AN ABSTRACT OF THE DISSERTATION OF

Seung-Hyuk Baik for the degree of Doctor of Philosophy in Nuclear Engineering presented on March 4 1999.

Title: Feasibility Study on the Medical Isotopes Production with Solution Target Using OSTR: ^{99}Mo and Related Isotopes

Abstract approved: Redacted for privacy

Jack F. Higginbotham

Molybdenum-99 (^{99}Mo) is the parent nuclide of Technetium-99m (^{99m}Tc), a radioisotope which is widely used in nuclear medicine. ^{99}Mo is produced from the fission of ^{235}U or the irradiation of ^{98}Mo. This study shows the feasibility of the using an 'aqueous homogeneous uranium solution target' for the production of a medical isotope, ^{99}Mo. Some of the advantages that the solution target has over a solid target include the inherent reactor safety features offered by large negative temperature and power reactivity coefficients, the fabrication convenience, the straightforward extraction process, and a low volume of waste generated.

To evaluate the core configuration and the production rate of ^{99}Mo, a three-dimensional model of the Oregon State University TRIGA Reactor (OSTR) core was developed for use with the Monte Carlo N-Particle Transport Code (MCNP)

and then verified by comparing with the measured values. Two values are in good agreement within one percent in the $k_{effective}$ values calculated.

Two types of solution targets are analyzed for the OSTR. The first one has the same outer-dimensions as an OSTR fuel element but is filled with a uranium solution. The other is the continuous flow target system (CFTS) like solution fuel reactors. Uranyl nitrate and uranyl sulfate solutions enriched to 20 % or 93 % are investigated as a target material without raising any safety concern to the OSTR operation. A seven-day irradiation of ten tube-type-93 % enriched uranyl nitrate solution targets would produce 43 % of the ^{99}Mo required in the US for one week. The CFTS would generate 31 % of the required ^{99}Mo in a 7-day cycle. The conceptual chemical extraction processes for irradiated solution targets are developed. This work also includes an analysis of nuclear safety issues such as the radiolytic gas, thermal hydraulics, the waste, and the radiological impacts of an accident.

The production of ^{99}Mo in the OSTR with the uranium solution is technically feasible as demonstrated in this work. The use of the uranium solution would increase the production efficiency by good neutron economy, reduction of the processing period, through the reuse of uranium, and by minimizing the waste generation.

Feasibility Study on the Medical Isotopes Production with Solution Target Using OSTR: ^{99}Mo and Related Isotopes

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Seung-Hyuk Baik, Author

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Dedicated to my father,

Nam-Jin Baik, Korean Army Colonel, Retired, with love and respect.

Feasibility Study on the Medical Isotopes Production with Solution Target Using OSTR: ^{99}Mo and Related Isotopes

CHAPTER 1
INTRODUCTION

1.1 Nuclear Medicine

In the practice of nuclear medicine radiation is used to provide information about the function of specific organs and patient's whole body, and can also be used to treat diseases such as tumors [1]. Nuclear medicine is divided into two major areas: diagnostics and therapeutics. Both areas use radioisotopes which emit radiation from within the body where the isotopes are given by injection, inhalation or orally to a patient.

Diagnostic radiopharmaceutical agents provide valuable information of a patient's condition by imaging organ metabolism. The radiation from injected nuclear agent in the body will be detected, and converted into images with sophisticated instruments and equipment. A radiopharmaceutical is a physiologically active carrier to which a radioisotope is attached. The chemical or biological carriers are manufactured to migrate it to a particular part of human body. For example, calcium is a 'bone seeker', and iodine concentrates in thyroid gland [2]. The radioisotope attached to these compounds emits radiation so that the relevant organ and its functioning can be observed. The radiation imaging provides a view of the position and concentration of the radioisotope. Organ malfunction can be identified if the isotope is either partially taken up in the organ, or taken up in excess. A series of images, which is taken over a period of time, could show malfunction in the organ through an unusual pattern or rate of isotope movement [1].

Over 100 diagnostic radiopharmaceutical products are available in the United States. The largest number of these applications is cardiology, followed by oncology and neurology. A few radiopharmaceuticals have applications in other areas, such as infection imaging and nephrology [3]. The most useful radioisotope for diagnostic purposes is Technetium-99m (Tc-99m), a daughter isotope of Molybdenum-99 (Mo-99). Table 1.1 exhibits a selected list of medical isotopes commonly used in nuclear medicine diagnostics.

Table 1.1 Selected Radioisotopes Commonly Used in Nuclear Diagnostics in U.S., 1997 [3].

Isotope	**Application**	**Source**
Tc-99m	Cardiology	Reactor
Tl-201	Cardiology	Accelerator
I-131	Oncology	Reactor
Xe-133	Respiratory	Reactor
In-111	Neurology	Accelerator
Ga-67	Oncology	Accelerator
P-32	Oncology	Reactor

Nuclear physicians would use therapeutic radiopharmaceuticals to treat diseases by attacking only the affected cells. Over ninety nuclear therapy research trials are in progress in the United States. These trials are using several isotopes to combat many diseases, such as: colorectal cancer, heart disease, rheumatoid arthritis, and non-Hodgkin's lymphoma [3]. Although a large number of therapy trials using radioisotopes are in progress, the nuclear therapy modality is in its developing stages. In fact only four therapeutic radioisotopes have received FDA approval and currently are used in the United States [3]. The list of therapeutic isotopes in clinical trial in the U.S. is included in Table 1.2, and four commercialized radiopharmaceutical-based therapeutic applications are exhibited in Table 1.3 with the isotopes.

In the four applications listed in Table 1.3, only thyroid cancer radiopharmaceutical products have experienced unqualified success. Radiopharmaceutical products designed to combat thyroid-rated diseases carry a heavy dose of I-131. Since the thyroid gland is receptive to iodine, I-131 radioisotope is very effective in treating thyroid gland diseases. I-131 has also been successfully used in treating hyperthyroidism (over-active thyroid) [3].

In the United States, 200,000 patients per year suffer the severe and chronic bone metastases pain. Sr-89 and Sm-153 have some success in bone pain palliation. In Polycythemia rubra vera, an excess of red blood cells is produced in bone marrow, P-32 is used to control this excess [1].

Table 1.2 Radioisotopes Used in Nuclear Therapy Research (U.S.), 1997 [3]

Disease Indication	Radioisotope
Bone Pain Palliation	Sr-89, Sm-153, Sn-117m, Re-186, Ra-223, P-32, Sc-47
Bladder Cancer	Ta-182
Brain Tumor	Cf-252, Sm-153, Y-90, Au-198, Ir-192, I-131
Breast Cancer	Re-186, Y-90, Y-91, Ir-192, Re-188, P-32
Cervical Cancer	Cf-252
Colon Cancer	Y-91
Colorectal Tumors	Y-90, Cu-64
Gastrointestinal Adenocarcinoma	Y-90
Heart Disease	Ir-192, P-32, Lu-177
Hemophilia	Dy-165, Ho-166, P-32
Hodgkin's Disease	Y-90, Y-91, I-131
Hyperthyroidism	I-131
Leukemia	Y-90, Y-91, I-131, P-32, Sm-153, In-111, Bi-213
Liver Cancer	I-131, Y-90
Lymphoma	I-131, Y-90, Y-91
Melanoma	Cf-252, I-131
Multiple Myeloma	Sr-89
Non-Hodgkin's Disease	I-131, Y-90, Y-91
Optical Tumors	Sm-145, P-32
Ovarian Cancer	Re-188, Ir-192, Y-90, Au-198, P-32
Pancreatic Cancer	P-32
Polycythaemia Rubra Vera	P-32
Prostate Cancer	Re-186, I-125, Ir-192, Pd-103, I-131, Au-198, Sr-89, P-32
Pulmonary Fibrosis	Ga-64
Rheumatoid Arthritis	P-32, Dy-165, Ho-166, Re-186, Sm-153, Er-169, Au-199, W-188, Y-90
Small-Cell Lung Cancer	Y-90, Y-91
Thyroid Cancer	I-131, Re-188, I-125
Uterine Cancer	Ir-192, P-32

Table 1.3 Approved Indications and Therapeutic Isotopes Sold in U.S., 1997 [3]

Indication	Isotope
Thyroid cancer	I-131
Hyperthyroidism	I-131
Bone pain palliation	Sr-89/Sm-153
Polycythemia rubra vera	P-32

Diagnostic nuclear medicines concentrated mostly on bone scanning and cardiology applications in early years. This has altered as competition from other imaging modalities, which intruded into nuclear medicine diagnostics' area. Nuclear medicine diagnostics has expanded into applications where other imaging modalities were not as effective, such as oncology, neurology, and infection imaging [3]. Experts believe that oncology is a very promising area.

Many trials have been conducted using a large number of radioisotopes in treating diseases. Some radiopharmaceutical companies are trying to design a "smart bullet" to deliver therapeutic radiopharmaceutical drugs to disease sites without affecting healthy tissue. Once a smart bullet is discovered, this treatment modality can be expected to expand rapidly.

Ninety percent of radioisotopes currently utilized by nuclear medicine in the United States come from overseas. One of the most utilized and important of radioisotope in nuclear medicine is Technicium-99m (Tc-99m), a daughter isotope of Molybdenum-99 (Mo-99). The largest supplier of Mo-99 to the United States nuclear medicine diagnostics market is MDS Nordion, located near Ottawa, Canada. It supplies 60 % of Mo-99 to United State. Labor strikes at the National Research Universal (NRU) reactor in Chalk River, Canada, which owned by the Atomic Energy of Canada Limited (AECL), and is operated by Nordion caused the shortage of Mo-99 in the United States medical community in 1997 [4]. Some hospitals had experienced the interruptions of the patient's examinations and delaying certain nuclear medicine studies using Tc-99m. This incident raises the issue of ensuring a stable and continuous supply of the medical isotopes. Thus the growth of nuclear medicine fields might be hindered by the unreliable supply of radioisotopes with the most promising future in nuclear medicine..

1.2 Characteristics of Mo-99/Tc-99m

The most common and import radioisotope in nuclear medicine is Tc-99m. Tc-99m is a decay product of Mo-99. Approximately 38,000 diagnostic procedures involving radioactive isotopes are performed each day in the United Stated with most of these procedures using Tc-99m [5].

1.2.1 Physical Properties of Tc-99m

Technetium, number 43 in the periodic table, was the first element to be produced artificially. Nineteen isotopes of technetium, with atomic masses ranging from 90 to 108, are known. Tc-99m was suggested by Richards for medical applications in 1960 [6] and was first used in humans by Harper, Andrus and Lathrop in 1962 [7].

According to the decay scheme exhibited in Figure 1.1 [8], Tc-99m decays by isomeric transition. The principle gamma-emission associated with the transition to ground state of Tc-99m is γ_2, 140 KeV photons which occurs at 90 % photon yield. The half –life of Tc-99m is 6.02 hours. Figure 1.2 shows the decay sequences of Mo-99 to Ru-99 with respective half-lives and branching fractions [9].

1.2.2 The Kinetics of Mo-99 and Tc-99m system

From Figure 1.2, the quantities (atoms or units of radioactivity) of Mo-99 and Tc-99m present at any time are expressed with certain mathematical formulas:

$$\frac{dN_1(t)}{dt} = -\lambda_1 N_1(t) \tag{1.1}$$

$$\frac{dN_2(t)}{dt} = k_1\lambda_1 N_1(t) - \lambda_2 N_2(t) \tag{1.2}$$

or

$$N_1(t) = N_1(0)\, e^{-\lambda_1 t} \tag{1.3}$$

$$N_2(t) = \frac{k_1\lambda_1}{\lambda_2 - \lambda_1} N_1(0)\,(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + N_2(0)\, e^{-\lambda_2 t} \tag{1.4}$$

where $N_1(t)$ = Number of Mo-99 atoms at time t,

λ_1 = Decay constant of Mo-99 (0.0105 sec^{-1}),

k_1 = Fraction of branching decay (0.875),

$N_2(t)$ = Number of Tc-99m atoms at time t, and

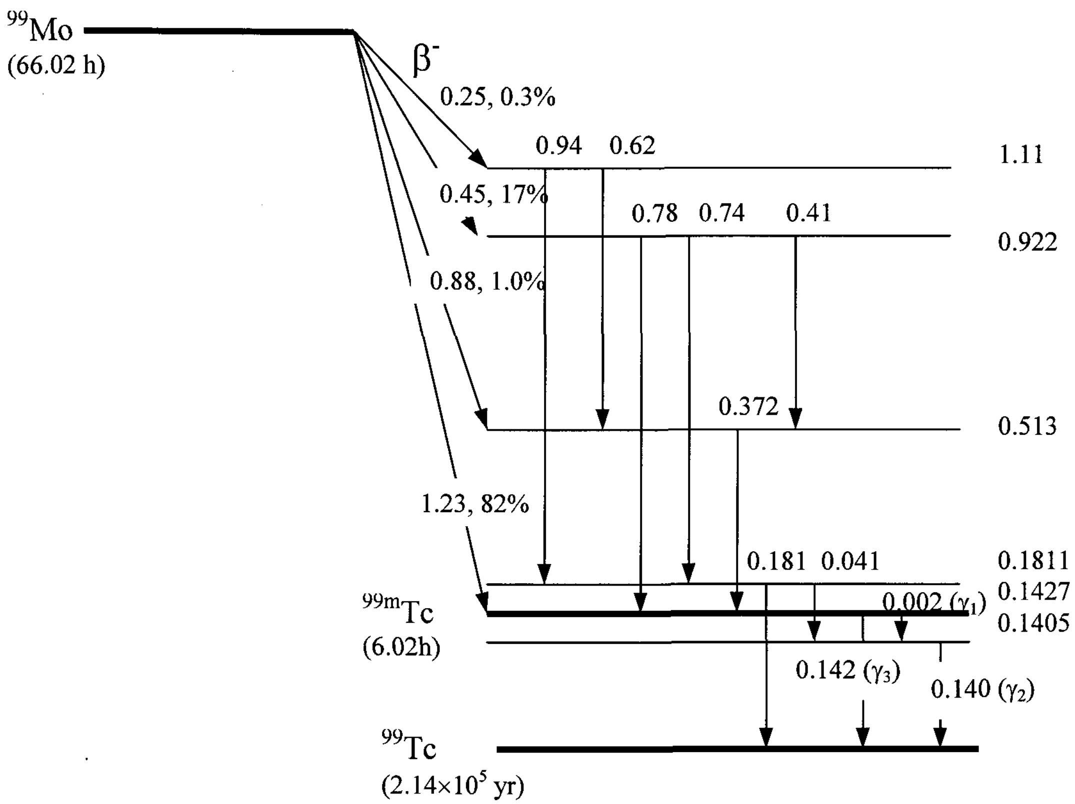

Figure 1.1 Principal Decay Scheme of Mo-99 and Tc-99m (Unit of energy = MeV) [8]

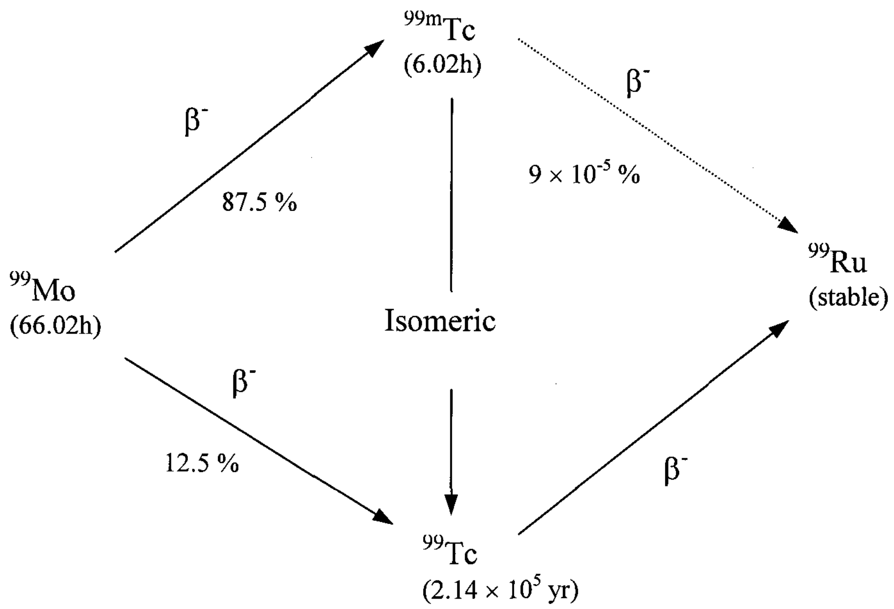

Figure 1.2 Decay Sequences of Mo-99 to Ru-99 [9]

λ_2 = Decay constant of Tc-99m (0.1151 sec^{-1}).

Converting Equation 1.3 and 1.4 from number of atoms to activity we obtain

$$A_1(t) = A_1(0)\, e^{-\lambda_1 t} \qquad (1.5)$$

where $A_1(t)$ = activity of Mo-99 at time t, and

$$A_2(t) = \frac{k_1 \lambda_2}{\lambda_2 - \lambda_1} A_1(0)\,(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + A_2(0)\, e^{-\lambda_2 t} \qquad (1.6)$$

where $A_2(t)$ = activity of Tc-99m at time t.

If the ratio of λ_1 and λ_2 is larger, say 0.01-1 [9], the parent-daughter system enters into a state of transient equilibrium in which

1. The daughter activity will achieve a value greater than that of the parent (assuming a decay scheme with no branching);
2. The daughter activity will reach a maximum value after which it will decline; and
3. Equilibrium between the activity of the parent and daughter species will be achieved where the rate of decay of the daughter is equal to its rate of formation from the parent. The daughter will appear to decay according to the half-life of the parent.

For Mo-99 and Tc-99m the values of λ_1 and λ_2 are such that a state of transient equilibrium will be achieved after the Tc-99m activity has gone through a maximum value. However, the activity of Tc-99m will never exceed the Mo-99 activity because only 87.5 % of the disintegration of Mo-99 results in Tc-99m.

After substituting the appropriate values to Equation 1.6, the growth of Tc-99m from the decay of Mo-99 can be calculated from

$$A_2(t) = 0.963\, A_1(0)\, (e^{-0.0105t} - e^{-0.1151t}) + A_2(0)\, e^{-0.1151t} \qquad (1.7)$$

Putting $A_2(0) = 0$ at $t = 0$, and differentiating, the time at which the maximum activity of Tc-99m occurs can be obtained;

$$\frac{dA_2(t)}{dt} = -0.963\, A_1(0)\, (0.0105\, e^{-0.0105t} - 0.1151\, e^{-0.1151t}) \qquad (1.8)$$

At $t = t_{max}$, $\frac{dA_2(t)}{dt} = 0$, and hence

$$t_{max} = \frac{\ln(0.0105/0.1151)}{0.0105 - 0.1151}$$

$$=22.89 \text{ hours.}$$

The decay-growth curve for the Mo-99 – Tc-99m system is shown in Figure 1.3. The activity contribution of Tc-99 is not significant because of its very long half-life of 2.14×10^5 years; for instance, 1 curie of Mo-99 will produce only 4×10^{-8} curies of Tc-99 [9].

1.2.3 Technetium Radiopharmaceuticals

Several combined factors make Tc-99m a widely used radioisotope in nuclear medicine today [10]: (1) It can be chemically incorporated into a wide range of diagnostic pharmaceutical agents, permitting selectivity for various procedures. (2) The radiation emitted, while easily detected, is relatively low energy, thus reducing the radiation dose to the patient. (3) Its short half-life also contributes to minimization of dose. (4) Usable amounts of the parent Mo-99 and associated Tc-99m can be transported to the medical facility in small package. (5) Separation of the Tc-99m and incorporation into diagnostic agents is simple and direct. (6) The short half-lives of both Mo-99 and Tc-99m result in essentially no radiological waste problems at the use site. (7) Currently, Mo-99 is available on demand at reasonable cost.

The readily available form of Tc-99m in aqueous solution is pertechnetate ion (TcO_4^-), which is eluted from the Mo-99/Tc99-m generator. The only known stable Tc(VII) compound in aqueous solution is pertechnetate. However, in the presence of appropriate ligands and reducing agents, $^{99m}TcO_4^-$ may be reduced to give stable complexes in lower oxidation states (III or V in most cases). Many of these complexes are useful forms of radiopharmaceuticals [11].

Technetium radiopharmaceuticals can be conveniently classified into two categories: Technetium-tagged radiopharmaceuticals and Technetium-essential radiopharmaceuticals [11]. Technetium-tagged radiopharmaceuticals encompasses agents in which Tc-99m functions solely as a radiolabel. The normal biodistributon of such substances is essentially unchanged by the attached nuclide. Tc-99m simply allows external monitoring of the *in viro* distribution of tagged substance. Technetium-tagged radiopharmaceuticals are primarily large substances (e.g., red blood cells, colloids, proteins, microspheres, etc.). The binding of Tc-99m to such large systems causes relatively minor perturbations of the overall biological, chemical and physical properties of the substance. Technetium-essential radiopharmaceuticals contains those species whose distribution is largely

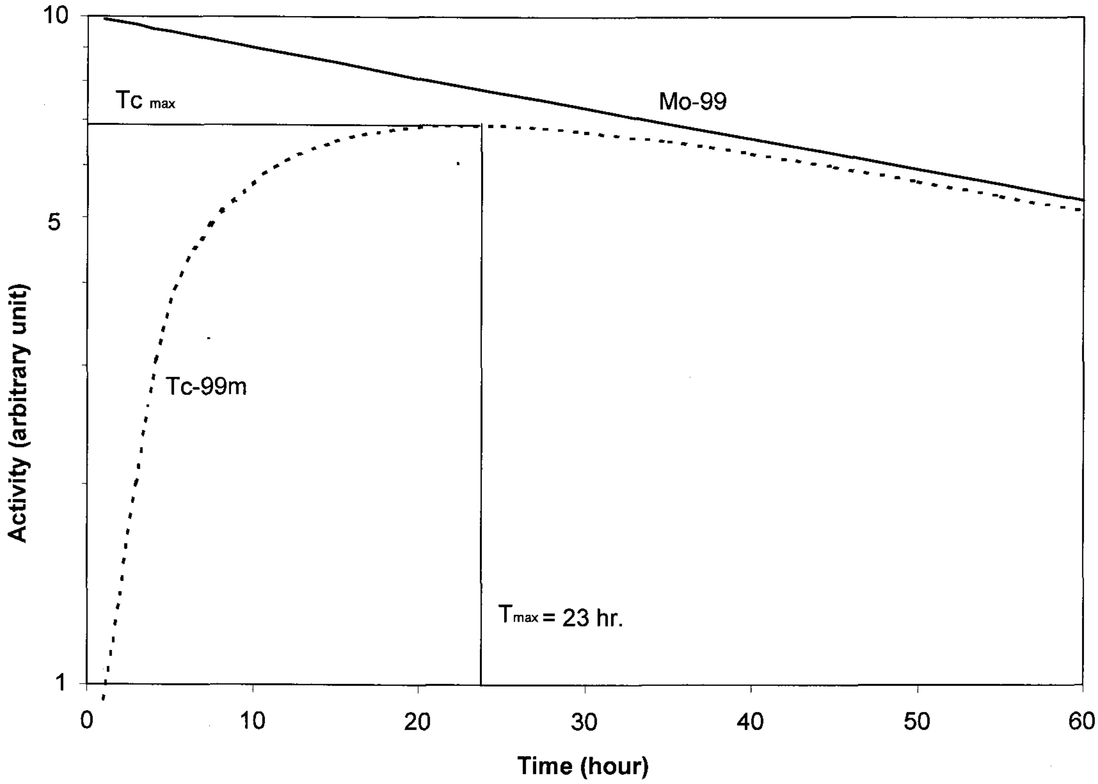

Figure 1.3 The Decay-Growth Curve of Mo-99/Tc-99m System

dependent on some physicochemical property of the Tc complex itself. When smaller molecules are labeled with Tc-99m (e.g., metabolic substances, drugs, low molecular-weight peptides, etc.) the biodistribution of radiopharmaceutical usually differs significantly from that of the starting molecules. Although this alteration in distribution has limited the predictive ability of the radiopharmaceutical chemist, many useful radiopharmaceuticals have been found, often by serendipity. Table 1.4 shows further subdivision of Technetium-radiopharmaceuticals.

Table 1.4 Tc-99m – Radiopharmaceuticals [11]

Technetium-tagged Radiopharmaceuticals	Technetium-essential Radiopharmaceuticals
1. Particles and colloids: Tc-macroaggregated albumin, Tc-albumin microspheres, Tc-albumin minimicrospheres, Tc-ferric hydroxide aggregates, Tc-sulfur colloid, Tc-antimony colloid, Tc-phytate	1. Kidney function agents: Tc-DTPA, Tc-EDTA, Tc-MIDA, Tc-citrate, Tc-DADS
2. Protein: Albumin, Streptokinase, Urokinase, Fibrinogen, Monoclonal antibodies	2. Kidney structure agents: Tc-gluconate, Tc-glucoheptonate, Tc-Fe-ascorbate, Tc-inulin, Tc-mannitol, Tc-dimercaptosuccinic acid
3. Cells: Erythrocytes, Leukocytes, Platelets, Lymphocytes	3. Heart-imaging agents: Tc-DIARS, Tc-DMPE, $Tc(CNR)_6^+$
4. Small molecules: Bone agents, e.g., polyphosphates, pyrophosphate, diphosphonates, iminodiphosphonates	4. Infarct-avid agents: Tc-pyrophosphate, Tc-glucoheptonate, Tc-tetracycline and Tc-HEDP
	5. Hepatobiliary agents: Tc-dihydrothioctic acid, Tc-HIDA, Tc-isomercaptobutyric acid, and Tc-pyridoxylideneglutamate

1.3 The Production of Molybdenum-99

Molybdenum-99 can be produced primarily in two essentially different techniques: one by uranium fission, the other by the neutron activation of molybdenum (see Figure 1.4). All of Mo-99 used in the U.S. is produced by fission, but neutron-capture material is still widely use in some countries. The specific activity of fission-produced material, the amount of Mo-99 reactivity per unit weight of molybdenum, is higher than that of neutron-capture Mo-99 by two to four orders of magnitude. However, the actual radioisotope used in the clinical procedure, Tc-99m, is the same, regardless of the production method of Mo-99 used.

1.3.1 Molybdenum-99 from the Fission of Uranium

Mo-99 is a product of the fission of uranium. The fission yield for this reaction is 6.1% and the irradiation of 1 g U-235 for 7 days in a neutron flux of 7×10^{13} n/cm^2/sec produces approximately 142 Ci Mo-99 [9]. Even though specific activity of Mo-99 produced by fission is higher than that from the (n, γ) reaction, it does not mean carrier free. Other molybdenum isotopes are also formed by the fission of uranium. The sources of other isotopes from fission are exhibited in Figure 1.5. These reactions reduce the specific activity of Mo-99 by an order of magnitude. A period of post-irradiation decay produces a further reduction in specific activity. Target used in the fission method is the highly enriched in 90 % or greater U-235.

The Brookhaven National Laboratory first developed Mo-99 extraction process from irradiated uranium [12]. In this process the target (93 % enriched U-235 alloyed with Al) was dissolved in 6 M nitric acid catalyzed by mercuric nitrate. Then, after the addition of tellurium carrier, the solution was passed through an alumina column that selectively absorbed the Mo-99 and the radiotellurium fission products. The uranium and the unabsorbed fission products were removed from the alumina by washing. The Mo-99 was then recovered from the column by elution with 1 M NH_4OH. An efficiency of approximately 70 %, for a product purity of 99.99 % Mo-99, was claimed for this process. To remove the trace radio-impurities, the Mo-99 was reabsorbed onto a strong anion exchange resin, washed and then eluted with 1.2 M HCl in a final purification step.

1.3.2 Neutron Activation of Molybdenum

Molybdeenum-99 may be produced by the irradiation of molybdenum-98 with neutrons. The cross-section of the $^{98}Mo\ (n,\gamma)\ ^{99}Mo$ reaction is small ($\sigma_{thermal}$ ~ 0.14 barns) and only a small portion of target is converted to Mo-99. The irradiation of natural molybdenum in a high flux reactor or the use of enriched Mo-98 can increase the specific activity. However, the resulting specific activity (~ 1Ci Mo-99/g) is much lower than that of the fission-produced Mo-99 [9].

The most frequently employed target materials are molybdenum trioxide (MoO_3) and molybdenum metal; both are suitable for use in high flux irradiation. Other molybdenum compounds have been used in lower neutron fluxes.

In chemical processing the irradiated molybdenum metal is dissolved in hydrogen peroxide. After reaction, the Mo-species is converted to molybdate by the addition of sodium hydroxide. This process is used commercially for the high purity Mo-99 from molybdenum metal [13].

The chemical processing of the irradiated molybdenum trioxide is very limited to dissolution in sodium, potassium, or ammonium hydroxide, followed by either acidification to pH 1.5 – 3 where the Mo-99 is destined for adsorption onto an alumina column, or adjustment of the excess alkalinity to produce the feed stock for the solvent extraction process [9]. When destined for use in a sublimation generator, the irradiated molybdenum trioxide requires no chemical processing after irradiation.

1.3.3 Mo-99 Production Method Choosing

The differences between the two type of production method are: the target materials, the complexities of the chemical processes, and the specific types of physical resources needed.

Molybdenum-99 production from the fission of U-235 requires elaborate processing facilities and considerable capital investment. The extreme caution must be taken to avoid contaminating the product with toxic fission products and transuranics (e.g., Pu-239). While the fission process generates large quantities of radioactive waste. It has a high specific activity (~ 10^4 Ci Mo-99/g Mo) [9].

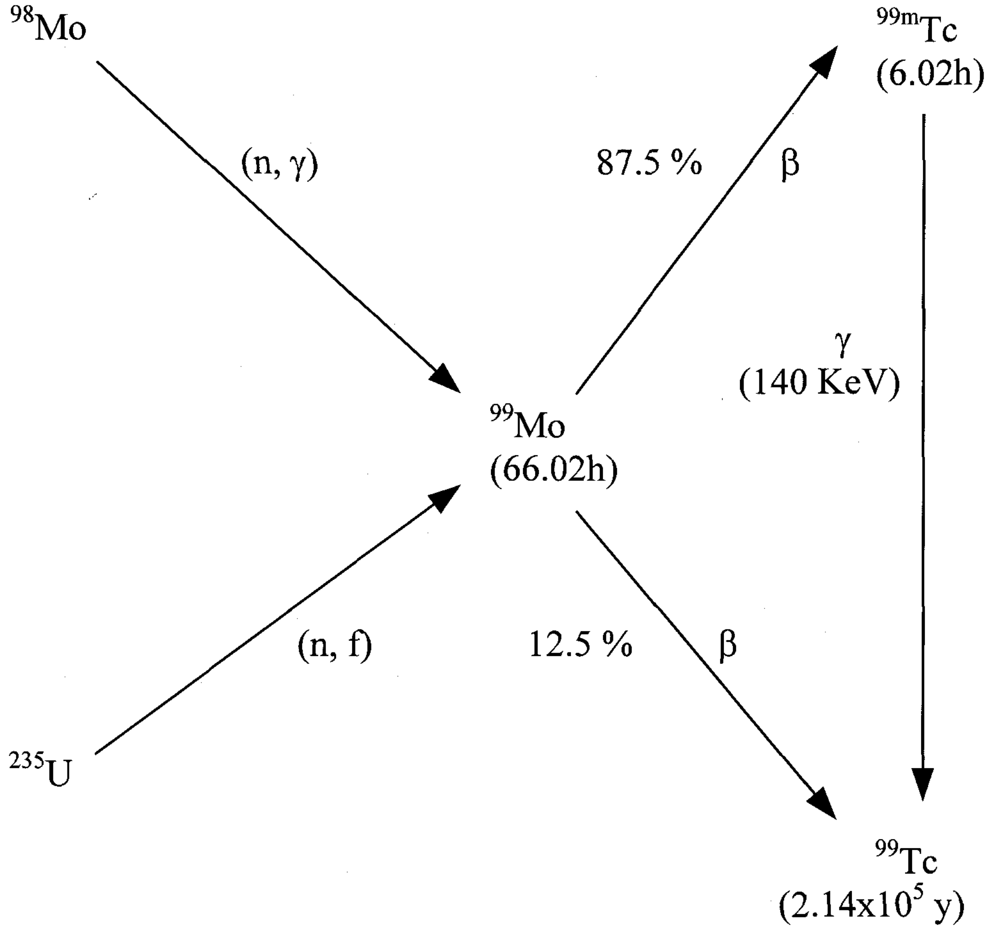

Figure 1.4 Fission and Capture based Mo-99 Production Method

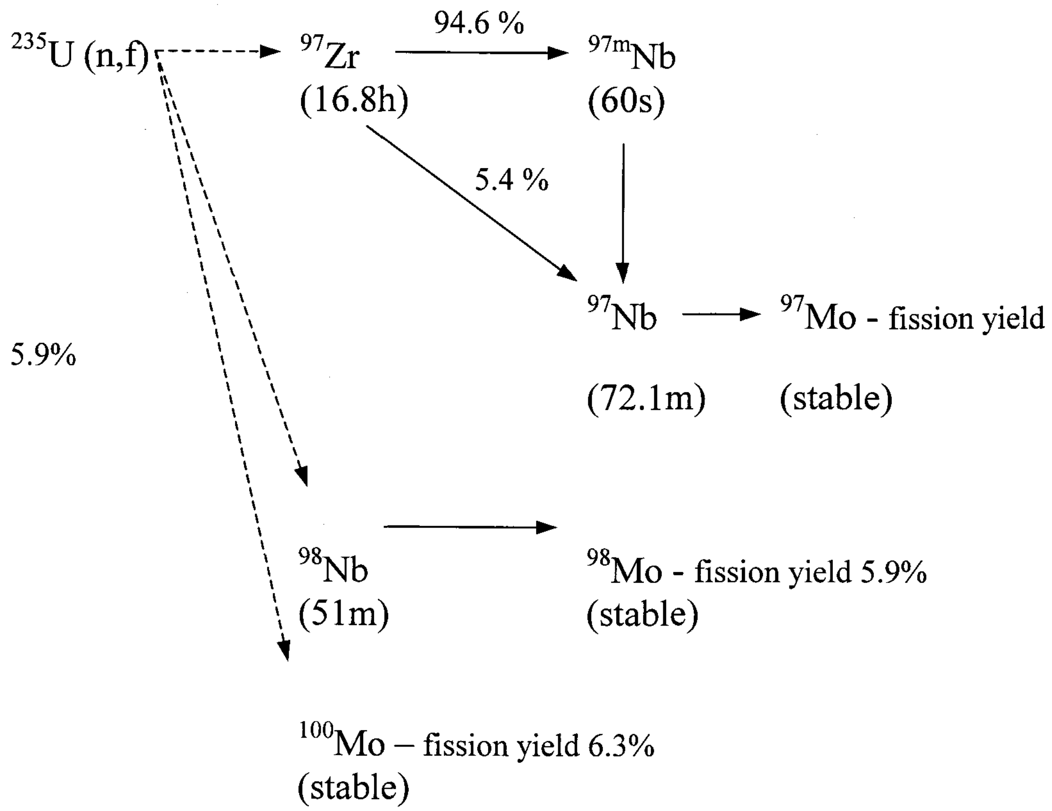

Figure 1.5 The Molybdenum Isotopes Formed by the Fission of Uranium [9]

Neutron capture method demands simple and inexpensive post-irradiation processing, and produces little radioactive waste. Neutron production needs more space and a high flux comparing with the fission method to achieve a high yield of Mo-99. Neutron activated Mo-99 is always low of specific activity (< 10 Ci Mo-99/g Mo) [9].

Some factors must be included for choosing the method of Mo-99 production: economics, resources and mode of utilization. The overall comparison is presented in Table 1.5.

1.3.4 Separation Methods Tc-99m from Mo-99

The three most common methods used to separate Tc-99m from Mo-99are chromatography, sublimation, and solvent extraction [9]. Since the kinetics of the system provides for the regrowth of Tc-99m after each separation cycle, the practical devices employed must be capable of repetitive operation for maximum effect. These devices, which are called generators, have variable designs.

The most common method of producing Tc-99m from Mo-99 is a chromatography separation, which was developed by Brookhaven National Laboratory [14]. The technique is based on the relative differences in the distribution coefficients of aluminum oxide for the anions, molybdate (MoO_4^{2-}) and pertechnetate (TcO_4). The passage of physiological saline through an alumina bed containing absorbed molybdate/ pertechnetate will result in the elution of the pertechnetate component. This type generator consists usually of a small glass column (2 – 3.5 cm in diameter) with fritted glass disc on the bottom. The column

Table 1.5 Overall Comparison of Fission and Neutron Capture Mo-99 Production Method [10]

Aspect	Fission Method	Neutron Capture Method
Target Fabrication		
Material	Highly enriched U-235	Non-radioactive molybdenum
Material availability	Currently available; questionable in future	Currently limited; increased production readily resumed
Facility requirement	Full radiological capability	Standard non-radiological lab.
Criticality	Control required	Not applicable
Accountability	Full accountability required	Not required
Technology	Established	General technique established; design required
Nonproliferation safeguards	Required	Not required
Reactor Irradiation		
Flux required	Low to moderate	Moderate to high
Space required	Low	Moderate
Effect on reactor operation	Location dependent; may be significant	Insignificant
Transport of irradiated target	High heat/radiation road; cooldown period required; container must be certified for fissile material	Insignificant heat load; modest radiation road; standard radioactive material container; no cooldown period required
Process Facility		
Radiological	High β-γ shielding; α handling capability, criticality control	Moderate β-γ shielding; no α; no criticality concern
Work space	Segregated work areas required for quality control; waste handling space required	Less space; less segregation than fission method; minimal waste
Special equipment	I-131 control; Xe-133 fixation; shielding for fresh targets and waste	None (process uses standard equipment)

is filled with the adsorbent, and placed into a suitable shielding [15].

Due to the volatile characteristic of technetium oxide (Tc_2O_7), the technique of sublimation could be used to separate technetium from molybdenum [16-20]. The different volatility of molybdenum trioxide and technetium heptoxide could be exploited to provide a source of medically acceptable Tc-99m. A stream of oxygen passed over a bed of molybdenum trioxide heated to 800 °C vaporizes the technetium oxide, which then condenses in a coil and can be dissolved in physiologic saline solution.

The solvent extraction generator has been widely utilized and considerable use made of its intrinsic advantage of economics and technical advantage. It is a relatively cheap method. It also provides a high concentration of Tc-99m with low levels of radionuclide impurities. Tc-99m is extracted from alkaline solutions of sodium molybdate using methyl ethyl ketone [21]. After extraction, the solution is evaporated off and remaining Tc-99m is dissolved in physiologic saline solution. The practical problems of this process are the radiation safety considerations [9]. The procedures should be performed under remote handling conditions.

1.4 Current Source and Situation of Mo-99 in U.S.

As mentioned previously approximately 38,000 diagnostic procedures involving radioactive isotopes are performed each day in the United States [5] with Tc-99m, daughter product of Mo-99, being the widely used isotope in the therapeutic applications. Because of these isotopes' short lifetimes, these can not be stored for a long time. Thus a stable and continuous supply is critical for medical use. The United States medical community consumes about 60 % of the worldwide production of Mo-99/Tc-99m [5]. But there is no current domestic production source for these isotopes.

Prior to 1989, Mo-99 was produced in the United States by a single supplier, Cintichem Inc., Tuxedo, NY [22]. Cintichem produced Mo-99 by irradiating of uranium deposited targets, and then separating the Mo-99 from the targets chemically, and purifying it. Because of problems associated with operating its facility in 1989, Cintichem decided to decommission the facility rather than incur the costs for repair. Since then, the U.S. has relied upon a single foreign source, Nordion International, located in Ottawa Canada. The Canadian company has only one reactor producing Mo-99 without backup reactor. An accidental shutdown of this reactor, such as the 6-days strike on June 1997 [4], could cause the shortage of Tc-99m to the United States medical community despite temporarily supplies from a European source.

The jeopardy of United States dependence on a single foreign source for the supply of such a critical isotope was addressed at hearings conducted before the Congressional Environment, Energy and National Resources Subcommittee of the Committee on Government Operation in 1992. The need for DOE to become a Mo-99 supplier was also affirmed at hearings. Congress provided the budget and supported for this effort [23]. In 1992 the DOE purchased the Cintichem process technology, equipment, and the FDA Drug Master Files for the production of Mo-

99, I-125, I-131, and Xe-133 [23]. In 1994 the DOE funded Sandia National Laboratories (SNL) to produce Mo-99.

The DOE would use the Chemistry and Metallurgy Research Facility at Los Alamos National Laboratory (LANL) to fabricate the targets consisted of highly enriched UO_2 coated stainless steel tubes. The targets would be shipped to the Annular Core Research Reactor (ACRR) at SNL for irradiation, and the irradiated targets would be processed in the adjacent Hot Cell Facility [23]. In 1997 five test targets were irradiated at ACRR and processed [22, 24-26]. This experimental campaign demonstrated that ACRR could be utilized for Mo-99 production and the produced Mo-99 with Cintichem process, which was compatible with pharmaceutical company ^{99m}Tc generators [22]. The production processes at SNL were submitted to the FDA, and are waiting approval [26].

1.5 Objective of Study

The objective of this study is to examine the feasibility of using solution targets in OSU TRIGA Reactor (OSTR) to produce molybdenum-99 and other medical isotopes. The following specifications were set to achieve this objective:

- Describing the OSU TRIGA reactor which would be use in this study for Mo-99 production with the solution uranium targets,
- Building a three-dimensional OSTR MCNP model and verifying it to examine the neutronic characteristics of OSTR,
- Describing the current target system and process for Mo-99 production and the characteristics of proposed solution targets which would include

the history of solution reactors, properties of solution fuels, and Mo-99 separation process from irradiated solution targets,

- Developing two kind solution targets and conducting the neutronic analysis with targets in the OSTR core,
- Outlining the processing methods of solution targets and the modification of OSTR for Mo-99 production purpose,
- Analyzing nuclear safety: radiological gas problem, thermal hydraulics, waste, and radioactive material release, and
- Recommending further research in this study.

CHAPTER 2
OREGON STATE UNIVERSITY TRIGA REACTOR (OSTR)

OSU TRIGA Reactor, OSTR, is designed by General Atomics for use in training, research, and isotope production. It will be used as design bases for this study on the production of medical isotopes, but the overall objective of the work is to produce a facility which will be applicable to all TRIGA type facilities. This chapter will briefly overview the OSTR core, fuel element, control rods, and irradiation facilities.

2.1 OSU TRIGA Reactor Overview [27]

The OSU TRIGA Mark II reactor (which has a Mark III core) is a pool type reactor which is built to fulfill the need for a safe reactor that combines radioisotope production and experimental facilities with training capacities. The reactor core utilizes a solid, fuel-moderator element in which the zirconium-hydride (Zr-H) moderator is homogeneously combined with 70 % enriched uranium. A unique feature of these fuel elements is a prompt negative temperature coefficient of reactivity that automatically limits the reactor power to a safe level in the event of sudden insertion of positive excess reactivity. The OSTR is capable of steady-state operation up to the licensed power levels of 1.1 MW.

The structure of OSTR consists of a concrete shield containing a water-filled aluminum reactor tank, with the core located near the bottom of the tank. The tank is approximately 198 cm (6.5 ft.) in diameter and 625 cm (20.5 ft.) in depth.

The core is shielded in the upward direction by approximately 488 cm (16.0 ft.) of demineralized water. A vertical section of OSTR is shown in Figure 2.1. A horizontal section view of OSTR is represented in the Figure 2.2. Four beam tubes and a graphite thermal column penetrate the concrete shield and reactor tank. A track-mounted, 19 ton rolling door is used to shield the outer face of the thermal column. A graphite thermalizing column penetrates the concrete shield and terminates in a bulk-shielding experiment tank that is part of the shielding structure.

2.2 Core

The core assembly is a right circular cylinder consisting of a compact, concentric array of cylindrical fuel-moderator elements, a central thimble, a neutron source, and control rods, all positioned vertically between two grid plates, which are fastened to the reflector assembly.

Several of the outer grid positions in the core contain graphite reflector elements. A doughnut-shaped radial reflector, approximately 25.4 cm (10 in.) thick, surrounds the core and is supported on an aluminum platform at the bottom of tank. The reflector consists of graphite with a 5.08 cm (2 in.) layer of lead on the periphery. Figure 2.3 shows the cutaway view of OSTR. The central thimble penetrates the center of the core, along its vertical axis, and has an aluminum plug inserted to displace the water (in the thimble) at the region of maximum flux. The core is cooled by the natural convection of water that occupies about one-third of the core volume.

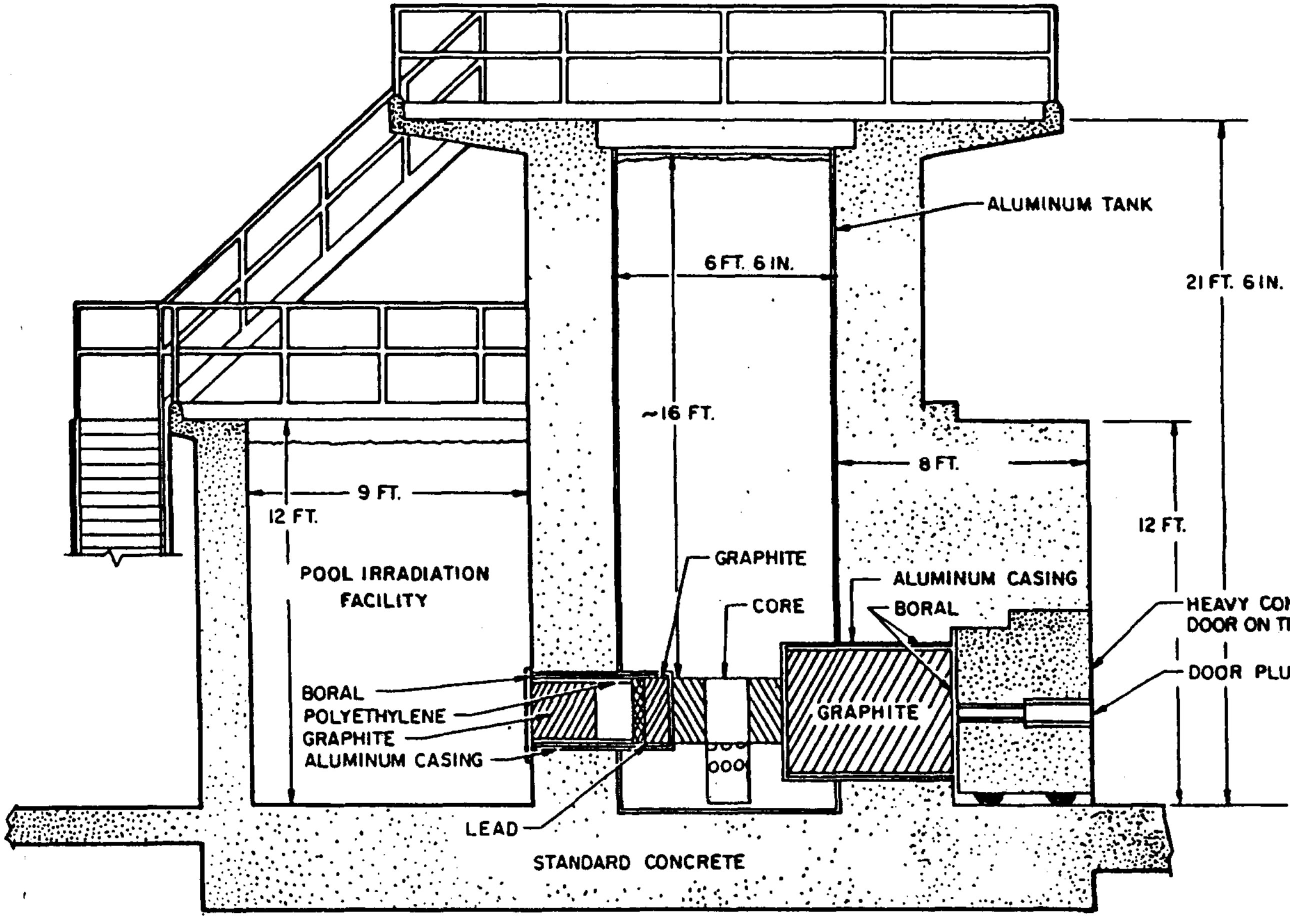

Figure 2.1 The Vertical Section View of OSTR [27]

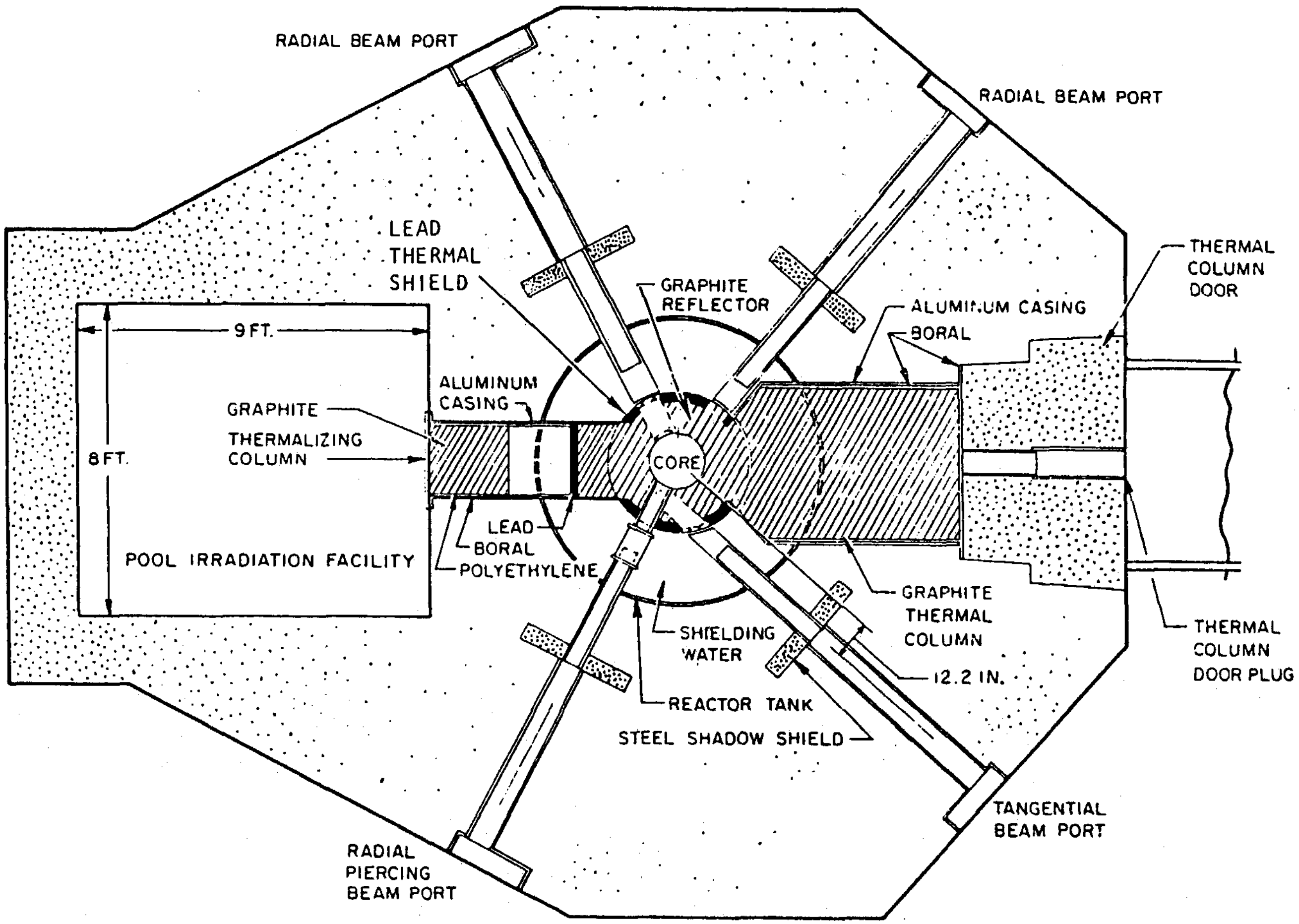

Figure 2.2 The Horizontal Section View of OSTR [27]

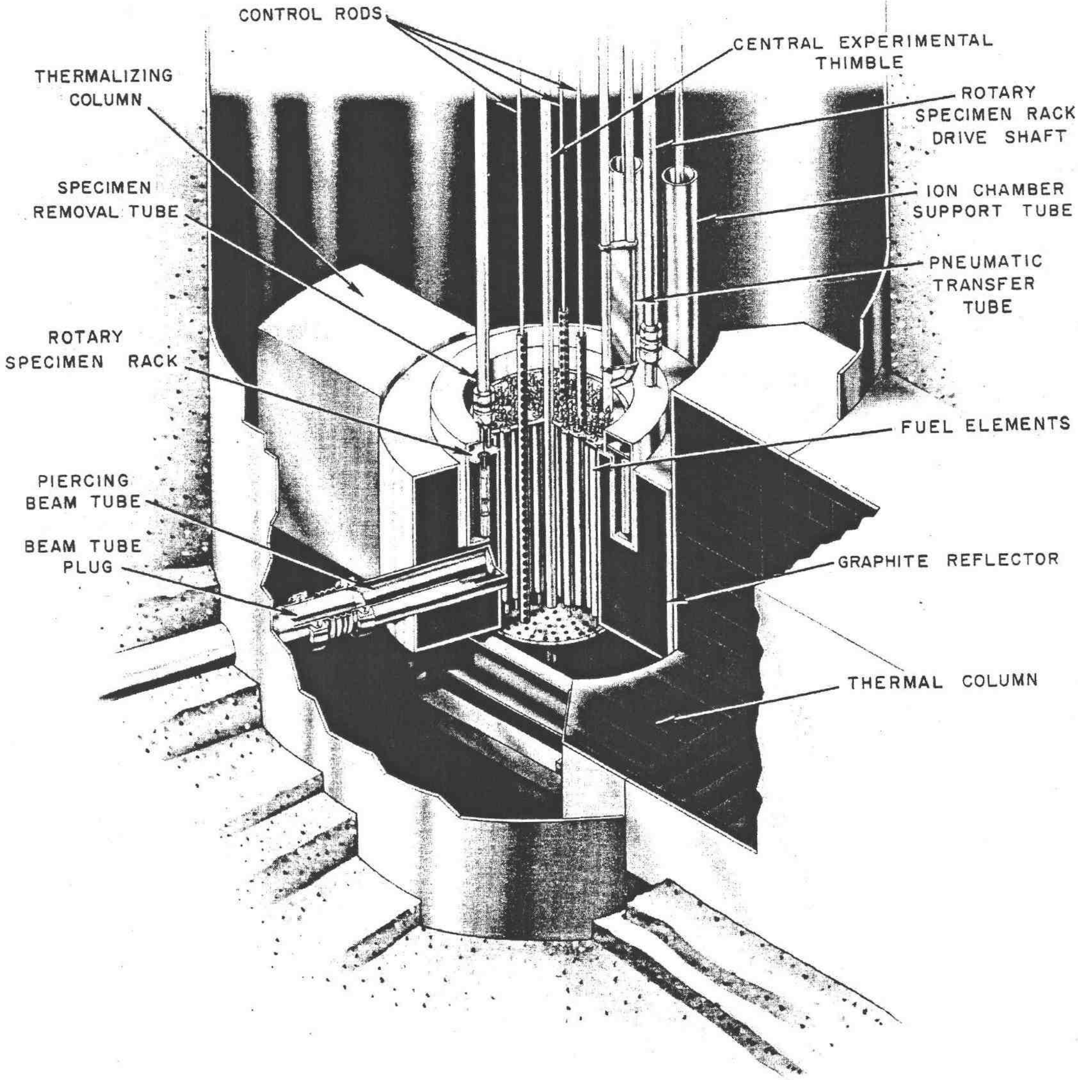

Figure 2.3 The Cutaway View of OSTR [27]

2.3 Fuel Elements

The fuel-moderator elements contain a zirconium-hydride moderator, homogeneously combined with enriched uranium fuel and a burnable poison. As indicated in Figure 2.4, the active section of this fuel-moderator element is 38.1 cm (15 in.) in length, 3.63 cm (1.43 in.) in diameter and contains approximately 8.5 wt. % uranium, enriched to 70 % in U-235. The hydrogen to zirconium atom ratio of the fuel-moderator material is about 1.6 to 1. The homogeneously mixed burnable poison is ~ 1.6 wt % erbium. After hydriding, a zirconium filler rod is inserted into a small diameter hole in the center of the active fuel section. The graphite slugs, approximately 8.89 cm (3.5 in.) in length and 3.56 cm (1.4 in.) in diameter, act as top and bottom reflectors.

The active fuel section and top and bottom graphite slugs are contained in a 0.0508 cm (0.020 in.) thick stainless steel cladding. The U-235 content ranges from about 136 to 138 grams per element.

2.4 Control Rods

The OSTR power is controlled and regulated by four control rods: a shim rod, a safety rod, a regulating rod, and a transient rod. The first three are standard control rods, which are clad in stainless steel and are long enough to protrude through both top and bottom grid plates, even if the rod drive is in the full up or down position. Figure 2.5 shows the withdrawn and inserted position of standard control rod. The control rods travel a vertical distance of approximately 38.1 cm

(15 in.) between their fully withdrawn and inserted positions. The standard control rod consists of: graphite, followed by 38.1 cm (15 in.) of neutron absorber (graphite impregnated with powdered boron carbide), a follower section consisting of 38.1 cm (15 in.) of U-$ZrH_{1.6}$ fuel, and a bottom section of graphite.

The transient rod may be rapidly withdrawn from the core using compressed air, to induce a prompt critical transient. The transient rod can also be used as a conventional control rod during steady state operation. The exterior of the transient rod is a 3.18 cm (1.25 in.) outer diameter aluminum tube with aluminum plugs welded in each end. The borated graphite poison section is 38.1 cm (15 in.) long. Unlike the standard rods, however, the transient rod has an air filled (void) follower. The transient control rod is indicated in Figure 2.6.

2.5 Grid Plates

There are two grid plates in the core, upper and lower grid plates. Both are made of aluminum. The upper grid plate, as shown in Figure 2.7, has locations for fuel elements, control rods, and pneumatic system termini arranged in six concentric rings around the center central thimble hole (A-1). The rings of the grid are lettered B through G and the positions in each ring are numbered clockwise starting from east. The diameters of the central thimble and fuel element holes are about 3.81 cm (1.5 in.). The top grid plate is about 53.3 cm (21 in.) in diameter.

A hexagonal grid plate section in the center of the upper grid plate which comprises the central thimble and B-ring (a total of seven fuel elements holes) can be removed from the plate. This removable plate was designed to allow experiments to be inserted in the center of the core. Two triangular holes in the upper grid plate provide additional experimental options. The lower grid plate provides accurate spacing between the fuel-moderator elements and supports the entire weight of the core.

2.6 Irradiation Facilities

The OSTR system is designed to provide intense radiation fluxes for research, and isotope productions. Experiments with the OSTR can be carried out using one or more of following facilities for their own purposes: rotating rack facility, pneumatic transfer system, cadmium-lined in-core irradiation tube, central thimble, 4 beam port facilities, thermal column, thermalizing column and bulk shielding experiment tank, and in-pool and in-core irradiation facilities which amount to placing experiments close to or in the reactor core. The experimental results of every facility are very sensitive to the change of core environments.

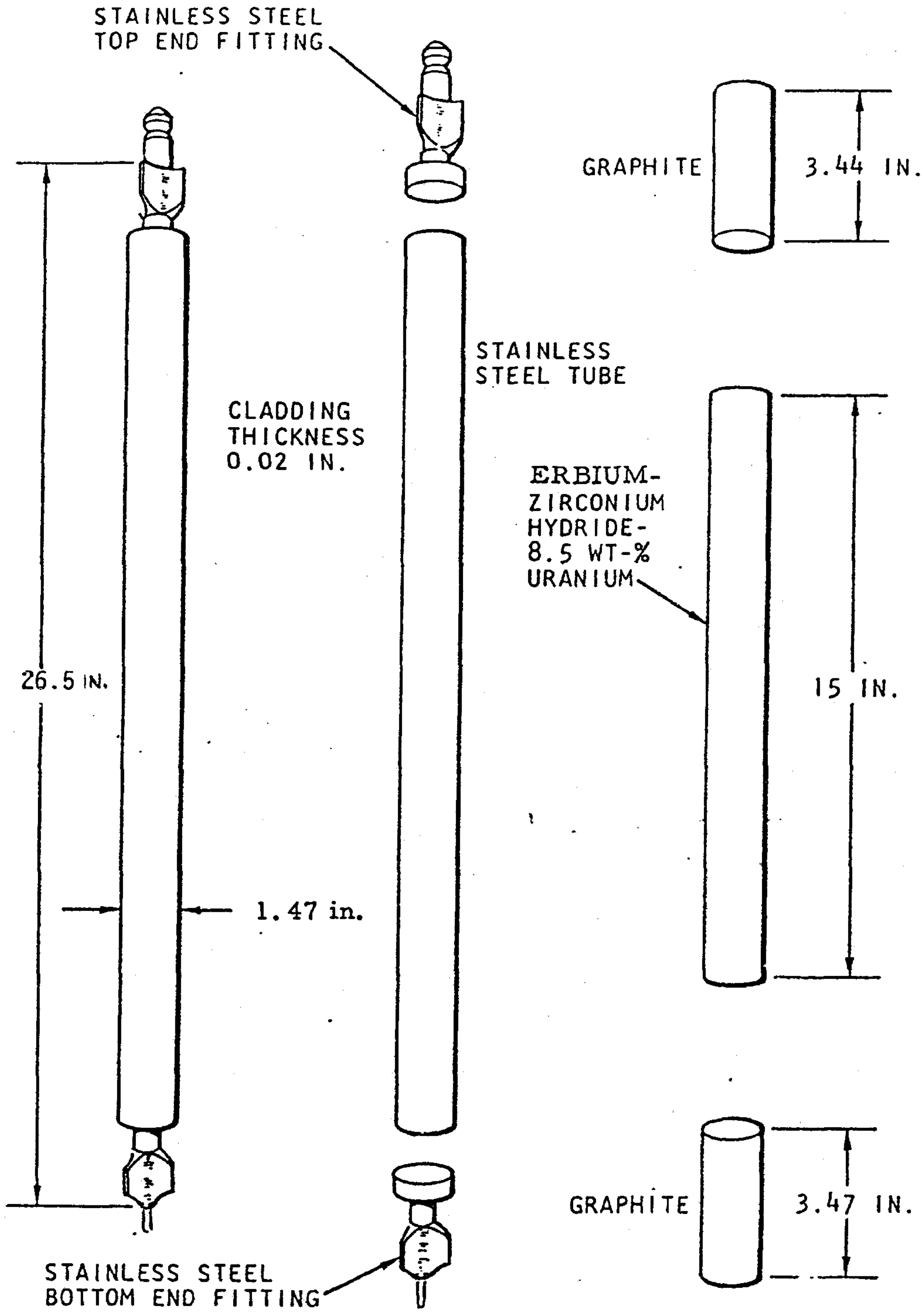

Figure 2.4 OSTR Fuel Element [27]

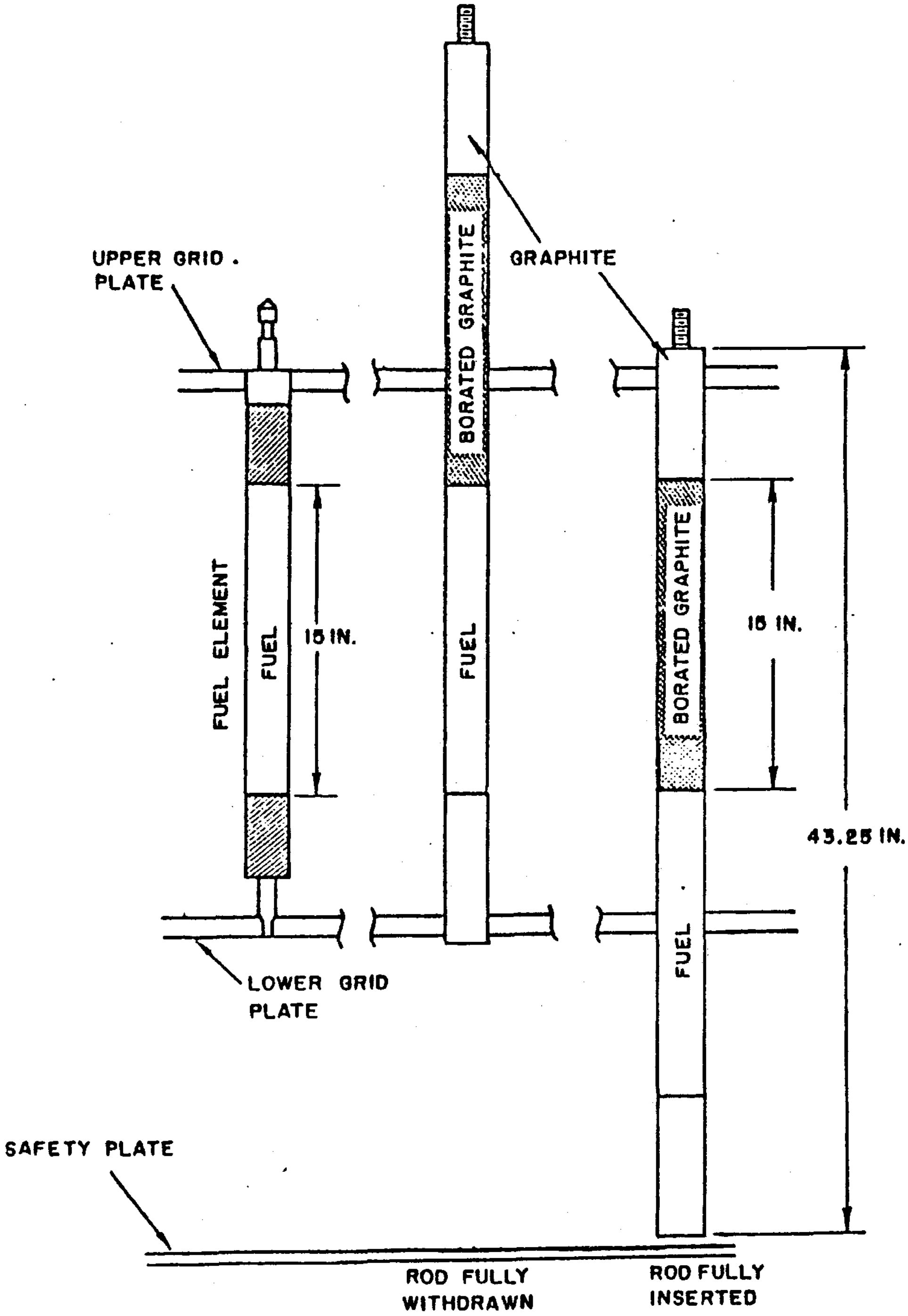

Figure 2.5 Standard Control Rod Shown Withdrawn and Inserted [27]

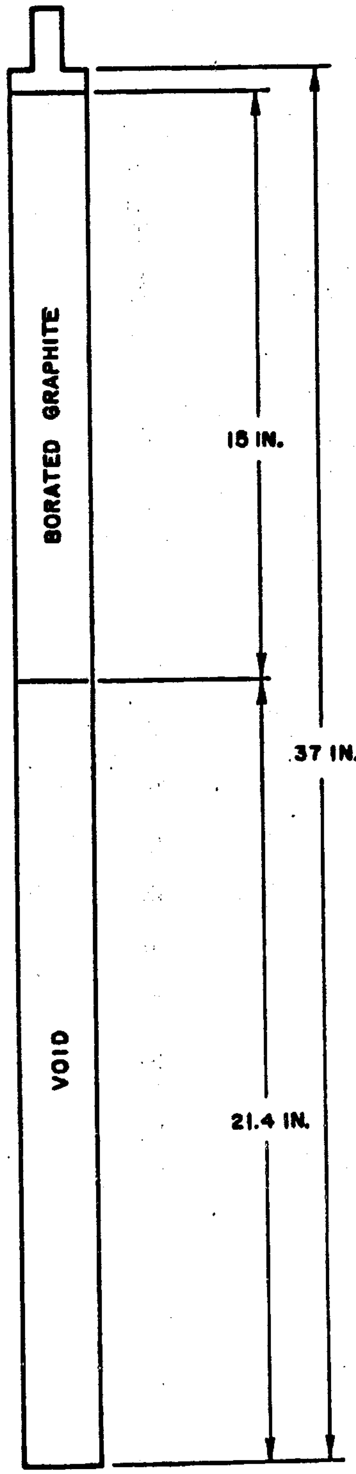

Figure 2.6 Transient Control Rod [27]

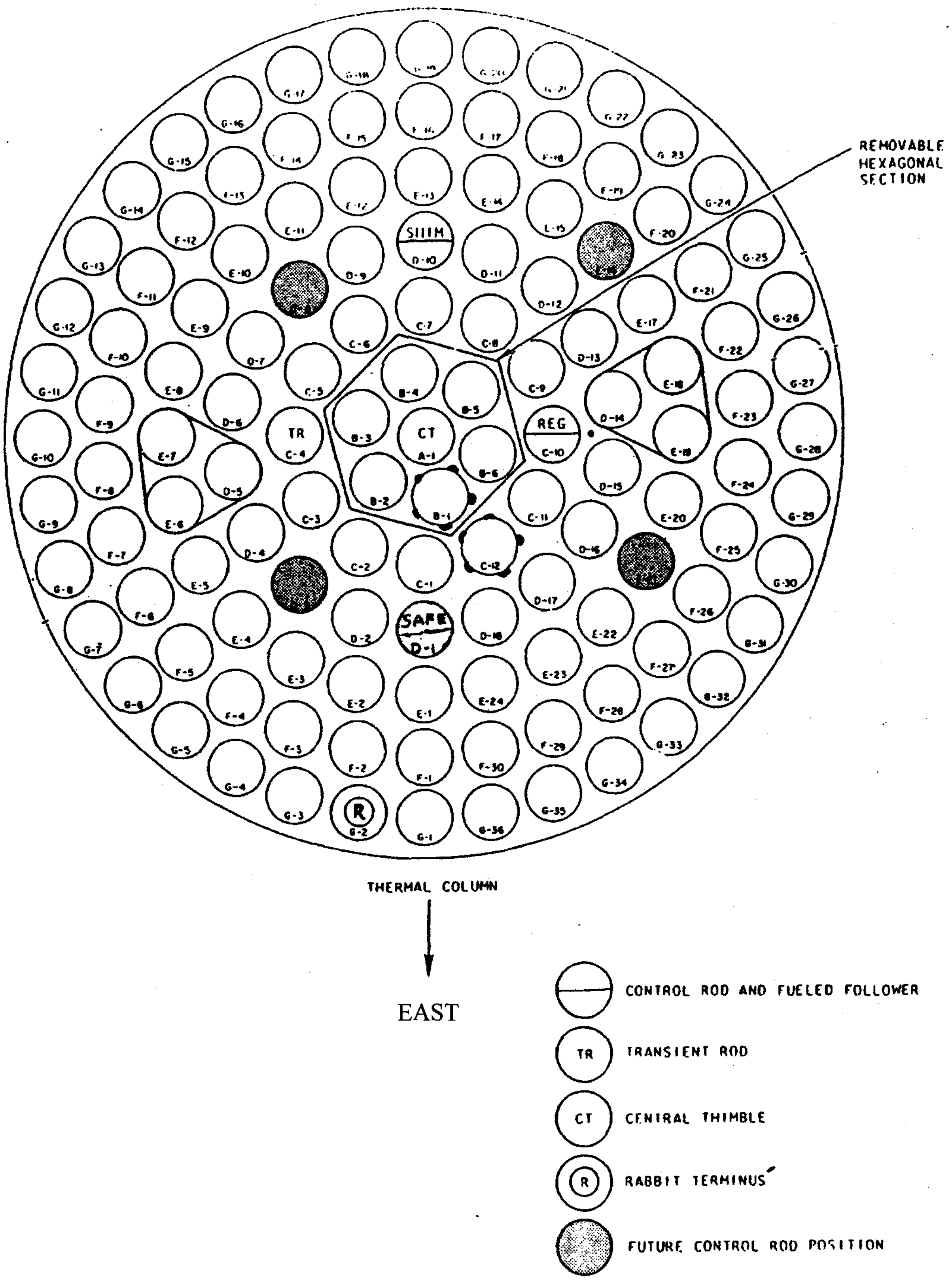

Figure 2.7 Core Upper Grid of OSTR [27]

CHAPTER 3
OSTR MCNP MODEL

MCNP code is used to determine the optimum configuration, and to obtain the fission rate and power generated in a simulated target. A three-dimensional MCNP model is developed and verified by comparing with the measured reactivity values and powers per elements.

3.1 MCNP Code Overview

Monte Carlo N-Particle Transport Code (MCNP) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, and coupled neutron/photon/electron Monte Carlo transport code [28]. The Monte Carlo Method does not solve an explicit equation, like the deterministic transport method, but rather obtains answers by simulating individual particles and recording some aspects (tallies) of their average behavior. The average behavior of particles in the physical system is then inferred from the average behavior of the simulated particles. It supplies information only about specific tallies requested by the user.

MCNP solves neutral particle transport problems and may be used in any of three modes: neutron transport only; photon transport only; combined neutron/photon transport, where the photons are produced by neutron interactions; electron transport only; and combined photon/electron. The neutron energy regime is from 0 to 60 MeV (data are generally available only up to 20 MeV) and photons and electrons energy regimes are from 1 keV to 1GeV. Pointwise continuous-energy cross section data are used in MCNP, although multigroup data may also be used. Fixed-source adjoint calculations may be made with the multigroup data option. For neutrons, all reactions in a particle cross-section evaluation (such as ENDF/B-V) are accounted. Both free gas and S (α, β) thermal treatments are used.

The user creates an input file that is subsequently read by MCNP. This file contains information about the problem in areas such as: the geometry specification; description of the materials with the cross-section used; the location and characteristics of the source; the type of tallies desired; and any variance reduction techniques used to make the problem run more efficiently.

3.2 The Monte Carlo Method

The Monte Carlo method regards neutrons as individual particles that interact with nuclei on a random basis, which obeys certain fundamental laws of probability. It is particularly useful for complex problems that cannot be modeled by computer code that use deterministic methods. The individual probabilistic events are simulated sequentially. The probability distributions governing these events are statistically sampled to describe the total phenomenon. The simulation is achieved on a computer because the number of trials necessary to describe the phenomenon adequately is quite large. The statistical sampling process is accomplished through the use of a random number, or, more correctly, pseudo-random number generator. In particle transport, the Monte Carlo technique is a theoretical experiment. It follows each of many particles from its birth to its death in some terminal events (absorption, escape, etc.). Probability distributions are randomly sampled using transport data to decide the outcome at each step of its life.

A simplified flow diagram for the effective multiplication factor calculation using an analog Monte Carlo method is shown in Figure 3.1 [29]. The procedure follows the generations of neutrons and compares the initial number of neutron to the total number produced to calculate k_{eff}. In an arbitrary generation, the locations for starting individual neutron histories are selected from the previous generation. The first generation has starting neutrons from an arbitrary distribution.

The energy and direction are selected randomly from cumulative distribution functions. Neutron path lengths between collisions depend on the total macroscopic cross section, $\Sigma_t(E)$. The geometry determines whether a neutron leaks or observes a collision at the end of its path length. Collision types are selected randomly with the proper reaction cross sections. Scattering events change the energy and direction of the neutron before continuing in the system. Leakage, capture, and fission terminate the history and signal the start of the next fission neutron. For fission reactions, the number of fission neutrons randomly is selected with the resulting number and the location of the event is stored for use as starting neutrons of the next generation.

3.3 OSTR MCNP Model

The nature of MCNP enables the core geometry to be described in as great a level of three-dimensional detail as necessary to achieve the purposes of the specific calculation. The 3-D core model developed for the OSTR is shown in Figure 3.2. Each grid position is modeled in its exact location in the grid plate. All components including fuel elements, control rods, graphite elements have the exact dimensions of their constituent materials and fit into the grid plate. The specifications of fuel elements in the core are shown in Table 3.1. The input file of OSTR MCNP model is attached in Appendix.

3.4 Verification of OSTR MCNP Model

Once the model is developed, different materials can be assigned to each of the grid locations. In this manner, it is possible to determine the number of elements required for criticality and the variation of excess reactivity with various cores.

Atom densities for each of constituent materials used in this work are determined from TRIGA data sets provided by the manufacturer General Atomics (GA) or from standard references for common materials. Table 3.2 shows the atom densities used in the analysis.

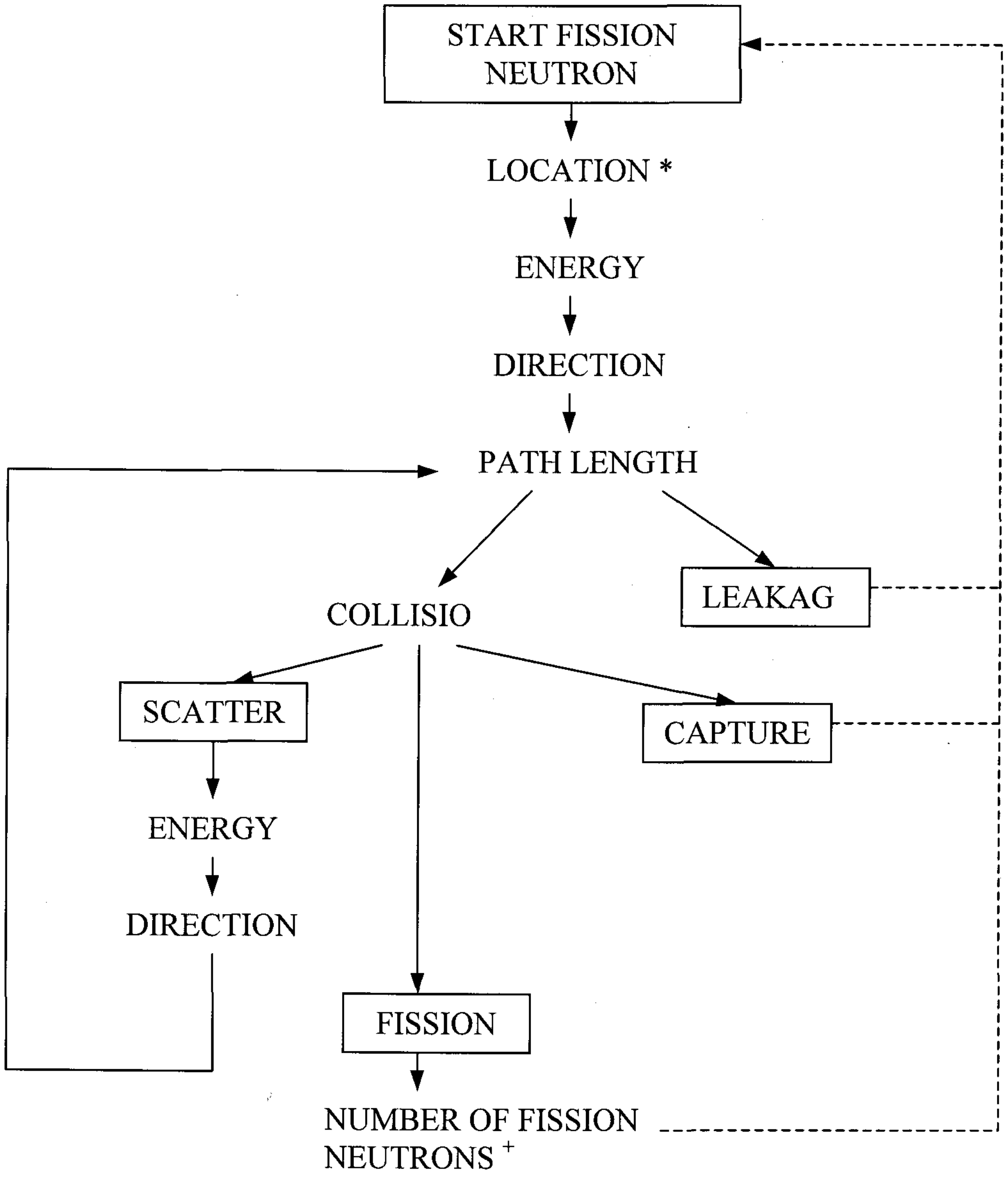

Figure 3.1 Flow Diagram for an Analog Monte Carlo Method Used to Calculate the Effective Multiplication Factor [29]

* Locations for generation N based on fission points from generation N-1

+ Record neutron number and fission location for generation N+1 starting location

Table 3.1 Material and Dimensional Specifications of FLIP Fuel Elements [30]

PROPERTY	DIMENSIONAL AND DENSITY DATA
Zr rod radius(cm)	0.3175
Fuel/graph. Radius(cm)	1.82245
Fuel/Zr length(cm)	38.10
Cladding radius(cm)	1.87325
Top graph. Length(cm)	8.738
Bottom graph. Length(cm)	8.814
Standard Control rod Fuel radius(cm)	1.665
Standard Control rod Cladding radius(cm)	1.7234
^{235}U/element(g)	134.279
U/element(g)	191.880
Enrichment(%)	70.0
Fuel density(g/cm^3)	5.999
SS density(g/cm^3)	7.86
Graphite density(g/cm^3)	1.60
Zirconium density(g/cm^3)	6.4
Aluminum density(g/cm^3)	2.7

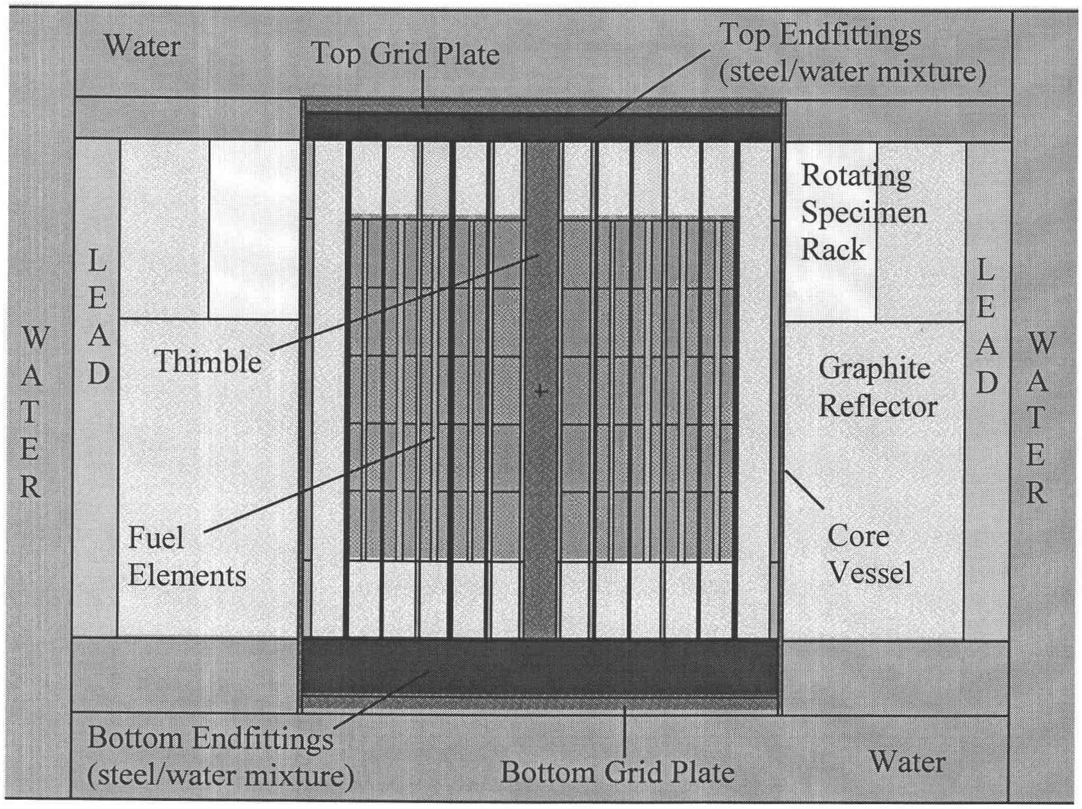

Figure 3.2 OSTR MCNP Model

3.4.1. k-effective

Verifications of the OSTR MCNP Model are performed by comparing with the experimental results. Criticality of the OSTR was achieved on 7 August 1976 with 62 70 % enriched FLIP TRIGA fuel elements and three fuel follower control rods (8.652 kg U-235) [27]. The air follower transient rod was used and the 21 graphite reflector elements were placed in the "G" ring. Figure 3.3 shows the initial FLIP critical core diagram. This critical configuration resulted in a core excess of 12 cents. The conversion to value of k-effective is 1.00084. The MCNP model calculation value of k-effective is 0.99858 ± 0.00066. It is only 0.22 % error to the measured value.

The operational FLIP core was finalized on 10 August 1976 and consisted of 82 TRIGA FLIP fuel elements, 3 fuel follower control rods, and 21 graphite reflector elements in the "G" ring [27]. This core configuration, as shown in Figure 3.4, consisted of 11.347 kg U-235 with a core excess of $7.17. This is k-effective value of 1.05019. The total rod worth was $11.73. The result of MCNP model is 1.05142 ± 0.00271 k-effective value. It is only 0.12 % error to the measured value.

Table 3.2 Atom Densities Used in Analysis [30]

Property	**Atom Densities**(x 10^{24} atoms/cm^3)
Control Rod	
Boron	0.175
Carbon	0.02687
304 Stainless Steel Cladding	
Carbon (0.08 wt %)	0.00031519
Chromium (19 wt %)	0.017290
Nickel (10 wt %)	0.0080622
Iron (70.92 wt %)	0.060088
Total Stainless	0.085755
Water	
Hydrogen	0.0668
Oxygen	0.0334
Other	
Graphite	0.080193
Zirconium	0.042234
Aluminum	0.06027

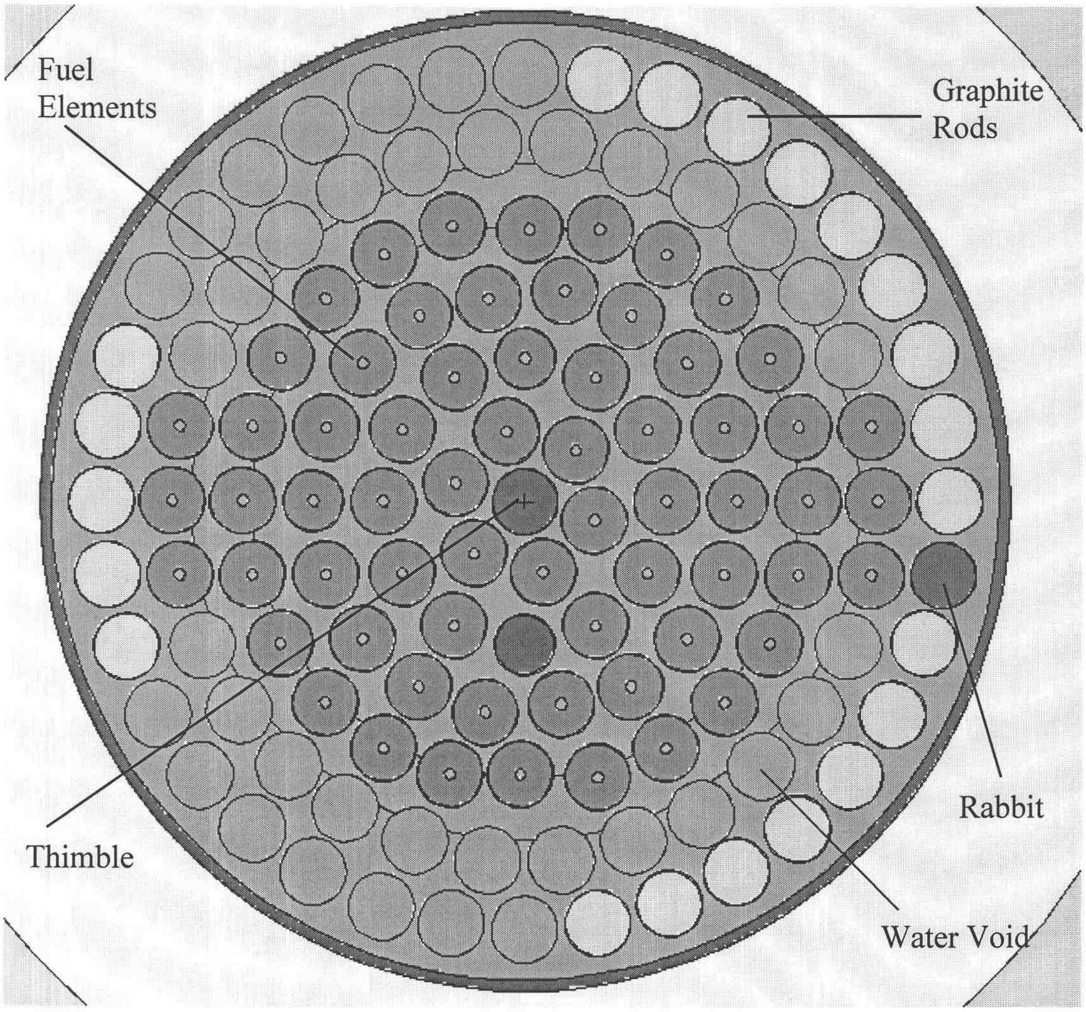

Figure 3.3 Initial FLIP Fueled Critical Core, 7 August 1976, Core Excess 27 cents.

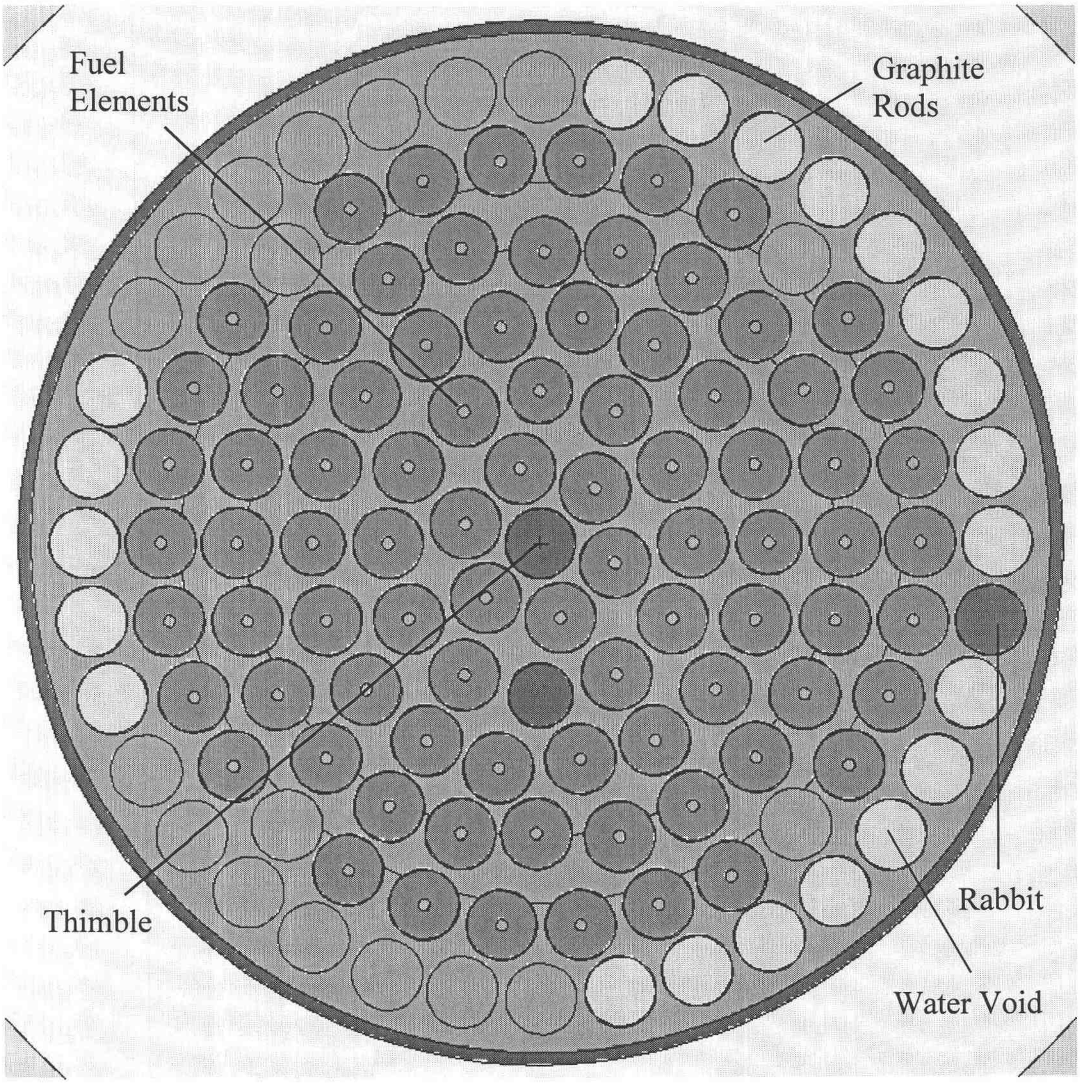

Figure 3.4 Operational FLIP Fueled Core, 10 August 1976, Core Excess $ 7.17.

3.4.2 Power per Element

Power density is a significant parameter to operating the OSTR. The measured results are listed in Table 3.3 at 1MW operation. As expected, the highest power density occurs in the "B" ring. The effect of the graphite elements in the outer ring is to slightly increase the power density in the outer fueled rings and to slightly reduce the power density in the inner fueled rings. This is expected as part of the reflector flux peaking.

In the MCNP mode, the tallies must be scaled by the steady state power level of the critical system in units of fission neutrons per unit time. The scaling factor can be induced with the F7 tally. The F7 fission heating tally indicates the fission energy deposition averaged over a cell (MeV/g). The total deposited energy in a cell or core is the multiplication of F7 tally and the total mass of cell which contains fissionable materials. This energy could be less than the actual steady state power. To convert this value to real one the scaling factor should be multiplied. The scaling factor can be calculate from the following equation:

$$P = F7 \times C \times M \times S_f \tag{3.1}$$

where P = power (W)

$F7$ = MCNP fission heating tally (MeV/g)

C = conversion factor, 1.602×10^{-13} W/MeV/sec

M = total mass of cell (g)

S_f = scaling factor (neutrons/sec), which can be found using Equation (3.2)

$$S_f = P/(F7 \times C \times M). \tag{3.2}$$

F7:n tally is 3.8241×10^{-4} MeV/g at 1 MW power operation of OSTR. The total mass of core which contains the U-235 is 194,703.89 gram. Then the scaling factor would be:

$$S_f = 1000000 \ / (3.8241\times10^{-4} \times 1.602\times10^{-13} \times 194{,}703.89)$$

$$= 8.38340 \times 10^{16} \text{ neutrons/sec.}$$

This is the source strength for 1 MW power level. This value can be used as normalization constant to convert the relative result to the absolute value of neutron flux and average power per element. The result of the calculated average power per element with the MCNP is listed in Table 3.3 and compared with the measured values at the Figure 3.5 [27]. The calculated values are well matched with the measured in B, C and D ring within two percent. While the deviation for E and F ring was 11.5 % and 7.9 %, respectively. Table 3.4 lists the measured and calculated maximum, minimum, and average power per element, along with ratios of the maximum to minimum power and the maximum to average power per element [27].

Table 3.3 Measured and Calculated Average Power per Element at Total Core Power of 1MW (unit = kW/element) [27]

	B ring	C ring	D ring	E ring	F ring
Measured Values	15.85	14.68	12.63	9.99	9.22
Calculated Values	15.57	14.62	12.81	11.14	9.95
Error (%)	1.77	0.46	1.43	11.50	7.93

Table 3.4 Measured and Calculated Maximum, Minimum, and Average Power per Element at Total Core Power of 1 MW (unit = kW/element) [27]

	P_{max}	P_{min}	P_{ave}	P_{max}/P_{min}	P_{max}/P_{ave}
Measured Values	15.85	9.22	11.24	1.72	1.41
Calculated Values	15.57	9.95	11.88	1.56	1.31

3.5 Flux Profile

Figure 3.6 shows the radial neutron flux profile of OSTR core calculated with MCNP. Values for three types of neutron flux are graphed. The total flux includes neutrons traveling with all velocities or energies. The neutron energy varies from several

MeV, for neutrons just produced in the fission reaction in U-235, to 0.025 eV for neutrons whose average energy is in thermal equilibrium with the room temperature water in the core.

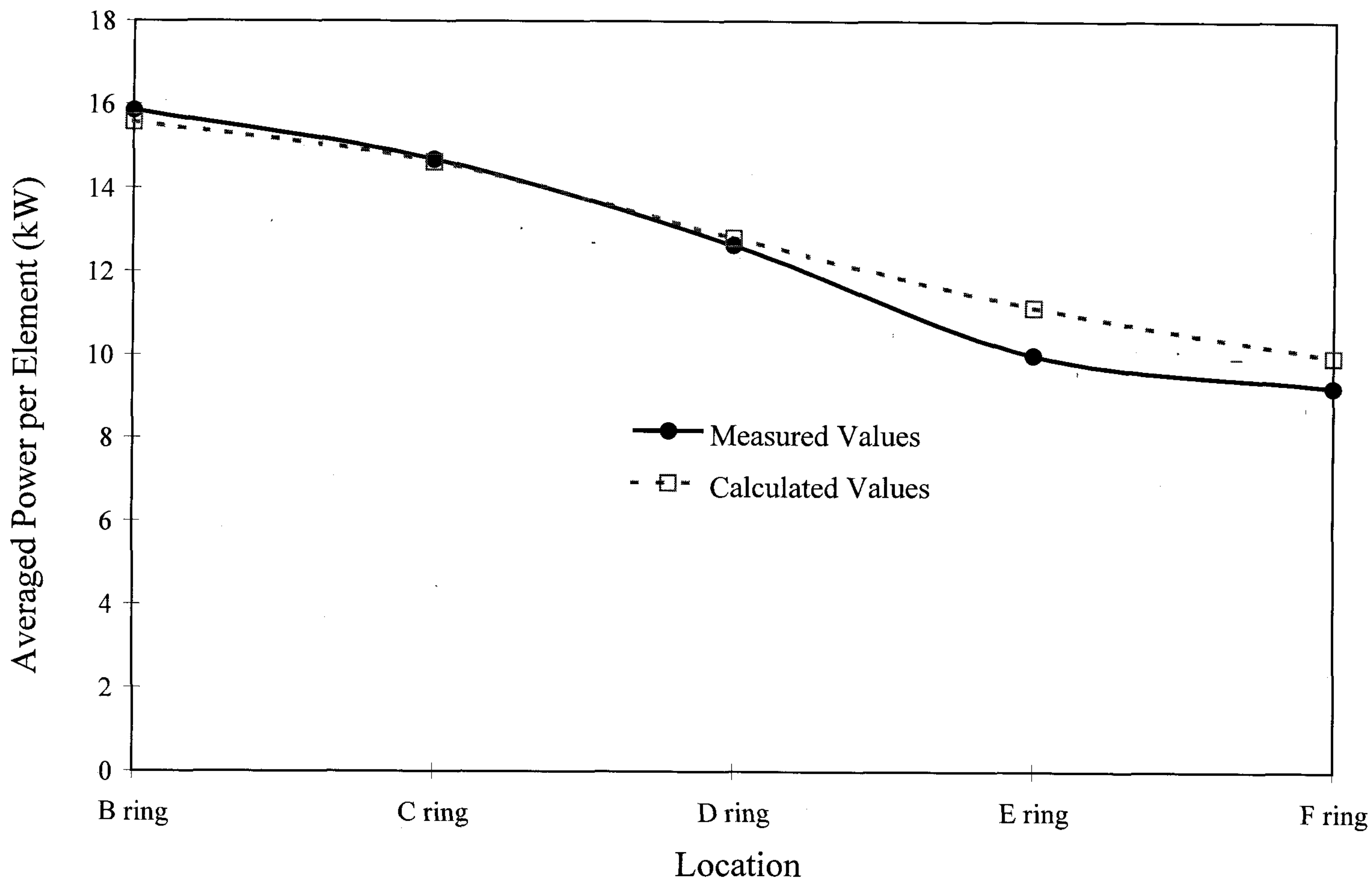

Figure 3.5 Comparison of Measured and Calculated Averaged Power per Element [27]

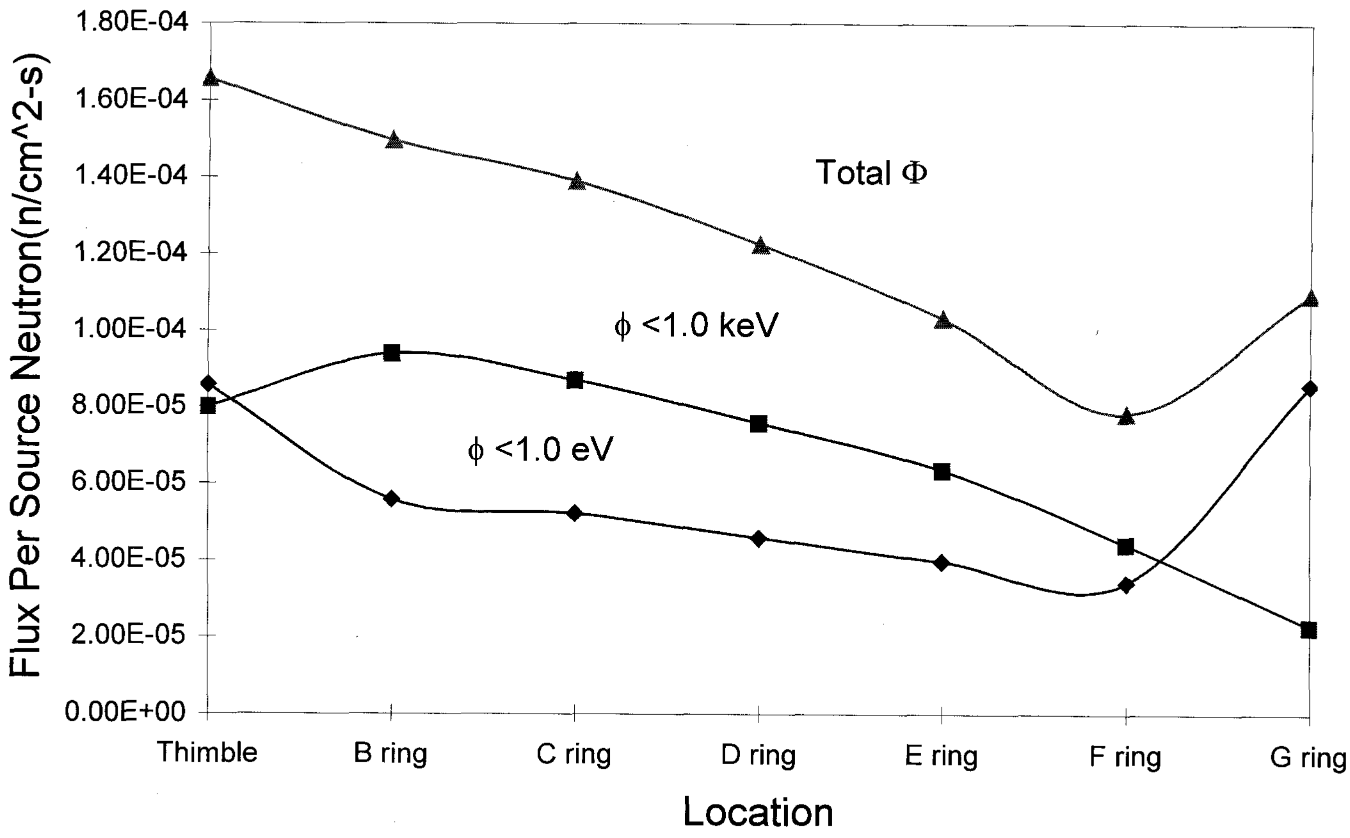

Figure 3.6 Radial Neutron Flux Profile of OSTR Estimated with MCNP

CHAPTER 4
IRRADIATION TARGET DESIGN

Currently, the Mo-99 on the U.S. market is generated from the fission of U-235 because of its high specific activity. Thus, this Mo-99 production work will focus on the fission Mo-99 production technique. The other technique for Mo-99 production is the neutron capture of Mo-98. This one is not practicable yet in the commercial purpose due to its low yield.

Two types of targets, which adopt the fission method, are used in Mo-99 production: tube type and plate type. The fission method uses a highly enriched uranium (HEU) target with a U-235 enrichment of 90% or greater. Concerns of nuclear proliferation are driving research to replace HEU with low enriched uranium (LEU) [31]. But, the HEU results in physically smaller target, and lower volumes of process chemical and waste. The HEU targets are typically 93% enriched uranium oxide, uranium-aluminum alloy, or uranium aluminide. The process of Mo-99 production with the solid target is stated in this part.

The homogeneous aqueous uranium solution is studied as a target material for producing medical isotopes. The characteristics of this solution are investigated with the history of the solution reactors. This solution target would be irradiated in the OSTR reactor. The design criteria and goal of the solution target are discussed for optimizing configurations.

4.1 Typical Targets for Fission

The target employed in the Nordion, who is the supplier of the most Mo-99 used in USA, is made from uranium metal enriched in U-235 as alloy with Al [32]. It is the same shape of the fuel used in National Research Universal (NRU) reactor, which located in Chalk River, Canada, and owned by the Atomic Energy of Canada Limited (AECL). The detail description is considered confidential information of the company.

Figure 4.1 shows the fission target used in DOE's Medical Isotopes Production Project at Sandia National Laboratory, which is the same style as the Chintichem target [5]. The target is constructed of number 304 stainless steel tubing, approximately 51 cm (20 inches) long and 3 cm (1.25 inches) in outer diameter with a wall thickness of 0.09 cm (0.035 inch). Caps are welded to close the top and bottom of tube. The top fitting includes a thin diaphragm that contains the tube contents, until it is punctured in the fission product recovery process. The inside tube wall of target is electroplated with highly enriched uranium (93% enriched). The uranium plating is approximately 50 microns thick and uniformly plated throughout the length of the tube.

South Africa produces the Mo-99 from a plate target, shown in Figure 4.2, which is a 46 % enriched U-Al alloy with Al cladding [32]. Each plate loads around 4.1 g of U-235.

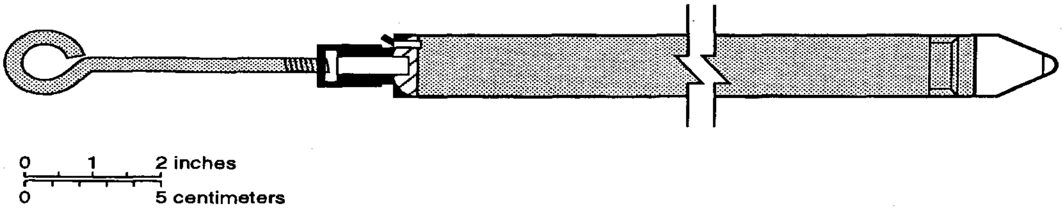

Figure 4.1 Configuration of MIPP Target in Sandia National Laboratory [5]

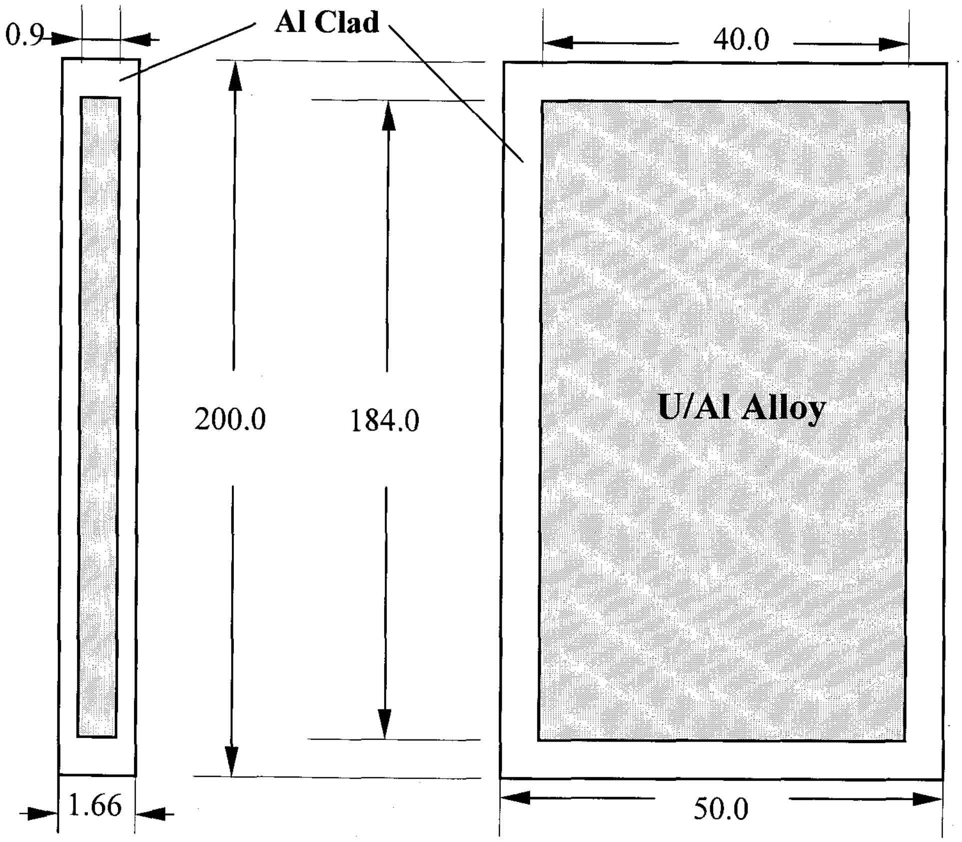

Figure 4.2 South Africa Target (unit = mm) [32]

4.2 Mo-99 Production Process

While different manufacturers may use different designs and materials for the Mo-99 production, there are little variations in the basic process. Figure 4.3 shows the steps of Cintichem process, which will be used by the Department of Energy in their Mo-99 production effort [5]. The first step is target fabrication. In this step highly enriched uranium (HEU) is coated on the inside of a stainless steel tube. The air in the tube is then evacuated, back-filled with helium and the fitting are welded onto the target body. This step is conducted remotely, inside a controlled-atmosphere facility, such as a glove box.

The second step is target irradiation in the Mo-99 production facility, such as a nuclear reactor. A target is usually irradiated in a reactor for a week, and then is removed for chemical separation. The third step is target processing in the Mo-99 separation facility. In this step, the irradiated target is placed into a heavily shielded hot cell facility. The top of the target is punctured, the gases inside the target are removed, and a chemical solution is poured into the target. This chemical solution dissolves the HEU coating from the inside of target. The chemical solution is then filtered to remove the molybdenum, which is packed for shipment to the radiopharmaceutical companies. The fourth step is the waste stream management. Materials used in the separation of the Mo-99 product become waste during the processing. The waste would be handled, processed, stored onsite, and then disposed in a low-level waste disposal site.

The chemical recovery of Mo-99 from the targets proceeds only after a decay period of one to six hours after removal from reactor. The processing takes place in sealed hot cells which have fixtures to facilitate remote handing. The molybdenum extraction process stages are represented in Figure 4.4 [33]. After the decay period, the gaseous fission productions are removed by condensation into a trap. Next, the uranium and fission products are dissolved by adding an acid cocktail, H_2SO_4 and HNO_3. The dissolution is aided by heating. Gases evolved during the dissolution are removed by a second trap/condensation step. The targets are then drained and rinsed of the uranium/fission production solution. NaI, $AgNO_3$, and HCl are then added to the raw fission productions to precipitate iodine. Following the iodine precipitation, a molybdenum carrier solution is added to the uranium fission production solution. This is followed by the addition of an oxidizing agent, $KMnO_4$. After the desired oxidation states of the species in solution are reached, carriers are added for rhodium and ruthenium, and then molybdenum is selectively precipitated by the addition of α-benzoin-oxime. The precipitate is separated from the solution by filtrating. Multiple acid rinse steps and filtration are necessary to insure maximum molybdenum recovery. The generated filtrate is set aside for neutralization and then is processed as waste.

The recovered molybdenum is then treated to several purification steps [33]. First the filtercake is washed repeatedly with H_2SO_4. The precipitated iodine is still present at this point of process. The molybdenum precipitate is then dissolved by adding a base solution, such as NaOH, containing an oxidizing agent (H_2O_2) and heating. This dissolution step is repeated twice and the resulting solutions are collected in a single vessel along with a rinse solution. By measuring the activity of the collected solution, the present of molybdenum is verified at this point. The solution is then purified by passing it through a column to adsorb impurities. This step removes iodine and other impurities. After rinsing the column, the resulting clear, colorless solution is monitored for activity to verify that the molybdenum was not retained on the column. Next, another iodine precipitation process is performed on the solution. The solution is then filtered through a second column containing three separate purifying agents, silver on charcoal, hydrated zirconium oxide, and activated carbon. The resulting final product solution is passed through a 0.2 micron (μm) filter into the final product bottle. The activity of the product is measured and samples are submitted for assay and quality control. Quality control checks are conducted on the Mo-99 concentration, α-contamination, and radionuclide purity. The batches, which fail to meet purity specifications, may be reprocessed and purified as necessary.

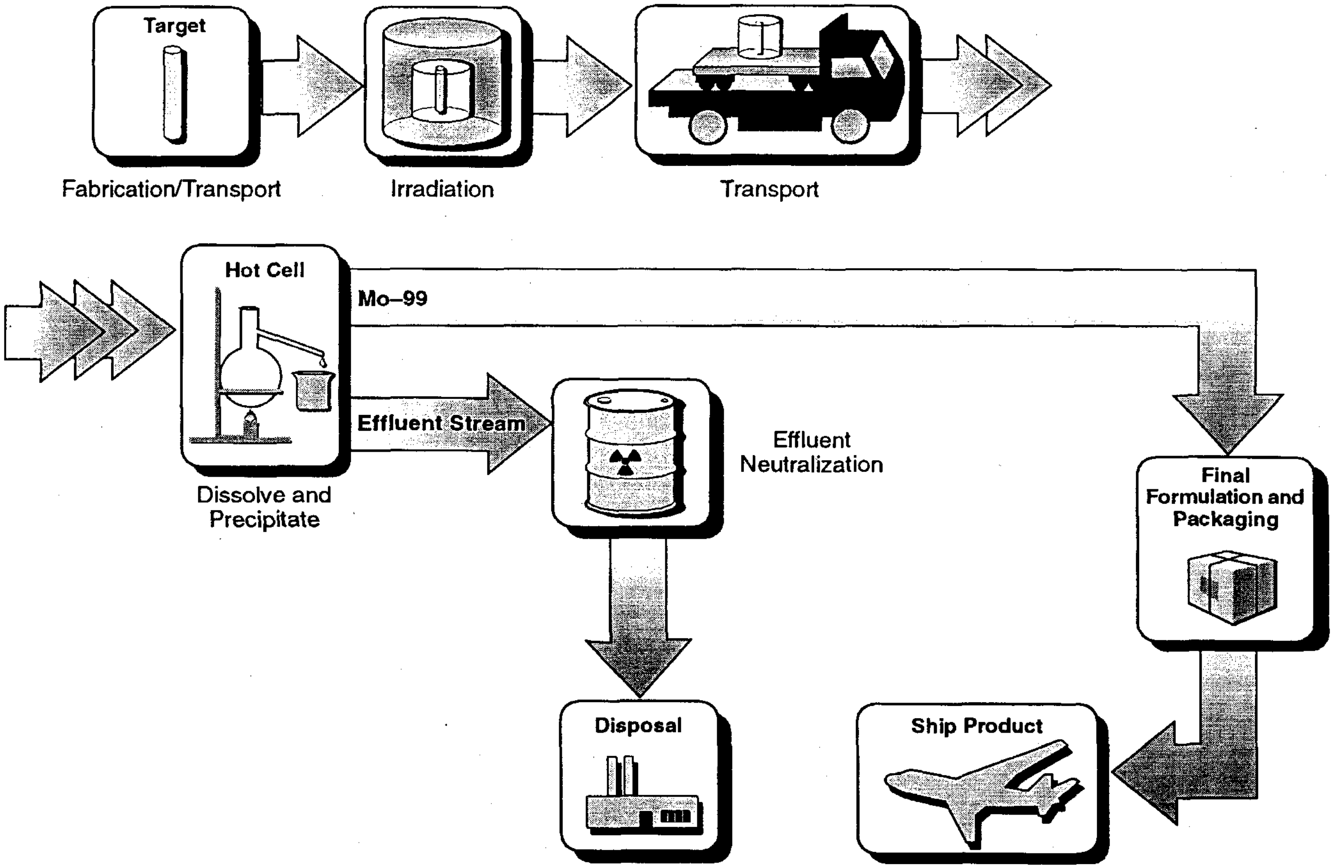

Figure 4.3 Mo-99 Production Process [5]

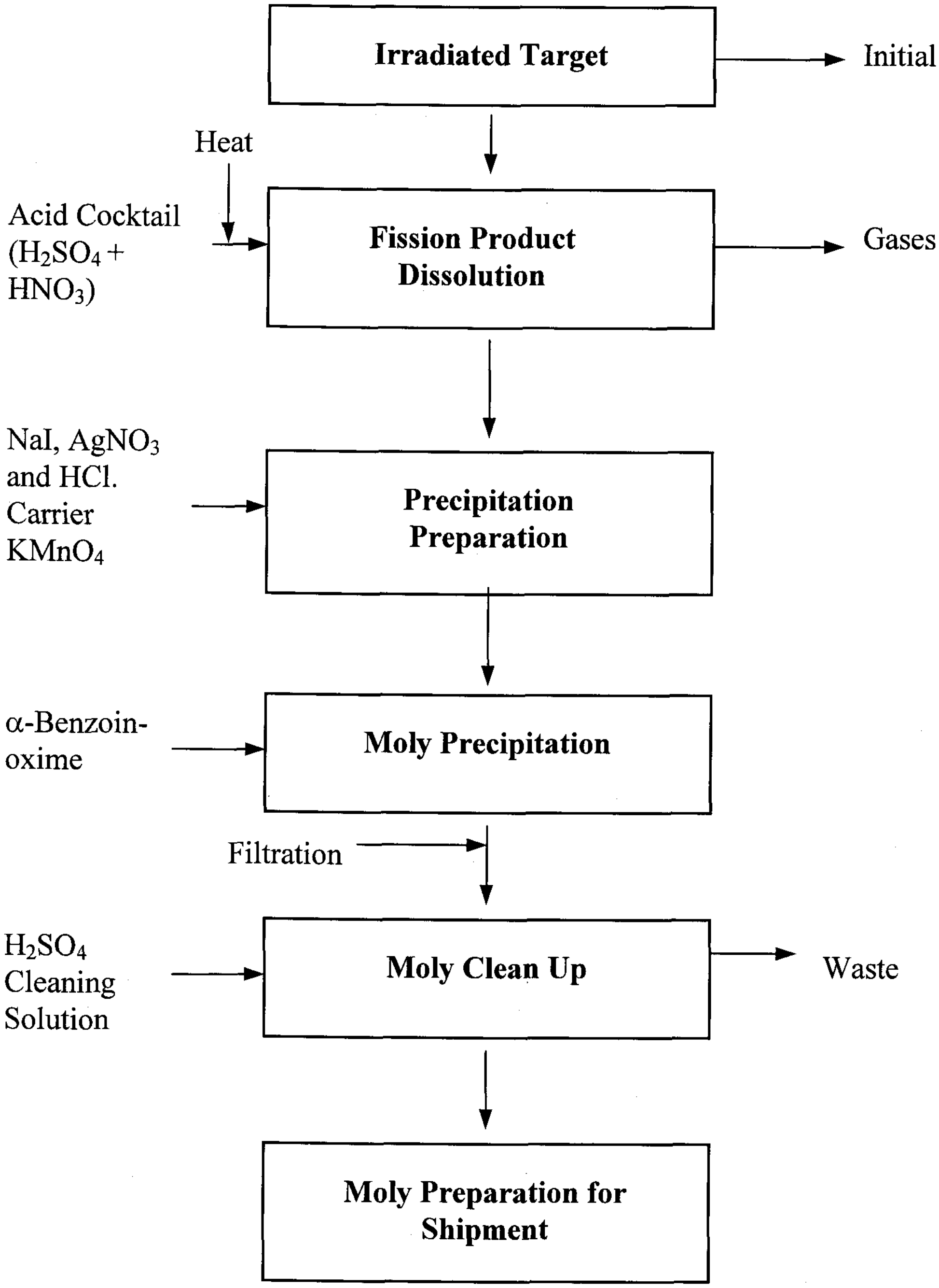

Figure 4.4 Cintichem Mo-99 Extraction Stages [33]

Although exact processing schedules would be different with facility and process conditions, main factors are common to all production modes: (1) a cooling period between discharge and processing, (2) processing, (3) assay, (4) loading for shipment, and (5) delivery to customer [10]. The cooling period is necessary to reduce the target radioactivity and heat from decay of isotopes with very short half-lives. Process time is determined primarily by target design and chemistry. Assay is necessary to ensure that the product is acceptable for medical use required by FDA. Loading includes measuring and dispensing, and preparation of packages for shipment. Shipping times depend on the carrier schedules. The example of representative process schedule, with the percentage of Mo-99 at each step, is given in Table 4.1 [10]. It shows that the invoice curie, which is the curie quantity billed to customer, is only 8% of the reactor curie, which refers to the curie content of the target at discharge from the reactor.

4.3 Proposed Solution Target

This study provides a method for producing medical isotopes such as Mo-99 from a homogeneous aqueous target of uranium solution. The advantage of such a target is its safety feature due to the large negative temperature and power reactivity coefficients, convenience for manufacturing, easy extraction process, small amount of waste generation, and low capital cost.

Table 4.1 Representative Process Schedule for Fission Based Mo-99 Production [10]

Operation	Operation Time(hr)	Elapsed Time (Hour)	(Day)	% of Reactor Curie (%)
Discharge from reactor	0	0	0	100
Cooling; transfer to process	24	24	1	78
Processing, assay(assume 10% process loss)	24	48	2	55
Preparation for shipment(assume 5% loading loss)	12	60	2.5	46
Shipment to customer	24	84	3.5	36
Decay allowance	144	228	9.5	8

The Medical Isotope Production Reactor (MIPR) concept developed by Babcock & Wilcox would use an aqueous solution of uranyl nitrate in an aluminum or stainless steel vessel immersed in a large pool of water, which can provide shielding and a medium of heat exchange [34]. The conceptual drawing of the MIPP is shown in Figure 4.5. The demonstration of Mo-99 production from a liquid-fueled reactor was performed with the LANL Solution High-Energy Burst Assembly (SHEBA) by Glenn [35].

4.3.1 Solution Reactors

Unlike conventional solid fuel type reactors, solution reactors employ a solution fuel, which contains enriched uranium in an aqueous solution. The first of such reactors, known as LOPO (for low power), went critical at Los Alamos National Laboratory (LANL) in 1944 with 565 grams of U-235 in a uranyl sulfate chemical form [36]. The uranium, containing 14.5 % U-235, was dissolved in approximately 13 liters of water contained in a type-347 stainless steel sphere 30.48 cm (1 ft) in a diameter and 0.079 cm (1/32 in.) in wall thickness. The sphere was surrounded by beryllium oxide as reflector in order to minimize the critical mass of the U-235. The lack of a shield and cooling system limited the heat power level of LOPO to 50 milliwatts. A cross-sectional drawing of the LOPO is shown in Figure 4.6.

Following successful low-power operation of the LOPO, it was modified to operate at a high-power and was renamed HYPO (high power) [36]. The critical mass of the modified reactor was increased to 808 grams of U-235 as uranyl nitrate at 14 % enrichment, contained in 13.65 liters of solution. The HYPO reactor operated at a normal power of 5.5 kW, and produced an average thermal neutron flux of 10^{11} neutrons/cm^2/sec.

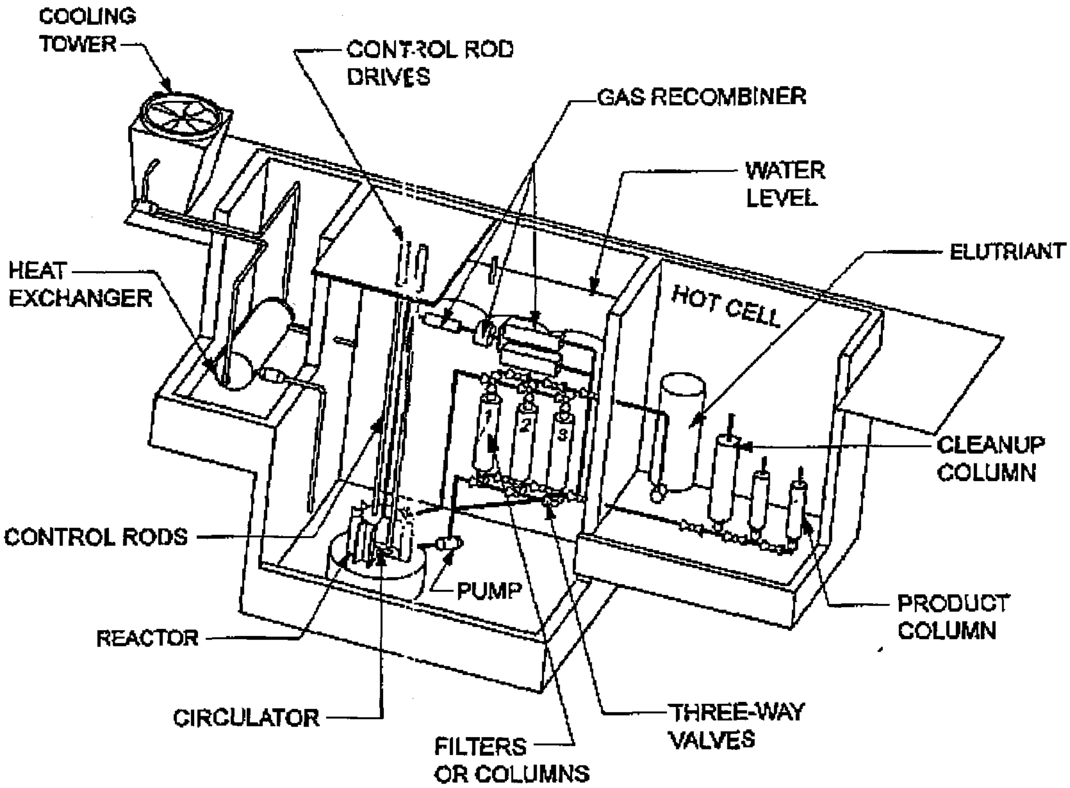

Figure 4.5 Conceptual Drawing of B&W Medical Isotope Production Reactor [34]

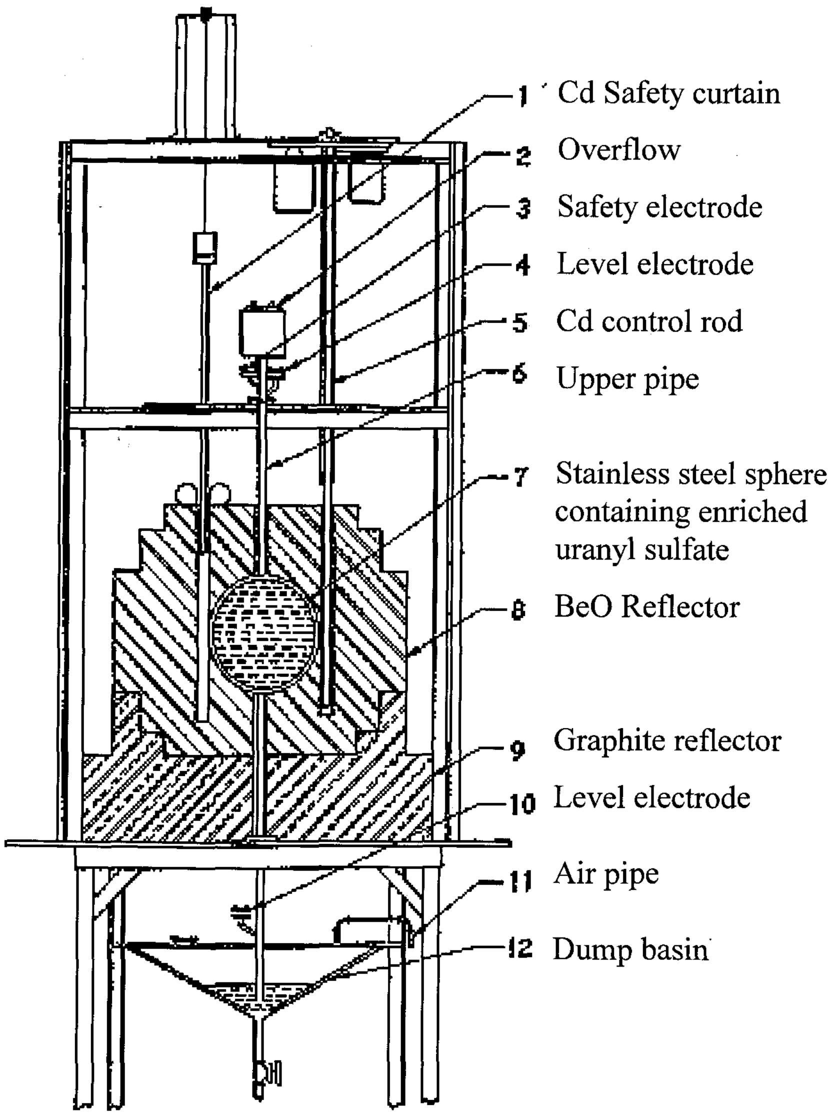

Figure 4.6 Cross Section of LOPO [36]

Since higher neutron fluxes were desired, as well as more research facilities than available from HYPO, the reactor was further modified and rechristened SUPO (super power water boiler). At a power levels of 45kW the peak thermal fluxes was 1.7×10^{12} neutrons/cm^2/sec [36]. These solution reactors were called as "Water Boilers" due to the bubbling that was observed. This bubbling was caused by the evolution of hydrogen and oxygen produced by the decomposition of the water by fission fragments. Reactivity of solution reactors was controlled by the use of control rods, or by the change of the amount of fuel solution in the core, or by the combination of both methods.

Nearly 30 solution reactors, ranging from 0.05 W to 5 MW have been built world-wide (excluding prior Soviet-block countries) [37]. The solutions which were used includes uranyl sulfate (UO_2SO_4), uranyl nitrate ($UO_2(NO_3)_2$), uranyl fluoride (UO_2F_2) or uranium phosphate (UO_2HPO_4) [38]. All of these reactors were built for experimental purposes and were not used for power production missions. Most of these reactors are no longer in service. Today there are only 5 known solution reactors/assemblies that are operating; SILENE, in France; SHEBA, in United States; ARGUS, in Russia; and STACY and TRACY, in Japan [35].

4.3.2 Current Solution Reactors

The Solution High-Energy Burst Assembly (SHEBA), which is located in LANL, was originally constructed during 1980 and was designed to be a clean free-field geometry, right-circular, cylindrically symmetric critical assembly employing a 5 % enriched uranyl fluoride (UO_2F_2) solution as fuel [39]. A second version of SHEBA, employing the same fuel but equipped with a fuel pump and shielding pit, was initiated in 1993. "The major goals of the SHEBA project are to study the behavior of nuclear excursions in a low-enrichment solution, to evaluate accidental criticality alarm detectors for fuel-processing facilities, to provide radiation spectra and dose measurements to benchmark radiation transport calculations on a low-enrichment solution system similar to that encountered in centrifuge enrichment plants, and to provide radiation fields to calibrate personnel dosimetry [39]".

SHEBA is the simplest possible design, in keeping with its application to benchmark calculation methods. The geometry is a simple, unreflected, cylindrical system. Figure 4.7 shows a layout of the critical assembly machine and the relationship between the critical assembly vessel (CAV) and the solution storage tanks. Reactivity is controlled by varying the solution level. A safety rod may be inserted in a thimble along the central axis of the CAV for fast shutdown. Complete shutdown is accomplished by solution dump through two parallel scram valves. The CAV is a 50.8 cm (20 in.) diameter by 76.2 cm (30 in.) long, schedule-20 pipe made of 304L stainless steel and having custom machined flanges welded at the top and bottom.

Japan operates two solution reactors for the nuclear fuel cycle safety analysis: Static Experiment Critical Facility (STACY) and Transient Experiment Critical Facility (TRACY) [40]. When spent fuels are reprocessed, uranium and plutonium are dissolved in nitric acid and treated chemically. This nitric acid solution must be treated with care because a fission reaction can occur under certain conditions. STACY measures the critical mass of uranium solution, plutonium nitrate solution, and their mixtures while varying the density of solution, the tank shape and size, and neutron reflector conditions. STACY attained the first criticality in Feb. 1995 with 35 kg of 10 % enriched uranyl nitrate solution.

TRACY is used to study the supercritical phenomenon of a uranium nitrate solution to confirm the safety margin used in the evaluation of postulated critical accidents in a reprocessing. TRACY attained the first criticality in Dec. 1995. STACY and TRACY are exhibited in Figure 4.8.

The ARGUS solution reactor is operated in Russian Research Center Kurchatov Institute and applied for the elementary analysis, the production of isotopes, and the training of operating personnel. ARGUS is a 50 kW reactor, which employs 21 % enriched uranyl sulfate solution fuel [41]. One of the early solution reactors, SILENE, is still operating in France.

4.3.3 Characteristics of Solution Reactors

The main advantages of the solution type reactors are the inherent safety due to the large negative temperature and power reactivity coefficients, low cost, simplicity of design, simple fuel preparation and reprocessing, high burnup of fuel, high neutron economy by eliminating neutron absorption in structural materials, and continuous purification of the fuel [38].

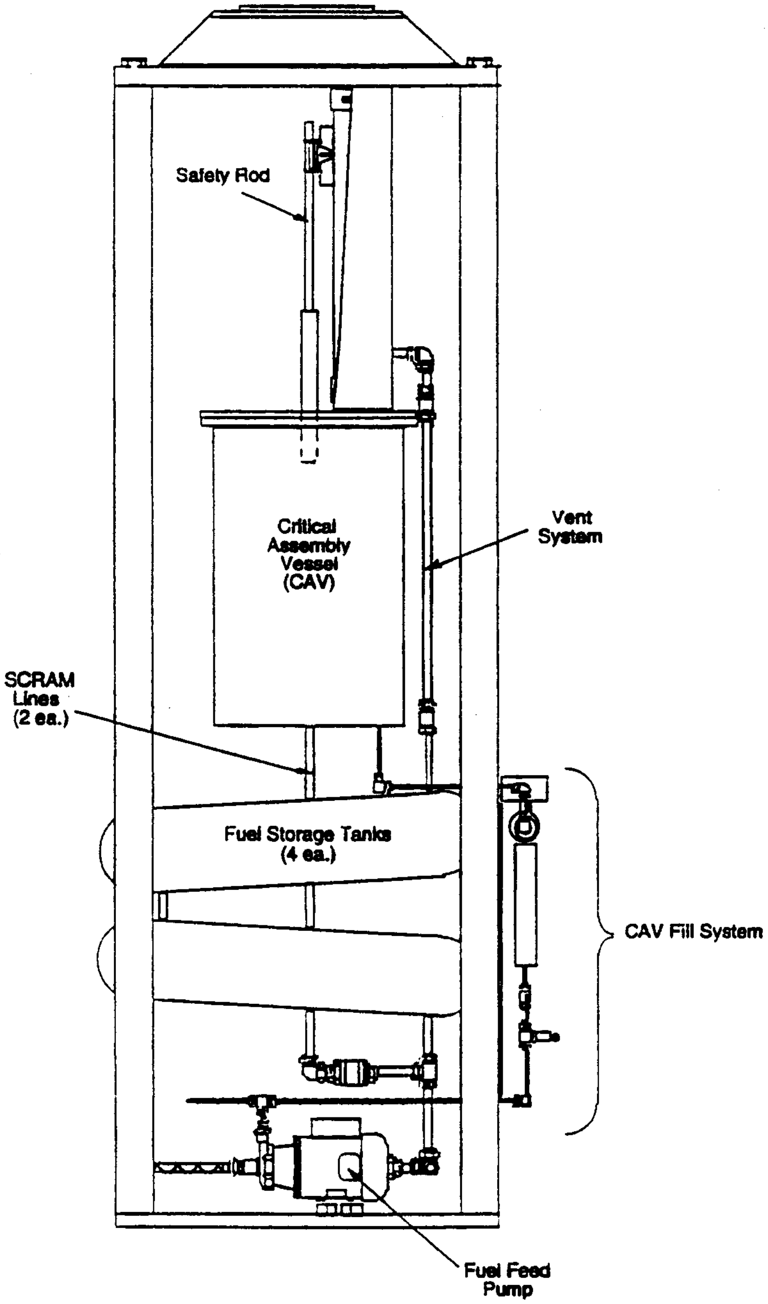

Figure 4.7 Layout of the SHEBA Critical Assembly [39]

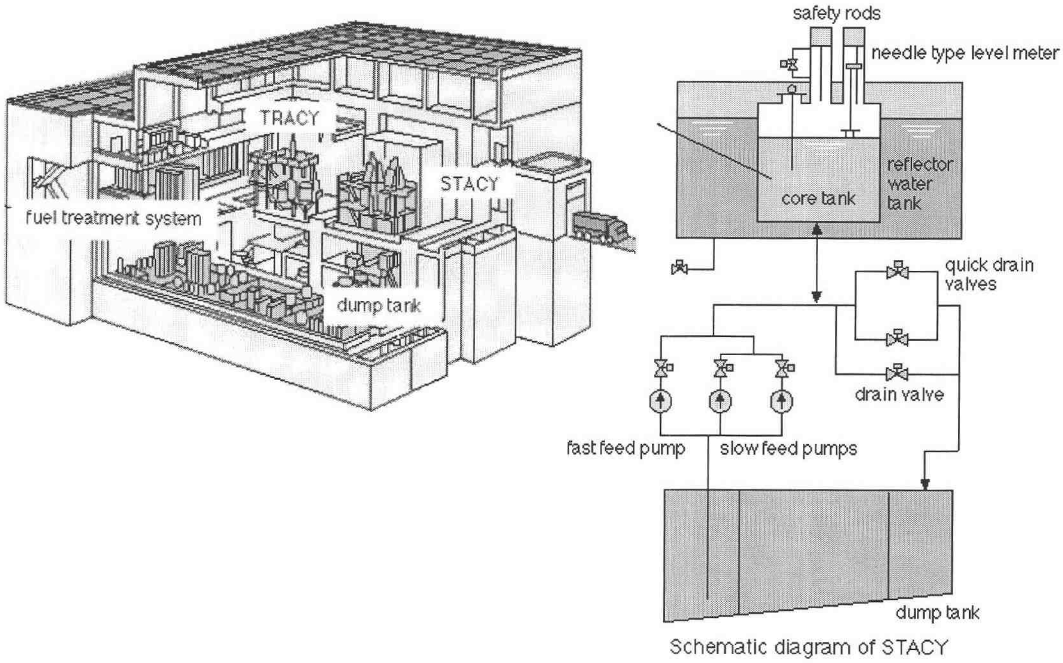

Figure 4.8 View of STACY and TRACY [40]

The disadvantages include the limitation of flux, the explosive product from the radiation-induced decomposition of water, the corrosion and erosion problem due to the acid solution fuel, and the possible precipitation of uranium peroxide if not monitored closely.

The water boiler reactors or aqueous homogeneous reactors have the highest safety margin of any known reactor because of the very large negative temperature coefficient. This characteristic is also found in a uranium solution target.

The solution target would eliminate the complicated fabrication process of the inside coated tube type target. This aqueous homogeneous target could skip the dissolution of the uranium coating from the inside of tube type target in the process. This makes the chemical process simple and can reduce the processing time and the volume of waste generated. The rapid processing period would increase the invoice curies without any changes of target or characteristics of the reactor. After the extraction of fission products, the recovered uranium solution is reused as target material without further processing. All of these factors make the solution target a favorable method for production of Mo-99.

4.3.4 Properties of Solution Fuels

Some of the properties of solution fuels, which effect the adoption as reactor fuel or target, include: chemical and nuclear stability, neutron absorption property, corrosion, and fuel handling and reprocessing.

The solutions used to date are uranyl sulfate, uranyl nitrate, and uranyl fluoride [38]. These solutions have compatible with the corrosion characteristics of stainless steel. In case of Water Boiler Reactor, which used a uranyl nitrate, the reduction of wall thickness was 0.000254 cm for 10-year operation [42]. If the corrosion is occurring uniformly over all exposed surfaces, it is not much serious problem. The chemical stability of uranyl nitrate solution may be somewhat less than that of sulfate and fluoride solutions, but it is satisfactory at low temperature [38].

From the viewpoint of neutron economy, the uranyl fluoride system is more desirable than the sulfate system because the neutron absorption cross section of fluoride is considerably lower than that of sulfur. Similarly, the high absorption cross section of nitrogen makes the nitrate system even less desirable. The chemical processing of aqueous fluoride solution is to be more difficult than that of sulfate or nitrate systems [38].

The irradiation of the water and the solute in solution reactors is of considerable importance in reactor design and operation. The energy dissipated in a fuel solution by fission fragments, the protons gamma rays, neutrons and fast electrons result in the water and fuel decomposition. The reaction products from the water decomposition are hydrogen, hydrogen peroxide, and oxygen. The decomposition may change the properties of ordinary fuel solution and reactor system. The solutes may be acted upon by direct absorption of radiation and also by reaction with the intermediate active species produced by the decomposition of the water.

The rate of hydrogen formation in aqueous homogeneous reactor, in moles per liter per minute, can be expressed to equation [38]:

$$\frac{d(H_2)}{dt} = 0.00622\,[\, G_f \times W_f + G_p \times W_p + G_e \times W_e \,] \qquad (4.1)$$

where G is the hydrogen yield in molecules per 100 eV absorbed, W is the power density in kW per liter, and the subscripts f, p, and e refer to the values for recoil fission particles, protons produced by neutron scattering, and electrons produced by gamma ray absorption, respectively. About 96 % of hydrogen gas produced in the solution reactor operation is from the fission recoil particles. Neutrons and gamma rays make 2 % of hydrogen gas each. Therefore the last two terms in equation (4.1) are usually neglected. The value of G_f can be obtained from Figure 4.9 and the value of W_f can be calculated from the nuclear data of a reactor operation. Along with the hydrogen, an equivalent amount of oxidant (either oxygen or peroxide) will be formed.

4.3.5 Separation of Molybdenum-99 from Irradiated Solution Fuel

Numerous methods had been reported for the separation of Mo-99 from fission products [43 –56]. Fission-produced Mo-99 is acquired from the separation of irradiated UO_2 or U-Al alloy. Most solid target processes started from the dissolution of irradiated target elements. A single separation step can not achieve

RADIATION EFFECTS

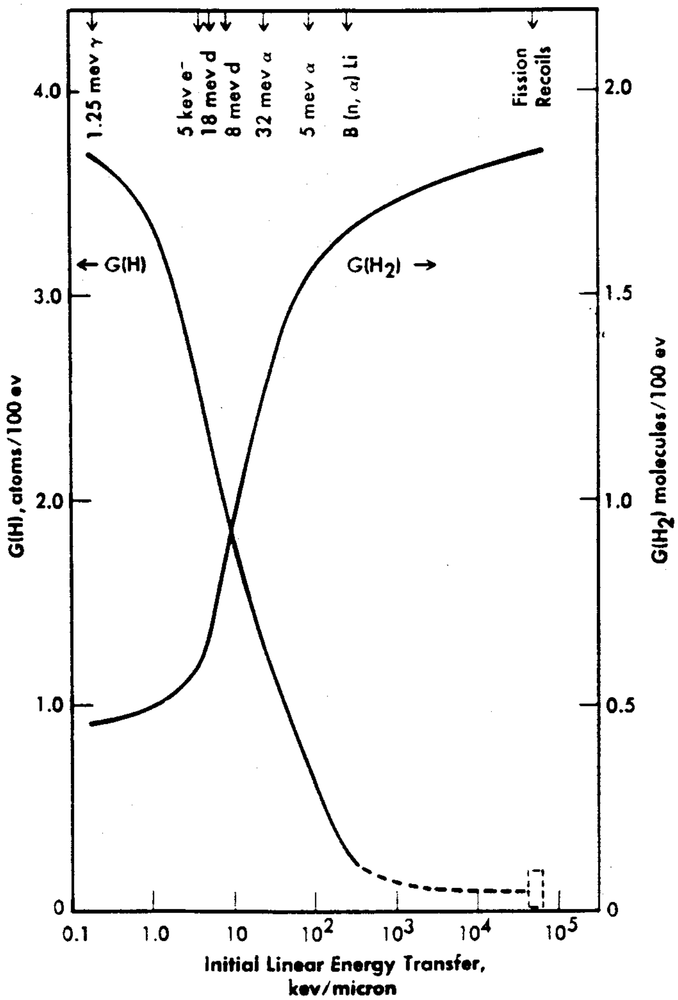

Figure 4.9 Yields of Atomic and Molecular Hydrogen from the Decomposition of Water by Various Ionizing Radiation [38]

the required purification of Mo-99 for the medical applications. The chemical process must be focused on the high recovery yield of Mo-99 and uranium, the high purity of Mo-99 product, minimum liquid and solid nuclear waste, and simple operation and easy remote maintenance.

A chemical process for the separation of fission Mo-99 from the liquid fuel solution of Water Boiler Reactor and the recycling of uranium to the reactor was developed by Chen *et al.* [53]. This study used a synthetic uranyl sulfate solution as a reactor fuel. The flow diagram of this process is represented in Figure 4.10.

Mo-99 is separated by the method of α-benzoin oxime precipitation from a large amount of uranium, which is contained in fuel solution. The α-benzoin oxime is a selective precipitant for molybdenum and is open used in the determination of molybdenum in steel and pig iron. After filtration, the Mo (α-benzoin oxime) precipitate is dissolved in an alkali solution. The pH of solution is adjusted to 2 with ascorbic acid. To remove the fission product impurities, Mo-99 is purified by a chelating ion-exchanger and washed successively with ascorbic acid at pH = 2, 0.05M HF, and distilled water. Further purification is carried out by alumina adsorption in diluted nitric acid. The eluate is directly passed through a calcium phosphate hydroxide column for decontamination of trace amounts of Pu-239, Sr-89, Sr-90, and other radionuclides. The Mo-99 product solution is finally concentrated and filtered for the preparation of a Tc-99m generator.

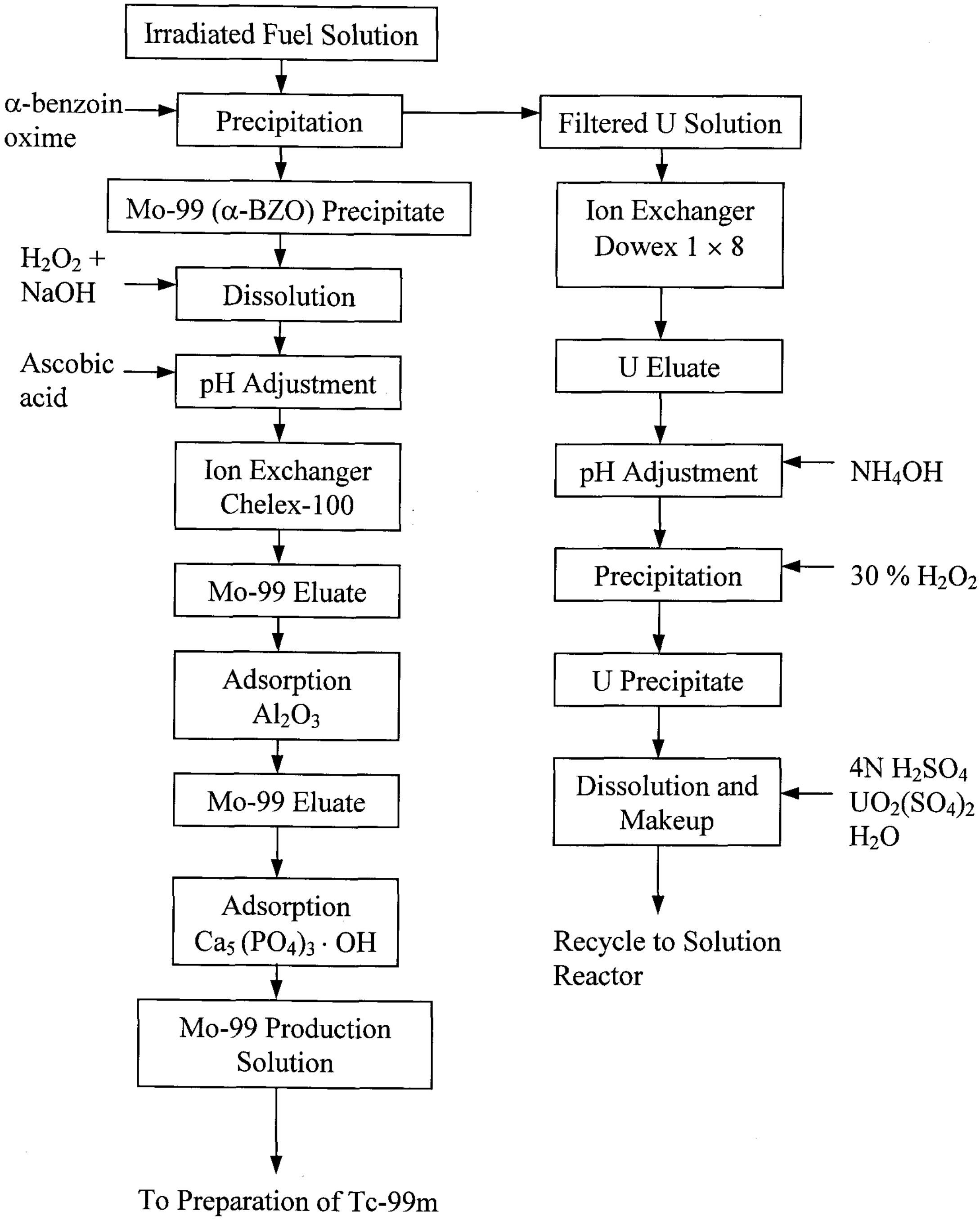

Figure 4.10 Mo-99 Separation and U Recycling Process from Fuel Solution [53]

Uranium in the filtrate after the precipitation of Mo-99 is separated by anion-exchanger AG 1 × 8. It is eluted with nitric acid and concentrated by precipitation with hydrogen peroxide at pH = 2 ~ 3. Th precipitate is then dissolved in appropriate amount of sulfuric acid and is made up the same composition as Water Boiler Reactor fuel solution for recycling to the reactor.

The experimental result of Chen's work concluded that overall recovery yield of Mo-99 product solution with this method, which is called PIAA (Precipitation/ Ion exchange/ Adsorption/ Adsorption) was 80.0 ± 1.5 %. Its purity from other fission products was quite satisfactory for medical application. The uranium recovery yield was 98.5 ± 0.3 %. The removal of gross γ activity is about 78 % with respect to the initial content of a synthetic fuel solution.

This Mo-99 separation and uranium recycling method can be applied to the solution target, which is investigated in this work. It could be performed in continuous operation in a hot cell where α-benzoin oxime precipitation can be used for the separation of fission Mo-99 in nitric acid medium [33].

4.3.6 The Goal of Target in This Study

TRIGA reactors are designed by General Atomics for use in training, research, and isotope production. A distinguishing characteristic of TRIGA design is the exceptionally large prompt negative temperature coefficient value due to the zirconium hydride in the fuel. This characteristic means that any increase in temperature results in a decrease in reactor power.

It has been suggested that TRIGA reactors could be used to produce Mo-99 in DOE's medical isotope production project. But this suggestion was rejected because of several reasons[5]. The primary concern is replacement of TRIGA fuel with fissionable material that contains no zirconium hydride could impacts the inherent safety mechanism of the TRIGA design. The zirconium hydride creates the strong negative feedback mechanism characteristic with the TRIGA reactor. As fuel is replaced, the reactor dynamic parameters would be changed and the licensing would be impacted.

The solution target can overcome the safety difficulty of replacing fissionable target that has no zirconium hydride. The early study of a solution fuel reactor showed that this type reactor had large negative temperature coefficient characteristic value. This unique aspect could be applied to solution target in TRIGA. The temperature coefficient value of the 70 % enriched FLIP in OSTR is ~ 1 ¢/ °C [27], while for the water boiler it is ~ 2.5 ¢/°C at 30 °C [42].

The following criteria are applied to target designs in this work: The design of target should be simple and approproately sized for installation in the OSTR and to be generally accepted by current and future producers of Mo-99. The manufacture of target and disassembly of irradiated target should be straightforward to minimize capital cost and processing time. The target should have good heat transfer properties to guarantee removal of fission heat. The target also should have safety features for minimizing the potential radionuclide release to the environment.

Removal of the uranium from an irradiated target for reuse would reduce the amount of mixed waste produced in the Mo-99 extraction and the cost of uranium.

The goal of the target design is to minimize the U-235 loading subject to important yield and safety constraints. The optimized constraints are:

- Mo-99 yield at equilibrium is greater than 25 Ci/g U-235 for economy.
- Target power and surface heat flux are must be less than the maximum allowable power and surface heat flux of fuel in core for safety.
- Target can be fitted in the fuel position or in a portion of core without modifying the core.

CHAPTER 5
MOLYBDENUM-99 PRODUCTION USING OSTR

Two types of target designs are considered in the analysis. The first is the same outer dimension as a standard OSTR fuel element but allows uranium solution inside. The other is the continuous flow target system like a solution fuel reactor system. Targets are examined with two chemical forms and compared with the conventional target. The analyses to be performed include the neutronic analysis, chemical separation process of Mo-99, and the modification of OSTR for Mo-99 production mission.

5.1 Tube Type Target

5.1.1 Designed Target Model

The tube type target is very similar shape to the OSTR fuel rod and is shown in Figure 5.1. It does not require any modifications to the existing core. This target just replaces a fuel rod in that position.

The active section of this target is 38.1 cm (15 in.) in length, 3.63 cm (1.43 in.) in diameter, and contains the enriched uranium solution. The bottom graphite slug, 8.89 cm (3.5 in.) in length and 3.56 cm (1.4 in.) in diameter, acts as a reflector. The top void remains for the thermal expansion of the solution and the radiolytic gases, which are produced. The active section, bottom graphite slug and top void section are contained in 0.0508 cm (0.02 in.) thick stainless steel cladding. The cladding is welded to the top and bottom fitting. The active section and the graphite reflector are divided with stainless steel. The U-235 loading and uranium compound of the active section can vary but will be 20% and 93% enriched uranyl nitrate and sulfate uranyl solution in this analysis.

5.1.2 Neutronic Analysis

Analyses using MCNP focused on the effect of targets to the OSTR and the amount of Mo-99 production in the location and number of targets. The targets are placed in the center area of the reactor (thimble, B-ring and C-ring) to maximize the neutron flux level. The active target section contains 7.3 weight percent uranium in solution, enriched to 20 or 93% in U-235 (6.689g or 31.104g of U-235, respectively). The effects of neutron flux and Mo-99 production with the insertion of the target were investigated for four plausible configurations: 1) one target in central thimble; 2) three targets in B1, B3, and B5; 3) six targets in "B" ring; 4) ten targets in " C " ring.

In practice, reactivity adjustments through the control rod movement or through the addition or removal of fuel elements would be necessary to achieve a k_{eff} of unity. The values of fuel element and target powers presented for a given configuration are subject to some change, depending on the method used to adjust reactivity. The reactivities were regulated by the control rods to achieve the k_{eff} of unity in these investigations.

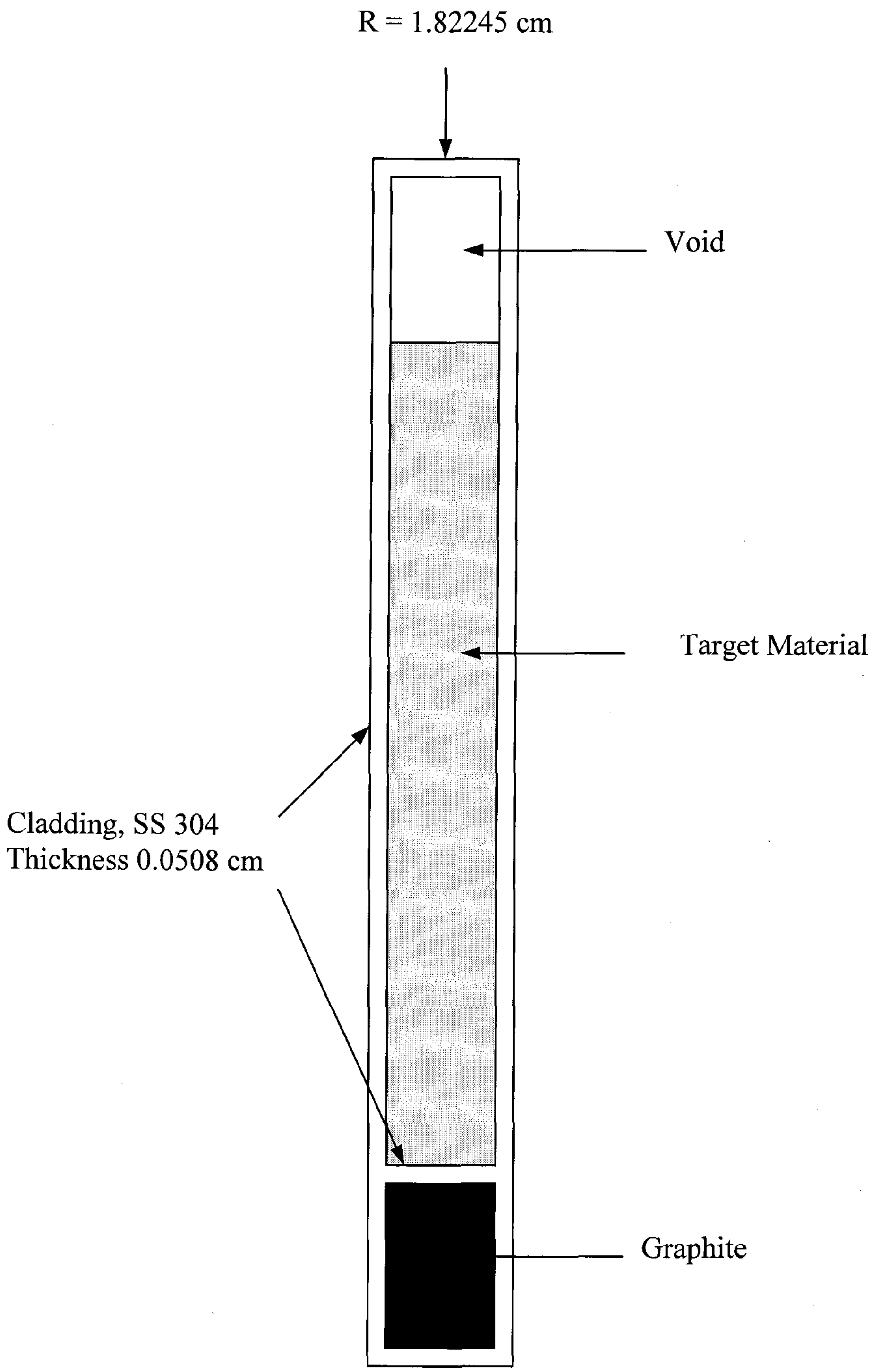

Figure 5.1 Tube Type Target Model

The build-up of Mo-99 balances between production and removal. Mo-99 only is produced by the fission of U-235 with the effective fission yield of 6.1 %, but is removed through decays and transmutation by the absorption of neutrons. The production rate is governed by the equation:

$$\frac{dMo}{dt} = \gamma\,\Sigma_f\,\phi - \lambda\,Mo - \sigma_a\,\phi\,Mo \qquad (5.1)$$

or

$$Mo(t) = \frac{\gamma\,\Sigma_f\,\phi_0}{\lambda}\,(1 - e^{-(\lambda + \sigma_a \phi)t}) \qquad (5.2)$$

where Mo is the atomic number of Mo-99 at time t

γ is the effective fission yield of Mo-99

Σ_f denotes the macroscopic fission cross section

ϕ denotes the flux at time t; ϕ_o is the flux at t = 0, and

λ is the decay constant of Mo-99.

In MCNP, the fission reaction rate ($\Sigma_f\phi$) can be evaluated directly from F4 flux tally card and FM tally multiplication card. The F4:n tally describes the flux averaged over a cell with a unit of particles/cm^2. The FM card is used to calculate any quantity of the form

$$C\int \varphi(E)\,R(E)\,dE \qquad (5.3)$$

where φ(E) is the energy-dependent fluence (particles/cm^2) and R(E) is an operator of additive and/or multiplicative response functions from MCNP cross-section libraries or specially designated quantities. MCNP has some unique cross-section library reaction numbers, which are listed in MCNP manual [28]. For instance, R = -6 in neutron mode means total fission cross section. The constant C is any arbitrary scalar quantity that can be used for normalization. The following is an example of the simple tally example for the total fission reaction numbers calculated for a 94% enriched uranium cell number 2.

```
F4:N   2                M = 1, material card number

FM4   -1      1      -6
                        R = -6, reaction number for total fission cross section
C = -1, multiply by atomic density of material 1

M1     92235  -94.00          92238  -6.00
```

This fission reaction includes (n, f), (n, n'f), (n, 2nf), and (n, 3nf) in the cell.

5.1.2.1 *Uranyl Nitrate Solution*

Enriched 20 % and 93 % uranyl nitrate solution targets were examined for four configurations. The proposed Medical Isotope Production reactor of Babcock & Wilcox will utilize uranyl nitrate solution either. The physical characteristics of the two uranyl nitrate solution targets are shown in Table 5.1 and 5.2, which have same uranium weight fraction (7.3 wt. %) in target. The data in Table 5.2 are modified from LANL Water Boiler Reactor [42]. It had used 88.7 % enriched uranium solution as a fuel.

Table 5.1 Physical Characteristics of Uranyl Nitrate Solution Target

Solution Volume	397.01475 cm^3
Solution Density	1.15197 g/cm^3
Uranium Weight Percent	7.3 %
U-235 in Target	31.104 g in 93 % enriched solution
	6.689 g in 20 % enriched solution

Table 5.2 Uranyl Nitrate Solution Target Composition in Weight Percent

	93 % Enriched Solution	20 % Enriched Solution
Uranium-235 (%)	6.801	1.4626
Uranium-238 (%)	0.5125	5.8509
Nitrogen (%)	1.2986	1.2986
Hydrogen (%)	9.6382	9.6382
Oxygen (%)	81.7497	81.7497

Case 1 - One 20 % enriched target in central thimble

This calculation examined one 20% enriched target simply placed in the center of core (central thimble). The results showed target power achieved 3.27 kW with 1 MW power operation. The peak neutron flux appeared at the central thimble. The maximum fuel power was 16.93 kW. With this configuration, 155 Ci of Mo-99 would be produced after 7-day irradiation.

Case2 - Three 20 % enriched targets in B-1, 3, 5

Three 20% enriched targets were placed in the B-ring instead of fuel; B-1, B-3, B-5. Because of a lower amount of U-235 compared to the Flip fuel, k_{eff} dropped below the unity. The control rods were moved to achieve the criticality. Average target power achieved was 3.78 kW for 1 MW operation. Maximum fuel power was 20.25 kW at B-ring with this configuration. The power peaking caused from more neutron moderation near the fuel elements in B-ring than normal operation was due to the water in solution targets. This peak power is below the allowable maximum Flip fuel element power (24 kW) [27]. The operation for 7 days would produce 534 Ci of Mo-99.

Case 3 - Six 20 % enriched targets in B-ring

Six Flip fuel elements were replaced with targets in B-ring. The k_{eff} also dropped below the unity and control rods were adjusted to achieve criticality. Average target power of 4.75 kW was found with this configuration for 1 MW operation. The fuel power was peaked at C-ring with 16.4 kW. This configuration produced 1344 Ci of Mo-99 for 7-day irradiation.

Case 4 - Ten 20 % enriched targets in C-ring

Ten 20 % enriched targets were placed in the C-ring instead of fuel. The k_{eff} dropped below the unity. The criticality was achieved with the movement of the control rods. Average target power of 4.19 kW was found with this configuration for 1 MW operation. The peak fuel power was 18.57 kW at B-ring. This configuration produced 1976 Ci of Mo-99 for 7-day irradiation.

Case 5 - One 93 % enriched target in central thimble

In this configuration a 93% enriched target was placed in the central thimble. The k_{eff} raised up the unity and was adjusted with control rods. The calculation showed 10.7 kW of fission power could be generated in the target for 1 MW operation. This would produce 504 Ci of Mo-99. The peak fuel power was 15.6 kW at B-ring.

Case 6 - Three 93 % enriched targets in B-1, 3, 5

Three 93 % enriched targets were placed in the B-ring: B-1, 3, 5. Criticality was again achieved through control rods movement. The results showed the average target power was 12.1 kW for 1 MW operation. This configuration achieved 1716 Ci of Mo-99. Maximum fuel power of 19 kW was found. This power peaking is a same reason as *case 2* mentioned early. It is below the safety level.

Case 7 - Six 93 % enriched targets in B-ring

This configuration examined six targets in the B-ring fuel element positions. Average target power of 14.9 kW was found with this configuration for 1 MW continuous operation. This configuration would produce 4225 Ci of Mo-99 for 7-day irradiation. The peak fuel power was 16.3 kW at C-ring.

Case 8 - Ten 93 % enriched targets in C-ring

This configuration examined ten 93 % enriched targets in the C-ring. The results showed the average target power was 12.58 kW for 1 MW operation. This configuration achieved 5930 Ci of Mo-99. Maximum fuel power of 17.98 kW was found.

The radial neutron fluxes at a center of the core (at z = 0) are shown in Figure 5.2 and 5.3 for various configurations. Due to the effect of neutron moderation in target, the neutron flux in all target positions is higher than normal FLIP core. Figure 5.4 and 5.5 show the averaged radial neutron flux (total and energy is less than 1.0 eV) over the active core length. Figure 5.6 indicates the total amount of Mo-99 produced and the yield to U-235 for each case. Low enrichment targets give higher yield than high enrichment. This says the decreasing water to U-235 ratio in the target locally causes the increases in thermal flux and target fission density of target. The pertinent characteristics for the examined configurations are summarized in Table 5.3.

5.1.2.2 *Uranyl Sulfate Solution*

Uranyl sulfate has been used as a fuel in some aqueous homogeneous reactors. The sulfate was preferred to the nitrate because of the greater radiation stability, smaller parasitic neutron absorption, and a higher uranium concentration. The uranyl sulfate solution targets are examined in this study and are compared with the uranyl nitrate solution targets. Table 5.4 and 5.5 show the physical characteristics of 20 % and 93 % enriched uranyl sulfate solution targets. These solutions are modified from the 1500-W L-6 reactor, which was operated by Atomics International in 1957 [57].

Table 5.3 Reactivity Worth, Target Power, Peak Fuel Power, and Mo-99 Production for Various Configurations of Targets in Core†.

Configuration	k_{eff}	Avg. Target Power(kW)	Peak Fuel Power(kW)	Total Activity of Targets(Ci)	Yield, (Ci/g U-235)
Standard Core	1.00454	NA	15.57	NA	NA
Case 1	1.01238	3.27	16.93	155	23.84
Case 2	0.99911	3.78	20.25	534	26.61
Case 3	0.97646	4.75	16.42	1344	34.52
Case 4	0.96880	4.19	18.57	1976	30.45
Case 5	1.01735	10.69	15.57	504	16.21
Case 6	1.01617	12.13	18.98	1715	18.38
Case 7	1.01870	14.93	16.35	4225	22.64
Case 8	1.02564	12.58	17.98	5930	19.06

† The values are based on a total (targets + fuel elements) power of 1 MW.

Table 5.4 Physical Constants of Uranyl Sulfate Solution Target [57]

Solution Volume	397.01475 cm^3
Solution Density	1.103 g/cm^3
Uranium Weight Percent	7.3 %
U-235 in Target	29.73 g in 93 % enriched solution
	6.393 g in 20 % enriched solution

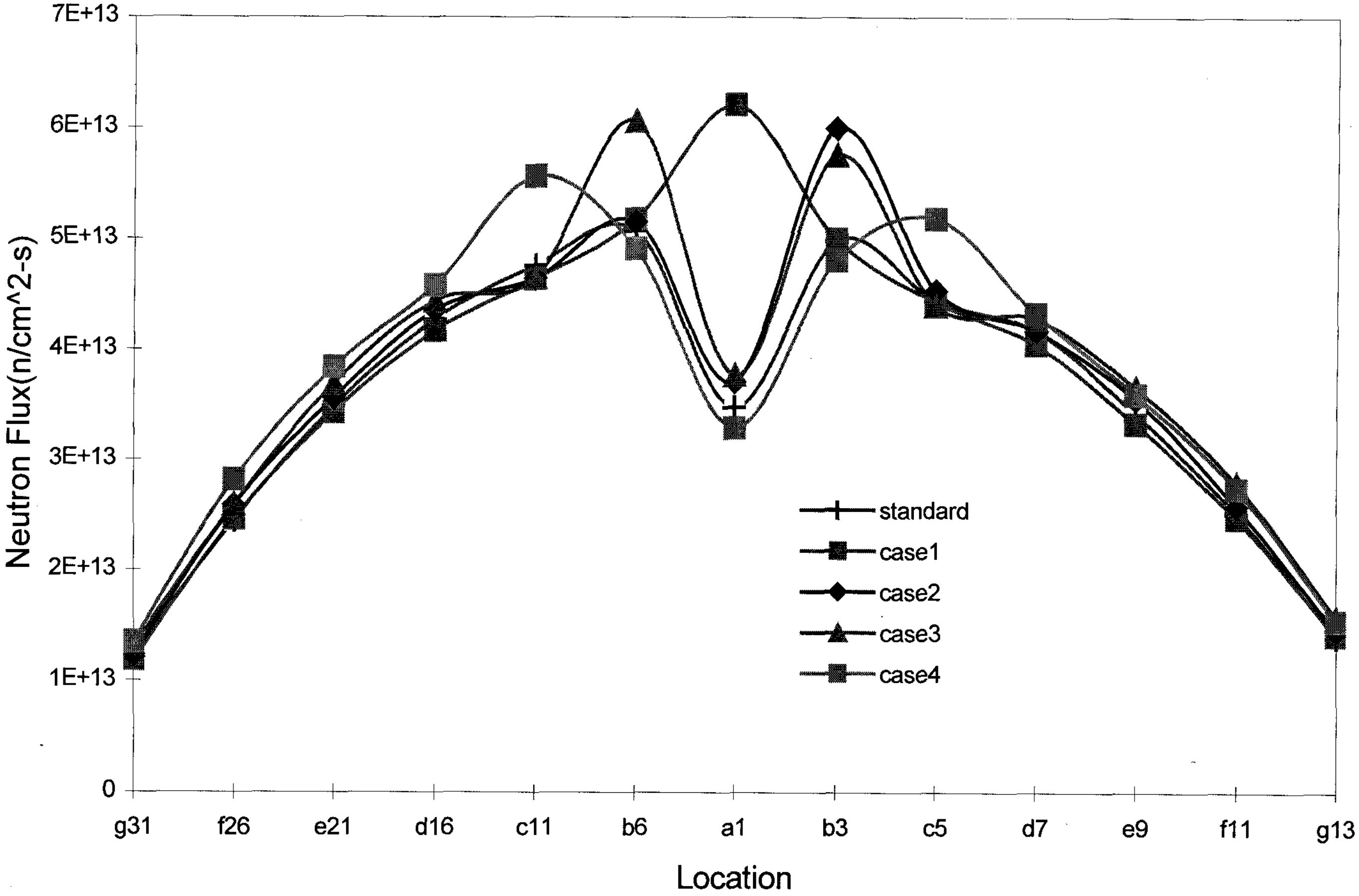

Figure 5.2 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 1 – Case 4

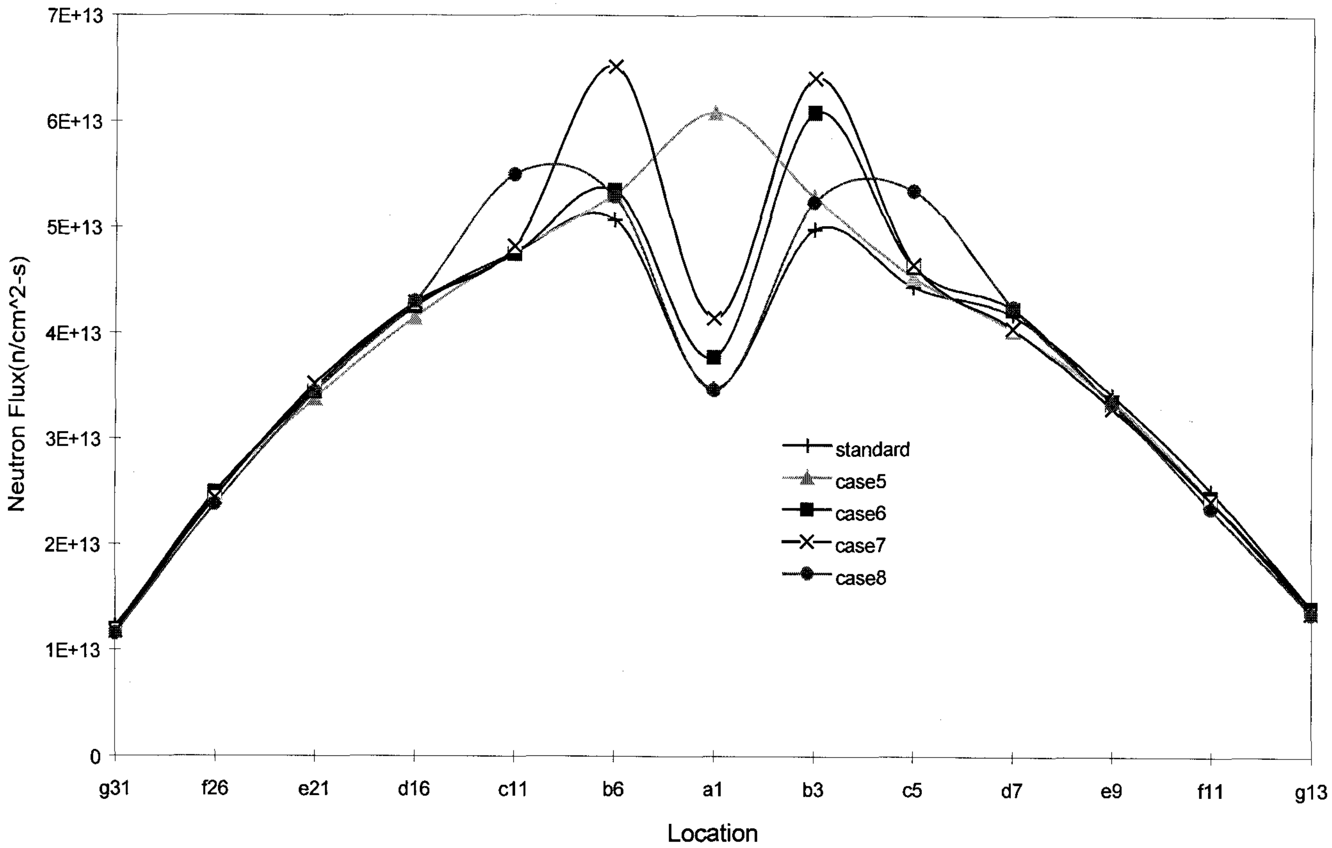

Figure 5.3 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 5 – Case 8

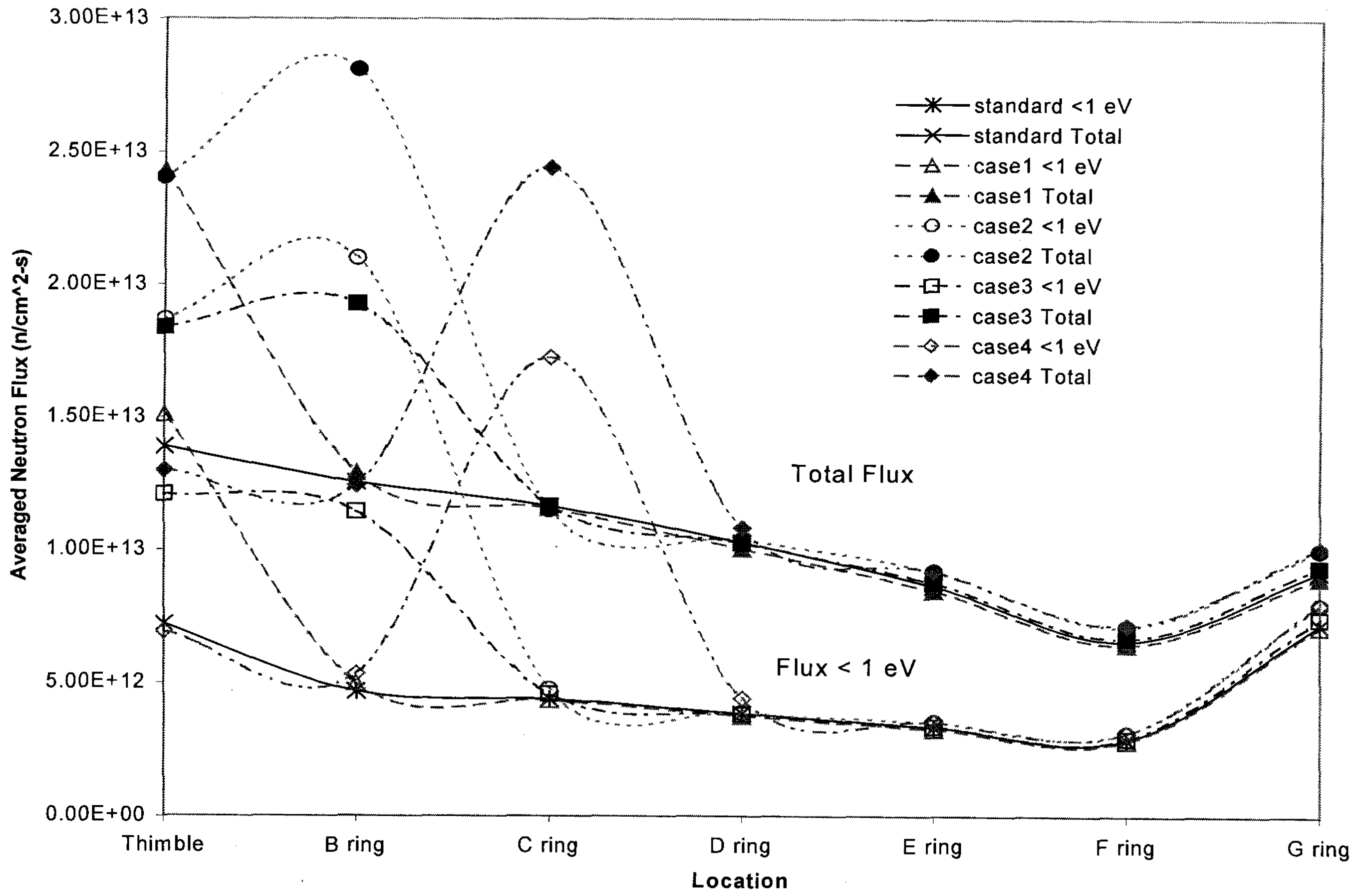

Figure 5.4 Averaged Neutron Flux over the Active Core Length, Case 1 – Case 4

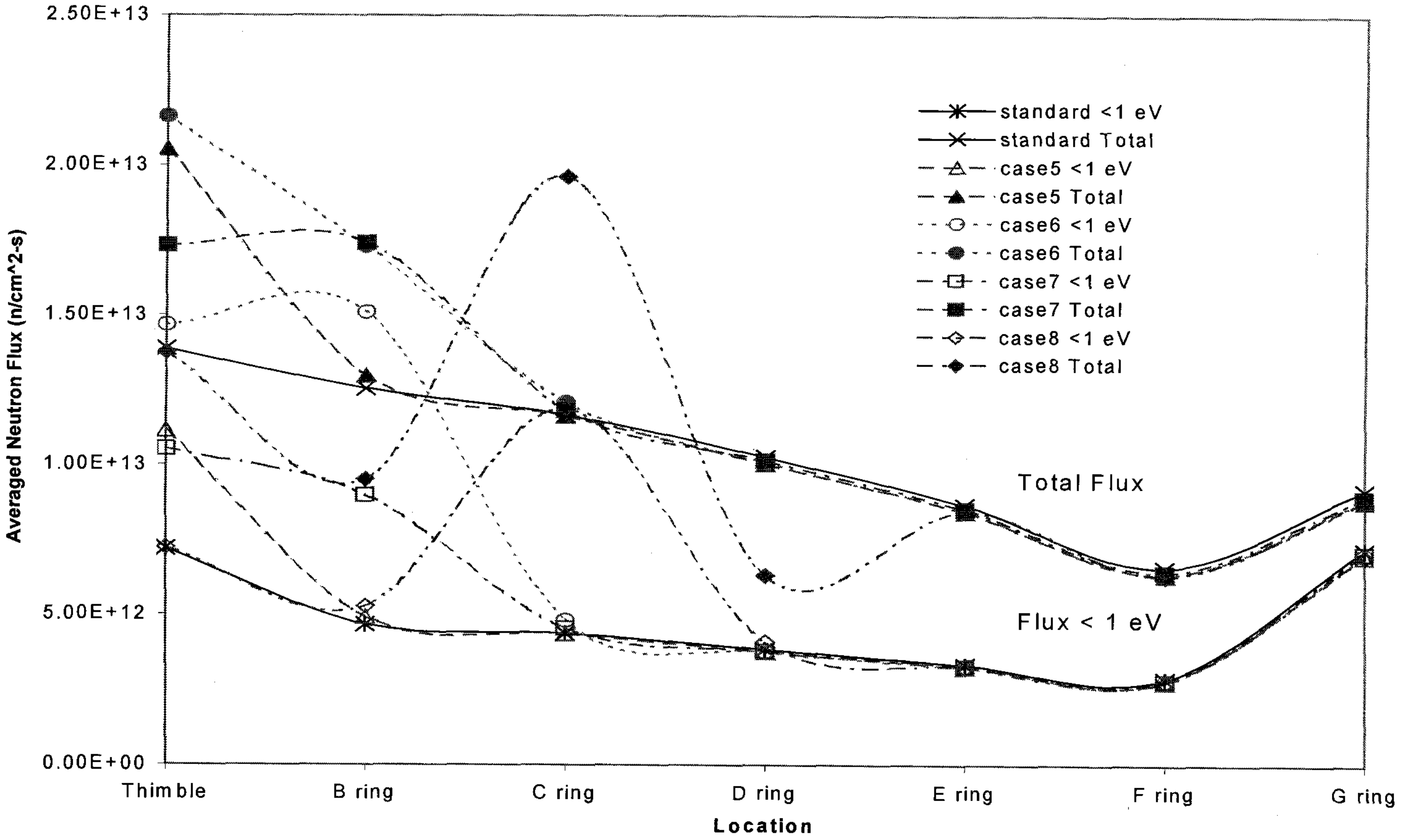

Figure 5.5 Averaged Neutron Flux over the Active Core Length, Case 5 - Case 8

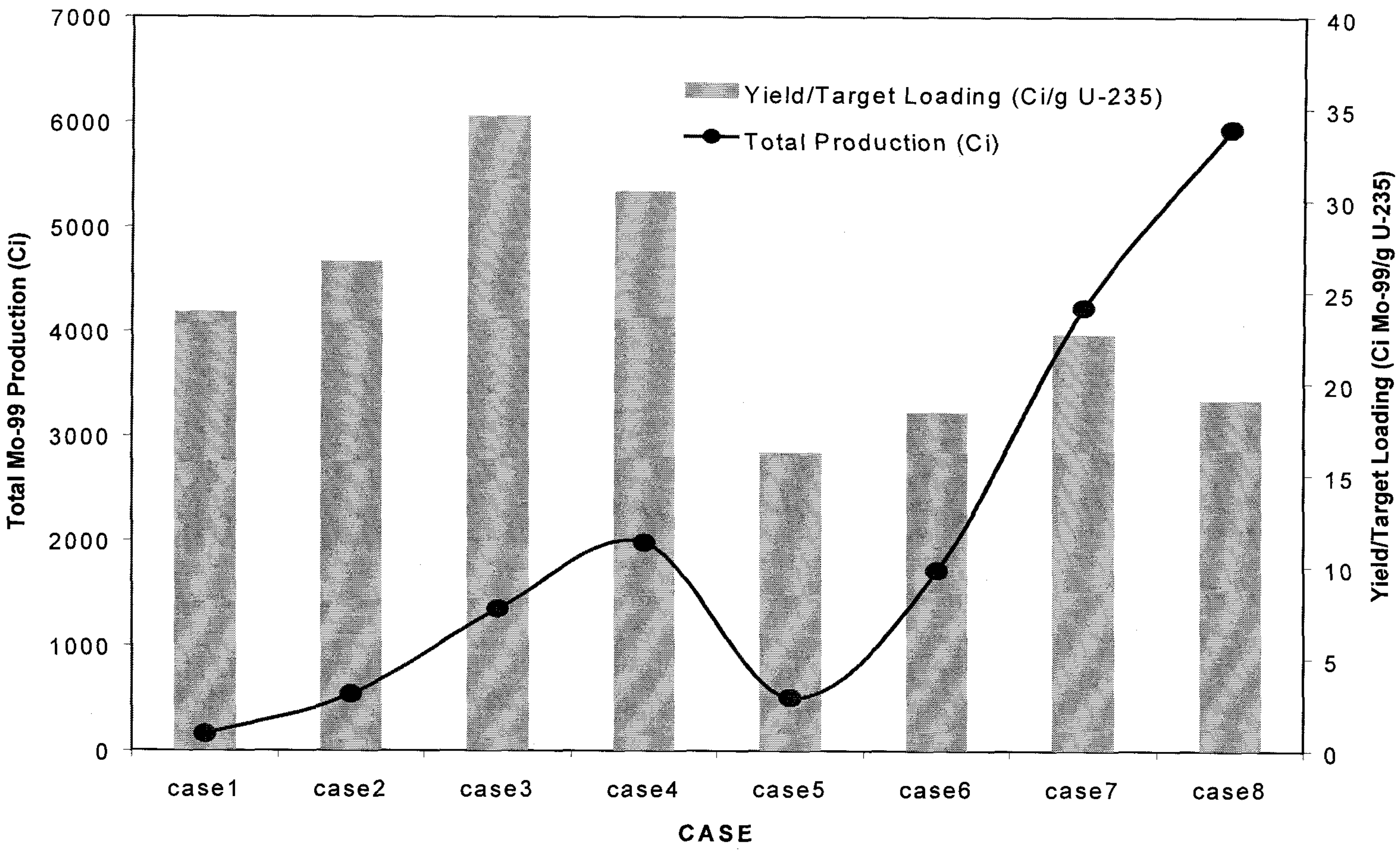

Figure 5.6 Mo-99 Production and Yield for Various Cases

Table 5.5 Uranyl Sulfate Solution Target Composition in Weight Percent

	93 % Enriched Solution	20 % Enriched Solution
Uranium-235 (%)	6.789	1.46
Uranium-238 (%)	0.5110	5.84
Sulfur (%)	1.1554	1.1554
Hydrogen (%)	9.763	9.763
Oxygen (%)	81.383	81.383

Case 9 – Ten 20 % enriched uranyl sulfate solution targets in C-ring

Ten 20 % enriched uranyl sulfate solution targets were placed in the C-ring instead of fuel. The k_{eff} dropped below the unity like a nitrate case. The control rods were used to achieve the unity. Average target power of 3.994 kW was found with this configuration for 1 MW operation. For 7-day irradiation, 1883 Ci 0f Mo-99 can be produced with this configuration. The peak fuel power was 18.577 kW at B-ring.

Case 10 – Ten 93 % enriched uranyl sulfate solution targets in C-ring

This configuration examined ten 93 % enriched uranyl sulfate solution targets inserted in the C-ring. The k_{eff} raised up the unity and was adjusted with control rods. This calculation showed 12.1 kW of target fission power could be generated for 1 MW operation. This would produce 5703 Ci of Mo-99 for 7-day irradiation. The peak fuel power was found in the B-ring with 17.97 kW.

Table 5.6 represents the comparison of the nitrate and sulfate solution. In spite of smaller neutron absorption cross section for sulfur, the Mo-99 production yield was relatively unchanged as shown in Table 5.6. The neutron absorption of a nitrogen and sulfur in the solutions does not affect to the neutron flux because of theirs low weight fraction (~ 1.2 w/o) and same enrichment (93 %). The radial neutron fluxes at a center of the core length (at z =0) and the averaged radial neutron flux over the active core length are given in Figure 5.7 and Figure 5.8, respectively. The flux profiles are consistent across the core.

Table 5.6 Comparison of Sulfate Solution with Nitrate Solution

Case	Enrichment (%)	k_{eff}	Target Power(kW)	Activity (Ci)	Yield (Ci/g ^{235}U)
Case4, Nitrate	20	0.96880	4.191	1976.078	30.45
Case9, Sulfate	20	0.96760	3.994	1883.025	29.46
Case8, Nitrate	93	1.02564	12.576	5929.645	19.06
Case10, Sulfate	93	1.02250	12.095	5702.879	19.18

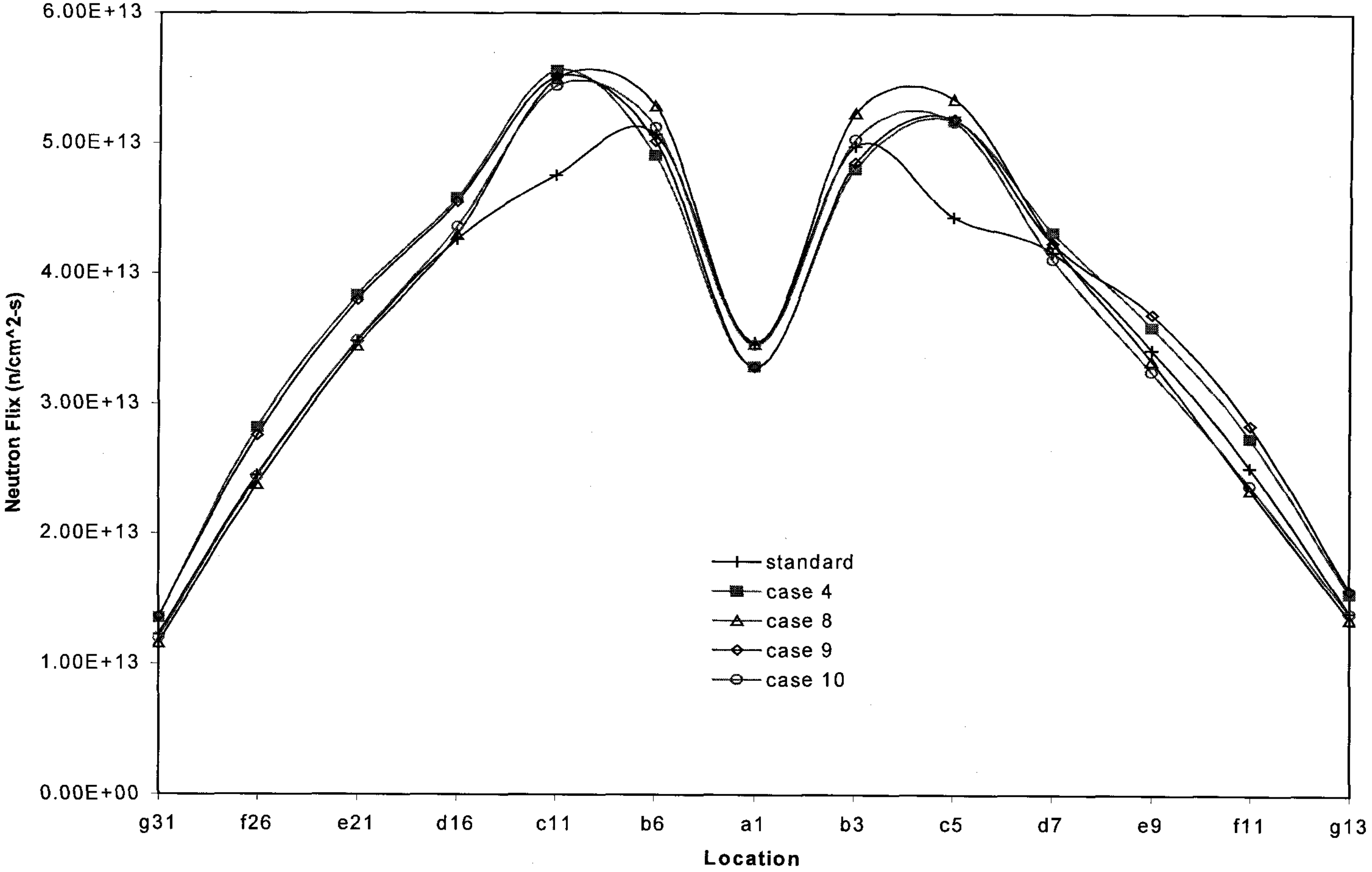

Figure 5.7 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 9 – Case 10

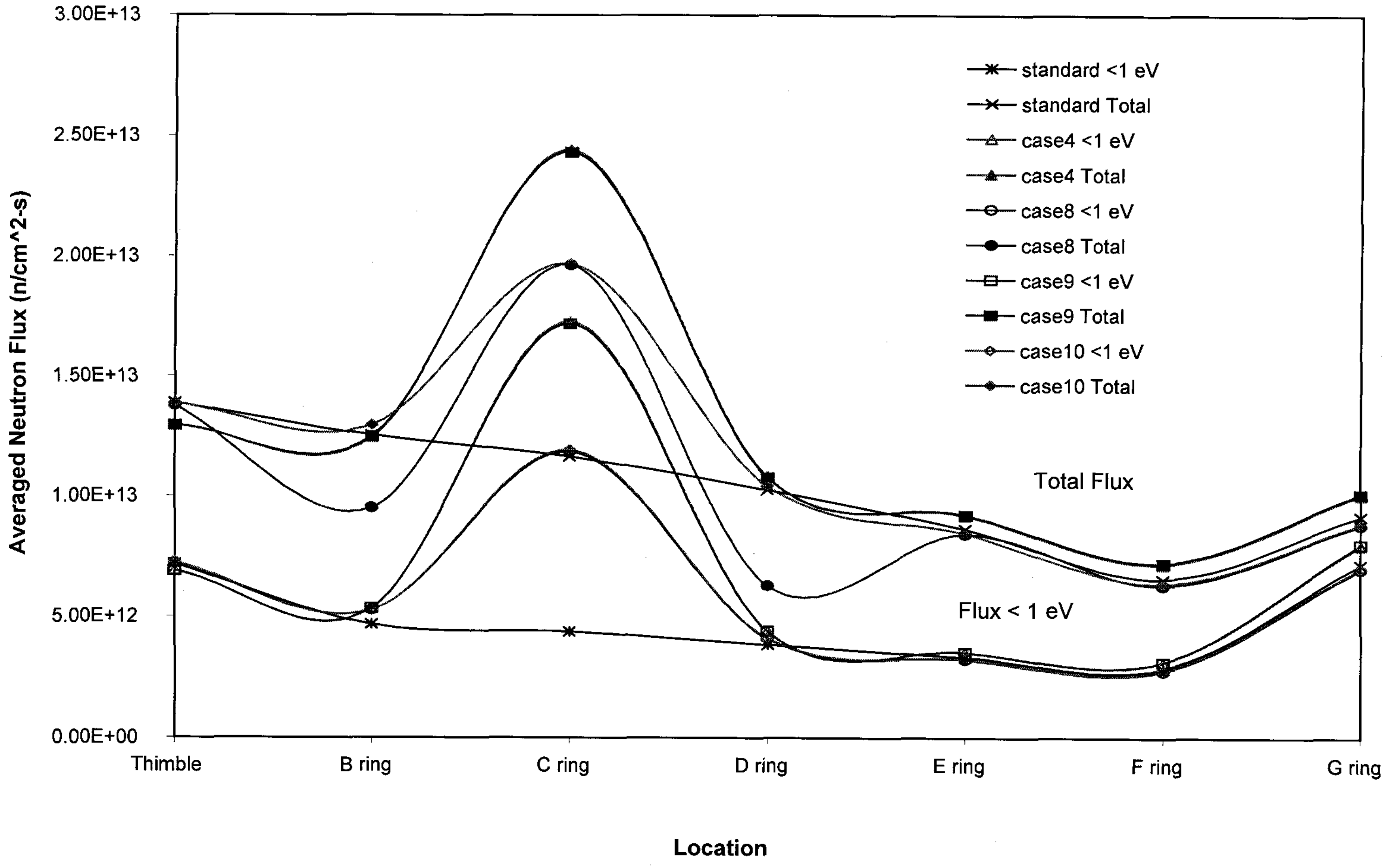

Figure 5.8 Averaged Neutron Flux over the Active Core Length, Case 9 - Case 10

5.1.2.3 *Change in Target; Uranium Weight Fraction*

The works in previous sections were performed with 7.3 weight percent of uranium in a target. The effect of changing the weight fraction of uranium was examined for determining the optimum target composition. The enrichment was maintained 93 % U-235 in a uranyl nitrate solution. The material characteristics of 4.96 and 9.99 weight percent of uranium in a solution shows in Table 5.7.

Table 5.7 Composition of Weight Fraction Changed Target in Weight Percent

	4.96 w/o Solution	9.99 w/o Solution
Density (g/cm^3)	1.08999	1.19954
Uranium-235 (%)	0.046146	0.092978
Uranium-238 (%)	0.003473	0.006997
Nitrogen (%)	0.005944	0.011977
Hydrogen (%)	0.102662	0.093286
Oxygen (%)	0.841775	0.794762

Case11 Ten 4.96 w/o Targets in C-ring

Ten targets, each with a 4.96 weight percent of uranium in a solution, were positioned in the C-ring. Even though a high enrichment was used, the core criticality was not changed because of the low uranium concentration in the solution.

The calculation showed that the target power was 10.40 kW with 1 MW power operation with a maximum fuel power of 18.3 kW in the B-ring. This configuration produced 4902 Ci of Mo-99 for 7-day irradiation. The fission product yield (Ci/g U-235) was 23.24. It is higher than the 7.3 w/o solution due to the high neutron flux in a target.

Case 12 Ten 9.99 w/o Targets in C-ring

This configuration examined 9.99 weight percent targets inserted in the C-ring. The k_{eff} value raised up the unity and was regulated with control rods. The averaged target power was 14.48 kW. The peak fuel power was 17.77 kW at B-ring, and 6828 Ci of Mo-99 would be produced after a 7-day operation.

The results of these configurations were described in Table 5.8, and compared with 7.3 w/o solution. A low uranium content solution target has high fission yield. But it produces small amount of Mo-99 in total. The flux profiles are given in Figure 5.9 and 5.10.

Table 5.8 The Results of Uranium Weight Fraction Changes in the Target

	Weight percent	U-235 (g)	k_{eff}	Target Power (kw)	Activity (Ci)	Yield (Ci/g ^{235}U)
Case 11	4.96	21.096	1.00976	10.40	4902.7	23.24
Case 8	7.3	31.049	1.02564	12.58	5929.6	19.06
Case 12	9.99	42.491	1.03745	14.48	6828.2	16.07

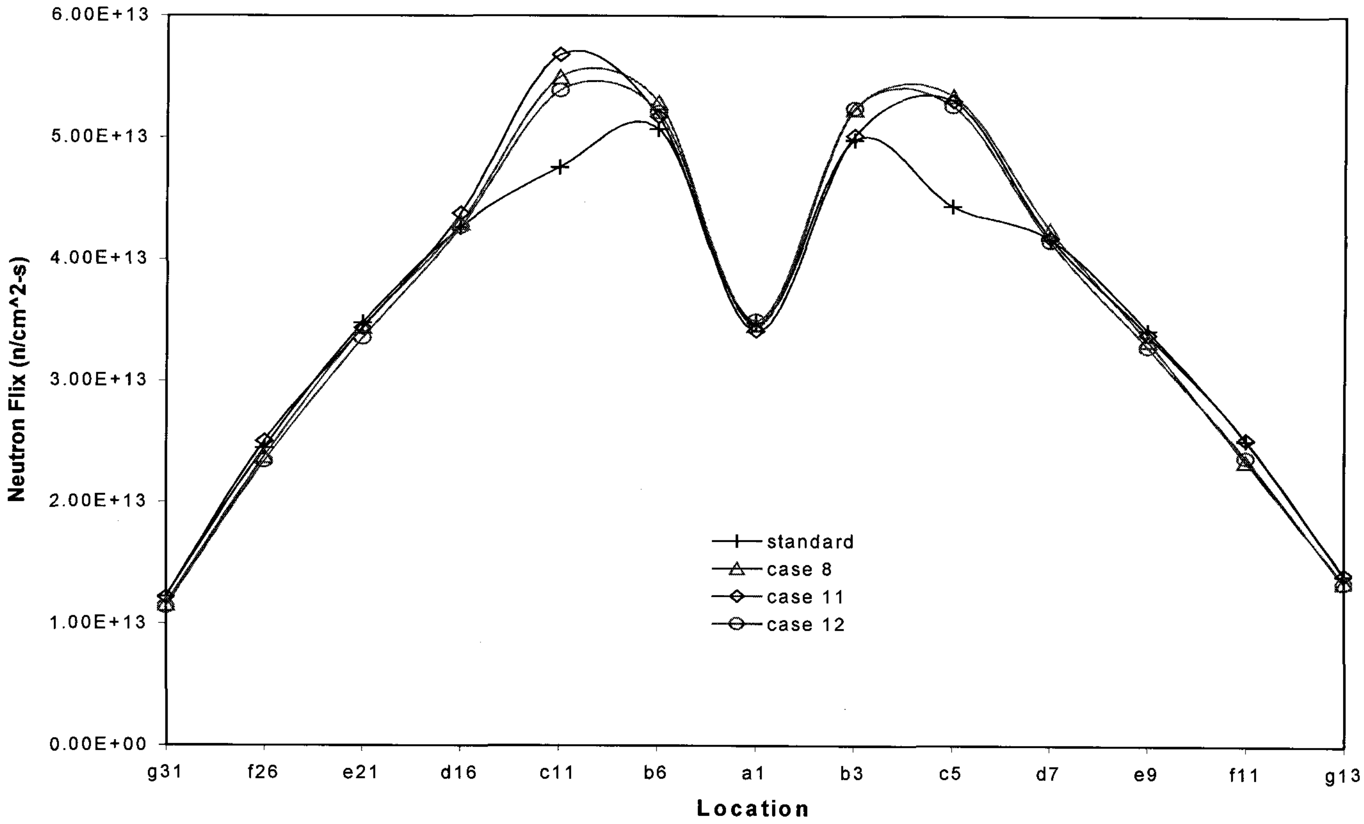

Figure 5.9 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 11 – Case 12

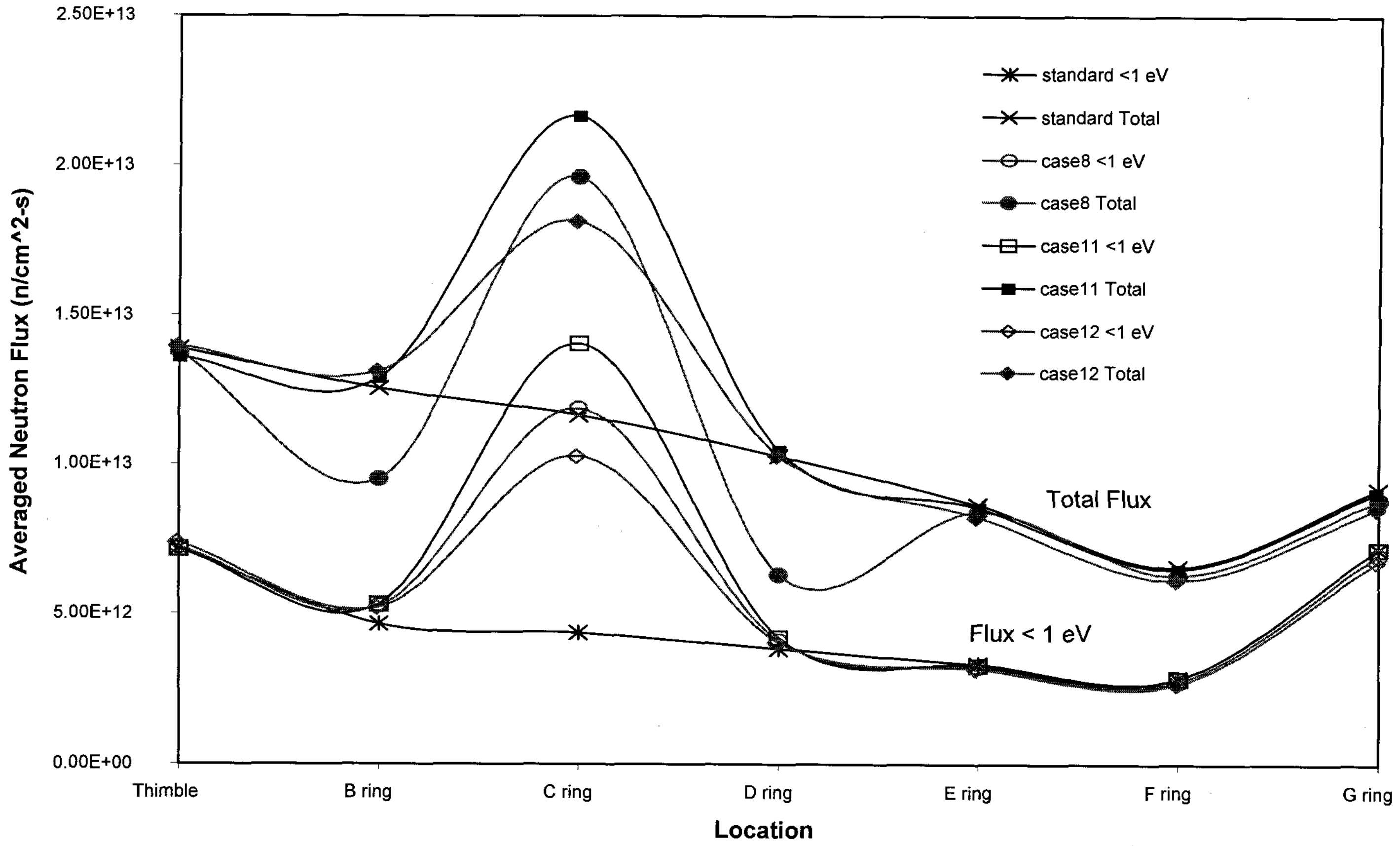

Figure 5.10 Averaged Neutron Flux over the Active Core Length, Case 11 – Case 12

5.1.3 Comparison with Typical Coated Target

DOE's Medical Isotope Production Project, MIPP, uses the Cintichem style target. The highly enriched fission material is electroplated on the inside of a cylindrical tube wall. The uranium plating is very thin and uniformly coated throughout the length of the tube. The MCNP model of the coated type target was developed and evaluated to compare with a solution type target. It was a same shape as TRIGA fuel, used 93 % enriched uranium oxide (U_3O_8), and had same amount of U-235 with a solution target. The thickness of uranium plating was 0.010963 cm.

Case 13 Six Coated Targets in B-ring

Six uranium-coated targets were placed in the B-ring. The results showed average target power level achieved 5.536 kW with 1 MW power operation. These coated targets could produce 1566.2 Ci of Mo-99 for 7-day irradiation. The thermal flux at a target was 2 times lower than a solution target, which has same amount of U-235. That means that a solution target serves as a much better moderator with better neutron economy when compared with a coated target. The coated target could be losing fission products due to the direct recoil of fission fragments from the surface of the target. The Mo-99 loss from the fission recoil is function of its fission fragment range in target material and the target geometry. The fractional release rate due to fission recoil can be calculated from the equation [58]:

$$F = \frac{1}{4}\frac{S}{V}\lambda \qquad (5.4)$$

where S = geometrical area of the target,

λ = fission fragment range,

V = target volume.

The fission fragment range in uranium oxide is 1.4×10^{-3} cm [59]. The fractional loss of Mo-99 for a range of thickness of uranium plating in a target was 3.18 %. It is not significant to total production rate except in very thin targets. The results of the coated target configuration were calculated in Table 5.9 and compared with the solution target results. The coated target generated only 37 % of Mo-99 produced by the solution target. The radial neutron flux at a center of the core (at z = 0) and the averaged neutron flux over active core length were plotted in Figure 5.11 and 5.12, respectively.

Table 5.9 The Comparison of Coated Target with Solution Target

	k_{eff}	^{235}U (g)	Target Power(kW)	Activity (Ci)	Yield (Ci/g ^{235}U)
Case 7, solution target	1.01870	31.104	14.93	4225.4	22.64
Case 13, coated target	0.98695	31.104	5.536	1566.2	8.39

5.1.4 Target Processing

A separation of fission Mo-99 from the target solution and a recycling of uranium to the target preparation are performed in the target processing after target irradiation in the reactor. The irradiated target is moved to a hot cell facility, the top of target is opened, the gases inside the target are removed, and the target solution is drained for a chemical process.

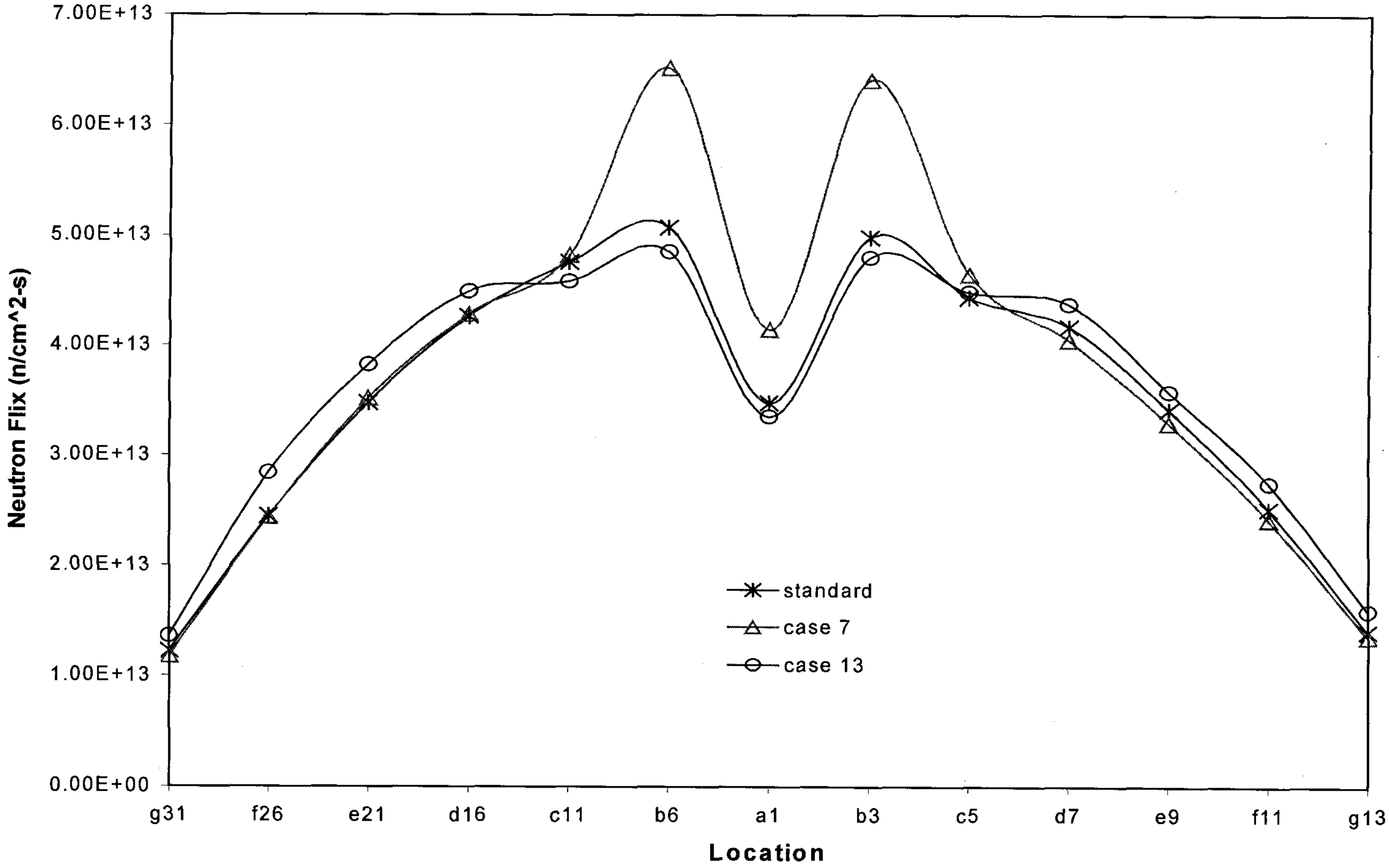

Figure 5.11 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 13

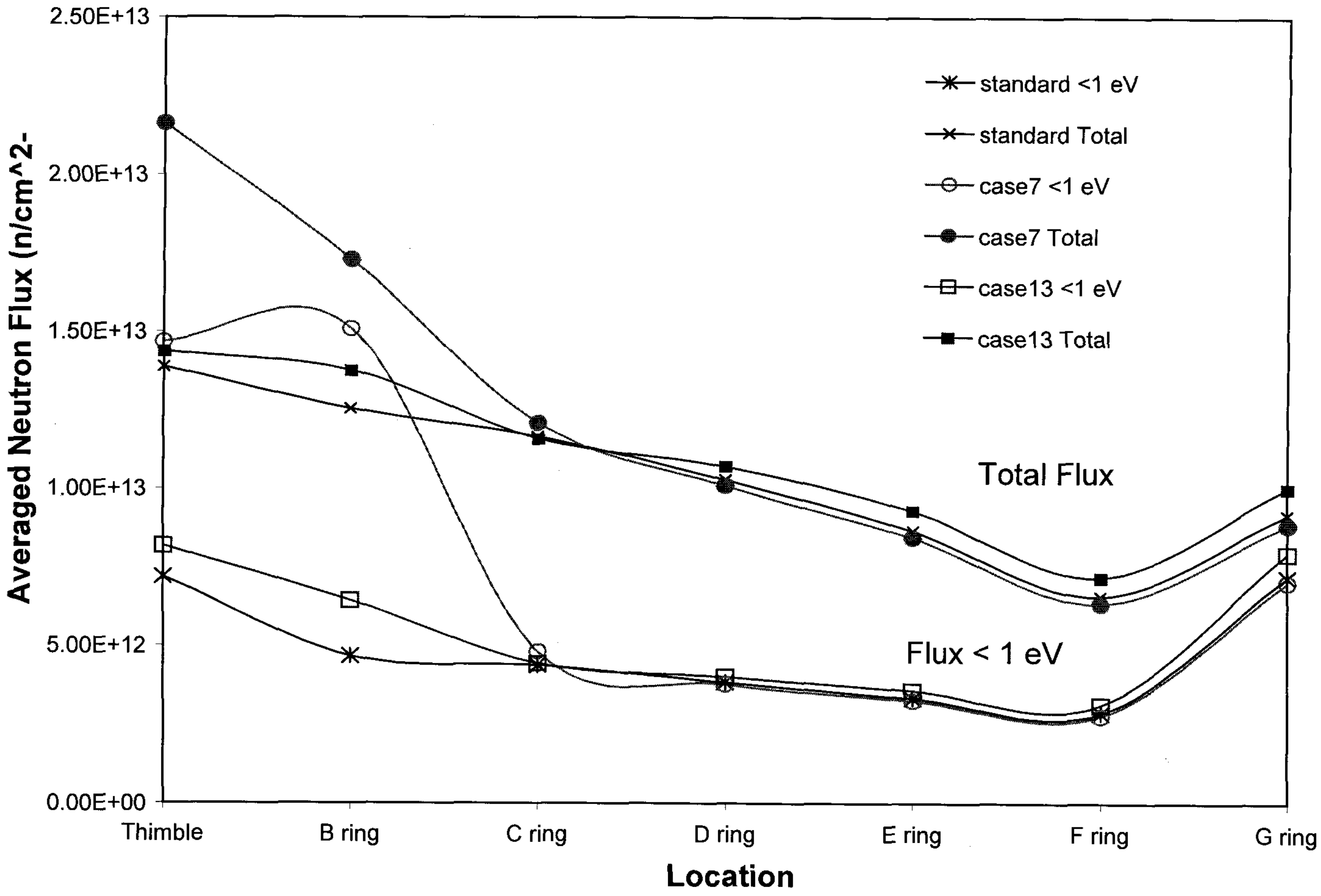

Figure 5.12 Averaged Neutron Flux over the Active Core Length, Case 13

Many methods for the separation of Mo-99 from fission products had been researched: adsorption by alumina [43, 53,54] or silver-coated activated charcoal [49], extraction with D2EHPA [48, 52] or TOA, precipitation by a-benzoin oxime [45] or toluene-3, 4-dithiol [51], or sulfur [60], ion exchange separation with chelating resin [46], high temperature distillation [47], vacuum sublimation [61], and chromatography with TBAH/SiO_2 [56]. In this work, the precipitation method was adopted because of its simplicity, good Mo-99 recovery capability, and satisfactory purity [53]. The conceptual extraction process is shown in Figure 5.13. A precipitant, such as a-benzoin oxime, is added to the solution for separating Mo-99 from uranium and other fission products, which are contained in target solution. After filtration, the Mo-precipitate is processed to pure Mo-99 following Cheng's method [53]. After the precipitation of molybdenum the remaining uranium in the filtrate is separated by passing through a fission product extraction column. The adsorbed fission products are separated from the column, and purified for use or sent to a waste storage. The uranium solution is adjusted chemically and reused in the target solution. Some studies were performed for the recovery of uranium from fission uranium: chromatography with TBP/SiO_2 [56], reaction with tri-n-butylphospate (TBP) [54], and ion exchange separation [53].

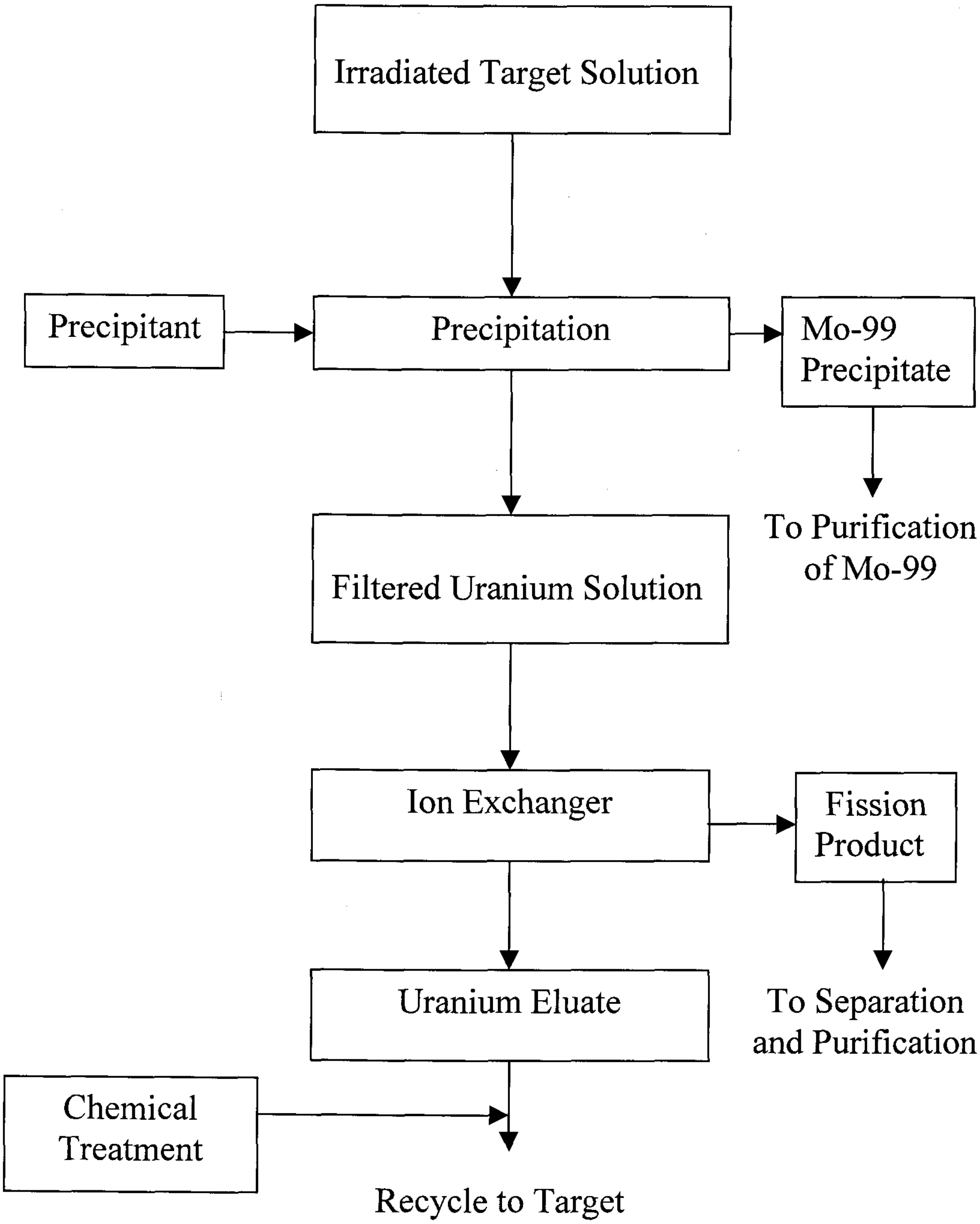

Figure 5.13 Conceptual Extraction Process of Tube Type Target

5.2 Continuous Flow Target System

Continuous Flow Target System (CFTS), which can supply the target material continuously and remove the irradiated solution at same time, is another possible target configuration, which can be proposed for the OSTR core. This continuous supply system is the same mechanism as homogeneous type reactors except that the reactor can remain in the operation for changing targets and processing. This would allow the production of medical isotopes would be a simple and direct procedure. This system also would reduce the processing time and the amount of radioactive waste.

5.2.1 Designed Target Model

CFTS would hold 20 liters of target material and to be located in the center of the core instead of central thimble and B-ring fuels. The schematic design is represented in Figure 5.14. The system consists of two parts: target material holding section and the recombiner apparatus, which converts radiolytic gas to steam, condenses it, and returns the water to the solution. The container is 1.2 mm thick stainless steel, 330 cm in length and 8.4 cm in diameter. The graphite bottom reflector is approximately 8.8-cm in length. The section holding the target is 38.1 cm in length. Fins put on the outside of the target material holding section serve the function of a heat exchanger. The fins are made of the same material and an integral part of the container. All external pipes are connected through the top cover. Thus the entire system can be installed and removed as a unit in the core.

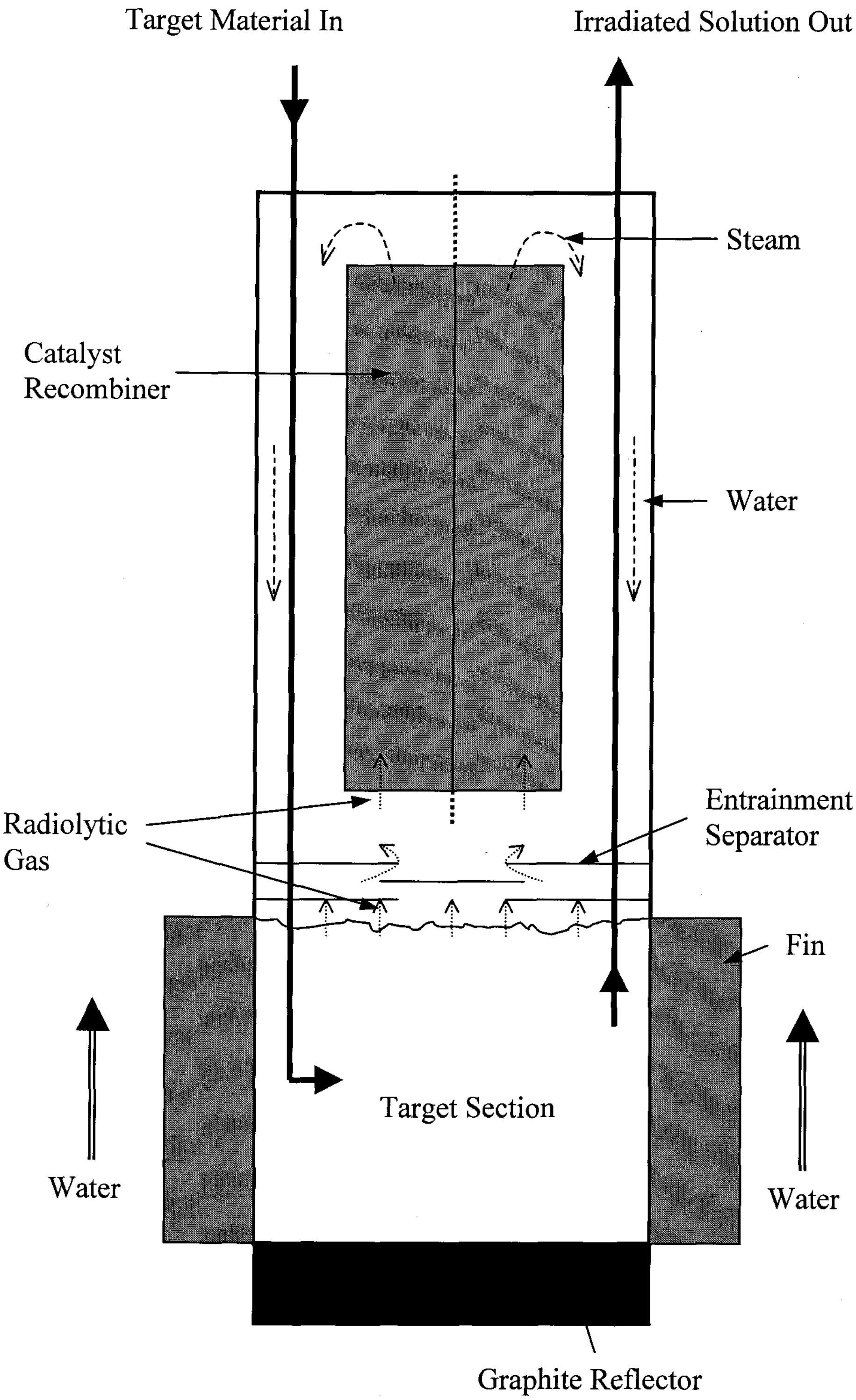

Figure 5.14 Schematic Design of Continuous Flow Target System

Most homogeneous reactors had the gas handling system for the produced radiolytic gas. It pumped or blew the gases over a catalyst chamber, which placed outside of the reactor, to circulate. The outside operating system could be troublesome portion of the homogeneous reactors.

The recombiner designed here is completely sealed and has no ventilation apparatuses. The system is contained entirely within the CFTS container. There are no pipes, connections, or values to leak or cause trouble.

In operation, the hydrogen and oxygen rise from the surface of the target solution and pass through the entrainment separator made by a roll of knitted stainless steel fabric into the catalyst region. The heated steam by the exothermic reaction of recombination rises and condenses on the cooled container wall. The water returned to the solution below and rinses off the separator en route. The convection of gases over the catalyst is rapid enough to maintain the hydrogen-oxygen concentration below the explosive limit [62]. The convection recombiner had been tested experimentally [63]. Catalyst pellets are made of 1/8-in × 1/8-in cylinders of alumina and have 0.3 % platinum back on the surface [62]. The pellets are supported as thin sheets between two layers of stainless steel screen. Six such plates are attached on the center thimble of recombination region vertically. The plates are electrically heated through the thimble. If at least 30,000 catalyst pellets are used, a smooth startup is achieved even if the full 100 kW gas-evolution rate falls on the cold catalyst [62]. Sixty thousand pellets (six 4-cm × 252-cm plates) would be used together with the electric heater in this study for an ample safety factor. The number of pellets that depends on the target operating power could decide the total length of the target system. In low operating power, the catalyst plates should be smaller than high power system. Several thermocouples are placed in the catalyst bed to indicate the operating temperature. Even though splashed with uranium solution, the pellets return to nearly full activity when dry. CFTS is shown in Figure 5.15.

5.2.2 Neutronic Analysis

Enriched 20 % and 93 % uranyl nitrate solutions were examined in the continuous supply system. The physical contents in solutions are the same as Table 5.1 and 5.2 except the total amounts of U-235 in 20-liter containers. CFTS contains 33.652 g or 156.482 g of U-235 for 20 % or 93 % enrichment solutions, respectively. For neutronic analysis, this study assumed that all fission products produced during target irradiation were removed through the continuous chemical process, and the recovered uranium returned to target container. Even though the continuous extraction and supply of target solution could change the inherent reactivity and could cause the complication of the reactor control, the reactivity of the core must be kept critical by using the control rods, and keeping same removal and supply flow rate of solution.

Two system flow rates were tested to determine the production yield: 1-day cycle and 7-day cycle. One-day cycle would circulate all target solution for an extraction of Mo-99 and other fission products each day. The flow rate of 1-day cycle is 14 ml/min, while 7-day cycle is 2 ml/min.

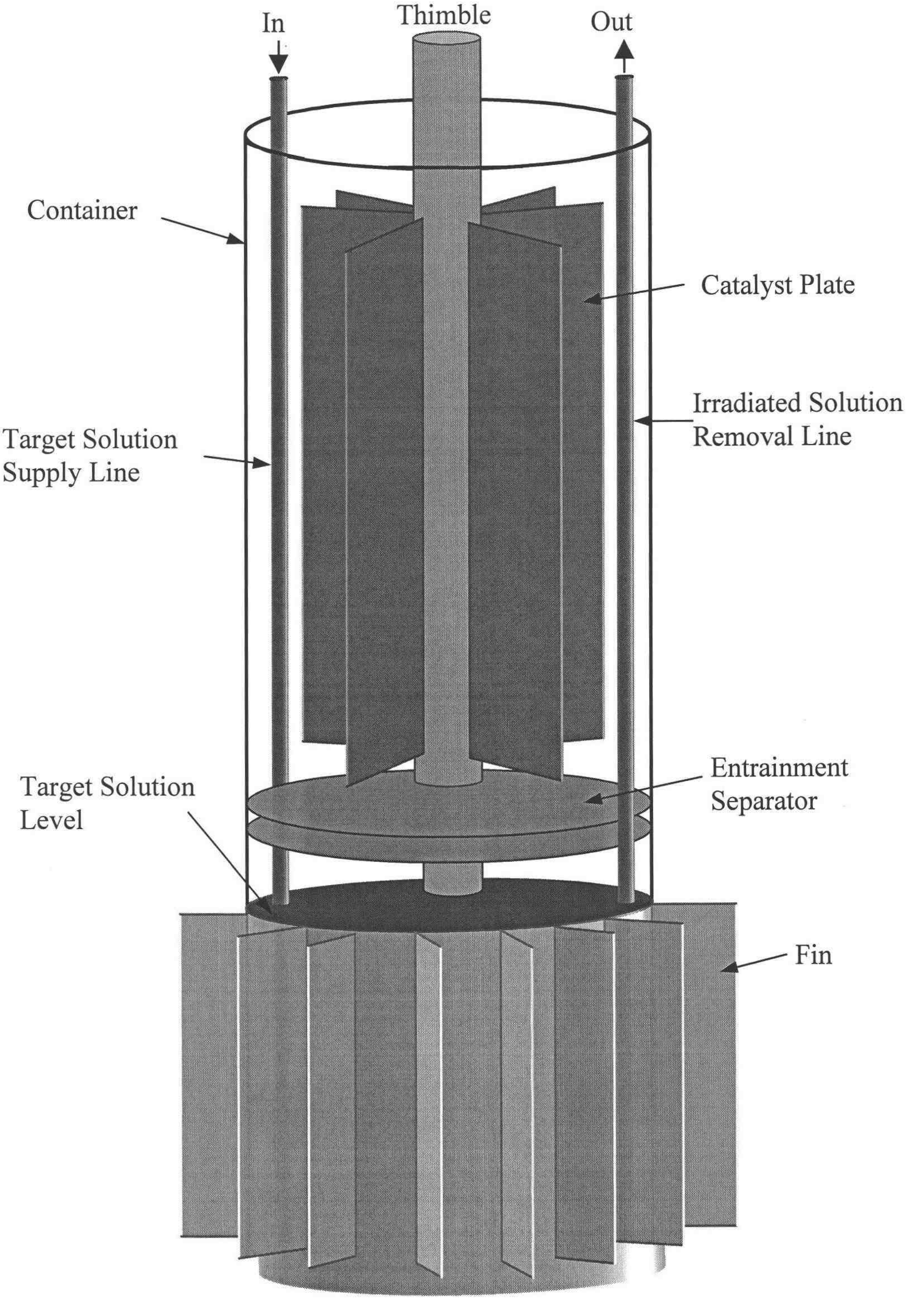

Figure 5.15 Continuous Flow Target System

Case 14 20-liter 20 % enriched solution in CFTS

Twenty liter of 20 % enriched uranyl nitrate solution was placed in the continuous system. The reactivity dropped below the unity due to a lower amount of U-235 compared to the Flip fuel configuration in a container. It was adjusted with the control rods to achieve the unity. The power of target was 31.56 kW, and peak fuel power in C-ring was 16.95 kW for 1 MW operation. This system would produce 400.1 Ci and 216.6 Ci per day on 1-day and 7-day cycle, respectively.

Case 15 20-liter 93% enriched solution in CFTS

Enriched 93 % uranyl nitrate solution placed in the system. The raised reactivity was adjusted with control rods. With 1 MW operation, 88.57 kW of target power and 17.46 kW of peak fuel power in C-ring were achieved. The amount of Mo-99 per day extracted would be 1122.6 Ci and 596.5 Ci of Mo-99 for 1-day and 7-day cycle, respectively.

The analysis results of these systems are summarized in Table 5.10 and Figure 5.16. A 1-day cycle would produce more Mo-99 than a 7-day cycle base. From Equation 5.2, the1-day irradiation can only reach 22 % of the equilibrium activity. While the 7-day irradiation yield 83 % of the equilibrium activity. Thus a 1-day cycle would produce 85.5 % more Mo-99 than a 7-day cycle by following indication:

$$(22 \times 7) \div 83 = 1.855.$$

Those evaluations were assumed that the condition of solution in container was kept the same condition as a daily batch or weekly batch extraction for that period even though the solution was circulated for extracting fission products during the circulation. That means whole solution in the container was irradiated for 1 day or 7 days and then poured for processing without any circulation. Since these values did not account for the Mo-99 decay and the loss of uranium during processing, the actual values must be lower than these values.

Table 5.10 The Results of The Continuous Flow Target System

	Enrichment	k_{eff}	Target Power, kW	1-day cycle		7-day cycle	
				Ci/week	Yield, Ci/g ^{235}U	Ci/week	Yield, Ci/g ^{235}U
Case 14	20 %	0.97795	31.56	2800.7	83.23	1488.2	44.22
Case 15	93 %	1.02201	88.57	7858.2	50.22	4175.8	26.69

5.2.3 Target Processing

The irradiated target solution circulates the processing steps to extract fission products, recover unused uranium, and return to the container. Mo-99 is separated first than other fission product to prevent the loss from decay during processing period. The extractor, tri-n-butylacetohydroxamic acid (TBAH), in a 0.05 mol/l solution in xylen adsorbed on hydrophophobic SiO_2 at a level of 30 % by weight is used to recover and purify Mo-99 from the irradiated solution. Three chromatographic extraction cycles are used in the process. Detail information on this extraction can be found in Bourges' work [56]. The solution from the first Mo-

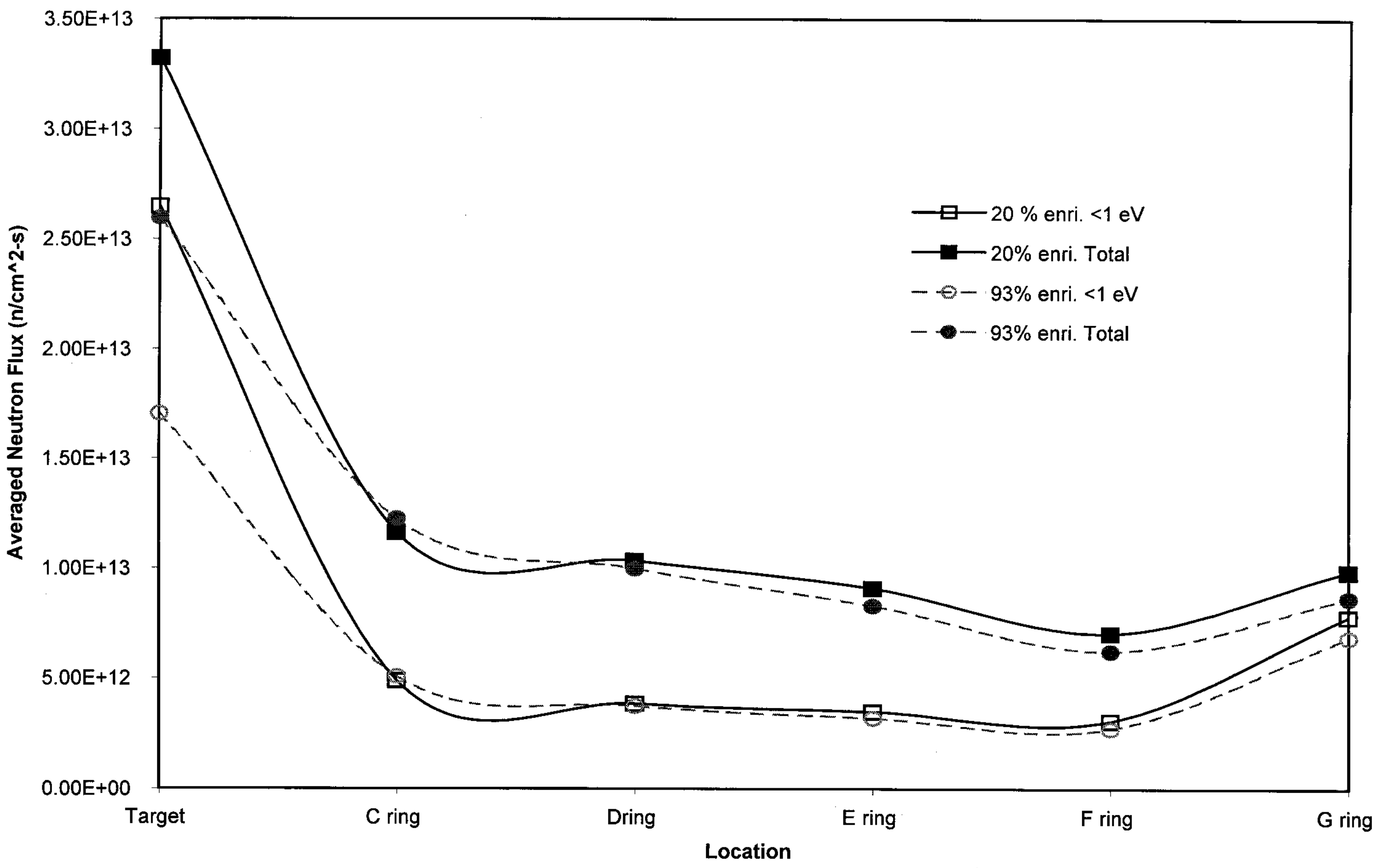

Figure 5.16 Averaged Neutron Flux over the Active Core Length of the Continuous Flow Target System

99 extraction cycle reacts with the alumina in the second column to remove other fission products, such as iodine, tellurium, and ruthenium isotopes. The removed fission products are eluted away from the alumina column with the sodium or ammonium hydroxide. The useful fission products would be extracted from this eluted solution. The processed uranium solution in which some fission products are removed is chemically conditioned, for example, adjustment of pH in a range 2 –5 by the nitric acid addition, and is passed back into the container for reuse. The flow rate of solution would be determined by the extraction capability of the columns. Usually the solution is removed from the irradiation container at a rate of 6 to 60 ml/min [64].

Figure 5.17 shows the flow diagram of Mo-99 production process of the continuous system, which consists of two identical separation systems. The duration time of the irradiated solution flow through the first processing columns is about 8 hours during which Mo-99 and other fission products are attached in columns by the extractors. After this time, the direction of the flow of solution is changed to the second separation system by the shift of the values. In the first separation system the extraction of fission products attached in the columns is followed with chemicals. Molybdenum is separated from the first TBAH/SiO_2 chromatography with a sulfuric acid and sodium hydroxide. The extracted molybdenum is purified in the series of Mo-99 chromatographic extraction with TBAH/SiO_2. The purification process is shown in Figure 5.18. For the quantitative extraction of molybdenum, it is necessary to guarantee that this element is present in the solution in the Mo(VI) oxidation state; $[Mo^{VI}O_4]^{-2}$. The use of TBAH extractant requires element to exist in the choromatographic feed solution in the oxidation state VI. The oxidation of Mo(III) to Mo(VI) could be achieved by two means: by adding a chemical reagent, such as hydrogen peroxide (H_2O_2), to feed solution or by its self-radiolysis [56]. This oxidation condition would be satisfied under radiolysis in the first chromatographic cycle simply by self-production of H_2O_2 in the uranium solution container, which is the decomposition product of water in uranium solution by the fission recoil particles, and by maturation of solution. No molybdenum oxidation state adjustment is required for the second and third chromatographic extraction cycles. Other fission products attached in the alumina column are removed with water, and sodium or ammonium hydroxide [43,53,64].

After the irradiated solution has passed for the suitable time period through the second separation system, the positions of values can be changed to the first separation system for processing. The use of two separation systems avoids time waste while Mo-99 is being extracted from the other column [64].

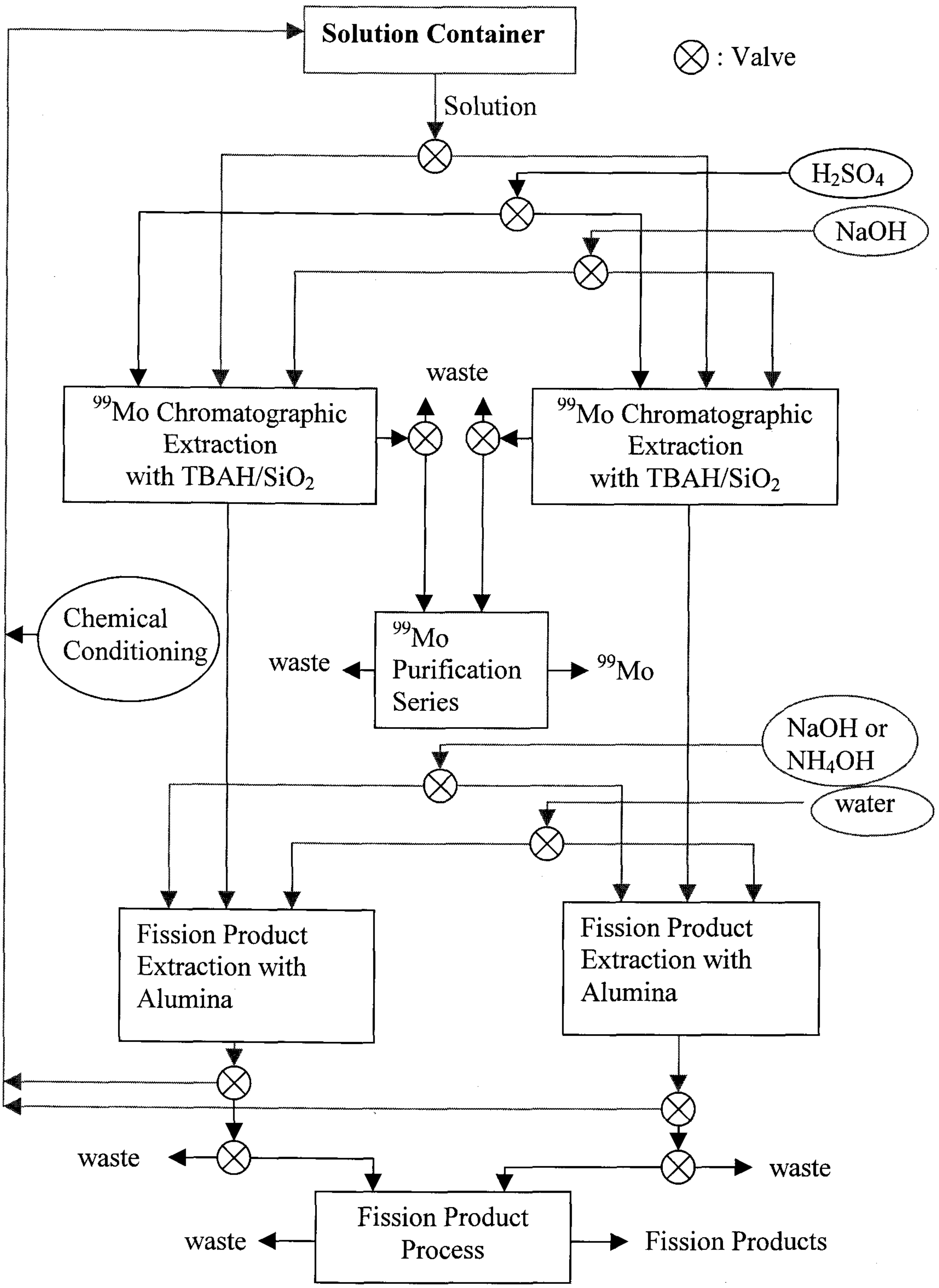

Figure 5.17 Mo-99 Production process of Continuous Flow Target System

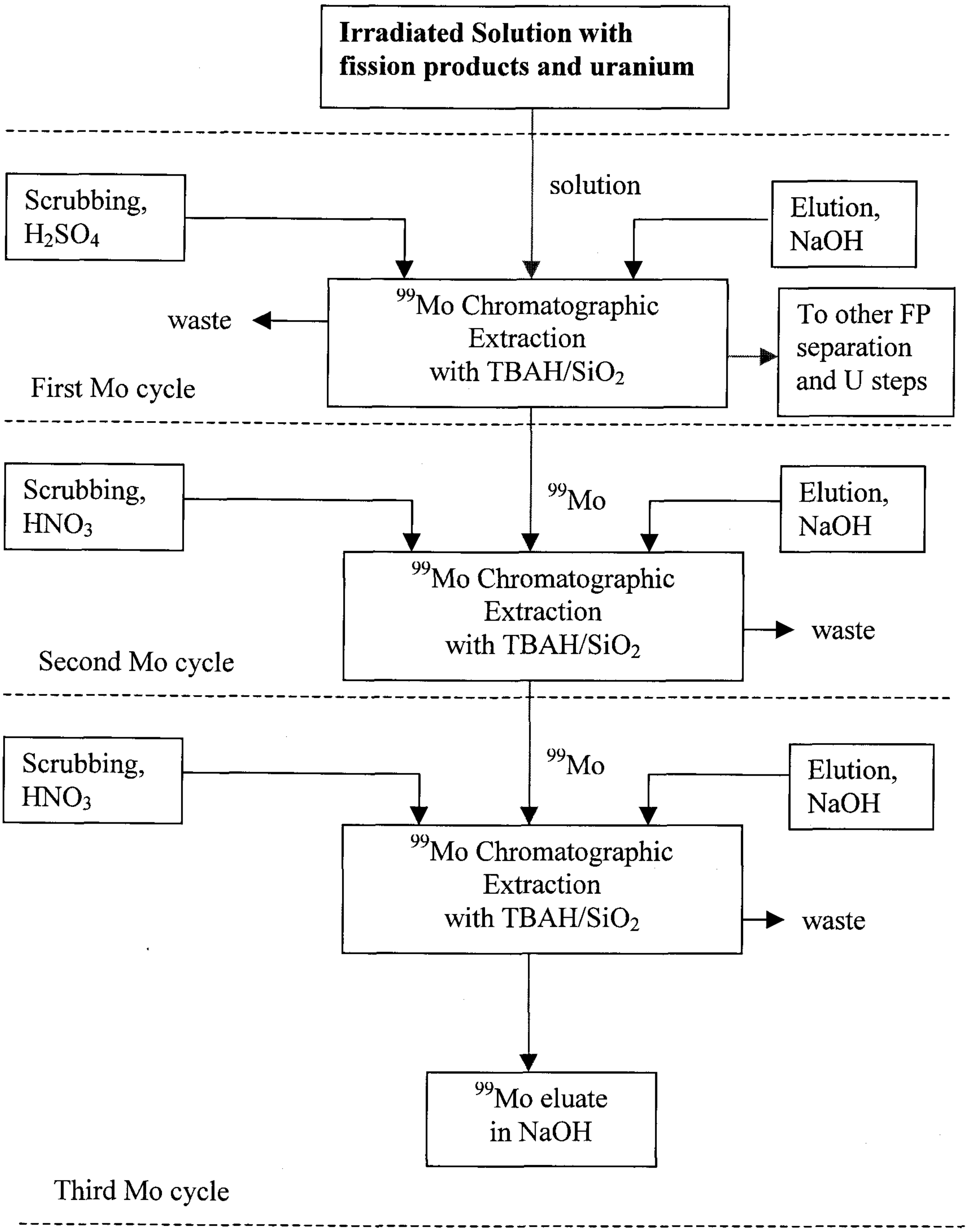

Figure 5.18 Molybdenum-99 Purification Cycles

5.3 Modifications of OSTR for Mo-99 Production

The OSTR would be modified and upgraded the hard wear to be an adequate medical isotope production system. Current core is not configured for the larger amount of isotope production. The targets would occupy the fuel locations. The change of the core characteristics with targets was predicted through the neutronic studies without any complications to nuclear safety. The required modifications for successful conduction of Mo-99 production are following:

Removal of a hexagonal grid plate section – The hexagonal grid plate would be removed for placing the continuous target supply system. Removing hexagonal section removes that portion from the upper grid plate, which includes the thimble and B-ring (a total of seven fuel element locations). This facility was designed to allow experiments to be inserted in the center of the core.

Cooling system upgrade – Because the Mo-99 production project in OSTR would require a continuous operation, the cooling system would be upgrade. The current steady state power limit of OSTR is 1 MW. The additional installation of heat exchanger and cooling tower would be required for the possible increment of power level of OSTR for producing more isotopes than a current system.

Ventilation and environmental monitoring system upgrade – The ventilation and radiation monitoring system would be upgraded for continuous operation and redundancy.

Target storage area – The target storage area would be established around the reactor to handle the receipt of targets. Current fuel storage pits could be modified for targets. If the tube type target would be processed in OSTR facility, the decay area for the irradiated targets would be required for the decays of short half-life isotopes before processing.

Special handling equipment – Target transfer cask of the tube type targets to move to hot cell facility, and special target handling equipment for loading and removing would be designed and fabricated to meet isotope production needs.

Target fabrication area and laboratory – The fabrication facility would be needed, if target would be produced in OSU. It would include the inspection facility for the fabricated targets. The quality of a uranium solution and the produced Mo-99 would be examined in the laboratory. The uranium solution would be produced in the laboratory.

Hot cell facility – The hot cell facility would be required for the processing of targets. The hot cell for the continuous target material supply system, which contains the Mo-99, fission product, and uranium separation system would be located near the reactor, but it must be a separated room for the safety. Also the hot cell facilities for the tube type target processing would be established, if the target process in the OSTR facility.

Waste storage area – The target processing would generate the radioactive waste. The waste storage area would be required for temporary storage until the waste is sent to the permanent disposal area.

CHAPTER 6
NUCLEAR SAFETY

6.1 Radiolytic Gas Treatment

The decomposition of water in the target solution by recoil fission fragments would form free hydrogen and an oxidant, either oxygen or peroxide. In order to minimize the explosion hazard these gases should be recombined. The rate of hydrogen production can be evaluated with Equation (4.1). The G_f value is 1.6 for dilute uranyl nitrate solution to 0.5 for concentrated solution [38]. In a15 kW power target, about 0.14 mole of hydrogen gas (3.13 liter) would be formed every minute. The thermal recombination of hydrogen and oxygen is very slow in the absence of an added catalyst. As a result, the steady-state pressure of gases is very high; e.g. at 250 °C the pressure is order of thousands of psi [38].

The copper salts had been shown to act as a catalyst in the thermal combination of hydrogen and oxygen in aqueous uranium solution [38]. This is a convenient method for recombination of the radiolytic hydrogen and oxygen gases in the tube type target. This method does not require any installation of apparatuses inside or outside of target.

The reaction rate is first order in hydrogen and in copper concentration and, is independent of oxygen concentration. The rate determining step is the reaction of hydrogen with catalyst, and the activation energy is about 24 kcal/mole. For a particular uranium solution, the rate of hydrogen removal in moles/liter/min can be expressed by [38]

$$\frac{-d(H_2)}{dt} = k_{Cu}(Cu)(H_2) \tag{6.1}$$

where k_{Cu} is catalytic constant in liters/mole/min, and copper and hydrogen are the concentrations in units of moles/liter. Selected values of k_{Cu} for water system at several temperatures and uranium concentrations are presented in Table 6.1. In case of above 15 kW-power target with a k_{Cu} value of 20 and 0.05 M of copper, the removal rate is 0.352 moles/liter/min. Then all produced hydrogen would be completely recombined and returned to the solution as water.

The use of copper dissolved in the fuel solution for the complete recombination of radiolytic gas was successfully demonstrated in the Homogeneous Reactor Experiment (HRE-1) of the Oak Ridge National Laboratory without any deleterious effects due to the presence of copper [65].

To examine the neutronic effects of adding a copper catalyst, two additional MCNP runs are made with 1.043 g of copper added to the 20 % and 93 % enriched target solutions (case 16 and case 17, respectively). The results are shown in Table 6.2 and Figures 6.1 and 6.2 with comparison with the solution. The amounts of Mo-99 produced are slightly smaller than the no copper solution due to the neutron absorption of copper. But the neutronic characteristics are not significantly changed. The changes of k_{eff} value are less then 0.5 %.

For the continuous flow target system a recombiner is added inside the container as described in Chapter 5. The recombiner consisting of six-catalyst plates is sufficient for the continuous isotope separation system. The activated copper ions could require the heavy shielding and an additional processing step for conditioning uranium solution in the system. These could increase the capital cost and the processing time.

Table 6.1 Selected Values of k_{Cu} at Several Temperatures and Uranium Concentrations (Cu = 10^{-3} M) [38]

Uranium Concentration (M)	Temperature (°C)	k_{Cu} (liters/mole/min)
0.17	190	4.3
0.17	220	26.2
0.17	250	90.0
0.01 to 0.1	250	133
0.01 to 0.1	275	380
0.01 to 0.1	295	850

Table 6.2 The Results of the Catalyst, Cu, Added Solution

	Enrichment (%)	Cu	k_{eff}	Target Power(kW)	Activity (Ci)	Yield (Ci/g ^{235}U)
Case 4	20	No	0.96880	4.19	1976	30.45
Case 16	20	Yes	0.96646	4.17	1965	30.29
Case 8	93	No	1.02564	12.58	5930	19.04
Case 17	93	Yes	1.02555	12.48	5883	18.89

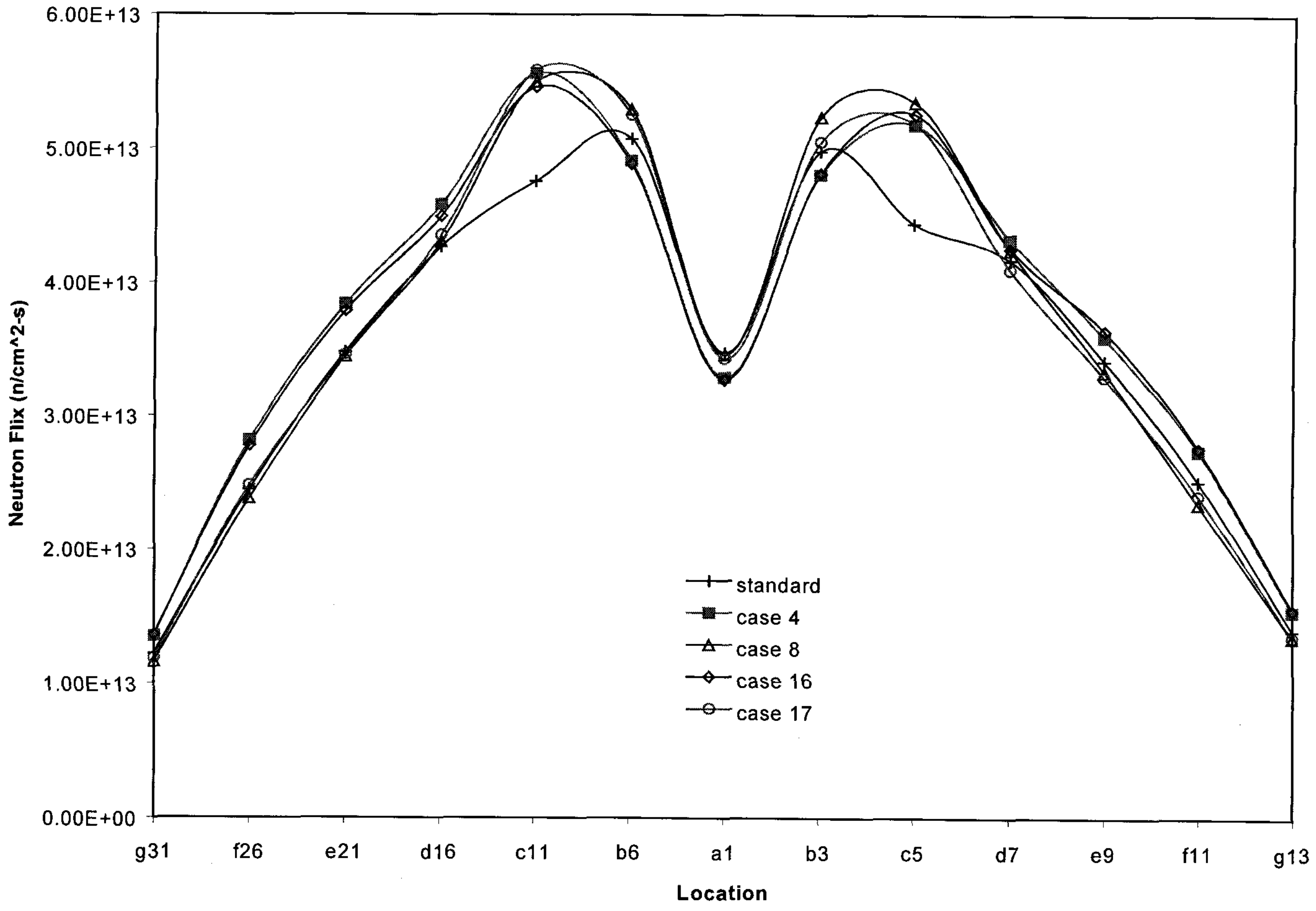

Figure 6.1 Radial Neutron Flux at Center of the Core Length (at z = 0), Case 16 – Case 17

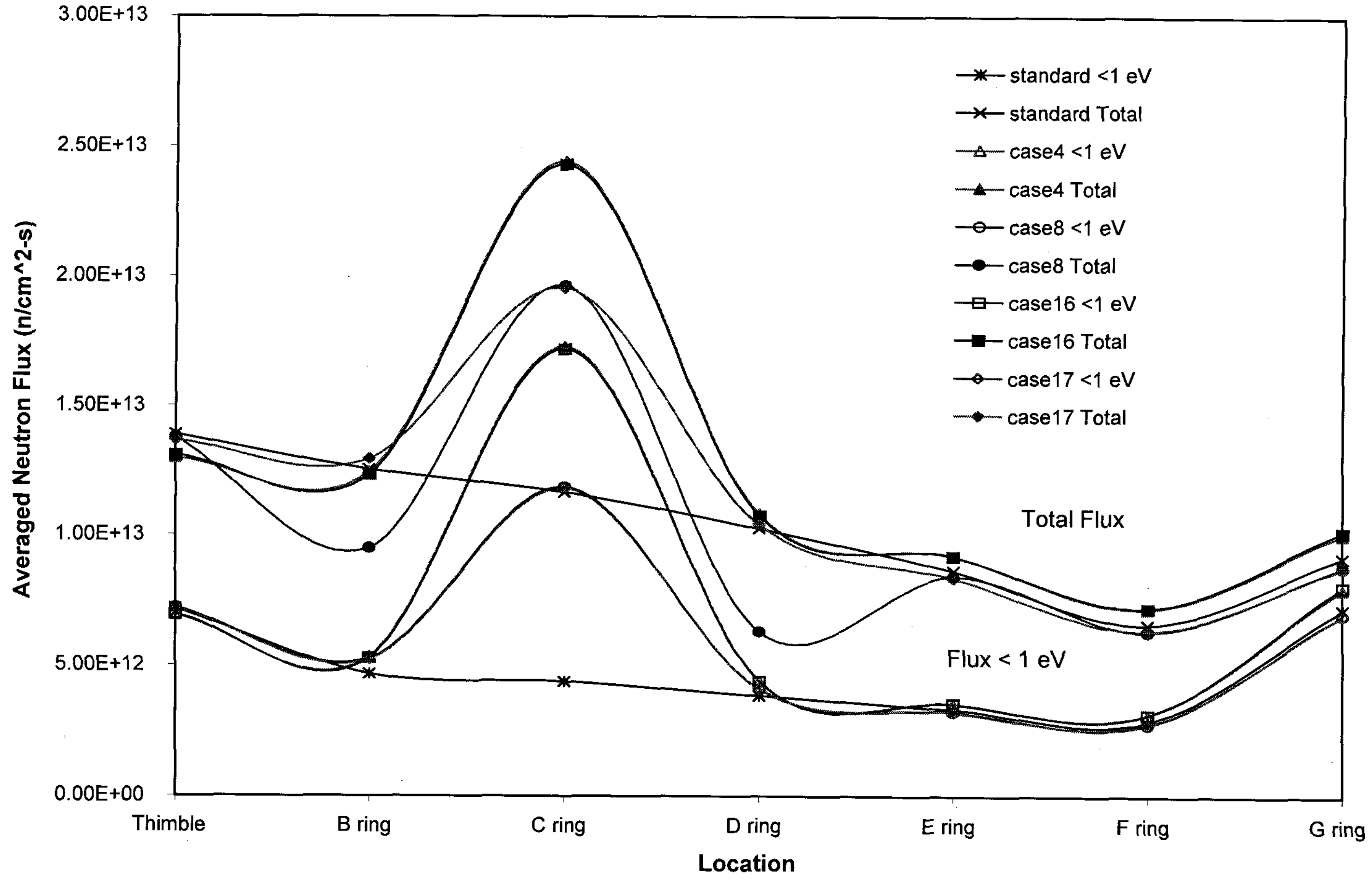

Figure 6.2 Averaged Neutron Flux over the Active Core Length, Case 16 – Case 17

6.2 Thermal Hydraulic Analysis

The heat from fuel element in the OSTR is removed by the convection of water surrounding the elements. The circulating flow rate of the water is 0.031545 m^3/sec (500 gpm). The bulk temperature of the water in the core could be maintained at 20 °C [27]. In the core with target inserted, the heat from the target and the fuel element would be cooled by water with the same flow rate and the same coolant temperature. The literature indicated that little data exists for the thermal hydraulic analysis of the solution target. This work takes the approach of evaluating the cladding temperature of the target, and as long as it stays below the melting point of the clad to prevent the rupture of the cladding and the release of fission products.

Newton's law of cooling describes the heat transfer, q (W), from a heated surface (of a fuel or target) to a moving fluid (coolant) [66]:

$$q = hA(t_c - t_f) \tag{6.2}$$

where h = coefficient of heat transfer by convection, W/m^2 °K

A= area, m^2, across which heat flows

t_c, t_f = heated surface and fluid-bulk temperature, °K.

The value of h is a function of coolant physical characteristics, such as thermal conductivity, specific heat, viscosity, etc, as well as operating condition and flow-channel geometry. The heat transfer coefficient, h, is given as part of the Nusselt number, a dimensionless group which includes the thermal conductivity of the fluid and the equivalent diameter of the channel. Equation 6.3 states that the Nusselt number is a function of the Reynolds and Prandtl numbers [66].

That is

$$Nu = f\,(Re,\ Pr) \tag{6.3}$$

where Nu = Nusselt number = $\dfrac{hD_e}{k}$ dimensionless (6.4)

Re = Reynolds number = $\dfrac{D_e V \rho}{\mu}$ dimensionless (6.5)

Pr = Prandtl number = $\dfrac{\upsilon}{\alpha} = \dfrac{c_p \mu}{k}$ dimensionless (6.6)

v = kinematic viscosity of fluid

α = thermal diffusivity of fluid

k = thermal conductivity of fluid, W/cm °C

μ = absolute viscosity of fluid, kg_m/sec m

c_p = fluid specific heat at constant pressure, kJ/kg °K

V = fluid speed, m/sec

ρ = density of fluid, kg/m^3

D_e = equivalent diameter of channel, m

In case of non-circular flow passage, the conception of equivalent diameter, D_e, is applied. It is used in place of the diameter, D, in various correlations. The value of D_e is to be computed from the formula [59]:

$$D_e = 4 \times \frac{A_c}{P} \tag{6.7}$$

where A_c is the cross sectional area of fluid channel, and P is the wetted perimeter of fluid channel, including all surfaces wetted by fluid. On the OSTR a total of 107 rods containing fuel elements, control rods, and graphite rods are loaded in the core. Then the equivalent diameter would be 3.35 cm.

The Grashof number is much greater then the Reynold number in the OSTR core, which dominates free convection. Thus the Dittus-Boelter equation is used for the correlation of Re, Nu, and Pr [66]:

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \tag{6.8}$$

The value of the heat transfer coefficient can be obtained from Equation (6.8) using the definition of the Nusselt number; thus

$$h = 0.023\left(\frac{k}{D_e}\right)\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{6.9}$$

The constants used the h calculation are listed in Table 6.3. The Reynolds number for OSTR flow is 9920, then the heat transfer coefficient would be 1415.4 W/m^2 ^{o}K.

Table 6.3 Thermodynamic Properties of Water at 20 °C [67]

Viscosity, μ	101 × 10^{-5} kg m/s
Thermal conductivity, k	0.603 W/m °K
Prandtle number, Pr	6.95

The outside cladding temperature can be estimated from Equation (6.2) with the calculated heat transfer coefficient. The cladding temperature is 277 °C in the case of maximum target power in B-ring, 16.35 kW. The temperature of the cladding's inside surface can be obtained from Laplace equation in case of steady state [66]:

$$t_s = \frac{q \, ln(\frac{R+c}{R})}{2\pi \, k_c \, L} + t_c \qquad (6.10)$$

where t_s = temperature of inside cladding, °K

t_c = temperature of outside cladding, °K

k_c = thermal conductivity of cladding, W/m °K

R, c = radius of target solution and thickness of cladding, respectively, m

L = length of target, m

The thickness of 304 stainless steel target cladding is 0.0508 cm (0.020 in.). The thermal conductivity of cladding is 0.1852 W/cm °C at 277 °C [66]. From Equation (6.10), the temperature of inside cladding would be 288 °C. Both inside and outside temperatures of cladding even in the case of the highest target power are below the melting point of cladding (1400 – 1454 °C). But those are higher than the OSTR fuel element cladding temperature of normal operation without targets in the core. The maximum cladding temperature of fuel cladding is about 140 °C [27]. If the mass flow rate of water in the core is increased to 100 kg/sec from 31.5 kg/sec, the temperature of outside cladding of target could be down to 114 °C. In the continuous flow target supply system, the temperatures of the outside and inside of the target cladding would be 246 °C and 269 °C, respectively.

The temperature of target solution itself in the container could be expected very high because of low thermal conductivity of a solution. The only thermal conductivity data for solution fuel can be obtained from SUPO, which used 7.3 wt. % uranium, 88.7 % enriched uranyl nitrate solution. It was 0.00666 W/cm °C at 86 °C [68]. But the heat transfer of target solution would be a combination of conduction and convection not just conduction like a solid fuel element. The radiolytic gas bubble evolution by the decomposition of water would agitate the fluid. This fluid agitation would increase the over-all heat transfer coefficients for the cooling system of the core [68]. More studies about the heat removal of self-heated target solution are required with more experimental hydraulic data. These works are left for future study.

6.3 Waste Stream

The Mo-99 production process would generate chemical and radioactive waste during the target fabrication, irradiation, and Mo-99 extraction steps.

In Cintichem target fabrication, 1.44 kg of uranium contaminated copper will be disposed as radioactive waste for each target during the electroplating process [5]. This solid Low Level Radioactive waste (LLW) will not be generated in the solution target fabrication. Only some chemicals and lab trash will be produced. The routine LLW generated during the irradiation operation consists of protective clothing and contaminated facility hardware.

A significant source of radioactive waste is due to the extraction of isotopes. The solution target system can bypass the target dissolution step unlike the coated target. Usually about total 130 g of acid cocktail solution and water waste is generated for dissolution of each coated target [5]. During Mo-99 extraction step, 70 g of solution waste is produced also. These high level and low level liquid wastes would be solidified to be disposed of in a metal container. The conventional Mo-99 process would not recycle uranium from solution. Thus 99.6 % of the uranium initially electroplated on the target would be discharged as waste [35]. In solution target system most of uranium is recovered and reused. Another source of waste in the extraction process is the used target tubes. These contaminated stainless steel tubes are compacted before disposal to reduce the volume. Each target produces ~33g of solid waste (~ 4 cm^3). Since the container is not removed in the continuous flow target supply system, disassembly and dissolution wastes are not generated. The solution target process would produce resin waste during extraction process. The extraction of Mo-99 from the irradiated solution is not fully developed, only conceptual methods are studied in this work. The extraction columns would use regenerative resins to reduce waste production. Assuming these columns are not reused, 2 – 4 columns will be disposed as waste (assuming volume of each column is 1000 *ml*). A genetic flow chart of waste production and management of solution target system in a Mo-99 production is provided in Figure 6.3. Table 6.4 summarizes the estimated amount of waste generated in a Mo-99 production of the conventional target and solution target for 1-year operation.

Table 6.4 Waste Generated in Mo-99 Production (10 targets/week, or weekly cycle)

	Inside Coated Target	Tube type solution target	20 *l* CFTS
Target Fabrication			
Routine LLW(m^3)	4	4	4
Copper (kg)	750 [5]	0	0
Liquid Waste(m^3)	260 [35]	0	0
Target Irradiation			
Routine LLW(m^3)	4	4	4
Extraction Process			
Routine LLW(m^3)	4	4	4
Stainless Steel(m^3)	17.2	17.2	0
Liquid LLW(m^3)	2.1 [32]	2.1 [53]	4.2 [56]
Extraction Column(m^3)	0	1.1 [53]	2.1 [56]

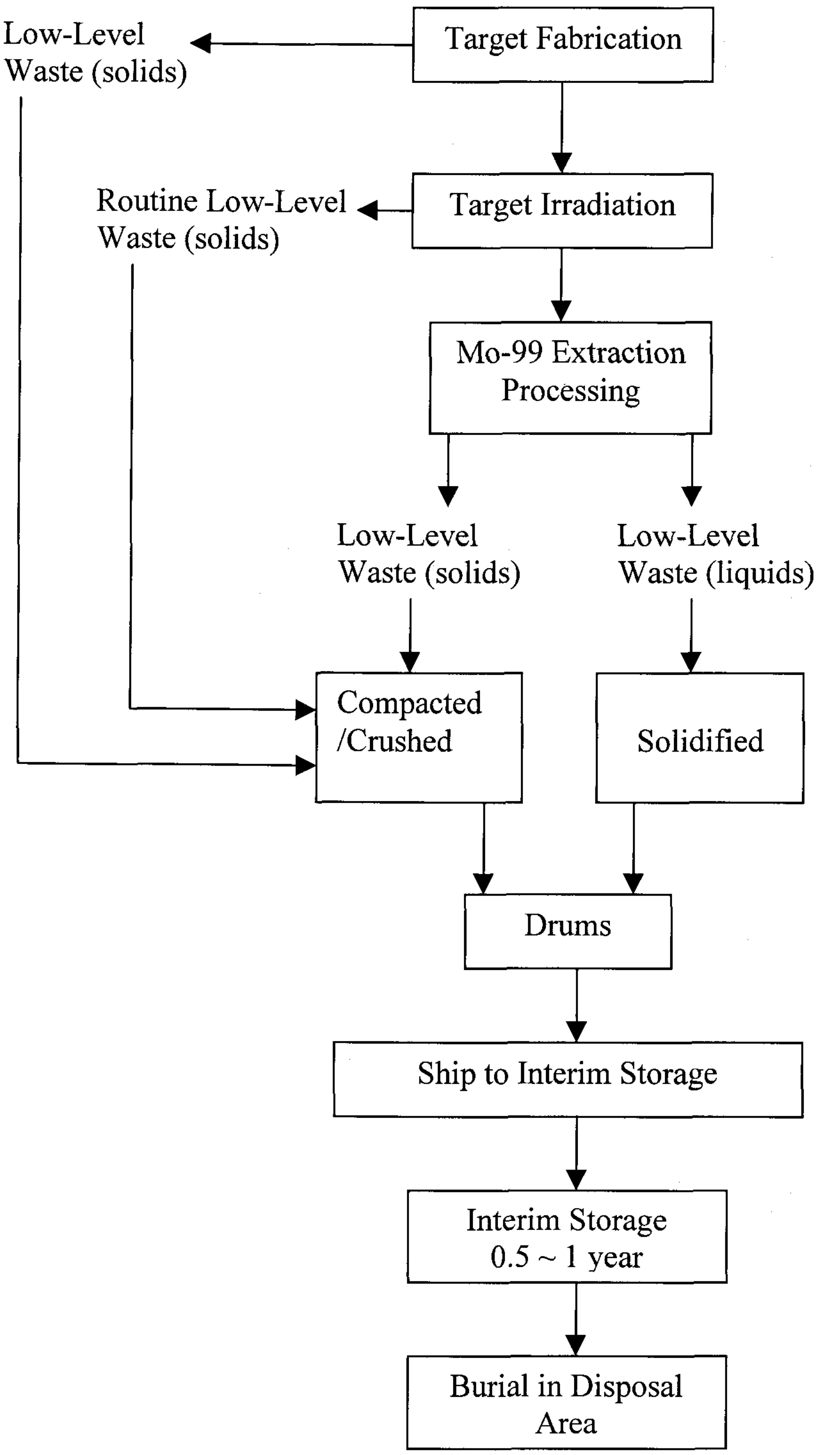

Figure 6.3 Genetic Flow Chart of Waste Production and Management of Solution Target

6.4 Accident Analysis

The rupture or failure of the cladding of a target would release the fission products to reactor containment and environment. The occupational exposure in the reactor room and the public exposure in the outside building are evaluated in this section.

In the analysis of fission product releases of target, it is assumed that the highest power density target in the core fails after 7-day irradiation with 1 MW operation of OSTR. Other assumptions are as follows:

1. All fission products are released to the cooling water in the core immediately. As shown in Table 6.5, due to the solubility characteristics in water, most of the isotopes released would be dissolved and thus remain in the core tank. For approximately 18,600 liters of water in a core tank, the solubility of these isotopes are much greater then the amount produced in target. Table 6.6 gives the inventory of gaseous fission products of target, which has 14.7 kW power and is irradiated for 7 days. Isotopes are only released to the reactor room through pool water evaporation (0.00086 *l*/sec) [33].
2. The water purification system would remove halogen isotopes from the pool [33]. The cleanup rate is 0.631 *l*/sec with efficiency 95 %[27].
3. The release is assumed to be of sufficient duration so that all isotopes reach saturation and are then assumed to be released to the environment.
4. The fission gas is released from reactor building at ground level, and is dispersed under Pasquill F conditions with a wind speed of 1 m/sec [59].

5. There is no depletion of the cloud as the result of deposition on the ground [59].
6. The ventilation rate of reactor building is 4.905 m^3/sec (10391 cfm) [69]. In case of the failure or shut down of ventilation system, 0.1 % per day of the contained gases is leaked to the atmosphere [59].
7. The volume of reactor building is 3.74×10^3 m^3 [69].

Table 6.5 Solubility of Fission Products in Water [70]

Elements	Solubility, *g/ml* H_2O	
	Cold, 25 °C	Hot, 50 °C
Bromine	0.0358	0.0352
Iodine	0.00030	0.00078
Krypton	0.00022	0.00017
Xenon	0.0007	0.00049

Using these assumptions, the total saturated activity released to a reactor room can be calculated as [33]:

$$R_i = S_i \frac{m_E}{V_p} \left(\frac{1}{\lambda_i + \dfrac{m_E + \gamma\, m_C}{V_P}} \right)$$

(6.11)

where R_i = the total saturated activity of isotope i released to the reactor room,

S_i = the activity of isotope i released from the target to the core tank,

λ_i = the decay constant for isotope i,

V_P = the water volume in the core tank,

m_E = the evaporation rate from the core tank,

m_C = the cleanup rate through the purification system with efficiency γ.

The calculation of whole body gamma and beta doses downwind from the reactor building can be accomplished through following equations. Doses were estimated with ventilation system operation and shutdown. The concentration of isotope as function of distance and time is [59]:

$$\chi = \frac{\lambda_l\, C_o\, e^{-\lambda_c t}}{\pi\, v \sigma_y \sigma_z}\, exp\left(-\frac{h^2}{2\sigma_z^2}\right), \tag{6.12}$$

where χ = the concentration of effluent as a function of space and time (Ci/m^3),

σ_y, σ_z = the horizontal and vertical dispersion coefficient with distance (m),

v = wind speed (m/sec),

λ_c = the total decay constant of the fission product in the building (sec^{-1},

$\lambda_c = \lambda + \lambda_l$),

λ_l = the release rate from the building (sec^{-1}),

λ = the decay constant (sec^{-1}),

h = the emitting altitude (m), and

C_o = the initial activity of isotope in the building (Ci).

Table 6.6 The Inventory of Fission Products in 14.3 kW Target after 7-day Irradiation

Nuclide	Half-life*	fission yield, (%)	Activity,(Ci)	Weight, (g)
Br-83	2.40 h	0.53070	7.2550E+01	4.6117E-06
Br-84	31.80 m	0.96650	1.3213E+02	1.8771E-06
Br-84m	6.0 m	0.01922	2.6275E+00	7.0430E-09
Br-85	2.87 m	1.29530	1.7708E+02	2.2975E-07
Br-87	55 s	1.56170	2.1349E+02	9.0553E-08
I-129	$10^{7.201}$ y	0.66490	7.6084E-08	4.3572E-04
I-131	8.04 d	2.83520	1.7562E+02	1.4166E-03
I-132	2.28 h	4.20834	5.7531E+02	5.5252E-05
I-133	20.80 h	6.76530	9.2143E+02	8.1343E-04
I-134	52.60 m	7.61170	1.0406E+03	3.9007E-05
I-135	6.58 h	6.40650	8.7581E+02	2.4826E-04
I-136	46 s	2.10950	2.8838E+02	8.2351E-05
Kr-83m	1.86 h	0.53070	7.2550E+01	3.5165E-06
Kr-85	10.73 y	0.28830	4.8797E-02	1.2441E-04
Kr-85m	4.48 h	1.31070	1.7918E+02	2.1773E-05
Kr-87	1.27 h	2.54210	3.4752E+02	1.2253E-05
Kr-88	2.80 h	3.58400	4.8996E+02	3.9075E-05
Kr-89	3.16 m	4.68120	6.3995E+02	9.5722E-07
Kr-90	32.3 s	4.68910	6.4103E+02	1.6518E-07
Kr-91	9 s	3.51180	4.8009E+02	3.4853E-08
Xe-131m	11.90 d	0.03969	1.8168E+00	2.1691E-05
Xe-133	5.29 d	6.77050	5.5568E+02	2.9942E-03
Xe-133m	2.23 d	0.19140	2.3195E+01	5.2687E-05
Xe-135	9.17 h	6.63340	9.0683E+02	3.5823E-04
Xe-135m	15.3 m	1.05640	1.4442E+02	1.5865E-06
Xe-137	3.84 m	6.13250	8.3835E+02	2.3457E-06
Xe-138	14.2 m	6.28360	8.5901E+02	8.9526E-06
Xe-139	39.7 s	5.15780	7.0510E+02	3.4490E-07
Xe-140	13.6 s	3.71810	5.0829E+02	8.5785E-08

* s = sec, m = minute, h = hour, d = day, and y = year.

The horizontal and vertical dispersion coefficient as a function of distance from source for various Pasquill conditions are given in "*Meteorology and Atomic Energy – 1968*" [71]. Table 6.7 represents these coefficients when Pasquill condition is F. The release rates from the building with ventilation system operation and shutdown are 6.3101×10^{-4} sec^{-1} and 1.16×10^{-8} sec^{-1}, respectively. The air is discharged at a point 16.8 m above the ground [69]. The most important fission products for dose calculation are shown in Table 6.8 with its average gamma and beta energy, and saturated activity in the reactor room.

Table 6.7 Horizontal and Vertical Dispersion Coefficient at Pasquill F Condition [71].

Distance, m	σ_y, m	σ_z, m
100	4	2.4
200	8	4
300	13	5.9
400	17	7.3
500	20	8.4
600	24	9.5
700	28	11
800	32	13
900	35	14
1000	38	15
1500	53	18
2000	70	22

Table 6.8 The Most Important Fission Products for Dose Calculation.

Nuclide	Saturated Activity, Ci	$E_{\gamma,\,avg.}$, MeV [8]	$E_{\beta,\,avg.}$, MeV [8]
Kr-85	0.04672711	0.00211	0.201
Kr-85m	0.19255986	0.151	0.246
Kr-87	0.10595351	1.37	1.14
Kr-88	0.33391942	1.74	0.84
Xe-133	16.4404137	0.03	0.146
Xe-133m	0.29432933	0.0326	0.155
Xe-135	1.99250912	0.246	0.276
Xe-135m	0.00884287	0.422	0.0974
I-131	0.24404189	0.371	0.182
I-132	0.22789283	2.39	0.636
I-133	1.02582295	0.477	0.381
I-134	0.19099522	1.94	0.729
I-135	0.65805786	1.78	0.42
Br-83	0.02981745	0.00742	0.279
Br-84	0.01544417	1.72	1.404

The total external dose to a person who is standing in the plume for the time t_o can be calculated as [59]:

$$H_\gamma = 0.262\, E_{\gamma,avg.} \int_0^{t_o} \chi \, dt \quad \text{rem} \tag{6.13}$$

and

$$H_\beta = 0.229\, E_{\beta,avg.} \int_0^{t_o} \chi \, dt \quad \text{rem,} \tag{6.14}$$

where H_γ and H_β are total gamma and beta whole body doses for time t_o.

Introducing χ of Equation 6.12 then gives

$$H_\gamma = \frac{0.262\, E_{\gamma,avg.}\, \lambda_l\, C_o\, \exp\left(-\frac{h^2}{2\sigma_z^2}\right)}{\pi\, v \sigma_y\, \sigma_z\, \lambda_c}\left(1 - e^{-\lambda_c t_o}\right) \text{ rem,} \qquad (6.15)$$

and

$$H_\beta = \frac{0.229\, E_{\beta,avg.}\, \lambda_l\, C_o\, \exp\left(-\frac{h^2}{2\sigma_z^2}\right)}{\pi\, v \sigma_y\, \sigma_z\, \lambda_c}\left(1 - e^{-\lambda_c t_o}\right) \text{ rem.} \qquad (6.16)$$

Figure 6.4 shows the whole body gamma and beta doses to a person who stands in a downwind location from the reactor building as a function of distance from the building for the release occurring under normal ventilation condition and under ventilation system shutdown. This dose is integrated over the first 12 hours after the release. Over 90 percent of this dose is received within 2 hours after the release. Within the 100 m downwind area, the total radiation dose to the whole body is 15.8 mrem even under normal ventilation condition. It is lower than an exclusion area limit of 10 CFR 100 (25 rem) [72]. Under ventilation system shutdown, the dose is 0.0054 mrem within 2 hours. For a 12 hour-exposure the maximum whole body doses under ventilating and non-ventilating are 15.9 mrem and 0.023 mrem, respectively.

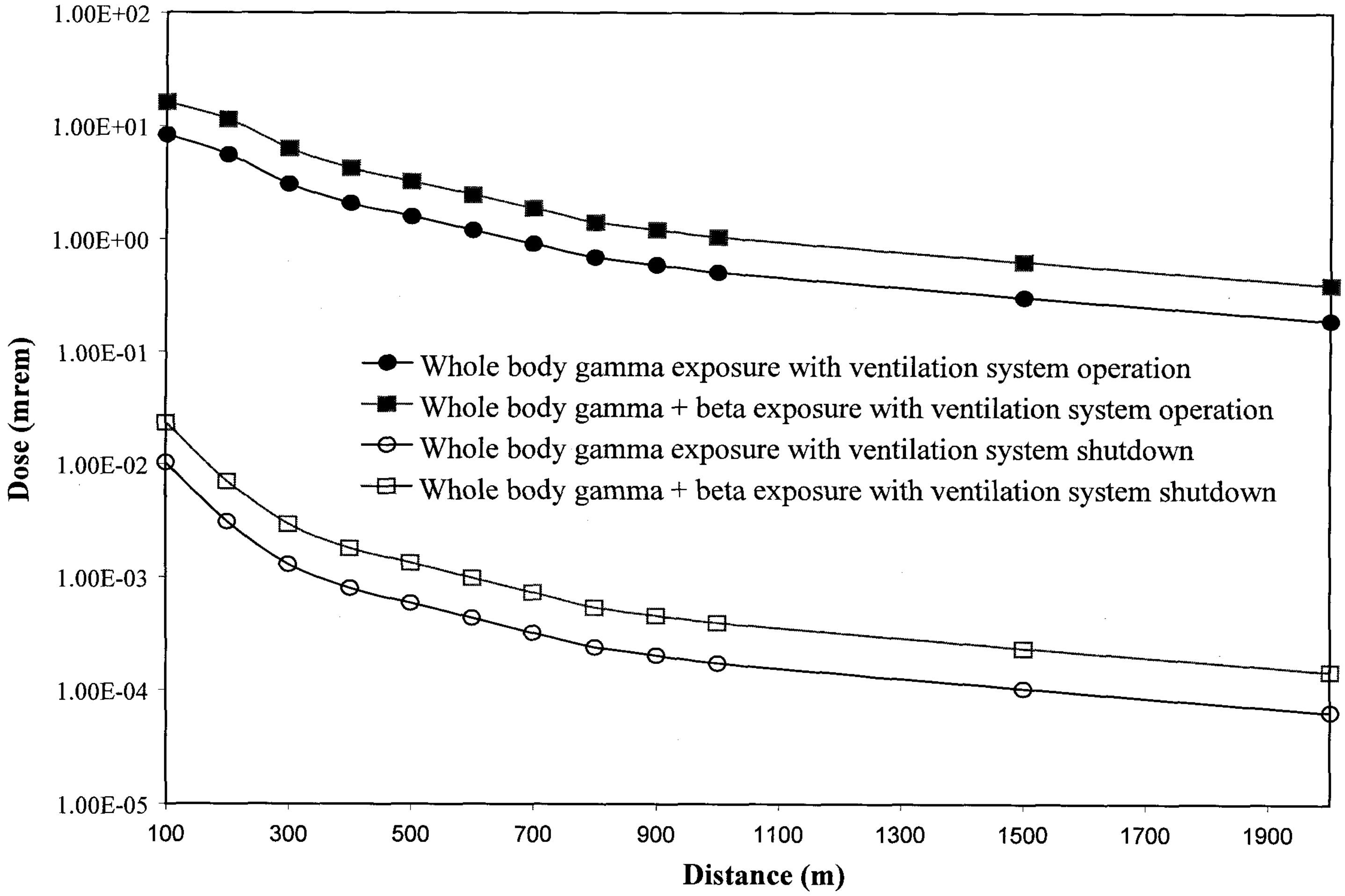

Figure 6.4 Whole Body Gamma and Beta Dose vs. Distance Downwind

The computation of gamma dose in the reactor room can be induced with Equation (6.15). In this time, the effect of dispersion by downwind is not considered. It only assumes that all released nuclides are located evenly in the room. The integrated dose for time t_o is:

$$H_\gamma = \frac{0.262\, E_{\gamma,avg.}\, \lambda_l\, C_o}{\lambda_c\, V}\left(1 - e^{-\lambda_c t_o}\right) \text{ rem} \qquad (6.17)$$

where V = the reactor room volume (m^3)

λ_c = the total decay constant of the fission product in the building (sec^{-1},

$\lambda_c = \lambda + \lambda_l$),

λ_l = the release rate from the building (sec^{-1}),

λ = the decay constant (sec^{-1}),

$E_{\gamma,\, avg.}$ = the average energy of all the γ-rays per disintegration (MeV), and

C_o = the initial activity of isotope in the building (Ci).

Figure 6.5 shows the whole body gamma ray dose to a person in the reactor room as a function of time after the concentration is saturated. Under normal ventilation condition, the dose to a person in the room is 0.82 rem for first 1 hour. When the ventilation system shuts down to prevent release to the environment at the instance of the radioactive material release, the dose in the room is 1.02 rem for first 1 hour.

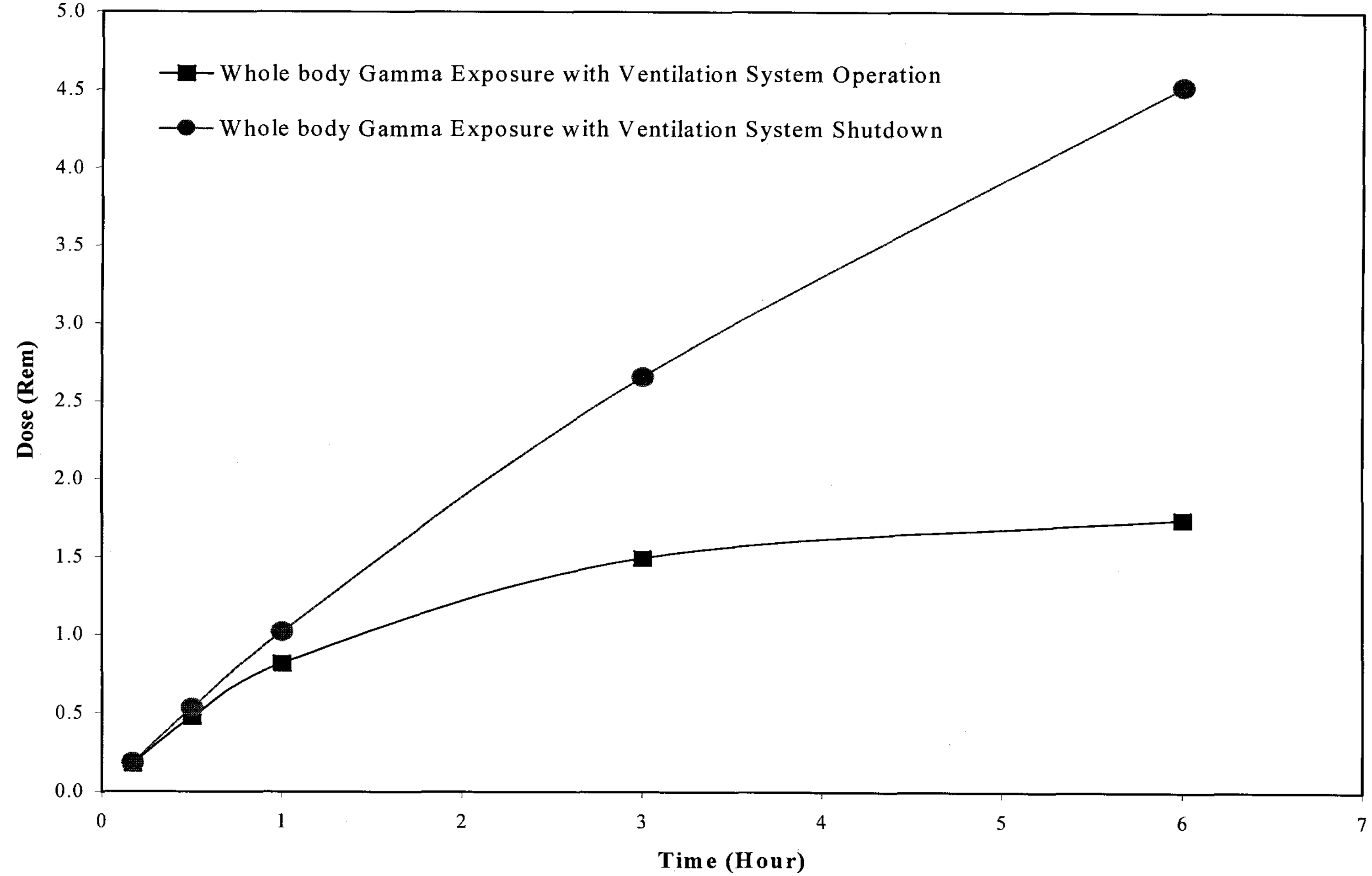

Figure 6.5 Whole Body Gamma Dose in the Reactor Room vs. Time

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Summary and Conclusions

One of the most useful radioisotopes in the nuclear medicine is Technetium-99m (Tc-99m), a daughter product of Molybdenum-99 (Mo-99). Because of the short half-lives of these isotopes (the half-lives of Mo-99 and Tc-99m are 66 hours and 6 hours, respectively), the ensuring of a stable and continuous supply is necessary for medical purpose. Two common techniques are used to produce Mo-99: fission of U-235 and neutron capture of Mo-98. Most Mo-99 used in U.S. is from the uranium fission.

In this work the feasibility of producing of Mo-99 using the OSU TRIGA reactor has been evaluated. The Mo-99 would be produced using the fission process by irradiating "homogeneous aqueous uranium solution target".

The Monte Carlo N-Particle Transport Code (MCNP) was used extensively in determining the optimum configuration, and obtaining the fission rate and power generated in the targets. A three-dimensional OSTR geometry with MCNP was modeled, and verified with experimental data. The core k-effective value of 1.05019 in experimental result is 1.05142 ± 0.00271 in MCNP model. It is 0.12 % error to the measured value. Also the power per element in the core as calculated by MCNP is compared with the measured value and the difference is minimal.

The typical fission target for Mo-99 production is a uranium-coated on the inside surface of an irradiation tube. On the inside wall of target, a very thin, highly enriched uranium (93 % enriched) coating is electroplated on the surface. This target fabrication process is very complicated and takes a great deal of time. Also it generates lots of waste during target fabrication and Mo-99 extraction process after irradiation.

The advantages of a homogeneous aqueous uranium solution target are the inherent safety features of a large negative temperature and power reactivity coefficients, convenience of target fabrication, straightforward Mo-99 extraction process, and the low volume of waste generation. The first solution fueled reactor was LOPO, which was built at Los Alamos National Laboratory in 1944. Currently there are five solution type reactors are operating in the world: Solution High-Energy Burst Assembly (SHEBA) in USA, Static Experimental Critical Facility (STACY) and Transient Experimental Critical Facility (TRACY) in Japan, ARGUS solution reactor in Russia, and SILENE in France. The conceptual design of the Medical Isotope Production Reactor (MIPP) developed by Babcock & Wilcox would use an aqueous solution of uranyl nitrate for Mo-99 production. The demonstration of Mo-99 production from a liquid-fueled reactor was performed with SHEBA by Glenn [35] with the chemical extraction process of Mo-99 from a irradiated solution fuel having been developed by Chen [53].

Two types of solution targets are developed in this study. The first is the same outer dimensions as a standard OSTR fuel element but allows a one-pass flow of the uranium solution fuel through a tube type encapsulation. The other is the continuous flow target system like a solution fuel reactor system. Neutronic analyses of the tube type 20 % and 93 % enriched uranyl nitrate solution targets were performed for four different core configurations. These analyses indicated that even 10 target-locations in the core would not effect to the safety of OSTR operation. Ten 93 % enriched uranyl nitrate solution targets would produce 5930 Ci of Mo-99 for 7-day irradiation. This represents 43 % of the Mo-99 used in US in a one week. The chemical form of the fuel was changed to uranyl sulfate and was examined as a target. The neutronic and Mo-99 production results were all most same as the uranyl nitrate case. The increment of uranium content in a solution would grow the amount of Mo-99 produced, hence would decline the yield to U-235 loaded (Ci/g ^{235}U). When same amount of U-235 was used in the typical coated target and the solution target, the typical target generated only 37 % of Mo-99 produced by the solution target. The conceptual chemical process was developed for extracting Mo-99 from the irradiated solution.

A continuous flow target system, which can supply the target material continuously and remove the irradiated solution at same time, was modeled for the OSTR core. This system consists of a 20 liter-target container and catalyst recombiner for recombining the radiolytic gas. In 7-day cycle, it would produce 4176 Ci of Mo-99. The continuous Mo-99 extraction process was developed.

Also analyzed issues were the radiolytic gas treatment, the thermal hydraulic analysis, the waste stream, and the radiological impacts in accident. The hydrogen and oxygen, which are the decomposition of water in the target solution by fission recoil, should be recombined to keep same target composition during operation and to remove the explosion hazard of the hydrogen. The addition of copper catalyst to the solution of the tube type target would help the recombination of the radiolytic gases. The recombiner in the continuous target material supply system, which consists of six-catalyst plates, reacts with these gases for recombination.

The heat from the target is removed by convection of water, as is the case of the standard fuel elements in the OSTR. The inside and outside temperature of cladding of the target in the highest target power case are 288 °C and 277 °C, respectively. Both temperatures are much below the melting point of cladding of 1400 – 1454 °C.

The simple target fabrication process and recycling of the used uranium would reduce the waste generation. The amount of waste produced from solution system was 6 –11 % of that of the typical coated target. The expected whole body dose in the outside building when the structural integrity of target fail was 15.9 mrem for a 12 hour stay in the plume at 100 m downwind under normal ventilation conditions. If the ventilation system was shut down, the dose was reduced to 0.023 mrem. The doses to a person in the reactor room for 1 hour period with ventilation system in operation and shutdown were 0.82 rem and 1.02 rem.

In conclusion, this study has shown that the production of molybdenum-99 in OSTR with the homogeneous aqueous of uranium solution is technically feasible. The simulation analysis indicated that it could provide 40 to 50 % of the weekly US demand of Mo-99. This work has also shown that the use of the solution target to produce Mo-99 production would increase the production efficiency by good neutron economy, reduction of processing period, through the reuse of uranium, and by minimizing the volume of the waste generated.

7.2 Recommendations for Future Work

During the course of this research, some areas were identified as requiring further study if the production of medical isotopes in OSTR with the homogeneous aqueous uranium solution was actually begun. These areas of potential research include:

1. *Thermal hydraulic analysis of the irradiating solution.* The heat transfer in the target solution is a complicated problem. The study about the thermodynamic behavior of uranium solutions is necessary because of rare data currently such as a thermal conductivity, heat transfer coefficient, etc.
2. *Effect of the bubble formation in the irradiating solution.* The effect of void formation by the decomposition of water in a solution also needs to be studied. It would harm a beneficial effect of the fluid solution with the potential benefit of enhancing heat removal from the target.
3. *Pilot production.* To verify the simulation results, small scale production facility should be constructed and tested.
4. *Development of chemical extraction process to be practical.* This study showed only a conceptual design of process. The Mo-99 extraction process of isotopes should be developed and performed.

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APPENDIX

```
OSU TRIGA REACTOR MCNP MODEL INPUT
C
C
1       0 #((-4000 -12 11) : (2619 -2618 -2601 2606 -2607 2612))
        -1 imp:n=0                          $ outside reactor void outside reactor
2        0 1 imp:n=0                                $ infinity void outside reactor
3       1 -2.7 (7:-9:2) -3 4 2 -5 -12 11 -14 imp:n=1 $  core vessel
4       1 -2.7 (7:-9:2) -3 6 -2 -12 11 -14 imp:n=0.5 $ top grid plate
5       2 0.0958666 (7:-9:2) -6 7 -2 -12 11 -14 imp:n=1 $ top end fittings
6       2 0.0958666 (7:-9:2) -9 8 -2 -12 11 -14 imp:n=1 $ bottom end fittings
7       1 -2.7 (7:-9:2) -8 4 -2 -12 11 -14 imp:n=0.5 $ bottom grid plate
8       3 -1.0 (7:-9:2) -3 7 5 -10 -12 11 -14 imp:n=1 $ water above reflector
9       3 -1.0 (7:-9:2) -9 4 5 -10 -12 11 -14 imp:n=1 $ water below reflector
10      3 -1.0 (7:-9:2) -4 11 -10 -12 11 -14 imp:n=1 $ water below reactor
11      3 -1.0 (7:-9:2) -12 3 -10 -12 11 -14 imp:n=1 $ water above reactor
12       3 -1.0 (7:-9:2) -12 11 -15 10 -14 -12 11 -14  $ water around reactor -y
          # (-3002 -14 3005 3008) # (-3004 -14 5 -15)
          # (2615 2613 2702 -14 -2607 2612 -2601 2606) imp:n=1
13       3 -1.0 (7:-9:2) -12 11 15 10 -14 -12 11 -14  $ water around reactor +y +
midplane beam4
          # (-3002 -14 3005 3008) # (-3004 -14 5 -15)
          # (2615 2613 2702 -14 -2607 2612 -2601 2606)
          # (5 -3102 15 -14) # (10 -3106 15 -14) imp:n=1
15       3 -1.0 32 38 41 47 50 53 56 59 62 65 68 71 74 77 80 83 86 89 $ center ring
water core
      92 95 98 101 104 110 113 119 122 125 128 131 134 137 140 143 146
      149 152 155 158 167 176 179 182 185 188 191 194 197 200 203 206
      209 212 215 218 221 284 288 292 295 297 -21 20 -19 -7 9 -2 -12
      11 -14 imp:n=1
16       3 -1.0 32 38 41 47 50 53 56 59 62 65 68 71 74 77 80 83 86 89 $ center ring
top reflector core
      92 95 98 101 104 110 113 119 122 125 128 131 134 137 140 143 146
      149 152 155 158 167 176 179 182 185 188 191 194 197 200 203 206
      209 212 215 218 221 284 288 292 295 297 -7 21 -19 -7 9 -2 -12 11
      -14 imp:n=1
17       3 -1.0 32 38 41 47 50 53 56 59 62 65 68 71 74 77 80 83 86 89  $ center
ring bottom reflector core
      92 95 98 101 104 110 113 119 122 125 128 131 134 137 140 143 146
      149 152 155 158 167 176 179 182 185 188 191 194 197 200 203 206
      209 212 215 218 221 284 288 292 295 297 -20 9 -19 -7 9 -2 -12 11
      -14 imp:n=1
18       3 -1.0 35 38 41 44 47 50 53 59 62 65 71 74 77 80 104 107 113  $ middle
ring water core
      116 119 143 146 161 164 170 173 185 194 197 200 203 212 221 224
      227 230 233 236 239 242 245 248 251 254 257 260 263 266 269 272
      275 298 299 300 301 -21 20 19 -22 -7 9 -2 -12 11 -14 imp:n=1
19       3 -1.0 35 38 41 44 47 50 53 59 62 65 71 74 77 80 104 107 113  $ middle
ring top reflector core
      116 119 143 146 161 164 170 173 185 194 197 200 203 212 221 224
      227 230 233 236 239 242 245 248 251 254 257 260 263 266 269 272
      275 298 299 300 301 -7 21 19 -22 -7 9 -2 -12 11 -14 imp:n=1
20       3 -1.0 35 38 41 44 47 50 53 59 62 65 71 74 77 80 104 107 113  $ middle
ring bottom reflector core
      116 119 143 146 161 164 170 173 185 194 197 200 203 212 221 224
      227 230 233 236 239 242 245 248 251 254 257 260 263 266 269 272
      275 298 299 300 301 -20 9 19 -22 -7 9 -2 -12 11 -14 imp:n=1
21       3 -1.0 35 44 107 116 161 164 170 173 224 227 230 233 236 239  $ outer hex
core  core
      242 245 248 251 254 257 260 263 266 269 272 275 298 299 300 301
      302 303 304 305 306 307 308 309 310 311 312 313 314 315 317 319
      321 323 325 327 329 331 333 335 337 339 341 343 345 347 349 351
      353 355 357 359 -21 20 22 -7 9 -2 -12 11 -14 imp:n=1
22       3 -1.0 35 44 107 116 161 164 170 173 224 227 230 233 236 239  $ outer top
hex reflector  core
      242 245 248 251 254 257 260 263 266 269 272 275 298 299 300 301
      302 303 304 305 306 307 308 309 310 311 312 313 314 315 317 319
      321 323 325 327 329 331 333 335 337 339 341 343 345 347 349 351
      353 355 357 359 -7 21 22 -7 9 -2 -12 11 -14 imp:n=1
```

```
23       3 -1.0 35 44 107 116 161 164 170 173 224 227 230 233 236 239  $ outer
bottom reflector hex region core
      242 245 248 251 254 257 260 263 266 269 272 275 298 299 300 301
      302 303 304 305 306 307 308 309 310 311 312 313 314 315 317 319
      321 323 325 327 329 331 333 335 337 339 341 343 345 347 349 351
      353 355 357 359 -20 9 22 -7 9 -2 -12 11 -14 imp:n=1
24       4 -1.35 -7 23 5 -24 -12 11 -14 imp:n=1 $ lazy susan reflector
25       5 0.080193 -7 23 24 -25 -12 11 -14 imp:n=1 $ gr outside lazys reflector
26       5 0.080193 -23 9 5 -25 15 -12 11 -14 $ gr below lazy susan +y + beam 4
midplane reflector
         # (-3002 -14 3005 3008) # (-3004 -14 5 -15)
         # (5 -3102 15 -14) # (10 -3106 15 -14) imp:n=1
c 27       5 0.080193 -23 9 5 -25 15 -12 11 -14 $ gr below lazy susan +y - beam 4
midplane reflector
c         # (-3002 -14 3005 3008) # (-3004 -14 5 -15) imp:n=1
28       5 0.080193 -23 9 5 -25 -15 -12 11 -14 $ gr below lazy susan -y reflector
         # (-3002 -14 3005 3008) # (-3004 -14 5 -15) imp:n=1
29       6 -11.35 -7 9 25 -10 15 -12 11 -14  $ lead liner +y + beam 4 midplane
reflector
         # (-3002 -14 3005 3008) # (-3004 -14 5 -15)
         # (5 -3102 15 -14) # (10 -3106 15 -14) imp:n=1
c 30       6 -11.35 -7 9 25 -10 15 -12 11 -14 $ lead +y - beam 4 midplane reflector
c         # (-3002 -14 3005 3008) # (-3004 -14 5 -15) imp:n=1
31       6 -11.35 -7 9 25 -10 -15 -12 11 -14 $ lead -y reflector
         # (-3002 -14 3005 3008) # (-3004 -14 5 -15) imp:n=1
40001    21 -3.965 14 -4000 -12 11 #(2619 -2618 -2601 2606 -2607 2612) $ concrete
shield
         # (-3002 -4000 3005 3008) # (-3004 -4000 5 -15)
         # (5 -3102 15 -4000) # (10 -3106 15 -4000) imp:n=1
32       425 -1.029e-3 -7 9 -28 -32 -7 9 -2 -12 11 -14 imp:n=1 vol=580.666 $ B1
Void
40       1 -2.7 -7 9 28 -32 -32 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ Al
cladding rod
41       7 0.042234 -21 20 -33 -35 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod F7**********
42       8 0.0927926 -21 27 33 -34 -35 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
43       8 0.0927926 -27 29 33 -34 -35 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
44       8 0.0927926 -29 30 33 -34 -35 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
45       8 0.0927926 -30 31 33 -34 -35 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
46       8 0.0927926 -31 20 33 -34 -35 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
47       5 0.080193 -7 21 -34 -35 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
48       5 0.080193 -20 9 -34 -35 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
49       13 -7.86 -7 9 34 -35 -35 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
50       7 0.042234 -21 20 -36 -38 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod
51       8 0.0927926 -21 27 36 -37 -38 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
52       8 0.0927926 -27 29 36 -37 -38 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
53       8 0.0927926 -29 30 36 -37 -38 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
54       8 0.0927926 -30 31 36 -37 -38 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
```

```
      vol=77.0958
55        8 0.0927926 -31 20 36 -37 -38 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
56        5 0.080193 -7 21 -37 -38 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
57        5 0.080193 -20 9 -37 -38 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
58        13 -7.86 -7 9 37 -38 -38 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
59        7 0.042234 -21 20 -39 -41 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod
60        8 0.0927926 -21 27 39 -40 -41 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
61        8 0.0927926 -27 29 39 -40 -41 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
62        8 0.0927926 -29 30 39 -40 -41 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
63        8 0.0927926 -30 31 39 -40 -41 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
64        8 0.0927926 -31 20 39 -40 -41 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
65        5 0.080193 -7 21 -40 -41 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
66        5 0.080193 -20 9 -40 -41 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
67        13 -7.86 -7 9 40 -41 -41 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
68        7 0.042234 -21 20 -42 -44 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod F8*********
69        8 0.0927926 -21 27 42 -43 -44 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
70        8 0.0927926 -27 29 42 -43 -44 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
71        8 0.0927926 -29 30 42 -43 -44 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
72        8 0.0927926 -30 31 42 -43 -44 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
73        8 0.0927926 -31 20 42 -43 -44 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
74        5 0.080193 -7 21 -43 -44 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
75        5 0.080193 -20 9 -43 -44 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
76        13 -7.86 -7 9 43 -44 -44 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
77        7 0.042234 -21 20 -45 -47 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod
78        8 0.0927926 -21 27 45 -46 -47 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
79        8 0.0927926 -27 29 45 -46 -47 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
80        8 0.0927926 -29 30 45 -46 -47 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
81        8 0.0927926 -30 31 45 -46 -47 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
```

```
82       8 0.0927926 -31 20 45 -46 -47 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
83       5 0.080193 -7 21 -46 -47 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
84       5 0.080193 -20 9 -46 -47 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
85       13 -7.86 -7 9 46 -47 -47 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
86       7 0.042234 -21 20 -48 -50 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod
87       8 0.0927926 -21 27 48 -49 -50 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
88       8 0.0927926 -27 29 48 -49 -50 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
89       8 0.0927926 -29 30 48 -49 -50 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
90       8 0.0927926 -30 31 48 -49 -50 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
91       8 0.0927926 -31 20 48 -49 -50 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
92       5 0.080193 -7 21 -49 -50 -7 9 -2 -12 11 -14 imp:n=1 vol=91.1953 $ gr
reflector
93       5 0.080193 -20 9 -49 -50 -7 9 -2 -12 11 -14 imp:n=1 vol=91.9257 $ gr
reflector
94       13 -7.86 -7 9 49 -50 -50 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
95       7 0.042234 -21 20 -51 -53 -7 9 -2 -12 11 -14 imp:n=1 vol=12.066 $ central
zr rod
96       8 0.0927926 -21 27 51 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
97       8 0.0927926 -27 29 51 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
98       8 0.0927926 -29 30 51 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
99       8 0.0927926 -30 31 51 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
100      8 0.0927926 -31 20 51 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
101       5 0.080193 -7 21 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
102       5 0.080193 -20 9 -52 -53 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
103       13 -7.86 -7 9 52 -53 -53 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
104       7 0.042234 -21 20 -54 -56 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
105      8 0.0927926 -21 27 54 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
106      8 0.0927926 -27 29 54 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
107      8 0.0927926 -29 30 54 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
108      8 0.0927926 -30 31 54 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
```

```
109       8 0.0927926 -31 20 54 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
110        5 0.080193 -7 21 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
111        5 0.080193 -20 9 -55 -56 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
112        13 -7.86 -7 9 55 -56 -56 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
113        7 0.042234 -21 20 -57 -59 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
114       8 0.0927926 -21 27 57 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
115       8 0.0927926 -27 29 57 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
116       8 0.0927926 -29 30 57 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
117       8 0.0927926 -30 31 57 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
118       8 0.0927926 -31 20 57 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
119        5 0.080193 -7 21 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
120        5 0.080193 -20 9 -58 -59 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
121        13 -7.86 -7 9 58 -59 -59 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
122        7 0.042234 -21 20 -60 -62 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
123       8 0.0927926 -21 27 60 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
124       8 0.0927926 -27 29 60 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
125       8 0.0927926 -29 30 60 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
126       8 0.0927926 -30 31 60 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
127       8 0.0927926 -31 20 60 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
128        5 0.080193 -7 21 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
129        5 0.080193 -20 9 -61 -62 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
130        13 -7.86 -7 9 61 -62 -62 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
131        7 0.042234 -21 20 -63 -65 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
132       8 0.0927926 -21 27 63 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
133       8 0.0927926 -27 29 63 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
134       8 0.0927926 -29 30 63 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
135       8 0.0927926 -30 31 63 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
```

```
      vol=77.0958
136        8 0.0927926 -31 20 63 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
137         5 0.080193 -7 21 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
138         5 0.080193 -20 9 -64 -65 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
139         13 -7.86 -7 9 64 -65 -65 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
140         7 0.042234 -21 20 -66 -68 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
141        8 0.0927926 -21 27 66 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
142        8 0.0927926 -27 29 66 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
143        8 0.0927926 -29 30 66 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
144        8 0.0927926 -30 31 66 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
145        8 0.0927926 -31 20 66 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
146         5 0.080193 -7 21 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
147         5 0.080193 -20 9 -67 -68 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
148         13 -7.86 -7 9 67 -68 -68 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
149         7 0.042234 -21 20 -69 -71 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
150        8 0.0927926 -21 27 69 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
151        8 0.0927926 -27 29 69 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
152        8 0.0927926 -29 30 69 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
153        8 0.0927926 -30 31 69 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
154        8 0.0927926 -31 20 69 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
155         5 0.080193 -7 21 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
156         5 0.080193 -20 9 -70 -71 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
157         13 -7.86 -7 9 70 -71 -71 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
158         7 0.042234 -21 20 -72 -74 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
159        8 0.0927926 -21 27 72 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
160        8 0.0927926 -27 29 72 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
161        8 0.0927926 -29 30 72 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
```

```
162      8 0.0927926 -30 31 72 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
163      8 0.0927926 -31 20 72 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
164       5 0.080193 -7 21 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
165       5 0.080193 -20 9 -73 -74 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
166       13 -7.86 -7 9 73 -74 -74 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
167       7 0.042234 -21 20 -75 -77 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
168      8 0.0927926 -21 27 75 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
169      8 0.0927926 -27 29 75 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
170      8 0.0927926 -29 30 75 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
171      8 0.0927926 -30 31 75 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
172      8 0.0927926 -31 20 75 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
173       5 0.080193 -7 21 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
174       5 0.080193 -20 9 -76 -77 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
175       13 -7.86 -7 9 76 -77 -77 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
176       7 0.042234 -21 20 -78 -80 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
177      8 0.0927926 -21 27 78 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
178      8 0.0927926 -27 29 78 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
179      8 0.0927926 -29 30 78 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
180      8 0.0927926 -30 31 78 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
181      8 0.0927926 -31 20 78 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
182       5 0.080193 -7 21 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
183       5 0.080193 -20 9 -79 -80 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
184       13 -7.86 -7 9 79 -80 -80 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
185       7 0.042234 -21 20 -81 -83 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
186      8 0.0927926 -21 27 81 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
187      8 0.0927926 -27 29 81 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
188      8 0.0927926 -29 30 81 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
```

```
      vol=77.0958
189      8 0.0927926 -30 31 81 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
190      8 0.0927926 -31 20 81 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
191       5 0.080193 -7 21 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
192       5 0.080193 -20 9 -82 -83 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
193       13 -7.86 -7 9 82 -83 -83 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
194       7 0.042234 -21 20 -84 -86 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
195      8 0.0927926 -21 27 84 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
196      8 0.0927926 -27 29 84 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
197      8 0.0927926 -29 30 84 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
198      8 0.0927926 -30 31 84 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
199      8 0.0927926 -31 20 84 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
200       5 0.080193 -7 21 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
201       5 0.080193 -20 9 -85 -86 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
202       13 -7.86 -7 9 85 -86 -86 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
203       7 0.042234 -21 20 -87 -89 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
204      8 0.0927926 -21 27 87 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
205      8 0.0927926 -27 29 87 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
206      8 0.0927926 -29 30 87 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
207      8 0.0927926 -30 31 87 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
208      8 0.0927926 -31 20 87 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
209       5 0.080193 -7 21 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
210       5 0.080193 -20 9 -88 -89 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
211       13 -7.86 -7 9 88 -89 -89 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
212       7 0.042234 -21 20 -90 -92 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
213       8 0.0927926 -21 27 90 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
214       8 0.0927926 -27 29 90 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
```

```
215       8 0.0927926 -29 30 90 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
216       8 0.0927926 -30 31 90 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
217       8 0.0927926 -31 20 90 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
218       5 0.080193 -7 21 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
219       5 0.080193 -20 9 -91 -92 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
220       13 -7.86 -7 9 91 -92 -92 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
221       7 0.042234 -21 20 -93 -95 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
222       8 0.0927926 -21 27 93 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
223       8 0.0927926 -27 29 93 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
224       8 0.0927926 -29 30 93 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
225       8 0.0927926 -30 31 93 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
226       8 0.0927926 -31 20 93 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
227       5 0.080193 -7 21 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
228       5 0.080193 -20 9 -94 -95 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
229       13 -7.86 -7 9 94 -95 -95 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
230       7 0.042234 -21 20 -96 -98 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
231       8 0.0927926 -21 27 96 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
232       8 0.0927926 -27 29 96 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
233       8 0.0927926 -29 30 96 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
234       8 0.0927926 -30 31 96 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
235       8 0.0927926 -31 20 96 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
236       5 0.080193 -7 21 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
237       5 0.080193 -20 9 -97 -98 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
238       13 -7.86 -7 9 97 -98 -98 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
239       7 0.042234 -21 20 -99 -101 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
240       8 0.0927926 -21 27 99 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
241       8 0.0927926 -27 29 99 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
```

```
      vol=77.0958
242        8 0.0927926 -29 30 99 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
243        8 0.0927926 -30 31 99 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
244        8 0.0927926 -31 20 99 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
245        5 0.080193 -7 21 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
246        5 0.080193 -20 9 -100 -101 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
247        13 -7.86 -7 9 100 -101 -101 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
248        7 0.042234 -21 20 -102 -104 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
249        8 0.0927926 -21 27 102 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
250        8 0.0927926 -27 29 102 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
251        8 0.0927926 -29 30 102 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
252        8 0.0927926 -30 31 102 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
253        8 0.0927926 -31 20 102 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
254        5 0.080193 -7 21 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
255        5 0.080193 -20 9 -103 -104 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
256        13 -7.86 -7 9 103 -104 -104 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
257        7 0.042234 -21 20 -105 -107 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
258        8 0.0927926 -21 27 105 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
259        8 0.0927926 -27 29 105 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
260        8 0.0927926 -29 30 105 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
261        8 0.0927926 -30 31 105 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
262        8 0.0927926 -31 20 105 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
263        5 0.080193 -7 21 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
264        5 0.080193 -20 9 -106 -107 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
265        13 -7.86 -7 9 106 -107 -107 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
266        7 0.042234 -21 20 -108 -110 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
267        8 0.0927926 -21 27 108 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
```

```
268       8 0.0927926 -27 29 108 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
269       8 0.0927926 -29 30 108 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
270       8 0.0927926 -30 31 108 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
271       8 0.0927926 -31 20 108 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
272       5 0.080193 -7 21 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
273       5 0.080193 -20 9 -109 -110 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
274       13 -7.86 -7 9 109 -110 -110 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
275       7 0.042234 -21 20 -111 -113 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
276       8 0.0927926 -21 27 111 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
277       8 0.0927926 -27 29 111 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
278       8 0.0927926 -29 30 111 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
279       8 0.0927926 -30 31 111 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
280       8 0.0927926 -31 20 111 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
281       5 0.080193 -7 21 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
282       5 0.080193 -20 9 -112 -113 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
283       13 -7.86 -7 9 112 -113 -113 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
284       7 0.042234 -21 20 -114 -116 -7 9 -2 -12 11 -14 imp:n=1 $central zr rod
F9******
      vol=12.066
285       8 0.0927926 -21 27 114 -115 -116 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
      vol=77.0958
286       8 0.0927926 -27 29 114 -115 -116 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
      vol=77.0958
287       8 0.0927926 -29 30 114 -115 -116 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
      vol=77.0958
288       8 0.0927926 -30 31 114 -115 -116 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
      vol=77.0958
289       8 0.0927926 -31 20 114 -115 -116 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
      vol=77.0958
290       5 0.080193 -7 21 -115 -116 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
291       5 0.080193 -20 9 -115 -116 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
292       13 -7.86 -7 9 115 -116 -116 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
293       7 0.042234 -21 20 -117 -119 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
```

```
294       8 0.0927926 -21 27 117 -118 -119 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
      vol=77.0958
295       8 0.0927926 -27 29 117 -118 -119 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
      vol=77.0958
296       8 0.0927926 -29 30 117 -118 -119 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
      vol=77.0958
297       8 0.0927926 -30 31 117 -118 -119 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
      vol=77.0958
298       8 0.0927926 -31 20 117 -118 -119 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
      vol=77.0958
299       5 0.080193 -7 21 -118 -119 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
300       5 0.080193 -20 9 -118 -119 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
301       13 -7.86 -7 9 118 -119 -119 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
302       7 0.042234 -21 20 -120 -122 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
303       8 0.0927926 -21 27 120 -121 -122 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
      vol=77.0958
304       8 0.0927926 -27 29 120 -121 -122 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
      vol=77.0958
305       8 0.0927926 -29 30 120 -121 -122 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
      vol=77.0958
306       8 0.0927926 -30 31 120 -121 -122 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
      vol=77.0958
307       8 0.0927926 -31 20 120 -121 -122 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
      vol=77.0958
308       5 0.080193 -7 21 -121 -122 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
309       5 0.080193 -20 9 -121 -122 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
310       13 -7.86 -7 9 121 -122 -122 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
311       7 0.042234 -21 20 -123 -125 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
312       8 0.0927926 -21 27 123 -124 -125 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
      vol=77.0958
313       8 0.0927926 -27 29 123 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
314       8 0.0927926 -29 30 123 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
315       8 0.0927926 -30 31 123 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
316       8 0.0927926 -31 20 123 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
317       5 0.080193 -7 21 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
318       5 0.080193 -20 9 -124 -125 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
319       13 -7.86 -7 9 124 -125 -125 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
320       7 0.042234 -21 20 -126 -128 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
```

```
        vol=12.066
321          8 0.0927926 -21 27 126 -127 -128 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
        vol=77.0958
322          8 0.0927926 -27 29 126 -127 -128 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
        vol=77.0958
323          8 0.0927926 -29 30 126 -127 -128 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
        vol=77.0958
324          8 0.0927926 -30 31 126 -127 -128 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
        vol=77.0958
325          8 0.0927926 -31 20 126 -127 -128 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
        vol=77.0958
326          5 0.080193 -7 21 -127 -128 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.1953
327          5 0.080193 -20 9 -127 -128 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.9257
328          13 -7.86 -7 9 127 -128 -128 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
        vol=32.8228
329          7 0.042234 -21 20 -129 -131 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
        vol=12.066
330          8 0.0927926 -21 27 129 -130 -131 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
        vol=77.0958
331          8 0.0927926 -27 29 129 -130 -131 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
        vol=77.0958
332          8 0.0927926 -29 30 129 -130 -131 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
        vol=77.0958
333          8 0.0927926 -30 31 129 -130 -131 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
        vol=77.0958
334          8 0.0927926 -31 20 129 -130 -131 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
        vol=77.0958
335          5 0.080193 -7 21 -130 -131 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.1953
336          5 0.080193 -20 9 -130 -131 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.9257
337          13 -7.86 -7 9 130 -131 -131 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
        vol=32.8228
338          7 0.042234 -21 20 -132 -134 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
        vol=12.066
339          8 0.0927926 -21 27 132 -133 -134 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section1
        vol=77.0958
340          8 0.0927926 -27 29 132 -133 -134 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section2
        vol=77.0958
341          8 0.0927926 -29 30 132 -133 -134 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section3
        vol=77.0958
342          8 0.0927926 -30 31 132 -133 -134 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section4
        vol=77.0958
343          8 0.0927926 -31 20 132 -133 -134 -7 9 -2 -12 11 -14 imp:n=1 $fuel rod
section5
        vol=77.0958
344          5 0.080193 -7 21 -133 -134 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.1953
345          5 0.080193 -20 9 -133 -134 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
        vol=91.9257
346          13 -7.86 -7 9 133 -134 -134 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
        vol=32.8228
```

```
347       7 0.042234 -21 20 -135 -137 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
348       8 0.0927926 -21 27 135 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
349       8 0.0927926 -27 29 135 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
350       8 0.0927926 -29 30 135 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
351       8 0.0927926 -30 31 135 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
352       8 0.0927926 -31 20 135 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
353       5 0.080193 -7 21 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
354       5 0.080193 -20 9 -136 -137 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
355       13 -7.86 -7 9 136 -137 -137 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
356       7 0.042234 -21 20 -138 -140 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
357       8 0.0927926 -21 27 138 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
358       8 0.0927926 -27 29 138 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
359       8 0.0927926 -29 30 138 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
360       8 0.0927926 -30 31 138 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
361       8 0.0927926 -31 20 138 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
362       5 0.080193 -7 21 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
363       5 0.080193 -20 9 -139 -140 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
364       13 -7.86 -7 9 139 -140 -140 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
365       7 0.042234 -21 20 -141 -143 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
366        8 0.0927926 -21 27 141 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
367       8 0.0927926 -27 29 141 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
368       8 0.0927926 -29 30 141 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
369       8 0.0927926 -30 31 141 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
370       8 0.0927926 -31 20 141 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
371       5 0.080193 -7 21 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
372       5 0.080193 -20 9 -142 -143 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
373       13 -7.86 -7 9 142 -143 -143 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
```

```
      vol=32.8228
374       7 0.042234 -21 20 -144 -146 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
375       8 0.0927926 -21 27 144 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
376       8 0.0927926 -27 29 144 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
377       8 0.0927926 -29 30 144 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
378       8 0.0927926 -30 31 144 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
379       8 0.0927926 -31 20 144 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
380       5 0.080193 -7 21 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
381       5 0.080193 -20 9 -145 -146 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
382       13 -7.86 -7 9 145 -146 -146 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
383       7 0.042234 -21 20 -147 -149 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
384       8 0.0927926 -21 27 147 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
385       8 0.0927926 -27 29 147 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
386       8 0.0927926 -29 30 147 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
387       8 0.0927926 -30 31 147 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
388       8 0.0927926 -31 20 147 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
389       5 0.080193 -7 21 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
390       5 0.080193 -20 9 -148 -149 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
391       13 -7.86 -7 9 148 -149 -149 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
392       425 -1.029e-3 -7 9 -151 -152 -7 9 -2 -12 11 -14 imp:n=1  $ central void
****D8
      vol=580.666
400       1 -2.7 -7 9 151 -152 -152 -7 9 -2 -12 11 -14 imp:n=1  $ cladding al
      vol=32.8228
401       7 0.042234 -21 20 -153 -155 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
402       8 0.0927926 -21 27 153 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
403       8 0.0927926 -27 29 153 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
404       8 0.0927926 -29 30 153 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
405       8 0.0927926 -30 31 153 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
406       8 0.0927926 -31 20 153 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
```

```
      vol=77.0958
407        5 0.080193 -7 21 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
408        5 0.080193 -20 9 -154 -155 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
409        13 -7.86 -7 9 154 -155 -155 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
410        7 0.042234 -21 20 -156 -158 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
411        8 0.0927926 -21 27 156 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
412        8 0.0927926 -27 29 156 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
413        8 0.0927926 -29 30 156 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
414        8 0.0927926 -30 31 156 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
415        8 0.0927926 -31 20 156 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
416        5 0.080193 -7 21 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
417        5 0.080193 -20 9 -157 -158 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
418        13 -7.86 -7 9 157 -158 -158 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
419        7 0.042234 -21 20 -159 -161 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F10*****
      vol=12.066
420        8 0.0927926 -21 27 159 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
421        8 0.0927926 -27 29 159 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
422        8 0.0927926 -29 30 159 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
423        8 0.0927926 -30 31 159 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
424        8 0.0927926 -31 20 159 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
425        5 0.080193 -7 21 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
426        5 0.080193 -20 9 -160 -161 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
427        13 -7.86 -7 9 160 -161 -161 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
428        7 0.042234 -21 20 -162 -164 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F11*******
      vol=12.066
429        8 0.0927926 -21 27 162 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
430        8 0.0927926 -27 29 162 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
431        8 0.0927926 -29 30 162 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
432        8 0.0927926 -30 31 162 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
```

```
      vol=77.0958
433        8 0.0927926 -31 20 162 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
434        5 0.080193 -7 21 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
435        5 0.080193 -20 9 -163 -164 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
436        13 -7.86 -7 9 163 -164 -164 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
437        7 0.042234 -21 20 -165 -167 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
438        8 0.0927926 -21 27 165 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
439        8 0.0927926 -27 29 165 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
440        8 0.0927926 -29 30 165 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
441        8 0.0927926 -30 31 165 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
442        8 0.0927926 -31 20 165 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
443        5 0.080193 -7 21 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
444        5 0.080193 -20 9 -166 -167 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
445        13 -7.86 -7 9 166 -167 -167 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
464        7 0.042234 -21 20 -174 -176 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
465        8 0.0927926 -21 27 174 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
466        8 0.0927926 -27 29 174 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
467        8 0.0927926 -29 30 174 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
468        8 0.0927926 -30 31 174 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
469        8 0.0927926 -31 20 174 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
470        5 0.080193 -7 21 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
471        5 0.080193 -20 9 -175 -176 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
472        13 -7.86 -7 9 175 -176 -176 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
473        7 0.042234 -21 20 -177 -179 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
474        8 0.0927926 -21 27 177 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
475        8 0.0927926 -27 29 177 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
476        8 0.0927926 -29 30 177 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
```

```
477       8 0.0927926 -30 31 177 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
478       8 0.0927926 -31 20 177 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
479       5 0.080193 -7 21 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
480       5 0.080193 -20 9 -178 -179 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
481       13 -7.86 -7 9 178 -179 -179 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
482       7 0.042234 -21 20 -180 -182 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
483       8 0.0927926 -21 27 180 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
484       8 0.0927926 -27 29 180 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
485       8 0.0927926 -29 30 180 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
486       8 0.0927926 -30 31 180 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
487       8 0.0927926 -31 20 180 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
488       5 0.080193 -7 21 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
489       5 0.080193 -20 9 -181 -182 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
490       13 -7.86 -7 9 181 -182 -182 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
491       7 0.042234 -21 20 -183 -185 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
492       8 0.0927926 -21 27 183 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
493       8 0.0927926 -27 29 183 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
494       8 0.0927926 -29 30 183 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
495       8 0.0927926 -30 31 183 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
496       8 0.0927926 -31 20 183 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
497       5 0.080193 -7 21 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
498       5 0.080193 -20 9 -184 -185 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
499       13 -7.86 -7 9 184 -185 -185 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
500       7 0.042234 -21 20 -186 -188 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
501       8 0.0927926 -21 27 186 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
502       8 0.0927926 -27 29 186 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
503       8 0.0927926 -29 30 186 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
```

```
      vol=77.0958
504        8 0.0927926 -30 31 186 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
505        8 0.0927926 -31 20 186 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
506        5 0.080193 -7 21 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
507        5 0.080193 -20 9 -187 -188 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
508        13 -7.86 -7 9 187 -188 -188 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
509        7 0.042234 -21 20 -189 -191 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
510        8 0.0927926 -21 27 189 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
511        8 0.0927926 -27 29 189 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
512        8 0.0927926 -29 30 189 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
513        8 0.0927926 -30 31 189 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
514        8 0.0927926 -31 20 189 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
515        5 0.080193 -7 21 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
516        5 0.080193 -20 9 -190 -191 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
517        13 -7.86 -7 9 190 -191 -191 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
518        7 0.042234 -21 20 -192 -194 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
519        8 0.0927926 -21 27 192 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
520        8 0.0927926 -27 29 192 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
521        8 0.0927926 -29 30 192 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
522        8 0.0927926 -30 31 192 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
523        8 0.0927926 -31 20 192 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
524        5 0.080193 -7 21 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
525        5 0.080193 -20 9 -193 -194 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
526        13 -7.86 -7 9 193 -194 -194 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
527        7 0.042234 -21 20 -195 -197 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
528        8 0.0927926 -21 27 195 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
529        8 0.0927926 -27 29 195 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
```

```
530        8 0.0927926 -29 30 195 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
531        8 0.0927926 -30 31 195 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
532        8 0.0927926 -31 20 195 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
533        5 0.080193 -7 21 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
534        5 0.080193 -20 9 -196 -197 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
535        13 -7.86 -7 9 196 -197 -197 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
536        7 0.042234 -21 20 -198 -200 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
537        8 0.0927926 -21 27 198 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
538        8 0.0927926 -27 29 198 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
539        8 0.0927926 -29 30 198 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
540        8 0.0927926 -30 31 198 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
541        8 0.0927926 -31 20 198 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
542        5 0.080193 -7 21 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
543        5 0.080193 -20 9 -199 -200 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
544        13 -7.86 -7 9 199 -200 -200 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
545        7 0.042234 -21 20 -201 -203 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
546        8 0.0927926 -21 27 201 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
547        8 0.0927926 -27 29 201 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
548        8 0.0927926 -29 30 201 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
549        8 0.0927926 -30 31 201 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
550        8 0.0927926 -31 20 201 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
551        5 0.080193 -7 21 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
552        5 0.080193 -20 9 -202 -203 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
553        13 -7.86 -7 9 202 -203 -203 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
554        7 0.042234 -21 20 -204 -206 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
555        8 0.0927926 -21 27 204 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
556        8 0.0927926 -27 29 204 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
```

```
      vol=77.0958
557       8 0.0927926 -29 30 204 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
558       8 0.0927926 -30 31 204 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
559       8 0.0927926 -31 20 204 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
560       5 0.080193 -7 21 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
561       5 0.080193 -20 9 -205 -206 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
562       13 -7.86 -7 9 205 -206 -206 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
563       7 0.042234 -21 20 -207 -209 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
564       8 0.0927926 -21 27 207 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
565       8 0.0927926 -27 29 207 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
566       8 0.0927926 -29 30 207 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
567       8 0.0927926 -30 31 207 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
568       8 0.0927926 -31 20 207 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
569       5 0.080193 -7 21 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
570       5 0.080193 -20 9 -208 -209 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
571       13 -7.86 -7 9 208 -209 -209 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
572       7 0.042234 -21 20 -210 -212 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
573       8 0.0927926 -21 27 210 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
574       8 0.0927926 -27 29 210 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
575       8 0.0927926 -29 30 210 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
576       8 0.0927926 -30 31 210 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
577       8 0.0927926 -31 20 210 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
578       5 0.080193 -7 21 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
579       5 0.080193 -20 9 -211 -212 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
580       13 -7.86 -7 9 211 -212 -212 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
581       7 0.042234 -21 20 -213 -215 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
582       8 0.0927926 -21 27 213 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
```

```
583      8 0.0927926 -27 29 213 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
584      8 0.0927926 -29 30 213 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
585      8 0.0927926 -30 31 213 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
586      8 0.0927926 -31 20 213 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
587      5 0.080193 -7 21 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
588      5 0.080193 -20 9 -214 -215 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
589      13 -7.86 -7 9 214 -215 -215 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
590      7 0.042234 -21 20 -216 -218 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
591      8 0.0927926 -21 27 216 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
592      8 0.0927926 -27 29 216 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
593      8 0.0927926 -29 30 216 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
594      8 0.0927926 -30 31 216 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
595      8 0.0927926 -31 20 216 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
596      5 0.080193 -7 21 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
597      5 0.080193 -20 9 -217 -218 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
598      13 -7.86 -7 9 217 -218 -218 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
599      7 0.042234 -21 20 -219 -221 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
      vol=12.066
600      8 0.0927926 -21 27 219 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
601      8 0.0927926 -27 29 219 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
602      8 0.0927926 -29 30 219 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
603      8 0.0927926 -30 31 219 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
604      8 0.0927926 -31 20 219 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
605      5 0.080193 -7 21 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
606      5 0.080193 -20 9 -220 -221 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
607      13 -7.86 -7 9 220 -221 -221 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
608      7 0.042234 -21 20 -222 -224 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F14**********
      vol=12.066
```

```
609       8 0.0927926 -21 27 222 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
610       8 0.0927926 -27 29 222 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
611       8 0.0927926 -29 30 222 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
612       8 0.0927926 -30 31 222 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
613       8 0.0927926 -31 20 222 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
614       5 0.080193 -7 21 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
615       5 0.080193 -20 9 -223 -224 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
616       13 -7.86 -7 9 223 -224 -224 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
617       7 0.042234 -21 20 -225 -227 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F3**********
      vol=12.066
618       8 0.0927926 -21 27 225 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
619       8 0.0927926 -27 29 225 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
620       8 0.0927926 -29 30 225 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
621       8 0.0927926 -30 31 225 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
622       8 0.0927926 -31 20 225 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
623       5 0.080193 -7 21 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
624       5 0.080193 -20 9 -226 -227 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
625       13 -7.86 -7 9 226 -227 -227 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
626       7 0.042234 -21 20 -228 -230 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F4************
      vol=12.066
627       8 0.0927926 -21 27 228 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
628       8 0.0927926 -27 29 228 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
629       8 0.0927926 -29 30 228 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
630       8 0.0927926 -30 31 228 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
631       8 0.0927926 -31 20 228 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
632       5 0.080193 -7 21 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
633       5 0.080193 -20 9 -229 -230 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
634       13 -7.86 -7 9 229 -230 -230 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
```

```
     vol=32.8228
635       7 0.042234 -21 20 -231 -233 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F29*********
     vol=12.066
636       8 0.0927926 -21 27 231 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
637       8 0.0927926 -27 29 231 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
638       8 0.0927926 -29 30 231 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
639       8 0.0927926 -30 31 231 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
640       8 0.0927926 -31 20 231 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
641       5 0.080193 -7 21 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
642       5 0.080193 -20 9 -232 -233 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
643       13 -7.86 -7 9 232 -233 -233 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
644       7 0.042234 -21 20 -234 -236 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
     vol=12.066
645       8 0.0927926 -21 27 234 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
646       8 0.0927926 -27 29 234 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
647       8 0.0927926 -29 30 234 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
648       8 0.0927926 -30 31 234 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
649       8 0.0927926 -31 20 234 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
650       5 0.080193 -7 21 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
651       5 0.080193 -20 9 -235 -236 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
652       13 -7.86 -7 9 235 -236 -236 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
653       7 0.042234 -21 20 -237 -239 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
     vol=12.066
654       8 0.0927926 -21 27 237 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
655       8 0.0927926 -27 29 237 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
656       8 0.0927926 -29 30 237 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
657       8 0.0927926 -30 31 237 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
658       8 0.0927926 -31 20 237 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
659       5 0.080193 -7 21 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
660       5 0.080193 -20 9 -238 -239 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
```

```
     vol=91.9257
661      13 -7.86 -7 9 238 -239 -239 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
671      7 0.042234 -21 20 -243 -245 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
     vol=12.066
672      8 0.0927926 -21 27 243 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
673      8 0.0927926 -27 29 243 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
674      8 0.0927926 -29 30 243 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
675      8 0.0927926 -30 31 243 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
676      8 0.0927926 -31 20 243 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
677      5 0.080193 -7 21 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
678      5 0.080193 -20 9 -244 -245 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
679      13 -7.86 -7 9 244 -245 -245 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
680      7 0.042234 -21 20 -246 -248 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
     vol=12.066
681      8 0.0927926 -21 27 246 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
682      8 0.0927926 -27 29 246 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
683      8 0.0927926 -29 30 246 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
684      8 0.0927926 -30 31 246 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
685      8 0.0927926 -31 20 246 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
686      5 0.080193 -7 21 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
687      5 0.080193 -20 9 -247 -248 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
688      13 -7.86 -7 9 247 -248 -248 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
689      7 0.042234 -21 20 -249 -251 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F28******
     vol=12.066
690      8 0.0927926 -21 27 249 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
691      8 0.0927926 -27 29 249 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
692      8 0.0927926 -29 30 249 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
693      8 0.0927926 -30 31 249 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
694      8 0.0927926 -31 20 249 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
695      5 0.080193 -7 21 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
```

```
     vol=91.1953
696       5 0.080193 -20 9 -250 -251 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
697       13 -7.86 -7 9 250 -251 -251 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
698       7 0.042234 -21 20 -252 -254 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F13*********
     vol=12.066
699       8 0.0927926 -21 27 252 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
700       8 0.0927926 -27 29 252 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
701       8 0.0927926 -29 30 252 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
702       8 0.0927926 -30 31 252 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
703       8 0.0927926 -31 20 252 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
704       5 0.080193 -7 21 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
705       5 0.080193 -20 9 -253 -254 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
706       13 -7.86 -7 9 253 -254 -254 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
716       7 0.042234 -21 20 -258 -260 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F6*********
     vol=12.066
717       8 0.0927926 -21 27 258 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
718       8 0.0927926 -27 29 258 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
719       8 0.0927926 -29 30 258 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
720       8 0.0927926 -30 31 258 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
721       8 0.0927926 -31 20 258 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
722       5 0.080193 -7 21 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
723       5 0.080193 -20 9 -259 -260 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
724       13 -7.86 -7 9 259 -260 -260 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
     vol=32.8228
770       419 -2.465 -7 285 -276 -284 -7 9 -2 -12 11 -14 imp:n=1  $ control rod
poison control rod  w/fuel-C10
     vol=91.1953
771       7 0.042234 -285 20 -278 -284 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
control rod  w/fuel
     vol=12.066
772       8 0.0927926 -285 27 278 -276 -284 -7 9 -2 -12 11 -14  $ fuel section1
control rod  w/fuel
     imp:n=1 vol=77.0958
773       8 0.0927926 -27 29 278 -276 -284 -7 9 -2 -12 11 -14  $ fuel section2
control rod  w/fuel
     imp:n=1 vol=77.0958
774       8 0.0927926 -29 30 278 -276 -284 -7 9 -2 -12 11 -14  $ fuel section3
control rod  w/fuel
     imp:n=1 vol=77.0958
```

```
775       8 0.0927926 -30 31 278 -276 -284 -7 9 -2 -12 11 -14  $ fuel section4
control rod  w/fuel
      imp:n=1 vol=77.0958
776       8 0.0927926 -31 20 278 -276 -284 -7 9 -2 -12 11 -14  $ fuel section5
control rod  w/fuel
      imp:n=1 vol=77.0958
777       5 0.080193 -20 9 -276 -284 -7 9 -2 -12 11 -14  $ gr below fuel control
rod
      imp:n=1 vol=91.1953
778       13 -7.86 -7 9 276 -284 -284 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
control rod  w/fuel
      vol=34.5958
779       419 -2.465 -7 285 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ control rod
poison control rod  w/fuel -D1
      vol=91.1953
780       7 0.042234 -285 20 -287 -288 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
control rod  w/fuel
      vol=12.066
781       8 0.0927926 -285 27 287 -286 -288 -7 9 -2 -12 11 -14  $ fuel section1
control rod  w/fuel
      imp:n=1 vol=77.0958
782       8 0.0927926 -27 29 287 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ fuel
section2 control rod  w/fuel
      vol=77.0958
783       8 0.0927926 -29 30 287 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ fuel
section3 control rod  w/fuel
      vol=77.0958
784       8 0.0927926 -30 31 287 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ fuel
section4 control rod  w/fuel
      vol=77.0958
785       8 0.0927926 -31 20 287 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ fuel
section5 control rod  w/fuel
      vol=77.0958
786       5 0.080193 -20 9 -286 -288 -7 9 -2 -12 11 -14 imp:n=1  $ gr below fuel
control rod  w/fuel
      vol=91.1953
787       13 -7.86 -7 9 286 -288 -288 -7 9 -2 -12 11 -14 imp:n=1  $cladding control
rod  w/fuel
      vol=34.5958
788       419 -2.465 -7 285 -289 -292 -7 9 -2 -12 11 -14 imp:n=1  $ control rod
poison control rod  w/fuel -D10
      vol=91.1953
789       7 0.042234 -285 20 -291 -292 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
control rod  w/fuel
      vol=12.066
790       8 0.0927926 -285 27 291 -289 -292 -7 9 -2 -12 11 -14  $ fuel section1
control rod  w/fuel
      imp:n=1 vol=77.0958
791       8 0.0927926 -27 29 291 -289 -292 -7 9 -2 -12 11 -14  $ fuel section2
control rod  w/fuel
      imp:n=1 vol=77.0958
792       8 0.0927926 -29 30 291 -289 -292 -7 9 -2 -12 11 -14  $ fuel section3
control rod  w/fuel
      imp:n=1 vol=77.0958
793       8 0.0927926 -30 31 291 -289 -292 -7 9 -2 -12 11 -14  $ fuel section4
control rod  w/fuel
      imp:n=1 vol=77.0958
794       8 0.0927926 -31 20 291 -289 -292 -7 9 -2 -12 11 -14  $ fuel section5
control rod  w/fuel
      imp:n=1 vol=77.0958
795       5 0.080193 -20 9 -289 -292 -7 9 -2 -12 11 -14 $ gr below fuel control rod
w/fuel
      imp:n=1 vol=91.1953
796       13 -7.86 -7 9 289 -292 -292 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
control rod  w/fuel
      vol=34.5958
797       425 -1.029e-3 -7 285 -293 -295 -7 9 -2 -12 11 -14 imp:n=1  $ air region
control rod w/o fuel
```

```
      vol=91.1953
798       425 -1.029e-3 -285 9 -293 -295 -7 9 -2 -12 11 -14 imp:n=1  $ air region
control rod w/o fuel
      vol=488.7403
799       13 -7.86 -7 9 293 -295 -295 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
control rod w/o fuel
      vol=34.5958
800       425 -1.029e-3 -7 9 -296 -297 -7 9 -2 -12 11 -14 imp:n=1  $ sample region
central thimble
      vol=580.666
801       1 -2.7 -7 9 296 -297 -297 -7 9 -2 -12 11 -14 imp:n=1  $ cladding central
thimble
      vol=32.8228
811  7 0.042234 -21 20 -1571 -307 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
g14************
      vol=12.066
1601  8 0.0927926 -21 27 1571 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1602  8 0.0927926 -27 29 1571 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1603  8 0.0927926 -29 30 1571 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1604  8 0.0927926 -30 31 1571 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1605  8 0.0927926 -31 20 1571 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1606  5 0.080193 -7 21 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1607  5 0.080193 -20 9 -1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1608  13 -7.86 -7 9 1572 -307 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
812       3 -1.0 -7 9 -308 -308 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g15
813       3 -1.0 -7 9 -309 -309 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g22
814       3 -1.0 -7 9 -310 -310 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g23
815       3 -1.0 -7 9 -311 -311 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g24
816       3 -1.0 -7 9 -312 -312 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g25
817       3 -1.0 -7 9 -313 -313 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g26
818       3 -1.0 -7 9 -314 -314 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g27
819       3 -1.0 -7 9 -315 -315 -7 9 -2 -12 11 -14 imp:n=1 vol=613.489 $ water
water -#g28
820       5 0.080193 -7 9 -316 -7 9 -2 -12 11 -14 imp:n=1  $ gr G1*******
      vol=580.666
821       13 -7.86 -7 9 316 -317 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
822       5 0.080193 -7 9 -318 -7 9 -2 -12 11 -14 imp:n=1  $ gr G3*******
      vol=580.666
823       13 -7.86 -7 9 318 -319 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
824       5 0.080193 -7 9 -320 -7 9 -2 -12 11 -14 imp:n=1  $ gr G4*******
      vol=580.666
825       13 -7.86 -7 9 320 -321 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
826       5 0.080193 -7 9 -322 -7 9 -2 -12 11 -14 imp:n=1  $ gr G5*******
      vol=580.666
827       13 -7.86 -7 9 322 -323 -7 9 -2 -12 11 -14 imp:n=1
```

```
      vol=32.8228
837         5 0.080193 -7 9 -332 -7 9 -2 -12 11 -14 imp:n=1  $ gr G16*******
      vol=580.666
5000         13 -7.86 -7 9 332 -333 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
838         425 -1.029e-3 -7 9 -334 -335 -7 9 -2 -12 11 -14 imp:n=1  $ Source G17
Viod*********
      vol=580.666
839         1 -2.7 -7 9 334 -335 -7 9 -2 -12 11 -14 imp:n=1  $ Source G17 Al
cladding*********
      vol=32.8228
840         5 0.080193 -7 9 -336 -7 9 -2 -12 11 -14 imp:n=1  $ gr g18*******
      vol=580.666
841         13 -7.86 -7 9 336 -337 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
842         5 0.080193 -7 9 -338 -7 9 -2 -12 11 -14 imp:n=1  $ gr G19*******
      vol=580.666
843         13 -7.86 -7 9 338 -339 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
844         5 0.080193 -7 9 -340 -7 9 -2 -12 11 -14 imp:n=1  $ gr G20*******
      vol=580.666
845         13 -7.86 -7 9 340 -341 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
858         5 0.080193 -7 9 -354 -7 9 -2 -12 11 -14 imp:n=1  $ gr G34*******
      vol=580.666
859         13 -7.86 -7 9 354 -355 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
860         5 0.080193 -7 9 -356 -7 9 -2 -12 11 -14 imp:n=1  $ gr G35*******
      vol=580.666
861         13 -7.86 -7 9 356 -357 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
862         5 0.080193 -7 9 -358 -7 9 -2 -12 11 -14 imp:n=1  $ gr G36*******
      vol=580.666
863         13 -7.86 -7 9 358 -359 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
c 864         425 -1.029e-3 5 -14 -13 -15 -12 11 -14 imp:n=1 $ beam 1  beams
c 865         425 -1.029e-3 5 -14 -18 15 -12 11 -14 imp:n=1 $ beam 4   beams
c 866         425 -1.029e-3 5 -14 17 -16 18 15 -12 11 -14 imp:n=1 $ beam 3 beams
446        5 0.080193 -7 9 -169 -7 9 -2 -12 11 -14 imp:n=1  $ gr F22*******
      vol=580.666
447         13 -7.86 -7 9 169 -170 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
455         5 0.080193 -7 9 -172 -7 9 -2 -12 11 -14 imp:n=1  $ gr F23*******
      vol=580.666
456         13 -7.86 -7 9 172 -173 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
707         5 0.080193 -7 9 -256 -7 9 -2 -12 11 -14 imp:n=1  $ gr F19*******
      vol=580.666
708         13 -7.86 -7 9 256 -257 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
725         5 0.080193 -7 9 -262 -7 9 -2 -12 11 -14 imp:n=1  $ gr F24*******
      vol=580.666
726         13 -7.86 -7 9 262 -263 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
734         5 0.080193 -7 9 -265 -7 9 -2 -12 11 -14 imp:n=1  $ gr F26*******
      vol=580.666
735         13 -7.86 -7 9 265 -266 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
743         5 0.080193 -7 9 -268 -7 9 -2 -12 11 -14 imp:n=1  $ gr F21*******
      vol=580.666
744         13 -7.86 -7 9 268 -269 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
752         5 0.080193 -7 9 -271 -7 9 -2 -12 11 -14 imp:n=1  $ gr F18*******
      vol=580.666
753         13 -7.86 -7 9 271 -272 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
761         5 0.080193 -7 9 -274 -7 9 -2 -12 11 -14 imp:n=1  $ gr F25*******
      vol=580.666
```

```
762        13 -7.86 -7 9 274 -275 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
1017        5 0.080193 -7 9 -5000 -7 9 -2 -12 11 -14 imp:n=1  $ gr F20*******
      vol=580.666
1018        13 -7.86 -7 9 271 5000 -300 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
1019        5 0.080193 -7 9 -5001 -7 9 -2 -12 11 -14 imp:n=1  $ gr F27*******
      vol=580.666
1020        13 -7.86 -7 9 5001 -301 -7 9 -2 -12 11 -14 imp:n=1
      vol=32.8228
1039  7 0.042234 -21 20 -1501 -298 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F5************
      vol=12.066
1040  8 0.0927926 -21 27 1501 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1041  8 0.0927926 -27 29 1501 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1042  8 0.0927926 -29 30 1501 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1043  8 0.0927926 -30 31 1501 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1044  8 0.0927926 -31 20 1501 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1045  5 0.080193 -7 21 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1046  5 0.080193 -20 9 -1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1047  13 -7.86 -7 9 1502 -298 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
1049  7 0.042234 -21 20 -1511 -299 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
F12************
      vol=12.066
1050  8 0.0927926 -21 27 1511 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1051  8 0.0927926 -27 29 1511 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1052  8 0.0927926 -29 30 1511 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1053  8 0.0927926 -30 31 1511 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1054  8 0.0927926 -31 20 1511 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1055  5 0.080193 -7 21 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1056  5 0.080193 -20 9 -1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1057  13 -7.86 -7 9 1512 -299 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
      vol=32.8228
1059  7 0.042234 -21 20 -1531 -303 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
G10************
      vol=12.066
1060  8 0.0927926 -21 27 1531 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1061  8 0.0927926 -27 29 1531 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
```

```
1062  8 0.0927926 -29 30 1531 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1063  8 0.0927926 -30 31 1531 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1064  8 0.0927926 -31 20 1531 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1065  5 0.080193 -7 21 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1066  5 0.080193 -20 9 -1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1067  13 -7.86 -7 9 1532 -303 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr rod
      vol=32.8228
1069  7 0.042234 -21 20 -1541 -304 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
G11************
      vol=12.066
1070  8 0.0927926 -21 27 1541 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1071  8 0.0927926 -27 29 1541 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1072  8 0.0927926 -29 30 1541 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1073  8 0.0927926 -30 31 1541 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1074  8 0.0927926 -31 20 1541 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1075  5 0.080193 -7 21 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1076  5 0.080193 -20 9 -1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1077  13 -7.86 -7 9 1542 -304 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr rod
      vol=32.8228
1079  7 0.042234 -21 20 -1551 -305 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
G12************
      vol=12.066
1080  8 0.0927926 -21 27 1551 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1081  8 0.0927926 -27 29 1551 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1082  8 0.0927926 -29 30 1551 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1083  8 0.0927926 -30 31 1551 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1084  8 0.0927926 -31 20 1551 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1085       5 0.080193 -7 21 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1086       5 0.080193 -20 9 -1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1087       13 -7.86 -7 9 1552 -305 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr rod
      vol=32.8228
1089       7 0.042234 -21 20 -1561 -306 -7 9 -2 -12 11 -14 imp:n=1  $ central zr
rod G11************
      vol=12.066
1090  8 0.0927926 -21 27 1561 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
```

```
      vol=77.0958
1091  8 0.0927926 -27 29 1561 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1092  8 0.0927926 -29 30 1561 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1093  8 0.0927926 -30 31 1561 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1094  8 0.0927926 -31 20 1561 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1095  5 0.080193 -7 21 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1096  5 0.080193 -20 9 -1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1097  13 -7.86 -7 9 1562 -306 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr rod
      vol=32.8228
1510       7 0.042234 -21 20 -1522 -328 -7 9 -2 -12 11 -14 imp:n=1  $ central zr
rod G8************
      vol=12.066
1511  8 0.0927926 -21 27 1522 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1512  8 0.0927926 -27 29 1522 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1513  8 0.0927926 -29 30 1522 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1514  8 0.0927926 -30 31 1522 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1515  8 0.0927926 -31 20 1522 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1516       5 0.080193 -7 21 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1517       5 0.080193 -20 9 -328 -329 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1099       13 -7.86 -7 9 328 -329 -329 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr
rod
      vol=32.8228
1107       7 0.042234 -21 20 -1523 -330 -7 9 -2 -12 11 -14 imp:n=1  $ central zr
rod G8************
      vol=12.066
1521  8 0.0927926 -21 27 1523 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
      vol=77.0958
1522  8 0.0927926 -27 29 1523 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
      vol=77.0958
1523  8 0.0927926 -29 30 1523 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
      vol=77.0958
1524  8 0.0927926 -30 31 1523 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
      vol=77.0958
1525  8 0.0927926 -31 20 1523 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
      vol=77.0958
1526       5 0.080193 -7 21 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.1953
1527       5 0.080193 -20 9 -330 -331 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
      vol=91.9257
1109       13 -7.86 -7 9 330 -331 -331 -7 9 -2 -12 11 -14 imp:n=1  $ cladding gr
rod
```

```
     vol=32.8228
1111  425 -1.029e-3 -7 9 -1017 -302 -7 9 -2 -12 11 -14 imp:n=1 vol=580.666 $ Rabbit
-g2
1112  13 -7.86 -7 9 1017 -302 -7 9 -2 -12 11 -14 imp:n=1 vol=32.8228 $ cladding
662       3 -1.0 -7 9 -242 -242 -7 9 -2 -12 11 -14 imp:n=1  $ water F2*******
     vol=613.489
828       3 -1.0 -7 9 -325 -325 -7 9 -2 -12 11 -14 imp:n=1  $ watre G6*******
     vol=613.489
830       7 0.042234 -21 20 -1521 -327 -7 9 -2 -12 11 -14 imp:n=1  $ central zr rod
G7************
     vol=12.066
1501  8 0.0927926 -21 27 1521 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section1
     vol=77.0958
1502  8 0.0927926 -27 29 1521 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section2
     vol=77.0958
1503  8 0.0927926 -29 30 1521 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section3
     vol=77.0958
1504  8 0.0927926 -30 31 1521 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section4
     vol=77.0958
1505  8 0.0927926 -31 20 1521 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $fuel rod
section5
     vol=77.0958
1506       5 0.080193 -7 21 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.1953
1507       5 0.080193 -20 9 -326 -327 -7 9 -2 -12 11 -14 imp:n=1  $ gr reflector
     vol=91.9257
831       13 -7.86 -7 9 326 -327 -327 -7 9 -2 -12 11 -14 imp:n=1  $ cladding
graphite rod
     vol=32.8228
846       3 -1.0 -7 9 -343 -7 9 -2 -12 11 -14 imp:n=1  $ water G21 *********
     vol=613.489
848       3 -1.0 -7 9 -345 -7 9 -2 -12 11 -14 imp:n=1  $ water G29 *********
     vol=613.489
850       3 -1.0 -7 9 -347 -7 9 -2 -12 11 -14 imp:n=1  $ water G30*********
     vol=613.489
852       3 -1.0 -7 9 -349 -7 9 -2 -12 11 -14 imp:n=1  $ water G31 *********
     vol=613.489
854       3 -1.0 -7 9 -351 -7 9 -2 -12 11 -14 imp:n=1  $ water G32 *********
     vol=613.489
856       3 -1.0 -7 9 -353 -7 9 -2 -12 11 -14 imp:n=1  $ water G33 *********
     vol=613.489
c thermal column
c 26000    3 -1.0 10 -2702 2615 2613 -2601 2606 2617 imp:n=1 $ water gap
26001    1 -2.7 2702 -2703 2615 2613 -2601 2606 2617 vol=31514.3997
          imp:n=1                                      $ front Al cladding
26002    1 -2.7 2615 -2616 2703 -2607 -2601 2606 2617 vol=3843.197 $ upper angle
          imp:n=1
26003    1 -2.7 2613 -2614 2703 2612 -2601 2606 2617 vol=3843.197 $ lower angle
          imp:n=1
26004    1 -2.7 2616 -2618 -2607 2608 -2601 2606  imp:n=1 $ upper
26005    1 -2.7 2614 -2618 -2611 2612 -2601 2606 imp:n=1 $ lower
26006    1 -2.7 2703 2616 2614 -2608 2611 -2618 -2601 2602 $ top
          imp:n=1
26007    1 -2.7 2703 2616 2614 -2608 2611 -2618 -2605 2606 $ bottom
          imp:n=1
26008    419 -2.48 2703 2616 2614 -2609 2610 -2618 -2602 2603 $b4c top
          imp:n=1
26009    419 -2.48 2703 2616 2614 -2609 2610 -2618 -2604 2605 $ b4c bottom
          imp:n=1
26010    419 -2.48 2616 -2618 -2608 2609 -2602 2605 imp:n=1 $ b4c upper
26011    419 -2.48 2614 -2618 -2610 2611 -2602 2605 imp:n=1 $ b4c lower
26012    5 0.080193 2703 2616 2614 -2609 2610 -2619 -2603 2604 $ graphite
          imp:n=1
26013    5 0.080193 2619 -2618 -2609 2610 -2603 2604 $ graphite
```

```
          #(2704 -2618 -2708 2709 -2710 2711) imp:n=1
26100    425 -1.029e-3 2704 -2705 -2706 2707 -2712 2713 imp:n=1 $ TC5( 1cm^3)
26101    425 -1.029e-3 2704 -2618 -2708 2709 -2710 2711
          # 26100  imp:n=1                               $ Tc5 hole
c 2700     3 -1.0 2702 -14 2615 2613 -2607 2612 2601 -12 imp:n=1
C Beam ports
c 30001    1 -2.7  -3001 5 -14 -15 imp:n=1 $ #3
c 30002    1 -2.7  -3002 5 -14 -15 imp:n=1 $ #4
30001     1 -2.7 3001 -3002 3006 -25 3008 imp:n=1 vol=1555.36 $ #3 void al pipe
30002     425 -1.029e-3 -3001 3006 -25 3008 imp:n=1 vol=7095.69 $ #3 void
30003     1 -2.7  -3002 -3006 3005 3008 imp:n=1 vol=57.91       $ plate
30004     1 -2.7  3001 -3002 25 -4000 3008 imp:n=1 vol=5077.89  $ al pipe
30005     425 -1.029e-3 -3001 25 -4001 3008 imp:n=1 vol=23165.75 $ air
30006   425 -1.029e-3 -3001 25 4001 -4000 3008 imp:n=1 vol=186.41  $ sample
position****
30011     1 -2.7 5 3007 -3004 -15 imp:n=1 vol=57.91               $ #4 plate
30012     1 -2.7 3003 -3004 -3007 -4000 -15 imp:n=1 vol=5877.69    $ #4 al pipe
30013     425 -1.029e-3 -3003 -3007 -4000 -15 imp:n=1 vol=26814.5    $ air
30021     1 -2.7 5 3101 -3102 15 -4000 imp:n=1 vol=5890.39           $ #1
30022     425 -1.029e-3 -3101 5 -4000 15 imp:n=1 vol=26872.42
30031     1 -2.7 10 3105 -3106 15 -4000 imp:n=1  vol=4874.77         $ #2
30032     425 -1.029e-3 -3105 10 -4000 15 imp:n=1 vol=22239.08

1        so 1000 $ infinity
2        cz 26.67 $ cylinder of water
3        pz 32.39 $ top of water
4        pz -36.2 $ bottom of reflector
5        cz 27.31 $ cylinder of vessel
6        pz 30.78 $ bottom of upper grid plate
7        pz 27.79 $ top of rod
8        pz -34.29 $ top of lower grid plate
9        pz -27.86 $ bottom of rod
10        cz 52.71 $ cylinder of lead
11        pz -83.36 $ bottom of water*****************
12        pz 100 $ top of water ***************
13       1 cy 7.62
14        cz 98.425 $ cylinder of water
15        py 0.0 $ y midplane
16       3 cy 7.62
17       4 py 0.0
18       4 cx 8.57
19        cz 15.3979
20        pz -19.05 $ bottom of fuel
21        pz 19.05 $ top of fuel
22        cz 18.8585
23        pz 7.62 $ bottom of lazy susan
24        cz 37.47 $ cylinder of lazy susan
25        cz 47.63 $ cylinder of graphite
26        c/z 3.91414 -1.04648 0.3175 $ zr rod
27        pz 11.43 $ segment bottom1
28        c/z 3.91414 -1.04648 1.82245 $ fuel
29        pz 3.81 $ segment bottom2
30        pz -3.81 $ segment bottom3
31        pz -11.43 $ segment bottom4
32        c/z 3.91414 -1.04648 1.87325 $ cladding
33        c/z 6.1468 -18.9154 0.3175 $ zr rod
34        c/z 6.1468 -18.9154 1.82245 $ fuel
35        c/z 6.1468 -18.9154 1.87325 $ cladding
36        c/z -7.95782 13.782 0.3175 $ zr rod
37        c/z -7.95782 13.782 1.82245 $ fuel
38        c/z -7.95782 13.782 1.87325 $ cladding
39        c/z -13.782 7.95782 0.3175 $ zr rod
40        c/z -13.782 7.95782 1.82245 $ fuel
41        c/z -13.782 7.95782 1.87325 $ cladding
42        c/z 2.07772 -19.9898 0.3175 $ zr rod
43        c/z 2.07772 -19.9898 1.82245 $ fuel
44        c/z 2.07772 -19.9898 1.87325 $ cladding
45        c/z -13.782 -7.95782 0.3175 $ zr rod
```

```
46        c/z -13.782 -7.95782 1.82245 $ fuel
47        c/z -13.782 -7.95782 1.87325 $ cladding
48        c/z 15.3721 -4.11988 0.3175 $ zr rod
49        c/z 15.3721 -4.11988 1.82245 $ fuel
50        c/z 15.3721 -4.11988 1.87325 $ cladding
51        c/z 15.9156 0.0 0.3175 $ zr rod
52        c/z 15.9156 0.0 1.82245 $ fuel
53        c/z 15.9156 0.0 1.87325 $ cladding
54        c/z -3.91414 1.04648 0.3175 $ zr rod
55        c/z -3.91414 1.04648 1.82245 $ fuel
56        c/z -3.91414 1.04648 1.87325 $ cladding
57        c/z 13.782 -7.95782 0.3175 $ zr rod
58        c/z 13.782 -7.95782 1.82245 $ fuel
59        c/z 13.782 -7.95782 1.87325 $ cladding
60        c/z -15.9156 0.0 0.3175 $ zr rod
61        c/z -15.9156 0.0 1.82245 $ fuel
62        c/z -15.9156 0.0 1.87325 $ cladding
63        c/z -15.3721 4.11988 0.3175 $ zr rod
64        c/z -15.3721 4.11988 1.82245 $ fuel
65        c/z -15.3721 4.11988 1.87325 $ cladding
66        c/z 2.07264 -11.303 0.3175 $ zr rod
67        c/z 2.07264 -11.303 1.82245 $ fuel
68        c/z 2.07264 -11.303 1.87325 $ cladding
69        c/z 11.2547 11.2547 0.3175 $ zr rod
70        c/z 11.2547 11.2547 1.82245 $ fuel
71        c/z 11.2547 11.2547 1.87325 $ cladding
72        c/z 4.11988 -15.3721 0.3175 $ zr rod
73        c/z 4.11988 -15.3721 1.82245 $ fuel
74        c/z 4.11988 -15.3721 1.87325 $ cladding
75        c/z -15.3721 -4.11988 0.3175 $ zr rod
76        c/z -15.3721 -4.11988 1.82245 $ fuel
77        c/z -15.3721 -4.11988 1.87325 $ cladding
78        c/z -11.2547 11.2547 0.3175 $ zr rod
79        c/z -11.2547 11.2547 1.82245 $ fuel
80        c/z -11.2547 11.2547 1.87325 $ cladding
81        c/z -1.04648 3.91414 0.3175 $ zr rod
82        c/z -1.04648 3.91414 1.82245 $ fuel
83        c/z -1.04648 3.91414 1.87325 $ cladding
84        c/z 2.86766 2.86766 0.3175 $ zr rod
85        c/z 2.86766 2.86766 1.82245 $ fuel
86        c/z 2.86766 2.86766 1.87325 $ cladding
87        c/z 3.99034 6.91134 0.3175 $ zr rod
88        c/z 3.99034 6.91134 1.82245 $ fuel
89        c/z 3.99034 6.91134 1.87325 $ cladding
90        c/z 6.91134 3.99034 0.3175 $ zr rod
91        c/z 6.91134 3.99034 1.82245 $ fuel
92        c/z 6.91134 3.99034 1.87325 $ cladding
93        c/z 7.98068 0.0 0.3175 $ zr rod
94        c/z 7.98068 0.0 1.82245 $ fuel
95        c/z 7.98068 0.0 1.87325 $ cladding
96        c/z -2.86766 -2.86766 0.3175 $ zr rod
97        c/z -2.86766 -2.86766 1.82245 $ fuel
98        c/z -2.86766 -2.86766 1.87325 $ cladding
99        c/z 1.04648 -3.91414 0.3175 $ zr rod
100        c/z 1.04648 -3.91414 1.82245 $ fuel
101        c/z 1.04648 -3.91414 1.87325 $ cladding
102        c/z -0.2413 -15.2019 0.3175 $ zr rod
103        c/z -0.2413 -15.2019 1.82245 $ fuel
104        c/z -0.2413 -15.2019 1.87325 $ cladding
105        c/z 19.8196 0.0 0.3175 $ zr rod
106        c/z 19.8196 0.0 1.82245 $ fuel
107        c/z 19.8196 0.0 1.87325 $ cladding
108        c/z -2.07264 11.303 0.3175 $ zr rod
109        c/z -2.07264 11.303 1.82245 $ fuel
110        c/z -2.07264 11.303 1.87325 $ cladding
111        c/z 0.2413 15.2019 0.3175 $ zr rod
112        c/z 0.2413 15.2019 1.82245 $ fuel
113        c/z 0.2413 15.2019 1.87325 $ cladding
```

```
114        c/z -2.07772 -19.9898 0.3175 $ zr rod
115        c/z -2.07772 -19.9898 1.82245 $ fuel
116        c/z -2.07772 -19.9898 1.87325 $ cladding
117        c/z -4.11988 15.3721 0.3175 $ zr rod
118        c/z -4.11988 15.3721 1.82245 $ fuel
119        c/z -4.11988 15.3721 1.87325 $ cladding
120        c/z 6.91134 -3.99034 0.3175 $ zr rod
121        c/z 6.91134 -3.99034 1.82245 $ fuel
122        c/z 6.91134 -3.99034 1.87325 $ cladding
123        c/z 3.99034 -6.91134 0.3175 $ zr rod
124        c/z 3.99034 -6.91134 1.82245 $ fuel
125        c/z 3.99034 -6.91134 1.87325 $ cladding
126        c/z -3.99034 -6.91134 0.3175 $ zr rod
127        c/z -3.99034 -6.91134 1.82245 $ fuel
128        c/z -3.99034 -6.91134 1.87325 $ cladding
129        c/z -6.91134 -3.99034 0.3175 $ zr rod
130        c/z -6.91134 -3.99034 1.82245 $ fuel
131        c/z -6.91134 -3.99034 1.87325 $ cladding
132        c/z -7.98068 0.0 0.3175 $ zr rod
133        c/z -7.98068 0.0 1.82245 $ fuel
134        c/z -7.98068 0.0 1.87325 $ cladding
135        c/z -6.91134 3.99034 0.3175 $ zr rod
136        c/z -6.91134 3.99034 1.82245 $ fuel
137        c/z -6.91134 3.99034 1.87325 $ cladding
138        c/z -3.99034 6.91134 0.3175 $ zr rod
139        c/z -3.99034 6.91134 1.82245 $ fuel
140        c/z -3.99034 6.91134 1.87325 $ cladding
141        c/z -4.20624 -15.2019 0.3175 $ zr rod
142        c/z -4.20624 -15.2019 1.82245 $ fuel
143        c/z -4.20624 -15.2019 1.87325 $ cladding
144        c/z -7.95782 -13.782 0.3175 $ zr rod
145        c/z -7.95782 -13.782 1.82245 $ fuel
146        c/z -7.95782 -13.782 1.87325 $ cladding
147        c/z -5.97408 -10.3454 0.3175 $ zr rod
148        c/z -5.97408 -10.3454 1.82245 $ fuel
149        c/z -5.97408 -10.3454 1.87325 $ cladding
150        c/z -9.15162 -7.67842 0.3175 $ zr rod
151        c/z -9.15162 -7.67842 1.82245 $ fuel
152        c/z -9.15162 -7.67842 1.87325 $ cladding
153        c/z -11.2243 -4.08432 0.3175 $ zr rod
154        c/z -11.2243 -4.08432 1.82245 $ fuel
155        c/z -11.2243 -4.08432 1.87325 $ cladding
156        c/z -11.2243 4.08432 0.3175 $ zr rod
157        c/z -11.2243 4.08432 1.82245 $ fuel
158        c/z -11.2243 4.08432 1.87325 $ cladding
159        c/z -6.1468 -18.9154 0.3175 $ zr rod
160        c/z -6.1468 -18.9154 1.82245 $ fuel
161        c/z -6.1468 -18.9154 1.87325 $ cladding
162        c/z -10.1194 -17.1323 0.3175 $ zr rod
163        c/z -10.1194 -17.1323 1.82245 $ fuel
164        c/z -10.1194 -17.1323 1.87325 $ cladding
165        c/z 2.2225 11.7653 0.3175 $ zr rod
166        c/z 2.2225 11.7653 1.82245 $ fuel
167        c/z 2.2225 11.7653 1.87325 $ cladding
168        c/z -6.1468 18.9154 0.3175 $ zr rod
169        c/z -6.1468 18.9154 1.82245 $ fuel
170        c/z -6.1468 18.9154 1.87325 $ cladding
171        c/z -2.07772 19.9898 0.3175 $ zr rod
172        c/z -2.07772 19.9898 1.82245 $ fuel
173        c/z -2.07772 19.9898 1.87325 $ cladding
174        c/z 5.97408 10.3454 0.3175 $ zr rod
175        c/z 5.97408 10.3454 1.82245 $ fuel
176        c/z 5.97408 10.3454 1.87325 $ cladding
177        c/z 9.15162 7.67842 0.3175 $ zr rod
178        c/z 9.15162 7.67842 1.82245 $ fuel
179        c/z 9.15162 7.67842 1.87325 $ cladding
180        c/z -2.2225 -11.7653 0.3175 $ zr rod
181        c/z -2.2225 -11.7653 1.82245 $ fuel
```

```
182     c/z -2.2225 -11.7653 1.87325 $ cladding
183     c/z 7.95782 -13.782 0.3175 $ zr rod
184     c/z 7.95782 -13.782 1.82245 $ fuel
185     c/z 7.95782 -13.782 1.87325 $ cladding
186     c/z -9.15162 7.67842 0.3175 $ zr rod
187     c/z -9.15162 7.67842 1.82245 $ fuel
188     c/z -9.15162 7.67842 1.87325 $ cladding
189     c/z -5.97408 10.3454 0.3175 $ zr rod
190     c/z -5.97408 10.3454 1.82245 $ fuel
191     c/z -5.97408 10.3454 1.87325 $ cladding
192     c/z 4.20624 15.2019 0.3175 $ zr rod
193     c/z 4.20624 15.2019 1.82245 $ fuel
194     c/z 4.20624 15.2019 1.87325 $ cladding
195     c/z 7.95782 13.782 0.3175 $ zr rod
196     c/z 7.95782 13.782 1.82245 $ fuel
197     c/z 7.95782 13.782 1.87325 $ cladding
198     c/z -11.2547 -11.2547 0.3175 $ zr rod
199     c/z -11.2547 -11.2547 1.82245 $ fuel
200     c/z -11.2547 -11.2547 1.87325 $ cladding
201     c/z 13.782 7.95782 0.3175 $ zr rod
202     c/z 13.782 7.95782 1.82245 $ fuel
203     c/z 13.782 7.95782 1.87325 $ cladding
204     c/z 11.2243 4.08432 0.3175 $ zr rod
205     c/z 11.2243 4.08432 1.82245 $ fuel
206     c/z 11.2243 4.08432 1.87325 $ cladding
207     c/z 11.2243 -4.08432 0.3175 $ zr rod
208     c/z 11.2243 -4.08432 1.82245 $ fuel
209     c/z 11.2243 -4.08432 1.87325 $ cladding
210     c/z 15.3721 4.11988 0.3175 $ zr rod
211     c/z 15.3721 4.11988 1.82245 $ fuel
212     c/z 15.3721 4.11988 1.87325 $ cladding
213     c/z 9.15162 -7.67842 0.3175 $ zr rod
214     c/z 9.15162 -7.67842 1.82245 $ fuel
215     c/z 9.15162 -7.67842 1.87325 $ cladding
216     c/z 5.97408 -10.3454 0.3175 $ zr rod
217     c/z 5.97408 -10.3454 1.82245 $ fuel
218     c/z 5.97408 -10.3454 1.87325 $ cladding
219     c/z 11.2547 -11.2547 0.3175 $ zr rod
220     c/z 11.2547 -11.2547 1.82245 $ fuel
221     c/z 11.2547 -11.2547 1.87325 $ cladding
222     c/z -18.1686 -8.0899 0.3175 $ zr rod
223     c/z -18.1686 -8.0899 1.82245 $ fuel
224     c/z -18.1686 -8.0899 1.87325 $ cladding
225     c/z 18.1686 -8.0899 0.3175 $ zr rod
226     c/z 18.1686 -8.0899 1.82245 $ fuel
227     c/z 18.1686 -8.0899 1.87325 $ cladding
228     c/z 16.0909 -11.6916 0.3175 $ zr rod
229     c/z 16.0909 -11.6916 1.82245 $ fuel
230     c/z 16.0909 -11.6916 1.87325 $ cladding
231     c/z 18.1686 8.0899 0.3175 $ zr rod
232     c/z 18.1686 8.0899 1.82245 $ fuel
233     c/z 18.1686 8.0899 1.87325 $ cladding
234     c/z -19.4539 -4.13512 0.3175 $ zr rod
235     c/z -19.4539 -4.13512 1.82245 $ fuel
236     c/z -19.4539 -4.13512 1.87325 $ cladding
237     c/z -19.8882 0.0 0.3175 $ zr rod
238     c/z -19.8882 0.0 1.82245 $ fuel
239     c/z -19.8882 0.0 1.87325 $ cladding
240     c/z 19.4539 -4.13512 0.3175 $ zr rod
241     c/z 19.4539 -4.13512 1.82245 $ fuel
242     c/z 19.4539 -4.13512 1.87325 $ cladding
243     c/z -19.4539 4.13512 0.3175 $ zr rod
244     c/z -19.4539 4.13512 1.82245 $ fuel
245     c/z -19.4539 4.13512 1.87325 $ cladding
246     c/z 19.4539 4.13512 0.3175 $ zr rod
247     c/z 19.4539 4.13512 1.82245 $ fuel
248     c/z 19.4539 4.13512 1.87325 $ cladding
249     c/z 16.0909 11.6916 0.3175 $ zr rod
```

```
250        c/z 16.0909 11.6916 1.82245 $ fuel
251        c/z 16.0909 11.6916 1.87325 $ cladding
252        c/z -16.0909 -11.6916 0.3175 $ zr rod
253        c/z -16.0909 -11.6916 1.82245 $ fuel
254        c/z -16.0909 -11.6916 1.87325 $ cladding
255        c/z -16.0909 11.6916 0.3175 $ zr rod
256        c/z -16.0909 11.6916 1.82245 $ fuel
257        c/z -16.0909 11.6916 1.87325 $ cladding
258        c/z 9.9441 -17.4523 0.3175 $ zr rod
259        c/z 9.9441 -17.4523 1.82245 $ fuel
260        c/z 9.9441 -17.4523 1.87325 $ cladding
261        c/z 2.07772 19.9898 0.3175 $ zr rod
262        c/z 2.07772 19.9898 1.82245 $ fuel
263        c/z 2.07772 19.9898 1.87325 $ cladding
264        c/z 10.1194 17.1323 0.3175 $ zr rod
265        c/z 10.1194 17.1323 1.82245 $ fuel
266        c/z 10.1194 17.1323 1.87325 $ cladding
267        c/z -9.9441 17.4523 0.3175 $ zr rod
268        c/z -9.9441 17.4523 1.82245 $ fuel
269        c/z -9.9441 17.4523 1.87325 $ cladding
270        c/z -18.1686 8.0899 0.3175 $ zr rod
271        c/z -18.1686 8.0899 1.82245 $ fuel
272        c/z -18.1686 8.0899 1.87325 $ cladding
273        c/z 6.1468 18.9154 0.3175 $ zr rod
274        c/z 6.1468 18.9154 1.82245 $ fuel
275        c/z 6.1468 18.9154 1.87325 $ cladding
276        c/z 0.0 7.98068 1.665 $ fuel
277        pz 9.525 $ top of fuel at0.0@7.98068
278        c/z 0.0 7.98068 0.3175 $ zr rod
279        pz -27.86 $ bottom of fuel
280        pz 1.905 $ segment bottom1
281        pz -5.715 $ segment bottom2
282        pz -13.335 $ segment bottom3
283        pz -20.955 $ segment bottom4
284        c/z 0.0 7.98068 1.7234 $ cladding control rod  w/fuel
285        pz 19.05 $ top of fuel at11.9456@0.0
286        c/z 11.9456 0.0 1.665 $ fuel
287        c/z 11.9456 0.0 0.3175 $ zr rod
288        c/z 11.9456 0.0 1.7234 $ cladding control rod  w/fuel
289        c/z -11.9456 0.0 1.665 $ fuel
290        pz 9.525 $ top of fuel at-11.9456@0.0
291        c/z -11.9456 0.0 0.3175 $ zr rod
292        c/z -11.9456 0.0 1.7234 $ cladding control rod  w/fuel
293        c/z 0.0 -7.98068 1.665 $ fuel
294        pz 9.525 $ top of fuel at0.0@-7.98068
295        c/z 0.0 -7.98068 1.7234 $ cladding control rod w/o fuel
296        c/z 0.0 0.0 1.82245 $ graph
297        c/z 0.0 0.0 1.87325 $ cladding central thimble
298        c/z 13.3071 -14.7803 1.87325 $ cladding water -#f5
299        c/z -13.3071 -14.7803 1.87325 $ cladding water -#f12
300        c/z -13.3071 14.7803 1.87325 $ cladding water -#f20
301        c/z 13.3071 14.7803 1.87325 $ cladding water -#f27
302        c/z 23.4975 -4.14274 1.87325 $ cladding water -#g2
303        c/z 0.0 -23.8608 1.87325 $ cladding water -#g10
304        c/z -4.14274 -23.4975 1.87325 $ cladding water -#g11
305        c/z -8.0772 -22.606 1.87325 $ cladding water -#g12
306        c/z -11.9304 -20.6654 1.87325 $ cladding water -#g13
307        c/z -15.3365 -18.2778 1.87325 $ cladding water -#g14
308        c/z -18.2778 -15.3365 1.87325 $ cladding water -#g15
309        c/z -20.6654 11.9304 1.87325 $ cladding water -#g22
310        c/z -18.2778 15.3365 1.87325 $ cladding water -#g23
311        c/z -15.3365 18.2778 1.87325 $ cladding water -#g24
312        c/z -11.9304 20.6654 1.87325 $ cladding water -#g25
313        c/z -8.16102 22.4206 1.87325 $ cladding water -#g26
314        c/z -4.14274 23.4975 1.87325 $ cladding water -#g27
315        c/z 0.0 23.8608 1.87325 $ cladding water -#g28
316        c/z 23.8608 0.0 1.82245 $ graph
317        c/z 23.8608 0.0 1.87325 $ cladding graphite rod
```

```
318       c/z 22.4206 -7.93242 1.82245 $ graph
319       c/z 22.4206 -7.93242 1.87325 $ cladding graphite rod
320       c/z 20.6654 -11.9304 1.82245 $ graph
321       c/z 20.6654 -11.9304 1.87325 $ cladding graphite rod
322       c/z 18.2778 -15.3365 1.82245 $ graph
323       c/z 18.2778 -15.3365 1.87325 $ cladding graphite rod
324       c/z 15.3365 -18.2778 1.82245 $ graph
325       c/z 15.3365 -18.2778 1.87325 $ cladding graphite rod
326       c/z 11.9304 -20.6654 1.82245 $ graph
327       c/z 11.9304 -20.6654 1.87325 $ cladding graphite rod
328       c/z 8.16102 -22.4206 1.82245 $ graph
329       c/z 8.16102 -22.4206 1.87325 $ cladding graphite rod
330       c/z 4.14274 -23.4975 1.82245 $ graph
331       c/z 4.14274 -23.4975 1.87325 $ cladding graphite rod
332       c/z -20.6654 -11.9304 1.82245 $ graph
333       c/z -20.6654 -11.9304 1.87325 $ cladding graphite rod
334       c/z -22.4206 -8.16102 1.82245 $ graph
335       c/z -22.4206 -8.16102 1.87325 $ cladding graphite rod
336       c/z -23.4975 -4.14274 1.82245 $ graph
337       c/z -23.4975 -4.14274 1.87325 $ cladding graphite rod
338       c/z -23.8608 0.0 1.82245 $ graph
339       c/z -23.8608 0.0 1.87325 $ cladding graphite rod
340       c/z -23.4975 4.14274 1.82245 $ graph
341       c/z -23.4975 4.14274 1.87325 $ cladding graphite rod
342       c/z -22.4206 7.93242 1.82245 $ graph
343       c/z -22.4206 7.93242 1.87325 $ cladding graphite rod
344       c/z 4.14274 23.4975 1.82245 $ graph
345       c/z 4.14274 23.4975 1.87325 $ cladding graphite rod
346       c/z 8.0772 22.606 1.82245 $ graph
347       c/z 8.0772 22.606 1.87325 $ cladding graphite rod
348       c/z 11.9304 20.6654 1.82245 $ graph
349       c/z 11.9304 20.6654 1.87325 $ cladding graphite rod
350       c/z 15.3365 18.2778 1.82245 $ graph
351       c/z 15.3365 18.2778 1.87325 $ cladding graphite rod
352       c/z 18.2778 15.3365 1.82245 $ graph
353       c/z 18.2778 15.3365 1.87325 $ cladding graphite rod
354       c/z 20.6654 11.9304 1.82245 $ graph
355       c/z 20.6654 11.9304 1.87325 $ cladding graphite rod
356       c/z 22.4206 8.16102 1.82245 $ graph
357       c/z 22.4206 8.16102 1.87325 $ cladding graphite rod
358       c/z 23.4975 4.14274 1.82245 $ graph
359       c/z 23.4975 4.14274 1.87325 $ cladding graphite rod
1001   c/z -13.3071 14.7803 1.82245 $ graphite -f20
1002   c/z 13.3071 14.7803 1.82245 $ graphite -f27
1003   c/z 13.3071 -14.7803 0.3175 $ zr rod -f5
1004   c/z 13.3071 -14.7803 1.82245 $ fuel
1005   c/z -13.3071 -14.7803 0.3175 $ zr rod -f12
1006   c/z -13.3071 -14.7803 1.82245 $ fuel
1007   c/z 0.0 -23.8608 0.3175 $ zr rod -g10
1008   c/z 0.0 -23.8608 1.82245 $ fuel
1009   c/z -4.14274 -23.4975 0.3175 $ zr rod -g11
1010   c/z -4.14274 -23.4975 1.82245  $ fuel
1011   c/z -8.0772 -22.606 0.3175 $ zr rod -g12
1012   c/z -8.0772 -22.606 1.82245 $ fuel
1013   c/z -11.9304 -20.6654 0.3175 $ zr rod -g13
1014   c/z -11.9304 -20.6654 1.82245 $ fuel
1015   c/z 8.16102 -22.4206 0.3175 $ zr rod -g8
1016   c/z 4.14274 -23.4975 0.3175 $ zr rod -g9
1017   c/z 23.4975 -4.14274 1.82245 $ inside g2
1501   c/z 13.3071 -14.7803 0.3175 $f5
1502   c/z 13.3071 -14.7803 1.82245
1511   c/z -13.3071 -14.7803 0.3175 $f12
1512   c/z -13.3071 -14.7803 1.82245
1521   c/z 11.9304 -20.6654 0.3175 $g7
1522   c/z 8.16102 -22.4206 0.3175 $g8
1523   c/z 4.14274 -23.4975 0.3175 $g9
1531   c/z 0.0 -23.8608 0.3175 $g10
1532   c/z 0.0 -23.8608 1.82245
```

```
1541    c/z -4.14274 -23.4975 0.3175 $g11
1542    c/z -4.14274 -23.4975 1.82245
1551    c/z -8.0772 -22.606 0.3175 $g12
1552    c/z -8.0772 -22.606 1.82245
1561    c/z -11.9304 -20.6654 0.3175 $g13
1562    c/z -11.9304 -20.6654 1.82245
1571    c/z -15.3365 -18.2778 0.3175 $g14
1572    c/z -15.3365 -18.2778 1.82245
2701       cz 53.815 $ water gap
2702       cz 56.46 $ cylinder of Al
2703       cz 59.0 $ outer cylinder of Al
2704       px 91.705 $ TC5******
2705       px 92.705
2706       pz 0.5
2707       pz -0.5
2708       pz 10.16
2709       pz -10.16
2710       py 10.16
2711       py -10.16
2712       py 0.5
2713       py -0.5
2601       pz 60.96 $ top of TC
2602       pz 59.691 $ b4c top of TC
2603       pz 59.373 $ Al top of TC
2604       pz -59.373 $ Al bottom of TC
2605       pz -59.691 $ b4c bottom of TC
2606       pz -60.96 $ bottom of TC
2607       py 60.96 $ right side of TC
2608       py 59.691 $ b4c right of TC
2609       py 59.373 $ Al right of TC
2610       py -59.373 $ Al left of TC
2611       py -59.691 $ b4c left of TC
2612       py -60.96 $ left side of TC
2613       p 13.38 0 0 13.38 0 1 63.623 -60.96 0 $ down outer angle of TC
2614       p 14.967 0 0 14.967 0 1 65.21 -60.96 0 $ down inner angle of TC
2615       p 13.38 0 0 13.38 0 1 63.623 60.96 0 $ upper outer angle of TC
2616       p 14.967 0 0 14.967 0 1 65.21 60.96 0 $ upper inner angle of TC
2617       px 0.0 $ center line
2618       px 219.405 $ front of region N
2619       px 65.21 $ back of region A********* from 63.623
3001       102 cx 7.62 $#3 ****************** beamport
3002       102 cx 8.4138
3003       101 cy 7.62 $ #4
3004       101 cy 8.4138
3005       101 px 8.4139 $ #3 plate
3006       101 px 8.7313
3007       101 py -27.6275 $ #4 plate
3008       101 px 0
3101       103 cx 7.62
3102       103 cx 8.4138
3105       104 cy 7.62
3106       104 cy 8.4138
4000       cz 174.625  $ concrete
4001       cz 173.625  $ beam port #3 sample position
5000       c/z -13.3071 14.7803 1.82245
5001       c/z 13.3071 14.7803 1.82245 $ f27

m1       13027 1.0 $ al
m2       6012 0.00009456 24000 0.005187 28000 0.00241866 26000  $ steel/h2o
       0.0180264 1001 0.04676 8016 0.02338
m3       1001 2.0 8016 1.0 $ h2o
mt3     lwtr.01t $ h2o  salphabeta card
m4       13027 1.0 $ al 50%
m5       6012 1.0 $ graphite
mt5     grph.01t $ graphite  salphabeta card
m6       82000 1.0 $ lead
m7       40000.60c 1.0 $ zr
m8       1001 0.0561083 40000.60c 0.0350677 92235 0.000892797 $ u-zr fuel
```

```
        92238 0.000378151 68167 0.0000793236 68166 0.000266313
mt8     h/zr.01t zr/h.01t $ u-zr fuel salphabeta card
m13     6012 0.00031519 24000 0.01729 28000 0.0080622 26000 0.060088 $ steel
m21     1001 -0.010 8016 -0.529 11023 -0.016 12000 -0.002
        13027 -0.034 14000 -0.337 19000 -0.013 20000 -0.044
        26000 -0.014 6012 -0.001 $ concrete
m419      5010.50c 0.15824 5011.56c 0.64176 6012 0.2 $ b4c
m425      7014.50c 0.79 8016 0.21                            $ air
*tr4    0 0 -6.985 60 30 90 150 60 90 90 90 0
*tr1    0 0 -6.985 30 60 90 120 30 90 90 90 0
*tr3    46.99 0 -6.985 48 42 90 138 48 90 90 90 0
*tr101  0 0 -6.985 27 117 90 63 27 90 90 90 0 $ #4
*tr102 -9.37 -36.49 -6.985 40 130 90 50 40 90 90 90 0 $#3
*tr103  0 0 -6.985 63 153 90 27 63 90 90 90 0 $ #1
*tr104  0 0 -6.985 40 130 90 50 40 90 90 90 0 $ #2
kcode     2000  1.05 50 1000 $  card
mode    n $  card
ksrc  6.4743 -18.5879 15.24 6.4743 -18.5879 7.62 6.4743 -18.5879
      -9.53674e-7 6.4743 -18.5879 -7.62 6.4743 -18.5879 -15.24 $ f7
      -7.63032 14.1095 15.24 -7.63032 14.1095 7.62 -7.63032 14.1095
      -9.53674e-7 -7.63032 14.1095 -7.62 -7.63032 14.1095 -15.24 $ e17
      -13.4545 8.28532 15.24 -13.4545 8.28532 7.62 -13.4545 8.28532
      -9.53674e-7 -13.4545 8.28532 -7.62 -13.4545 8.28532 -15.24 $e15
      2.40522 -19.6623 15.24 2.40522 -19.6623 7.62 2.40522 -19.6623
      -9.53674e-7 2.40522 -19.6623 -7.62 2.40522 -19.6623 -15.24 $ f8
      -13.4545 -7.63032 15.24 -13.4545 -7.63032 7.62 -13.4545 -7.63032
      -9.53674e-7 -13.4545 -7.63032 -7.62 -13.4545 -7.63032 -15.24 $ e11
      15.6996 -3.79238 15.24 15.6996 -3.79238 7.62 15.6996 -3.79238
      -9.53674e-7 15.6996 -3.79238 -7.62 15.6996 -3.79238 -15.24 $ e2
      16.2431 0.3275 15.24 16.2431 0.3275 7.62 16.2431 0.3275
      -9.53674e-7 16.2431 0.3275 -7.62 16.2431 0.3275 -15.24 $ e1
      -3.58664 1.37398 15.24 -3.58664 1.37398 7.62 -3.58664 1.37398
      -9.53674e-7 -3.58664 1.37398 -7.62 -3.58664 1.37398 -15.24 $ b4
      14.1095 -7.63032 15.24 14.1095 -7.63032 7.62 14.1095 -7.63032
      -9.53674e-7 14.1095 -7.63032 -7.62 14.1095 -7.63032 -15.24 $ e3
      -15.5881 0.3275 15.24 -15.5881 0.3275 7.62 -15.5881 0.3275
      -9.53674e-7 -15.5881 0.3275 -7.62 -15.5881 0.3275 -15.24 $ e13
      -15.0446 4.44738 15.24 -15.0446 4.44738 7.62 -15.0446 4.44738
      -9.53674e-7 -15.0446 4.44738 -7.62 -15.0446 4.44738 -15.24 $ e14
      2.40014 -10.9755 15.24 2.40014 -10.9755 7.62 2.40014 -10.9755
      -9.53674e-7 2.40014 -10.9755 -7.62 2.40014 -10.9755 -15.24 $ d5
      11.5822 11.5822 15.24 11.5822 11.5822 7.62 11.5822 11.5822
      -9.53674e-7 11.5822 11.5822 -7.62 11.5822 11.5822 -15.24 $ e22
      4.44738 -15.0446 15.24 4.44738 -15.0446 7.62 4.44738 -15.0446
      -9.53674e-7 4.44738 -15.0446 -7.62 4.44738 -15.0446 -15.24 $ e6
      -15.0446 -3.79238 15.24 -15.0446 -3.79238 7.62 -15.0446 -3.79238
       -9.53674e-7 -15.0446 -3.79238 -7.62 -15.0446 -3.79238 -15.24 $ e12
       -10.9272 11.5822 15.24 -10.9272 11.5822 7.62
      -10.9272 11.5822 -9.53674e-7 -10.9272 11.5822 -7.62 -10.9272
      11.5822 -15.24 $ e16
      -0.71898 4.24164 15.24 -0.71898 4.24164 7.62
      -0.71898 4.24164 -9.53674e-7 -0.71898 4.24164 -7.62 -0.71898
      4.24164 -15.24 $b5
      3.19516 3.19516 15.24 3.19516 3.19516 7.62
      3.19516 3.19516 -9.53674e-7 3.19516 3.19516 -7.62 3.19516
      3.19516 -15.24 $ b6
       4.31784 7.23884 15.24 4.31784 7.23884 7.62
      4.31784 7.23884 -9.53674e-7 4.31784 7.23884 -7.62 4.31784
      7.23884 -15.24 $c11
      7.23884 4.31784 15.24 7.23884 4.31784 7.62
      7.23884 4.31784 -9.53674e-7 7.23884 4.31784 -7.62 7.23884
      4.31784 -15.24 $ c12
      8.30818 0.3275 15.24 8.30818 0.3275 7.62 8.30818
      0.3275 -9.53674e-7 8.30818 0.3275 -7.62 8.30818 0.3275 -15.24 $c1
      -2.54016 -2.54016 15.24 -2.54016 -2.54016 7.62 -2.54016 -2.54016
      -9.53674e-7 -2.54016 -2.54016 -7.62 -2.54016 -2.54016 -15.24 $ b3
      1.37398 -3.58664 15.24 1.37398 -3.58664 7.62 1.37398 -3.58664
      -9.53674e-7 1.37398 -3.58664 -7.62 1.37398 -3.58664 -15.24 $ b2
```

```
0.0862 -14.8744 15.24 0.0862 -14.8744 7.62 0.0862 -14.8744
-9.53674e-7 0.0862 -14.8744 -7.62 0.0862 -14.8744 -15.24 $ e7
20.1471
0.3275 15.24 20.1471 0.3275 7.62 20.1471 0.3275 -9.53674e-7
20.1471 0.3275 -7.62 20.1471 0.3275 -15.24 $ f1
-1.74514 11.6305
15.24 -1.74514 11.6305 7.62 -1.74514 11.6305 -9.53674e-7
-1.74514 11.6305 -7.62 -1.74514 11.6305 -15.24 $ d14
0.5688 15.5294
15.24 0.5688 15.5294 7.62 0.5688 15.5294 -9.53674e-7 0.5688
15.5294 -7.62 0.5688 15.5294 -15.24 $ e19
 -1.75022 -19.6623 15.24
-1.75022 -19.6623 7.62 -1.75022 -19.6623 -9.53674e-7 -1.75022
-19.6623 -7.62 -1.75022 -19.6623 -15.24 $f9
-3.79238 15.6996 15.24
-3.79238 15.6996 7.62 -3.79238 15.6996 -9.53674e-7 -3.79238
15.6996 -7.62 -3.79238 15.6996 -15.24 $ e18
7.23884 -3.66284 15.24
7.23884 -3.66284 7.62 7.23884 -3.66284 -9.53674e-7 7.23884
-3.66284 -7.62 7.23884 -3.66284 -15.24 $ c2
4.31784 -6.58384 15.24
4.31784 -6.58384 7.62 4.31784 -6.58384 -9.53674e-7 4.31784
-6.58384 -7.62 4.31784 -6.58384 -15.24 $ c3
-3.66284 -6.58384 15.24
-3.66284 -6.58384 7.62 -3.66284 -6.58384 -9.53674e-7 -3.66284
-6.58384 -7.62 -3.66284 -6.58384 -15.24 $ c5
-6.58384 -3.66284 15.24
-6.58384 -3.66284 7.62 -6.58384 -3.66284 -9.53674e-7 -6.58384
-3.66284 -7.62 -6.58384 -3.66284 -15.24 $c6
-7.65318 0.3275 15.24
-7.65318 0.3275 7.62 -7.65318 0.3275 -9.53674e-7 -7.65318 0.3275
-7.62 -7.65318 0.3275 -15.24 $c7
-6.58384 4.31784 15.24 -6.58384
4.31784 7.62 -6.58384 4.31784 -9.53674e-7 -6.58384 4.31784 -7.62
-6.58384 4.31784 -15.24 $ c8
-3.66284 7.23884 15.24 -3.66284 7.23884
7.62 -3.66284 7.23884 -9.53674e-7 -3.66284 7.23884 -7.62
-3.66284 7.23884 -15.24 $ c9
 -3.87874 -14.8744 15.24 -3.87874
-14.8744 7.62 -3.87874 -14.8744 -9.53674e-7 -3.87874 -14.8744
-7.62 -3.87874 -14.8744 -15.24 $ e8
-7.63032 -13.4545 15.24 -7.63032
-13.4545 7.62 -7.63032 -13.4545 -9.53674e-7 -7.63032 -13.4545
-7.62 -7.63032 -13.4545 -15.24 $e9
-5.64658 -10.0179 15.24 -5.64658
-10.0179 7.62 -5.64658 -10.0179 -9.53674e-7 -5.64658 -10.0179
-7.62 -5.64658 -10.0179 -15.24 $ d7
-10.8968 -3.75682 15.24 -10.8968
-3.75682 7.62 -10.8968 -3.75682 -9.53674e-7 -10.8968 -3.75682
-7.62 -10.8968 -3.75682 -15.24 $ d9
-10.8968 4.41182 15.24 -10.8968
4.41182 7.62 -10.8968 4.41182 -9.53674e-7 -10.8968 4.41182 -7.62
-10.8968 4.41182 -15.24 $ d11
-5.8193 -18.5879 15.24 -5.8193 -18.5879
7.62 -5.8193 -18.5879 -9.53674e-7 -5.8193 -18.5879 -7.62 -5.8193
-18.5879 -15.24 $ f10
 -9.79186 -16.8048 15.24 -9.79186 -16.8048 7.62
-9.79186 -16.8048 -9.53674e-7 -9.79186 -16.8048 -7.62 -9.79186
-16.8048 -15.24 $ f11
 2.55 12.0928 15.24 2.55 12.0928 7.62 2.55
12.0928 -9.53674e-7 2.55 12.0928 -7.62 2.55 12.0928 -15.24 $ d15
6.30158 10.6729 15.24 6.30158 10.6729 7.62 6.30158 10.6729
-9.53674e-7 6.30158 10.6729 -7.62 6.30158 10.6729 -15.24 $ d16
9.47912
8.00592 15.24 9.47912 8.00592 7.62 9.47912 8.00592 -9.53674e-7
9.47912 8.00592 -7.62 9.47912 8.00592 -15.24 $ d17
-1.895 -11.4378
15.24 -1.895 -11.4378 7.62 -1.895 -11.4378 -9.53674e-7 -1.895
```

```
-11.4378 -7.62 -1.895 -11.4378 -15.24 $ d6
8.28532 -13.4545 15.24
8.28532 -13.4545 7.62 8.28532 -13.4545 -9.53674e-7 8.28532
-13.4545 -7.62 8.28532 -13.4545 -15.24 $ e5
 -8.82412 8.00592 15.24
-8.82412 8.00592 7.62 -8.82412 8.00592 -9.53674e-7 -8.82412
8.00592 -7.62 -8.82412 8.00592 -15.24 $ d12
 -5.64658 10.6729 15.24
-5.64658 10.6729 7.62 -5.64658 10.6729 -9.53674e-7 -5.64658
10.6729 -7.62 -5.64658 10.6729 -15.24 $ d13
4.53374 15.5294 15.24
4.53374 15.5294 7.62 4.53374 15.5294 -9.53674e-7 4.53374 15.5294
-7.62 4.53374 15.5294 -15.24 $ e20
 8.28532 14.1095 15.24 8.28532
14.1095 7.62 8.28532 14.1095 -9.53674e-7 8.28532 14.1095 -7.62
8.28532 14.1095 -15.24 $ e21
 -10.9272 -10.9272 15.24 -10.9272 -10.9272
7.62 -10.9272 -10.9272 -9.53674e-7 -10.9272 -10.9272 -7.62
-10.9272 -10.9272 -15.24 $ e10
14.1095 8.28532 15.24 14.1095 8.28532
7.62 14.1095 8.28532 -9.53674e-7 14.1095 8.28532 -7.62 14.1095
8.28532 -15.24 $ e23
 11.5518 4.41182 15.24 11.5518 4.41182 7.62
11.5518 4.41182 -9.53674e-7 11.5518 4.41182 -7.62 11.5518
4.41182 -15.24 $ d18
 11.5518 -3.75682 15.24 11.5518 -3.75682 7.62
11.5518 -3.75682 -9.53674e-7 11.5518 -3.75682 -7.62 11.5518
-3.75682 -15.24 $ d2
 15.6996 4.44738 15.24 15.6996 4.44738 7.62
15.6996 4.44738 -9.53674e-7 15.6996 4.44738 -7.62 15.6996
4.44738 -15.24 $ e24
9.47912 -7.35092 15.24 9.47912 -7.35092 7.62
9.47912 -7.35092 -9.53674e-7 9.47912 -7.35092 -7.62 9.47912
-7.35092 -15.24 $ d3
 6.30158 -10.0179 15.24 6.30158 -10.0179 7.62
6.30158 -10.0179 -9.53674e-7 6.30158 -10.0179 -7.62 6.30158
-10.0179 -15.24 $ d4
 11.5822 -10.9272 15.24 11.5822 -10.9272 7.62
11.5822 -10.9272 -9.53674e-7 11.5822 -10.9272 -7.62 11.5822
-10.9272 -15.24 $ e4
 -17.8411 -7.7624 15.24 -17.8411 -7.7624 7.62
-17.8411 -7.7624 -9.53674e-7 -17.8411 -7.7624 -7.62 -17.8411
-7.7624 -15.24 $ f14
 18.4961 -7.7624 15.24 18.4961 -7.7624 7.62
18.4961 -7.7624 -9.53674e-7 18.4961 -7.7624 -7.62 18.4961
-7.7624 -15.24 $ f3
 16.4184 -11.3641 15.24 16.4184 -11.3641 7.62
16.4184 -11.3641 -9.53674e-7 16.4184 -11.3641 -7.62 16.4184
-11.3641 -15.24 $ f4
 18.4961 8.4174 15.24 18.4961 8.4174 7.62 18.4961
8.4174 -9.53674e-7 18.4961 8.4174 -7.62 18.4961 8.4174 -15.24 $ f29
-19.1264 -3.80762 15.24 -19.1264 -3.80762 7.62 -19.1264 -3.80762
-9.53674e-7 -19.1264 -3.80762 -7.62 -19.1264 -3.80762 -15.24 $ f15
-19.5607 0.3275 15.24 -19.5607 0.3275 7.62 -19.5607 0.3275
-9.53674e-7 -19.5607 0.3275 -7.62 -19.5607 0.3275 -15.24 $ f16
-19.1264 4.46262 15.24 -19.1264 4.46262 7.62 -19.1264 4.46262
-9.53674e-7 -19.1264 4.46262 -7.62 -19.1264 4.46262 -15.24 $ f17
19.7814 4.46262 15.24 19.7814 4.46262 7.62 19.7814 4.46262
-9.53674e-7 19.7814 4.46262 -7.62 19.7814 4.46262 -15.24 $ f30
16.4184
12.0191 15.24 16.4184 12.0191 7.62 16.4184 12.0191 -9.53674e-7
16.4184 12.0191 -7.62 16.4184 12.0191 -15.24 $ f28
 -15.7634 -11.3641
15.24 -15.7634 -11.3641 7.62 -15.7634 -11.3641 -9.53674e-7
-15.7634 -11.3641 -7.62 -15.7634 -11.3641 -15.24 $ f13
10.2716 -17.1248
15.24 10.2716 -17.1248 7.62 10.2716 -17.1248 -9.53674e-7 10.2716
-17.1248 -7.62 10.2716 -17.1248 -15.24 $ f6
```

```
     0.3275 8.30818 5.715 0.3275 8.30818 -1.905 0.3275 8.30818 -9.525
     0.3275 8.30818 -17.145 0.3275 8.30818 -24.4075 0.01 7.99068
     -27.86 $ c10
      12.2731 0.3275 15.24 12.2731 0.3275 7.62 12.2731 0.3275
     -9.53674e-7 12.2731 0.3275 -7.62 12.2731 0.3275 -15.24 11.9556
     0.01 -23.455 $ d1
      -11.6181 0.3275 5.715 -11.6181 0.3275 -1.905
     -11.6181 0.3275 -9.525 -11.6181 0.3275 -17.145 -11.6181 0.3275
     -24.4075 -11.9356 0.01 -27.86 $ d10
C changed position
     13.6346 -14.4528 15.24 13.6346 -14.4528 7.62 13.6346 -14.4528
     -9.53674e-7 13.6346 -14.4528 -7.62 13.6346 -14.4528 -15.24
     -12.9796 -14.4528 15.24 -12.9796 -14.4528 7.62 -12.9796 -14.4528
     -9.53674e-7 -12.9796 -14.4528 -7.62 -12.9796 -14.4528 -15.24
     12.2579 -20.3379 15.24 12.2579 -20.3379 7.62 12.2579 -20.3379
     -9.53674e-7 12.2579 -20.3379 -7.62 12.2579 -20.3379 -15.24
      8.48852 -22.0931 15.24 8.48852 -22.0931 7.62 8.48852 -22.0931
      -9.53764e-7 8.48852 -22.0931 -7.62 8.48852 -22.0931 -15.24
      4.47024 -23.17 15.24 4.47024 -23.17 7.62 4.47024 -23.17
      -9.53674e-7 4.47024 -23.17 -7.62 4.47024 -23.17 -15.24
      0.3275 -23.5333 15.24 0.3275 -23.5333 7.62 0.3275 -23.5333
      -9.53674e-7 0.3275 -23.5333 -7.62 0.3275 -23.5333 -15.24
      -3.81524 -23.17 15.24 -3.81524 -23.17 7.62 -3.81524 -23.17
      -9.53674e-7 -3.81524 -23.17 -7.62 -3.81524 -23.17 -15.24
      -7.7497 -22.2785 15.24 -7.7497 -22.2785 7.62 -7.7497 -22.2785
      -9.53674e-7 -7.7497 -22.2785 -7.62 -7.7497 -22.2785 -15.24
      -11.6029 -20.3379 15.24 -11.6029 -20.3379 7.62 -11.6029 -20.3379
      -9.53674e-7 -11.6029 -20.3379 -7.62 -11.6029 -20.3379 -15.24
      -15.009 -17.9503 15.24 -15.009 -17.9503 7.62 -15.009 -17.9503
      -9.53674e-7 -15.009 -17.9503 -7.62 -15.009 -17.9503 -15.24 $ g14
f7:n  (231 232 233 234 235  $b3
      186 187 188 189 190   $b5
      240 241 242 243 244   $b2
      105 106 107 108 109   $b4
      195 196 197 198 199)   $b6
      (222 223 224 225 226   $c1
      303 304 305 306 307
      312 313 314 315 316
      321 322 323 324 325
      330 331 332 333 334
      339 340 341 342 343
      348 349 350 351 352
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