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THORIUM FUEL CYCLE STUDIES — FUEL FABRICATION

PROCESS AND COST ESTIMATION

A. R. Olsen

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A. R. Olson

ABSTRACT

Early in 1976 a study was made to assess the relative economics and fuel utilization of thorium and uranium fuel cycles in various types of reactors. It was to be completed in approximately two months, so all component parts had to be developed in a short time with a high degree of dependence on existing information. One of the components required for the study was a consistent set of relatively accurate fuel fabrication costs for the various reactor-fuel combinations. Our report documents the rationale used in generating these cost estimates and presents in some detail the basis and methodology employed.

Since three types of thermal flux reactors (LWR, HWR, and HTGR) and two types of fast flux reactors (liquid metal and gas cooled) together with three fuel forms (oxides, carbides, and metal) were included in the study with various combinations of the fissionable metals U, Th, and Pu, it was necessary to define a methodology that would permit a rapid relative estimate for each case.

We chose existing cost studies for a Light-Water Reactor with low-enriched uranium fuel and for a High-Temperature Gas-Cooled Reactor with highly enriched uranium and thorium fuel as the reference cases with which we could compare other reactor-fuel combinations.

We identified specific fuel element designs and defined process flowsheets. A list of fuel characteristics, process requirements, and regulatory requirements that could affect plant design and operating conditions were compiled. By using these inputs we then estimated each fractional increment in the fabrication cost for each reactor-fuel combination to provide a relative value factor. Finally the relative values were converted to unit costs (dollars per kilogram of heavy metal) by establishing a cost for the reference cases and multiplying this cost by the relative value factor for each derived estimate.

We believe that the relative values are more accurate than the unit costs because of the uncertainties both in the costs for the reference cases and in the regulatory requirements that might be imposed at the time the plants are constructed. However, the unit costs are sufficiently accurate for our overall study purposes, and the set is internally consistent.

Although many of these estimates have been superseded by subsequent studies, the rationale for this original estimate is largely still pertinent. Our subsequent estimates have largely resulted from a modification of this process, with

increased consideration of details within each broad cost category. However, we have applied the cost influencing factors associated with fuel materials characteristics, safety considerations, safeguards, process complexity, and fuel element designs in our subsequent studies.

INTRODUCTION

Early in 1976 ORNL was requested to conduct a short, concentrated study to assess the relative economics and fuel use of thorium and uranium fuel cycles in various types of reactors.¹ The study was to be completed in about two months, which necessarily required a high degree of dependence on existing, readily available information.

Our component of this study was to develop a consistent set of fuel fabrication costs for each reactor-fuel combination that could be used in other components. These data were needed early in the study and consequently were generated in about one month. The objective of our report is to present the rationale used in generating these cost estimates for fuel fabrication and to present in some detail the bases and methodology.

Although many of these estimates have been superseded by subsequent studies the rationale for this original estimate is largely still pertinent. Our subsequent estimates have largely resulted from a modification of this process, with increased consideration of details within each broad cost category. However, we have applied the cost influencing factors associated with fuel materials characteristics, safety considerations, safeguards, process complexity, and fuel element designs in our subsequent studies.

REACTOR SYSTEMS AND FUELS

The initial study was to consider three types of thermal flux reactors: the Light-Water Reactor (LWR), the Canadian Deuterium Uranium Reactor (CANDU), and the High-Temperature Gas-Cooled Reactor (HTGR) together with two types of fast flux breeder reactors: the Liquid-Metal-Cooled Fast Breeder Reactor (LMFBR) and the Gas-Cooled Fast

Breeder Reactor (GCFR). The study was later extended to include the thermal flux Light-Water Breeder Reactor (LWBR) to the extent that available information would permit.

For each reactor a series of fuel cycles was defined for three fissile components — ^{235}U , ^{233}U , and Pu — and two fertile components — ^{238}U and Th. The cycles considered are in Table 1. By eliminating duplications, estimations were reduced to 21 reactor-fuel combinations.

Table 1. Fuel Cycles Considered for Each Reactor Type

Reactor Type	Initial Fuel	Recycle Fuel
LWR	$(^{235}\text{U}, ^{238}\text{U})\text{O}_2$	$(\text{Pu}, ^{238}\text{U})\text{O}_2$
	$(^{235}\text{U}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
	$(\text{Pu}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
CANDU	Normal UO_2	$(\text{Pu}, ^{238}\text{U})\text{O}_2$
	$(^{233}\text{U}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
	$(\text{Pu}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
LMFBR	$(\text{Pu}, ^{238}\text{U})\text{O}_2$	$(\text{Pu}, ^{238}\text{U})\text{O}_2$
	$(\text{Pu}, ^{238}\text{U})\text{C}$	$(\text{Pu}, ^{238}\text{U})\text{C}$
	$^{233}\text{U}\text{-Th}(\text{alloy})$	$^{233}\text{U}\text{-Th}(\text{alloy})$
GCFR	$(\text{Pu}, ^{238}\text{U})\text{O}_2$	$(\text{Pu}, ^{238}\text{U})\text{O}_2$
	$(^{233}\text{U}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
	$(\text{Pu}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
LWBR	$(^{233}\text{U}, \text{Th})\text{O}_2$	$(^{233}\text{U}, \text{Th})\text{O}_2$
HTGR	$^{235}\text{UO}_2\text{-ThO}_2$	$^{233}\text{UCO}\text{-ThO}_2$
	$^{235}\text{UO}_2\text{-}^{238}\text{UO}_2$	$\text{PuO}_2\text{-}^{238}\text{UO}_2$
	$\text{PuO}_2\text{-ThO}_2$	$^{233}\text{UCO}\text{-ThO}_2$

BASIS OF THE ESTIMATES

The objective of our component of the study was to provide a consistent set of fabrication cost factors wherein the relative costs of different reactor-fuel combinations would be as accurate as possible.

Since other components would assess the value of various combinations, it was necessary to define the cost estimates to suit these other components. To meet this need the relative costs were:

1. normalized to reasonable actual dollar values based on available data,
2. reduced to a unit cost basis of dollars per kilogram of heavy metal (\$/kg HM) for a nominal production plant capacity, and
3. provided with a scaling factor for variations of cost estimation with industry size.

We derived relative fabrication cost factors from previously reported formal estimation procedures.^{2,3}

The preliminary requirements for defining basic data when estimating costs are:

1. establish reference fuel element designs for each reactor-fuel combination,
2. define reference fuel fabrication processes for each fuel, and
3. identify factors that could influence costs.

How these preliminary requirements were met is discussed in subsequent sections of this report.

To maintain consistency and provide the best possible relative cost factors, we decided to compare the various reactor-fuel combinations with common references. Nuclear fuel fabrication is a manufacturing operation, and the basic steps in both fresh and recycle fabrication are essentially the same. However, nuclear fuel for power generating reactors is available in two forms:

1. oxide fuel pellets contained in metal tubes arranged in a mechanical assembly — fuel for commercial Light-Water Reactors [pressurized-water reactors (PWRs) and boiling-water reactors (BWRs)^{4,5}], Heavy-Water Reactors (HWRs), Light-Water Breeder Reactors (LWBRs), and fast breeder reactors (either liquid metal or gas cooled) is in this form; and

2. microspheres coated with layers of ceramic coatings contained in a graphite assembly — fuel for High-Temperature Gas-Cooled Reactors is of this form.

Thus, two references were selected. All metal clad fuel rod types were compared with the current LWR low-enriched fuel fabrication process with use of the Westinghouse PWR element design. The HTGR elements were compared with ^{235}UO fissile particle and ThO_2 fertile particle fuel fabrication with use of the General Atomic prismatic fuel element design.

The LWR reference cost factors were derived from an earlier study³ and were modified and updated to accommodate current licensing restrictions. The HTGR reference case was derived from an ERDA study⁶ and fit to the LWR cost factors.

REFERENCE FUEL ELEMENT DESIGNS

As indicated earlier it was necessary to define reference fuel element designs for each reactor-fuel combination. We needed these designs primarily for our fabrication cost estimate but also used them to estimate the amount and types of nonfuel materials to be handled during reprocessing.

To define these element designs we consulted readily available literature. The various reactor elements are compared briefly in Table 2. Each combination is discussed by reactor type in the following sections, and the design details are presented in the tables of Appendix A.

Light-Water Reactors (LWR)

Both pressurized-water reactors (PWRs) and boiling-water reactors (BWRs) exist in the current commercial reactor economy. Each type of reactor and each reactor vendor have different fuel element designs. Since Westinghouse has the largest number of operating reactors and a readily available reasonable description of its fuel element design, this design was chosen as the base case for our cost estimate. The information in Appendix A, Table A1, was extracted from a preliminary

Table 2. Typical Fuel Element Characteristics^a

Attribute	Reactor Type						
	CANDU	PWR	BWR	LWBR		LMFBR	HTGR (Prismatic)
				Seed	Blanket		
Cross section shape	Circ	Square	Square	Hex	Ann-Hex	Hex	Hex
Approx dimension, m (in.)	0.1 (4)	0.21 (8.4)	0.14 (5.4)	0.25 (10)	0.43 (17)	0.12 (4.7)	0.36 (14)
Length, m (in.)	0.495 (19.5)	4.06 (160)	4.47 (176)	4.27 (168)	4.27 (168)	4.27 (168)	0.76 (30)
Pins per assembly (HTGR fuel columns)	37	264	63	619	444	271	132
Pin diameter, mm (in.) (HTGR column diameter)	1.3 (0.53)	3.5 (0.37)	12 (0.49)	6.6 (0.26)	14 (0.57)	7.9 (0.31)	16 (0.62)
Approx heavy metal content, kg	20	461	190	620	1760	148	10

^aSee Appendix A for additional details.

safety analysis report (Sect. 4) for a given reactor design.⁷ The currently preferred design is the 17 by 17 array fuel assembly. Although the pin diameters are different from those used by other PWR manufacturers (Combustion Engineering and Babcock and Wilcox), the competitive nature of the industry would indicate that fabrication costs should be comparable and well within the uncertainties of our estimate. An additional factor that influenced our choice was the availability of an earlier detailed cost estimate for a similar design.^{3,8}

CANDU Reactors (HWR)

The principal sources of information on the CANDU element design were three papers published in 1970.⁹⁻¹¹ Although these references discuss several element designs, we chose one representative of recent reactor fuel. Details of this design are presented in Appendix A, Table A3. Time limitations precluded any consideration of design changes with type of fuel. Thus, a common element design was assumed for all CANDU-fuel combinations.

Liquid-Metal Fast Breeder Reactors (LMFBR)

Selection of a reference fuel element design for the LMFBR was complicated by a variety of considerations. There are two competing commercial power reactor designs in the U.S. This is further complicated by consideration of first generation reactors, the so-called Early Oxide Designs and the later Advanced Oxide Designs. In addition, advanced concepts involving the carbides, nitride, or possible metal alloy fuels clearly require different designs.

For the oxide fuels most information was readily available for the Fast Flux Test Facility (FFTF)¹² reactor driver fuel and the Clinch River Breeder Reactor (CRBR)^{13,14} fuel elements. These were considered in addressing the complexity of the element assembly and fuel parameters, while tabular data¹⁵ for a Westinghouse target plant design were used to generate the fuel rod dimensional data for the commercial power reactor design for our study. The details are given in Appendix A, Table A4.

The carbide fuel element design, also thought to be applicable to nitride fuels, was derived from a Combustion Engineering parameter analysis.¹⁶ The 9.40-mm-OD (0.370-in.) pin design was selected for the reference in that study. We chose sodium for the fuel-to-cladding thermal bond, although the use of helium-bonded pins may ultimately be identified as a better design. The design parameters are given in Appendix A, Table A5.

The use of thorium in fast breeder reactors has been under consideration for a long time. However, only a limited amount of performance data is available, and no information was available for a specific design for this fuel combination. Since thorium alloys are not subject to the large swelling rates of uranium alloys¹⁷⁻²⁰ during irradiation exposure, development of this alloy fuel was assumed. A similar conclusion is indicated in a more recent study reported by Electric Power Research Institute (EPRI).²¹ As a result of the lack of any specific design information, we chose a reference that was essentially the same as for the carbide fuels. The reference parameters are given in Appendix A, Table A6.

Gas-Cooled Fast Breeder Reactor (GCFR)

Data for the cost estimate reference design for the Gas-Cooled Fast Reactor were derived from a General Atomic report.²² Only oxide fuels were considered, and the parameters given in Appendix A, Table A7, were used for all GCFR-fuel combinations.

High-Temperature Gas-Cooled Reactors (HTGR)

There are currently two types of HTGR fuels — the German Pebble Bed Concept and the General Atomic prismatic fuel element. Our study was restricted to the prismatic fuel because design information and other data on which to establish the base case cost estimates for this type of fabrication were readily available. The base case design parameters are presented in Appendix A, Table A8. We recognized that different designs involve variations in the conversion ratio, but the effects of these on fabrication were considered to be within the uncertainties of the estimate;

thus, the element design for a conversion ratio of 0.66 was the only one considered. This design was assumed for all HTGR fuel combinations.

Light-Water Breeder Reactors (LWBR)

As indicated in the introduction, the LWBR was added to the study later. Published information on a commercial scale breeder reactor of this type was not available. Consequently, the reference design used in this study was based on the available demonstration plant design data.²³⁻²⁵ Although the current LWBR reactor development program envisages a prebreeder as well as a breeder reactor phase, we considered only the seed and blanket assemblies for the breeder reactor phase. Prebreeder fabrication costs were considered comparable to LWR-UO₂ (low-enrichment) costs. Only a single fuel system was considered in this estimate, as the uncertainties in fuel design for a commercial scale reactor were too high to incorporate in this report.

General

In addition to the specific parameters for each reference design in Appendix A, all available information, including drawings, tolerance, and quality control features for each assembly, were considered in our cost estimation.

REFERENCE PROCESS DEFINITION

A second prerequisite for making the cost estimates was to establish reference process flowsheets for each of the fuels and fuel elements. We used these flowsheets to assess the relative requirements in equipment, manpower, and time.

For most of the fuels considered the fuel element fabrication process starts with the receipt of fissile and fertile oxide powders. The conversion processes are included in the reprocessing cost estimates. The powder preparation step includes both conditioning and blending, which must precede pellet fabrication, grinding (if necessary), inspection, and a final conditioning to remove dust and moisture. The third stage

of rod fabrication includes hardware preparation and actual insertion of the fuel and other internal components into the cladding, final closure and complete quality control testing. The final step of element assembly involves hardware preparation, assembly, and extensive quality control testing to assure element integrity and performance in the reactor.

Each process step, particularly powder preparation and pellet fabrication, generates a significant amount of scrap material. To produce a unit of acceptable product industrial experience has shown that between 1.1 and 1.2 units must be processed in the early fuel fabrication. This scrap is far too valuable to discard, so a scrap recycle system is economically justified. In addition, after recovering the valuable fissile materials the reusable chemicals should be reclaimed and all other wastes treated and prepared for final disposition. Current federal regulations have placed tight restrictions on liquid, gaseous, and solid wastes. Thus, the auxiliary processes of scrap recovery and waste treatment have become important economic considerations in fuel manufacturing. Though we did not develop reference flowsheets for these auxiliary systems, we considered the degree of complexity and extent of these systems in our actual estimation.

The actual processing must be tailored for each reactor type and each fissile and fertile component. However, the main steps can be generically identified on the basis of compounds and compositions to provide an adequate reference, which can provide a basis for relative cost estimation. To this end we prepared simplified process flowsheets, which are described below.

Both the generic nature of these flowsheets and the similarity between fresh and recycle fuel manufacturing can be seen in Fig. 1. This flow diagram addresses the typical steps in processing oxide powders to fuel elements and can be used for the LWR, CANDU, or LWBR reactors, which contain fuel pellets in Zircaloy tubes for the individual fuel rods. The process steps are essentially unchanged with fuel composition variables although batch and lot sizes may vary significantly because of considerations such as prevention of criticality. Thus, low-enriched UO_2 for the LWR fresh fuel would start with UO_2 powder of the appropriate

enrichment in large batches and lot sizes to minimize process adjustments in the subsequent pelletizing processes. On the other hand, for recycle fabrication using plutonium as the fissile component, the PuO_2 batch sizes would have to be restricted, and separate conditioning of the UO_2 and PuO_2 before batch blending would probably be required. The mixed oxide, with about 3% PuO_2 , would permit the accumulation of larger lots than would be permissible with the fast reactor fuels in which the PuO_2 content might be as high as 30%.

Figure 2, while very similar to Fig. 1, introduces some of the complications associated with variable fuel rod contents, specifically the axial blanket UO_2 in the fast breeder reactor. This flowsheet is applicable to oxide fuels for both the LMFBR and GCFR.

The reference process flowsheet for carbide fuels in Fig. 3 was based on the carbothermic reduction of oxide powders. Although this process has not been proven on a commercial scale, we felt that its economic advantages would result in its being chosen for fabrication of advanced fuels. Because of the lack of commercial experience the process flowsheets and the resulting estimates have a somewhat higher degree of uncertainty than those for oxide fuels.

The uranium-thorium alloy process in Fig. 4 has an even higher degree of uncertainty than the carbide system. Each of the process steps has been proven on a laboratory scale,²⁶ and a significant amount of ^{235}U -Th alloy fuel has been irradiated in core II of the Sodium Reactor Experiment.²⁷ However, commercial scale processing, particularly with ^{233}U , has not been demonstrated. This process flowsheet represents only one of several alternatives.

The HTGR fuel fabrication process in Fig. 5 is based on our development of HTGR fuels and our recent work in the development of processes and equipment to be used in a proposed High-Temperature Gas-Cooled Reactor Recycle Demonstration Facility (HRDF).²⁸ As with other fuels the fresh and recycle fuel manufacturing processes are very similar.

Fig. 1. Oxide Fuel Element Fabrication.

Fig. 2. FBR Oxide Fuel Element Fabrication.

Fig. 4. FBR ^{233}U -Th Metal Fuel Element Fabrication.

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Fig. 5. Process for HTGR Recycle Fabrication.

COST INFLUENCE FACTORS

The fabrication costs for each reactor-fuel combination are subject to a number of imposed influences. For example, the product attributes are defined by both reactor designers and safety analysis considerations, while the fabrication plant design and operating procedures depend highly on both material characteristics and licensing regulations. In preparing a relative cost estimate we must consider all these factors. However, five major considerations predominate: fuel materials, safety, safeguards, process complexity, and fuel element design. Except for fuel materials these considerations are all interdependent; each is influenced by all of the others and in turn influences them.

Fuel Materials is the most important consideration. Fuel materials are the basic constituents in the fissile and fertile components.

Each fissile component has a set of characteristics that determine safety and safeguard considerations. The relatively low specific activity and biological hazards of ^{235}U permit the design and operation of a plant that uses contact (hands-on) fabrication. On the other hand, biological hazards of plutonium require that all operations be performed in contained equipment to prevent operator exposure. In addition, depending on the plutonium isotopic distribution, shielding against penetrating radiation may be required. The chemical characteristics increase both process complexity and safeguards considerations. Similar to plutonium as a biological hazard from ingestion,²⁹ ^{233}U requires significant shielding as well as containment of most of its processes because of the high energy of the gamma rays from a decay product of contained ^{232}U . A relative comparison of radiation dose levels for the three types of fissile components is given in Table 3.

The fertile components ^{238}U and thorium have a less significant effect on cost because of their lower inherent biological hazard but do influence the process complexity because of different chemical characteristics.

Safety Considerations, as discussed above, is predominantly influenced by the inherent characteristics of the fissile component. Included in these characteristics is the potential for accumulating a

Table 3. Radiation Dose Levels for Various Fissile Components

Fissile Component	Radiation Dose Rate, ^a millirem/h	
	Gamma	Neutron
UO ₂ (3-4 wt % ²³⁵ U)	<0.01	~0
PuO ₂ (100 d after separation) ^b	5	1
²³³ U (100 d after separation) ^b	750	0.1

^a Measured at 0.5 m from steel container (0.5 mm wall) loaded with 0.5 kg HM.

^b Isotopic compositions: Pu — ²³⁶Pu, 0.45 × 10⁻⁵%; ²³⁸Pu, 1.92%; ²³⁹Pu, 63.3%; ²⁴⁰Pu, 19.2%; ²⁴¹Pu, 11.68%; and ²⁴²Pu, 3.88%. ²³³U — ²³²U, 0.05%; ²³³U, 92.1%; ²³⁴U, 7.35%; and ²³⁵U, 0.57%.

critical mass. Although the precise quantities required for a critical mass depend upon a number of conditions, significantly less material is required for either Pu or ²³³U than for ²³⁵U. Thus, cost can significantly increase from fabrication equipment component size and spacing requirements together with batch and lot size limitations.

Safeguards is predominantly a social and political consideration. However, some of the requirements are met naturally by good business practice for both economic and safety reasons. The value of the fissile material is such that a loss represents a significant economic penalty, and the orderly movement and monitoring of material through the fabrication process is required to assure product acceptability and reduce rejects with their obvious effects on profits.

Other safeguard features require that plant design and operational procedures detect and prevent unauthorized removal of the material by either covert or overt actions. The extent of these features will vary with the fissile component and enrichment. Since plutonium is readily separable by chemical processes from other fuel components and a relatively small amount is needed for an explosive device, it will require the most stringent protection. Highly enriched uranium containing either ²³⁵U or ²³³U must also be provided with this high degree of protection.

Process Complexity can be derived from analysis of the reference process flowsheets described earlier. However, additional items that influence fabrication cost were considered. Product quality assurance activities vary with the process and are increased as batch and lot sizes decrease or design tolerances tighten. Typically, quality assurance can account for up to 30% of the operating cost in current LWR fabrication. Equipment maintenance is an extremely important part of the cost in that space, and equipment to accommodate these activities must be incorporated in the plant design, operating personnel exposures must be considered, and a judgment must be made on the need for installed spares to assure continued plant productivity. Two additional elements, scrap recovery and waste treatment, are strongly influenced by both the fissile and fertile components. The chemical characteristics of both plutonium and thorium require the use of halides in the scrap recovery dissolution process, which increases the system costs and complicates the waste treatment and recycle of liquids. The decay products of the ^{232}U isotope in the ^{233}U fissile component increase the complexity of off-gas treatment systems. Both plutonium and ^{233}U in solid waste can change the storage category.

Fuel Element Design has been addressed earlier in defining the reference designs. The dominant factors influencing cost are fuel diameter, fuel density, fabrication tolerances, contaminant specifications, hardware complexity, and enrichment variables.

RELATIVE COST ESTIMATION

To obtain a consistent set of costs for all the reactor-fuel combinations we wanted to establish a systematic cost component breakdown. Typically, costs cover capital, hardware, and operation. These define the fabrication costs exclusive of any fissile component costs. In the past where detailed element designs, plant conceptual designs, and specific process definitions have been available, cost has been estimated with sophisticated computer codes.^{2,3}

Cost Category Definition

The large variety of fuel materials and fuel element designs in our study precluded the use of computerized estimation. However, the LWR(PWR) case³ from FABCØST 9 formed the basis for the reference for metal clad cylindrical fuel rod types and provided the appropriate distribution of cost elements under the categories of capital, hardware, and operation, as shown in Table 4.

This table is similar to the breakdown given in the reference document³ but varies in two important ways. First, a fourth category covering fuel element design factors has been added. It is included to accommodate both the effects of fuel rod diameter changes for the metal clad tubular rod fuel elements and the density changes associated with fuel compound variations. These factors are used to adjust the cost estimates for different design and fuel compounds when they are converted to a unit basis. The adjustment is usually made on the sum because all categories are affected by changes in fuel mass per unit length of rod. The second modification is the addition of scrap recovery and waste treatment. These elements were added because they are currently required or anticipated for licensing³⁰ U.S. commercial fabrication plants. They must be considered in both capital and operating cost categories.

The numerical values for each category were derived from the earlier study³ after making adjustments to incorporate the new features. These adjustments were based on the anticipated effect of new regulations pertaining to material accountability, environmental protection, scrap recovery, and waste treatment. We assumed an increase of 50% for capital and 40% for operation. Both were based on an assumed recycle fraction of 30% for the fuel material, which includes quality control samples and preparation of all waste for solid disposal.

The cost element fractions⁵ were also derived from the previous study³ of a contact operation plant. The fractional breakdown of the operating cost was recalculated after the addition of the manpower units for scrap recovery and waste treatment. For the capital costs two sets of elemental fractions are included. The contact-operation breakdown of 0.66 for equipment and 0.33 for building was derived from the earlier

Table 4. Cost Estimation Component Factors^a

Categories	Percent of Total for Categories for Current PWR Elements	Element Fraction	
		Contact	Other
A. Capital costs	33		
1. Equipment		0.66	0.5
2. Building		<u>0.33</u>	<u>0.5</u>
		1.00	1.0
B. Fuel element hardware	38		
1. Cladding with end caps		0.36	
2. Fuel rod internals		Neg	
3. Assembly hardware		<u>0.64</u>	
		1.00	
C. Operation ^b	29		
1. Cladding preparation		0.19	
2. Fuel preparation		0.48	
3. Rod loading		0.02	
4. Element assembly, inspection and packaging		0.04	
5. Scrap recovery ^b		0.14	
6. Waste treatment ^b		<u>0.14</u>	
		1.00	
Total	100		
D. Fuel element design factors (metal clad)			
1. Fuel density [case fuel density (g/cm ³) ÷ 10.4 = X]			
2. Fuel diameter [diam (in.) ÷ 0.315 = Y]			
	100(X)(Y)		

^aFactors derived from FABCOST 9 PWR case: A. L. Lotts, T. N. Washburn, and F. J. Homan, *FABCOST 9, A Computer Code for Estimating Fabrication Costs for Rod-Bundle Fuel Elements*, ORNL-4287 (August 1968).

^bFactors adjusted to include scrap recovery and waste treatment that were added for current licensing considerations.

study. However, in view of the additional costs involved in the more complicated building structure, the additional services, and the additional space requirements for maintenance functions needed for other types of operations, we split the capital costs for all other types of operation equally between the equipment and building. Multiplying the category fraction times the cost element fraction defines explicitly the cost contribution for that element for the reference case. This is the reference element increment. Each increment represents a specific fraction of the fuel fabrication costs for the reference reactor-fuel combination.

Relative Cost Development

After establishing the element fractional estimates for the reference cycles, we estimated the cost for alternative reactor fuel by assigning an incremental multiplier to each fractional element for a given reactor-fuel combination. For the capital and operating categories no single incremental modifier can be considered separately. One must judge between additional capital costs to provide mechanized process equipment, spares, maintenance space and accessories, etc., and lower operating costs by reducing manpower requirements, plant availability, etc.

Since most of the fuels considered represent a significant safety hazard to operating personnel and more restrictive regulations on permissible operating personnel radiation exposures are anticipated, we assumed a high degree of process automation for all plants. These considerations were augmented by the economics of material flow monitoring and accountability, the generally more uniform product characteristics of mechanized operation, and the large amount of quality control data and records that must be collected and collated to satisfy both the customer and the Nuclear Regulatory Commission auditors that the product element is suitable for use in a commercial power reactor. Finally, the higher degree of automation is more readily adapted to provide process information that may be needed to satisfy safeguards requirements and to reduce the man-material interfaces that must be monitored to prevent overt removal of material.

Changing federal regulations, the cost of construction, the availability of skilled manpower, and other business considerations can alter the balance between the capital and operating categories for a given commercial venture. Therefore, each incremental multiplier, element fraction, and category fraction is considered less reliable than the integral of all these components for each reactor-fuel combination estimate.

In selecting the incremental multipliers we considered all the reference fuel element designs and reference process flowsheets. The primary influence on the value of the multiplier was, as indicated earlier, the fissile component of the fuel. The tables in Appendix B include the specific incremental multipliers for each reactor-fuel combination.

The equation for calculating the individual portions of each reactor-fuel combination cost factor is

$$\text{CF (Category Fraction)} \times \text{EF (Element Fraction)} \times \text{IM (Incremental Multiplier)} = \text{Estimated Incremental Relative Cost Factor}$$

The summation of the relative element increments yields the total relative cost factor of the given combination.

The final adjustment of the reactor-fuel combination relative cost factors involved corrections for fuel density and fuel diameter for each of the tubular rod assemblies. The needed data derived from the element descriptions of Appendix A and the factors derived are presented in Appendix B.

Table 5 is an example of the development of relative cost factors for LWR (PWR) fuel elements where dimensional and density adjustments are not required. In this example two types of commercial fabrication plants were considered for the Mixed Oxide (MOX) $\text{PuO}_2\text{-}^{238}\text{UO}_2$ recycle fuel. For both the glove-box and fully remote operations the fuel assembly hardware cost elements neither increase nor decrease when compared with the current LWR $(^{235}\text{U-}^{235}\text{U})\text{O}_2$ fuel; so the incremental multipliers are 1. This unit multiplier does not apply to most of the elements of the capital and operating cost categories. Consideration

Table 5. Example of Relative Cost Estimation

	Category Fraction	Element Fraction	LWR-MOX Glove Box		LWR-MOX Remote	
			IM ^a	Estimate	IM ^a	Estimate
I. Capital costs	0.33					
Equipment		0.5	1.5	0.25	3	0.50
Building		0.5	3.0	<u>0.50</u>	6	<u>0.99</u>
Estimated factor				0.75		1.49
II. Hardware costs	0.38					
Cladding plus end plugs		0.36	1	0.14	1	0.14
Rod internals			1	Neg	1	Neg
Assembly hardware		0.64	1	<u>0.24</u>	1	<u>0.24</u>
Estimated factor				0.38		0.38
III. Operating costs	0.29					
Cladding preparation		0.19	1	0.06	1	0.06
Fuel preparation		0.48	5	0.70	5	0.70
Rod loading		0.02	2	0.01	2	0.01
Element assembly inspection and packaging		0.04	2	0.02	10	0.12
Scrap recovery		0.14	4	0.16	4	0.16
Waste treatment		0.14	10	<u>0.40</u>	10	<u>0.40</u>
Estimated factor				1.35		1.45
Total estimated relative cost factor				2.48		3.32

^aIncrement multiplier.

must be given to other factors as indicated in Table 6. For example, the equipment cost for glove-box operation is 1.5 times as expensive as that for contact operations. This is a result of space and access restrictions, sealed service connections through the containment wall, and localized shielding for regions of high plutonium material accumulation. The fully remote equipment is 3 times as expensive as contact operations. This increased cost provides for remote component replaceability and other maintenance as well as the additional equipment to replace some operations (such as pressure adjustment controls for the pellet press), which could be done by the operators in the glove-box operations. Batch and lot size restrictions for both glove-box and remote operations increase the number of process lines in the system to provide equivalent annual capacity. This is needed only in the early stages of fabrication when plutonium is concentrated. Building cost incremental multipliers are influenced by similar considerations, as shown in Table 6. However, the additional ventilation requirements; space needed for maintenance operations; isolation of plutonium scrap; waste treatment of chemical processing liquids, which may contain corrosive chemicals; and safeguards considerations make these incremental multipliers larger. A similar rationale is used for each operating cost element in this example and in each of the other reactor-fuel combination estimates.

The resulting relative cost comparisons for all combinations are presented in Table 7. These include the adjustments for fuel diameter and density for the tubular rod assemblies. There are no such adjustments for the HTGR fuel elements since a common design was considered for the base case and each of the alternative fuel selections. Note that there are minor differences between this table and a similar table given by Kasten et al.¹ These are the result of arithmetical errors discovered during the preparation of our report, rather than changes in the estimating procedure or evaluation made at that time. The two significant errors are associated with the $(^{233}\text{U},\text{Th})\text{O}_2$ fuel for a LWR and a gas-cooled FBR where the effects of fuel density were not included in the original estimate. This consideration increases the total factor by

Table 6. Capital Cost Considerations

A. Building

1. Environmental containment
2. Safeguards
3. Mode of operation and maintenance
 - (A) Contact
 - (B) Lightly shielded
 - (C) Heavily shielded
4. Process area environment
 - (A) Air
 - (B) Inert
5. Process complexity

B. Equipment

1. Environmental containment
 2. Safeguards
 3. Mode of operation and maintenance
 - (A) Contact
 - (B) Lightly shielded
 - (C) Heavily shielded
 4. Process area environment
 - (A) Air
 - (B) Inert
 5. Process complexity
 6. Criticality considerations
 7. Accountability requirements
 8. Degree of automation
-

Table 7. Relative Fabrication Cost Comparison^a

Reactor Fuel	Fuel Material	Relative Cost Factors			
		Capital	Hardware	Operating	Total
Part A					
LWR (PWR)	(²³⁵ U,U)O ₂	0.33	0.38	0.29	1.00 ^b
	(Pu,U)O ₂	1.49	0.38	1.45	3.32
	(²³⁵ U,Th)O ₂	0.41	0.42	0.44	1.27
	(²³³ U,Th)O ₂	2.18	0.42	1.60	4.19
	(Pu,Th)O ₂	1.49	0.38	1.53	3.40
CANDU	Natural UO ₂	0.33	0.09	0.11	0.53
	(Pu,U)O ₂	1.49	0.09	0.50	2.08
	(²³³ U,Th)O ₂	1.98	0.12	0.55	2.65
	(Pu,Th)O ₂	1.49	0.09	0.55	2.13
LMFBR	(Pu,U)O ₂	3.19	0.58	2.10	5.87
	(Pu,U)C	2.68	0.37	1.66	4.72
	²³³ U,Th	2.73	0.35	1.61	4.69
GFBR	(Pu,U)O ₂	3.19	0.90	2.29	6.38
	(²³³ U,Th)O ₂	5.01	0.99	2.64	8.64
	(Pu,Th)O ₂	3.64	0.90	2.40	6.94
Part B					
HTGR	²³⁵ UO ₂ -ThO ₂	0.26	0.42	0.32	1.00 ^c
	²³³ UCO-ThO ₂	1.23	0.42	0.96	2.61
	²³⁵ UO ₂ -UO ₂	0.23	0.35	0.32	0.90
	PuO ₂ -ThO ₂	1.23	0.42	0.96	2.61

^aAll cost comparisons are relative to the given base case factors, with a plant output of 2 t/d and 260 full operating days per year (520 t/year).

^bBase case for metal clad fuel rods based on FABCOST 9 estimates [Source: A. L. Lotts, T. N. Washburn, and F. J. Homan, *FABCOST 9, A Computer Code for Estimating Fabrication Costs for Rod-Bundle Fuel Elements*, ORNL-4287 (August 1968).] escalated to 1977 with additions for current scrap and waste treatment requirements.

^cBase case for all HTGR (Prismatic Fuel Element) fuels based on personal communication, A. L. Lotts, Oak Ridge National Laboratory, April 11, 1975.

about 10% for these two cases and therefore was considered too small to warrant publication of errata for the above report.

The legislative restrictions on environmental releases are currently well defined. However, the current restrictions on personnel exposures are under review. Experience with limited plutonium production has indicated that current operational exposure restrictions are difficult to meet. As a result of a reduction in the allowable exposure level, all fabrication processes using plutonium were assumed to be done remotely in facilities equipped for remote maintenance.

COST NORMALIZATION

As indicated earlier, our fabrication cost estimate data was to be used by others to study the relative merits of different fuels within a given reactor and to eventually compare different reactor-fuel combinations. Thus, it was necessary to reduce the relative cost estimates to a dollar basis. Further, since different reactors require different fuel quantities and all fabrication costs vary with plant capacity, some means had to be derived for scaling costs as a function of demand, which would establish the plant capacities. In this section we will address how we established a dollar value for each of the base case reactor-fuel combinations and the proposed scaling factors.

Cost Estimates for Metal Clad Cylindrical Fuel Rod Types

The LWR (PWR) fueled with low-enriched UO_2 was chosen earlier for the base case for all fuel assemblies containing cylindrical metal clad fuel rods. Although there are several manufacturing plants in operation, the necessary cost data for fabrication of this fuel are not readily available. Therefore, the detailed cost estimates³ made in 1968 were updated to form the new base case costs.

The available data from the earlier estimate for fabrication of low-enriched UO_2 for a PWR reactor in a plant with a capacity of 2-t HM/d throughout and a 260 d/year operating schedule were (in 1968 dollars):

Capital cost (at a 30% fixed charge rate)	= \$15/kg HM
Hardware cost	= \$26/kg HM
Operating cost	= \$14/kg HM

Since these estimates were for plants constructed under the rules and regulations in effect in 1968, the estimates were modified to conform to current licensing requirements. Consequently, the capital costs were increased by 50% to accommodate current requirements for natural disaster phenomena, such as earthquakes and tornadoes; to provide the high level of physical security and accountability to comply with safeguards requirements; and to incorporate the necessary facilities and equipment to provide for scrap recovery, no liquid effluent release, and solid waste treatment and packaging. We also corrected the operating costs to accommodate the new operations. The initial manpower loading of 1011 men was increased to 1411. The additional personnel were divided equally between the two activities of scrap recovery and waste treatment for estimating convenience, although it is recognized that some of the additions would be distributed over all process activities.

The modified base cost was escalated to the 1977 level. The escalation was based on the official Energy Research and Development Agency-Oak Ridge Operations Office (ERDA-ORO) escalation modifier for the years 1968 to 1977 — 2.164.

The resulting base case estimate in 1977 dollars is:

Capital cost (at a 30% fixed charge rate)	= \$48.70/kg
Hardware cost	= \$56.26/kg
Operating cost	= <u>\$42.20/kg</u>
Total	\$147.16/kg

This total rounded to \$150/kg.

Cost Estimates for Prismatic HTGR Fuel Elements

Unlike the metal clad cylindrical fuel rod containing assemblies, a base cost estimate for the fresh fuel fabrication costs for HTGR fuels was not readily available. General Atomic Company was known to have made such studies; but like the data for current LWR production facilities,

such information is proprietary. However, an ERDA draft document⁴ was available from which most of the cost information could be derived for a recycle fuel fabrication plant.

The ERDA study was based on a low-capacity demonstration facility; but the capital cost information had been derived from an earlier conceptual design study for a commercial-scale plant with a capacity slightly less than 1 t/d (Target Recycle Plant). The following is a description of the derivation of the capital cost increment for a 2-t/d recycle plant from this information.

A capital investment of \$706 million was quoted for a total recycle demonstration plant. The figure was reportedly derived by escalating the commercial plant conceptual design and cost estimate by 10% to convert from 1975 to 1976 dollars and by using a scaling factor of 0.74 for capacity reduction. Since this escalation rate was inconsistent with the ERDA-ORO rates and we wished to work with the higher capacity plant values, these modifications were reversed.

Thus, the capital investment for the commercial plant was calculated in 1975 dollars as

$$706 \times 10^6 / 1.1 (0.74) = \$867 \times 10^6 .$$

Then, from available information we assigned 50% of the total capital cost to the refabrication portion of the recycle plant and escalated the costs to 1977 dollars by using the ERDA-ORO escalation factor:

$$(867 \times 10^6 / 2) \times 1.332 = \$577.4 \text{ million} .$$

This gave the cost for a fabrication facility with a capacity of 25,000 fuel elements per year. A 2-t HM/d plant operating 260 d/y will produce 54,300 fuel elements per year (based on an average of 9.57 kg HM per fuel element). The capital cost (in 1977 dollars) for the 2-t/d plant was estimated as follows:

$$\$577 \text{ million} (54,300/25,000)^{0.5} = \$851 \text{ million} .$$

We used a factor of 0.5 rather than the 0.4 from the reference study because of the high level of mechanical equipment in the refabrication area that will require duplication rather than increased capacity.

A capital charge in \$/kg HM was calculated by using the 30% fixed charge rate that was applied to the capital costs for the metal clad fuels and an annual capacity of 0.52 Gg. This provided a capital cost of \$490/kg HM.

Hardware cost data were also available in the same report; however, some estimates appeared to be too low. Both the reference information and the revised estimates are presented in Table 8. Since the major difference is associated with the cost of the graphite block and no information based on large-scale operations is available, a compromise hardware estimate of \$168/kg HM was used for this study.

Operating cost data were also derived from the Alternate Program Plan. The estimate in the document was \$26 million per year for a production rate of 7600 fuel elements. The costs were \$6 million expendables and \$20 million for manpower. This estimate reduces to \$357/kg in 1976 dollars or \$379/kg in 1977 dollars. At the time these estimates were made, we did not attempt to correct the manpower costs for the increased scale of production. Consequently, the operating costs are probably conservative.

The final dollar value for the prismatic HTGR elements can be summarized for the $^{233}\text{UCO}-\text{ThO}_2$ remotely fabricated fuel as:

	<u>\$/kg HM</u>
Capital cost	490
Hardware cost	168
Operating cost	<u>379</u>
Total	\$1037

This cost was divided by the ratio of the relative cost factors for the $^{235}\text{UO}_2-\text{ThO}_2$ and the $^{233}\text{UCO}-\text{ThO}_2$ fuels. The resulting \$402/kg HM was rounded to \$400 and used as the base case cost for this fuel element.

Table 8. Hardware Cost Estimates for HTGR Prismatic Fuel Elements

Item	Alternate Program Plan ^a		Current Estimate ^b	
	Unit Costs (\$/Fuel Element)	\$/kg HM	Unit Cost	\$/kg HM
Graphite block and plugs	784	81.91	\$1500/fuel element	156
Fertile coated particles	190	19.85	\$40/kg	42
Shim particles	88	9.19	\$68/kg	39
Miscellaneous				
Poison	6	0.63		
Matrix	5	0.52		
Totals		112.10		238

^aData derived from personal communication, A. L. Lotts, Oak Ridge National Laboratory, April 11, 1975.

^bProjected from available cost data for items purchased for development program.

Effects of Plant Capacity on Fabrication Costs

Different types of reactors and different reactor build scenarios both affect required fuel fabrication capacity. Since the cost of fabrication depends on fabrication plant capacity, we established scaling factors to adjust the base case 2-t HM/d capacity costs to a variety of capacities based on fuel fabrication demand.

Although each of the three components comprising the total fabrication costs scale with capacity at different rates, the needs of the study were best met with a single capacity factor applied to the total costs. Again, we referred to the earlier detailed FABCOST 9 study³ to obtain the appropriate factors. Table 9 lists the scaling factors for each component of the cost as well as the weighted total for different fabrication capacities from Appendix F of the above report. Although this case dealt specifically with carbide fuels for an LMFBR, similar factors were calculated for other cases in the early study. The actual scaling factors in our study are in Table 10. These factors have also been plotted⁶ and were compared with some known cost data at the time of that report.

Scaling factors, particularly those applicable to capital costs, are affected by such things as batch and lot size restrictions resulting from criticality considerations, etc., so that different factors apply to different reactor-fuel combinations. However, we did not refine our estimates to account for this.

UNIT COST ESTIMATION SUMMARY

Our cost estimation net results are summarized in Table 11.

The cost estimates are based on a given fuel element design for each reactor-fuel combination. Minor changes in element design parameters can be accommodated with the fuel element design parameter corrections for the metal clad cylindrical fuel rod assemblies, but major changes would require reevaluation. The relative cost factors are considered more accurate than the absolute dollar costs. The accuracy is limited

Table 9. Effects of Plant Capacity on Fuel Fabrication Costs^a

Plant Capacity (t HM/d)	Scaling Factors			
	Capital Costs	Hardware Costs	Operating Costs	Weighted Costs
0.5	1.67	1.21	1.62	1.46
0.75	1.42	1.14	1.38	1.29
1.0	1.28	1.09	1.25	1.19
1.5	1.10	1.04	1.09	1.07
2.0 ^b	1.00	1.00	1.00	1.00
3.0	0.87	0.95	0.89	0.91
4.0	0.79	0.92	0.83	0.86
5.0	0.70	0.89	0.76	0.79
6.0	0.64	0.86	0.72	0.75
7.0	0.60	0.84	0.69	0.73

^aData from A. L. Lotts, T. N. Washburn, and F. J. Homan, *FABCOST 9, A Computer Code for Estimating Fabrication Costs for Rod-Bundle Fuel Elements*, ORNL-4287 (August 1968).

^bBase case capacity in this study.

Table 10. Fabrication Cost as a Function of Processing Rate

Rate (t HM/d)	Cost Fraction
0.5	1.53
1.0	1.23
2.0	1.00
3.0	0.90
4.0	0.84
5.0	0.79
6.0	0.76
7.0	0.73

Table 11. Estimated Fabrication Cost Comparison^a Summary

Reactor Type	Fuel Material	Relative Cost Factors				Estimated Costs (\$/kg) ^b
		Capital	Hardware	Operating	Total	
Part A						
LWR (PWR)	(²³⁵ U,U)O ₂	0.33	0.38	0.29	1.00	150 ^c
	(Pu,U)O ₂	1.49	0.38	1.45	3.32	500
	(²³⁵ U,Th)O ₂	0.41	0.42	0.44	1.27	190
	(²³³ U,Th)O ₂	2.18	0.42	1.60	4.19	630
	(Pu,Th)O ₂	1.49	0.38	1.53	3.40	510
CANDU	Normal UO ₂	0.33	0.09	0.11	0.53	80
	(Pu,U)O ₂	1.49	0.09	0.50	2.08	310
	(²³³ U,Th)O ₂	1.98	0.12	0.55	2.65	400
	(Pu,Th)O ₂	1.49	0.09	0.55	2.13	320
LMFBR	(Pu,U)O ₂	3.19	0.58	2.10	5.87	880
	(Pu,U)C	2.68	0.37	1.66	4.72	710
	²³³ U,Th	2.73	0.35	1.61	4.69	700
GFBR	(Pu,U)O ₂	3.19	0.90	2.29	6.38	960
	(²³³ U,Th)O ₂	5.01	0.99	2.64	8.64	1300
	(Pu,Th)O ₂	3.64	0.90	2.40	6.94	1040
Part B						
HTGR	²³⁵ UO ₂ -ThO ₂	0.26	0.42	0.32	1.00	400 ^d
	²³³ UCO-ThO ₂	1.23	0.42	0.96	2.61	1030
	²³⁵ UO ₂ -UO ₂	0.23	0.35	0.32	0.90	360
	PuO ₂ -ThO ₂	1.23	0.42	0.96	2.61	1030

^aAll cost comparisons are relative to the given base case factors.

^b1977 dollars assumed for total kilograms of heavy metal product with a plant output of 2 t/d and operating 260 d/year (520 t/year).

^cBase case for metal clad fuel rods based on FABCØST 9 estimates [Source: A. L. Lotts, T. N. Washburn, and F. J. Homan, *FABCØST 9, A Computer Code for Estimating Fabrication Costs for Rod-Bundle Fuel Elements*, ORNL-4287 (August 1968).] escalated to 1977 with additions for current scrap and waste treatment requirements.

^dBase case for all HTGR (Prismatic Fuel Element) cases based on data from personal communication, A. L. Lotts, Oak Ridge National Laboratory, April 11, 1975.

by the lack of plant designs, operating experience, etc., and is, therefore, estimated to be about $\pm 25\%$.

All costs are for a common plant design capacity of 2-t HM/d product with a capital cost increment based on a fixed charge rate of 30%. Although the dollar values represent a cost to the reactor in 1977 dollars, they are in fact a price from the fuel manufacturer's point of view since they include a return on investment. The fixed charge rate appears to be reasonable but is near the high side of the range (15-36%) for such rates quoted in the GESMO report.³¹

Although we referred to some previous studies and cost estimates^{2,3,6} in developing the factors for the categories and increments, we did not attempt to normalize the estimates in this study to any of the earlier estimates. Such normalization would be essentially impossible since the rationale of each reference was not available and could have adversely affected our intent to provide a consistent set of estimates for comparative evaluation.

The estimates in this study can be improved and the uncertainties reduced only by extensive additional effort. This effort should be directed in four areas:

1. commercial involvement in the review and improvement of the existing estimates,
2. development of conceptual plant layouts and cost estimates with which to define the capital cost component,
3. improved definition of production requirements, and
4. stabilization of NRC requirements. Current uncertainties require conservative approaches in terms of production worker protection and safeguards requirements.

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APPENDIX A — DESCRIPTIVE DATA FOR FUEL ELEMENTS USED IN COST ESTIMATES

The assumed reference designs for each reactor type and fuel combination have been collected in tabular form. These are given in the following tables.

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Table A1. Pressurized-Water Reactor Fuel Element Design Description^a

Component	Description
Assembly	
Geometry	17 × 17 square
End fitting material	304 SS
End fitting mass, kg (total)	10
Grid spacers	8
Grid spacer mass, kg (total)	5.5
Assembly length, m	4.06
Assembly gross mass, kg	668.6
Fuel rods per assembly	264
Thimble tubes per assembly	24
Instrument tubes per assembly	1
Enrichments per assembly	1
Heavy metal per assembly, kg	461
Structural materials per assembly, kg	
304 SS	10
Zircaloy-4	130
Alloy 718	5.5
Fuel Rods	
Cladding material	Zircaloy-4
Cladding outside diameter, mm	9.50
Cladding inside diameter, mm	8.36
Cladding length, m	3.85
Fuel material	UO ₂
Fuel form	Right circular cylinder pellets
Fuel diameter, mm	8.19
Fuel stack height, m	3.65
Fuel density, Mg/m ³	10.41

Table A1 (continued)

Component	Description
Fuel Rods	
Enrichment, %	
Region 1	~2.1
Region 2	~2.6
Region 3	~3.2
End caps	Zircaloy-4
Fuel-to-cladding thermal bond	He + Ar
Approximate pressure, MPa	4.03
psi	585
Reactor Requirements	
Fuel assemblies in core	193
Frequency of reloading	Annual
Fuel assemblies per reload	64
Burnup at discharge, MWd/t	33,000
TJ/kg	2.9

^aRESAR 3S.

Table A2. Boiling-Water Reactor Fuel Element Design Description

Component	Description
Assembly	
Geometry	8 × 8 square
Channel material	Zircaloy-4
Channel thickness, mm	2.03-2.54
End fitting material	304 SS
End fitting mass, kg (total)	8.2
Grid spacers	7
Grid spacer material	Zircaloy-4 (Inconel springs)
Grid spacer mass	
Assembly length, m	4.47
Assembly gross mass, kg	279
Fuel rods per assembly	63
Enrichments per assembly	4 (Typical)
Heavy metal per assembly, kg	189
Structural materials, kg	
304 SS	8.2
Zircaloy-4	56.7
Fuel Rods	
Cladding material	Zircaloy-2
Cladding outside diameter, mm	12.52
Cladding length, m	4.06
Fuel material	UO ₂
Fuel form	Right circular cylinder pellets
Fuel diameter, mm	12.45
Fuel stack height, m	3.76
Fuel density, Mg/m ³	10.41
Fuel enrichment, %	~2.6 (Average)
End caps	Zircaloy-2

Table A2 (continued)

Component	Description
Fuel Rods	
Fuel rod internals	
Spring	
302 SS	
Getter	
Proprietary	
Fuel-to-cladding thermal bond	
He (slight positive pressure)	

Table A3. CANDU Fuel Element Design Description

Component	Description
Assembly	
Geometry	Circular
End fitting material	Zircaloy-2
Assembly length, m	0.495
Assembly gross mass, kg	24.8
Fuel rods per assembly	28
Heavy metal per assembly, kg	19.9
Structural material mass, kg	2.1
Fuel Rods	
Cladding material	Zircaloy-4
Cladding outside diameter, mm	15.2
Cladding inside diameter, mm	14.4
Cladding length, m	0.49
Fuel material	UO ₂
Fuel form	Right circular cylinder pellets
Fuel diameter, mm	14.4
Fuel density, Mg/m ³	10.55
Enrichment	0.711 (Natural U)
Fuel-to-cladding thermal bond	He (slight positive pressure)
Reactor Requirements	
Initial core assemblies	
Frequency of reloading	On line
Burnup at discharge, MWd/t HM	7500
TJ/kg HM	0.65

Table A4. LMFBR Oxide Fuel Element Design Description

Component	Description			
Assembly				
Geometry	Hexagonal			
Shroud material	316 SS			
Assembly length				
Assembly gross mass, kg	480			
Fuel rods per assembly	271			
Enrichments per assembly	1			
Heavy metal per assembly, kg	148			
Fuel Rods				
Cladding material	316 SS			
Cladding outside diameter, mm	7.87			
Cladding inside diameter, mm	7.11			
Fuel material	(Pu,U)O ₂			
Fuel form	Pellet			
Fuel diameter, mm	6.81			
Fuel stack height, m	1.22			
Fuel density, Mg/m ³	10.5			
Fuel composition, wt %	(Z-1)	(Z-2)	(Z-3)	(Z-4)
Uranium	75.2	74	73.7	67.9
Plutonium	12.8	14	14.3	20.1
Fissile material	Pu	Pu	Pu	Pu
Fissile material per total heavy metal, wt %	14.5	15.9	16.3	22.9
Axial blanket length				
Top, mm	356			
Bottom, mm	356			
Axial blanket material	UO ₂			
Axial blanket form	Pellet			
Axial blanket pellet diameter, mm	6.81			
Axial blanket pellet density, Mg/m ³	10.4			

Table A4 (continued)

Component	Description
End cap material	316 SS
Fuel-to-cladding thermal bond	He (slight positive pressure)
Reactor Requirements	
Initial core assemblies	409
Frequency of reloading	Annual
Assemblies per reload	136
Burnup at discharge, MWd/t HM	75,000
TJ/kg	6.5

Table A5 (continued)

Component	Description
Fuel Rods	
Fuel-to-cladding thermal bond	Na
Reactor Requirements	
Core assemblies	230

Table A5. LMFBR Carbide Fuel Element Design Description

Component	Description
Assembly	
Geometry	Hexagonal
Shroud material	316 SS
Shroud mass, kg	0.348
Fuel rods per assembly	91
Enrichments per assembly	1
Heavy metal per assembly, kg	102.1
Fuel Rods	
Cladding material	316 SS
Cladding outside diameter, mm	9.4
Fuel material	(Pu,U)C
Fuel form	Pellet
Fuel diameter, mm	7.98
Fuel density, Mg/m ³	12.9
Fuel stack height, m	0.914
Enrichment, %	9.36 (Z-1), 11.32 (Z-2), 10.34 (average)
Axial blanket material	UC
Axial blanket form	Pellet
Axial blanket diameter, mm	7.98
Axial blanket pellet density, Mg/m ³	12.9
Axial blanket stack heights (top and bottom), m	0.457
Reflector material	316 SS
Pellet fragment screen	
Material	316 SS
Outside diameter, mm	8.13
Thickness, mm	0.08

Table A6. LMFBR Metal Fuel Element Design Description

Component	Description
Assembly	
Geometry	Hexagonal
Shroud material	316 SS
Shroud mass, kg	0.348
Fuel rods per assembly	91
Enrichments per assembly	1
Heavy metal per assembly, kg	105.6
Fuel Rods	
Cladding material	316 SS
Cladding outside diameter, mm	9.40
Fuel material	^{233}U -Th alloy
Fuel form	Metal slugs
Fuel diameter, mm	7.98
Fuel density, Mg/m^3	12.7
Fuel stack height, m	0.914
Uranium content, %	15
Axial blanket material	U metal
Axial blanket form	Metal slug
Axial blanket diameter, mm	7.98
Axial blanket density, Mg/m^3	12.7
Axial blanket stack heights (top and bottom), m	0.457
Reflector material	316 SS
Fuel-to-cladding thermal bond	Na
Reactor Requirements	
Core assemblies	230

Table A7. GCFR Fuel Element Design Description

Component	Description
Assembly	
Geometry	Hexagonal (167.6 mm across flats)
Shroud thickness, mm	16.38
End fitting material	316 SS
Grid spacers	10
Grid spacer material	316 SS
Assembly length, m	3.45
Fuel rods per assembly	270 (Z-1), 232 (Z-3), 126 (radial blanket)
Enrichments per assembly	1
Heavy metal per assembly, kg	123.12
Fuel Rods	
Cladding material	316 SS
Cladding outside diameter, mm	7.16 (core), 12.80 (radial blanket)
Cladding inside diameter, mm	6.20 (core), 12.04 (radial blanket)
Cladding length, m	2.21
Fuel material	(Pu,U)O ₂ (core), ThO ₂ (radial blanket)
Fuel form	Annular pellets (core), Pellets (radial blanket)
Fuel diameter, mm	6.10 × 1.27 (core), 6.15 (radial blanket)
Fuel stack height, m	0.996
Fuel density, Mg/m ³	10.0 (core), 9.8 (radial blanket)
Fissile material	Pu
Axial blanket length, m	0.450 (top and bottom)
Plenum spring	Inconel

Table A7 (continued)

Component	Description
Reactor Requirements	
Burnup at discharge, MWd/t HM	75,000
TJ/kg	6.5

Table A8. HTGR Fuel Element Design Description

Component	Description
Assembly	
Geometry	Hexagonal
Fuel block	Graphite
Assembly length, mm	793
Assembly gross mass, kg	117
Fuel block mass, kg	109
Fuel rods per assembly	1566 (132 stacks)
Enrichments per assembly	1
Heavy metal assembly (total), kg	9.57
U	0.742
Th	8.83
Fuel Rods	
SiC coating mass, kg	1.1
Fuel material	²³⁵ U, Th
Fuel form	Coated particles
Fuel diameter, mm	15.7
Fissile material	²³⁵ U
Enrichment, %	93
Reactor Requirements	
Frequency of reloading	4 years
Burnup at discharge, MWd/t	85,000
TJ/kg	7.3

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APPENDIX B — DETAILED RELATIVE COST ESTIMATION — INCREMENTAL FACTORS

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Table B1. Detailed Cost Estimation Incremental Factors for Light-Water Reactors

	Category Fraction	Element Fraction		(235U, 238U)O ₂		(Pu, 238U)O ₂				(235U, Th)O ₂		(233U, Th)O ₂		(Pu, Th)O ₂ Remote		(233U, 238U)O ₂	
		Contact	Other	IM ^a	Estimate	Glove Box		Remote		IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate
						IM ^a	Estimate	IM ^a	Estimate								
A. Capital cost	0.33																
Equipment		0.66	0.5	1	0.22	1.5	0.327	3	0.495	1.2	0.261	4	0.66	3	0.495	3	0.495
Building		0.33	0.5	1	<u>0.11</u>	3	<u>0.327</u>	6	<u>0.99</u>	1	<u>0.11</u>	10	<u>1.32</u>	6	<u>0.99</u>	6	<u>0.99</u>
Estimated factor					0.33		0.65		1.49		0.37		1.98		1.49		1.49
											(0.40) ^b		(2.18) ^b				
B. Hardware costs	0.38																
Cladding plus end plugs		0.36	0.36	1	0.14	1	0.14	1	0.14	1	0.14	1	0.14	1	0.14		0.14
Rod internals		Neg		1		1		1		1		1		1			
Assembly hardware		0.64	0.64	1	<u>0.24</u>	1	<u>0.24</u>	1	<u>0.24</u>	1	<u>0.24</u>	1	<u>0.24</u>	1	<u>0.24</u>		<u>0.24</u>
Estimated factor					0.38		0.38		0.38		0.38		0.38		0.38		0.38
											(0.42) ^b		(0.42) ^b				
C. Operating costs	0.29																
Cladding preparation		0.19	0.19	1	0.06	1	0.055	1	0.055	1	0.055	1	0.055	1	0.055	1	0.055
Fuel preparation		0.48	0.48	1	0.14	5	0.696	5	0.696	1.2	0.167	5	0.696	5	0.696	5	0.696
Rod loading		0.02	0.02	1	0.01	2	0.012	2	0.012	1	0.006	2	0.012	2	0.012	2	0.012
Element assembly, inspection, and packaging		0.04	0.04	1	0.01	2	0.023	10	0.116	1	0.012	10	0.116	10	1.116	10	0.116
Scrap recovery		0.14	0.14	1	0.04	4	0.162	4	0.162	2	0.081	4	0.162	6	0.244	2	0.081
Waste treatment		0.14	0.14	1	<u>0.04</u>	10	<u>0.406</u>	10	<u>0.406</u>	2	<u>0.081</u>	10	<u>0.406</u>	10	<u>0.406</u>	10	<u>0.406</u>
Estimated factor					0.29		1.35		1.45		0.40		1.45		1.53		1.37
											(0.44) ^b		(1.60) ^b				
D. Fuel element design factors (metal clad rods only)	NA																
Fuel density				1		1		1		1.1		1.1		1		1	
Fuel diameter				1		1		1		1		1		1		1	
Total estimated factor					1.0		2.38		3.32		1.27		4.19		3.40		3.24

^aIncremental multiplier estimate.^bNumbers in parentheses are IM values after corrections for fuel density and diameter

Table B2. Detailed Cost Estimation Increments Factors for CANDU Reactors

	Category Fraction	Element Fraction		$(^{235}\text{U}, ^{238}\text{U})\text{O}_2$		$(\text{Pu}, ^{238}\text{U})\text{O}_2$ Remote		$(^{233}\text{U}, \text{Th})\text{O}_2$		$(\text{Pu}, \text{Th})\text{O}_2$ Remote	
		Contact	Other	IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate
A. Capital cost	0.33										
Equipment		0.66	0.5	1	0.218	3	0.495	7	0.660	3	0.495
Building		0.33	0.5	1	<u>0.109</u>	6	<u>0.990</u>	8	<u>1.32</u>	6	<u>0.990</u>
Estimated factor					0.33		1.49		1.98		1.49
B. Hardware costs	0.38										
Cladding plus end plugs		0.36	0.36	2	0.274	2	0.274	2	0.274	2	0.274
Rod internals		Neg									
Assembly hardware		0.64	0.64	0.1	<u>0.024</u>	0.1	<u>0.024</u>	0.1	<u>0.024</u>	0.1	<u>0.024</u>
Estimated factor					0.30 (0.09) ^b		0.30 (0.09) ^b		0.30 (0.12) ^b		0.30 (0.09) ^b
C. Operating costs	0.29										
Cladding preparation		0.19	0.19	2	0.110	2	0.110	2	0.110	2	0.110
Fuel preparation		0.48	0.48	1	0.139	5	0.696	5	0.696	5	0.696
Rod loading		0.02	0.02	1	0.006	1	0.006	2	0.006	2	0.006
Element assembly, inspection, and packaging		0.04	0.04	2	0.023	2	0.023	20	0.232	20	0.232
Scrap recovery		0.14	0.14	1	0.041	4	0.162	4	0.162	6	0.244
Waste treatment		0.14	0.14	1	<u>0.041</u>	10	<u>0.406</u>	10	<u>0.406</u>	10	<u>0.406</u>
Estimated factor					0.36 (0.11) ^b		1.40 (0.43) ^b		1.61 (0.55) ^b		1.78 (0.55) ^b
D. Fuel element design factors ^b (metal clad rods only)	NA										
Fuel density					1.0		~1		1.1		~1
Fuel diameter					<u>0.31</u>		<u>0.31</u>		<u>0.31</u>		<u>0.31</u>
Total estimated factor					0.53		2.02		2.65		2.13

^a Incremental modifier estimate.^b The fuel element design factors have been applied only to the hardware and operating categories for these fuel elements because of the estimated space and equipment required to deal with the large number of small elements and the jiggling, etc., required for the furnace brazing rather than mechanical assembly. Numbers in parentheses are IM values after correction for fuel density and diameter.

Table B3. Detailed Cost Estimation Incremental Factors for
Liquid-Metal-Cooled Fast Breeder Reactors

	Category Fraction	Element Fraction		(Pu, ²³⁸ U)O ₂ Remote		(Pu, ²³⁸ U)C		²³³ U-Th	
		Contact	Other	IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate
A. Capital cost	0.33								
Equipment		0.66	0.5	6	0.990	10	1.650	10	1.650
Building		0.33	0.5	8	<u>1.320</u>	10	<u>1.650</u>	10	<u>1.650</u>
Estimated factor					2.31 (3.19) ^b		3.30 (2.68) ^b		3.30 (2.73) ^b
B. Hardware costs	0.38								
Clad plus end plugs		0.36	0.36	1	0.137	1	0.137	1	0.137
Rod internals		Neg			0.038		0.076		0.038
Assembly Hardware		0.64	0.64	1	<u>0.243</u>	1	<u>0.243</u>	1	<u>0.243</u>
Estimated factor					0.42 (0.58) ^b		0.46 (0.37) ^b		0.42 (0.35) ^b
C. Operating costs	0.29								
Clad preparation		0.19	0.19	0.6	0.033	1	0.055	0.6	0.033
Fuel preparation		0.48	0.48	5	0.696	8	1.114	8	1.114
Rod loading		0.02	0.02	2	0.012	4	0.023	4	0.023
Element assembly, inspection, and packaging		0.04	0.04	10	0.116	10	0.116	10	0.116
Scrap recovery		0.14	0.14	6	0.244	8	0.325	6	0.244
Waste treatment		0.14	0.14	10	<u>0.406</u>	10	<u>0.406</u>	10	<u>0.406</u>
Estimated factor					1.51 (2.08) ^b		2.04 (1.66) ^b		1.94 (1.61) ^b
D. Fuel element design factors (metal clad rods only)	NA								
Fuel density					~1		0.805		0.82
Fuel diameter					<u>1.38</u>		<u>1.01</u>		<u>1.01</u>
Total estimated factor					5.85		4.72		4.69

^aIncremental modifier estimate.

^bNumbers in parentheses are IM values after correction for fuel density and diameter.

Table B4. Detailed Cost Estimation Incremental Factors for Gas-Cooled Fast Breeder Reactors

	Category Fraction	Element Fraction		(Pu, ²³⁸ U)O ₂		(²³³ U, Th)O ₂		(Pu, Th)O ₂	
		Contact	Other	IM ^a	Estimate	IM ^a	Estimate	IM ^a	Estimate
A. Capital cost	0.33								
Equipment		0.66	0.5	6	0.990	10	1.650	8	1.320
Building		0.33	0.5	8	<u>1.320</u>	10	<u>1.650</u>	8	<u>1.320</u>
Estimated factor					2.31 (3.19) ^b		3.3 (5.01) ^b		2.64 (3.64) ^b
B. Hardware costs	0.38								
Cladding plus end plugs		0.36	0.36	1	0.137	1	0.137	1	0.137
Rod internals		Neg			0.15		0.15		0.15
Assembly hardware		0.64	0.64	1.5	<u>0.365</u>	1.5	<u>0.365</u>	1.5	<u>0.365</u>
Estimated factor					0.65 (0.90) ^b		0.65 (0.99) ^b		0.65 (0.90) ^b
C. Operating costs	0.29								
Cladding preparation		0.19	0.19	1	0.055	1	0.055	1	0.055
Fuel preparation		0.48	0.48	5	0.696	5	0.696	5	0.696
Rod loading		0.02	0.02	4	0.023	4	0.023	4	0.023
Element assembly, inspection, and packaging		0.04	0.04	20	0.232	20	0.232	20	0.232
Scrap recovery		0.14	0.14	6	0.244	8	0.325	8	0.325
Waste treatment		0.14	0.14	10	<u>0.406</u>	10	<u>0.406</u>	10	<u>0.406</u>
Estimated factor					1.66 (2.29) ^b		1.74 (2.64) ^b		1.74 (2.40) ^b
D. Fuel element design factors (metal clad rods only)	NA								
Fuel density					1		1.1		1
Fuel diameter					<u>1.38</u>		<u>1.38</u>		<u>1.38</u>
Total estimated factor					6.38		8.64		6.94

^aIncremental modifier estimate.

^bNumbers in parentheses are IM values after corrections for fuel density and diameter.

Table B5. Detailed Cost Estimation Incremental Factors for High-Temperature Gas-Cooled Reactors^a

	Category Fraction	Element Fraction		(235UO ₂ -ThO ₂)		(233UCO-ThO ₂)		(235U, 238U)O ₂		(PuO ₂ -ThO ₂)	
		Contact	Other	IM ^b	Estimate	IM ^b	Estimate	IM ^b	Estimate	IM ^b	Estimate
A. Capital cost	0.26										
Equipment		0.66	0.5	1	0.17	3.5	0.45	0.9	0.15	3.5	0.45
Building		0.33	0.5	1	<u>0.09</u>	6	<u>0.78</u>	0.9	<u>0.08</u>	6	<u>0.78</u>
Estimated factor					0.26		1.23		0.23		1.23
B. Hardware costs	0.42										
Miscellaneous components		0.09		1	0.038	1	0.038	1	0.038	1	0.038
Fertile particles		0.18		1	0.076	1	0.076	0		1	0.076
Graphite blocks and plugs		0.73		1	<u>0.307</u>	1	<u>0.307</u>	1	<u>0.307</u>	1	<u>0.307</u>
Estimated factor					0.42		0.42		0.35		0.42
C. Operating Cost	0.32										
Lump sum estimate				1	<u>0.32</u>	3	<u>0.96</u>	1	<u>0.32</u>	3	<u>0.96</u>
Total estimated factor					1.00		2.61		0.90		2.61

^aThis is a new category of fuel element design and, therefore, not comparable with data in Tables B1 through B4.

^bIncremental modifier estimate.

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