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Estimation of Costs for Fabrication of Pressurized-Water Reactor Fuel

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ABSTRACT

Information about the costs associated with the fabrication of nuclear fuel is required by the Nonproliferation Alternative Systems Assessment Program (NASAP) and the International Nuclear Fuel Cycle Evaluation (INFCE). Several fuel cycles and reactor types, including light-water reactors, are under consideration in these programs.

To provide a reference case on which to base cost estimates of the several fuel cycles to be considered, we examined the facility, equipment, and operating requirements for the fabrication of fuel for current-design pressurized-water reactors. From an analysis of these requirements, we estimated the capital and operating costs of a plant with a capacity of two metric tons of heavy metal per day (MTHM/day). In a cash flow analysis, the lifetime of the plant was assumed to be 20 y, and the income from the sale of nuclear fuel assemblies over this period was equated to the total capital and operating expenses of the plant, including a specified 15% return on investment. In this way we obtained a levelized unit price for the fuel. The effects of inflation were not considered since the purpose of these estimates and the determination of unit price was to permit comparison of different types of fuels.

The capital costs of the fuel fabrication plant were estimated at $32 million for the facility — land, site preparation, building — and $34 million for equipment. Annual operating costs — labor, management, materials, and utilities — were estimated to be $36.5 million. From these estimates, the unit price for fabricating the fuel for the reference pressurized-water reactor was determined to be $138/kg of heavy metal or $63,600 per fuel assembly.

The reference fuel fabrication facility and the method of economic analysis described in this report will be the basis for estimating costs and determining the unit price associated with the fabrication and refabrication of the several types of fuel considered in the NASAP and INFCE programs.

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*Work performed as part of Nuclear Energy Assessments — Studies and Evaluations (189a 01303).

INTRODUCTION

Cost estimates for fabricating and refabricating nuclear fuel for a variety of fuel cycles for several types of reactors are required by the Nonproliferation Alternative Systems Assessment Program (NASAP) and the International Nuclear Fuel Cycle Evaluation (INFCE). These cost estimates are important to the selection of alternative fuel cycles in the two programs. Presumably, if two technically acceptable fuel cycles are equally resistant to proliferation and diversion, then fabrication cost would be very important in the selection of the fuel cycle to be employed. Alternatively, by comparing the cost of two fuel cycles, we can estimate the incremental cost of additional resistance to diversion.

For consistency in estimating the costs of the various reactor and fuel cycle combinations, we adopted certain assumptions about the design of fuel assemblies and fuel fabrication facilities. These assumptions about design are to be used, to the extent possible, in estimating the costs of fabricating all the designated alternative fuels. For the light-water reactors, the reference fuel assembly had the 17- by 17-rod array designed for current-vintage pressurized-water reactors (PWR) and described in the Westinghouse Electric Corporation Reference Safety Analysis Report (RESAR 3S)[1] dated July 1975. The reference fabrication facility for this fuel was a 2-MTHM/d (MTHM: metric tons of heavy metal) plant.

This report provides information about estimating the costs and determining the prices associated with the fabrication of low-enriched uranium fuel for light-water reactors. Furthermore, the report is the foundation for the cost estimation procedures and economic analyses for the other fuel cycles considered in the NASAP and INFCE programs. Information presented in this report represents an update and extension of similar information previously presented.[2]

DESIGN BASES

Fuel Assembly Design

The parameters for the mechanical design of the reference fuel assembly are summarized in Table 1 and the fuel assembly [1,3] is shown in Fig. 1. Basically, the reference fuel assembly is a mechanical assemblage of 264 fuel rods arranged in a 17 by 17 square array. The structural integrity of the array of fuel rods is maintained by a fuel assembly skeleton that consists of two end fittings or nozzles, eight grids, 24 control rod guide thimbles, and an instrument tube. The fuel rods, control rod guide thimbles, and instrument tube occupy the 289 lattice positions of the 17 by 17 array. The fuel material is low-enriched uranium (461 kg HM per assembly) in the form of UO_2 pellets.

Table 1. Components of Fuel Assembly for a Pressurized-Water Reactor[a]

Component[b]	Material	Number per Fuel Assembly
Control rod guide Thimbles	Zircaloy-4	24
Instrument guide thimbles	Zircaloy-4	1
Grids		
Top	Inconel-718 (304 SS sleeves)	1
Middle	Inconel-718 (304 SS sleeves)	6
Bottom	Inconel-718 (304 SS inserts)	1
Nozzles		
Top	304 SS with Inconel-718 Hold down springs and Inconel 600 bolts	1
Bottom	304 SS	1
Fuel cladding	Zircaloy-4	264
End plugs		
Top	Zircaloy-4	264
Bottom	Zircaloy-4	264
Plenum springs	302 SS	264
Fuel pellets	UO_2 (95% theoretical density)	∿71,544

[a]Sources: *RESAR-3S, Reference Safety Analysis Report Vol. 2,* Docket STN 50545-2, Westinghouse Electric Corporation, Pittsburgh (July 1975); T. M. Helm et al., eds., *Pressurized Water Reactor Design Information and Material Inventory Data for Low Enriched U-235 (PWR-U5 (LE)/U',* Hanford Engineering Development Laboratory, Richland, Wash. (September 1977).

[b]Includes only major hardware.

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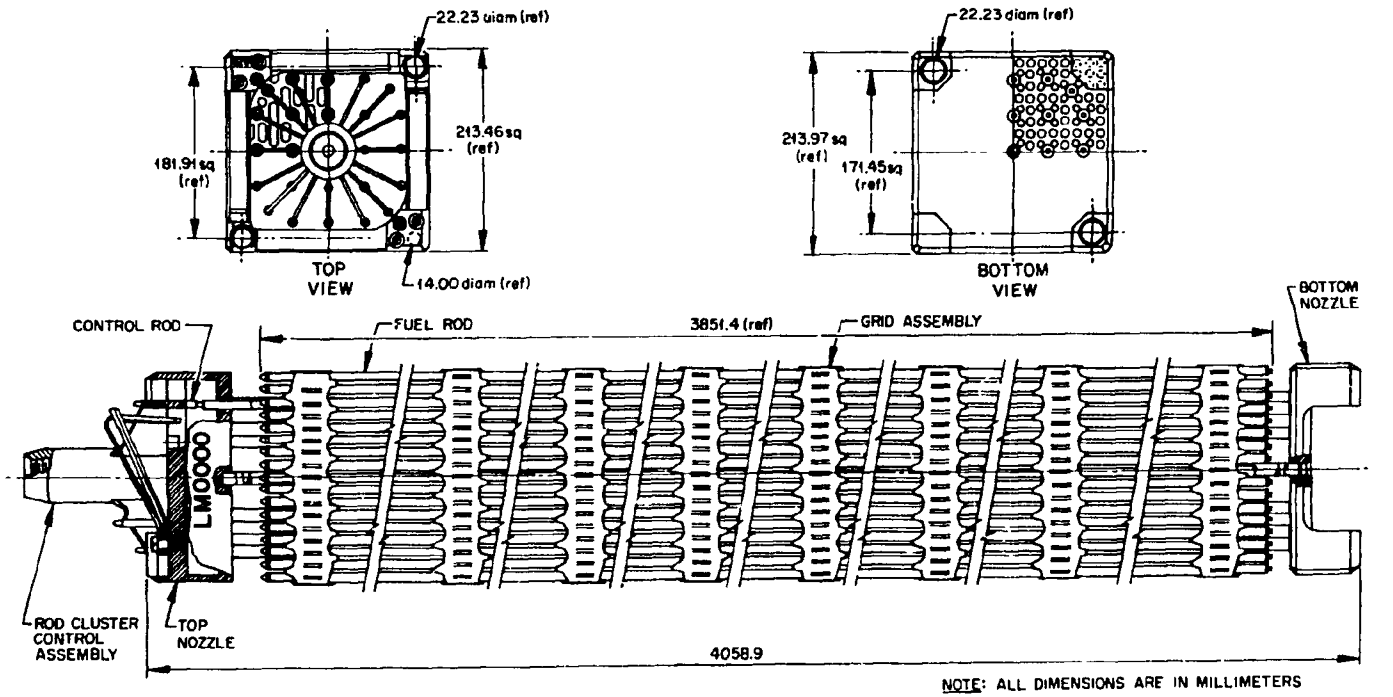

Fig. 1. Pressurized-Water Reactor Fuel Assembly with a 17 by 17 Rod Array.

Fabrication Facility Design

The reference fuel fabrication facility is based on state-of-the-art UO_2 pellet fabrication. The facility has an output capacity of 2 MTHM/d in the form of finished fuel assemblies, and is operated on a 24 h/d, 7 d/week schedule. The production realized is assumed equivalent to 260 effective full-production days each year. Thus, 520 MTHM is produced each year.

The fuel materials handling section is designed on the concept of parallel processing lines and each fuel line has a capacity of 1 MTHM/d. Although some equipment on each processing line can accommodate surges from the second line, they generally operate on a segregated basis with no flow of materials from one processing line to the other. The reference fuel fabrication facility design is summarized in Table 2.

FUEL FABRICATION PROCESS

The process for fabricating the fuel assemblies is generally the same as that employed by commercial processors. Process flowsheets for the fabrication of the fuel are presented in Figs. 2, 3, and 4, and some details of the various operations are presented in the following paragraphs.

Uranium hexafluoride (UF_6) is the usual feed material sent to the fuel fabrication facility, although uranyl nitrate may be used. The UF_6 is heated in a steam- or electrically heated chest, vaporized, and transferred to a hydrolysis tank for conversion to uranyl fluoride (UO_2F_2). The concentration and pH of the UO_2F_2 are adjusted and ammonia is added to precipitate the uranium as ammonium diuranate (ADU). The ADU slurry is centrifuged and transferred to a furnace for calcination, in a hydrogen atmosphere, to uranium dioxide (UO_2) powder. After calcination, the UO_2 powder is milled, blended, slugged, granulated, and mixed with a press lubricant. The resulting powder is fed to a rotary pellet press and pressed into right circular cylinder pellets 45–65%

Table 2. Factors in the Design of a Low-Enriched Uranium Fuel Assembly Plant

Mode	Operation: Period (h/d)	Operation: Period (d/week)	Effectiveness, % of Full Productivity Over Years: 1	2	All Subsequent	Production: Period[a] (d/year)	Production: Output[a] (MTHM/year)	Hardware: Product Type	Hardware: State at Purchase	Hardware: Work Done to Piece at Plant
Contact (Hooded)	24	7	33	67	100	260	520	Tubing	Finished	
								End plugs	Finished	
								Plenum springs	Finished	
								Nozzles	Stock	Machining and welding
								Grids		Assembling, welding, or brazing
								Straps	*Strips*	*Punching*
								Sleeves	Finished	
								Guide thimbles	Lack end plugs	
								End plugs	Finished	Welding onto tubes
								Instrument tubes	Finished	

[a]Accounts for nonproductive periods due to maintenance, etc.

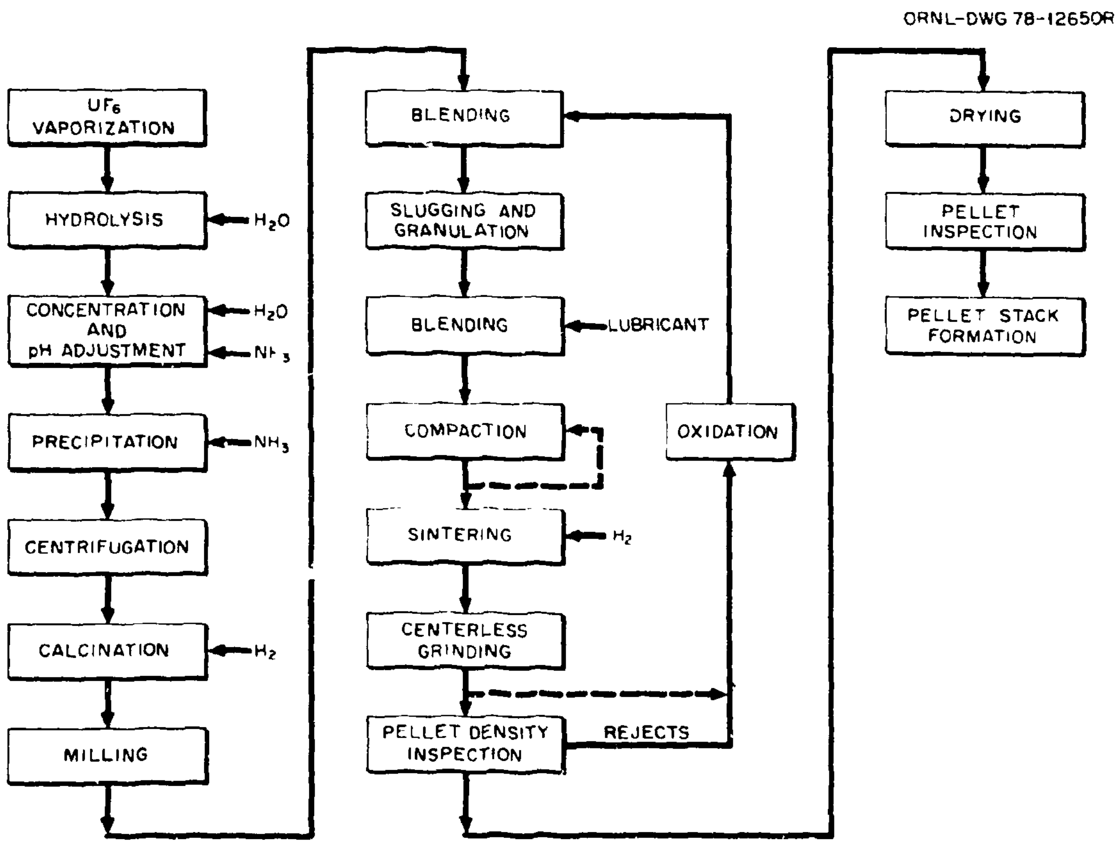

Fig. 2. Flowsheet of UO_2 Pellet Fabrication.

of the theoretical density of UO_2. These "green" pellets are sintered at 1650–1750°C for 4–8 h, depending on the sintering characteristics of the UO_2 powder. The sintered pellets are ground to the proper diameter on a centerless grinder. The ground pellets are dried, sampled, inspected, and stacked for loading into fuel rods.

The ground UO_2 pellets are loaded into Zircaloy-4 fuel tubes, a plenum spring is inserted, and a Zircaloy-4 plug is inserted and welded to the tube. The fuel rod is pressurized with helium and the pressurization hole is closed by welding. Fuel rod pressurization prevents clad flattening during the core life of the fuel, and it depends on the fuel design as well as the fuel burnup planned.

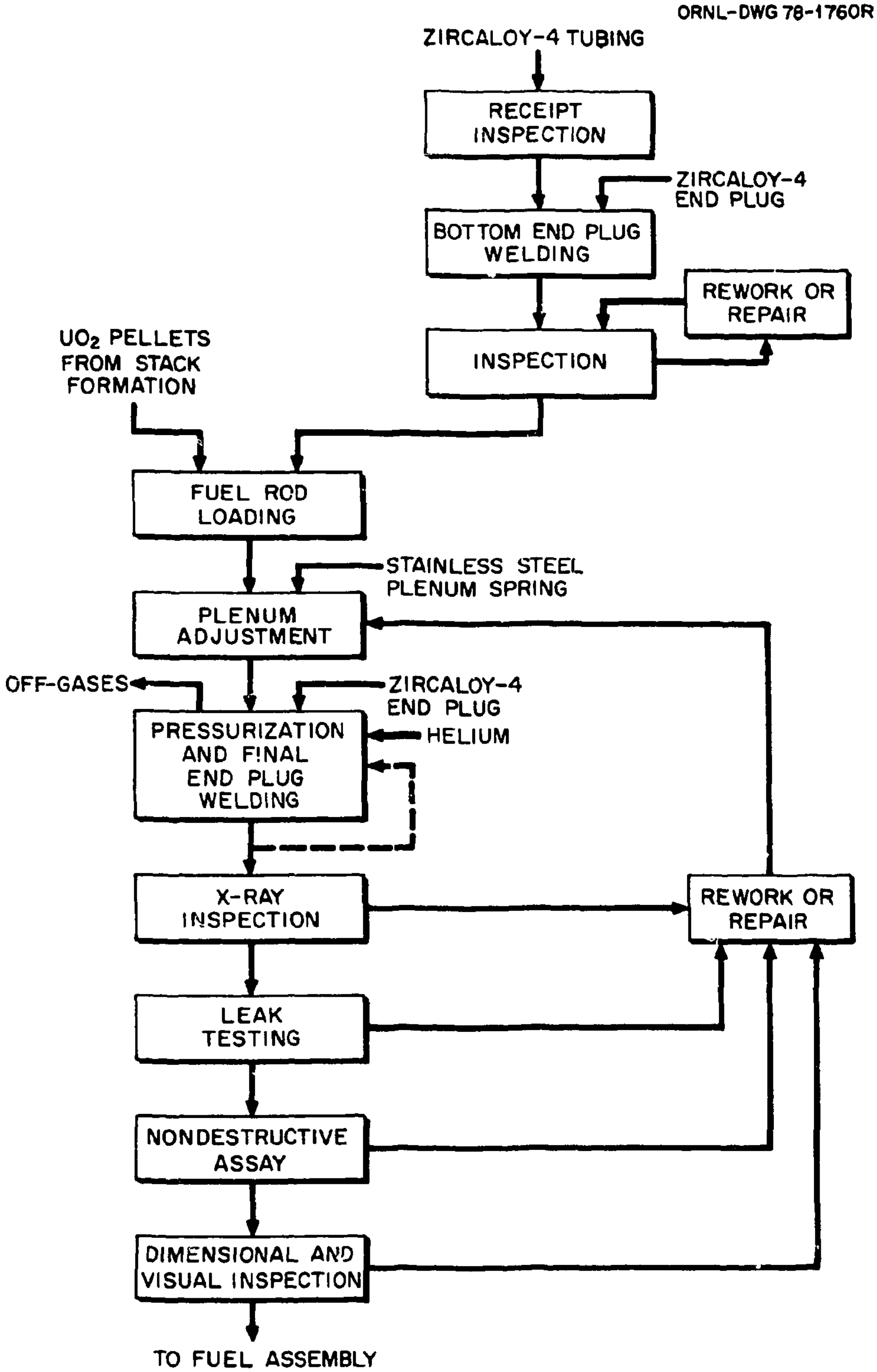

Fig. 3. Fuel Rod Fabrication Flowsheet.

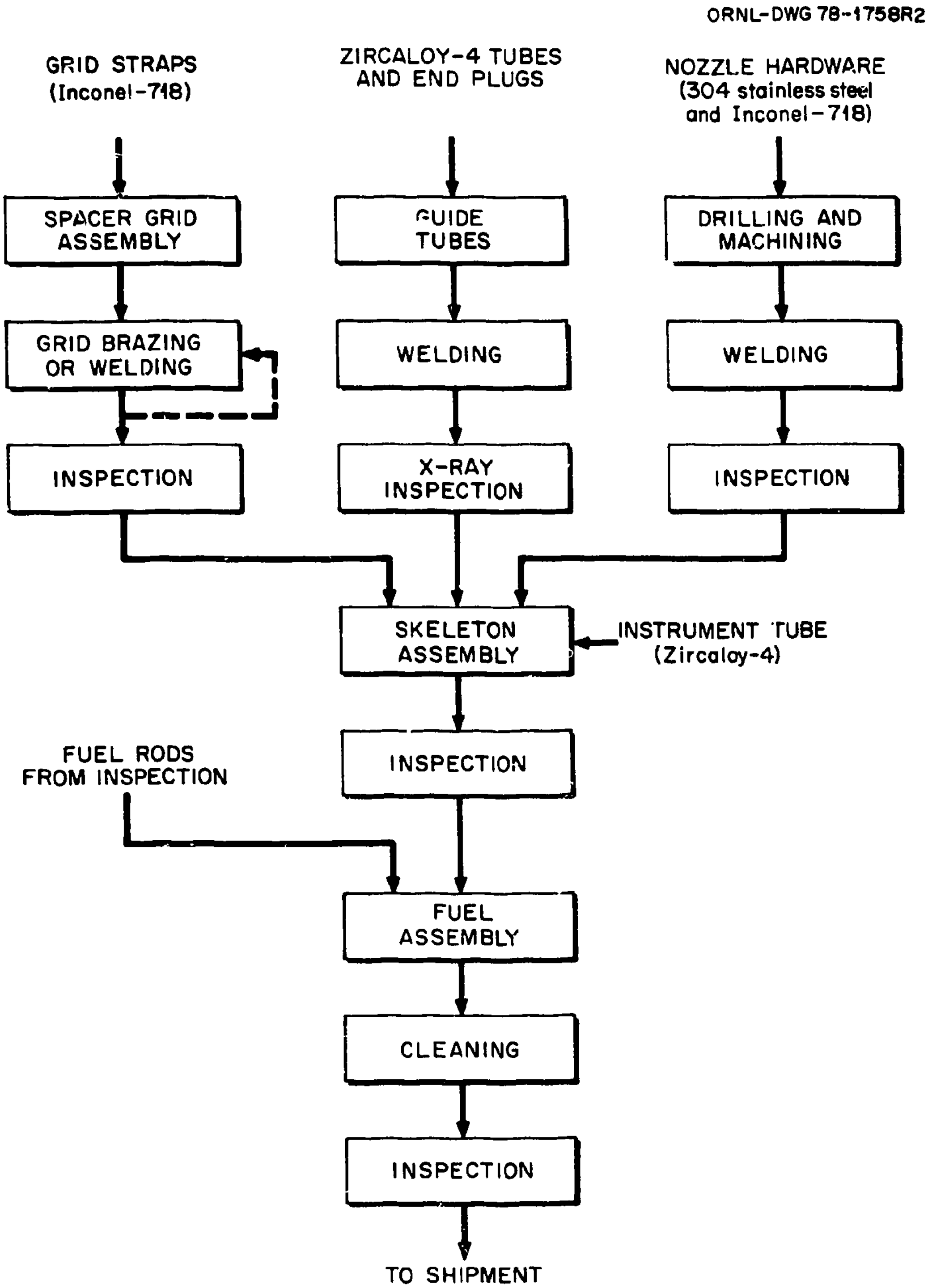

Fig. 4. Fuel Assembly Fabrication Flowsheet.

The fuel rods are x rayed for weld integrity, examined by fluoroscope for chips and voids, and by helium mass spectrometry for leaks. A nondestructive assay technique, active gamma scanning, verifies the enrichment of fuel within the rods. Finally, the mechanical characteristics of the fuel rods are dimensionally and visually inspected for correctness.

The fuel rods are loaded into a supporting skeleton that consists of a mechanically joined assemblage of spacer grids and control rod guide thimbles. Top and bottom end fittings, or nozzles, are attached to the assembly and the assembly is inspected for structural integrity and mechanical design. The fuel assemblies are then cleaned and packaged for shipment to reactor sites.

COST ESTIMATION PROCEDURE

The reference fuel fabrication facility is operated as a toll processing facility. That is, the customers for the fuel assemblies provide the required fuel feed material (uranium) in an appropriate form and the facility operator fabricates this feed material into finished fuel assemblies. The cost estimates we present exclude the costs of uranium feed material. All materials other than fuel materials are provided by the fuel fabricator. Fuel assembly hardware may be purchased finished, or raw material such as metal stock may be purchased for further fabrication. Thus, the costs determined in this study include all costs associated with fabricating customer-owned feed material into finished fuel assemblies.

The cost estimation procedure used is systematic: the process flowsheets were analyzed and functional areas were identified. Detailed assessments of the space, major equipment items, fuel assembly hardware, materials, supplies, and manpower required for each functional area were made. Costs were estimated from this detailed assessment of requirements for each functional area. These estimates were made for three categories — capital, material, and operating costs. The bases for the cost estimates are described in the following paragraphs.

Capital costs of the reference fuel fabrication facility were divided into two categories: facility costs and equipment costs. Operating costs for the facility include labor and supervision, overhead and general and administrative costs, materials and supplies, and utilities. Taxes, insurance, and the cost of expendable equipment were not included in the operating cost estimates, but were determined separately in the economic analysis to determine the price, that is, the cost to a customer, of the finished fuel assemblies.

To estimate the cost of the facility, we divided the facility into several process areas and their space requirements were estimated from the throughput requirements of the facility as previously defined. The process areas and the estimated space requirements for each area are presented in Table 3.

We estimated the unit area cost of the building at $200/ft^2 for all process areas except the quality control laboratories, to which we applied a unit area cost of $400/ft^2. In addition to the building costs, costs were estimated for land and site preparation, licensing, environmental assessment, a site security system, an office building, and engineering. The total costs for the facility are summarized in Table 4.

Equipment requirements for the various process steps were determined and the cost of installing the equipment was estimated. Cost estimates for several major equipment items were verified by the appropriate suppliers.[4–9] No attempt was made to verify the cost estimates of minor equipment, since this study was not based on a detailed facility design. Rather, we tried to determine whether the cost estimates were reasonable by verifying the cost of several major items of equipment. The capital cost estimates for equipment for the reference fuel fabrication facility are summarized in Table 5.

The two major costs of operation are labor — direct labor, supervision, and management — and materials. The requirements and costs of these components were examined in some detail to ensure reasonably accurate estimates of the costs associated with each.

Table 3. Area Requirements for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Facility

Operation	Area (ft^2)
UF_6—UO_2 conversion	5,500
UO_2 milling, blending, and storage	4,700
UO_2 powder preparation and pelleting	1,900
UO_2 pellet sintering, grinding, and inspection	5,850
Fuel rod loading and welding	2,780
Fuel rod inspection and storage	7,000
Fuel assembly fabrication	3,000
Fuel assembly weighing, cleaning, and inspection	3,400
Fuel assembly packaging and shipping	4,000
Scrap recovery and waste processing	2,000
Operational support (includes fuel assembly hardware fabrication)	20,065
Stores	2,000
Facility support	9,135
Change rooms (contaminated areas)	2,005
Quality control laboratories	7,000
Maintenance	19,665
Total facility area	100,000

Table 4. Facility Costs for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Plant

Item	Cost ($)
Building	21,400 × 1,000
Land	500
Site preparation	500
Licensing and environmental	400
Security system	300
Office building	1,500
Subtotal	24,600
Engineering and contingency (30%)	7,380
Total	31,980

Table 5. Summary of Equipment Costs for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Plant

Operation	Equipment Costs ($)
UF_6—UO_2 conversion	1,434 × 1,000
UO_2 milling, blending, and storage	520
UO_2 powder preparation and pelleting	320
UO_2 pellet sintering, grinding, and inspection	3,816
Fuel rod loading and welding	650
Fuel rod inspection and storage	1,010
Fuel assembly fabrication	280
Fuel assembly weighing, cleaning, and inspection	700
Fuel assembly packaging and shipping	2,500
Scrap recovery and waste processing	150
Operational support (includes fuel assembly hardware fabrication)	4,268
Stores	60
Facility support	5,690
Change rooms (contaminated areas)	—
Quality control laboratories	1,423
Maintenance	11,380
Total equipment costs	34,201

An organization chart for the reference fuel facility was developed and is presented as Fig. 5. This organization may represent a division of a multiple-industry company or it may represent a company devoted only to the fabrication of nuclear fuel. The organization as depicted in Fig. 5 is not intended to reflect any current organization, nor to represent the organizational structure desired by a particular company. Rather, the chart represents an organization able to fabricate nuclear fuel at the prescribed rate of 2 MTHM/d. Manpower costs based on this organization are summarized in Table 6. Although the basic manpower costs were assigned arbitrarily, this assignment was guided by documents[10] from the United States Department of Labor Bureau of Labor Statistics. The manpower costs presented in Table 6 include a 33% burden due to FICA, workmen's compensation insurance, vacation, holidays, and other benefits.

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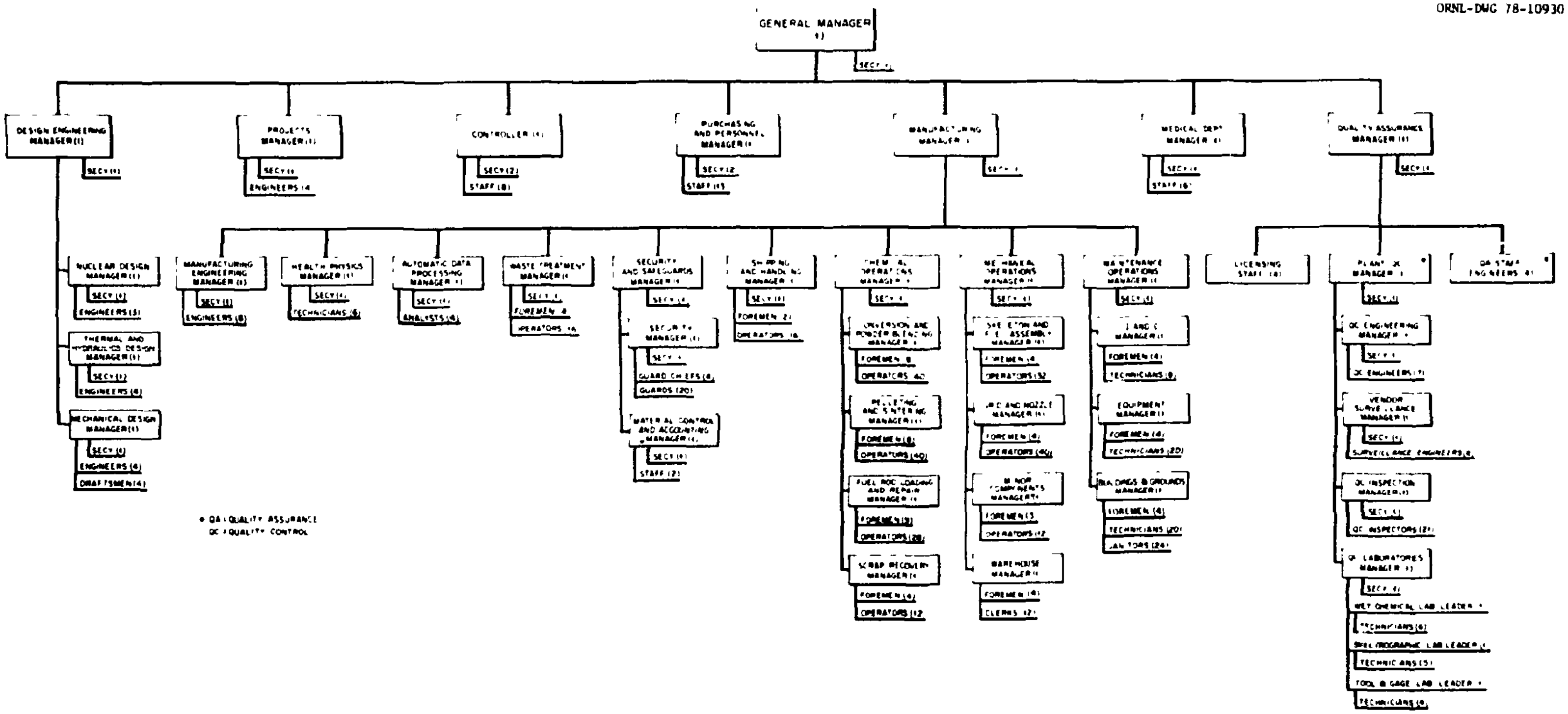

Fig. 5. Organization Chart for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Plant.

Table 6. Personnel Costs for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Facility

Department	Annual Costs[a] ($)
General management	80 × 1,000
Design engineering	720
Projects	189
Finance	309
Purchasing/personnel	455
Manufacturing	9,345
Medical	237
Quality assurance	1,632
Total annual personnel costs	12,967

[a]Includes 33% burden.

Fuel fabrication requires materials used in the process itself, such as ammonia to precipitate the uranium, and hydrogen to reduce the ammonium diuranate to uranium dioxide; materials used indirectly, such as waste-processing chemicals; and fuel assembly hardware. Of these, the material making the most significant impact on cost is the fuel assembly hardware. For this reason, we contacted some fuel assembly hardware component suppliers[11-13] to verify cost estimates. Costs of other materials were estimated by reference to trade journals or by direct contacts with suppliers.[14-16] Material costs are summarized in Table 7.

The costs of supplies and utilities were estimated from requirements dictated by the number of personnel, the equipment used in the various fabrication operations, and the amount of material produced. A summary of the total annual operating costs is presented in Table 8.

ECONOMIC ANALYSIS

To determine the price to be charged for the fuel assemblies, we analyzed the cost estimates previously presented. This economic analysis represents a method consistent with current commercial practice for a high-risk industry, although specific features of the analysis may differ from certain commercial pricing. The assumptions used in the

Table 7. Material Costs for a 2-MTHM/d Pressurized-Water Reactor Fuel Fabrication Facility

Item	Annual Costs ($)
Direct and indirect materials	1,014 × 1,000
Supplies	1,128
Hardware	20,899
Total annual material costs	23,041

Table 8. Summary of Annual Operating Costs for a 2-MTHM/d Fuel Fabrication Facility

Operating Cost Component	Annual Costs ($)
Labor and supervision	10,164 × 1,000
Overhead and general and administrative[a]	2,980
Materials	23,041
Utilities	239
Total annual operating costs	36,424

[a]Includes management personnel costs, travel, telephone, office supplies, postage, professional and legal fees, and miscellaneous fees, assessments, contributions, memberships, and subscriptions.

determination of price are presented in Table 9. Basically, the method is a cash flow analysis in which the unit price of the fuel is adjusted to permit income to just equal capital and operating expenses plus a prescribed rate of return on investment of 15%. Price is determined with an automatic data-processing code — ACFAC (A Cash Flow Analysis Code). The unit price of a reference PWR fuel assembly as determined by this code and the cost estimates presented earlier is presented in Table 10. The unit price so determined remains constant over the life of the facility and is given in terms of dollars of constant purchasing power, that is, January 1, 1978 dollars, and does not include the

Table 9. Economic Assumptions for Determining Pressurized-Water Reactor Fuel Assembly Unit Price

Analysis methodology	Discounted cash flow
Financing, % of equity	100
Economic factors,	
Rate of return, %	15
Income tax rate (effective), %	50
Property tax, % of initial capital	2.5
Property insurance, % of initial capital	0.5
Expendable equipment charge, % of initial equipment cost	1.0
Depreciation method for tax purposes	Sum of years digits
Capital life, years	
Facility	20
Equipment	10
Plant operating factors, %	
First year	33
Second year	67
Subsequent years	100
Preoperational expenses (% of operating costs)	
Three years before startup	10
Two years before startup	25
One year before startup	50
Cash flow during construction	
Years −8 to −1	0.045, 0.072, 0.115, 0.172 0.208, 0.162, 0.144, 0.082
Replacement equipment	Year 11
Working capital	3 months receivables on operating costs
Decommissioning fund, % of sales	1
Investment tax credit, %	
Facility	5
Equipment	10

Table 10. Summary of Costs for the Determination of the Unit Price of a Pressurized-Water Reactor Fuel Assembly

Component	Cost ($/kg HM)
Capital recovery	40.44
Material	44.31
Operating[a]	26.64
Property tax	3.66
Property insurance	0.73
Replacement equipment	0.66
Working capital	3.04
Income tax	17.03
Decommissioning	1.38
Total	137.89

[a]Excluding materials.

escalation of material, labor, or other costs. This approach was selected to facilitate comparison of fuel fabrication costs of the various fuel cycles to be considered subsequently. Of course, the base costs given may be adjusted to reflect the effects of escalation.

SUMMARY AND CONCLUSIONS

The cost of fabricating a PWR fuel assembly, as determined by the techniques of estimating and economic analysis considered in this report, is about $138/kg HM or about $63,600/fuel assembly.

Although the actual cost to a customer for fuel fabrication depends on a number of factors more or less controlled by corporate structure and financing, we compared the estimated cost of fuel fabrication with the actual cost of fuel fabrication by a major supplier. Such a comparison was assumed to indicate the reasonableness of the estimate. To make this comparison, we reviewed the court records[17] of a suit involving three electric utility companies and a major fuel fabricator in which the fuel fabricator was to provide fuel fabrication services in lieu of uranium. The unit cost, base date December 1976, of fabricating 17 by 17 fuel assemblies as indicated by these records was about $121/kg HM. The unit costs reported were subject to adjustment based on the Bureau of Labor Statistics and the American Iron and Steel Institute indices. If an inflation rate of 8%/year is assumed, the December 1976 price becomes about $131/kg HM in January 1, 1978 dollars. Thus, the unit price of a PWR fuel assembly determined by the methods presented in this report appears to agree reasonably well with the actual price.

ACKNOWLEDGMENTS

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