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PROPOSED DRAFT PAPER:

LIGHT WATER REACTOR

WITH A DENATURED THORIUM FUEL CYCLE

DRAFT

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LIGHT WATER REACTOR WITH A DENATURED THORIUM FUEL CYCLE

INTRODUCTION

The International Fuel Cycle Evaluation (INFCE) is directed toward the identification of nuclear fuel cycle options which pose inherently low risk of nuclear weapons proliferation while retaining the major benefits of nuclear energy. In order to limit the availability of nuclear materials from which weapons can be constructed, it is desirable to fuel the reactors located throughout the world with nuclear fuels which are inherently unsuitable for use in weapons. At the same time, it is recognized that the benefits of nuclear power are limited by the size of the uranium resource base and by the efficiency with which that base can be utilized.

A great majority of nuclear power stations, either in operation or planned worldwide, are light-water reactors (LWRs) of either the pressurized-water reactor (PWR) or the boiling-water (BWR) variety. Sixty-six such light water reactors are currently in operation in the United States and an additional 128 are under construction or planned; a similar number of light-water reactors are in operation, under construction, or planned in other nations. Consequently, it is clear that if uranium demand is to be significantly reduced in the near and intermediate time span, the uranium utilization efficiency of the light-water reactor must be improved.

One alternative for improving the resource utilization of the LWR, that of the improved once-through uranium fuel cycle, is addressed in a companion paper. This paper addresses the use of the denatured thorium fuel cycle in the pressurized-water reactor, and is being presented at this time to provide preliminary technical and economic data to INFCE for use in early comparisons

of alternate nuclear systems. Since programs to develop the denatured thorium fuel cycle for the light-water reactor are ongoing, the information presented in this report is preliminary and will be updated in the future as available.

Discussed in this paper is the performance of denatured thorium fuel cycles in PWR plants of conventional design, such as those currently in operation or under construction. Although some improvement in U_3O_8 utilization is anticipated in PWRs optimized explicitly for the denatured thorium fuel cycle, this paper is limited to a discussion of the performance of denatured thorium fuels in conventional PWRs and consequently the data presented is representative of the use of thorium fuel in existing PWRs or those presently under construction. In subsequent sections of this paper, the design of the PWR, its performance on the denatured thorium fuel cycle, safety, accident and environmental considerations, and technological status and R&D requirements are discussed.

I. SYSTEM DESIGN AND PERFORMANCE DATA

The light-water reactor operating on the denatured thorium fuel cycle described in this report employs a nuclear steam supply system and balance of plant design which is identical to that of LWRs currently in operation and under construction throughout the world. An unmodified reactor plant design was utilized since preliminary evaluations indicate the suitability of such designs for thorium fueling[1]. The reactor design which was used to generate the fuel cycle data discussed in this report is the PWR; however, similar performance could be achieved in other LWR designs.

In arriving at the decision to utilize an unmodified nuclear steam supply system as the reference LWR design, modifications to such parameters as lattice pitch, fuel rod diameter, and fuel density were briefly considered. Although this evaluation indicated that some improvements in resource utilization and/or fuel cycle cost economics could be obtained with these design modifications, the improvements which can be readily realized are relatively small. Furthermore, the incorporation of such modifications would necessitate changes in reactor design, delaying the date denatured thorium fueling could be initiated. Consequently, the use of an unmodified NSSS was elected in order to evaluate an option which might be realized in a relatively short time span -- one applicable to existing PWR plants or those under construction. In the longer term, however, modifications to system design might be considered to realize further reductions in uranium ore requirements.

General reactor performance specifications are summarized in Table I-1. The plant has a core thermal power of 3800 Mwt and a net electrical power

output of 1260 MW(e). The reactor arrangement and fuel assembly design are illustrated in Figure I-1. The reactor core is fueled with 241 assemblies, each of which contains 236 fuel rods having an active length of 150 inches. As shown in Figure I-1, each assembly contains five guide tubes located in the otherwise regular array of fuel rods; the outer four of these guide tubes serve as thimbles for control rods, while the center guide tube is available for in-core instrumentation. The vertical arrangement of the reactor is shown in Figure I-2. The fuel consists of slightly-enriched uranium-oxide fuel pellets encapsulated in zircaloy-4 clad having an outside diameter of 9.73 mm and a cladding wall thickness of 0.635 mm.

PWRs are typically operated until the depletion of fissile materials and the buildup of parasitic fission product poisons will no longer support the neutron chain reaction; at this point, the most highly irradiated fuel is discharged and replaced with fresh fuel assemblies. Soluble boron poison additions to the coolant and burnable poison lattice shims are provided to control core reactivity between refueling intervals. Control rods, inserted within the fuel assemblies, are also utilized to provide slight reactivity adjustments between changes in coolant soluble boron concentration. These control rods are also utilized to rapidly insert negative reactivity upon reactor trip.

The balance of plant is completely conventional in nature, and several different balance of plant designs are employed, depending upon the architectural engineering firm responsible for plant construction.

II. FUEL MANAGEMENT AND HANDLING INFORMATION

Two denatured thorium fuel cycles are discussed in this paper: the U-235 enriched (U-235/Th cycle) and the U-233 enriched (U-233/Th cycle) fuel cycles. In the U-235/thorium fuel cycle, U-235, extracted from natural uranium by isotopic enrichment facilities, is utilized to supplement recycle fissile uranium recovered from the spent fuel of previous cycles of operation. In this fuel cycle, the core is initially comprised of thorium fuel enriched with uranium containing 20 w/o U-235. Beginning in the fourth cycle of operation, uranium (containing U-235, U-233, and small quantities of other uranium isotopes) is recycled to reduce the requirements for U-235.

Since the fissile content of this recycle material is less than that required to acheive the specified cycle length (because of the depletion of fissile material during the prior cycle of irradiation), U-235 must be added. There are several options for adding the required quantities of U-235. One option is to add denatured uranium (20 w/o U-235 in uranium) in sufficient quantities to increase the fissile content to that required to achieve the specified cycle length. This option has the advantage that only denatured makeup uranium is required. However, because of the U-238 present in the denatured uranium makeup, the total U-238 content will increase and the thorium content will decrease from recycle pass to recycle pass; as a result, increasing large quantities of plutonium would be generated at the expense of diminished U-233 production. A second option would be to "top" the recycle fuel with highly enriched uranium to provide the additional U-235 requirements; depending on the particular cycle, uranium enriched to 60-85% U-235 would be employed so as to provide the required U-235

while limiting the total fissile uranium content to a denatured level. This option has the disadvantage of requiring highly enriched uranium but avoids the dilution of the recycle uranium with excess quantities of U-238 with the concomitant increase in plutonium production and reduction in U-233 production. A somewhat similar third option is to use fully enriched (93 w/o U-235) uranium to "top" the recycle material. Such highly enriched material is added until the enrichment limit for denatured uranium is reached. The topped recycle uranium is then mixed with thorium in such proportions as required to achieve the specified cycle length; the remaining fuel consists of 20 w/o U-235 uranium mixed with thorium (fresh denatured fuel). This alternative has both the advantages and disadvantage of the previous option, but it has the additional advantage of slightly lower fabrication costs since the more costly to fabricate recycle fuel is concentrated into a fewer number of fuel rods. This last option was assumed in developing the fuel management information discussed in subsequent sections of this paper.

The U-233/thorium cycle is similar, except that U-233 is utilized in place of U-235 to provide the initial and makeup fissile inventories. Since U-233 is not found in nature, it must be created by irradiating thorium bearing fuels. U-233 can be created, for example, by utilizing thorium fuel enriched with plutonium in converter reactors (LWR, HWR, etc.) or by thorium blanketed LMFBRs. The design of reactors to produce U-233 is not discussed in this paper; rather, it is assumed that U-233 is obtained from a stockpile produced by one of the previous mentioned options.

Figure II-1 provides a schematic diagram of the facilities required for the U-235/Th and U-233/Th fuel cycles; also shown in this figure are the

equilibrium cycle mass flows. Both fuel cycles require a modified form of Thorex reprocessing in order to recover fissile uranium for recycle. Because of the U-238 present in denatured thorium fuels, plutonium will be produced and recovered during reprocessing. This plutonium may be stored for future use, as shown in the figure, or alternately utilized in transmuter reactors (such as the Pu/Th fueled PWR or thorium-blanketed LMFBRs) to produce additional quantities of U-233. Both fuel cycles also require the fabrication of U-233-bearing fuels; these fabrication facilities must be remotely operated and maintained because of the presence of U-232 which is produced in trace quantities in thorium-bearing fuels and whose decay products emit a series of penetrating gamma rays during decay. In the U-235/Th cycle, an isotopic enrichment facility is required to produce the U-235 necessary for the initial core and to replace the fissile material consumed during each cycle of operation. This enrichment plant might be incorporated within the confines of the secured energy center in order to avoid shipping the highly-enriched uranium utilized to re-enrich recycled fuels. In the case of the U-233/Th fuel cycle, a source of U-233 is required to provide the fissile material necessary for initial core and makeup loadings.

Fuel management information for both the U-235/Th and U-233/Th cycles are summarized in Tables II-1 and II-2. Fuel cycle information presented in these tables is based upon a fuel management scheme similar to that currently employed in PWRs in which one-third of the core is replaced at annual refueling intervals. The U_3O_8 and separative work requirements tabulated in Table II-1 assumed that plutonium has been stored for future use, i.e., no credit has been taken for plutonium production.

III. TECHNOLOGICAL STATUS AND R&D REQUIREMENTS

As discussed in Section I, the PWR nuclear steam supply system and balance of plant are identical to those already in commercial operation with uranium fueling in the U.S. and in many nations of the world. Consequently, no basic reactor development R&D is required.

However, the technology for the utilization of thorium-bearing fuels and for the recycle of U-233 is much less well developed than is the technology of the uranium fuel cycle. The use of the denatured thorium fuel cycle will therefore necessitate significant R&D effort in the areas of fuel fabrication, reprocessing, and for reactor-related data base and verification-type development.

The fabrication of U-233-bearing fuels is significantly different from the fabrication of uranium- or plutonium-bearing fuels due to the radioactivity resulting from trace quantities of U-232 which is produced along with the fissile material U-233 from thorium fuels. Since the decay of U-232 leads to daughter products which emit highly energetic gamma rays, the fabrication of U-233-bearing fuels necessitates remote operations and shielded facilities. Although such remote and shielded facilities are easy to visualize conceptually, the fabrication process is complex and such facilities have yet to be engineered for reactor-grade U-233. One significant problem which must be addressed is the maintenance of such remote equipment; equipment must be quickly maintainable to avoid long downtimes for repair which would compromise the economics of the fabrication process. Because of the complexity of the pelletization process, it may be desirable to fabricate U-233-bearing fuels using VIPAC or SPHEREPAC technologies--technologies which appear more amenable

to remote operations. The use of VIPAC or SPHEREPAC fabrication would, of course, necessitate additional R&D for process development and also for in-reactor performance qualifications, since neither of these alternate fabrication technologies is employed for the manufacture of commerical-grade fuels.

The denatured thorium fuel cycle also introduces significant new requirements for fuel reprocessing and waste treatment R&D. Reprocessing of thorium-based fuels is based upon the Thorex process. Although this process has been demonstrated for lower radiation exposure fuel, it is much less developed than the Purex process utilized for reprocessing uranium-based fuels. Since spent denatured thorium fuels will contain significant quantities of plutonium, as well as uranium and thorium, a modified version of the Thorex process will have to be developed and tested. Reprocessing of the thorium-based fuels is also complicated by the fact that, unlike urania, thoria dissolves very slowly in nitric acid unless fluoride ion is present. The introduction of fluoride complicates the treatment of waste from the fuel-dissolving process, and will necessitate additional R&D in this area. The fluoride ion also complexes with the zirconium cladding so that thoria dissolution is severely retarded unless excess fluoride is added (which would severely increase equipment corrosion). A more acceptable approach may be to remove the cladding before dissolving the thoria by some chemical or mechanical method. Here again, additional R&D will be required both to develop the dissolution process itself and for the treatment of waste which results from this process.

Although there has been some experience with the irradiation of thorium-based fuels in LWRs, additional R&D will also be required in this area. The major

areas requiring R&D consist of data-base development and fuel performance qualification. This R&D is necessary to ensure that fuel performance meets licensing requirements, and to develop the information required for licensing thorium-fueled cores. Such information as in-reactor densification and swelling behavior, fission gas release, thermal conductivity of the fuel, pellet cladding interaction, and coefficients of reactivity must be established. Subsequent R&D would consist of in-pile irradiation demonstrations where significant quantities of thorium-based fuels, fabricated with processes and equipment representative of commercial fabrication technology, would be irradiated to provide a demonstration of in-reactor fuel performance.

The cost of the R&D program designed to implement the denatured thorium fuel cycle in LWRs has been estimated in Reference 2. The estimated R&D costs for reprocessing, refabrication, waste treatment, and fuel qualification development are about one billion dollars. In addition, the cost for the design, construction, and operation of demonstration fabrication and reprocessing facilities has been estimated to be about $500 million in capital outlays and $300 million in operating expenses. The R&D program is estimated to require about 14 years to complete (1992 completion), while the reprocessing demonstration facility could begin operation in about the year 2000, assuming that design and construction were initiated in 1989.

IV. SAFETY AND ACCIDENT CONSIDERATIONS

Since the reactor plant employed in this evaluation of the denatured thorium fuel cycles is identical to plants currently in operation, it can be readily

concluded that the concept is fundamentally licensable from a reactor safety viewpoint. However, although preliminary evaluations of the characteristics of thorium-bearing cores indicate that the response during postulated accidents is satisfactory,[1] the physical properties of thorium-bearing fuels and core properties (such as the coefficients of reactivity and control rod worth) are somewhat different from those of UO_2-fueled cores, and consequently, a thorough reevaluation of the performance of the thorium fueled LWR for anticipated operational occurrence and other postulated accidents will be necessary. Consequently, it will be necessary to reanalyze the range of events typically reported in the Safety Analysis Report to demonstrate that the safety performance of the thorium-fueled LWR falls within the criteria established for uranium-fueled operation.

V. ECONOMIC INFORMATION

A. Capital Cost

As noted previously, the reactor plant which has been utilized for the evaluation of the denatured thorium fuel cycle consists of an unmodified conventional PWR; consequently, capital costs are identical to those of the PWR. Capital cost information for the conventional PWR, based on that reported in Reference 3 (NUREG-0241), is provided in Table V-1. The NUREG-0241 individual accounts were escalated from July 1976 price data for which they were developed to January 1978, using an 8%/yr escalation rate. The resulting values were then scaled from a PWR of 1139 Mw(e) to a PWR of 1260 Mw(e) using a 0.7 exponential scaling factor. The resulting total capital cost is $541/kwe. As noted in the discussion of capital cost ground rules discussed below, this cost of $541/kwe

excludes interest during construction, escalation during construction, contingency allowance, and owner's cost. The contingency allowance has been excluded since it is assumed that the unit is one of an established standard plant design. In order to establish power costs, interest during construction must be added to the base capital cost of $541/kwe. Interest during construction will vary depending upon the length of time required for construction, the schedule of payments during this period, and the cost of money (interest). Using the 10-year total construction period and schedule of payments of Reference 4 and a 4.525% cost of money (deflated effective interest rate) results in an interest during construction cost of 21% of the base capital cost, or a total capital cost of $655/kwe in January 1978 U.S. Dollars. This value is utilized to establish the capital cost contribution to the total power costs discussed in Section V-C. The capital cost of the plant delivered at some future date will, of course, be higher when viewed in terms of the then current dollars because of escalation. For example, the cost of a plant for 1990 operation would be about $1474/kwe in 1990 dollars assuming an 8% escalation rate; however, a 1990 dollar would be worth only about 0.40 1978 dollars if there were an 8% inflation rate.

Included in these capital costs are the following:

1. A full complement of current local licensing and design criteria, based upon U.S. Safety classifications, seismic classifications, and design codes.

2. A single unit on a typical new site with sufficient land area to accommodate a second unit.

3. Mechanical draft evaporative cooling towers are utilized for the main heat rejection system.

4. On-site fuel storage capacity for four-fifths of the total core loading.

5. A design lifetime of 30 years of base-loaded operation.

Items which are not included in the plant capital costs are summarized below.

Items Excluded From Capital Cost Estimates

1. Main transformer, switchyard, and transmission facility costs

2. Owner's costs, including consultants, site selection, spare parts, etc.

3. Off-site waste disposal costs

4. Nuclear liability insurance

5. Initial fuel loading

6. Interest during construction

7. Escalation during construction

8. Contingency allowance

B. Operating and Maintenance Costs

A detailed estimate of the O&M costs has not been made. However, since the reactor plant is comprised of a conventional PWR, and since annual refueling is maintained, O&M costs should be comparable to those of the conventional PWR cycle. O&M costs of 0.83* mills/kw-hr (in January 1978 dollars), quoted in Reference 4 for the uranium-fueled PWR, were consequently employed.

C. Fuel Cycle and Power Costs

Economic parameters which have been utilized in the calculation of fuel cycle costs are tabulated in Table V-2. The fabrication and reprocessing costs shown in this table are those estimated in Reference 4 to be characteristic of an established and mature fuel cycle service industry, i.e., they are estimated long term costs. The resulting fuel cycle and power costs for the U-235/Th fuel cycle are given in Table V-3, where fuel cycle and power costs for the standard PWR operating on the once-through uranium fuel cycle are also given for comparison. The components which comprise the total fuel cycle cost are also shown in this table to facilitate adjustment to other economic cost parameters. As the table illustrates, reduced U_3O_8 requirements contribute to reducing fuel cycle costs compared to the conventional uranium-fueled PWR, while increased carrying charges (because of the higher fissile

*The 0.83 mills/kw-hr O&M cost is recognized to be low based on recent experience, but is used herein to represent a long-term steady state. Actual O&M costs in the U.S. for 1976 were 2.3 mills/kw-hr. This rather high O&M cost resulted from the unsatisfactory operation of several units (when the worst 10 units are excluded, the O&M cost was 1.2 mills/kw-hr).

loading of thorium systems) and the cost of fabrication and reprocessing contribute to increasing the fuel cycle cost with respect to the once-through uranium cycle. Since denatured thorium fuels have as yet not been fabricated or reprocessed commercially, the costs for these services are highly uncertain, and result in a significant uncertainty in the overall fuel cycle cost. Also shown in Table V-3 is the approximate credit for the use of plutonium rather than its long term storage. The value of plutonium will, of course, depend on the reactor in which it is used; the values given in this table are approximate worth of plutonium in the LWR evaluated under the economic ground rules of Table V-2.

Estimates of the fuel cycle cost for the U-233/Th fuel cycle are given in Table V-4. Since this fuel cycle requires an exogenous source of U-233, fuel cycle costs will depend upon the price for which U-233 can be purchased. Consequently, fuel cycle costs have been tabulated for several U-233 prices in Table V-4. Comparing the fuel cycle costs of Table V-4 with those of the once-through uranium and U-235/Th cycles (Table V-3) indicates that, if U_3O_8 costs 40 \$/lb, U-233 fueling is more economical than the once-through uranium or U-235/Th cycle if U-233 costs less than 18 or 34 \$/gm, respectively. If U_3O_8 costs 100 \$/lb, the U-233 indifference value becomes 53 and 60 \$/gm for the once-through uranium and U-235/Th cycles, respectively.

VI. ENVIRONMENTAL INFORMATION

The most significant area of potential environmental impact associated with the use of the denatured thorium fuel cycle is in reprocessing. As noted previously, the question of wastes from the Thorex process, particularly if complicated by the presence of zirconium cladding, has yet to be fully addressed. Recycled thorium fuels also pose a significant radiological hazard because of the substantial quantities of U-232 present in the fuel, the daughters of which emit fairly high energy gamma rays. This activity will require increased shielding for fresh fuel handling and/or revised fuel handling procedures to minimize the occupational exposure of plant personnel. The increased activity of thorium fuels has a much greater impact, however, on the fuel fabrication industry and, as a consequence, results in significantly higher fabrication costs for denatured U-233/Th fuel than for uranium fuel. Other than the potential for increased occupational exposures due to handling of fresh recycled fuels, no significant environmental impact is anticipated at the reactor plant site.

On the positive side, the use of the denatured thorium fuel cycle reduces the requirements for U_3O_8. The impact of reduced uranium mining is generally thought to be more significant than the attendant environmental effects associated with reprocessing or of the smaller thorium mining industry which would be required.

REFERENCES

1. EPRI NP-359, "Assessment of Thorium Fuel Cycles," February 1977.

2. ORNL-5388, "Interim Assessment of the Denatured U-233 Fuel Cycle: Feasibility and Nonproliferation Characteristics (3-13-78 Draft).

3. "Capital Cost: Pressurized Water Reactor Plant," NUREG-0241, June 1977.

4. D. R. Haffner et. al., "An Evaluation Uniform Data Base for Use in Nuclear Energy System Studies," Hanford Engineering Development Laboratory, October 18, 1977.

TABLE I-1

General Reactor Performance Specifications

A. Power Plant Performance		
Core Thermal Power (MW)	3800	
Electrical Power (MW)		
Gross	1344	
Net	1270	
Thermal Efficiency (%)	33.4	
B. Reactor Parameters		
Core Volume (liters)	40,050	
Equivalent Core Diameter (m)	3.66	
Core Height (m)	3.81	
Core Power Density (MW/ℓ)	0.095	
Coolant Flow Rate (Mg/Sec)	20.66	
Coolant Inlet Temperature (^{o}C)	296	
Coolant Outlet Temperature (^{o}C)	327	
Primary System Pressure (PSIA)	2250	
C. Fuel Parameters		
Average Fuel Temperature (^{o}C)	688	
Maximum Fuel Temperature (^{o}C)	1882	
Cladding Temperature (^{o}C)	342	
Core Fuel Loading, Initial Core (kg)	U-235/Th	U-233/Th
Total Heavy Metal	93,543	93,558
Fissile Material	3,299	2,429
Discharge Exposure (MWD/MG)		
Average	33,400	33,400
Peak	55,000	55,000

TABLE II-1

Fuel Management Information

	Denatured U-235/Th Cycle	Denatured U-233/Th Cycle
Average Capacity Factor, %	75	75
Fraction of Core Replaced/Refueling	0.33	0.33
Refueling Interval, yrs.	1	1
Fuel Composition	See Table II-2	
Fissile Fabrication Loss Fraction	.015	.015
U_3O_8 Requirements (ST/GWe)[1,2]		
Initial Core	666	NA
Annual Equilibrium Reload	112	NA
30-Year Cumulative	4177	NA
30-Year Consumptive(3)	3623	NA
Separative Work Requirements (10^3 SWU/GWe)[1,2]		
Initial Core	604	NA
Annual Equilibrium Reload	107	NA
30-Year Cumulative	4002	NA
30-Year Consumptive	3505	NA
U-233 Requirements (kg HM/GWe)		
Initial Core	NA	1904
Annual Equilibrium Reload (Makeup)	NA	316
30-Year Cumulative (Makeup)	NA	11,795
30-Year Consumptive (Net)		10,207
ThO_2 Requirements (MT/GWe)		
Initial Core	78.9	57.9
Annual Equilibrium Reload	23.7	17.4
30-Year Cumulative	780.0	573.3
Uranium Tails (MT HM/GWe)		
Initial Core	NA	17.6
Annual Equilibrium Reload	NA	0.5
30-Year Cumulative	NA	46.0
Plutonium in Spent Fuel		
Annual Equilibrium Discharge $Pu^{fissile}$ (kg HM/GWe)	64	70
30-Year Cumulative Discharge $Pu^{fissile}$ (kg HM/GWe)	1819	1929

1. Tails composition 0.2 w/o
2. Assumes Pu is stored
3. 30-year cumulative requirement less inventory (in-core and ex-core) at the end of 30 years of operation. The 30-year consumptive requirements are the appropriate lifetime time requirements for units added to replace reactors which have reached their assumed 30-year life.

Table II - 2(a)

Reactor Fresh and Spent Fuel Characterization

TYPE (General Description) U-235/Th Cycle: Denatured U-235 in ThO_2 (makeup fuel)

Refueling Method: On-line ___; Batch X ; (Refueling frequency annual)

Fuel Assembly Characteristics: (where applicable)

a) type: Oxide ✓; Metal ___; Carbide ___;

b) weight: 650 kg

c) length: 4.3 m

d) core load: 7391 mass (kg HM): (Eq. Cycle)

e) annual reload: 2464 mass (kg HM): (Eq Cycle)

Design burnup: 33,400 (MWd/MT) discharge batch average

Discharge fuel radiation level: _____ r/hour @ 1 meter (also provide a curve of radiation level versus cooling time following discharge) NA

Discharge fuel energy generation rate as a function of cooling time. W/hr/element) - provide curve. NA

Heavy Element Isotopic Content (kg/fuel element) at discharge

ISOTOPE	Fresh Fuel Element		Discharged Fuel Element	
	initial	equilibrium	initial	equilibrium
Th-232	319.7	303.9	314.7	296.3
U-232	-	-	0.01	0.02
U-233	-	-	3.39	4.27
U-234	-	-	0.27	0.43
U-235	13.69	17.18	5.90	5.88
U-236	-		1.44	2.02
U-238	54.76	68.71	53.95	65.85
Np-237			0.05	0.04
Pu-238			0.02	0.04
Pu-239			0.59	0.73
Pu-240			0.15	0.22
Pu-241			0.13	0.21
Pu-242			0.02	0.06
Am-241			NA	NA
Cm-242			NA	NA

* Also provide graphs of fissile content (Pu and U) vs Burnup (GWD/MT)

Table II-2(b)

Reactor Fresh and Spent Fuel Characterization

TYPE (General Description) U-235/Th Cycle; Denatured U in ThO_2 (recycle fuel)

Refueling Method: On-line ___; Batch X ; (Refueling frequency annual)

Fuel Assembly Characteristics: (where applicable)

a) type: Oxide ✓; Metal ___; Carbide ___;

b) weight: 650 kg

c) length: 4.3 m

d) core load: 86151 mass (kg HM): (eq Cycle)

e) annual reload: 28717 mass (kg HM): (Eq Cycle

Design burnup: 33,400 (MWd/MT) discharge batch average

Discharge fuel radiation level: ___ r/hour @ 1 meter (also provide a curve of radiation level versus cooling time following discharge) NA

Discharge fuel energy generation rate as a function of cooling time. W/hr/element) - provide curve. NA

Heavy Element Isotopic Content (kg/fuel element) at discharge

ISOTOPE	Fresh Fuel Element		Discharged Fuel Element	
	initial	equilibrium	initial	equilibrium
Th-232		289.3		282.4
U-232		0.02		0.02
U-233		6.07		5.83
U-234		2.56		2.63
U-235		11.19		4.75
U-236		6.43		7.05
U-238		74.18		71.27
Np-237				0.14
Pu-238				0.17
Pu-239				0.82
Pu-240				0.24
Pu-241				0.21
Pu-242				0.05
Am-241				NA
Cm-242				NA

* Also provide graphs of fissile content (Pu and U) vs Burnup (GWD/MT)

Table II-3

Reactor Fresh and Spent Fuel Characterization

TYPE (General Description) U-233/Th Cycle : Denatured U-233 in ThO_2 (with some U)

Refueling Method: On-line ___; Batch X ;(Refueling frequency annual)

Fuel Assembly Characteristics: (where applicable)

a) type: Oxide ✓; Metal ___; Carbide ___;

b) weight: 650 kg

c) length: 4.3 m

d) core load: 93558 (kg HM):

e) annual reload: 31186 mass (kg HM):

Design burnup: 33,400 (MWd/MT) discharge batch average

Discharge fuel radiation level: ___ r/hour @ 1 meter (also provide a curve of radiation level versus cooling time following discharge) See Figure II-2

Discharge fuel energy generation rate as a function of cooling time. W/hr/element) - provide curve. See Figure II-3

Heavy Element Isotopic Content (kg/fuel element) at discharge

ISOTOPE	Fresh Fuel Element		Discharged Fuel Element	
	initial	equilibrium	initial	equilibrium
Th-232	305.4	275.6	300.9	268.5
U-232	0.015	0.046	0.021	0.040
U-233	9.93	12.25	6.72	7.43
U-234	—	3.15	0.86	3.64
U-235	0.18	0.88	0.18	0.94
U-236	—	0.41	0.03	0.51
U-238	72.73	47.30	70.87	93.80
Np-237			NA	NA
Pu-238			NA	NA
Pu-239			0.60	0.88
Pu-240			0.19	0.29
Pu-241			0.14	0.24
Pu-242			0.04	0.09
Am-241			NA	NA
Cm-242			NA	NA

* Also provide graphs of fissile content (Pu and U) vs Burnup (GWD/MT)

TABLE V-1

Cost Estimate Summary for 1260 Mwe PWR

January 1978 Dollars

Acct. No.	Account Description	Total Costs (Millions)
20	Land and Land Rights	$ 2.4
21	Structures and Improvements	122.4
22	Reactor Plant Equipment	161.1
23	Turbine Plant Equipment	134.3
24	Electric Plant Equipment	47.6
25	Miscellaneous Plant Equipment	14.2
26	Main Condenser Heat Rejection System	26.1
91	Construction Services	84.5
92	Main Office Engineering & Service	59.4
93	Field Office Engineering & Service	34.5
	Total Costs	$ 686.5

TABLE V-2

Economic Parameters

U_3O_8 Cost ($/kg)	88 and 220
Separative Work Cost ($/SWU)	80
Enrichment Plant Tails (w/o)	0.2
Plant Factor (%)	75
Plant Life (yrs)	30
ThO_2 Cost ($/kg)	33
Reprocessing ($/kg)	150-250
Spent Fuel Shipping and Waste Storage ($/kg)	70
Pu Storage ($/gm-yr)	2
Fabrication ($/kg)	
Denatured U-235/Th	150
Denatured U-233/Th	550
Spent Fuel Storage (for once-through UO_2 cycle)	115

TABLE V-3

FUEL CYCLE AND POWER COSTS

DENATURED U-235/Th CYCLE

(U-235 Makeup)

	U-235/Th Cycle U_3O_8 Price $/lb	
	40	100
Fabrication	1.94	
U_3O_8	1.47	3.67
ThO_2	0.09	
Separative Work	1.49	
Fuel Disposal or Reprocessing[3]	1.10	
Carrying Charges	2.05	3.39
Total Fuel Cycle Cost	8.04	11.58
Plutonium Credit [1]	-0.48	-0.66
O & M	0.82	
Capital Cost [2]	9.97	
Total Power Cost	18.35	21.71

(1) Assumed credit for fissile plutonium at a price of 15 or 34 $/gm for 40 or 100 $/lb U_3O_8, rather than storage at 2 $/gm-yr.

(2) Includes interest during construction.

(3) Based on reprocessing cost at lower end of range of $150/kgHM

TABLE V-4

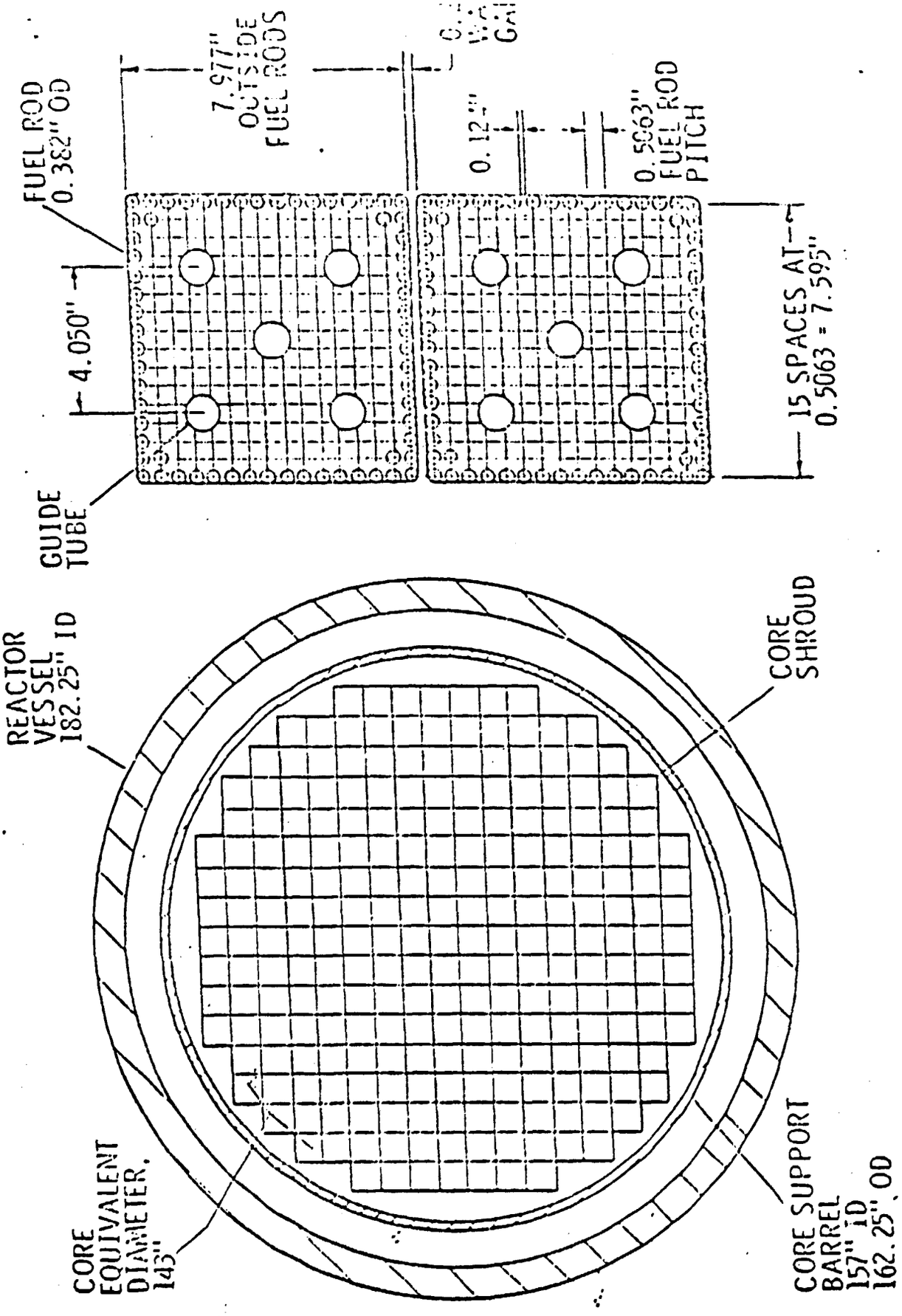
FUEL CYCLE AND POWER COSTS

DENATURED U-233/Th CYCLE

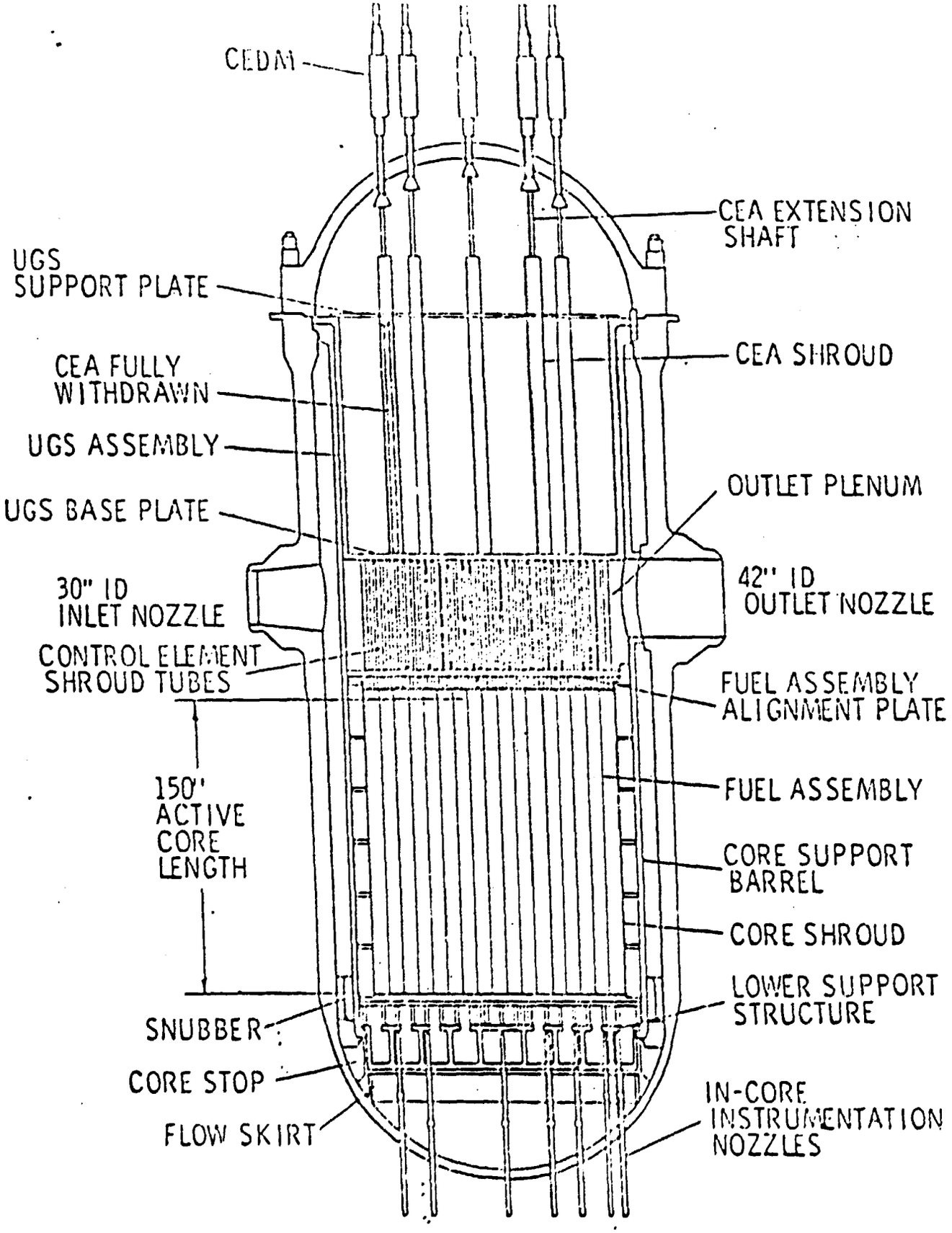
(U-233 Makeup)

		Fuel Cycle Cost Mills/Kw-Hr	Power Cost Mills/Kw-Hr
Fabrication	2.05		
ThO_2	0.09		
Reprocessing[1]	1.01		
Carrying Charges (Excluding U-233)	0.27	3.44	
U-233 (Including U-233 Carrying Charges)			
10 $/gm	1.35	4.79	15.58
20 $/gm	2.70	6.14	16.93
40 $/gm	5.40	8.84	19.63
60 $/gm	8.10	11.54	22.33

(1) Based on reprocessing cost at lower end of range of $150/kgHM



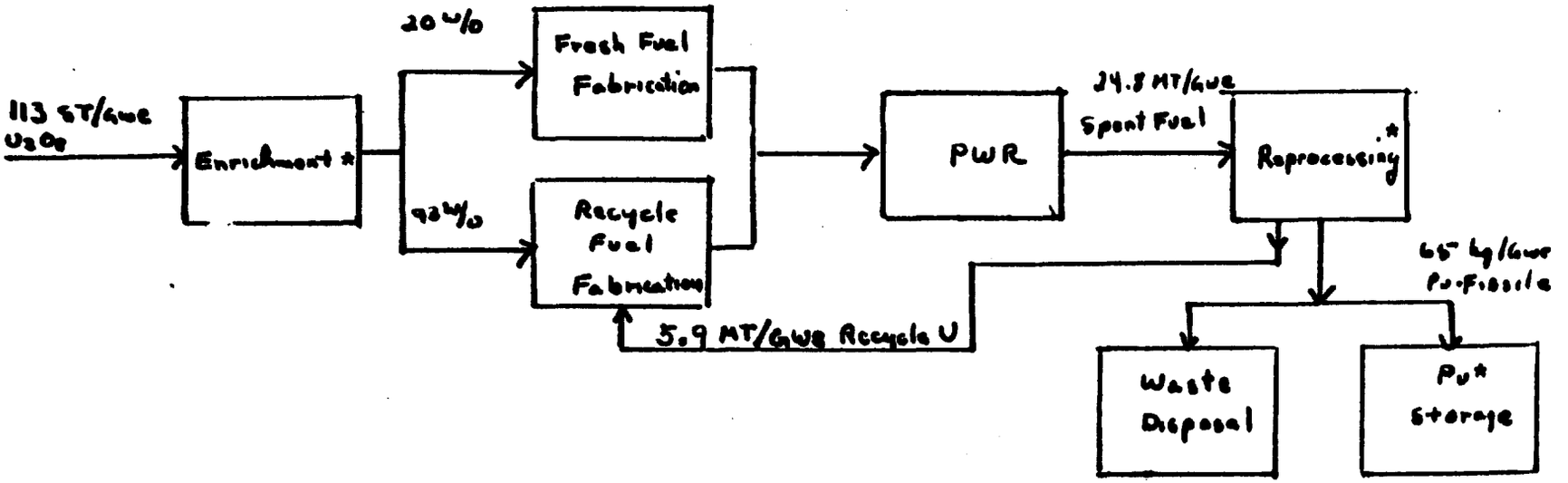
C-E System 80	REACTOR CORE CROSS SECTION 241 FUEL ASSEMBLIES	Figure H-1



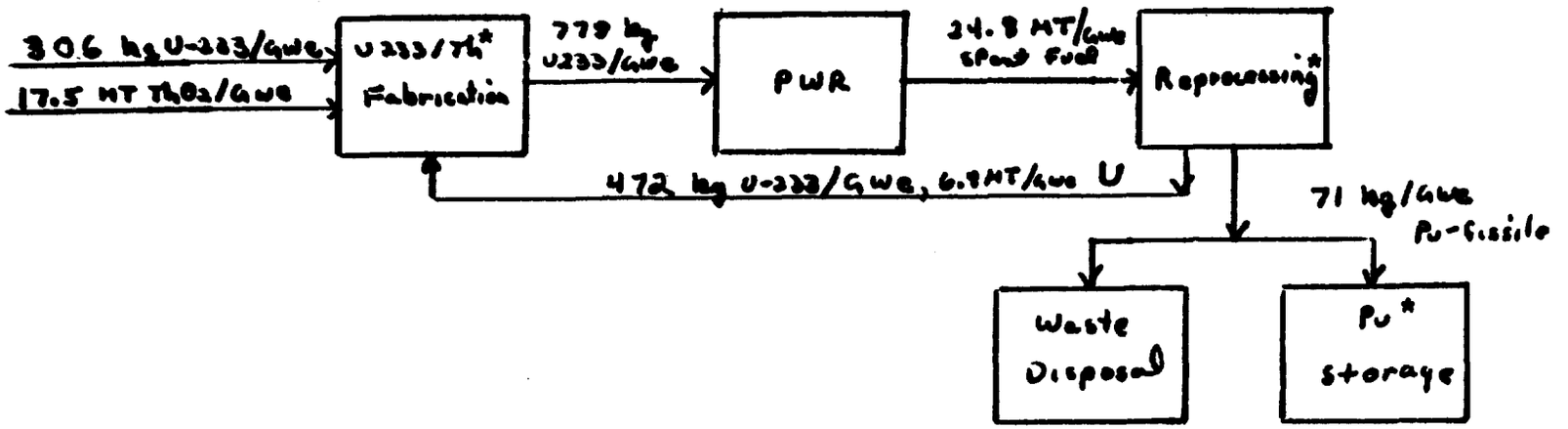
C-E System 80	REACTOR VERTICAL ARRANGEMENT	Figure I-2

Figure II-1
Fuel Cycle Facilities

1) U235/Th Cycle



2) U233/Th Cycle



*Located in secured areas.

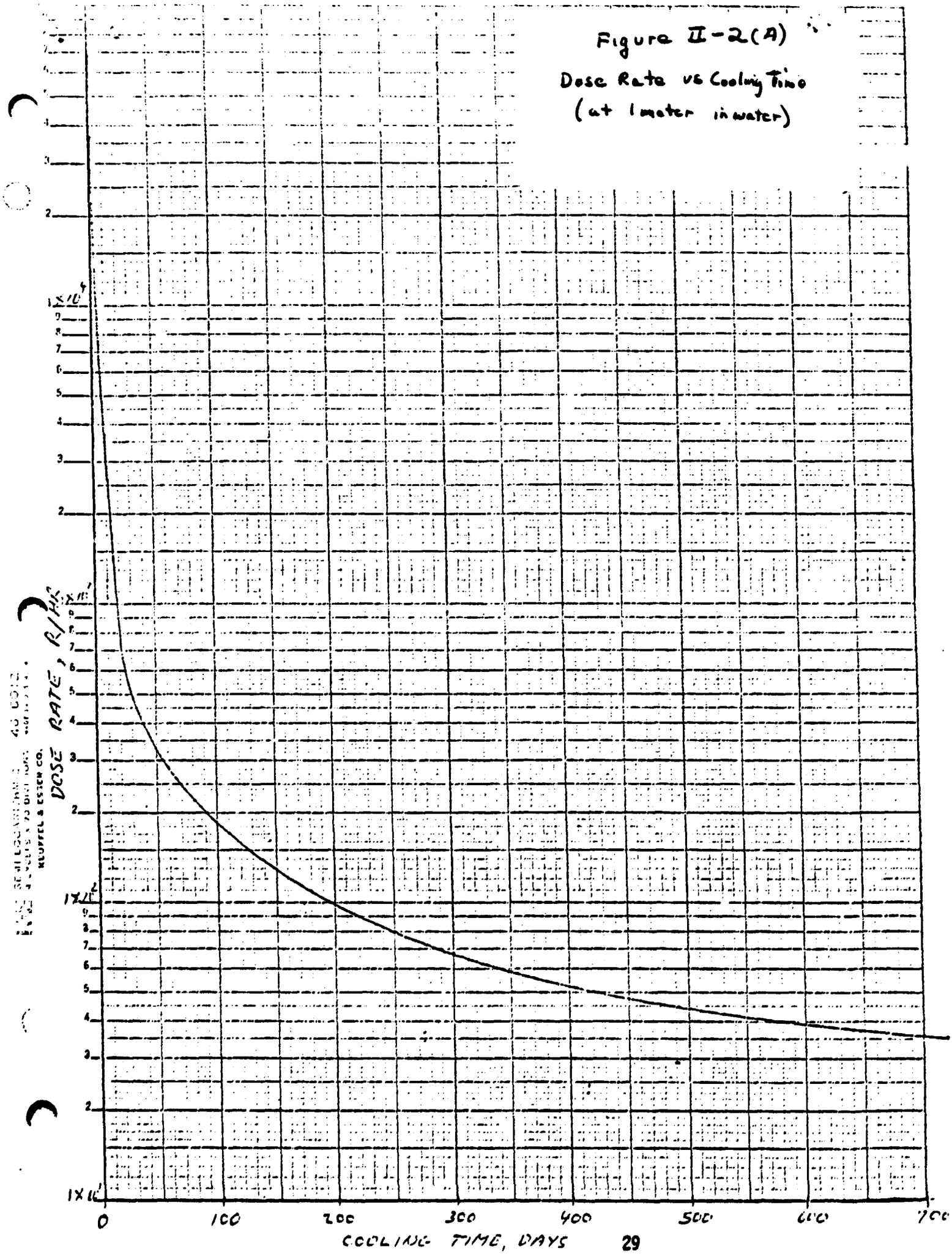


Figure II-2(A)
Dose Rate vs Cooling Time
(at 1 meter in water)
DOSE RATE, R/hr
1 x 10⁴
1 x 10³
1 x 10²
1 x 10¹
0
100
200
300
400
500
600
700
COOLING TIME, DAYS

FIG II-2(B)

PWR DENATURED THORIUM (SINGLE FUEL ELEMENT)

DOSE RATE VS COOLING TIME AT 1 METER IN AIR

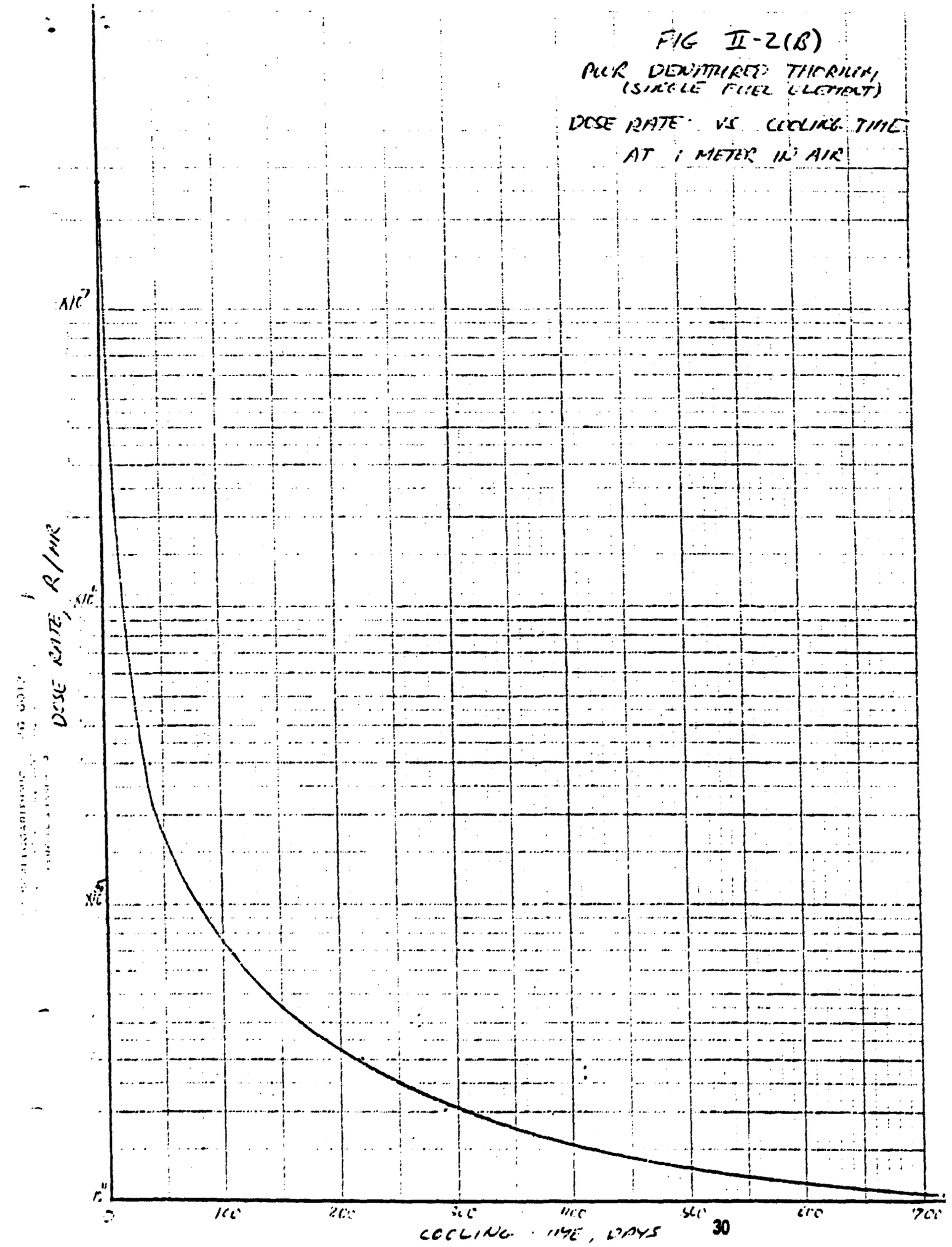


Figure II-3

Decay Heat Generation

vs

Cooling Time