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Actinide Behavior in the Integral Fast Reactor

Final Project Report

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ABSTRACT

The Integral Fast Reactor (IFR) under development by Argonne National Laboratory uses metallic fuels instead of ceramics. This allows electrorefining of spent fuels and presents opportunities for recycling minor actinide elements. Four minor actinides (^{237}Np, ^{240}Pu, ^{241}Am, and ^{243}Am) determine the waste storage requirements of spent fuel from all types of fission reactors. These nuclides behave the same as uranium and other plutonium isotopes in electrorefining, so they can be recycled back to the reactor without elaborate chemical processing. An experiment has been designed to demonstrate the effectiveness of the high-energy neutron spectra of the IFR in consuming these four nuclides and weapons grade plutonium. Eighteen sets of seven actinide and five light metal targets have been selected for seven day exposure in the Experimental Breeder Reactor-II which serves as a prototype of the IFR. Post-irradiation analyses of the exposed targets by gamma, alpha, and mass spectroscopy are used to determine nuclear reaction rates and neutron spectra. These experimental data increase our confidence in our ability to predict reaction rates in candidate IFR designs using a variety of neutron transport and diffusion programs.

INTRODUCTION

The Integral Fast Reactor (IFR) under development by Argonne National Laboratory (ANL) differs from the present generation of power reactors in that it uses a metallic, rather than a ceramic, form of fuel and that it uses a liquid metal, sodium, to remove the heat produced by fission.[1,2] Materials in these type of reactors are ineffective in reducing neutron energies, so they are characterized as "fast"; that is, the neutrons have much higher speeds than in the present generation of power reactors that use water to remove the heat produced by fission. Water is an effective moderator of neutron energies. Lower energy neutrons have high fission and nonfission capture cross sections in ^{235}U and ^{239}Pu, but the ratio of capture to fission reactions are much higher for other actinides than in a fast reactor.

The IFR incorporates an innovative pyrometallurgical technique to process the spent metallic fuel instead of using the aqueous processes associated with ceramic forms of fuel. While the IFR has been pursued formally since 1984, much of its technology is based on development programs that have been pursued since the 1950s.[3] Of specific interest are the characteristics of the processing technique that causes all of the actinide elements and most of the lanthanide fission products to be collected in the same mass. This mixture of materials can be used as fuel for fast reactors that keep most of the neutrons in the core at energies greater than several KeV, but is unsuitable for use as fuel for nuclear weapons.

Figure 1 describes the major steps in the IFR fuel cycle. The electrochemical properties of the various elements that are important in the processes that take place in an electrorefiner operating at 500 °C with a KCl-LiCl electrolyte. It is the Gibb's free energies of formation in this chloride salt system that set its basic attributes. First, there are sufficient separations of the free energies of the fission products from those of the actinide elements to permit rough, but not total actinide separation. Second, there is sufficient proximity of the free energy of plutonium and the minor actinides so that they are all extracted together. The spent fuel is sheared in short pieces and electrolytically removed from the cladding which stays behind as hulls. Actinide elements are deposited in one of two types of cathodes - one that is highly dendritic, predominantly uranium, of about 10 Kg heavy metal in the current device. The other cathode is a crucible containing cadmium which is operated once the uranium has been substantially extracted. Into this cathode goes uranium and plutonium, and inherently, the minor actinides as well. Either type of cathode is then retorted in the cathode processor machine to drive off adhering electrolyte (and/or cadmium) and recover metal ingots.

The processed metal contains enough fission product carryover (principally rare earths) so that it is quite radioactive. New fuel elements are formed by injection casting the product from the cathode processor into glass molds. These metallic slugs are inserted into the cladding and welded closed to form the fuel element. Fuel elements are assembled into hexagonal arrays to make the completed subassembly that will be transferred to the reactor. All of the processing operations shown in Figure 1 are carried out in a dedicated alpha-gamma hot cell that provides materials confinement and shielding of the penetrating radiations from the spent fuel.

ACTINIDE MANAGEMENT OPTIONS

An important characteristic of fast reactors like the IFR is that they can consume the minor actinides as well as ^{239}Pu by fission. In thermal neutron spectra reactors, most of the heavy element isotopes do not fission with sufficient probability to prevent the buildup of the long-lived minor actinides. In fast reactors, the ratio of the fission to capture cross-sections is much greater. Essentially all of the actinides will fission to an extant that ensures their ultimate elimination if they are recycled and kept out of the waste streams. For a given amount of fission energy generated, fewer transuranic elements are produced in fast reactors than in thermal reactors. Also, a higher fraction of nonfissile nuclides can be accommodated in fuels for fast reactors. Thus fast reactors offer the potential to manage inventories of all of the actinide elements.

Plutonium inventories are of growing concern brought into focus by the dramatic dismantlement of weapons in the United States and the former Soviet Union. The current inventory of weapons-grade plutonium in the United States is about 33.5 metric tons.[4] This is greatly in excess of our current defense requirements. Additionally, highly enriched uranium is available from our defense establishment. It is likely that our nation will purchase weapons grade plutonium and uranium from the Congress of Independent States to keep these materials off of

the world market. The United States is now considering its options for safe, secure disposal of weapons grade actinides. Only nuclear reactions can truly denature actinides to make them unsuitable for weapons; that is, the isotopic content of ^{239}Pu and ^{235}U must be reduced for these two elements. The pyrometallurgical processes developed for the IFR can accept the materials from weapons with very little modification. Other alternatives involve more elaborate processing to produce fuel for reactors or accelerator targets.

Civilian power reactor production of plutonium now amounts to some thousand metric tons in the 30 nations that have nuclear programs. About 200 Kg of elemental plutonium is discharged annually from each 1000 MW-electrical light water cooled and moderated unit. At current production levels, this amounts to about 70 metric tons per year, worldwide. Without some fast reactor alternative that will consume it, there is little hope of managing stocks of plutonium. They will continue to grow, and require more and more secure storage space. Storage does not insure that plutonium could not be diverted to produce explosives in the future; what is stored can be retrieved, even from geological repositories. Only nuclear reactions can transform weapons-grade plutonium to a mix of nuclides unsuitable for weapons use. nuclides unsuitable for nuclear explosives.

In addition to the nuclear reactions in an IFR or other fast reactor, the processing of spent fuel plays an important role in the management of the actinides. The electrochemical process incorporated in the IFR fuel cycle does not produce pure plutonium. Other actinides and some of the fission products follow plutonium to the cathode making the product unsuitable for weapons fuel. The complete absence of separated plutonium makes this fuel cycle more resistant to proliferation than processes based on solvent extraction, such as the PUREX process.[5]

REACTOR EXPERIMENTS TO SUPPORT ACTINIDE CONSUMPTION STUDIES

Louisiana State University and ANL are engaged in a long-term experimental program to determine the neutron reaction rates in fast reactors. Such data are needed to design advanced reactors cooled by liquid metals that use metallic alloys of uranium and zirconium (binary fuel) or uranium/plutonium/zirconium (ternary alloy) for fuel. Fission and non-fission capture rates are strongly dependent on the neutron energy; comparison of calculated and measured neutron spectra is an important factor in determining the validity of reactor designs.

In February and March 1994, two irradiations of binary fuel subassemblies were conducted in the Experimental Breeder Reactor-II (EBR-II) located at the ANL site on the Idaho National Engineering Laboratory. This reactor uses metallic fuel and sodium coolant; it serves as a prototype for other IFR designs. Each of the subassemblies had some fuel replaced by an inventory of target materials selected to define the neutron spectra and to determine reaction rates in actinide in nine locations within the reactor. The neutron spectra and reaction rates vary strongly with the locations in EBR-II. Comparisons of measured and calculated data provide

confirmation of our ability to calculate reaction rates for a wide range of materials and configurations. Differences indicate where improvements can be made.

Activation and fission products are being determined by high resolution gamma spectroscopy at the ANL Analytic Laboratory. Photons from all of the irradiated capsules are being measured directly. After several months, selected capsules will be dissolved in nitric acid to obtain aqueous solutions. Aliquots of the solutions will be used to obtain alpha spectra, and in isotopic-dilution mass spectroscopy. Gamma spectrometry is used to find both fission and capture reaction rates. Alpha and mass spectrometry provide information on capture rates. Each sample is being measured several times to maximize the reliability of the data. As the shorter lived nuclides decay away, there are fewer interferences with the remaining radionuclides. Data analysis is underway as this document is being written and is expected to continue for several years.

APPLICATIONS OF EXPERIMENTAL DATA

In addition to providing information of interest to designers of the next generation of advanced reactors, the measurements in EBR-II can be used directly to predict the reaction rates of the four nuclides that set the containment criteria for transuranic waste in spent nuclear fuel. Of all the actinides produced by capture reactions, only four minor actinides, ^{237}Np, ^{240}Pu, ^{241}Am, and ^{243}Am, are important in human exposure by the ingestion pathway.[6] Figure 2 presents the risk from fission products and actinides in spent fuel that produced 33,000 Megawatt-days of fission energy in a light water cooled and moderated reactor. After about 300 years, the risk from all of the fission products is less than that of the uranium that was mined to produce the initial charge of fuel in which that amount of waste was formed. After about 50 years, the risk of the actinides exceeds that of the fission products.

Note that the risk from actinides increases with decay time for about a century; this is a result of a serial decay chain. The ^{241}Am is produced by the decay of Pu which has a 14.4 year half-life.[7] Consequently, at decay times between 10 and 500 years, the activity of ^{241}Am increases because it is a long-lived daughter (half-life of 432.3 years) of a shorter lived parent.[7] The same effect is noted in the increase of ^{237}Np, the long-lived daughter (2.14×10^6 years) of ^{241}Am.[7] This serial decay chain keeps the risk from actinides above the uranium reference for times in excess of two million years.

If the four minor actinides shown in Figure 2 are separated from the fission products and recycled, they can produce useful energy and be eliminated from the waste stream. Such an approach reduces the severity of the confinement criteria for any repository for spent fuel. This method of waste management eliminates the most important of decay heat from spent fuel for post-irradiation cooling times of 100 years or more. There is concern over the impact of heat production on the engineered and geological barriers to the release of materials into the environment. In summary, separation and recycle of the actinides reduces the management of

spent fuel to a several hundred year concern from a problem involving time spans greater than that of recorded history.

DESIGN OF THE EXPERIMENT

Twelve high purity target materials have been selected to provide the information of most interest to the IFR Project. Rates of capture and fission are measured in milligram amounts of twelve targets that are in one of three forms: a metallic foil, a ceramic wire, or an oxide powder. Additional materials could have been selected, but each dosimetry package would be so large that the top and bottom targets would be in substantially different neutron spectra. Table I describes these targets; each is encapsulated in a welded high purity vanadium cylinder. Vanadium is the capsule material because no significant activation products are formed in this element that would interfere with measurements of photons emitted by the targets. Also, vanadium has excellent structural properties and is easily welded. Capsules were fabricated from three lots of 99.65% pure vanadium; the primary impurities (by weight) were 40 to 310 ppm of iron and 30 to 260 ppm of molybdenum.[8,9] None of the impurity elements are abundant enough to interfere with the measurements of target activities.

The masses of the individual targets were determined based on experience gained from previous spectrometry investigations in fast reactors.[10,11] If the masses are too small, there will not be enough activity for the desired precision in the measurements. If the masses are too large, there will be self-shielding effects during the irradiation, and impurities can contribute unacceptable levels of interference, especially in gamma-ray spectrometry. We assumed that the minimum decay time between the end of the irradiation in EBR-II and the analyses would be ten days. The actual minimum time of decay was slightly less than eight days.

Because of the difficulty encountered in handling metallic foils and the $^{241}AmO_2$ powder, a large (0.56 cm) diameter capsule was designed and built at ANL. After they are welded closed, the capsules contain about 0.65 grams of vanadium in addition to the target materials. Metallic and ceramic wires fit in a smaller diameter (0.13 cm) capsule. Masses of the smaller capsules depend on their length; they range from 0.022 to 0.052 grams. The two types of encapsulation are shown in Figure 3. Sets of 9 or 12 encapsulated targets are inserted into a stainless steel holder that fits inside of a standard EBR-II fuel pin for a 37-pin subassembly. Originally the design specified a standard 61 pin subassembly, but the fuel element diameter is too small to accommodate the larger diameter capsules.

Five light metals in the form of wires serve as threshold detectors for neutron capture reactions. Impurities are less than 0.25% by weight in the titanium and iron; the other three metal wires were at least 99.97% pure.[12] All unirradiated actinide targets were assayed by gamma spectroscopy to determine impurities. This technique provides an independent check on the ^{237}Np, ^{241}Am, and ^{243}Am masses in the capsules. The measured photons from ^{237}Np and ^{243}Am are actually from the decay of shorter-lived decay products in equilibrium with the target of

interest. The gamma emissions of the other actinides are too low for effective mass determination.

To assure that an appropriate range of spectra are measured, dosimeters are loaded into two subassemblies as shown in Figure 4. Both subassemblies contain 34 elements filled with binary fuel enriched to 67% in ^{235}U; dosimeters are in the other 3 positions in this 37 pin hexagonal array. The first exposure of 90 targets was made in a subassembly designated as X-502; it was placed in the center of the reactor at the 1A1 location. The second irradiation was conducted 11 days later; the same configuration of dosimeters, designated as X-503, was placed in the 6D3 location, near the core/blanket interface. Four axial locations have dosimetry in two of the elements; the third has the dosimeters only on the centerline as shown in Figure 5. Twelve targets are placed in the holders located on the axial centerline. Nine dosimeters are in the other three axial locations: the bottom of the fuel, the top of the fuel, and in the unfueled or plenum region above the core. Axial variations of neutron spectra are the greatest at locations away from the center of the reactor, so smaller packages are appropriate in those locations. Measurements at these 18 locations provide adequate data to cover a wide range of possible IFR designs.

The light metal threshold targets furnish information on the neutron populations above several reference energies; the cobalt activation also measures capture rates of low-energy neutrons. The two uranium and the ^{239}Pu measure fission and capture reaction rates for the most common fast reactor fuels. Years of operational experience give a high confidence in our ability to predict reaction rates in these three targets. These three well-known materials serve as references from which we can derive fission rates in the four minor actinides by simple ratios of activities of selected fission products. One of these, ^{237}Np, also serves as a threshold fission reference for neutrons with energies above about 0.2 MeV.[13] Another, ^{238}U, has a fission threshold of about 1.5 MeV.[13] The ^{235}U and ^{239}Pu are fissioned with neutrons of all energies. Combined with the determination of reaction rates in the four minor actinides, the other seven targets characterize the efficiency of the reactor for consuming heavy elements.

For both subassemblies, structural hardware was constructed from Type 304 stainless steel; this material is acceptable because of the short length of the irradiation. For extended exposures in EBR-II, other steels, such as HT-9 or D-9, less subject to fast neutron-induced swelling are needed. All dosimeter holders were separated with Type 304 rods to maintain their axial positions in the dosimetry pins that replaced three fueled pins in the standard 37 element driver subassembly. Dosimeter holders were filled with helium gas and placed within a sodium bonded clad tube to form the dosimeter element.

After the irradiation time of 6.88 days, X-502 and X-503 were removed from the reactor grid and allowed to cool for 4 days in the EBR-II spent fuel storage basket. The 34 fueled pins in Subassembly X-502 in the central core (1A1) position developed 913.5 KW of fission power 2933 grams of ^{235}U and 1140 grams of ^{238}U for a total burnup of 6.28 MW-days. Subassembly X-503 in position 6D3 produced 550 Kw for 6.88 days for a burnup of 4.77 MW-days in the

same mass of enriched uranium fuel. Contributions from fissions in the dosimeter materials were negligible.

Five criteria must be met before irradiated fuel can be transferred from the EBR-II tank into the Interbuilding Cask (IBC) for transfer into a hot cell. First, the total decay heat must be less than 1000 Watts. A dedicated cooling system supplies a flow of argon gas to remove decay heat whenever the fuel is not immersed in sodium. The second and third criteria are applied for argon cooling conditions: the maximum cladding temperature must be less than 1000 °F and the estimated time to clad failure must be less than 20 minutes. When the spent fuel subassembly is in the IBC, the fourth and fifth criteria apply: the maximum clad temperature must be less than 520 °F and the estimated time to clad failure must be greater than 20 minutes. It took four days cooling under sodium for both X-502 and X-503 to meet these criteria.

Each subassembly was then transferred in the IBC to the Fuel Cycle Facility where the sodium was washed from the cladding and hardware. After a thorough washing, the IBC was used to move the subassemblies to the Hot Fuel Examination Facility (HFEF), a hot cell where the three elements containing the dosimeters were removed from the rest of the subassembly. The nine dosimeter capsule holders were cut open remotely; each dosimeter capsule was placed in a plastic vial bearing an identification number. No additional examinations or tests were performed on the other 34 pins in the assembly. The vials were carried to the ANL Analytic Laboratory in a small shielded container.

As of this writing, gamma spectroscopy of the targets is underway. While the first count rate data were obtained in March, measurements are projected to continue for the rest of the year. Repeated measurements of the activated targets and standard calibration sources traceable to the National Institute of Standards and Technology are necessary to obtain the desired quantitative accuracy. Also, interferences from shorter-lived gamma emitters are reduced with cooling time. Fission rates are being determined by measurement of photons from the ^{106}Ru-^{106}Rh, ^{140}Ba-^{140}La, and ^{137}Cs-^{137m}Ba isobaric decay chains. Capsules and their contents are not scheduled to be dissolved for alpha isotopic-dilution mass spectrometry until 1995. This is acceptable because of the long half-lives of the actinides of interest. Alpha and mass spectrometry are used in determining capture rates in the actinide elements.

The first targets were counted about eight days after the end of the irradiation. Because of the delay between the last neutron-induced reactions and the analyses, the shortest-lived radionuclides of interest are ^{239}Np and ^{238}Np. Both have half-lives of about three days. Capture rates in the ^{238}U are found from the ^{239}Np activity. This is a key parameter because all of the long-lived minor actinides are formed from the ^{238}U placed in the reactor. The ^{238}Np measures the capture rates in the ^{237}Np, one of the minor actinides of interest in waste management. preliminary data indicate that the reaction rates that led to the formation of both of these short-lived actinides were successfully determined.

PREIRRADIATION ACTIVITIES

The design of the irradiation packages and the initial predictions of the consumption rates of the targets were completed in the first two years of this grant. An important element in the design of the experimental package was the prediction of actinide fission rates in the target dosimeters. Figure 6 shows the fraction fissioned of the four minor actinides of interest when placed in the energetic neutron spectrum of EBR-II. Because these nuclides would be recycled and combined with additional heavy elements, eventually an equilibrium concentration would be achieved in the fuel. Effects of the neutron spectra in metallic versus oxide fuels were quantified for the minor actinides early in the project. As an example of these studies is shown in Figure 7, a plot of the amount of ^{237}Np remaining in samples irradiated in an oxide fueled and in a metallic fueled reactor core about five years. The higher fission cross section associated with the more energetic neutron spectrum in the metal fuel accounts for most of the difference shown.

A significant problem was encountered when Oak Ridge National Laboratory (ORNL) was unable to supply the actinide targets. Procurement of the light metal wire presented no problem, but the unavailability of the five actinides nearly doomed this project. It took several years, but finally the actinides were located at both Argonne sites. The Engineering Physics Division had several unirradiated ^{240}Pu foils that were donated to the project; they were left over from some neutron measurements performed at the Zero Power Physics Reactor. Several grams of high-purity ^{237}Np metal were located in storage at ANL-East. There was no shortage of $^{241}AmO_2$, but it was all in the form of "scrap". A diligent search uncovered a 7.62 gram sample of ^{243}Am metal foil that had been declared as surplus. Of all the targets, the ^{243}Am is by far the most expensive and most difficult to obtain. The Laboratory-wide review of heavy element inventories also unearthed some ^{235}U, ^{238}U, ^{237}Np and ^{239}Pu ceramic wires already in vanadium capsules! When these targets were in hand, the pace of the project increased dramatically.

Many individuals were involved in this work since the inception of the project. While the staff of Argonne National Laboratory bore the responsibility of conducting the irradiation and the subsequent analysis of the data, Louisiana State University provided an experimental design that was essentially unchanged by Argonne. Table 2 provides a listing of the graduate and undergraduate students supported by this grant. Other students and faculty have benefitted from the cooperative efforts that were needed to accomplish the multitude of tasks required. The Principle Investigator continues to be involved with this project and other related activities at Argonne.

While current Department of Energy Policy has steered research toward other directions than the IFR, information garnered by this project will prove valuable to the management of actinide materials. Of specific concern are the weapons grade plutonium and enriched uranium stocks no longer needed for national defense applications. Also, the large inventory of actinides in spent fuel from power reactors will be a continuing problem. Actinide burning provides a technical option that could be pursued if nuclear energy policies change.

CONCLUSIONS

Irradiations of 180 dosimeters have been completed in the EBR-II to determine neutron reaction rates in the center of the core and at the core-blanket interface. These data will be used to increase confidence in analyses of various designs of the next generation of liquid metal-cooled fast reactors that use metallic forms of the actinides as fuel. Such reactors, termed IFRs, have the capability to consume the minor actinides If these four nuclides can be removed from the waste stream and recycled to reactors, design and licensing of repositories for spent nuclear fuel can be greatly simplified. Because of the metallic form of its fuel, IFRs can efficiently denature weapons reserve plutonium and uranium making them unusable for nuclear explosives. The experimental program provides direct measurement of the parameters needed to quantify the behavior of actinides in IFRs.

ACKNOWLEDGEMENTS

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Table I
Targets for Actinide Dosimetry Irradiation

Target Material	Target Form	Target Mass (mg)	Capsule Diameter	Target Function
Co	MW	19.8 - 20.6	S	Threshold Rates
Cu	MW	19.9 - 20.9	S	Threshold Rates
Fe	MW	16.6 - 18.3	S	Threshold Rates
Ni	MW	17.9 - 18.6	S	Threshold Rates
Ti	MW	9.7 - 10.4	S	Threshold Rates
^{235}U	CW	0.9 - 1.2	S	Fission Rates
^{235}U	MF	7.9 - 12.5	L	Fission Rates
^{238}U	MF	6.3 - 14.6	L	Consumption Rates
^{239}Pu	CW	1.0 - 1.3	S	Fission Rates
^{237}Np	CW	5.0 - 8.2	S	Consumption Rates
^{237}Np	MF	7.5 - 16.8	L	Consumption Rates
^{240}Pu	MF	7.4 - 12.1	L	Consumption Rates
^{241}Am	OP	7.6 - 24.7	L	Consumption Rates
^{243}Am	MF	6.6 - 12.7	L	Consumption Rates

Nomenclature: Target Form: MW - metal wire; CW - ceramic wire; MF - Metal Foil; OP - oxide powder. Capsule Diameter: S - small (0.13 cm); L - large (0.56 cm).

Table 2
Students Supported by the USDOE Grant

Graduate Assistants

Sami Aoud - MS in Nuclear Engineering - Now employed at the Louisiana Department of Environmental Quality, Radiation Protection Division - Thesis: "Consumption of Minor Actinides in the Integral Fast Reactor Fuel Cycle".

Pradeep Patra - MS in Nuclear Engineering - Now in LSU Medical Physics Program - Thesis: "Nuclear Criticality Safety Considerations in the Integral Fast Reactor Fuel Cycle Facility.

Nafiz Ahmed - MS in Engineering Science - Now employed at a software firm in Dallas, TX - Project Report: "Radiation Shielding of a Hot Repair Facility".

Roy Hensley - MS in Electrical Engineering with a minor in Nuclear Engineering - Summer 1992 Assignee at ANL-W in the EBR-II Controls Engineering Section.

Ravi Errguntla - MS in Nuclear Engineering - Now in Doctoral program in Electrical Engineering - Thesis: "Neutron Transport and Thermalization Outside of Pressure Vessels".

Rahman Tashakkori - MS in Nuclear Engineering - Now in the engineering interdisciplinary doctoral program at LSU - Thesis: "Comparison of Pointwise and Group Averaged Cross-Sections in Calculating Neutron Spectra".

Harish Manohara - MS in Nuclear Engineering - Now in the engineering interdisciplinary doctoral program at LSU - Thesis: "Neutron Transport Analysis of Reactor Cores".

Syed Ali - Left the University - Location Unknown.

Venkate Nandimandalam - Left the University - Location Unknown.

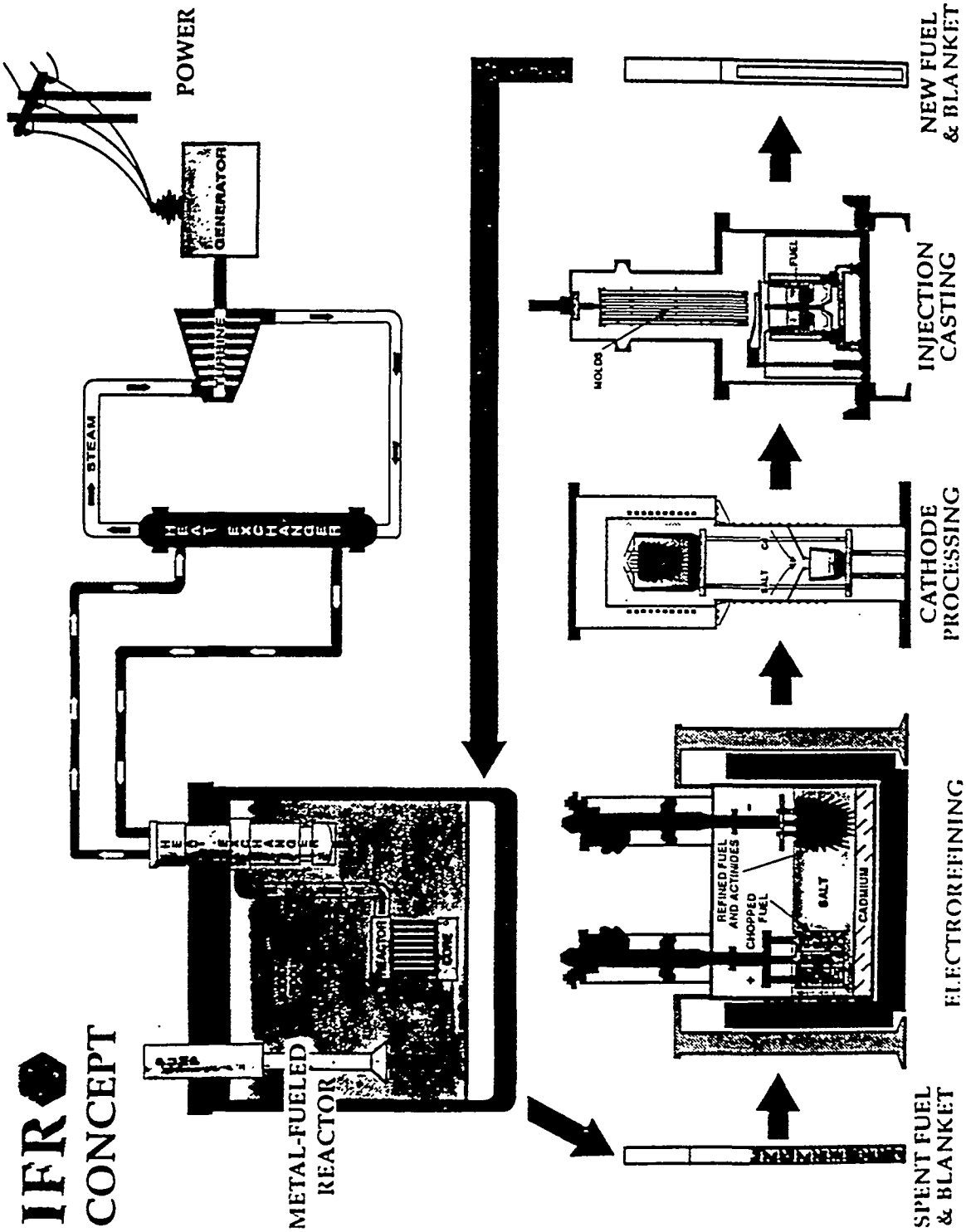
Undergraduate Assistants

Clifford Russell - Magna Cum Laude Graduate of LSU in Mechanical Engineering, MS in Nuclear Engineering from Texas A&M - Three summers at ANL-W as an Integral Fast Reactor Fellow - Now employed at the Louisiana Department of Environmental Quality, Radiation Protection Division.

Steven Harmon - Junior in Mechanical Engineering.

Susan Dodson - Received BS in Psychology from LSU in May 1994.

Figure 1


IFR
CONCEPT
METAL-FUELED
REACTOR
HEAT EXCHANGER
STEAM
TURBINE
GENERATOR
POWER
SPENT FUEL
& BLANKET
ELECTROREFINING
REFINED FUEL
AND ACTINIDES
CHOPPED
FUEL
SALT
CADMIUM
CATHODE
PROCESSING
INJECTION
CASTING
MOLDS
FUEL
NEW FUEL
& BLANKET

Time Dependence of Risk from Stored Spent Fuel

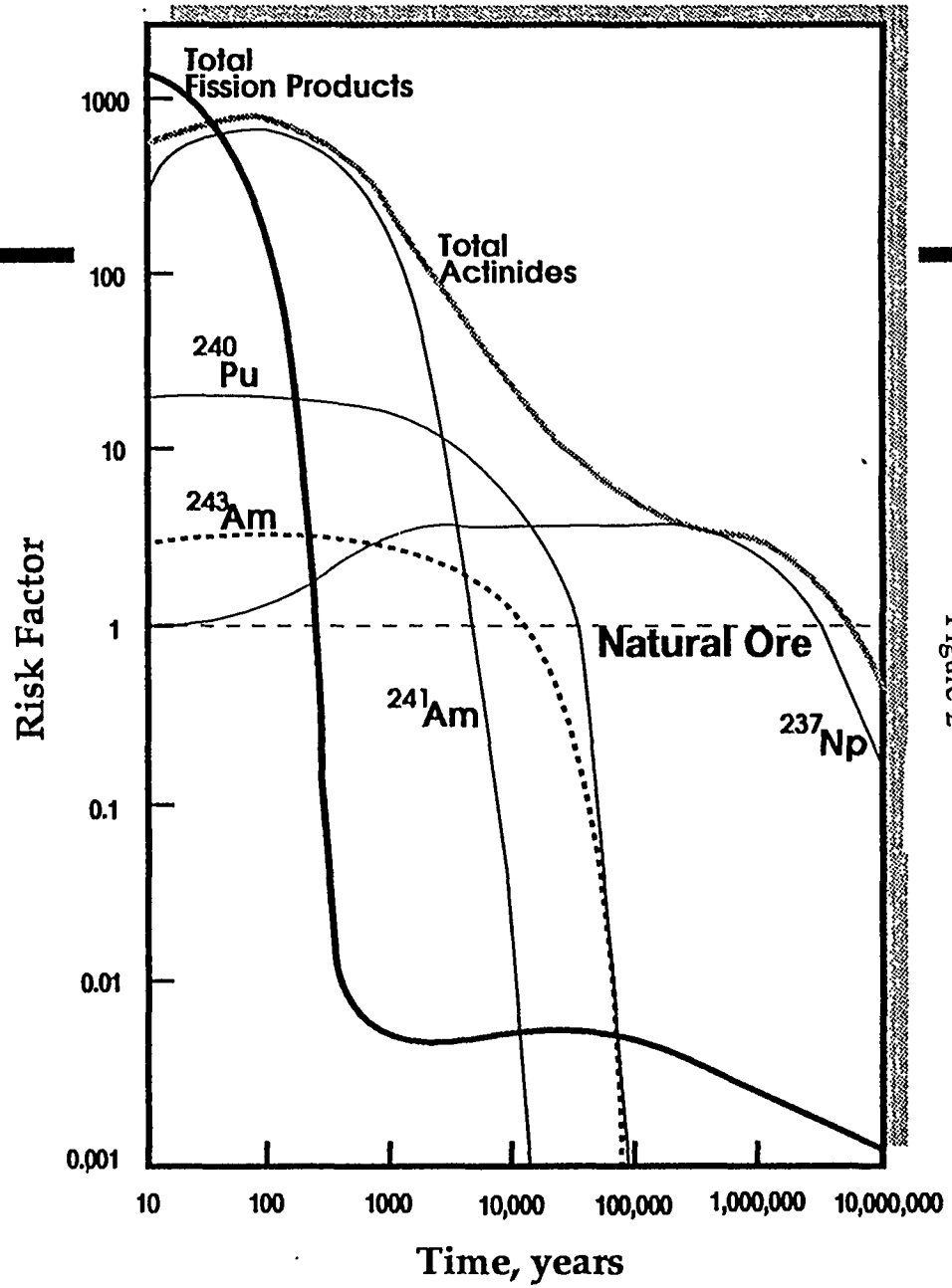
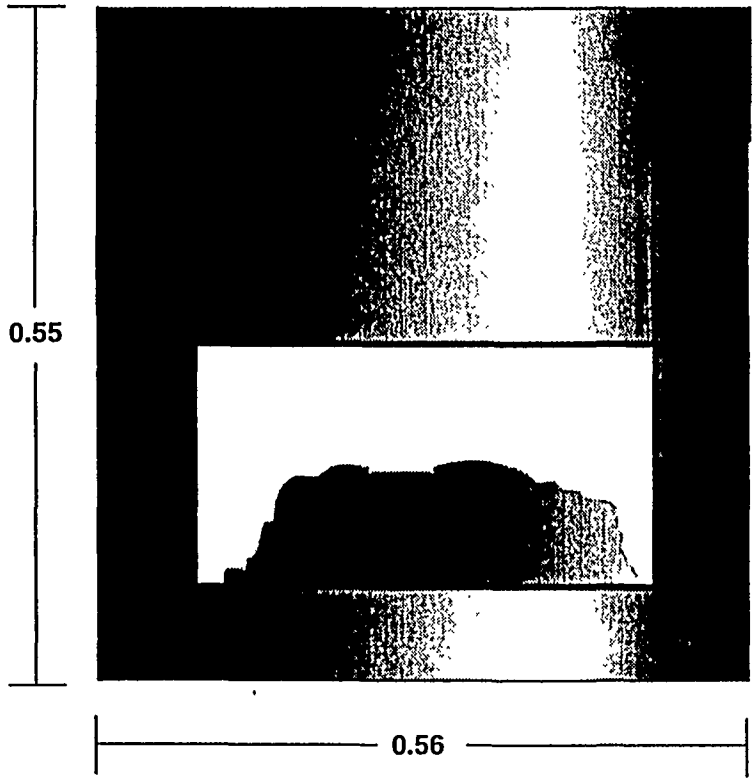


Figure 2

Targets in Vanadium Capsules

All ^{238}U, ^{240}Pu, ^{241}Am, and ^{243}Am, some ^{235}U and ^{237}Np

All Co, Cu, Fe, Ni, Ti, and ^{239}Pu some ^{235}U and ^{237}Np



Dimensions in centimeters

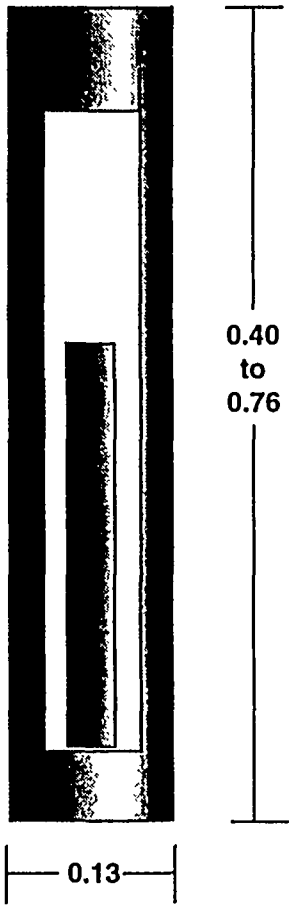
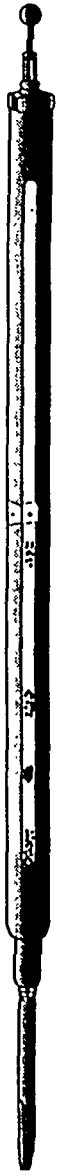
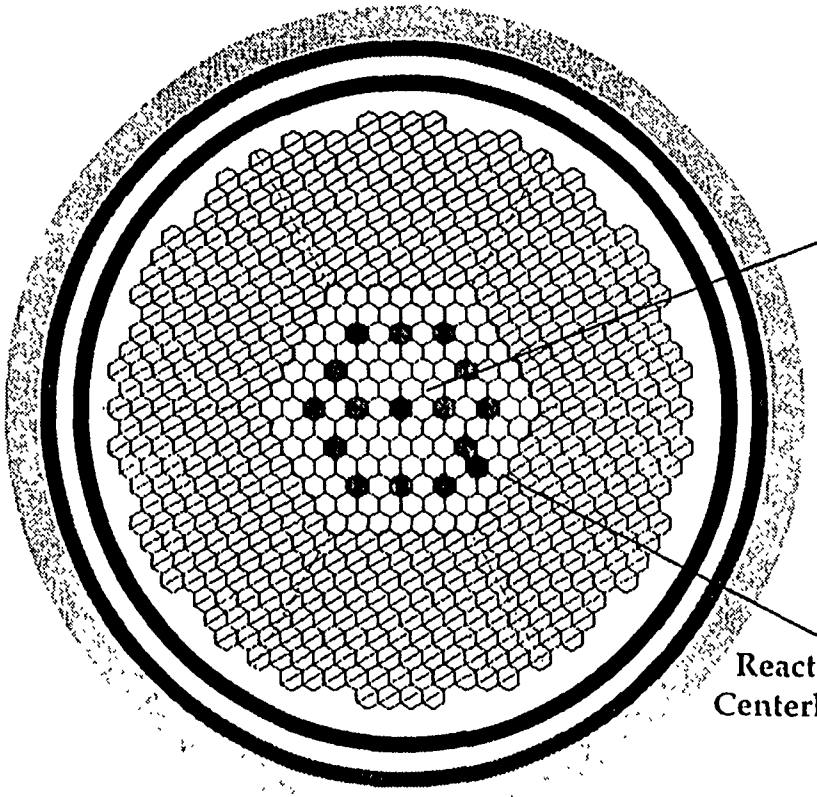


Figure 3

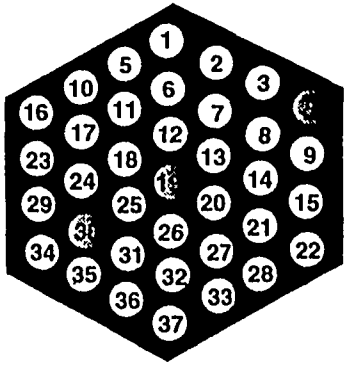
Irradiation Positions in EBR-II

Driver Subassembly 34 Binary Fuel Elements & 3 Dosimetry Elements

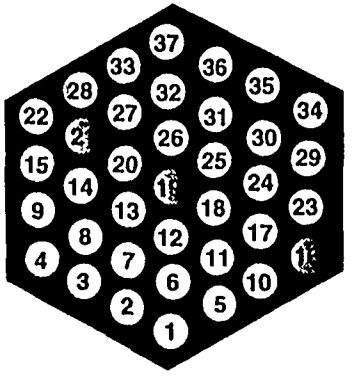




Subassemblies



X-502 in 1A1



X-503 in 6D3

Figure 4

Target Configuration for Dosimetry Run

Rows are in Central S/A (1A1) and Row 6 S/A (6D3) of EBR-II

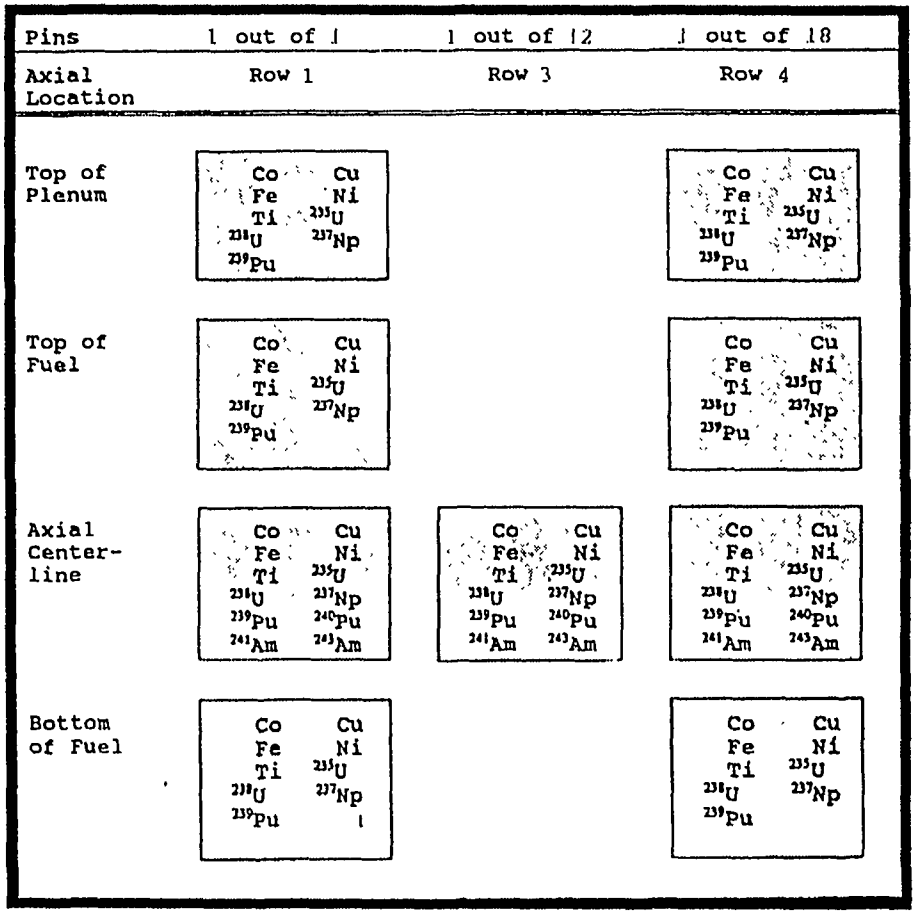


Figure 5

Fission of Actinide Target

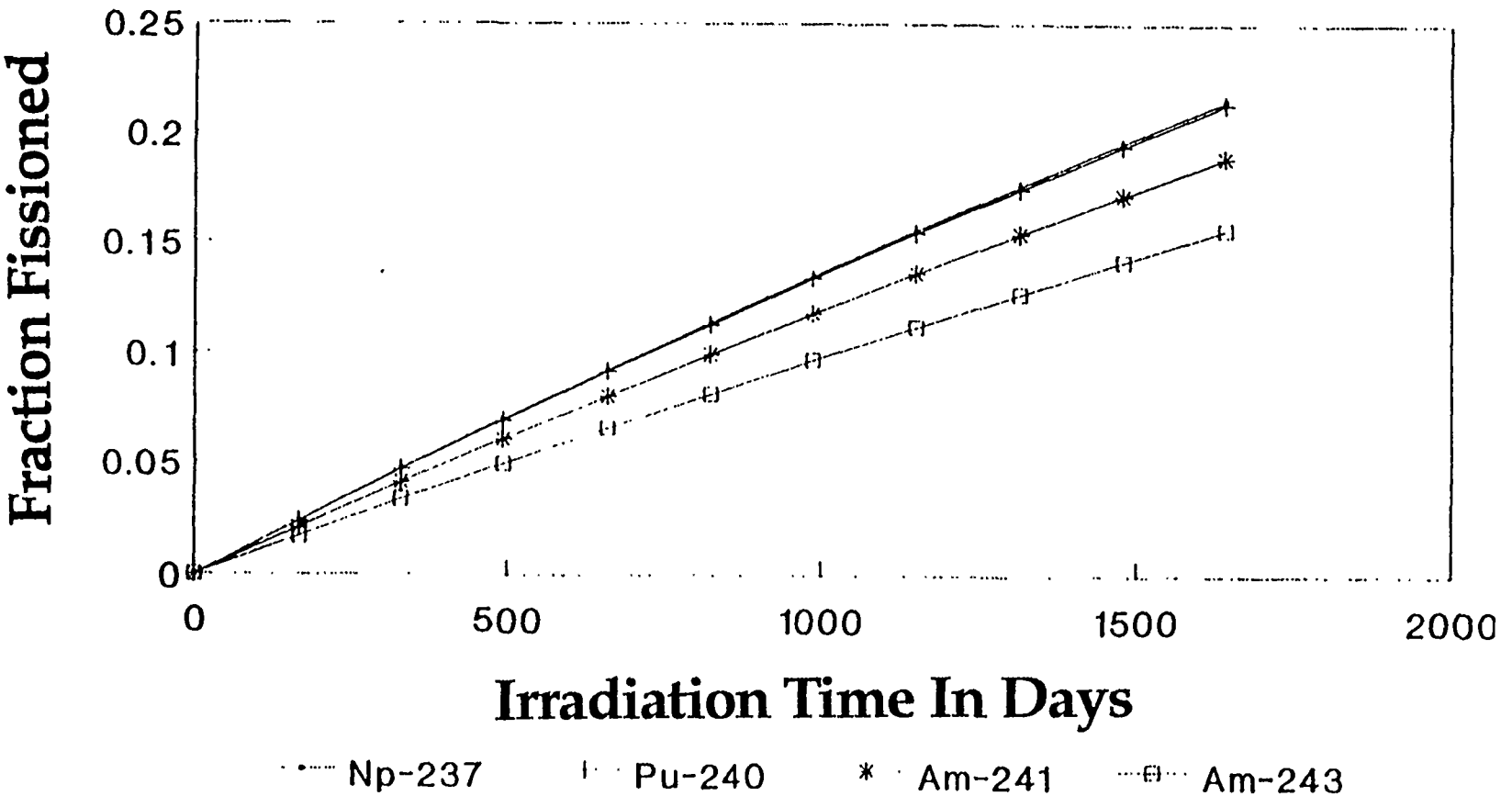


Figure 6

Burnup Comparison for Np-237

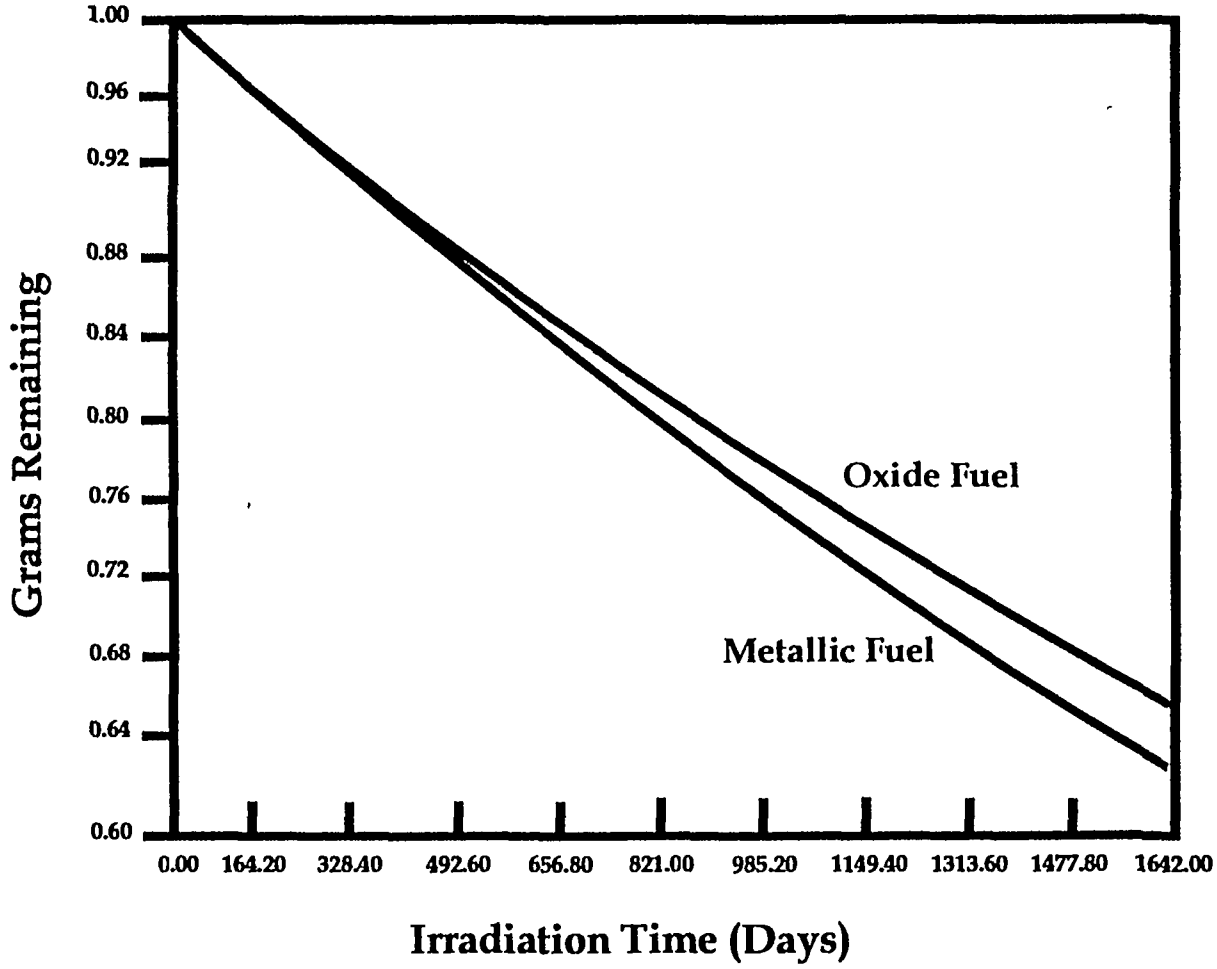


Figure 7