NUCLEAR FUEL LOGISTICS

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INTRODUCTION

Nuclear fuel logistics, as interpreted in this paper, relate to the composite of decisions and operations necessary for efficient supply, utilization, and salvage of power reactor fuel. The many operations which make up the familiar nuclear fuel cycle are schematically depicted in Figure 1. These operations include uranium mining and milling, uranium purification and enrichment, fresh and recycle fuel feed preparation and fabrication, fuel reprocessing and recovery of residual values, low and high level waste disposal, nuclear power plant on-site fuel handling and in-core fuel management, and transportation of nuclear materials.

It is appropriate to recall that we are dealing here with a very broad and essentially inexhaustible topic on which much has already been written and on which much more will be said in the future. In our instructions from the program chairmen, we were asked to cover "the technical and economic features as well as the projected timing of uranium, plutonium, and thorium utilization in thermal and fast reactors. Discussions of possible implications regarding the impact of nuclear fuel resources and requirements for enrichment capacity should be also included." About 35 minutes have been allotted for this subject including discussion.

In order to meet this challenge we have taken certain liberties with these instructions. First, as our colleagues on this panel will be concentrating on the fuel utilization and salvage aspects, we shall emphasize the supply aspects of the nuclear fuel cycle. Second, we shall limit our

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remarks to the U.S. nuclear economy, with particular attention to the 1980's and beyond rather than the near-term. Third , in preparing our remarks we had no choice but to draw heavily on many sources of information, some of which we have not referenced, but for which we are very appreciative. Lastly, in the time available we can only highlight some of the more important considerations for the reactor systems of greatest interest in the U.S., namely: the light water reactor (LWR), the high temperature gas cooled thermal reactor (HTGR), and the liquid metal cooled fast breeder reactor (LMFBR or FBR). With these qualifications in mind, we will first discuss the specific nuclear fuel requirements as determined by reactor characteristics; we will then relate these specific requirements to industry-wide requirements in an expanding nuclear economy, and finally, we will comment on the factors which strongly influence the planning of nuclear fuel facilities and capabilities for meeting these requirements.

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SPECIFIC REQUIREMENTS

Table 1 summarizes the specific fuel logistical requirements for each of the three systems of interest based on a 1000 Mwe plant. These requirements, which were obtained from AEC and industry sources, are believed to represent performance levels anticipated by the late 1980's. It is difficult to compare these requirements as each system has its own unique characteristics. However, some of the important differences and similarities, as they relate to the future demand of nuclear materials and services, are noteworthy.

FUEL CYCLE

The LWR and FBR are both based on the uranium-plutonium cycle whereas the HTGR utilizes the thorium cycle with U-235 (or Pu) feed and U-233 recycle. The use of the uranium-plutonium cycle in the HTGR was found to be economically inferior under U.S. conditions.¹ Plutonium produced by the LWR and FBR can and will probably be used by all three systems. The preferred use for the available plutonium depends on prevailing technological and economic conditions at a particular point in time. Ours and other studies^{2,3} indicate that the FBR is by far the best plutonium user as a result of the superior nuclear characteristics for plutonium in a fast neutron spectrum. The next best user for plutonium might well be the HTGR, once the technology and facilities for U-233 recycle become available. Studies by ORNL⁴ indicate a \$2-3/gm greater fissile plutonium value when used as makeup for an HTGR than for an LWR. This is because, with the required remote fabrication for U-233, there is little additional fabrication cost penalty for plutonium. Also such plutonium replaces the more expensive U-235 in fully enriched uranium used by HTGR's rather than the less expensive U-235 used by LWR's. As commercial introduction of the FBR and U-233 recycle are not anticipated until the mid 1980's, much of the plutonium produced in the interim will be recycled into LWR's.

TABLE 1. TYPICAL FUEL CYCLE LOGISTIC REQUIREMENTS FOR 1000 Mwe NUCLEAR PLANTS

Plant Type	LWR (PWR)		HTGR		LMFBR Early / Adv.
	No Recycle	Pu Recycle	Thorium with U235 Makeup and U233 Recycle	Thorium With Pu Makeup and U233 Recycle	Depleted Uranium with Pu Recycle
Fuel Cycle					
Initial Loading Requirements					
• M. T. Fuel (Heavy Isotopes)		74		35	27 / 17 (Core) 30 / 33 (Blank)
• M. T. Fissile		1.9 (2.6 w/o U235)		1.5 (93 w/o U235)	2.5 / 1.8 (Pu)
• Tons U_3O_8 (1)		500		400	-0-
• M. T. Separative Work Units (1)		230		330	-0-
Annual Replacement Requirements at 0.8 L.F.					
• M. T. Fuel (Heavy Isotopes)	27	27	8	8	14 / 9 (Core) 12 / 15 (Blank)
• M. T. Fissile Purchased	0.64 (U235)	0.50 (U235)	0.32 (U235)	0.38 (Pu)	-0-
• M. T. Fissile Recycled	-0-	0.17 (Pu)	0.19 (U233)	0.25 (U233)	1.30 / 0.80 (I)
• M. T. Fissile Sold	0.17 (Pu)	-0-	-0-	-0-	0.19 / 0.30 (I)
• Tons U_3O_8 (1)	180	140	92	-0-	-0-
• M. T. Separative Work Units (1)	110	86	76	-0-	-0-

(1) Based on 0.25% tails.

Uranium Requirements

The LWR and HTGR need for uranium relates primarily to its U-235 content whereas the FBR need for uranium relates primarily to its much more abundant U-238 content. Comparing the thermal reactors in the self-recycle mode (columns 2 and 3), we note that the LWR requires about 25% more uranium for the initial loading and about 50% more uranium for replacement than the HTGR. This is primarily due to the higher neutron yield per absorption (η) for the U-235/U-233 mixtures used in the HTGR and partly due to the higher plant thermal efficiency of the HTGR.

On the other hand, because of the large difference in required uranium enrichment, separative work requirements per Mwe are 43% higher for the initial loading of the HTGR. Separative work requirements for replacements are comparable for both thermal reactors. The FBR utilizes depleted uranium for its feed and consequently does not require any separative work for either its initial loading or replacements. New FBR's will require open market plutonium produced by others and to that extent they do contribute to the total separative duty being required.

Fabrication and Reprocessing

Table 2 compares some of the design and performance characteristics as they relate to fabrication and reprocessing. Of principle interest are LWR and FBR fuel with Pu recycle, and HTGR fuel with U-233 recycle. LWR recycle and fabrication problems are discussed extensively in the literature⁵ and will, therefore, not be dealt with here. The fabrication process for FBR fuel is very similar to that of LWR recycle fuel and, in fact, much of the experience gained in fabrication of uranium and plutonium oxide fuels will be used in FBR fuel fabrication.

Nevertheless, FBR fuels are expected to cost significantly more than LWR fuels. This is primarily due to the smaller fuel rods, higher fissile concentrations, and the lower fabrication demand, particularly during

TYPICAL PLANT AND FUEL CHARACTERISTICS AFFECTING FUEL LOGISTICS

	LWR(PWR)	HTGR	FBR
Thermal Efficiency (%)	33	39	39
Ave. Specific Power (Kwt/KgH)	41	73	120-160 (Core)
Ave. Discharge Exposure (MWD/KgH)	33	94	40-50 (Fuel + Blanket Mixture)
Fuel Type	UO ₂ or (Pu, U)O ₂ in Zr tubes	Th/U ceramic coated particles in graphite blocks	(Pu, U)O ₂ /UO ₂ in Stainless Steel Tubes
Fuel Assembly Geometry	204 rods square array, 8.4 inch side, 12 feet long	210 fuel cavities 108 coolant holes Hex. graphite block 14.2 inch across flats, 31.2 inch high	217-331 rods, Hex array, 5.6 inch across flats, 9-15 feet long
KgH/Fuel Assembly	450	10	65 (Core)
Fissile content, %			
• Fabricated Fuel	2.5 - 3.5	6-7	12-15 (Ave. Core)
• Spent Fuel	1-2 (Open Cycle) 2-3 (Pu Recycle)	2-3	6-8 (Core + blanket mixture)

the early period of FBR introduction. An FBR fuel rod contains about 1/10 the fuel of an LWR rod and its fissile content is about five times as high. Because of these differences and the lower fabrication loads, FBR fuel fabrication costs during the later 1980's are expected to be 3 to 5 times higher than those for LWR recycle fuel.⁶ Furthermore, because of the higher fissile concentrations and higher specific powers, FBR fuels pose some added challenges in spent fuel shipping and reprocessing. These will be discussed in detail by others on the panel, so I shall move on to the HTGR fuel.

HTGR fuel has a number of unique features that strongly affect its fabrication and reprocessing.⁷ Most noteworthy is the use of graphite as an integral part of the fuel assembly. This contributes significantly to the processing and shipping costs. A special head-end reprocessing operation is needed to separate the thorium and fissile components from the graphite and to avoid degradation of U-233 by the U-236. The latter results from parasitic captures in the initially fed U-235. With the recycle of U-233, one encounters shielding and alpha containment problems in fabrication similar to those encountered with Pu fuel.⁵ From a fabrication and reprocessing cost viewpoint, HTGR fuel is quite similar to FBR fuel. Both are designed for a factor of 3-4 higher exposures than LWR fuel and, hence, result in correspondingly lower processing throughputs; both require semi-remote or even remote fabrication techniques⁵; both will require special head-end reprocessing facilities because of their peculiar fuel properties; and both will be using rather small-scale processing facilities during the late 1980's as compared to LWR fuel facilities. Consequently, processing costs (\$/KgH) for the HTGR recycle fuel and FBR fuel can be expected to be much higher than those for LWR fuels during the late 1980's, costs which must be offset by savings in other areas of the fuel cycle in order for these systems to be competitive at that time.

INDUSTRY-WIDE REQUIREMENTS

Having established specific fuel logistical requirements, we can now combine these requirements with a plausible model of the future growth of nuclear power to assess the industry-wide requirements for nuclear materials and services. Fortunately, such a study has recently been performed by the AEC in support of the Updated (1970) Cost Benefit Analysis for the U.S. Breeder Reactor Program⁸; some of the results from this study are used here.

MODEL

To simulate the U.S. electrical energy economy, the AEC studies employ a mathematical model which selects the mix of energy sources over the specified time period, such that the total discounted cost to meet the energy demand is at a minimum. In such a model, many assumptions are necessary in order to characterize the candidate energy sources and to define the economic environment in which these energy sources are to operate. Some of the more important assumptions are the total energy demand, technical and economic characteristics of the competing energy sources, FBR commercial introduction date, coal and uranium price trends, and cost vs. volume relationships for nuclear fuel services. These were determined by the AEC after considerable study and judgment and are described in available AEC publications.^{8,9}

The AEC model contains special subroutines which track the requirements for natural uranium, thorium, separative work, fabrication and reprocessing services, and disposition of bred nuclear materials, -- notably plutonium and U-233.

Selected Growth Patterns

The AEC studies covered a number of situations involving different energy demands, varying degrees of optimism with regard to the available uranium supply, and different introduction dates for the FBR. We will limit our discussion to the AEC's best estimate or "probable"

assumptions with respect to energy demand and uranium supply and examine the influence of FBR timing on fuel cycle requirements. For obvious reasons, caution must be employed in the interpretation of these projections. These are clearly not intended as authoritative predictions of things to come, but rather as cause-and-effect relationships under specifically assumed conditions.

The assumed electrical energy demand and the specific reactor economies selected for this discussion are shown in Table 3. The electrical energy demand is based on 1969 FPC projections which, as a matter of interest, are lower than the latest projections by the FPC. The nuclear market was limited to the non-peaking steam capacity portion only.

The bottom three lines indicate the projected market penetrations for the selected reactor economies. The difference between the total electrical capacity and the total nuclear capacity represents coal fired steam capacity. The "LWR plus HTGR" economy was selected for reference purposes to show what might happen if the FBR does not become available. The other two economies were selected to assess the impact of the FBR and the significance of a four-year delay in its introduction.

A comparison of the nuclear market penetrations by the various reactor economies indicates that the FBR increases the total nuclear market fraction. The primary reasons for this may be seen from Figure 2, which shows the anticipated trends in uranium costs and plutonium values with and without the FBR. As can be seen from this figure, the FBR slows down the increase in uranium costs and increases the value of plutonium. Both of these effects enhance the market for LWR's by reducing their lifetime fuel cycle costs.

Let us now turn to the various projected fuel cycle requirements.

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TABLE 3

PROJECTED TOTAL AND NUCLEAR ELECTRICAL CAPACITY

Year	1980 1980	1990 1990	2000 2000	2010 2010
Total Energy Demand (10^{12} Kwh/yr)	3.2	6.0	10	16
Total Non-Peaking Capacity (GWe)	530 600	1050 1100	1800 1900	2900 3000
Total Nuclear/FBR Capacity ^(GWe) Extrapolated				
• LWR + HTGR (Case 1)*	150/-0- 29/-	520/-0- 58/-	1350/-0- 97/-	2500/-0- 87/-
• LWR + HTGR + FBR by 1986 (Case 3)*	158/-0- 31/-	600/40 61/-5	1500/170 837/40	2700/1700 967/65
• LWR + HTGR + FBR by 1990 (Case 4)*	154/-0- 30/-	560/4 55/-4	1400/360 80/-25	2600/1500 934/54
		570	1460	

* Refers to case identification in WASH-1184.

Uranium and Thorium Requirements

Figure 3 shows the potential trends for annual U_3O_8 requirements for the three reactor economies. Also indicated is the AEC estimated U.S. production capacity as of January 1972.¹⁰

As shown, without the FBR, annual uranium demand increases unabated at almost a constant annual rate of about 3500 tons per year, requiring the duplication of our present production capacity about every 5 years. With the FBR, uranium demand would actually increase faster during the FBR introduction period and peak out at around 100,000 tons per year by mid 1990's. The higher uranium demand during the 1985-1995 period is largely due to the increased nuclear market penetration discussed earlier and partly due to the diversion of a significant fraction of the available plutonium supply to fuel the increasing number of FBR's.

Figure 4 shows the cumulative U_3O_8 requirements, including an 8-year forward reserve, for the three reactor economies. The decreasing annual uranium demand, anticipated in later years due to FBR introduction, is clearly evident here. This slowdown is caused by excess plutonium production from breeders which by the 1990's not only meets the requirements for the continued power demand but also provides a major portion of the makeup requirements for the still operating thermal reactors. Ultimately, a balance is reached between the supply and demand for fissile material and no further uranium mining is required for its U-235 content. At that point in time the primary feed to the reactor economy would be depleted uranium stockpiled from prior thermal reactor operations which should last for many generations to come.

The horizontal lines in Figure 4 show the current AEC estimated resources recoverable at the indicated costs. One is tempted to conclude from this that uranium costs will remain below \$10/lb (in 1972 dollars) at least through the mid 1980's. Such a conclusion would be rather tenuous as it almost totally ignores the practical economic aspects of mineral extraction and related market place considerations such as supply and demand pressures.¹¹

Thorium requirements for HTGR's are projected to be relatively small when compared to uranium requirements. For example, even with a delayed (1990) FBR introduction, annual requirements peak out at around 10,000 tons and cumulative requirements are less than 300,000 tons. These requirements are well within the estimated available resources at less than \$10/lb.¹²

Uranium Enrichment Requirements

The projected trends for separative work demand are shown in Figure 5. Also shown is the anticipated supply trend based on current AEC plans. The indicated trends in demand closely parallel the annual U_3O_8 requirements discussed earlier.

From a short-term viewpoint and based only on U.S. requirements, the existing and currently planned capacity will be outstripped by the growing demand around 1983. If the U.S. were to meet a significant fraction of the foreign demand, this crossover point would of course be reached earlier. Preliminary estimates by the AIF Enrichment Committee indicate that new capacity would be required as early as 1980, taking the foreign requirements into account.⁴

The long-term outlook for enrichment demand is much less certain, as it is strongly dependent on the introduction date, performance and degree of penetration of fast breeders. This is clearly evident from the sharply different levels and trends for separative work demand in the 1990's and beyond. For example, a four year delay in FBR introduction means about 30,000 metric tons in added enrichment capacity. The indicated rapid rise in demand in the 1984-1994 period, followed by a potential for a sharply downward demand trend, clearly introduces some difficult problems for the long-range planning of new enrichment facilities. A rather thriving uranium enrichment plant equipment and construction industry can be expected over the next 20 years, however. The required investment for new enrichment facilities, including power supplies, would reach 11-13 billion (1972) dollars by the early 1990's.

Fabrication Requirements

Figure 6 shows the expected trends in annual fuel fabrication requirements with and without the FBR. We can clearly expect a dramatic increase in LWR fuel fabrication capacity over the next 20 years. The bulk of the LWR fuel produced during this period will be of the conventional Zircaloy-clad- UO_2 type. By 1985 reload fuel would account for 65% of the total LWR fuel demand, and of this reload fuel about 18% would be LWR Pu recycle fuel.¹³ Beyond the mid 1980's, the fuel fabrication market is quite sensitive to the degree of market penetration by the HTGR and FBR. The utilization of the recovered plutonium after this time period is also quite uncertain at this time. Figure 7 shows the projected plutonium balance in the U.S. economy based on a 1986 FBR introduction date. This figure indicates that significant quantities of plutonium would be available for LWR and HTGR's well into the 1990's. As noted previously, the preferred use for this excess plutonium would be in HTGR's, in conjunction with U-233 recycle. However, such recycle is not expected until the mid 1980's and will comprise a rather small fraction of the total HTGR fuel fabrication load until the early 1990's (compare Figures 6 and 8). It thus appears that a significant fraction of the available plutonium may continue to be recycled by LWR's well into the 1990's.

The late 1980's would be particularly critical to the introduction of the FBR because of the large disparity in fuel fabrication volumes during this period. FBR fuel fabrication costs would be disproportionately high during these years because of the relatively low throughputs. This could be ameliorated in three ways. First, early requirements could be met by taking maximum advantage of the available LWR recycle facilities and capabilities. Second, as the plutonium supply would not be limited, FBR's can take advantage of this over-supply by using larger fuel rods, and thus, reduce both fabrication and energy costs.¹⁴ Third, as HTGR's create a premium market for U-233, FBR's can produce such U-233 by loading thorium into their blankets instead of uranium.¹⁵ This suggests a three way

synergistic reactor economy whereby FBR's would be getting their plutonium from LWR's and HTGR's would be supplementing their U-233 with material produced rather conveniently by FBR's.

Reprocessing Requirements

Figure 8 shows the expected trends in annual fuel reprocessing requirements with and without the FBR. These are quite similar to the trends of fuel fabrication requirements except for the differences in time delays due to fuel irradiation and decay cooling. LWR fuel reprocessing loads by the late 1980's would be sufficient to support 4-6, 10 ton/day, plants whereas FBR and HTGR reprocessing loads are only sufficient to support 1-3, 1 ton/day, plants. The favorable economies of scale which characterize reprocessing plants would thus, again, favor LWR's. Early FBR and HTGR reprocessing requirements could be met through the use of lower capacity early LWR reprocessing plants in conjunction with special head-end facilities. Single purpose HTGR and FBR reprocessing facilities may not be required until the early 1990's.

Transportation

Figure 9 provides typical trends for the various types of large radioactive shipments. These include shipments of spent fuel, fresh fuel with plutonium and U-233, plutonium and U-233 mixtures, 93% w/o enriched uranium, and solidified high-level wastes. The assumed quantities per shipment are representative of the 1980's and may, therefore, underestimate the traffic during the 1970's and overestimate the traffic in the 1990's. It is quite obvious that the bulk of the shipments are likely to be of spent and recycle fuel. The shipment of plutonium and U-233 mixtures would probably be minimized because of the economic incentives for locating fabrication facilities adjacent to or within close proximity of fuel reprocessing plants. Spent fuel shipments are based on off-site reprocessing plants. The possible advent of nuclear power parks with their own reprocessing facilities could change the spent fuel shipping picture drastically.

Comparison with Coal

These nuclear logistical requirements may seem to be very large and, in fact, they are. However, in order to put these into perspective, let's take a quick look at the magnitude of the logistics problems in the year 2000 if nuclear power were not available. The AEC projections anticipate that nuclear power would account for 83% of the non-peaking power generating capacity around the year 2000. This corresponds to an annual generation of about 8×10^{12} kwh. Coal is the only option, among the alternatives currently available, which can substitute for a demand of this magnitude. Accordingly, Table 4 compares some elements of fuel cycle logistics in the year 2000 assuming that the total projected nuclear energy demand would be supplied by coal. This additional demand is about 6 times the projected use of coal around 2000, with nuclear power. Coal is expected to supply a little more than 10% of the nation's electric energy at that time, which is only 50% greater than the energy produced by coal in 1971. Although these numbers are subject to the same qualifications mentioned earlier, they are indicative of the relative logistics associated with the different energy economies.

TABLE 4. COMPARATIVE ANNUAL FUEL CYCLE
LOGISTICS IN CIRCA 2000 (Nuclear
Electrical Energy Demand of 8 Trillion kwh per year)

	<u>Nuclear *</u>	<u>Coal Equivalent **</u>
Mining (Million Tons)		
Fuel	0.1 (U_3O_8)	3,000
Ore	50	3,500
Transportation (Thousand car loads)		
Fuel	50 - 100	30,000
Waste	1 - 3	2,500 (ash) 400 (sulfur)
Waste Management (Million cubic feet)	0.1 - 0.3	2,500 (ash) 600 (sulfur)

* Reflect total nuclear economy logistics including U_3O_8 , UF_6 , enriched uranium fuel for LWR and HTGR, and low level waste.

** Based on 10,000 Btu per pound, 9% ash, and 70% removal of 2% sulfur.

EXPANSION OF NUCLEAR FUEL FACILITIES

The overall industry growth depicted in Figures 3 through 9 indicates that over the next 30 years the demand for nuclear fuel materials and services will increase dramatically; about a factor of 10 in the fuel supply areas and a factor of 50 in the fuel recovery areas. Such rapid expansion is not unprecedented in American industry, as witness the growth of the petroleum industry from 150,000 barrels/day in 1890 to 3,000,000 barrels/day in 1928.¹⁶ ✓

To develop an estimate of the new facilities required and their cost, we have first summarized the characteristics of typical nuclear fuel facilities, as shown in Table 5. Nuclear power plants are included for comparison. For typical plant sizes, the table shows approximate capital investments, investment scaling factors, product unit values, annual sales, ratio of investment to annual sales, useful life, and time required from inception to commercial operation. Most nuclear fuel facilities are highly capital intensive, meaning that the capital contribution to the cost of product is large compared to that of the other factors of production such as labor, utilities, and raw materials. The ratio of investment to annual sales is a partial measure of capital intensiveness.

Expansion Planning

The rapid growth of the nuclear fuel industry will create many opportunities and at the same time many problems. The firm considering building a new plant must face such questions as:

1. What size plant shall we build?
2. When shall we built it?
3. What will our share of the market be? How will this be affected by the future entry of new competitors?
4. What will happen to the product price as a result of capacity growth and other actions of our competitors?
5. How will we be affected by government regulations and licensing procedures?

Table 5. TYPICAL NUCLEAR FUEL FACILITY CHARACTERISTICS

Type of Facility	Capacity	Investment, 10 ⁶ \$ ^a	Scaling Factor	Product Unit Value	Annual Sales, 10 ⁶ \$ ^a	Investment Annual Sales	Useful Life, yr	Lead Time, yr
Nuclear Power Plant	1000 MWe	250-300	0.7-0.8 ^b	8-10 mills/kWh	56-66	4.4-4.6	30-40	7-9
Uranium Exploration, Mining, and Milling	2000 tons U ₃ O ₈ /yr	40-60 ^c	0.7-1.0	7-9 \$/lb U ₃ O ₈	26-36	1.4-1.7	10-20	6-10
Uranium Purification and Fluorination	5000 tons U/yr	20-30 ^d	0.6-0.7	2.2-2.7 \$/kg U	10-13	2.0-2.3	15-25	3-5
Uranium Enrichment (GD Process)	8.8 x 10 ⁶ SW units/yr	1600-1800 ^{e,f}	0.7-0.8 ^f	30-40 \$/SWU	260-350	5.1-6.1	20-40	7-9
Fuel Fabrication								
LWR-U	1300 MTU/yr	60-70 ^g	0.8-0.9 ^g	60-80 \$/kg U	78-104	0.7-0.8	15-25	2-4
HTGR-U235	230 MTH/yr ^h	20-25 ^h	0.7-0.9	100-140 \$/kg H ⁱ	23-32	0.8-0.9	15-25	2-4
LWR-Pu	130 MTH/yr	16-20 ^g	0.8-0.9 ^g	80-110 \$/kg H	10-14	1.4-1.6	15-25	3-5
FBR-Pu (Core)	130 MTH/yr	35-45 ^{g,j}	0.7-0.9	200-300 \$/kg H	26-39	1.2-1.4	15-25	3-5
HTGR-U233	130 MTH/yr	25-35 ^g	0.7-0.9	150-180 \$/kg H	20-24	1.3-1.5	15-25	3-5
Chemical Reprocessing								
LWR	1300 MTH/yr	70-80 ^{g,j}	0.3-0.4 ^{g,j}	20-30 \$/kg H	26-39	2.0-2.7	15-25	4-6
LWR	2600 MTH/yr	90-100 ^g	0.3-0.4 ^g	14-20 \$/kg H	36-52	1.9-2.5	15-25	4-6
HTGR	260 MTH/yr	80-90 ^k	0.3-0.4	110-150 \$/kg H	29-39	2.3-2.8	15-25	4-6
FBR	260 MTH/yr	60-70	0.3-0.4	80-100 \$/kg H	21-26	2.7-2.9	15-25	4-6

^aAll costs in 1971/72 \$.^bP. C. Zmola, "Size Effect and Cost of Incremental Capacity for LWR's," IAEA-SM-139/41, Oct. 1970.^cE. A. Youngberg, GJO USAEC (\$20,000-\$30,000/annual ton of U₃O₈).^dNuclear News, January 1970.^eIncludes power facilities.^fORO-685.^gR. Salmon et al., Geneva IV paper.^hNucleonics Week, August 31, 1972.ⁱGGA Bid to WSPPS (L. Geller et al., Geneva IV paper).^jNuclear News, July 1970, FORATOM Study.^kWASH-1152.

Considerable attention has been given in the literature to the problem of determining the optimal expansion path for an industry. The optimal path is typically based on the trade-off between economies of scale and the time value of money. For many process plants, capital investment can be approximately expressed by an equation of the form

$$\text{Cost} = AX^b$$

in which X is the plant capacity, A is the cost of a plant of unit capacity, and b is the investment scaling factor referred to earlier. Usually b is between 0 and 1. If economies of scale are present, b is less than 1; the smaller the value of b, the greater the economies of scale. If a projection can be made of future industry demand, then it is possible to calculate a theoretically optimal expansion path for any given discount rate (cost of money). For either a linearly-increasing or a geometrically-increasing growth of demand, it can be shown¹⁷ that there is an optimal time interval between successive new plants. Decreasing the discount rate or the cost scaling factor causes the optimal time interval to increase.

In practice, it is reasonable to expect that new plants generally will not be as large as the optimal expansion model would indicate, because of the risk and uncertainty in making large capital investments, especially since the risk of technological obsolescence is great, and because of the effect of competition in splitting up the market. The highly capital-intensive nature of the industry implies a high degree of risk with respect to downward variation of demand. Also, it is frequently cheaper to add new capacity by expanding an existing plant than by building a new one. Because of considerations such as these, the studies reported in References 8 and 9 assumed that the nuclear fuel industry would grow in smaller increments than those indicated by the theoretically optimal path, and we have followed the same policy here.

New Facilities Required

Table 6 summarizes existing nuclear fuel capabilities and estimated new requirements by the year 2000. The new requirements are based on

Table 6. PROJECTED INVESTMENT REQUIREMENTS FOR NUCLEAR
FUEL FACILITIES TO YEAR 2000^a

	Present Capacity (1972)	Capacity Required by Year 2000	New Capital Investment, \$10 ⁹
Uranium Exploration, Mining, and Milling (short tons U ₃ O ₈ /yr)	16,000 ^b	62,000-109,000	5.0 - 8.0 ^c
Uranium Purification and Fluorination (short tons U/yr)	19,000 ^b	80,000-93,000	0.3 - 0.8
Uranium Enrichment (kg SWU/yr)	17.2 x 10 ⁶	80-134 x 10 ⁶	11.0 - 20.0 ^d
Fuel Fabrication (MTH/yr)	3000 ^e	20,000-28,000	3.0 - 4.0
Chemical Reprocessing (MTH/yr)	300 ^f	18,000-24,000	1.6 - 2.4
Total ^g			20.9 - 35.2

^aAll costs are expressed in 1972 dollars. Investment includes new plants required due to retirement of old plants.

^bWASH-1174-71.

^cCost includes development of an 8-year forward reserve beyond year 2000.

^dCost includes facilities for supplying electric power.

^eRough estimate; actual capacities are proprietary.

^fExcluding capacity of government-owned plants.

^gDoes not include permanent waste disposal facilities.

the industry demand projections shown in Figures 3 through 8 and include replacement of facilities retired due to age. For example, Figure 6 shows fabrication requirements of 20,000 - 28,000 MT/yr in year 2000, but total new capacity built is 34,000 - 40,000 MT/yr because of replacement of plants built through 1985. Estimated new capital investments are also shown, based on the figures used in Table 5. The total new investment required is from 21 to 35 billion dollars, of which over half is for uranium enrichment plants and their associated electric power supply. It is assumed that the useful life of existing uranium enrichment facilities can be extended to the year 2000 following the cascade improvement and uprating programs. Fuel supply facilities account for about 93% of the new investment, and chemical reprocessing for about 7%.

In chemical reprocessing, FBR and HTGR fuels are assumed to be processed at half the nominal LWR fuel capacity. Using a weighting factor of 2 for FBR and HTGR, the total weighted capacity required in year 2000 is 26,000 - 36,000 MT/yr. Because of plant retirements, total new plant construction is 36,000 - 46,000 MT/yr (equivalent LWR capacity), representing 14 - 20 new plants. Permanent waste disposal facilities have not been included; these would add perhaps 0.1 to 0.3 billion dollars to the total investment.

The capital investment in the fuel cycle industry is placed in better perspective by comparing it with the capital requirements for the nuclear electric power plants which it serves. The capacity of new nuclear power plants required to year 2000 is 1300 - 1500 GWe, and the investment in these plants will be about 400 billion dollars. Thus the investment in fuel facilities is only about 5 to 9% of the total. Assuming that the capital for the power plants can be obtained, it seems clear that raising the additional capital for the fuel facilities is a relatively small problem.

SUMMARY

This paper provides an overview of the nuclear fuel cycle logistical requirements under conditions anticipated in the U.S. over the next 30 years. The requirements in the pre-1990 period will be dominated by LWR's and involve little uncertainty from a new facility planning viewpoint. The requirements in the post-1990 period involve major uncertainties as they are strongly dependent on the sharing of the market between LWR, HTGR and FBR systems. Large-scale FBR introduction by the mid 1980's would significantly reduce the required capital investment for uranium supply and enrichment facilities and would provide investment protection to thermal reactor operators by slowing down the drain on our low cost uranium reserves. New capital investment in the nuclear fuel cycle industry would average around 1.5 billion (1972) dollars per year over the next 20 years of which about 90 percent would be needed for the supply of U_3O_8 and separative work and 10 percent for fuel fabrication and reprocessing.

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THE NUCLEAR FUEL CYCLE

FIGURE 2

TYPICAL TRENDS OF URANIUM COSTS AND PLUTONIUM VALUES WITH AND WITHOUT FBR

-- LWR + HTGR ONLY
— WITH FBR BY 1986

Constant Separative
Work Cost @ \$22/unit

U_3O_8
COST, \$/lb

FISSILE Pu
VALUE, \$/GM

Annual Uranium Requirements

FIGURE 3

FIGURE 4

Cumulative Uranium Requirements

- Includes 8 year Forward Reserve
- U.S. Resources as of Jan. 1971

FIGURE 5

Annual Uranium Requirement

Million Separative Units

EXISTING CAPACITY

Year

With FER by 1986

With FER by 1990

LWR+FER Only

CIP+CUP 27.7

17.2

Figure 6
Annual Fuel Fabrication Requirements

Figure 7

Figure 8

Annual Fuel Reprocessing Requirements

Figure 9.

PROJECTED ANNUAL TRAFFIC OF LARGE RADIOACTIVE SHIPMENTS

Assumed Average Shipments

① SPENT FUEL

- LWR @ 2 MTH
- FBR @ 1.2 MTH *
- HTGR @ 0.6 MTH

② FRESH FUEL WITH PU or U233

- LWR @ 4 MTH
- FBR @ 1.2 MTH *
- HTGR @ 0.5 MTH

③ PU / U233 MIXTURES @ 100 Kg

④ 93% ENRICHED U @ 100 Kg

⑤ HIGH LEVEL WASTE PER ORNL-4682 AND 5-Yr Delay.

* FBR Fuel Represents a 40/60 WEIGHT MIXTURE OF CORE PLUS BLANKET

Thousands of Shipments

1975

1980

1985
Year

1990

1995

2000