-06	2.94E-06	4.33E-07	7.39E-07	1.55E-06	7.76E-06	4.87E-06	7.59E-06	6.66E-05	4.49E-05	1.44E-07	1.44E-11	9.21E-06
Pu240	1.63E-02	4.73E-06	4.69E-11	2.55E-06	8.13E-07	9.78E-07	1.64E-06	5.62E-12	2.42E-06	3.65E-08	3.71E-09	3.01E-09	5.98E-07	4.58E-11	1.13E-05
Pu-241	1.48E+00	2.34E-04	1.35E-14	1.18E-04	5.49E-05	8.33E-05	1.03E-04	1.95E-16	5.96E-05	8.39E-09	9.85E-12	9.69E-12	2.57E-05	2.15E-09	9.21E-04
Pu-242	2.49E-04	9.01E-09	1.75E-24	3.87E-09	1.61E-08	1.02E-08	5.00E-09	3.05E-27	8.33E-10	8.66E-16	1.18E-20	1.40E-20	8.70E-09	7.81E-13	1.44E-07
Pu-244	2.29E-10	1.72E-16	0.00E+00	6.13E-17	2.01E-14	3.22E-15	2.69E-16	0.00E+00	2.52E-18	1.66E-28	3.09E-37	5.32E-37	7.95E-14	3.03E-18	1.36E-13
Am-241	1.44E-01	2.99E-05	1.73E-15	1.46E-05	5.80E-06	8.84E-06	1.15E-05	2.50E-17	7.66E-06	1.07E-09	1.26E-12	1.24E-12	2.35E-06	2.12E-10	9.21E-05
Am-243	2.44E-03	2.76E-08	2.31E-29	1.04E-08	2.10E-07	7.75E-08	1.90E-08	4.83E-33	1.06E-09	9.06E-18	1.44E-24	2.06E-24	1.37E-07	1.20E-11	1.40E-06
Cm-243	4.36E-04	2.57E-08	2.90E-29	1.00E-08	4.26E-08	2.89E-08	1.22E-08	6.09E-33	1.19E-09	1.14E-17	1.82E-24	2.60E-24	1.12E-08	1.34E-12	2.56E-07
Cm-244	2.75E-01	5.93E-07	1.89E-33	1.97E-07	4.23E-05	5.67E-06	5.73E-07	0.00E+00	8.90E-09	5.92E-19	1.10E-27	1.89E-27	7.61E-05	4.74E-09	1.62E-04
Cm-245	5.15E-05	6.31E-11	0.00E+00	1.92E-11	9.90E-09	9.93E-10	6.82E-11	0.00E+00	4.68E-13	2.95E-25	6.37E-36	1.32E-35	1.85E-08	1.18E-12	3.07E-08
Cm-246	4.32E-05	1.02E-11	0.00E+00	2.68E-12	1.67E-08	5.36E-10	1.47E-11	0.00E+00	2.91E-14	1.43E-28	7.87E-42	7.65E-41	1.27E-07	4.98E-12	3.39E-08
Cm-247	1.94E-10	1.18E-17	0.00E+00	2.75E-18	1.22E-13	1.72E-15	2.19E-17	0.00E+00	1.38E-20	5.48E-37	0.00E+00	0.00E+00	1.76E-12	5.82E-17	2.39E-13
Cm-248	9.05E-10	1.29E-17	0.00E+00	2.62E-18	1.11E-12	5.50E-15	3.07E-17	0.00E+00	6.00E-21	1.91E-39	0.00E+00	0.00E+00	5.29E-11	1.18E-15	4.29E-12
% of Total Reactor Activity	55.60%	2.03%	1.7E-06%	0.226%	0.607%	0.331%	0.166%	4.1E-07%	4.02%	0.10167%	4.1E-05%	0.00013%	1.09865%*	35.80920%	100%

*Per Dr. Parry, during the MCNP4C and ORIGEN2 modeling of the poison sections of the Black Control Rods, the neutron flux was over estimated by as much as a factor of 2. The tally region was set up incorrectly such that the flux acting on the poison section of the controls rods was that of the core region. The Black Control Rods would have been completely withdrawn from the core during reactor operation so that they would not have been in this high flux region. This difference in flux does not effect the scaling factors between the radionuclides but does change the percentage these poison sections contribute to the total reactor activity. Thus, the 1.09865% value shown represents the activity if the control rods had been in the highest flux region.

6. CONCLUSION

The data presented in the results section above is based on activity values determined for the significantly activated sections of components in the ETR. The listed data may be used in MicroShield models for reactor source term determinations. Once the reactor source term is determined, activity values for the individual components may be determined either by MicroShield models and dose rate measurements (if possible) or by the percentage that the component contributes to the total reactor source term.

7. REFERENCES

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9. ETR Operations Branch Progress Report for Cycle No. 45.

10. MicroShield v6.10 Shielding Code, Grove Engineering.

8. APPENDIXES

Appendix A, Assumed Impurity and alloy data used in the MCNP4C and ORIGEN2 models

Appendix B, Radionuclide half lives used in the ORIGEN2 models

Appendix C, Impurity data

Appendix D, An MCNP Model of the Engineering Test Reactor by Dr. J. Parry

Appendix E, ORIGEN2 activity values

Appendix A

Impurity and Alloy Data

Appendix A

Impurity and Alloy Data

Table 1. Impurity and Alloy Data Used in the Computer Models (as generated by Michael L. Carboneau).

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
H-1	0.006998	0.006998	0.000000	0.000000	0.000000	0.000000
H-2	0.000002	0.000002	0.000000	0.000000	0.000000	0.000000
He-3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
He-4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Li-6	0.000008	0.000008	0.000019	0.000000	0.000000	0.000000
Li-7	0.000122	0.000122	0.000281	0.000650	0.000000	0.000000
Be-9	0.000000	0.000000	0.000000	988.011752	0.000000	0.000000
Be-10	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
B-10	0.000922	0.000922	0.000000	0.000120	0.000000	0.000000
B-11	0.004078	0.004078	0.000000	0.000530	0.000000	0.000000
C-12	0.790473	0.632378	3.260701	0.790473	0.000000	1.482137
C-13	0.009527	0.007622	0.039299	0.009527	0.000000	0.017863
N-14	0.468137	0.358573	0.083667	0.204586	0.000000	0.000033
N-15	0.001863	0.001427	0.000333	0.000814	0.000000	0.000000
O-16	0.149599	0.149599	0.000000	5.345666	0.000000	0.000011
O-17	0.000064	0.000064	0.000000	0.002277	0.000000	0.000000
O-18	0.000337	0.000337	0.000000	0.012057	0.000000	0.000000
F-19	0.000000	0.000000	0.000000	0.069167	0.000000	0.000000
Ne-20	0.000000	0.000000	0.000000	1.277352	0.000000	0.000000
Ne-21	0.000000	0.000000	0.000000	0.004002	0.000000	0.000000
Ne-22	0.000000	0.000000	0.000000	0.143646	0.000000	0.000000
Na-23	0.009700	0.009700	0.040000	0.000874	0.000000	0.000001
Mg-24	0.000000	0.000000	0.000000	0.025334	0.000000	0.000000
Mg-25	0.000000	0.000000	0.000000	0.003341	0.000000	0.000000
Mg-26	0.000000	0.000000	0.000000	0.003825	0.000000	0.000000
Al-27	0.100000	0.100000	0.050000	0.495000	0.000000	0.000007
Si-28	9.187333	5.879893	2.756200	0.863609	0.000000	3.215567
Si-29	0.481808	0.308357	0.144542	0.045290	0.000000	0.168633
Si-30	0.330858	0.211749	0.099258	0.031101	0.000000	0.115800
P-31	0.450000	0.250000	3.500000	0.050000	0.000000	0.000032
S-32	0.284238	0.180018	0.378984	0.007106	0.000000	0.473731
S-33	0.002314	0.001465	0.003085	0.000058	0.000000	0.003856
S-34	0.013381	0.008474	0.017841	0.000335	0.000000	0.022301
S-35	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
S-36	0.000067	0.000043	0.000090	0.000002	0.000000	0.000112
Cl-35	0.052315	0.052315	0.000000	0.037368	0.000000	0.000004
Cl-36	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cl-37	0.017685	0.017685	0.000000	0.012632	0.000000	0.000001
Ar-36	0.000000	0.000000	0.000000	0.000019	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Ar-37	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ar-38	0.000000	0.000000	0.000000	0.000004	0.000000	0.000000
Ar-39	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ar-40	0.000000	0.000000	0.000000	0.006347	0.000000	0.000000
K-39	0.002788	0.002788	0.002788	0.012147	0.000000	0.000000
K-40	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
K-41	0.000212	0.000212	0.000212	0.000922	0.000000	0.000000
Ca-40	0.018366	0.018366	0.013533	0.014499	0.000000	0.000001
Ca-41	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ca-42	0.000129	0.000129	0.000095	0.000102	0.000000	0.000000
Ca-43	0.000027	0.000027	0.000020	0.000022	0.000000	0.000000
Ca-44	0.000435	0.000435	0.000320	0.000343	0.000000	0.000000
Ca-45	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ca-46	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000
Ca-47	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ca-48	0.000043	0.000043	0.000031	0.000034	0.000000	0.000000
Sc-45	0.000030	0.000030	0.000000	0.002300	0.000000	0.000000
Ti-46	0.046067	0.007678	0.000154	0.004735	0.000000	0.000003
Ti-47	0.042950	0.007158	0.000143	0.004414	0.000000	0.000003
Ti-48	0.443447	0.073908	0.001478	0.045576	0.000000	0.000031
Ti-49	0.033737	0.005623	0.000112	0.003467	0.000000	0.000002
Ti-50	0.033799	0.005633	0.000113	0.003474	0.000000	0.000002
V-50	0.001226	0.000980	0.000074	0.000008	0.000000	0.000000
V-51	0.498774	0.399020	0.029926	0.003415	0.000000	0.000035
Cr-50	7.837717	7.386986	0.000003	0.005279	0.000000	0.000556
Cr-51	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cr-52	157.190152	148.150463	0.000050	0.105882	0.000000	0.011148
Cr-53	18.164744	17.120126	0.000006	0.012236	0.000000	0.001288
Cr-54	4.607387	4.342426	0.000001	0.003103	0.000000	0.000327
Mn-55	14.100000	16.400000	9.000000	0.094000	0.000000	3.500000
Fe-54	38.889965	43.220933	55.696735	0.053567	0.001140	0.227943
Fe-55	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Fe-56	626.965796	696.787643	897.916676	0.863577	0.018374	3.674798
Fe-57	14.611201	16.238373	20.925609	0.020125	0.000428	0.085640
Fe-58	1.982338	2.203101	2.839030	0.002730	0.000058	0.011619
Co-59	1.700000	1.000000	0.093000	0.001000	0.000000	2.000000
Ni-58	62.204445	11.052577	0.000202	0.062339	0.000000	662.134379
Ni-59	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ni-60	24.601143	4.371167	0.000080	0.024654	0.000000	261.866533
Ni-61	1.082859	0.192404	0.000004	0.001085	0.000000	11.526475
Ni-62	3.496630	0.621286	0.000011	0.003504	0.000000	37.219829
Ni-63	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ni-64	0.914924	0.162565	0.000003	0.000917	0.000000	9.738893
Cu-63	1.712489	0.958994	1.301492	0.036647	0.547997	1.712489

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Cu-64	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cu-65	0.787511	0.441006	0.598508	0.016853	0.252003	0.787511
Zn-64	0.047510	0.047510	0.010452	0.011877	0.004751	0.000003
Zn-65	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Zn-66	0.028126	0.028126	0.006188	0.007032	0.002813	0.000002
Zn-67	0.004196	0.004196	0.000923	0.001049	0.000420	0.000000
Zn-68	0.019527	0.019527	0.004296	0.004882	0.001953	0.000001
Zn-69	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Zn-70	0.000642	0.000642	0.000141	0.000160	0.000064	0.000000
Ga-69	0.076656	0.076656	0.011885	0.000511	0.000000	0.000005
Ga-70	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ga-71	0.052344	0.052344	0.008115	0.000349	0.000000	0.000004
Ge-70	0.000000	0.000000	0.000000	0.000987	0.000000	0.000000
Ge-71	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ge-72	0.000000	0.000000	0.000000	0.001357	0.000000	0.000000
Ge-73	0.000000	0.000000	0.000000	0.000392	0.000000	0.000000
Ge-74	0.000000	0.000000	0.000000	0.001857	0.000000	0.000000
Ge-75	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ge-76	0.000000	0.000000	0.000000	0.000408	0.000000	0.000000
As-75	0.100000	0.100000	0.160000	0.001782	0.007000	0.000007
Se-74	0.001685	0.001685	0.000076	0.000020	0.000000	0.000000
Se-75	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Se-76	0.017496	0.017496	0.000787	0.000208	0.000000	0.000001
Se-77	0.014804	0.014804	0.000666	0.000176	0.000000	0.000001
Se-78	0.046567	0.046567	0.002096	0.000555	0.000000	0.000003
Se-79	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Se-80	0.100987	0.100987	0.004544	0.001203	0.000000	0.000007
Se-81	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Se-82	0.018462	0.018462	0.000831	0.000220	0.000000	0.000001
Br-79	0.001001	0.001001	0.001001	0.026034	0.000000	0.000000
Br-80	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Br-81	0.000999	0.000999	0.000999	0.025966	0.000000	0.000000
Kr-78	0.000000	0.000000	0.000000	0.000277	0.000000	0.000000
Kr-79	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Kr-80	0.000000	0.000000	0.000000	0.001827	0.000000	0.000000
Kr-81	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Kr-82	0.000000	0.000000	0.000000	0.009657	0.000000	0.000000
Kr-83	0.000000	0.000000	0.000000	0.009690	0.000000	0.000000
Kr-84	0.000000	0.000000	0.000000	0.048610	0.000000	0.000000
Kr-85	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Kr-86	0.000000	0.000000	0.000000	0.015105	0.000000	0.000000
Rb-85	0.007169	0.007169	0.051617	0.005568	0.000000	0.000001
Rb-86	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Rb-87	0.002831	0.002831	0.020383	0.002199	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Sr-84	0.000001	0.000001	0.000001	0.000032	0.000000	0.000000
Sr-85	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sr-86	0.000019	0.000019	0.000015	0.000580	0.000000	0.000000
Sr-87	0.000014	0.000014	0.000010	0.000417	0.000000	0.000000
Sr-88	0.000166	0.000166	0.000124	0.004971	0.000000	0.000000
Y8-9	0.005000	0.005000	0.004000	0.001000	0.000000	0.000000
Zr-90	0.005071	0.005071	0.002028	0.019377	0.000000	0.000000
Zr-91	0.001118	0.001118	0.000447	0.004273	0.000000	0.000000
Zr-92	0.001728	0.001728	0.000691	0.006603	0.000000	0.000000
Zr-93	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Zr-94	0.001789	0.001789	0.000716	0.006837	0.000000	0.000000
Zr-95	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Zr-96	0.000294	0.000294	0.000118	0.001125	0.000000	0.000000
Nb-93	0.120000	7.000000	0.040000	0.011700	0.000000	0.000009
Mo-92	0.526062	0.540280	0.000064	0.001422	0.000000	0.000037
Mo-93	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Mo-94	0.335031	0.344086	0.000041	0.000905	0.000000	0.000024
Mo-95	0.582749	0.598499	0.000071	0.001575	0.000000	0.000041
Mo-96	0.616996	0.633672	0.000075	0.001668	0.000000	0.000044
Mo-97	0.356936	0.366583	0.000043	0.000965	0.000000	0.000025
Mo-98	0.911168	0.935794	0.000111	0.002463	0.000000	0.000065
Mo-99	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Mo-100	0.371058	0.381086	0.000045	0.001003	0.000000	0.000026
Tc-99	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ru-96	0.000000	0.000000	0.000000	0.000263	0.000000	0.000000
Ru-97	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ru-98	0.000000	0.000000	0.000000	0.000090	0.000000	0.000000
Ru-99	0.000000	0.000000	0.000000	0.000621	0.000000	0.000000
Ru-100	0.000000	0.000000	0.000000	0.000623	0.000000	0.000000
Ru-101	0.000000	0.000000	0.000000	0.000854	0.000000	0.000000
Ru-102	0.000000	0.000000	0.000000	0.001593	0.000000	0.000000
Ru-103	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ru-104	0.000000	0.000000	0.000000	0.000956	0.000000	0.000000
Rh-103	0.000000	0.000000	0.000000	0.000994	0.000000	0.000000
Pd-102	0.000000	0.000000	0.000000	0.000049	0.000000	0.000000
Pd-103	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pd-104	0.000000	0.000000	0.000000	0.000544	0.000000	0.000000
Pd-105	0.000000	0.000000	0.000000	0.001101	0.000000	0.000000
Pd-106	0.000000	0.000000	0.000000	0.001360	0.000000	0.000000
Pd-107	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pd-108	0.000000	0.000000	0.000000	0.001341	0.000000	0.000000
Pd-109	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pd-110	0.000000	0.000000	0.000000	0.000605	0.000000	0.000000
Ag-107	0.001028	0.001028	0.001028	0.000514	0.102753	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Ag-108	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ag-109	0.000972	0.000972	0.000972	0.000486	0.097247	0.000000
Cd-106	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
Cd-107	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cd-108	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
Cd-109	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cd-110	0.000000	0.000000	0.000000	0.000024	0.000000	0.000000
Cd-111	0.000000	0.000000	0.000000	0.000025	0.000000	0.000000
Cd-112	0.000000	0.000000	0.000000	0.000048	0.000000	0.000000
Cd-113	0.000000	0.000000	0.000000	0.000025	0.000000	0.000000
Cd-114	0.000000	0.000000	0.000000	0.000058	0.000000	0.000000
Cd-115	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Cd-116	0.000000	0.000000	0.000000	0.000015	0.000000	0.000000
In-113	0.000000	0.000000	0.000000	0.000003	0.000000	0.000000
In-114	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
In-115	0.000000	0.000000	0.000000	0.000066	0.000000	0.000000
Sn-112	0.000914	0.000914	0.000001	0.000027	0.000064	0.000000
Sn-113	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sn-114	0.000624	0.000624	0.000001	0.000019	0.000044	0.000000
Sn-115	0.000348	0.000348	0.000000	0.000010	0.000024	0.000000
Sn-116	0.014187	0.014187	0.000013	0.000426	0.000993	0.000001
Sn-117	0.007563	0.007563	0.000007	0.000227	0.000529	0.000001
Sn-118	0.024055	0.024055	0.000022	0.000722	0.001684	0.000002
Sn-119	0.008594	0.008594	0.000008	0.000258	0.000602	0.000001
Sn-120	0.032917	0.032917	0.000030	0.000988	0.002304	0.000002
Sn-121	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sn-122	0.004754	0.004754	0.000004	0.000143	0.000333	0.000000
Sn-123	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sn-124	0.006043	0.006043	0.000005	0.000181	0.000423	0.000000
Sb-121	0.056999	0.056999	0.009120	0.000137	0.003990	0.000004
Sb-122	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sb-123	0.043001	0.043001	0.006880	0.000103	0.003010	0.000003
Te-120	0.000000	0.000000	0.000000	0.000042	0.000000	0.000000
Te-121	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Te-122	0.000000	0.000000	0.000000	0.001175	0.000000	0.000000
Te-123	0.000000	0.000000	0.000000	0.000414	0.000000	0.000000
Te-124	0.000000	0.000000	0.000000	0.002208	0.000000	0.000000
Te-125	0.000000	0.000000	0.000000	0.003309	0.000000	0.000000
Te-126	0.000000	0.000000	0.000000	0.008867	0.000000	0.000000
Te-127	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Te-128	0.000000	0.000000	0.000000	0.015084	0.000000	0.000000
Te-129	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Te-130	0.000000	0.000000	0.000000	0.016368	0.000000	0.000000
I-127	0.000000	0.000000	0.000000	0.010000	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Xe-124	0.000000	0.000000	0.000000	0.000507	0.000000	0.000000
Xe-125	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Xe-126	0.000000	0.000000	0.000000	0.000464	0.000000	0.000000
Xe-127	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Xe-128	0.000000	0.000000	0.000000	0.009998	0.000000	0.000000
Xe-129	0.000000	0.000000	0.000000	0.139278	0.000000	0.000000
Xe-130	0.000000	0.000000	0.000000	0.021798	0.000000	0.000000
Xe-131	0.000000	0.000000	0.000000	0.113578	0.000000	0.000000
Xe-132	0.000000	0.000000	0.000000	0.145216	0.000000	0.000000
Xe-133	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Xe-134	0.000000	0.000000	0.000000	0.056994	0.000000	0.000000
Xe-135	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Xe-136	0.000000	0.000000	0.000000	0.049501	0.000000	0.000000
Cs-133	0.000300	0.000300	0.000000	0.000201	0.000000	0.000000
Ba-130	0.000501	0.000501	0.000802	0.000006	0.000000	0.000000
Ba-131	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ba-132	0.000485	0.000485	0.000776	0.000006	0.000000	0.000000
Ba-133	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ba-134	0.011799	0.011799	0.018878	0.000142	0.000000	0.000001
Ba-135	0.032384	0.032384	0.051815	0.000389	0.000000	0.000002
Ba-136	0.038844	0.038844	0.062150	0.000466	0.000000	0.000003
Ba-137	0.055978	0.055978	0.089564	0.000672	0.000000	0.000004
Ba-138	0.360009	0.360009	0.576014	0.004320	0.000000	0.000026
La-138	0.000000	0.000000	0.000000	0.000001	0.000000	0.000000
La-139	0.000200	0.000200	0.000200	0.000999	0.000000	0.000000
Ce-136	0.000684	0.000684	0.000000	0.000002	0.000000	0.000000
Ce-137	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ce-138	0.000913	0.000913	0.000000	0.000002	0.000000	0.000000
Ce-139	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ce-140	0.327583	0.327583	0.000000	0.000883	0.000000	0.000023
Ce-141	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ce-142	0.041821	0.041821	0.000000	0.000113	0.000000	0.000003
Pr-141	0.000000	0.000000	0.000000	0.001000	0.000000	0.000000
Nd-142	0.000000	0.000000	0.000000	0.001335	0.000000	0.000000
Nd-143	0.000000	0.000000	0.000000	0.000603	0.000000	0.000000
Nd-144	0.000000	0.000000	0.000000	0.001187	0.000000	0.000000
Nd-145	0.000000	0.000000	0.000000	0.000417	0.000000	0.000000
Nd-146	0.000000	0.000000	0.000000	0.000869	0.000000	0.000000
Nd-147	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Nd-148	0.000000	0.000000	0.000000	0.000295	0.000000	0.000000
Nd-149	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Nd-150	0.000000	0.000000	0.000000	0.000293	0.000000	0.000000
Pm-145	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sm-144	0.000003	0.000003	0.000000	0.000015	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Sm-145	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sm-146	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sm-147	0.000015	0.000015	0.000000	0.000073	0.000000	0.000000
Sm-148	0.000011	0.000011	0.000000	0.000056	0.000000	0.000000
Sm-149	0.000014	0.000014	0.000000	0.000068	0.000000	0.000000
Sm-150	0.000007	0.000007	0.000000	0.000037	0.000000	0.000000
Sm-151	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sm152	0.000027	0.000027	0.000000	0.000135	0.000000	0.000000
Sm-153	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sm-154	0.000023	0.000023	0.000000	0.000116	0.000000	0.000000
Eu-151	0.000009	0.000009	0.000095	0.000237	0.000000	0.000000
Eu-152	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Eu-153	0.000011	0.000011	0.000105	0.000263	0.000000	0.000000
Gd-152	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Gd-153	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Gd-154	0.000000	0.000000	0.000000	0.000004	0.000000	0.000000
Gd-155	0.000000	0.000000	0.000000	0.000029	0.000000	0.000000
Gd-156	0.000000	0.000000	0.000000	0.000041	0.000000	0.000000
Gd-157	0.000000	0.000000	0.000000	0.000031	0.000000	0.000000
Gd-158	0.000000	0.000000	0.000000	0.000050	0.000000	0.000000
Gd-159	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Gd-160	0.000000	0.000000	0.000000	0.000044	0.000000	0.000000
Tb-159	0.000470	0.000470	0.000000	0.001000	0.000000	0.000000
Dy-156	0.000001	0.000001	0.000000	0.000000	0.000000	0.000000
Dy-157	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Dy-158	0.000001	0.000001	0.000000	0.000000	0.000000	0.000000
Dy-159	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Dy-160	0.000023	0.000023	0.000000	0.000005	0.000000	0.000000
Dy-161	0.000187	0.000187	0.000000	0.000037	0.000000	0.000000
Dy-162	0.000254	0.000254	0.000000	0.000051	0.000000	0.000000
Dy-163	0.000250	0.000250	0.000000	0.000050	0.000000	0.000000
Dy-164	0.000284	0.000284	0.000000	0.000057	0.000000	0.000000
Ho-165	0.001000	0.001000	0.000000	0.001000	0.000000	0.000000
Er-162	0.000000	0.000000	0.000000	0.000001	0.000000	0.000000
Er-163	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Er-164	0.000000	0.000000	0.000000	0.000008	0.000000	0.000000
Er-165	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Er-166	0.000000	0.000000	0.000000	0.000167	0.000000	0.000000
Er-167	0.000000	0.000000	0.000000	0.000115	0.000000	0.000000
Er-168	0.000000	0.000000	0.000000	0.000135	0.000000	0.000000
Er-169	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Er-170	0.000000	0.000000	0.000000	0.000076	0.000000	0.000000
Tm-169	0.000000	0.000000	0.000000	0.000500	0.000000	0.000000
Yb-168	0.000003	0.000003	0.000001	0.000000	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Yb-169	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Yb-170	0.000060	0.000060	0.000030	0.000006	0.000000	0.000000
Yb-171	0.000283	0.000283	0.000141	0.000028	0.000000	0.000000
Yb-172	0.000435	0.000435	0.000218	0.000044	0.000000	0.000000
Yb-173	0.000322	0.000322	0.000161	0.000032	0.000000	0.000000
Yb-174	0.000639	0.000639	0.000320	0.000064	0.000000	0.000000
Yb-175	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Yb-176	0.000258	0.000258	0.000129	0.000026	0.000000	0.000000
Lu-175	0.000779	0.000779	0.000292	0.000649	0.000000	0.000000
Lu-176	0.000021	0.000021	0.000008	0.000017	0.000000	0.000000
Hf-174	0.000003	0.000003	0.000001	0.000001	0.000000	0.000000
Hf-175	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Hf-176	0.000103	0.000103	0.000031	0.000022	0.000000	0.000000
Hf-177	0.000369	0.000369	0.000111	0.000078	0.000000	0.000000
Hf-178	0.000544	0.000544	0.000163	0.000115	0.000000	0.000000
Hf-179	0.000273	0.000273	0.000082	0.000058	0.000000	0.000000
Hf-180	0.000708	0.000708	0.000212	0.000150	0.000000	0.000000
Ta-180M	0.000000	0.000955	0.000000	0.000000	0.000000	0.000000
Ta-181	0.000750	7.999045	0.000300	0.000433	0.000000	0.000000
W-180	0.000218	0.000218	0.000006	0.000090	0.000000	0.000000
W-181	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
W-182	0.048413	0.048413	0.001301	0.019837	0.000000	0.000003
W-183	0.026431	0.026431	0.000711	0.010830	0.000000	0.000002
W-184	0.057134	0.057134	0.001536	0.023411	0.000000	0.000004
W-185	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
W-186	0.053804	0.053804	0.001446	0.022046	0.000000	0.000004
Re-185	0.000000	0.000000	0.000000	0.000239	0.000000	0.000000
Re-186	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Re-187	0.000000	0.000000	0.000000	0.000405	0.000000	0.000000
Os-184	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Os-185	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Os-186	0.000000	0.000000	0.000000	0.000010	0.000000	0.000000
Os-187	0.000000	0.000000	0.000000	0.000010	0.000000	0.000000
Os-188	0.000000	0.000000	0.000000	0.000084	0.000000	0.000000
Os-189	0.000000	0.000000	0.000000	0.000102	0.000000	0.000000
Os-190	0.000000	0.000000	0.000000	0.000168	0.000000	0.000000
Os-191	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Os-192	0.000000	0.000000	0.000000	0.000264	0.000000	0.000000
Ir-191	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
Ir-192	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Ir-193	0.000000	0.000000	0.000000	0.000003	0.000000	0.000000
Pt-190	0.000000	0.000000	0.000000	0.000010	0.000000	0.000000
Pt-191	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pt-192	0.000000	0.000000	0.000000	0.000792	0.000000	0.000000

Concentration (g/kg)						
Isotope	**304 SS**	**347 SS**	**SA-212 Grade B Steel**	**Be**	**Pb**	**Ni**
Pt-193	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pt-194	0.000000	0.000000	0.000000	0.033323	0.000000	0.000000
Pt-195	0.000000	0.000000	0.000000	0.034411	0.000000	0.000000
Pt-196	0.000000	0.000000	0.000000	0.025889	0.000000	0.000000
Pt-197	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pt-198	0.000000	0.000000	0.000000	0.007443	0.000000	0.000000
Au-197	0.000000	0.000000	0.000000	0.024800	0.000000	0.000000
Hg-196	0.000000	0.000000	0.000000	0.000006	0.000000	0.000000
Hg-197	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Hg-198	0.000000	0.000000	0.000000	0.000402	0.000000	0.000000
Hg-199	0.000000	0.000000	0.000000	0.000683	0.000000	0.000000
Hg-200	0.000000	0.000000	0.000000	0.000938	0.000000	0.000000
Hg-201	0.000000	0.000000	0.000000	0.000539	0.000000	0.000000
Hg-202	0.000000	0.000000	0.000000	0.001222	0.000000	0.000000
Hg-203	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Hg-204	0.000000	0.000000	0.000000	0.000284	0.000000	0.000000
Tl-203	0.000000	0.000000	0.000000	0.007329	0.000000	0.000000
Tl-204	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Tl-205	0.000000	0.000000	0.000000	0.017671	0.000000	0.000000
Pb-204	0.000276	0.000276	0.000551	0.000014	13.765884	0.000000
Pb-205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Pb-206	0.004791	0.004791	0.009582	0.000240	239.293092	0.000000
Pb-207	0.004415	0.004415	0.008830	0.000221	220.499962	0.000000
Pb-208	0.010518	0.010518	0.021037	0.000526	525.340062	0.000001
Bi-209	0.000000	0.000000	0.000000	0.000000	0.050000	0.000000
Th-232	0.001000	0.001000	0.004000	0.000438	0.000000	0.000000
U-234	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
U-235	0.000014	0.000014	0.000014	0.000213	0.000000	0.000000
U-236	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
U-237	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
U-238	0.001986	0.001986	0.001986	0.029785	0.000000	0.000000

Appendix B

Radionuclide Half Lives of Interest

Appendix B

Radionuclide Half Lives of Interest

Table 1. Half Life Data used in the Computer Models.

Isotope	Half Life (yr)		Isotope	Half Life (yr)
H-3	1.23E+01		Th-228	1.91E+00
Be-10	1.60E+06		Th-229	7.30E+03
C-14	5.73E+03		Th-230	7.54E+04
Cl-36	3.01E+05		Th-232	1.40E+10
Mn-54	8.55E-01		Pa-231	3.28E+04
Ni-59	7.60E+04		U-232	7.00E+01
Co-60	5.27E+00		U-233	1.59E+05
Ni-63	1.00E+02		U-234	2.46E+05
Zn-65	6.68E-01		U-235	7.04E+08
Sr-90	2.91E+01		U-236	2.35E+07
Nb-94	2.00E+04		U-238	4.47E+09
Tc-99	2.13E+05		Np-237	2.14E+06
Ru-103	1.08E-01		Pu-238	8.77E+01
Ru-106	1.02E+00		Pu-239	2.41E+04
Ag-108m	1.30E+02		Pu-240	6.56E+03
Ag-110m	6.84E-01		Pu-241	1.44E+01
Sb-125	2.76E+00		Pu-242	3.75E+05
I-129	1.57E+07		Pu-244	8.00E+07
Cs-134	2.07E+00		Am-241	4.33E+02
Cs-137	3.02E+01		Am-243	7.37E+03
Ce-144	7.25E-01		Cm-243	2.91E+01
Eu-152	1.35E+01		Cm-244	1.81E+01
Eu-154	8.59E+00		Cm-245	8.50E+03
Pb-210	2.23E+01		Cm-246	4.76E+03
Ra-226	1.60E+03		Cm-247	1.56E+07
Ac-227	2.18E+01		Cm-248	3.48E+05

Appendix C

Material Impurities

Appendix C

Material Impurities

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Table 1. Best-estimate compositions for ATR in-core materials: Al-6061, Be, Hf, Inconel X-750, Inconel 600, SS304, and SS347/348
Key elements important in waste disposal issues are highlighted. One-sigma uncertainties are shown as ± % values.

Atomic Number	Element	2.70 g/cm³ Al-6061 (wt %)	1.85 g/cm³ Be (wt %)	13.3 g/cm³ Hf (wt %)	8.30 g/cm³ Inconel X-750 (wt %)	8.47 g/cm³ Inconel 600 (wt %)	8.02 g/cm³ SS304 (wt %)	8.02 g/cm³ SS347 or SS348 (wt %)
1	H	0.000001		0.0006	0.0001	0.0001	0.0007	
3	Li	0.0005	≤ 0.0003					
4	Be	0.00001	≥ 98.613					
5	B	0.001	0.0002		0.0043		0.0005	
6	C	0.001	0.10 ± 30%	0.0029	0.048 ± 16%	0.08	0.07 ± 14%	0.064
7	**N**	**0.0005**	**0.023 ± 25%**	**0.0031**	**0.0035**	**0.0055 (a)**	**0.047 ± 27%**	**0.036**
8	O	0.05	1.0 ± 27%	0.033	0.002	0.002	0.015	0.011
11	Na	0.006	≤ 0.0003				0.0037	0.0037
12	Mg	0.90	0.02 ± 60%					
13	Al	97.6	0.04 ± 20%	0.0027	0.70 ± 7%	1.0	0.01	
14	Si	0.65	0.03 ± 16%		0.14 ± 76%	0.2	0.60	0.64
15	P	0.001	≤ 0.005	0.01	0.0052	0.0052	0.03 ± 20%	0.025
16	S	0.002	≤ 0.001	0.01	0.0012	≤ 0.015	0.024 ± 10%	0.019
20	Ca	0.0011	≤ 0.002					
22	Ti	0.02	0.0055 ± 30%	≤ 0.025	2.6	≤ 2.75	0.05	0.01
23	V	0.02	0.0003 ± 30%				0.05	0.04
24	Cr	0.06 (600 ppm)	0.0090 ± 14%	≤ 0.002	15.34 ± 2%	15.5	18.8 ± 2%	18.0
25	Mn	0.04	0.0080 ± 30%	0.01	0.11 ± 62%	0.5	1.41 ± 26%	1.64
26	Fe	0.22	0.100 ± 34%	0.0089	7.8 ± 7%	8.0	69.0	68.0
27	**Co**	**≤ 0.0002**	**0.0008 ± 38%**	**0.0005**	**0.04 ± 57%**	**≤ 1.0**	**0.17 ± 50%**	**≤ 0.10 (b)**
28	**Ni**	**0.007 ± 20%**	**0.0130 ± 40%**	**≤ 0.0025**	**72.0 ± 1%**	**72.0**	**9.0 ± 8%**	**10.0**
29	Cu	0.25	0.0050 ± 46%	≤ 0.0026	0.09 ± 150%	0.2	0.25 ± 60%	0.14
30	Zn	0.02	≤ 0.0010				0.01	
31	Ga	0.02	≤ 0.0005				0.045	
33	As	?	≤ 0.0025				0.01	
34	Se	?	≤ 0.0005				0.02	
38	Sr	0.00001	≤ 0.0006				0.00002	
40	Zr	0.02	0.0040 ± 32%	1.6			≤ 0.01	
41	**Nb**	**0.0006**	**0.000022**	**≤ 0.0050**	**0.97± 9%**	**≤ 1.2**	**0.012 ± 67%**	**0.87**
42	Mo	0.0001	≤ 0.0010	0.001	≤0.04	≤ 0.04	0.37 ± 43%	0.38
48	Cd	0.0001	≤ 0.0002					
50	Sn	0.0024	≤ 0.0003				0.01	
51	Sb	0.01	≤ 0.0015				0.01	
72	Hf	≤0.05	0.00005 ± 44%	98.26				
73	Ta	≤0.05	0.0010	≤ 0.01	0.01			≤ 0.10
74	W		≤ 0.0025	0.015				
82	Pb	0.0006 (6 ppm)	≤ 0.0020				0.002	0.002
92	U		0.0060 ± 40%	0.001				
	Total =	100.004142	100.000072	100.0058	99.9577	102.4978	100.25992	100.0807

a. Nitrogen concentration in Inconel 600 samples averaged 0.0055.
b. Applies to SS348 obtained under Spec. No. E-568642 Rev. 12. The normal SS348 limit for Co is 0.20 wt%.

Appendix D

An MCNP Model of the Engineering Test Reactor

Appendix D

An MCNP Model of the Engineering Test Reactor

Background

The Engineering Test Reactor (ETR) was completed in 1957 to provide improved materials testing capability over the Materials Testing Reactor (MTR) which was built in 1952. The ETR design provided a very flexible core configuration based on a 10 x 10 square lattice. There were provisions for 9 in-pile tubes or loops (IPT) in the core with another 8 locations in the aluminum reflector area. Capsule irradiation facilities could be placed almost anywhere. There are accommodations in the core for 3 inch, 6 inch, and 9 inch IPT's. The reflector region accommodates 3 inch and 6 inch IPT's.

The fuel in the ETR was aluminum clad, flat plate fuel. The fuel elements were about 3 inches square and 54 inches long with 19 fuel plates per element. The fuel plates were about 38 inches long with the meat being 36 inches long composed of a uranium-aluminum alloy enriched to 93.5% in U-235.

Control of the reactor was originally accomplished with 12 shim rods (called gray rods), 4 safety rods (called black rods), and 2 reg rods. The shim and safety rods had fuel followers which were similar to the fuel elements except that they were about 2.5 inches square and had only 16 fuel plates. The gray rods used a type A nickel for the poison while the black rods used boron enriched stainless steel. The reg rods used cadmium for the poison. In the early years of operation, it was determined that the reg rods did not have enough worth to be effective in fine tuning the power of the reactor. The reg rods were removed from the reactor and servo controls were placed on two of the gray rods so they could be used as reg rods. It was also decided to replace the boron enriched stainless steel section of the black control rods with cadmium (later, these rod were replaced with those made of hafnium).

The active core was surrounded on four sides by a beryllium reflector made of stacks of beryllium bricks. The beryllium reflector was about 4.5 inches thick and contained many holes for placement of capsule irradiation facilities. Outside of the beryllium reflector was an aluminum reflector which extended to the inner reactor tank wall. Between the inner and outer reactor tanks were 4 thermal shields made of 304 SS. The reactor tank was made of SA-212 carbon steel clad in 304 SS. The whole system is cooled with light water.

There was a lead thermal shield surrounding the external reactor tank which had stainless steel cooling coils encased in it. 8 feet of magnetite concrete comprised the biological shield around the entire structure.

MCNP Model

The model of the ETR was created for and run in MCNP4C[1]. The model consists of explicitly modeled components and homogenous mixtures in areas deemed appropriate. Dimensions of the model were based on text descriptions from Kaiser et. al.[2] and Phillips Petroleum Company[3] as well as various

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1. "MCNP4C: Monte Carlo N-Praticle Transport Code System," RSICC Code Package CCC-700, Code Contributor: Los Alamos National Laboratory, Los Alamos, New Mexico, March 2001.

2. L. L. Kaiser, R. L. Rolfe, B. J. Sneed, E. L. Wills, "Characterization of the Engineering Test Reactor Facility," EG&G Idaho, Inc., September 1982.

3. "Fundamentals in the Operation of Nuclear Test Reactors," Phillips Petroleum Company, Atomic energy Division.

drawings[4]. The core configuration modeled contained 49 fuel elements and all the IPT's filled with water. The explicitly modeled components include:

- Fuel plates
- In-Pile tubes
- Control rods
- Control rod guide tubes
- Beryllium reflector (simplified geometry)
- Aluminum reflector (simplified geometry)
- Internal tank (simplified geometry)
- Internal thermal shield (simplified geometry)
- External thermal shield (simplified geometry)
- Biological shield (simplified geometry).

The rest of the reactor components were modeled as homogenous mixtures of the major materials in the volume occupied by the component. A cross sectional view of the whole reactor through the vertical core center can be seen in Figure 1. A close up of the core can be seen in Figure 2. A cross sectional view through the horizontal centerline is shown in Figure 3.

4. Engineering Test Reactor drawings

- 400579, "Guide Tube Control Rod ETR"
- 126220, 55-4694-7, "Reactor Pressure Vessel Internal Thermal Shield"
- 126218, 55-4694-5, "Reactor Pressure Vessel Inner Reactor Tank"
- 126214, 55-4694-1, "Reactor Pressure Vessel Assembly"
- 101082, ETR-5528-MTR-642-M-771, "Beryllium Reflector Assembly"
- 101060, ETR-5528-MTR-642-M-726, "Regulating Rod Drive Assembly"
- 100963, ETR-5528-MTR-642-M-34, "Reactor Building External Thermal Shield Assembly + Sections"
- 021103, ETR-E-1724, "ETR Reac Cont SP Latch Cont Rod Gray Poison Sect Assy & Details"
- 020688, ETR-E-1390, "ETR Reac Cont SP Latch Cont Rod Cadmium Poison Sect Assy"
- 020624, ETR-E-1257, "ETR Reac Cont SP Latch Cont Rod Shock Sect Assy"
- 020126, ETR-D-1052, "ETR Reg Rod Cadmium Poison Sect Assy"

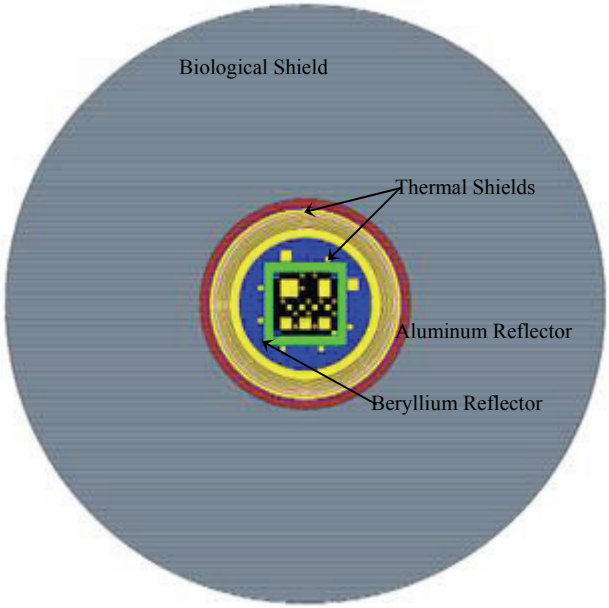

Figure 1: Reactor cross section showing the biological shield, thermal shields, and the core internals.

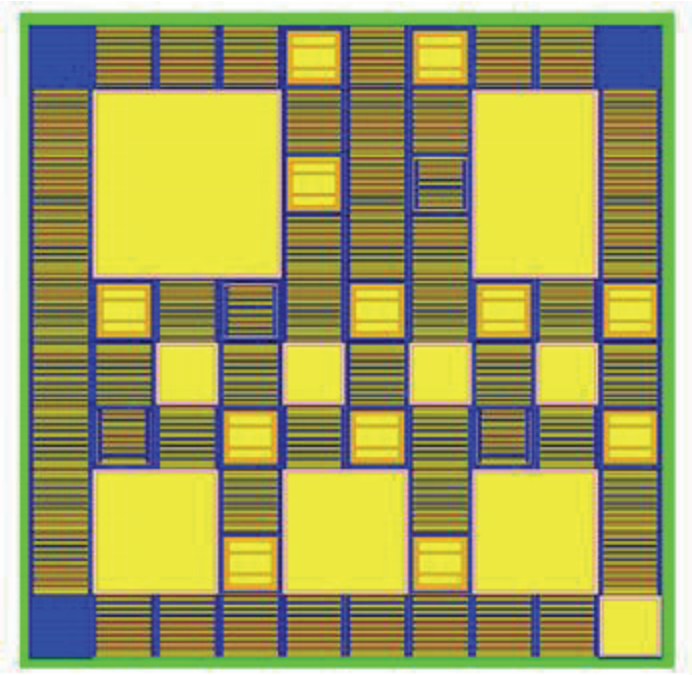

Figure 2: Reactor cross section showing a close-up of the active core.

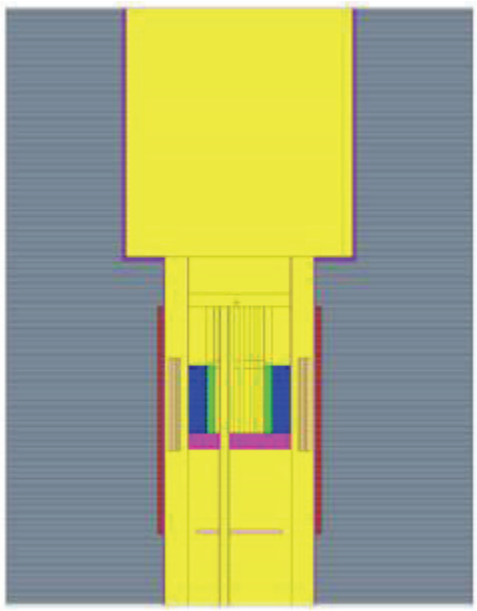

Figure 3: Vertical cross section of the reactor showing the biological shield, thermal shields, and the core internals.

In an attempt to model actual operation, the black rods were raised to their limit and the gray rods were set in a ganged fashion to a level resulting in a value of K_{eff} very close to 1.00. Flux tallies were defined in the components deemed important in the activation analysis.

Results

The results showed that any significant distance through water decreases the neutron flux to extremely low levels as would be expected. Components at distances from 4 to 5 feet above or below the core did not register any flux in the MCNP calculation. Around the core there is less water, but beryllium and aluminum are used as neutron reflectors to reflect many of the neutrons back to the core. This also decreases the flux significantly in the radial direction. The components of concern which registered a flux are listed in Table 1 below along with the neutron flux result from the MCNP run.

Table 1. ETR Component List and the Corresponding Neutron Flux.

Component		Material	Mass (gm)	Neutron Flux (nt/cm^2-sec/MW)
Gray Control Rods				
H5	Poison	Type A Nickel	1.284E+04	2.759E+12
J5	Poison	Type A Nickel	1.284E+04	2.609E+12
J7	Poison	Type A Nickel	1.284E+04	3.183E+12
E9	Poison	Type A Nickel	1.284E+04	8.870E+11
G9	Poison	Type A Nickel	1.284E+04	1.737E+12
I9	Poison	Type A Nickel	1.284E+04	3.191E+12
M9	Poison	Type A Nickel	1.284E+04	2.278E+12
E11	Poison	Type A Nickel	1.284E+04	7.432E+11
I11	Poison	Type A Nickel	1.284E+04	1.389E+12
K11	Poison	Type A Nickel	1.284E+04	1.668E+12
H13	Poison	Type A Nickel	1.284E+04	6.141E+11

Component		Material	Mass (gm)	Neutron Flux (nt/cm^2-sec/MW)
K13	Poison	Type A Nickel	1.284E+04	7.672E+11
Black Control Rods				
H7	Poison	Cadmium	1.021E+03	4.537E+12
	Stainless Steel	304 SS	8.312E+03	4.537E+12
K9	Poison	Cadmium	1.021E+03	2.997E+12
	Stainless Steel	304 SS	8.312E+03	2.997E+12
G11	Poison	Cadmium	1.021E+03	1.508E+12
	Stainless Steel	304 SS	8.312E+03	1.508E+12
M11	Poison	Cadmium	1.021E+03	3.222E+12
	Stainless Steel	304 SS	8.312E+03	3.222E+12
External Thermal Shield				
Whole Component		Lead	3.479E+07	7.057E+06
		SS-304	1.819E+05	7.057E+06
		Carbon Steel	2.581E+06	7.057E+06
Small External Tank				
Carbon Steel		SA 212 GR B	4.819E+06	4.200E+05
SS Cladding		SS-304	6.896E+05	2.866E+07
Internal Thermal Shields				
1st (innermost) Shield		304 SS	1.285E+06	2.695E+09
2nd Shield		304 SS	1.574E+06	5.563E+08
3rd Shield		304 SS	2.129E+06	1.984E+08
4th (outermost) Shield		304 SS	3.257E+06	7.407E+07
Inner Tank				
Whole Component		304 SS	2.769E+06	7.252E+10
Beryllium Reflector				
Whole Component		Beryllium	7.142E+05	2.518E+12
3 X 3 IPT's				
F10	Above Active Core	304 SS	1.042E+04	2.280E+09
	Active Core	304 SS	1.041E+04	4.112E+12
	Below Active Core	304 SS	1.354E+04	9.016E+10
N14	Above Active Core	304 SS	1.042E+04	1.961E+09
	Active Core	304 SS	1.041E+04	1.586E+12
	Below Active Core	304 SS	1.354E+04	1.867E+10
M13	Above Active Core	304 SS	1.042E+04	4.596E+09
	Active Core	304 SS	1.041E+04	3.655E+12
	Below Active Core	304 SS	1.354E+04	5.626E+10
6 X 6 IPT's				
C7	Above Active Core	304 SS	1.042E+04	3.804E+08
	Active Core	304 SS	3.172E+04	3.913E+11
	Below Active Core	304 SS	3.159E+04	1.394E+10
Upper Support Frame				
Whole Component		304 SS	2.197E+05	9.193E+04
Support Grid				
Whole Component		347 SS	2.277E+06	1.713E+11
I-Beams				
Whole Component		304 SS	1.082E+05	7.631E+05

A comparison of MCNP results with published data[5] can be made of the neutron flux in various experimental facilities. Since an exact comparison cannot be made due to possible core loading differences and operational differences, the following data can only be used as a general comparison. Core loading as well as control rod position will affect the results significantly. It is assumed that the values in the reference are for full power (175 MW) operation. It is also assumed that the flux in the reference is considered representative and not absolute. It can be seen from Table 2 that the MCNP result are consistent with the published values in the reference. It can be inferred from this comparison that the model is an accurate representation of the ETR reactor.

Table 2: A flux comparison in the experimental facilities of the ETR at 175 MW.

Facility		Thermal Flux (nt/cm2-s)	
		MCNP	IAEA
3 × 3	F10	3.299E+14	2.E+14
	H10	5.583E+14	to
	J10	6.079E+14	
	L10	5.429E+14	7.E+14
6 × 6	G13	2.247E+14	5.E+14
	J13	2.977E+14	
	M13	3.875E+14	
6 × 9	G7	6.069E+14	6.E+14
9 × 9	M7	5.427E+14	6.E+14
3 × 3	C13	3.41E+13	1.E+14
	G16	3.80E+13	to
	M16	4.96E+13	
	P7	1.03E+14	
	P12	1.20E+14	2.E+14
	F3	1.15E+14	
6 × 6	C7	4.74E+13	1.E+14
	M3	8.42E+13	

5. IAEA, 1964, *Directory of Nuclear Reactors, Volume V*, International Atomic Energy Agency.

Appendix E

ORIGEN2 Acitibity Values by Component

Isotope	Be Reflector (Be)	Grid Plate (304-SS)	I-Beams (304-SS)	C-7 In-Pile Tube (304-SS)	F-10In-Pile Tube (304-SS)	M-13 In-Pile Tube (304-SS)	N-14 In-Pile Tube (304-SS)	Upper Support Frame (304-SS)	Inner Tank (304-SS, Steel)	Internal Thermal Shields (304-SS)	External Thermal Shield (304-SS, Pb)	External Tank (304-SS, Steel)	Black Rod Poison & Shock Assys (Cd)	Gray Rod Poison & Shock Assys (Ni)
H-3	7.84E+04	1.13E+01	3.73E-06	3.51E-01	2.66E-01	2.67E-01	2.15E-01	9.12E-07	7.62E+00	2.26E-01	1.96E-03	4.54E-03	2.83E-01	3.32E-04
Be-10	8.88E-01	2.04E-06	6.49E-13	7.19E-08	2.00E-07	9.02E-08	4.62E-08	1.59E-13	1.39E-06	3.92E-08	4.34E-10	1.00E-09	4.65E-07	2.98E-06
C-14	7.06E+00	1.12E+01	3.11E-06	4.21E-01	1.29E+00	5.70E-01	2.79E-01	7.61E-07	7.57E+00	1.89E-01	1.71E-04	4.98E-04	2.98E+00	9.50E-04
Cl-36	8.63E-02	1.15E-01	2.47E-08	3.30E-03	9.31E-03	4.34E-03	2.17E-03	6.05E-09	5.97E-02	1.50E-03	3.85E-07	1.76E-06	1.89E-02	3.19E-05
Mn-54	2.18E-08	3.87E-06	7.39E-13	1.15E-07	3.90E-07	3.46E-07	1.50E-07	1.81E-13	1.80E-06	4.48E-08	2.45E-10	5.78E-10	8.89E-07	1.44E-08
Ni-59	6.40E-02	1.32E+01	1.74E-05	2.15E+00	4.15E+00	2.47E+00	1.37E+00	4.26E-06	4.05E+01	1.06E+00	2.71E-04	1.24E-03	5.17E+00	2.45E+02
Co-60	2.64E+00	1.31E+03	4.93E-04	7.10E+01	1.93E+02	1.38E+02	6.72E+01	1.21E-04	1.18E+03	2.99E+01	1.36E-02	4.85E-02	3.31E+02	1.37E+03
Ni-63	9.23E+00	1.51E+03	1.84E-03	2.45E+02	6.58E+02	3.26E+02	1.65E+02	4.51E-04	4.43E+03	1.12E+02	3.01E-02	1.32E-01	1.21E+03	4.89E+04
Zn-65	1.02E-10	9.15E-11	1.83E-17	3.12E-12	1.59E-11	1.10E-11	4.22E-12	4.46E-18	4.65E-11	1.11E-12	6.60E-15	3.29E-15	5.61E-11	7.66E-11
Sr-90	1.79E+00	1.16E-01	8.16E-09	3.24E-03	1.48E-02	6.46E-03	2.60E-03	2.00E-09	4.24E-02	5.01E-04	1.99E-06	4.78E-06	3.09E-02	7.77E-06
Nb-94	1.95E-02	1.13E+01	4.23E-08	5.60E-03	1.51E-02	7.25E-03	3.67E-03	1.03E-08	1.02E-01	2.56E-03	3.77E-06	1.00E-05	2.87E-02	7.72E-06
Tc-99	1.31E-03	7.65E-03	1.68E-09	2.15E-04	5.36E-04	2.68E-04	1.40E-04	4.10E-10	3.93E-03	1.01E-04	2.68E-08	1.21E-07	9.05E-04	2.54E-07
Ru-106	7.30E-07	9.17E-09	4.14E-17	2.88E-10	1.10E-09	1.10E-09	4.28E-10	1.01E-17	3.04E-09	3.43E-12	9.84E-15	2.37E-14	1.77E-09	3.98E-13
Ag-108m	8.33E-02	1.55E-01	3.37E-08	4.49E-03	1.23E-02	5.97E-03	3.01E-03	8.24E-09	8.11E-02	2.04E-03	1.00E-02	1.91E-05	2.20E-01	6.29E-06
Ag-110m	6.21E-11	2.92E-11	8.35E-18	9.95E-13	7.76E-13	1.82E-12	1.16E-12	2.04E-18	1.79E-11	5.06E-13	2.49E-12	4.74E-15	5.87E-11	9.30E-17
Sb-125	1.64E-03	6.79E-03	1.44E-09	2.22E-04	7.80E-04	5.91E-04	2.58E-04	3.53E-10	3.49E-03	8.74E-05	3.23E-07	1.03E-07	1.87E-03	3.60E-07
I-129	9.74E-06	2.26E-07	5.17E-15	6.11E-09	2.84E-08	1.20E-08	4.74E-09	1.27E-15	7.22E-08	3.28E-10	1.23E-12	2.96E-12	5.27E-08	1.45E-11
Cs-134	5.55E-03	7.78E-04	1.80E-10	2.57E-05	5.93E-05	6.07E-05	3.03E-05	4.39E-11	4.19E-04	1.09E-05	2.79E-09	1.28E-08	7.68E-05	1.98E-08
Cs-137	5.99E+00	2.40E-01	8.87E-09	6.64E-03	3.24E-02	1.41E-02	5.47E-03	2.17E-09	7.98E-02	5.53E-04	2.15E-06	5.16E-06	6.63E-02	1.68E-05
Ce-144	5.23E-09	8.83E-11	3.38E-18	2.80E-12	1.04E-11	1.03E-11	4.07E-12	8.26E-19	3.23E-11	2.12E-13	8.25E-16	1.98E-15	1.75E-11	3.87E-15
Eu-152	3.64E-02	8.91E-02	6.55E-07	3.73E-03	1.61E-05	2.25E-04	1.34E-03	1.60E-07	2.58E-01	3.90E-02	1.46E-03	3.30E-03	1.26E-05	4.18E-09
Eu-154	2.14E+00	2.15E-01	3.74E-08	6.54E-03	4.97E-03	7.56E-03	5.07E-03	9.15E-09	1.05E-01	2.27E-03	8.31E-05	1.89E-04	2.35E-03	8.79E-07
Pb-210	3.82E-11	3.96E-11	1.04E-13	9.83E-13	1.08E-11	2.21E-12	6.23E-13	2.10E-13	1.39E-11	8.01E-12	2.65E-12	5.28E-12	4.14E-11	9.00E-15
Ra-226	5.34E-11	9.71E-11	3.00E-13	2.47E-12	9.33E-12	3.36E-12	1.43E-12	6.09E-13	3.71E-11	2.31E-11	7.66E-12	1.53E-11	1.44E-11	4.79E-15
Ac-227	3.01E-07	1.21E-06	1.88E-12	3.53E-08	3.78E-08	3.03E-08	2.03E-08	3.22E-12	7.24E-07	2.03E-08	3.41E-10	7.70E-10	2.95E-08	1.10E-11
Th-228	1.50E-04	1.51E-04	1.18E-08	3.96E-06	2.74E-05	1.08E-05	3.49E-06	2.39E-08	3.80E-05	9.06E-07	1.14E-06	2.17E-06	3.84E-05	1.21E-08

Isotope	Be Reflector (Be)	Grid Plate (304-SS)	I-Beams (304-SS)	C-7 In-Pile Tube (304-SS)	F-10In-Pile Tube (304-SS)	M-13 In-Pile Tube (304-SS)	N-14 In-Pile Tube (304-SS)	Upper Support Frame (304-SS)	Inner Tank (304-SS, Steel)	Internal Thermal Shields (304-SS)	External Thermal Shield (304-SS, Pb)	External Tank (304-SS, Steel)	Black Rod Poison & Shock Assys (Cd)	Gray Rod Poison & Shock Assys (Ni)
Th-229	2.51E-07	1.45E-06	5.44E-13	4.26E-08	3.01E-08	2.71E-08	2.17E-08	1.33E-13	9.81E-07	3.04E-08	4.89E-10	1.12E-09	2.55E-08	9.28E-12
Th-230	7.79E-09	9.01E-09	3.03E-11	2.35E-10	9.11E-10	3.87E-10	1.56E-10	6.15E-11	3.32E-09	2.32E-09	7.74E-10	1.54E-09	1.31E-09	4.20E-13
Th-232	3.09E-08	2.42E-07	1.19E-08	7.88E-09	3.16E-09	3.49E-09	3.63E-09	2.41E-08	3.00E-07	9.05E-07	1.15E-06	2.19E-06	2.38E-09	8.70E-13
Pa-231	4.80E-07	1.75E-06	3.73E-12	5.16E-08	5.70E-08	4.71E-08	3.12E-08	6.71E-12	1.04E-06	2.92E-08	5.16E-10	1.16E-09	4.61E-08	1.67E-11
U-232	1.46E-04	1.46E-04	5.95E-16	3.85E-06	2.67E-05	1.05E-05	3.39E-06	1.07E-16	3.67E-05	8.51E-09	1.57E-12	4.32E-12	3.74E-05	1.18E-08
U-233	8.31E-05	4.02E-04	1.52E-10	1.22E-05	8.41E-06	8.64E-06	6.89E-06	3.72E-11	2.74E-04	8.53E-06	1.37E-07	3.13E-07	6.63E-06	2.37E-09
U-234	3.27E-05	1.71E-05	7.32E-08	4.61E-07	1.85E-06	1.01E-06	3.78E-07	1.49E-07	5.89E-06	5.57E-06	1.87E-06	3.73E-06	2.26E-06	6.86E-10
U-235	9.08E-09	2.40E-08	3.33E-09	8.74E-10	1.45E-10	1.20E-10	2.80E-10	6.76E-09	5.37E-08	2.53E-07	8.50E-08	1.69E-07	2.02E-10	5.91E-14
U-236	1.31E-06	2.24E-07	7.91E-14	6.78E-09	5.36E-09	4.55E-09	3.75E-09	1.93E-14	1.54E-07	4.78E-09	1.87E-11	4.49E-11	9.00E-09	2.32E-12
U-238	5.72E-06	1.43E-06	7.23E-08	4.65E-08	1.58E-08	1.95E-08	2.12E-08	1.47E-07	1.80E-06	5.51E-06	1.85E-06	3.68E-06	9.01E-09	3.72E-12
Np-237	4.49E-06	4.26E-07	1.44E-14	1.13E-08	1.69E-08	1.37E-08	7.88E-09	3.52E-15	1.23E-07	8.61E-10	3.40E-12	8.17E-12	2.05E-08	5.92E-12
Pu-238	1.85E-01	1.03E-02	2.86E-16	2.21E-04	8.30E-04	4.88E-04	1.58E-04	8.44E-18	9.86E-04	1.32E-08	6.23E-13	1.81E-12	5.49E-04	2.07E-07
Pu-239	3.01E-02	6.64E-03	3.84E-09	2.09E-04	8.36E-05	1.02E-04	1.04E-04	9.39E-10	5.75E-03	2.27E-04	9.06E-07	2.18E-06	4.78E-05	1.97E-08
Pu240	4.31E-02	6.20E-03	2.31E-14	1.81E-04	1.57E-04	1.35E-04	1.10E-04	6.80E-16	2.86E-03	1.09E-06	5.04E-11	1.46E-10	1.98E-04	6.27E-08
Pu-241	3.90E+00	3.06E-01	6.65E-18	8.37E-03	1.06E-02	1.15E-02	6.93E-03	2.36E-20	7.03E-02	2.51E-07	1.34E-13	4.70E-13	8.51E-03	2.95E-06
Pu-242	6.57E-04	1.18E-05	8.63E-28	2.75E-07	3.10E-06	1.41E-06	3.36E-07	3.69E-31	9.83E-07	2.59E-14	1.61E-22	6.81E-22	2.88E-06	1.07E-09
Pu-244	6.05E-10	2.25E-13	0.00E+00	4.35E-15	3.88E-12	4.44E-13	1.81E-14	0.00E+00	2.97E-15	4.97E-27	4.20E-39	2.58E-38	2.63E-11	4.15E-15
Am-241	3.79E-01	3.92E-02	8.53E-19	1.04E-03	1.12E-03	1.22E-03	7.70E-04	3.03E-21	9.04E-03	3.21E-08	1.72E-14	6.03E-14	7.79E-04	2.91E-07
Am-243	6.44E-03	3.61E-05	1.14E-32	7.38E-07	4.05E-05	1.07E-05	1.28E-06	5.84E-37	1.25E-06	2.71E-16	1.96E-26	1.00E-25	4.54E-05	1.64E-08
CM-243	1.15E-03	3.37E-05	1.43E-32	7.10E-07	8.22E-06	3.99E-06	8.18E-07	7.37E-37	1.40E-06	3.41E-16	2.47E-26	1.26E-25	3.72E-06	1.84E-09
CM-244	7.27E-01	7.77E-04	9.30E-37	1.40E-05	8.16E-03	7.83E-04	3.85E-05	0.00E+00	1.05E-05	1.77E-17	1.49E-29	9.18E-29	2.52E-02	6.49E-06
CM-245	1.36E-04	8.26E-08	0.00E+00	1.36E-09	1.91E-06	1.37E-07	4.58E-09	0.00E+00	5.52E-10	8.83E-24	8.66E-38	6.42E-37	6.13E-06	1.62E-09
CM-246	1.14E-04	1.33E-08	0.00E+00	1.90E-10	3.23E-06	7.40E-08	9.90E-10	0.00E+00	3.43E-11	4.27E-27	1.07E-43	3.71E-42	4.21E-05	6.82E-09
CM-247	5.11E-10	1.55E-14	0.00E+00	1.95E-16	2.36E-11	2.37E-13	1.47E-15	0.00E+00	1.63E-17	1.64E-35	0.00E+00	0.00E+00	5.81E-10	7.98E-14
CM-248	2.39E-09	1.69E-14	0.00E+00	1.86E-16	2.14E-10	7.59E-13	2.06E-15	0.00E+00	7.08E-18	5.70E-38	0.00E+00	0.00E+00	1.75E-08	1.61E-12