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REFABRICATION TECHNOLOGY AND COSTS FOR
HIGH-TEMPERATURE GAS-COOLED REACTOR FUELS

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A. L. Lotts, D. A. Douglas, Jr., and R. L. Pilloton

MAY 1965

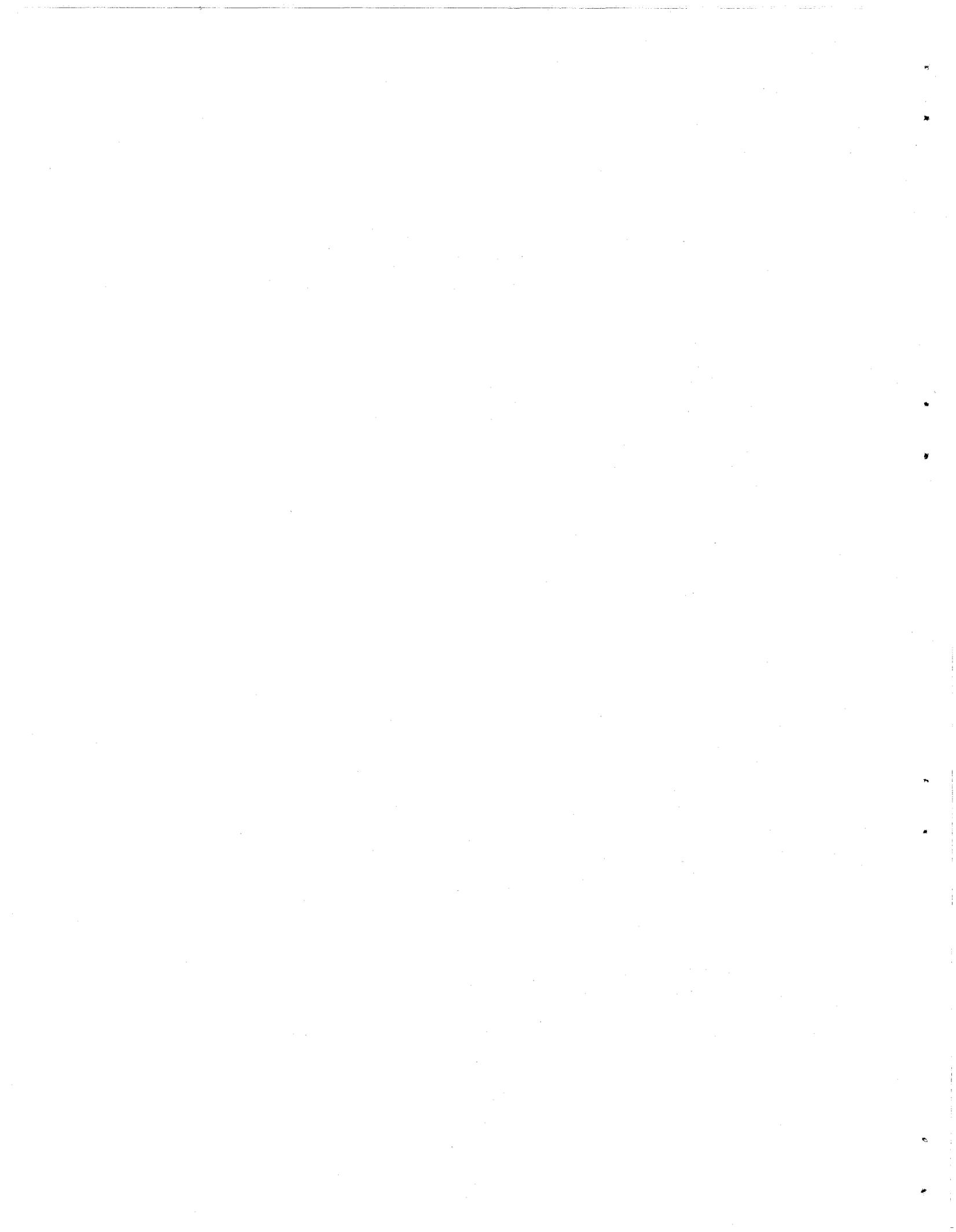
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ABSTRACT

High-temperature gas-cooled reactors utilizing the thorium-uranium-233 cycle have the potential of achieving low power costs and high fuel utilization. However, the realization of this potential depends on the development of technology for the economical refabrication of the fuel of these reactors. This paper describes the findings of the Oak Ridge National Laboratory in its investigation of this problem.

A brief description of typical nuclear fuels for HTGR reactors is followed by a discussion of the many problems concerning the refabrication of a hypothetical fuel element. Alternate fabrication flowsheets are shown, and data are presented which describe the effect of the amount of radioactive material in the fuel on fabrication plant design. Fuel refabrication costs are discussed in the second part of the paper. The effect of ^{232}U concentration, mode of fabrication, amortization rate, plant capacity, and alternative fuel designs are represented by tables and curves. The third part of the paper describes the fuel refabrication program of ORNL. This includes a description of the ORNL Thorium-Uranium Recycle Facility (TURF) and the plans for equipment which is to be used in the facility for demonstration of refabrication technology. The investigation indicates that several refabrication process improvements are in sight at ORNL and that the cost penalties associated with refabrication of HTGR fuels are not prohibitive.

INTRODUCTION

High-temperature gas-cooled reactors using the thorium-uranium-233 cycle are under development in the United States because of their potential for achieving low power costs and high fuel utilization. The attainment of low power costs depends to a great extent upon the development of technology for the economical recycle of fuel from such reactors, particularly coated-particle fuels. (1) Technical development is required for shipping, chemical processing, fuel preparation, and refabrication of bred fuel. Since the cost of fabrication of fuel is a major contributor to the cost of any fuel cycle, it is imperative that we consider the technology and the economics that are involved in refabrication of high-temperature gas-cooled reactor fuels.

The task of assessing the refabrication technology and the costs for refabricating HTGR fuel is difficult for two reasons. First, current fuel element designs are based principally on processes optimized for initial and, therefore, contact fabrication. This could lead to heavy penalties in calculating refabrication costs because certain contact steps become extremely awkward and expensive when they are automated and performed under the conditions imposed by recycle fuel. If we assume a design and a fabrication technique suitable for refabrication, we may err in estimating certain costs which are sensitive to assumptions regarding manufacturing tolerances. Second, there is a lack of experience in several key areas: (1) fabrication of fueled graphite fuel elements has not been done on a significant scale; (2) there is little experience with recycle fuel and none with refabrication of fueled graphite; and (3) there is no relevant experience with large plant processing or the economies to be effected in large plants fabricating fuel elements for power reactors.

At the Oak Ridge National Laboratory, we have taken some preliminary steps to an understanding of areas of technology in which information is incomplete. We are engaged in the ORNL Thorium Utilization Program, which has as its prime objective, the eventual economical utilization of thorium in power reactor systems. The objectives of the program include the

refabrication technology for various fuel elements; among those being studied are fuel element design concepts for high-temperature gas-cooled reactors. We are attempting to develop suitable technology for economical recycle of fuel in such reactors.

In developing a technology for economical recycle of fuel, we are placing a strong emphasis on the economics of refabrication. Therefore, we have done extensive cost analyses to determine areas where work should be performed; that is, to delineate those areas that appear most promising for a return on the investment of the development dollar. We have also performed many cost analyses to evaluate reactor systems and to compare the high-temperature gas-cooled reactors with other competitive reactor systems. (2)

We are concerned in this paper with the speculative refabrication technology for fuel elements that would be used in high-temperature gas-cooled reactors. The text will discuss our preliminary plans for the refabrication of HTGR fuel and our economic analyses to determine the incremental costs in the process. We shall project the cost of fabricating one such fuel element using remote fabrication technology and shall offer comparisons of the cost of fuel refabrication with the cost of fabrication of the original ^{235}U -bearing cores.

FUELS FOR HIGH-TEMPERATURE GAS-COOLED REACTORS

Table 1 lists the main characteristics of the fuels of typical high-temperature gas-cooled reactors (i.e., AVR, Peach Bottom, and an advanced HTGR concept). These fuels have a common characteristic - they contain carbides of uranium, thorium, or zirconium or of a mixture of those elements. These carbides are in the form of microspheres or of nearly spherical particles (150 to 1000 μ in diameter). These particles are covered with an impervious fission-product-retaining coating (50 to 100- μ thick) which consists of pyrolytic carbon, either alone or in combination with silicon carbide.

The methods of agglomeration of the coated particles to form fuel elements vary widely. General Atomic* has proposed for advanced HTGR

*Division of General Dynamics.

Table 1. Typical Fuel Elements for High-Temperature Gas-Cooled Reactors

Reactor Name	Core Zone	Fertile Material	Other Materials	Fuel Microform			Fuel Macroform			Fuel Element		Fuel Elements per Bundle	References		
				Compounds	Kernel Geometry	Coating Material	Geometry	Dimension (in.)			Form			Dimension (in.)	
								OD	ID	H				OD	L
AVR		²³⁵ U 93% enrichment	Th Th/U=8	Carbides	150-μ micro-spheres	80-μ pyrolytic carbon	No intermediate shape				Graphite sphere	2.4	1	(<u>3,4</u>)	
Dragon	A	²³⁵ U 93% enrichment	Th Th/U=15	Carbides	250-420-μ micro-spheres	100-μ SiC + pyrolytic carbon	Annular compacts	1.75	1.37	2.0	Graphite tube	2.88	90	7	(<u>5-8</u>)
	B	²³⁵ U 93% enrichment	Zr Zr/U=5	Carbides	250-420-μ micro-spheres	100-μ pyrolytic carbon	Annular compacts	1.75	1.37	2.0	Graphite tube	2.88	90	7	(<u>6-9</u>)
Peach Bottom		²³⁵ U 93% enrichment	Th Th/U=8	Carbides	100-400-μ micro-spheres	50-60-μ pyrolytic carbon	Annular compacts	2.7	1.7	1.5	Graphite tube	3.5	144	1	(<u>9-12</u>)
Advanced HTGR Concept		²³⁵ U 93% enrichment	Th Th/U=27	Carbides	UC ₂ : 200-μ micro-spheres ThC ₂ : 1000-μ micro-spheres	100-μ pyrolytic carbon 100-μ pyrolytic carbon	None (loose particles in 14 cylindrical cavities in each graphite rod)				Graphite tube	4.5	240	1	(<u>2</u>)

concepts, that the coated particles be poured loosely into cavities of the graphite fuel element bodies. In the AVR reactor, coated particles are dispersed in a graphite matrix within each spherical fuel element. In the Dragon and Peach Bottom reactors, the coated-fuel particles are blended with graphite powder and pressed into intermediate-size annular compacts; these compacts are then placed into graphite tubes to form the fuel elements.

Fabrication techniques reflect these characteristics of the fuels, and consequently, the various methods used for preparing carbides and for coating particles have many similarities. However, the processes used for introducing these particles into the fuel element matrix differ widely from one designer to another.

To make this paper meaningful, we must discuss the fabrication of a fuel element of a specific design. Therefore, we shall use as the reference fuel element in these analyses a hypothetical design which, if certain developments are successful, should be useful in high-temperature gas-cooled reactors. This fuel element, shown in Fig. 1, has a diameter of 4 1/2 in. and has 10 equally spaced 3/4-in.-diam holes in the cross section between the outside diameter and the 3/4-in.-inside diameter. These holes are filled with fuel bodies consisting of an aggregate of coated fuel particles held together by a graphite matrix. The fuel element is 20 ft in overall length, and has two identical fuel subassemblies, each having an active fuel length of 7 1/2 ft. These fuel subassemblies can be fabricated separately, can be attached to either a reflector assembly or a fission-product trap assembly, and can be joined by the central coupling to form a complete fuel element.

REFABRICATION OF HTGR FUEL

Although we have selected a specific fuel element design for fabrication, there are some major decisions to be made before the refabrication of HTGR fuel can be attempted. One must choose the method of making spherical particles, the exact flowsheet to be used in fabrication, and the expected isotopic content of the processed fuel. We have studied a number of alternatives to be discussed subsequently, which must be

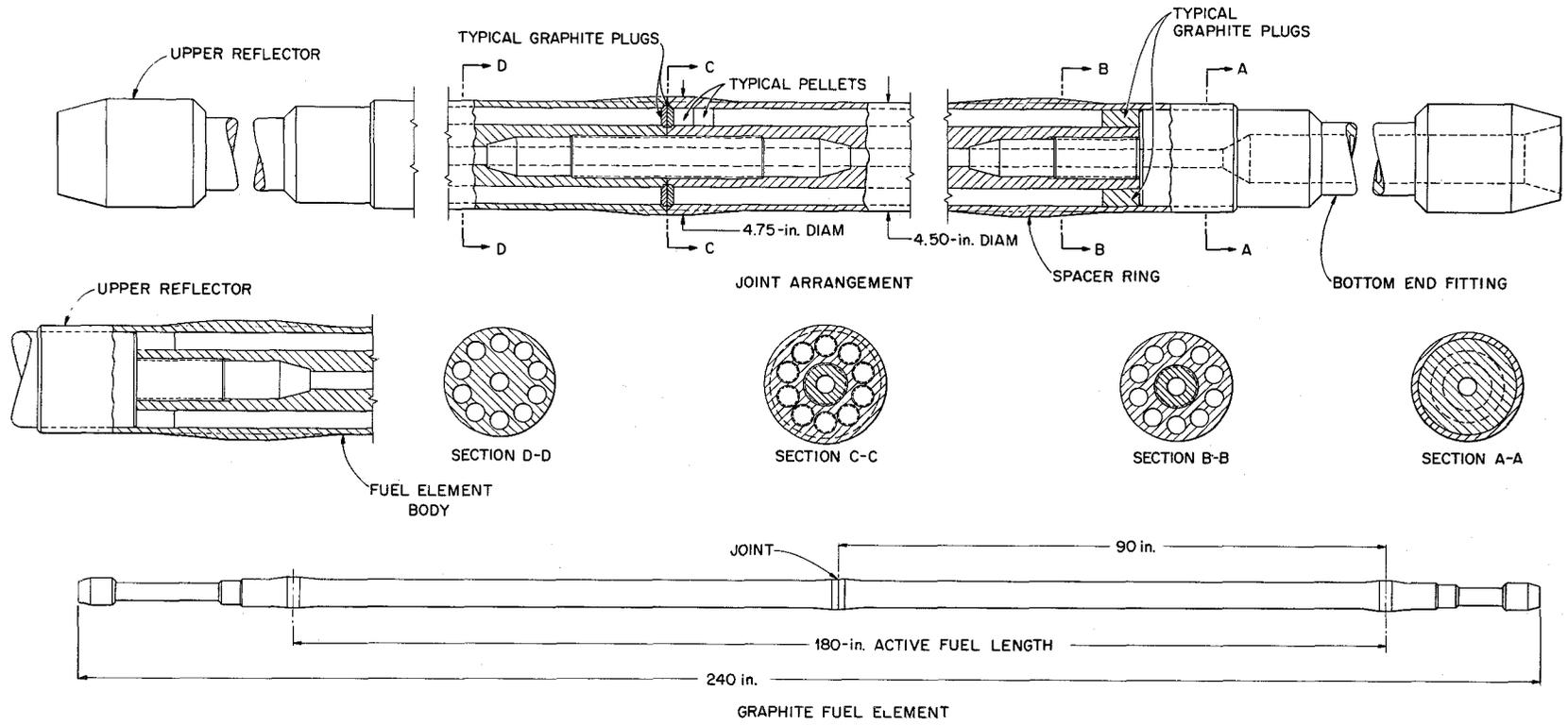


Fig. 1. A Reference Design for an HTGR Fuel Element for Remote Fabrication.

considered in the refabrication of virtually any fuel element for high-temperature gas-cooled reactors.

Preparation of Fuel Particles

Heretofore, the technology for making spherical particles has consisted of various mechanical methods of consolidating combinations of the solid materials of UO_2 , ThO_2 , and carbon and then treating these at high temperature to complete the necessary reactions and to densify the material. These methods invariably involve tedious techniques which become more complicated when special operating conditions are imposed in the recycle of fuel. Therefore, an objective of ORNL has been to simplify the manufacture of spherical particles.

We believe the sol-gel process (13) meets this objective. Clinton (14) at ORNL has demonstrated on a pilot scale the preparation of thoria-urania microspheres, which can be used as oxide or converted to carbide, as we shall discuss later. Following the flowsheet for the process, shown in Fig. 2, the microspheres are prepared by dispersing the sol at room temperature in an immiscible organic liquid which has some solubility for water. The sol droplets must be suspended in the organic phase until enough water is extracted from the aqueous sol to cause gelation. After drying, the gel spheres are calcined at 1150°C to complete the preparation of dense (99.4% of theoretical is typical) oxide microspheres.

We shall assume that oxide microspheres, whether ThO_2 , UO_2 , or $(\text{U-Th})\text{O}_2$, have been prepared by the sol-gel process.

Fabrication Flowsheet

Before discussing the details of a manufacturing flowsheet for large-scale production of HTGR fuel, we shall first consider the various alternatives which are possible in the fabrication of HTGR fuel. The alternatives are depicted in Fig. 3. One can use homogeneous fuel particles containing $(\text{U-Th})\text{C}_2$ as a solid solution, or discrete particles of UC_2 and ThC_2 . The use of discrete particles would allow the preparation of virgin ThC_2 in a hooded plant. There is also the possibility of

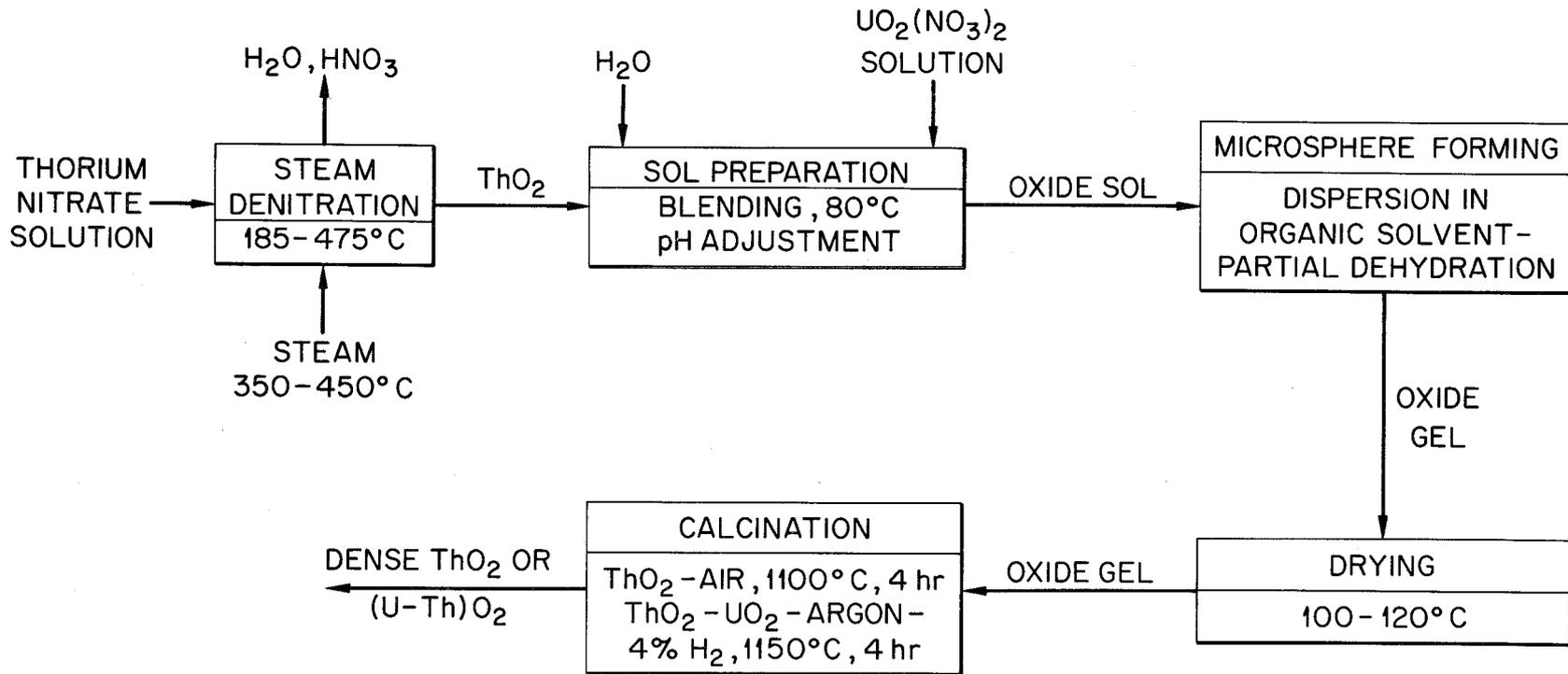


Fig. 2. Flowsheet for Preparation of Oxide Microspheres by the Sol-Gel Process.

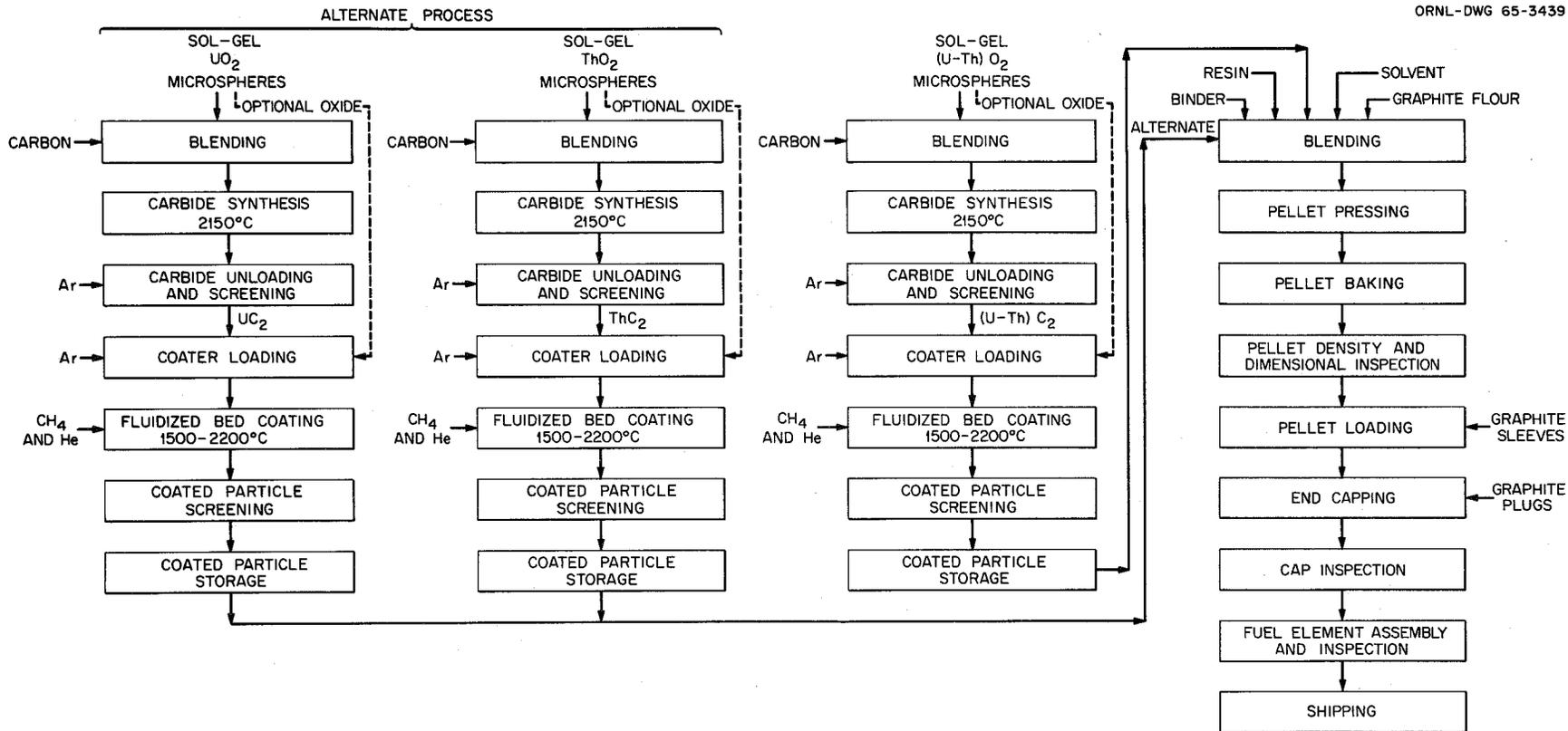


Fig. 3. Flowsheet for Fabrication of HTGR Fuel Elements.

using either mixed or discrete oxide particles instead of carbide. These alternatives are depicted as optional materials on the flowsheet.

To convey our impressions of how the manufacturing operations involved in the flowsheet would proceed, we shall describe briefly the process that starts with $(U-Th)O_2$ sol-gel microspheres. We envision that microspheres would be fed to a continuous rotating induction-heated graphite tube furnace along with carbon. As the particles move through the furnace, they would be reacted at $2150^\circ C$ to form carbide. On a continuous basis, the carbide-carbon mixture would be unloaded and the carbide separated from the carbon. The particles would be conveyed under inert atmosphere to the coaters, where the particles would be coated in batches at temperatures ranging from 1500 to $2200^\circ C$.

The particles would then be blended with resin, graphite flour, binder, and solvent; the mixture would be pressed into cylindrical compacts on automatic presses and subsequently baked in continuous furnaces at approximately $1000^\circ C$. The compacts would be inspected for density and conformity to dimensional specifications.

The pellets would be loaded into the holes in the graphite segment; the holes capped with a graphite plug, sealed, and inspected. Finally, two segments would be joined by a threaded or bayonet central fitting and sealed. After inspection of the seal for leaks and the element for dimensions, weight, and transferrable contamination, the element would be shipped. In addition to these principal steps, routine inspections and tests would be performed to assure maintenance of quality.

Effect of Fuel Isotopic Content on Fabrication Plant Design

Several recycling systems can be used for HTGR fuel. For example, one may choose not to recycle the thorium, but to recycle the ^{233}U . With $(U-Th)C_2$ particles, all of the material would be handled in the refabrication plant; but when discrete particles are used, the virgin thorium could be prepared in a hooded operation. The other alternative is to recycle the thorium and the ^{233}U .

Thus, in any proposed fabrication plant, one has the problem of selecting for the given isotope the type or mode of fabrication that is to be employed in the fabrication of either first cycle or recycle fuel. The possibilities are contact, hooded, glove box, semiremote, or remote operation. We have chosen to define these terms as follows: (1) Contact operations are those in which the operator has direct contact with the material. (2) Hooded operations are those which are contained in ventilated enclosures that are not hermetically sealed. (3) Glove box operations are those requiring hermetic sealing of the equipment. (4) Semiremote operations are those requiring light shielding. (5) Remote operations are those requiring heavy shielding and totally remote manipulation. The type and quantity of the isotope in the fuel and the quantity of fuel being processed dictate the type of operation to be selected.

In the fuel cycle of interest, thorium-uranium-233, the mode of fabrication depends upon the ^{232}U concentration in the fuel, its age, and whether virgin or recycle thorium is being used. The amount of fuel being processed, its concentration, and its proximity to the operator is also important. We have analyzed the effect of ^{232}U concentration on the type of facility which should be employed in the fabrication of HTGR fuel. In this analysis, we used the flowsheet shown in Fig. 3 and considered both discrete particles of UC_2 and ThC_2 and particles of $(\text{U-Th})\text{C}_2$. To perform the shielding calculations and to determine the mode of fabrication, the fuel element fabrication facility was divided into three zones.

Zone 1. The oxide microspheres are received from the sol-gel facility, converted to carbide, and inspected.

Zone 2. The fuel particles are coated with pyrolytic carbon and inspected.

Zone 3. Compacts are prepared, inspected, and loaded into the graphite sleeves. Finally, two fuel segments are assembled together with end pieces, inspected, and shipped to the reactor site.

Shielding was calculated for plants having daily processing capacities ranging from 10 to 3700 kg of heavy metal per day. Typical material flow rates for $(\text{U-Th})\text{C}_2$ particles are shown in Table 2; those for UC_2 particles in Table 3.

Table 2. Material Location, Quantity, and Age
in Fabrication Plant Processing (U-Th)C₂

	Plant Capacity(kg heavy metal/day)			
	60	230	930	3700
Zone 1				
(1) In-process material at a given time, kg	22	88	352	1408
(2) Time since in-process material received from sol-gel plant, hr	16	16	16	16
(3) Material held up in equipment, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	5.7	5.7	5.7	5.7
Zone 2				
(1) In-process material at a given time, kg	20	80	320	1280
(2) Time since in-process material received from sol-gel plant, hr	26	26	26	26
(3) Material held up in equipment, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	6	6	6	6
Zone 3				
(1) In-process material at a given time, kg	15	30	60	60
(2) Time since in-process material received from sol-gel plant, days	1.7	1.3	1.3	1.2
(3) Hold-up material in any element, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	6.7	6.4	6.3	6.3

Table 3. HTGR Material Location, Quantity, and Age
in Fabrication Plant Processing UC_2 and ThC_2

	Plant Capacity(kg heavy metal/day)			
	60	230	930	3700
Zone 1				
(1) In-process material at a given time, kg	3	4	16	64
(2) Time since in-process material received from sol-gel plant, hr	16	16	16	16
(3) Material held up in equipment, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	5.7	5.7	5.7	5.7
Zone 2				
(1) In-process material at a given time, kg	3	6	24	96
(2) Time since in-process material received from sol-gel plant, hr	26	26	26	26
(3) Material held up in equipment, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	6	6	6	6
Zone 3				
(1) In-process material at a given time, kg	15	30	60	60
(2) Time since in-process material received from sol-gel plant, days	1.7	1.3	1.3	1.2
(3) Hold-up material in any element, kg	3	3	3	3
(4) Time since hold-up material received from sol-gel plant, days	6.7	6.4	6.3	6.2

The following assumptions were made in calculating shielding requirements:

1. The time between solvent extraction and receipt of material at the fuel element fabrication plant is five days.
2. A major cleanup of the equipment and enclosures is performed after five working days.
3. No substantial quantity of material is located closer than 1 ft to the enclosure wall.
4. The amount of material retained in the equipment during processing is 3 kg, but the material is released and continued in process at five-day cleanup intervals.
5. The plant processes 110% of the quantity shipped.

The results of our shielding calculations for semiremote and remote plants fabricating HTGR fuel elements with (U-Th) C_2 particles are shown in Table 4. The results for fuel elements containing discrete particles of UC_2 and ThC_2 are shown in Table 5. As can be observed in the tables, we have used approximately 3.5 in. of steel as the practical limit for semiremote fabrication because of the difficulty of working through a greater distance with glove hands or tongs. Also, radiation from sources requiring greater than 3.5 in. of steel would prohibit, or at least greatly inhibit, contact maintenance of equipment. It should be noted that there are differences in shielding requirements for fabrication of (U-Th) C_2 particles and fabrication of discrete UC_2 and ThC_2 particles. The discrete particles of UC_2 require greater shielding because they are not diluted with thorium during conversion and coating operations. In all of these results, the shielding is calculated to limit body exposure to 1 mr/hr.

The shielding required for 60 to 930 kg/day plants is plotted versus ^{232}U concentration in Fig. 4. As can be seen, the limit for semiremote fabrication of UC_2 plus ThC_2 particles is approximately 2 ppm ^{232}U in total heavy metal. Beyond 2 ppm for these particles, a designer would probably use normal concrete. The concentration of ^{232}U limiting semiremote fabrication of (U-Th) C_2 is higher than that for discrete particles. The shielding requirements for fabrication of fuel elements containing (U-Th) C_2 particles vary with the amount of material being processed in the plant; as can be seen in Fig. 4, the 930 kg/day plant requires slightly more shielding than the 60 kg/day plant.

Table 4. Shielding for Semiremote and Remote Plants Fabricating Fuel Elements Containing (U-Th)C₂ Particles

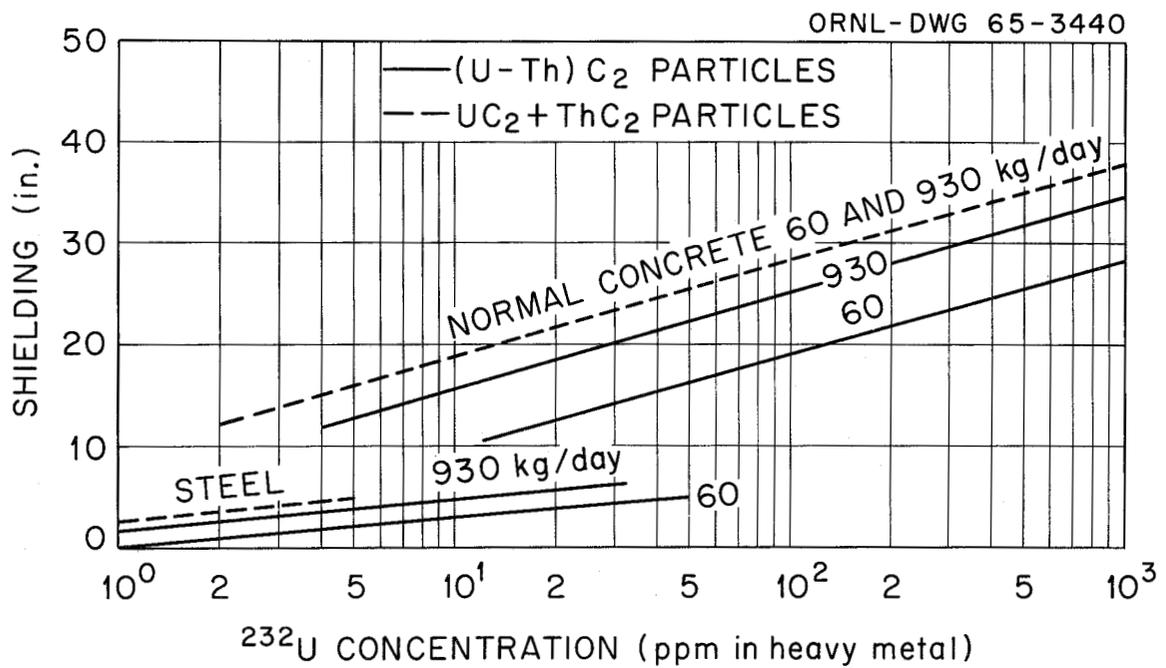
ppm ^a	Plant Capacity (kg heavy metal/operating day)									
	10	60	100	230	500	750	930	1250	1500	3700
	<u>Steel (in.)</u>									
1	0.2	0.2	0.6	1.2	1.6	1.8	1.9	1.9	1.9	2.0
2	1.1	1.1	1.4	2.0	2.4	2.6	2.7	2.8	2.8	2.9
5	2.2	2.2	2.5	3.1	3.5					
10	3.0	3.0	3.4							
	<u>Normal Concrete (in.)</u>									
5						12.4	12.8	13.0	13.2	13.9
10				13.2	14.5	15.3	15.6	15.9	16.1	17.0
20	12.7	12.7	14.0	16.0	17.3	18.1	18.4	18.8	19.0	20.0
50	16.4	16.4	17.7	19.6	21.0	21.8	22.2	22.6	22.9	24.1
100	19.2	19.2	20.4	22.4	23.9	24.6	25.0	25.5	25.8	27.2
500	25.6	25.6	26.9	28.8	30.4	31.2	31.6	32.2	32.5	34.3
1000	28.4	28.4	29.6	31.6	33.2	34.0	34.4	35.1	35.4	37.4
Recycle Th		33.0		36.0			39.0			42.5

^aParts per million ²³²U in heavy metal.

Table 5. Shielding for Semiremote and Remote Plants Fabricating Fuel
Elements Containing UC₂ and ThC₂ Particles

ppm ^a	Plant Capacity (kg heavy metal/operating day)									
	10	60	100	230	500	750	930	1250	1500	3700
	<u>Steel (in.)</u>									
1	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.9	3.0	3.2
	<u>Normal Concrete (in.)</u>									
2	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.5	12.6	13.5
5	15.9	15.9	15.9	15.9	15.9	15.9	15.9	16.1	16.3	17.2
10	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.9	19.1	20.0
20	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.7	21.9	22.8
50	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.3	25.5	26.5
100	27.9	27.9	27.9	27.9	27.9	27.9	27.9	28.1	28.3	29.3
500	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.5	34.7	35.8
1000	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.3	37.5	38.6
Recycle Th		41.5		41.5			41.5			43.0

^aParts per million ²³²U in heavy metal.



Shielding Required to Limit Body Exposure to 1 mr/hr.

Fig. 4. Effect of ²³²U Concentration on Fabrication Plant Shielding.

Although we are not certain as to the ^{232}U concentration that can be expected in equilibrium cycle fuel, 50 ppm in heavy metal would probably be a realistic value. We, therefore, conclude from our analysis that a remote plant is required for refabrication of such fuel.

REFABRICATION COSTS

Several detailed cost studies for medium-temperature gas-cooled reactors have recently been published in the United Kingdom (15) and in France; (16) in the USA, a few broad cost estimates have been presented for high-temperature gas-cooled reactors. (2, 17, 18) At the Oak Ridge National Laboratory, we have as an objective the complete analysis of the refabrication costs for any reactor fuel element, including fueled graphite elements. This objective requires a tremendous number of calculations. Therefore, during the past two years, we have developed a computer program for the calculation of the cost of fabricating fueled graphite elements. We have used this computer program to derive the data which will be presented subsequently.

Method of Analysis

The computer program was written from data evolved in the following manner. The basic equipment required in the plant was selected, and the uninstalled cost of this equipment was estimated. These costs were multiplied by various factors to determine the final capital cost of the fabrication plant. The multiplication factors were obtained from studies conducted jointly with construction engineers in which detailed plant layouts were examined for various sizes and types of fabrication plants. These studies yielded detailed breakdowns of such cost elements as building construction, equipment installation, instrumentation, engineering, and pre-operation charges. In the computer program, equations are included for each step in the process such that, upon description of the size and type of plant in which the fabrication is to occur, proper capital cost of that step can be obtained.

Operating costs were determined by similar methods. Material costs in the manufactured product were obtained through consultations with industrial manufacturers. In this manner, the costs, shown in Table 6, for the large pieces were obtained.

Table 6. Basic Costs of Graphite Hardware

Plant production rate, kilogram of heavy metal per operating day	10	100	500	1000
Dollars per fuel element	300	290	270	230

Cost of Preparing Spherical Oxide Particles

The computer program does not calculate the cost of preparing spherical particles of oxide which is the starting material in the fabrication flowsheet. But, the cost of producing spherical oxide particles by the sol-gel process has been estimated by Harrington and Chandler (19) and is shown in Fig. 5 for a large range of production rate and for processing the different isotopes of interest in the thorium fuel cycle. The cost of oxide particle preparation is not included, unless specifically noted, in the fabrication costs presented in this paper.

Basis for Calculation of Fabrication Costs

In calculating the fabrication costs which are subsequently presented, we used as a basis the fuel element shown in Fig. 1 and the flowsheet presented in Fig. 3. We made the following assumptions.

1. The fabrication plants would be single purpose; that is, only fueled graphite elements would be fabricated.

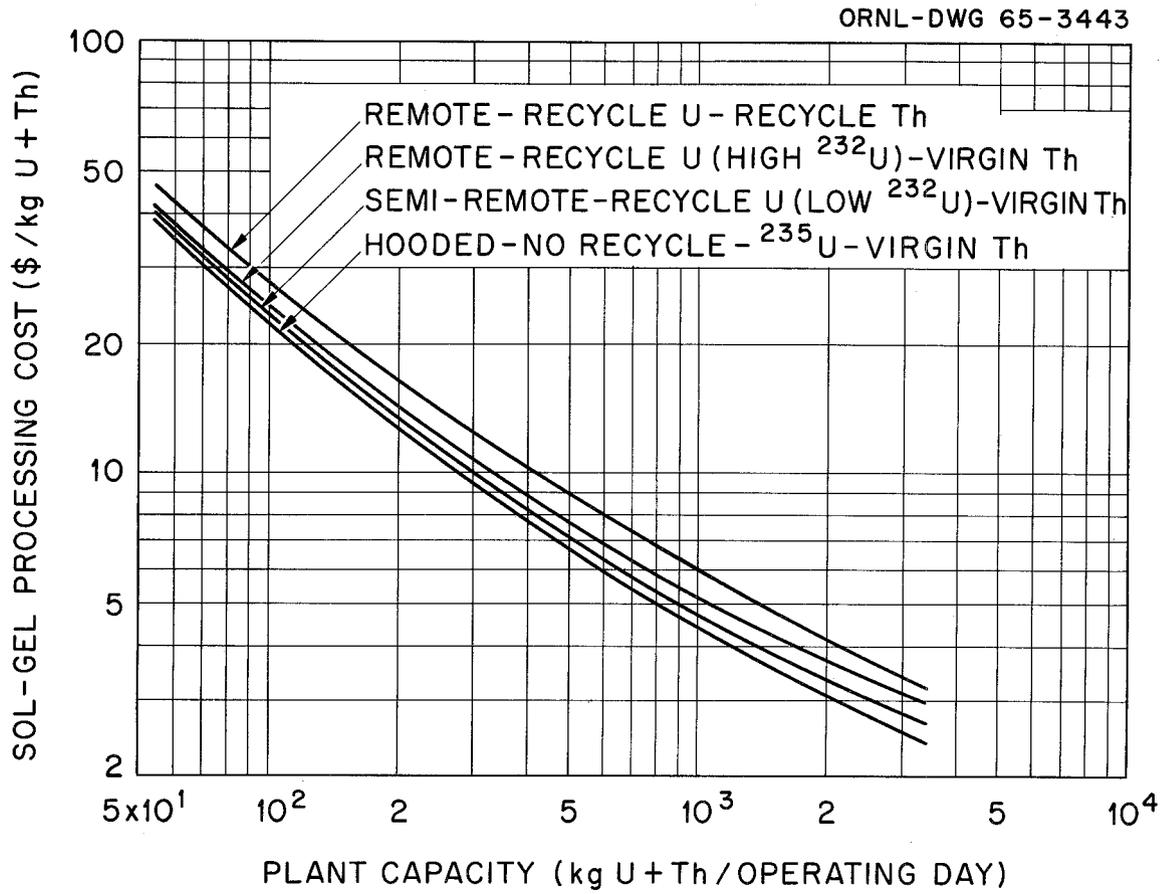


Fig. 5. Cost of Preparation of Spherical $(\text{U-Th})\text{O}_2$ Particles by the Sol-Gel Process.

2. The (U-Th) C_2 particles would be 1000 μ in diameter with 100 μ pyrolytic-carbon coating.
3. When discrete particles of UC_2 and ThC_2 are used, the UC_2 would be 200 μ in diameter; the ThC_2 would be 1000 μ in diameter; and both would have 100 μ of carbon coating.
4. The fabrication plants would operate 260 days per year, three shifts per day.

The data do not include charges for profit and for inventory or cost of source or fissionable material. Non-nuclear hardware costs are included.

Effect of Mode of Fabrication and Production Rate on Cost

One comparison of interest is that between the costs of various modes of fabrication. The cost of fabrication of fuel elements containing particles of (U-Th) C_2 in plants amortized at a rate of 22% is shown in Fig. 6. The cost of fabrication of elements containing discrete particles of uranium carbide and thorium carbide amortized at an annual rate of 22% is shown in Fig. 7. Both figures present the cost of recycling of thorium; as can be seen, the penalty for recycling thorium as discrete particles is quite high. All of these curves show the substantial effect of production rate on fabrication cost. The predicted cost reductions are a factor of 4 when production rates are scaled from 60 to 3700 kg/day.

Effect of Recycle Method and Amortization Rate on Cost

In Fig. 8 we have replotted the data to show the difference in cost of fabricating HTGR fuel elements containing recycle ^{233}U , using (U-Th) C_2 particles in one instance and discrete particles of UC_2 and ThC_2 in a second case. The thorium in each case is virgin. The figure also compares amortization rates of 15 and 22%. The curves indicate that there is little difference between the costs of fabricating the two fueling systems, even though in the case of the discrete particles a substantial quantity of fuel is not being fabricated in a remote plant. Presumably, the fact that two separate fabrication facilities must be built and

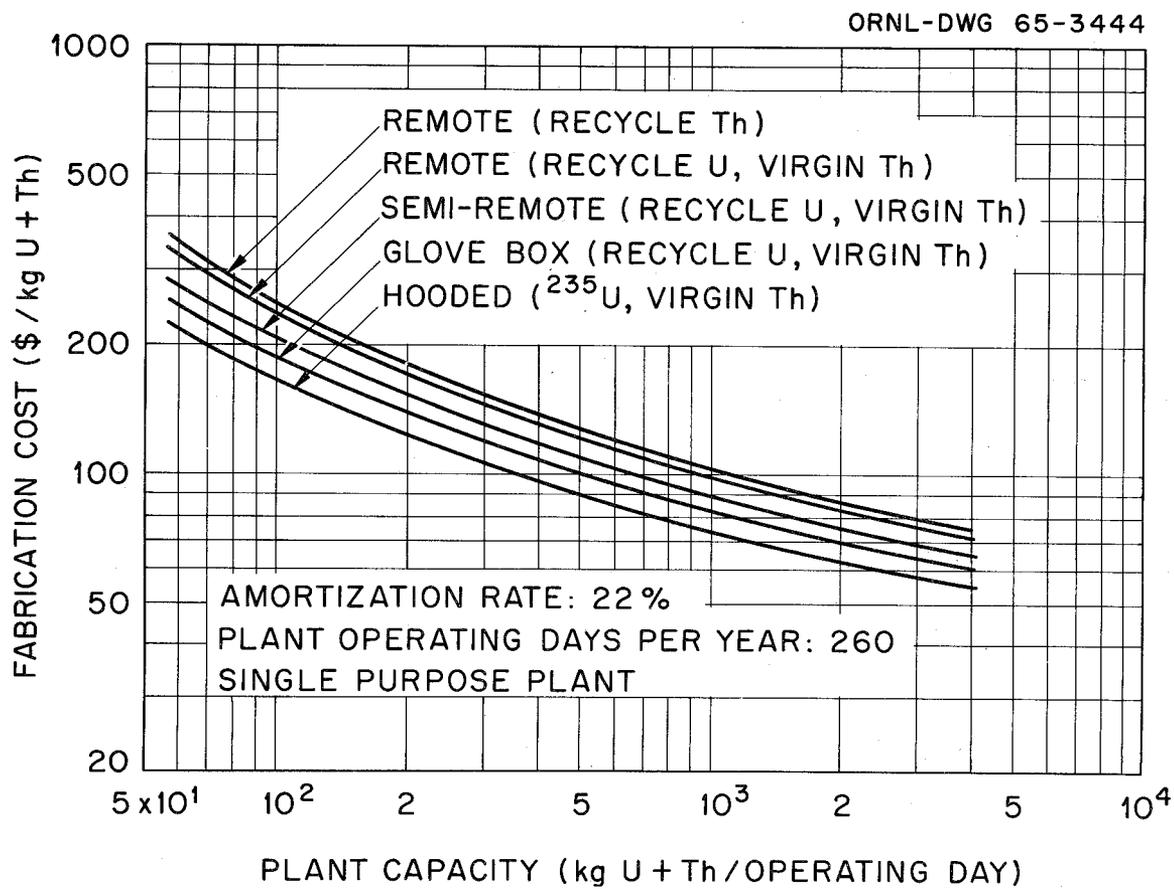


Fig. 6. Effect of Mode of Fabrication on Costs of HTGR Fuel Elements Containing (U-Th)₂ Particles.

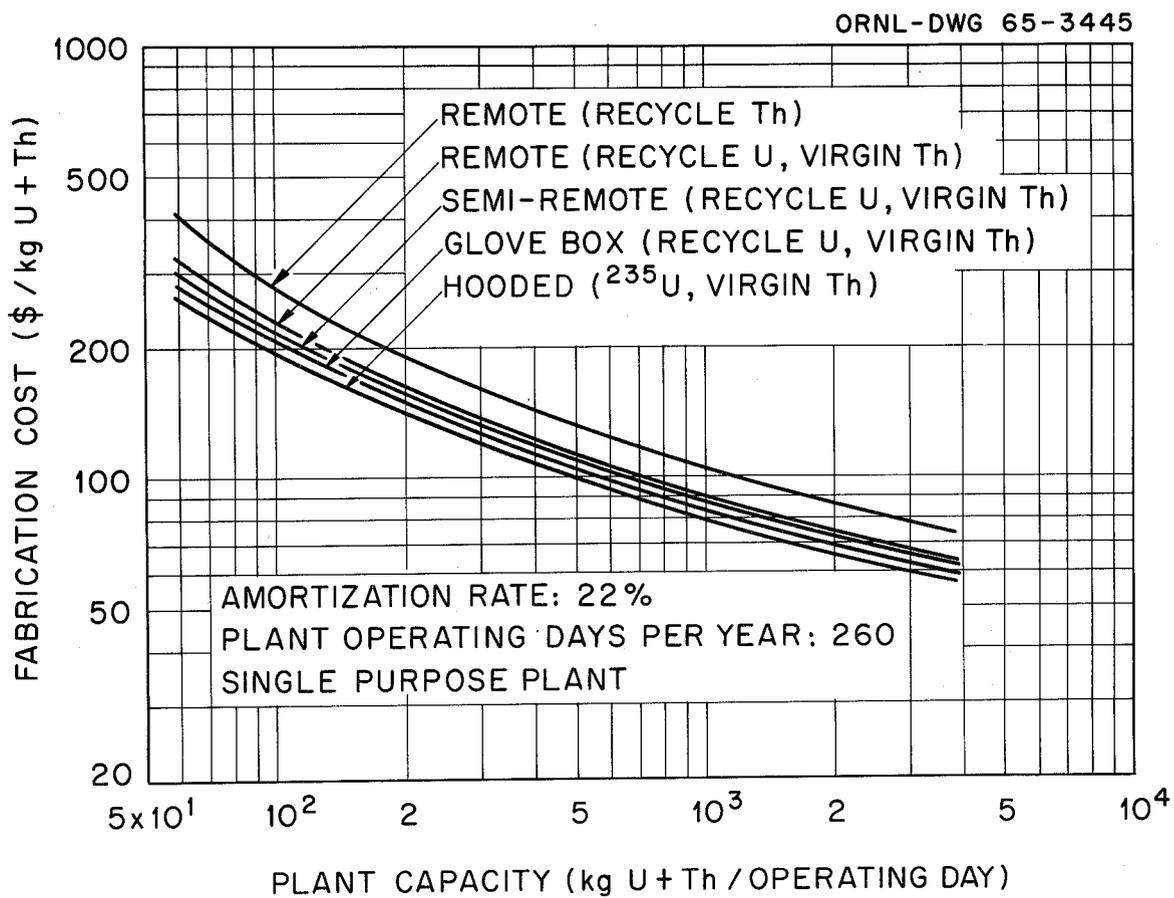


Fig. 7. Effect of Mode of Fabrication on Costs of HTGR Fuel Elements Containing UC_2 and ThC_2 Particles.

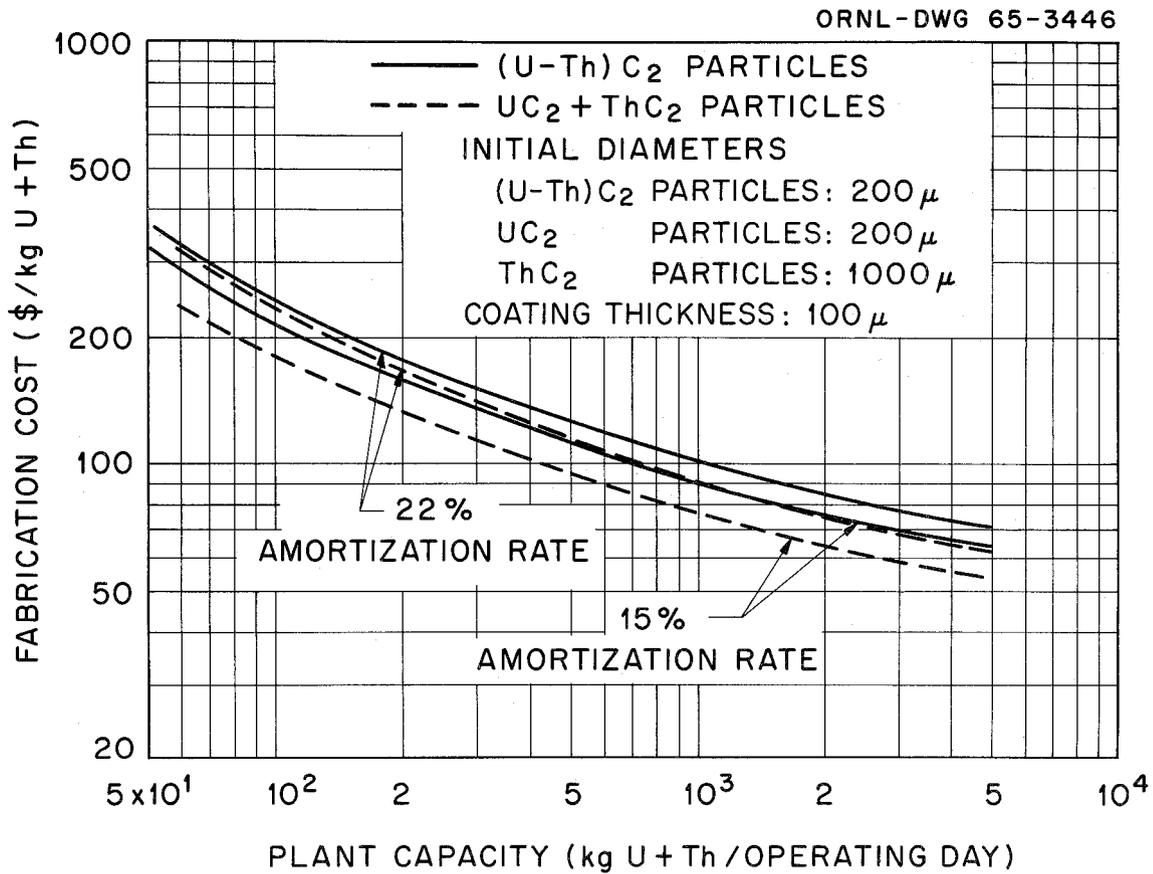


Fig. 8. Effect of Amortization Rate and Type of Fuel Particles on Cost of Remote Fabrication.

operated offsets the advantages of performing the conversion and coating of thorium-bearing particles in a hooded plant.

Comparison of Costs of Oxide with Carbide Fueled Elements

Figure 9 exhibits the cost difference between fabrication of fueled graphite elements containing carbide particles and those containing oxide particles. The curves are for remote fabrication (24-in. concrete shielding) of particles at a plant amortization rate of 22%. The curves reveal that the savings in the cost of fabrication by using oxide particles in the fuel element would range from approximately 15% at low production rates to 5% at high production rates. A simplified process for conversion of oxide to carbide has been used for these calculations. If conventional technology were used, we believe that the cost of conversion would be somewhat higher.

Variations in Cost as a Function of Shielding

The effect of ^{232}U concentration on the cost of fuel elements is presented in Fig. 10. Using plant amortization rates of 22%, the effects are shown for both discrete particles and the particles of $(\text{U-Th})\text{C}_2$. Curves are plotted for 60, 230, 930, and 3700 kg/day plants. The curves indicate that as the plant capacity increases fabrication costs become more insensitive to the ^{232}U concentration in the fuel. We do not know exactly the transition points between semiremote operation and remote operation; but, as can be seen from the curves, from the standpoint of cost it is not extremely important that the transition points be determined precisely.

Incremental Cost Elements

Because of the importance of incremental cost elements, we have performed a detailed analysis of the factors which contribute to the cost for both hooded plants and remote refabrication plants. Tables 7 and 8, respectively, contain data for $(\text{U-Th})\text{C}_2$ particles and discrete particles of UC_2 and ThC_2 , both with concentrations of 50 ppm ^{232}U in heavy metal.

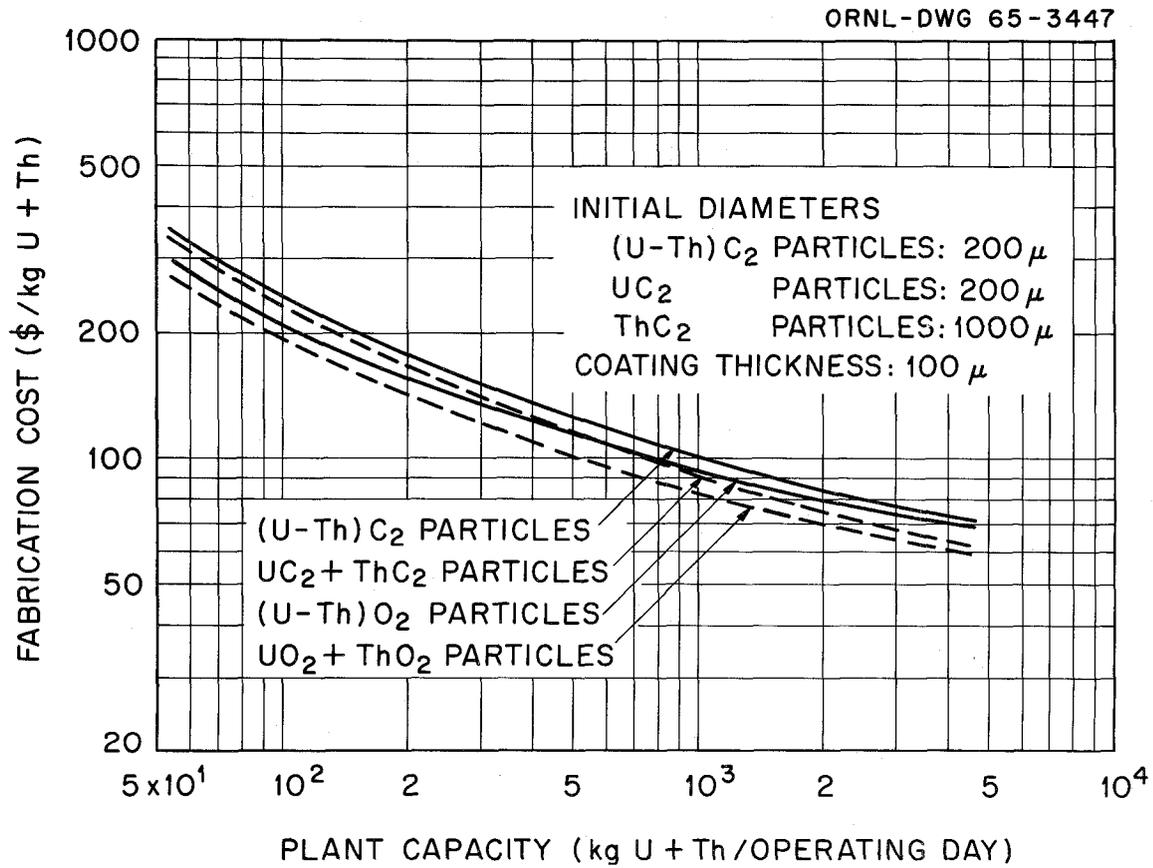


Fig. 9. Comparison of Remote Fabrication Costs of Fuel Elements Containing Oxide and Carbide Particles.

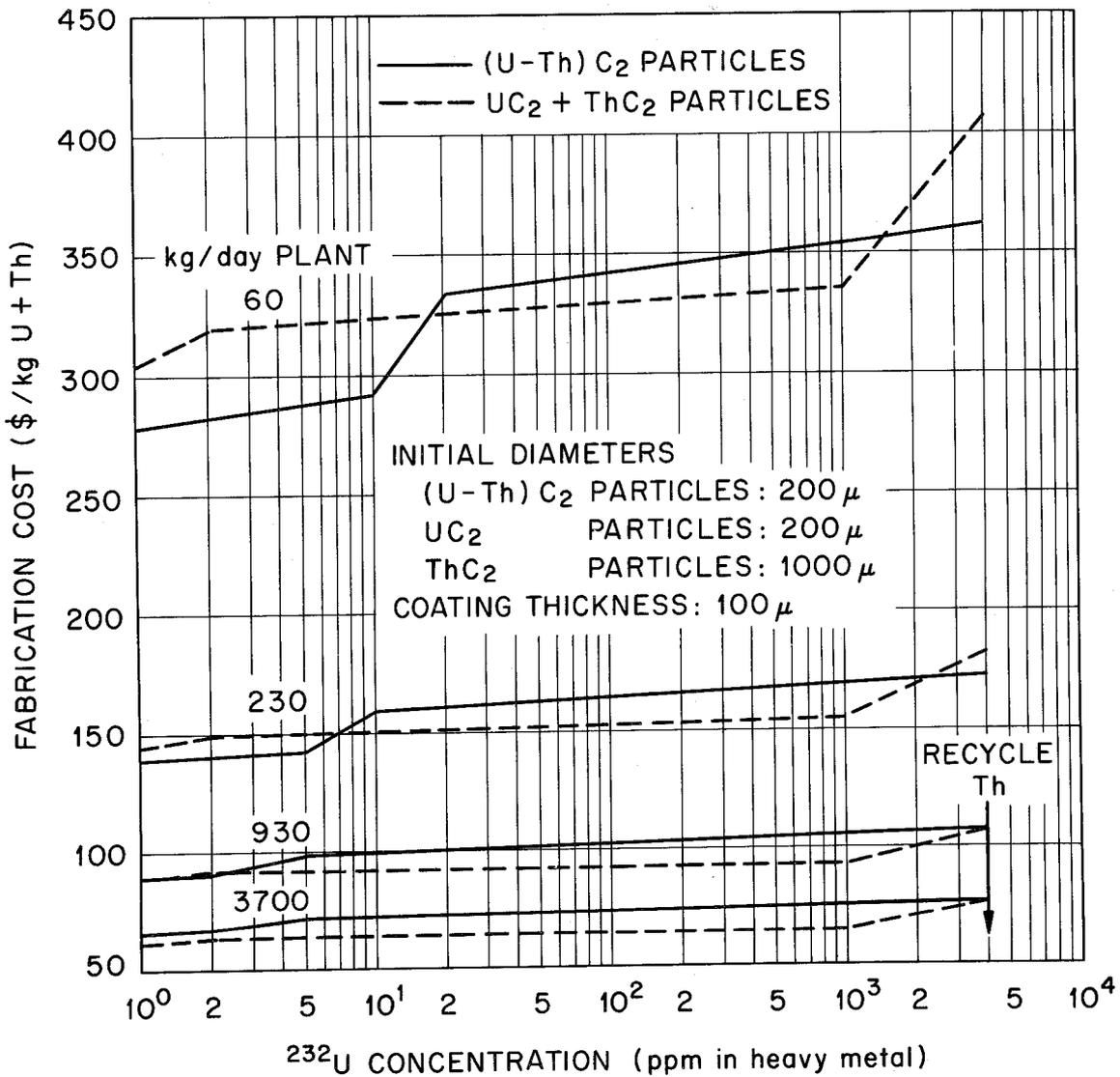


Fig. 10. Effect of ²³²U Concentration on Cost of Refabrication.

Table 7. Breakdown of Costs for Refabrication^a
with (U-Th)C₂ Particles

	Plant Capacity (kg heavy metal/day)			
	60	230	930	3700
	\$/kg heavy metal			
Capital Cost				
Conversion	17	5	3	2
Coating	42	28	21	18
Assembly	<u>74</u>	<u>28</u>	<u>14</u>	<u>8</u>
Subtotal	133(71)	61(34)	38(22)	28(16)
Operating Cost				
Conversion	27	8	3	2
Coating	48	19	11	9
Assembly	<u>97</u>	<u>43</u>	<u>23</u>	<u>15</u>
Subtotal	172(117)	70(49)	37(27)	26(19)
Hardware Cost	<u>33</u>	<u>32</u>	<u>27</u>	<u>19</u>
TOTAL COST	338(221)	163(115)	102(76)	73(54)

^a50 ppm ²³²U in heavy metal; virgin thorium; 22% amortization rate.

NOTE: Numbers in parentheses represent non-recycle fuel in hooded plant.

Table 8. Breakdown of Costs for Refabrication^a
with UC₂ and ThC₂ Particles

	Plant Capacity (kg heavy metal/day)			
	60	230	930	3700
	\$/kg heavy metal			
Capital Cost				
Conversion	13	4	2	2
Coating	36	22	17	14
Assembly	<u>74</u>	<u>28</u>	<u>14</u>	<u>8</u>
Subtotal	123(95)	54(45)	33(28)	24(22)
Operating Cost				
Conversion	27	7	2	1
Coating	47	16	8	6
Assembly	<u>97</u>	<u>43</u>	<u>23</u>	<u>15</u>
Subtotal	171(136)	66(54)	33(28)	22(19)
Hardware Cost	<u>33</u>	<u>32</u>	<u>27</u>	<u>19</u>
TOTAL COST	327(264)	152(131)	93(83)	65(60)

^a50 ppm ²³²U in heavy metal; virgin thorium; 22% amortization rate.

NOTE: Numbers in parentheses represent non-recycle fuel in hooded plant.

The tables show that the capital cost per kilogram of fuel processed for conversion decreases rapidly with increasing plant capacity. The capital cost for assembly operations show the same trend. However, for the coating operations, the decrease in cost with increase in plant capacity is not comparable to the other two categories of operation. This is attributable to the fact that the coaters quite rapidly reach their maximum practicable size. Although some economy would be effected by purchasing multiple units, this is not sufficiently great to have a marked effect. Most of the effect of scale in the coating operation is caused by the peripheral equipment, such as weighing devices, conveyors, and inspection equipment, all of which are sensitive to production rate. In the assembly operation, one does not approach the maximum capacity of a single item of equipment at a very low production rate; and, therefore, the effect of plant capacity reflects the increased utilization of the equipment.

The operating costs shown in the tables reflect the effect of automation of the operation and the effect of a large amount of overhead in plants with very low production rates. Again, we observe that the production rate has less effect on coating cost than the other two categories of operation. Production rate also affects the hardware costs significantly.

As can be seen in these tables, the coating operation accounts for approximately 25% of the costs at a plant capacity of 60 kg/day in remote plants and 38% of the costs in 3700 kg/day plants. Obviously, in order to reduce costs, one should strive to increase the efficiency of the coating step.

Using the data in Tables 7 and 8, one can approximate the incremental cost factors which can be applied to similar fabrication processes to obtain the refabrication cost if the cost of fabricating non-recycle fuel is known. Tables 9 and 10 present the ratios of remote to hooded plant costs, which can be used for this purpose. It is clear that the capital and operating factors decrease as plant capacity increases. The decrease in these factors is understandable because there are certain costs which are only first costs in remote operations. For example, health physics facilities are required in a 60-kg/day plant as well as a 3700-kg/day

Table 9. Cost Ratios for Comparison of Remote and Hooded Plants Fabricating (U-Th)C₂ Particles^a

	Plant Capacity (kg heavy metal/day)			
	60	230	930	3700
	Ratio of Remote to Hooded Cost			
Capital	1.87	1.79	1.73	1.75
Operating	1.47	1.43	1.37	1.37
Total (including Hardware)	1.53	1.42	1.34	1.35

^a50 ppm ²³²U in heavy metal; virgin thorium.

Table 10. Cost Ratios for Comparison of Remote and Hooded Plants Fabricating UC₂ and ThC₂ Particles^a

	Plant Capacity (kg heavy metal/day)			
	60	230	930	3700
	Ratio of Remote to Hooded Cost			
Capital	1.29	1.20	1.18	1.09
Operating	1.26	1.22	1.18	1.16
Total (including Hardware)	1.24	1.16	1.12	1.08

^a50 ppm ²³²U in heavy metal; virgin thorium.

plant; and probably the facilities would be of the same type and very nearly the same size in both cases. Thus, we are observing the effect of more efficient utilization of certain service personnel and facilities in the larger plants. It is notable that most of the difference falls between plant capacities of 60 and 230 kg/day, indicating that additional facilities and personnel are required for the next larger plant.

Variations in Cost with Particle Size and Coating Thickness

Another comparison which may be of interest is that of coating particles of different size and with different coating thicknesses. The effect of larger particles on coating efficiency is not accurately known; problems could be encountered in the decreased surface area per kilogram of fuel. A much increased gas velocity is required to fluidize the particles; there is poorer gas solid contact; the particle motion characteristics change; and there might be increased maintenance due to sooting.

From theoretical consideration of these effects, we derived the following relationship of initial particle diameter and coating efficiency:

$$CK = \left(\frac{D_o}{250} \right)^{0.1}$$

where

CK = coating efficiency coefficient,

D_o = initial particle diameter in microns.

This relationship was used in the computer program to adjust the cost of the coating operation. The factor was not applied to other processing steps. The fabrication costs at three production rates, 60, 230, and 930 kg/day, for fueled graphite elements containing particles of various diameters and various coating thickness are given in Fig. 11.

Refabrication Cost of a Typical HTGR Fuel Element

In the preceding discussion, we have been concerned with all of the factors which affect cost. As a final note to our discussion, we would like to present the predicted costs, including that for spherical

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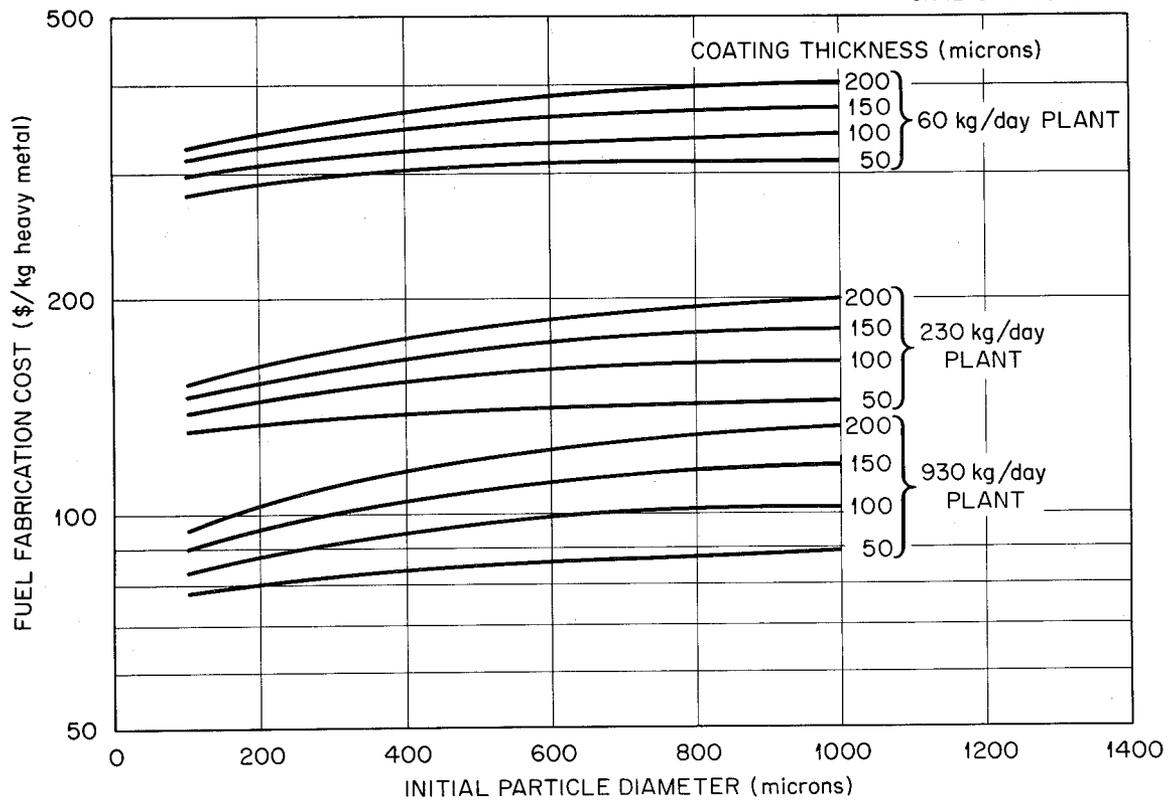


Fig. 11. Relationship of Fuel Fabrication Cost to Particle Diameter and Coating Thickness for Elements Containing $(U-Th)C_2$ Particles.

particle preparation, for a typical fuel element that might be refabricated. We shall assume that the fuel element contains 8.8 kg of 400- μ diam (U-Th) O_2 particles with 100- μ pyrolytic carbon coating, that the fuel contains 50 ppm ^{232}U in total heavy metal, and that the sol-gel and fabrication plant is amortized at an annual rate of 22%. We believe the use of coated oxide particles to be a realistic projection of technology because of the excellent irradiation performance of this material to date. (20) The results are given in Table 11 for several production rates.

Table 11. Fuel Preparation and Fabrication Costs
for a Typical Recycle HTGR Element

	Plant Capacity (kg heavy metal/day)			
	60	230	930	3700
	\$/kg heavy metal			
Particle Preparation				
Capital Charge	14	5	1.4	1.3
Operating Charge	25	7	2.6	1.2
Fabrication				
Capital Charge	106	49	29	21
Operating Charge	135	57	31	21
Hardware	33	32	27	19
TOTAL COST	313	150	91	63.5

ORNL PILOT-SCALE REFABRICATION PROGRAM

We are conducting an extensive program for the development of an economical procedure for the remote, automated refabrication of HTGR fuel. Processes which are developed will be demonstrated in the Thorium-Uranium Recycle Facility (TURF), (21,22) which is now ready for construction at ORNL.

Description of the Thorium-Uranium Recycle Facility (TURF)

The TURF will furnish the necessary space and shielding to perform all of the operations required for the processing of a spent HTGR fuel element through the various phases of the fuel cycle. The facility has been sized to accommodate integrated recycle processes with equipment scaled down from the anticipated production units so that a realistic and reliable basis for technical and economical analyses will exist.

The facility will be an irregularly shaped three-story building approximately 162 ft long, 124 ft wide, with a partial basement. The first floor, shown in Fig. 12, provides space for offices, change rooms, operating areas around the cell enclosures, a fuel storage basin, and a receiving area. The second floor provides space for chemical makeup, sampling of in-cell processes, cask decontamination, a shop for contaminated equipment, a development laboratory, and the mechanical and electrical equipment for the building. The third floor is a high bay area which includes the cell roof area and provides facilities for entry of cell services and cell access. The bay is provided with a 50-ton crane to handle casks large enough to accommodate fuel elements up to 12 ft in length. The basement will provide space for access to the equipment storage cell and for the vulnerable equipment associated with the chemical cell. The building acts as a second line of containment for the cell complex.

The primary zone of containment for the facility consists of six shielded cells and associated glove maintenance room and air lock, all of which are depicted in Fig. 13. Four of the cells provide the operating space for the process equipment while two provide supporting functions. The mechanical processing and chemical processing cells will be used for operations incidental to irradiated fuel recovery and reconstitution of fissile and fertile materials into forms suitable for use in fuel element manufacture. The contaminated fabrication cell provides space for fabrication operations through the point where all fissile and fertile material is contained and sealed in fuel cladding. The clean fabrication cell will be used for final assembly and inspection of fuel elements.

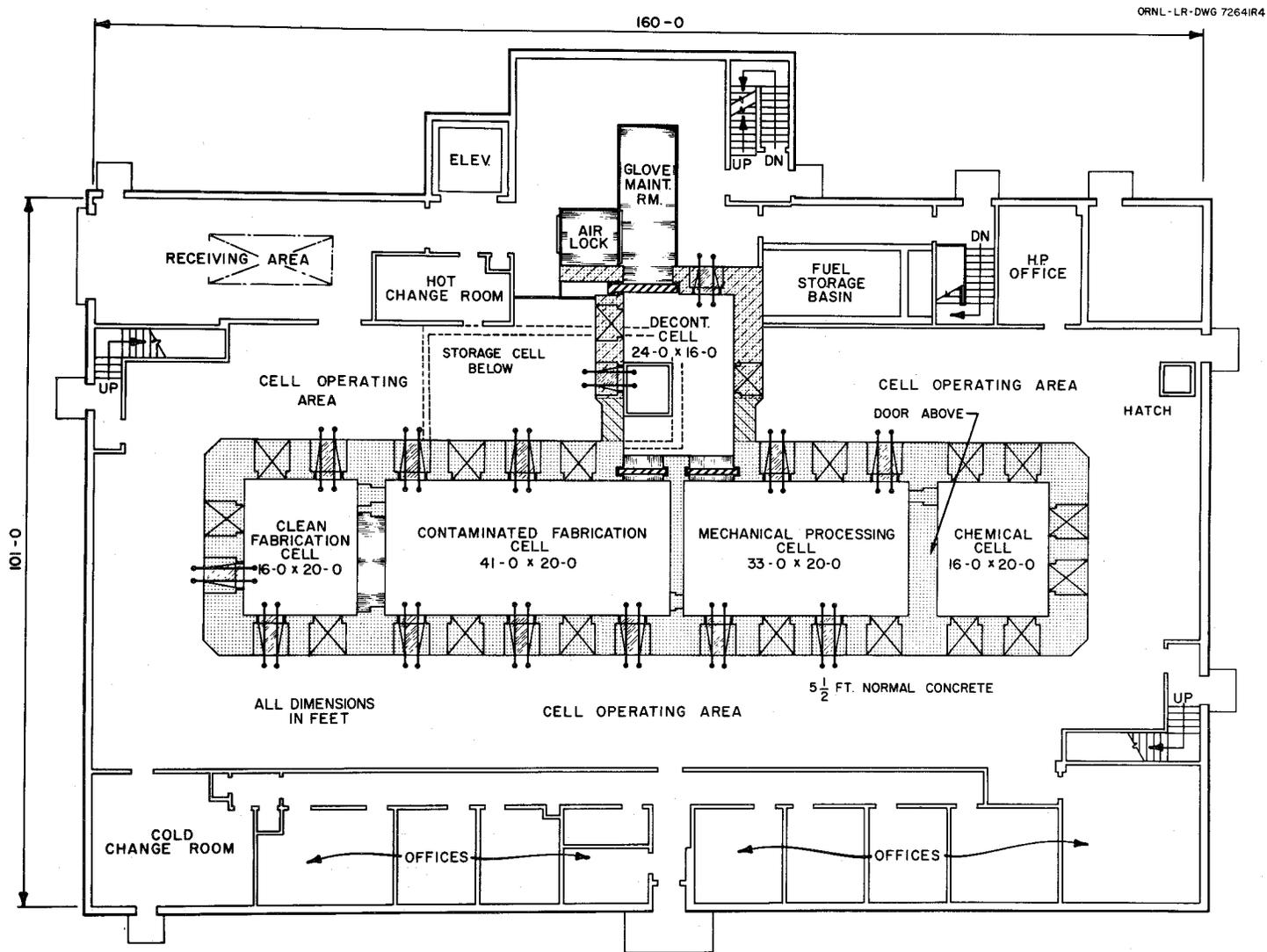


Fig. 12. ORNL Thorium-Uranium Recycle Facility - First Floor.

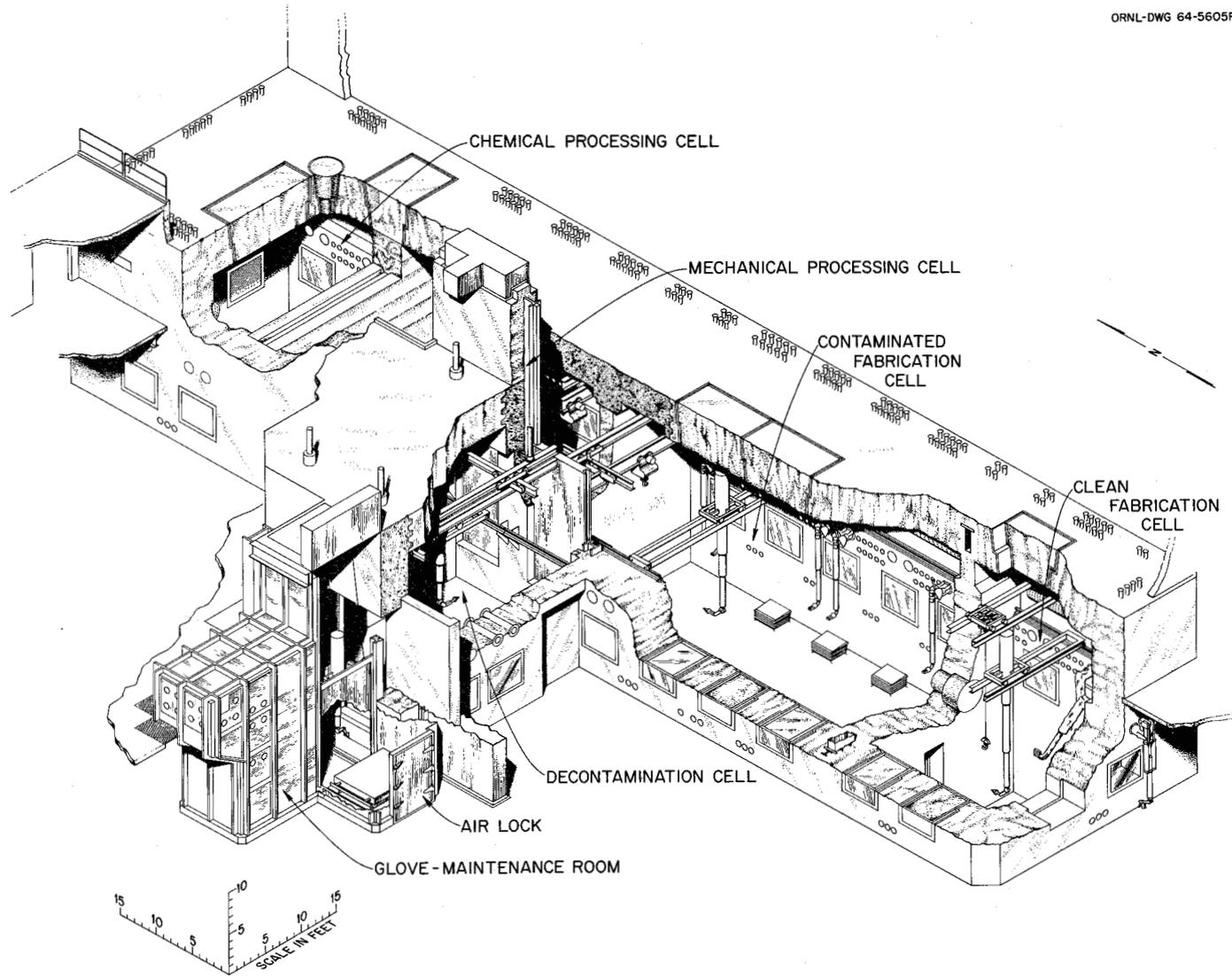


Fig. 13. ORNL Thorium-Uranium Recycle Facility - Hot Cells.

The two large cells, mechanical processing and contaminated fabrication, are to be maintained remotely; the clean fabrication cell will be maintained by a contact means. The chemical cell has the flexibility of allowing either method of maintenance.

All the remote maintenance cells and the decontamination cell are lined with stainless steel. The service penetrations for all cells are provided with seals to confine radioactivity. Provisions have been made for future conversion to an inert atmosphere in the remote maintenance cells, the decontamination cell, equipment storage cell, and the glove maintenance room to permit processing of pyrophoric materials on a large scale.

The cells are capable of processing and refabricating fuel assemblies as long as 12 ft and containing as much as 35 kg of Th-U fuel irradiated to 25,000 Mwd/MT and decayed for 90 days. All of the operating cells are provided with the equivalent of 5 1/2 ft of normal concrete up to the electromechanical manipulator bridge level and 4 1/2 ft of concrete above this level. Figure 14 is a section elevation showing the common roof line of all operating cells with the varying floor levels required to provide different in-cell height to permit processing and refabrication of power reactor size fuel elements. The section also shows the crane and electromechanical manipulator system and the modular arrangement of windows and master-slave manipulators.

Refabrication Equipment for HTGR Fuel

We are now conceptually designing equipment to be used for demonstration of refabrication technology for the fueled graphite element depicted in Fig. 1. The flowsheet that is being used for the conceptual design is shown in Fig. 15 and is an expansion of the one presented in Fig. 3.

The equipment for demonstration of refabrication technology for fueled graphite elements will be of production type so that the information gained will be applicable both technically and economically to a full-scale production facility. The equipment is to be sized for the production of approximately 35 kg of heavy metal per day. The

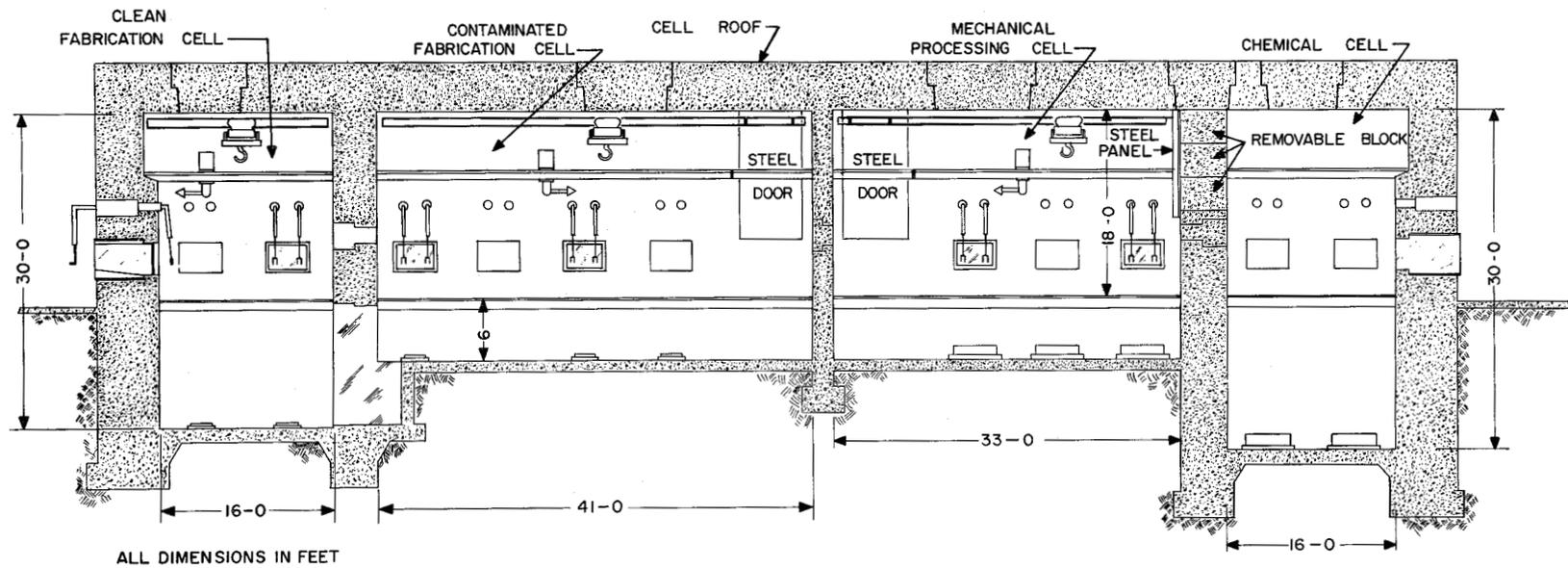
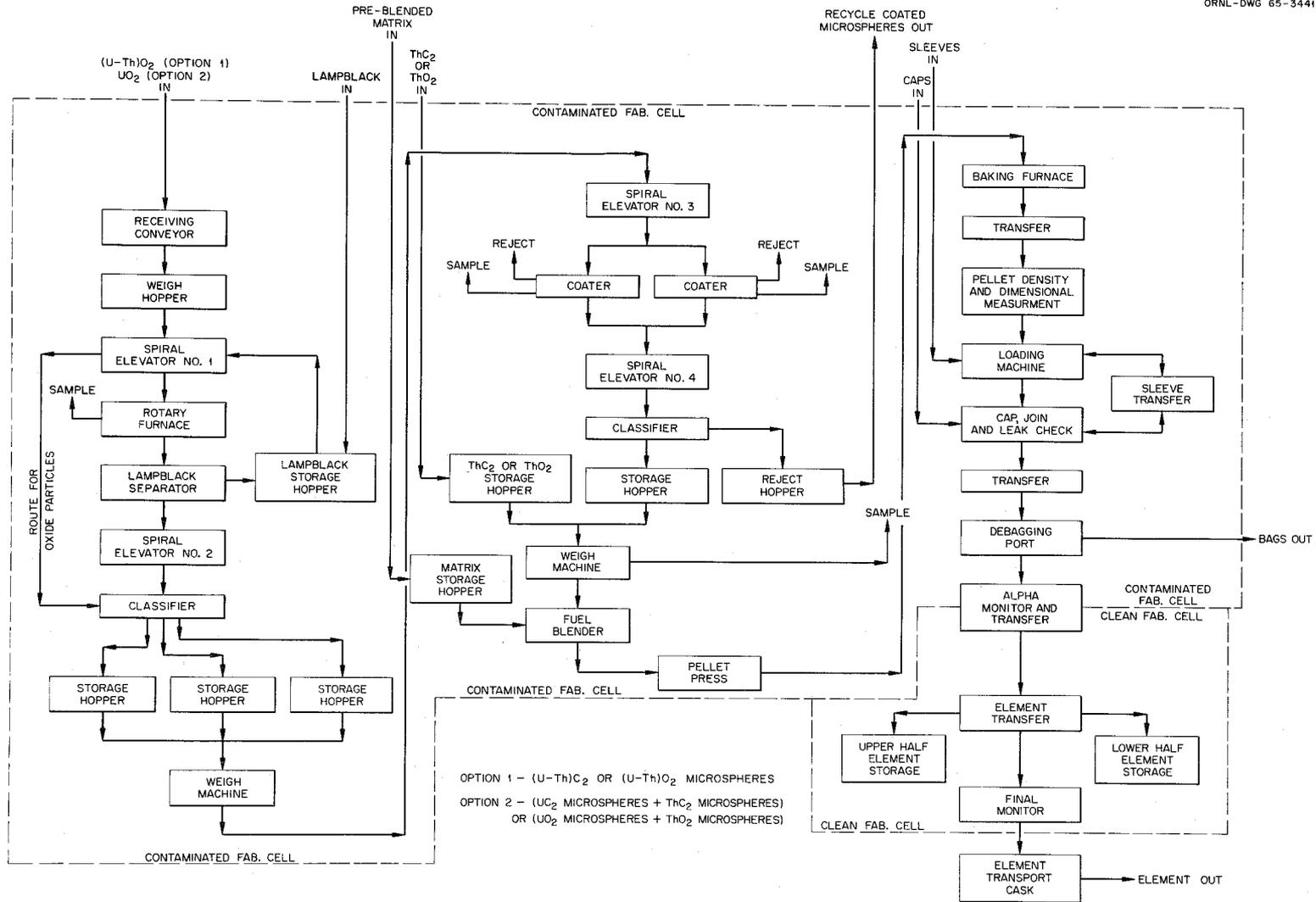


Fig. 14. ORNL Thorium-Uranium Recycle Facility - Section Elevation.



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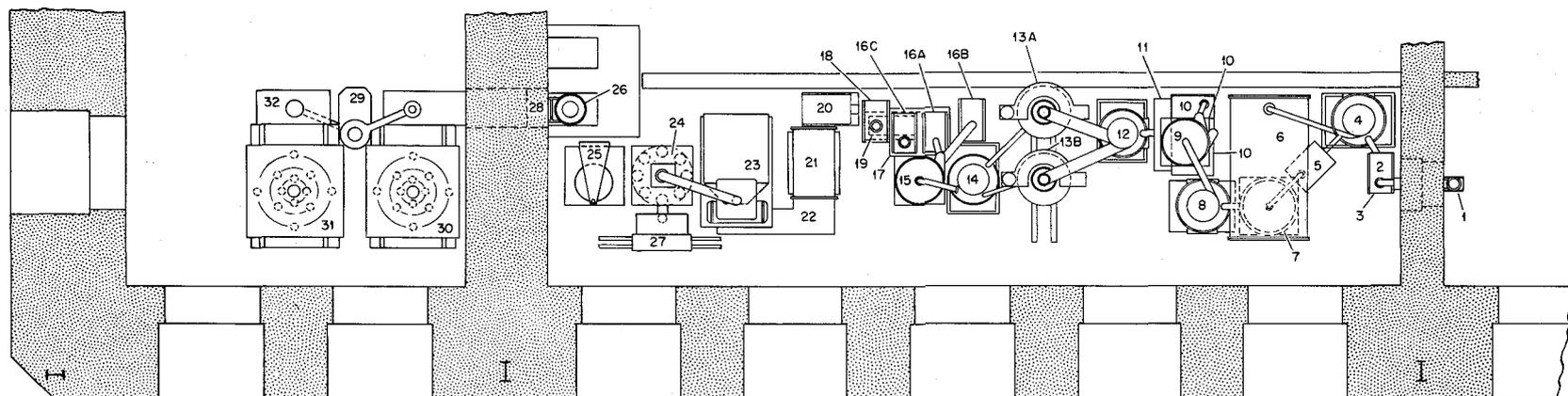
Fig. 15. Flowsheet for Refabrication of HTGR Fuel Elements in TURF.

principal barrier to this goal, as far as capacity is concerned, is the coating process. We do not yet have a solution to the relatively low processing rate which is inherent to the coating step. Accordingly, we are exerting a substantial portion of our development program toward the solution of this problem.

A preliminary layout of the fabrication equipment in the TURF is shown in Fig. 16. The equipment will occupy approximately one-half of the space in the contaminated fabrication and clean fabrication cells. The dried sol-gel oxide microspheres are fed from the mechanical processing cell by means of a transfer conveyor (1) through the cell wall to the contaminated fabrication cell where they are charged to the inventory hopper (2). As required by the process, the particles are fed from the inventory hopper to the batch weighing device (3), then conveyed by the spiral elevator (4) to the rotary converter furnace (6). As the particles are charged to the spiral elevator (4), lamp black is dispensed from the lamp black storage hopper (5). After the reaction of the particles in the furnace, the lamp black and carbide particles are partitioned in the separator (7).

The carbide particles are then transferred to the top of the cell by means of the spiral elevator (8), and charged to the agglomerate separator (9), which separates particles that are stuck together. The material is stored in the storage hoppers (10). The material is dispensed from the storage hoppers by means of the batch weighing machine (11) and transferred vertically by the spiral elevator (12). The spiral elevator charges the coaters (13a and b) on a batch basis. The coated particles are removed from the coaters and fed to the spiral elevator (14) and through the elevator to the classifier (15) for separation of particle agglomerates. Material from the separator is fed to the storage hopper for useable material (16a); reject material is stored in another hopper (16b). [When particles bearing thorium alone are used, the material would be stored in a third storage hopper (16c)].

Batches of particles are dispensed by the weighing device (17) and mixed with the graphite flour, resin, binder, and solvent in the blender (19). The material which is mixed with the particles is preblended outside of the hot cell and charged to the storage hopper (18) by the cell manipulation



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- | | | | |
|------------------------------|----------------------------|--|---|
| 1. TRANSFER CONVEYOR | 9. AGGLOMERATE SEPARATOR | 16A. STORAGE HOPPER (USEABLE MATERIAL) | 22. UNLOADING CONVEYOR |
| 2. INVENTORY HOPPER | 10. STORAGE HOPPERS (3) | 16B. STORAGE HOPPER (REJECT MATERIAL) | 23. PELLET DENSITY AND DIMENSIONAL INSPECTION |
| 3. BATCH WEIGHING MACHINE | 11. BATCH WEIGHING MACHINE | 16C. STORAGE HOPPER (Th PARTICLES INPUT) | 24. PELLET LOADING MACHINE |
| 4. SPIRAL ELEVATOR NO. 1 | 12. SPIRAL ELEVATOR NO. 3 | 17. BATCH WEIGHING MACHINE | 25. CAP, JOIN, AND LEAK CHECKING MACHINE |
| 5. LAMP BLACK STORAGE HOPPER | 13A. COATER | 18. STORAGE HOPPER (PREBLENDED GRAPHITE) | 26. DEBAGGING PORT |
| 6. ROTARY CONVERTOR FURNACE | 13B. COATER | 19. BLENDER | 27. FUEL ELEMENT TRANSFER MACHINE NO. 1 |
| 7. SEPARATOR | 14. SPIRAL ELEVATOR NO. 4 | 20. PELLET PRESS | 28. ALPHA MONITOR |
| 8. SPIRAL ELEVATOR NO. 2 | 15. AGGLOMERATE SEPARATOR | 21. BAKING FURNACE | 29. FUEL ELEMENT TRANSFER MACHINE NO. 2 |
| | | | 30. UPPER HALF ELEMENT STORAGE |
| | | | 31. LOWER HALF ELEMENT STORAGE |
| | | | 32. FINAL MONITOR |

Fig. 16. Layout of Refabrication Equipment in TURF.

system. This mixture is pressed in an automatic pellet press (20). After pressing, the green compacts are transferred to the furnace (21) where they are baked at a temperature of 1000°C. By means of the unloading conveyor (22), the pellets are discharged and removed to the inspection equipment (23). This inspection determines the pellet density and the conformity to the dimensional tolerances.

The pellets are loaded into the fuel channels in the graphite segments by the pellet loading machine (24). After loading, the segments are moved to the next machine (25) where they are capped with a graphite cap, sealed, and inspected. Following loading, the fuel segments are moved to the debagging port (26), where the protective covering for the elements is removed. Transfer operations involving the individual fuel segments are carried out by the fuel element transfer machine (27). After the fuel segment drops through the debagging port, it is placed in an alpha monitor (28) where it is monitored for contamination. Clean fuel segments are then moved into the clean fabrication cell by a transfer device (29). Fuel segments containing upper end cap fittings are placed in the upper storage area (30). Elements containing bottom end cap fittings are placed in the lower half element storage area (31). Before the fuel segment leaves the cell, it is monitored for gamma and alpha radiation (32).

Because of the handling limitations imposed by the building clearances, a fuel element longer than 12 ft cannot be handled in the facility; therefore, it will be necessary to accomplish the assembly operations for the fueled graphite element in another facility or at the reactor site. This could be done by means of a central fitting of the threaded or bayonet type, and the joint could be sealed with an inductively heated braze joint.

All of the hardware which is used in the fabrication of the fuel elements will be loaded into magazines and brought into the cell by means of the cell manipulation and crane system.

Development Program

To provide a basis for process and equipment design, we are conducting experiments in several areas including spherical particle preparation, conversion of oxide particles to carbide (23), and coating

with pyrolytic carbon. (24,25,26) Most of this work is directed toward the scaleup of these processes. In fact, we are now equipping a pilot-scale laboratory in which we shall accumulate data that we hope will lead to efficient remote fabrication processes and equipment. The facility is to process non-recycle material.

SUMMARY

We have just begun to investigate the technology for refabrication of fueled graphite elements. Much more evaluation needs to be done and much thought must go into systems required for recycle of such fuel. However, it is encouraging that, despite the cost penalties associated with recycle of HTGR fuel, the concept shows promise for an economically attractive fuel cycle.

We have been reasonably optimistic in our cost analyses in that we have assumed that the sol-gel technique can be adapted satisfactorily to large production operations, that the conversion of sol-gel oxide microspheres to carbide on a large scale is within our grasp, and that some increase in the efficiency and capability of fluidized-bed coaters can be attained. It is clear that we must press development in these areas if we are to attain an economical thorium-uranium-233 recycle technology for high-temperature gas-cooled reactors.

We are conducting a comprehensive program at the Oak Ridge National Laboratory aimed at meeting these objectives. With the forthcoming pilot-scale demonstration of the sol-gel technique for making spherical particles, coupled with the coating process, we should have a better basis for the design of equipment for remote fabrication of the fuel in the TURF. Once equipment is operated in the TURF, we shall have a much better basis than we do now for the evaluation of the technical feasibility and cost of refabricating fueled graphite elements.

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