phil 74
3-6-67
MASTER

BNWL-131 E

**AEC
RESEARCH
and
DEVELOPMENT
REPORT**

Re
FABRICATION COSTS FOR PLUTONIUM FUEL ELEMENTS

PART E:

**THE VARIATION IN FABRICATION COST
WITH SOME FUEL DESIGN PARAMETERS**

C. H. BLOOMSTER

FEBRUARY, 1967

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

BATTELLE-NORTHWEST

BATTELLE MEMORIAL INSTITUTE / PACIFIC NORTHWEST LABORATORY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/ FOR THE U. S. ATOMIC ENERGY COMMISSION

H.C. \$ 3.00, MN. 65

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

BNWL-131 E

UC-25, Metals, Ceramics
and MaterialsFABRICATION COSTS FOR PLUTONIUM FUEL ELEMENTSPART E: THE VARIATION IN FABRICATION COST
WITH SOME FUEL DESIGN PARAMETERS

By

C. H. Bloomster

Plutonium Fuels Engineering Section
Materials Department

February, 1967

FIRST UNRESTRICTED
DISTRIBUTION MADE

FEB 22 '67

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON**LEGAL NOTICE**

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information

National Bureau of Standards, U. S. Department of Commerce

Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

FABRICATION COSTS FOR PLUTONIUM FUEL ELEMENTS

PART E: THE VARIATION IN FABRICATION COST WITH SOME FUEL DESIGN PARAMETERS.

C. H. Bloomster

INTRODUCTION

The purposes of this report are to analyze the effect on fabrication cost of some fuel design parameters and to construct a model which will permit fabrication costs to be estimated for a wide variety of fuel designs.

In the first four reports of this series (BNWL-131, A, B, C, D) the fabrication costs for four specific fuel designs-Plutonium Recycle Critical Facility (PRCF), Experimental Boiling Water Reactor (EBWR), Saxton and Plutonium Recycle Test Reactor (PRTR), respectively, were determined. These costs varied widely. Although all of these fuels were rod geometry similar in general design; specific variations occurred in the length, diameter, unit fuel weight, plutonium enrichment, U-235 enrichment, and specifications of the fuel rods. In addition, during the time period spanned by the fabrication of the fuel rods, modifications were made to the fabrication processes which improved quality or reduced cost. These many variations afford an excellent opportunity to analyze the effect of several parameters on fuel fabrication costs.

The processing costs referred to in this report series are the observed costs of fabricating between 150 rods in the Saxton case and 500 fuel rods

in the PRCF and PRTR cases. Larger scale fabrication and further process development may be expected to result in significantly lower fabrication costs; therefore, the effect of scale on fabrication costs is examined. These reports pertain to vibrationally compacted UO_2 - PuO_2 fuels for thermal reactors, but the data have been presented in sufficient detail to permit comparison with other fuel fabrication processes. Although the cost data were obtained only on fuels with rod geometries, vibrational compaction is readily adaptable and indeed may be the preferred process, for other more complex geometries.

SUMMARY

The variable fabrication costs for vibrationally compacted plutonium fuel elements were analyzed and shown to vary in a consistent manner which may serve as a basis for predicting fabrication costs for other similar geometries. The dominant factors affecting variable costs are the weight of fuel, the size of the fuel rod, the cladding cost, and the plutonium enrichment. Unit costs per kg are nearly constant for preparing the UO_2 - PuO_2 bulk fuel, and unit costs per piece are nearly constant for fuel rod fabrication. Fabrication costs, expressed in \$/kg

of fuel, decrease rapidly as the weight of fuel in the fuel rod increases. Although the plutonium nuclear materials charges at high plutonium enrichment levels are a significant percentage of the total variable fabrication cost, most of the shop costs were unaffected by the enrichment level; therefore virtually no processing penalty is paid for increasing plutonium enrichment as long as criticality limits are not restricting the operation. Two models were presented from which fabrication costs may be estimated over a wide range of fuel sizes, enrichment levels, and throughputs.

A COST MODEL

THE COMPONENTS OF VARIABLE COSTS

The variable costs of fabricating nuclear fuel elements can be described with three variables.

- The fabrication or jacketing costs where A is the cost of preparing the bulk fuel and B, the cost of loading the fuel into the jacket and completing the fuel assembly.
 - The nuclear material cost which can be subdivided into C, costs associated with plutonium enrichment and D, costs associated with U^{235} enrichment.
 - The cladding and hardware cost, E.
- The total variable cost (TVC) then, is the sum of the independent variable costs or:

$$TVC = A + B + C + D + E$$

For vibrationally compacted plutonium fuel elements, empirical values for the variable components, A, B, and E may be determined from the costs

reported in the first four reports in this series. The accounting method used throughout this series makes it convenient now to introduce a dependent variable, F, an indirect labor cost related to A and B, the direct fabrication cost. The determination of these empirical values is discussed on pages 8 through 13 of this report. Values for the variable nuclear material cost components, C and D, may be calculated from applicable price and processing cost schedules and assumptions. The calculation of these values is described in a later section.

The empirical values in \$/kg of oxide fuel for the variables components were determined to be:

$$A = \$28/\text{kg of fuel.}$$

$$B = G/\text{kg of fuel in an individual fuel rod, } G = \$50 \text{ for single fuel rods and } \$55/\text{rod for assembled fuel elements.}$$

$$C = \$8 + \$0.3 P/\text{kg oxide/\% PuO}_2 \text{ where } P \text{ is the price of fissile plutonium expressed in } \$/\text{g. For } \$10/\text{g plutonium, } C = \$11/\text{kg/\% PuO}_2.$$

$$D = \$2 + \$2 (\%U^{235})/\text{kg for natural and depleted UO}_2 \text{ only.}$$

$$E = \text{Actual or anticipated cladding and hardware costs.}$$

$$F = 1/4 (A + B).$$

A, B, and F are primarily labor dependent costs related to wage and overhead rates, and C, D, and E are primarily material dependent costs. Variations in the price of plutonium and the enrichment level enter into term C, and variations in the price

of U^{235} and U^{235} enrichment level enter into term D. Variations in cladding costs enter into term E.

The direct processing cost is approximately $A + B$. The variable shop cost is approximately $A + B + 0.2C + E + F$, and the nuclear material cost is approximately $0.8C + D$. The term E may vary widely with fuel design specifications and tolerances. In the following examples, the cost model is applied to several fuel designs and compared with the observed costs. The observed values for the cladding cost, E, are used in the examples, and plutonium nitrate is valued at \$10/g fissile.

For the PRTR fuel elements:

$$\begin{aligned} \text{TVC} &= A + B + C + D + E + F \\ &= \$28 + \frac{\$55}{1.8} + [\$8 + \$0.3 (10)] + 2 \\ &\quad + [\$2 + \$2 (0.7)] + \$26 \\ &\quad + \left(\frac{\$28 + \frac{\$55}{1.8}}{4} \right) \\ &= \$125/\text{kg} \quad (\text{Table I}) \end{aligned}$$

Similarly for the EBWR fuel rods:

$$\begin{aligned} \text{TVC} &= \$28 + \frac{\$50}{0.83} + (11) (1.5) \\ &\quad + [\$2 + \$2 (0.2)] + \$52 \\ &\quad + \frac{\$28 + \$60}{4} \end{aligned}$$

= \$181/kg (Table I), representing \$169 in shop costs and \$12 in nuclear materials costs. The difference between the actual shop cost, \$198, and \$169, computed cost, is in the end cap replacement steps, \$20, and the crushing and sieving step, \$8. Both of these costs may be neglected. The need for the end cap replacement step was eliminated through process improve-

TABLE I.

VARIABLE COSTS OF PLUTONIUM FUELS

(Plutonium Nitrate at \$10/g Fissile)

Observed Shop Cost	EBWR	\$/kg Oxide Fuel Saxton	PRTR
Fabrication	\$198	\$252	113
Calculated Nuclear Materials Cost			
Uranium	2	3	3
Plutonium	9	27	10
Total Variable Costs	\$209	\$282	126

ment, and the excess crushing and screening costs were incurred through the use of less efficient equipment (see p. 10). Abnormally high testing and inspection costs (estimated at \$22/kg) were acquired on the EBWR tubing. Elimination of these abnormal costs would reduce EBWR cladding costs, term E, from \$52 to \$30/kg (fuel) so that the estimated variable shop cost of fabricating EBWR fuel rods on a routine (PRTR) basis is \$144/kg, in contrast with (198/kg actual cost), part B.

Similarly for the Saxton fuel rods:

$$\begin{aligned} \text{TVC} &= 28 + 94 + 11(6.6) + 3 + 44 \\ &\quad + 31 = \$266/\text{kg}. \quad (\text{See Table I}). \end{aligned}$$

The differences with Table I are unusual costs in crushing and sieving, \$8, and rod fabrication, \$4, and higher plutonium losses, \$8, resulting from small batch size. If the cladding costs are reduced to \$30/kg, as with the EBWR above, the calculated shop cost for fabricating the Saxton fuel rods on a routine basis is \$220/kg.

Applying the cost model to the solution of the 1 wt% $\text{PuO}_2\text{-UO}_2$ PRTR

elements* fabricated previous to the 2 wt% PRTR design, we have

$$\begin{aligned} \text{TVC} &= \$28 + \frac{55 + 21^{**}}{2.7} (1) + 3 \\ &\quad + 25 + \frac{28 + 20}{4} \\ &= \$109/\text{kg as oxide or} \\ &\quad \$124/\text{kg as metal} \end{aligned}$$

which is in good agreement with \$128/kg (metal) observed cost reported in 1964⁽¹⁾ using a different accounting system. The 1964 report also included \$11 in fixed cost items, for a total fabrication cost of \$139/kg. The fixed cost items included \$5/kg depreciation expense and \$6/kg engineering expense; these fixed cost items are not included in the cost model.

In summary, the cost per kg of fabricating plutonium fuel rods is strongly influenced by two variables; the unit weight of a fuel rod which affects fabrication costs and the plutonium enrichment and price which affects nuclear materials costs. Thus, the causes of the widely varying fabrication costs per kilogram of fuel in the EBWR, PRTR, and Saxton fuel rods are apparent. The cost model was used to estimate the fabrication cost of a fuel element outside the observed

range with good agreement with previously observed costs.

GRAPHICAL SOLUTION

The variation of fabrication costs with fuel weight is shown graphically in Figure 1. An empirical approximation for hardware costs, $E \approx 9 + B/3$ is used in deriving the curve for hardware costs. The rod fabrication costs do not include fuel assembly cost. The shop cost for a given fuel weight is found on Curve A, which is the sum of the powder preparation, rod fabrication, indirect labor, and hardware costs, plus the PuO_2 preparation costs obtained from curve 1 in Figure 2. Other charges for plutonium enrichment are shown in Figure 2. In addition to the shop cost for PuO_2 preparation, the plutonium nuclear materials charges are the sum of the reject cost, curve 2, the materials (use charge plus losses) cost at the assumed plutonium price level, curve 3, 4, or 5, and the conversion to metal cost, curve 6, if deemed necessary. Curves 2 and 3 coincide. In addition to the cost obtained from Figures 1 and 2, the UO_2 conversion charge of \$2/kg must be added also and the uranium nuclear materials charge, ~\$2/kg for normal, less for depleted, and any unusual charge associated with the fuels design. For the 2 wt% PRTR element this is \$3/kg assembly labor costs and \$8/kg special assembly hardware costs. For example

*The 1 wt% PuO_2 — UO_2 elements contained 2.7 kg of fuel per rod. The fuel rods were fabricated by the pneumatic impaction, vibrational compaction process. The fuel design was similar to the 2 wt% PRTR design except the rod length was 80 cm longer.

**The plutonium costs were computed at \$43/kg fissile in the above reference.

1. Albaugh, F. W. Technology for Plutonium Fuels in Thermal Reactors, HW-SA-3772, p.10. General Electric Company, Richland, Washington, November 10, 1964.

*This relationship holds for the Zircaloy-2 clad fuel used in this study, because B is related to rod geometry which in turn is related to E.

FIGURE 1. Variation In Fabrication Costs with Unit Fuel Weight Per Rod

FIGURE 2. Variation of Incremental Fabrication Costs with Plutonium Enrichment.

	<u>\$/kg</u>
(Figure 1) Partial Shop Cost	88
(Figure 2) PuO ₂ Prep	11
Shop Cost for Rod Fabrication	99
Assembly Costs { Assembly Hardware Cost	8
{ Assembly Labor Cost	<u>3</u>
Total Shop Cost	\$110

EFFECT OF SCALE

$$C = a R^X \quad \text{or} \quad \frac{C1}{C2} = \left(\frac{R1}{R2}\right)^h$$

The empirical values for the cost model used in the previous section were based on an average fabrication rate of 50 kg of fuel per day. Burnham,⁽⁴⁾ computed the cost of fabricating vibrationally compacted plutonium fuel elements at a 1000 kg/day fabrication rate. By applying the cost model to the reference fuel design used by Burnham,⁽⁴⁾ we obtain two costs at two capacities (50 kg/day and 1000 kg/day) from which constants a and X may be determined by simultaneous solution.

$$\text{TVC} = \$28 + \frac{\$55}{2.1} + \$8 (2.5) + 2$$

$$+ 9 + \frac{26}{3} + \frac{28 + 26}{4} = \$108 \text{ kg/oxide}$$

2. S. C. Schuman. "How Plant Size Affects Unit Costs," Cost Engineering in the Process Industries, edited by C. H. Chilton. McGraw Hill, New York, 1960. p. 307.

3. C. H. Chilton, "'Six-Tenths Factor' applies to complete plant costs," Cost Engineering in the Process Industries, p. 282, edited by C. H. Chilton, McGraw-Hill, 1960.

4. J. B. Burnham, L. G. Merker, D. E. Deonigi. Comparative Cost of Oxide Fuel Elements. BNWL-273. July 1966.

nuclear materials prices from the Burnham⁽⁴⁾ data, we obtain a cost at a throughput of 1000 kg/day of \$42/kg oxide. The excluded items were building and equipment, nuclear losses, working capital, use charge, and fixed manufacturing costs.

Using these values to solve the equation $C = aR^X$, we obtain $X = -0.32$ and $a = 382$; the cost C at any other capacity R may then be estimated. The exponent -0.32 falls in the typical range -0.3 to -0.5 suggested by Schuman in his analysis of the effect of plant size on unit cost in the manufacture and distribution of industrial chemicals.

The effect of scale on the excluded items related to fixed costs can be estimated in a similar manner using the six-tenths factor rule.

In summary, preliminary estimates of the fabrication costs for various designs and throughputs of vibrationally compacted plutonium fuel elements may be made through application of the cost model in the previous section and the power factors in this section.

VARIATION OF FABRICATION COSTS

In this section the nature of the variable fabrication (shop) costs is analyzed. The analysis is based on costs determined in the laboratory scale fabrication of UO_2 - PuO_2 fuel elements for the PRCF, EBWR, Saxton, and PRTR reactors, and reported in Parts, A, B, C, and D of this series. The fuel elements were fabricated by the pneumatic impaction, vibrational compaction processes, where the equipment capacity of most process steps is

100-300 kg of fuel per day. The primary function of the operating group was development. The normal operating rate was approximately 50 kg of fuel per day which maintained fuel for a 70 MW_t experimental reactor, the PRTR, in addition to experimental fuel for other reactors. The equipment capacity was sufficient with minor exceptions to fuel a reactor in the 300-500 MW_t range.

The fabrication costs vary with

- 1) Weight of fuel,
- 2) Piece count,
- 3) Total processing costs,
- 4) The plutonium enrichment,
- 5) The U^{235} enrichment, and
- 6) Specifications and tolerances

unique to fuel design.

Some of these costs are depicted graphically on a typical process flow diagram (Figure 3). The classifications are of two types. The first three classifications are primarily labor dependent, and the absolute cost is related to wage and overhead rates. The last three classifications are primarily material dependent, and the absolute cost is related to material price schedules. Generally, the labor dependent costs represent the value added by the fuel fabricator, and, although the rates may vary, the relative costs for different fuel designs may be expected to remain the same. Normally, material dependent costs are not subject to control by the fuel fabricator and are not related to the labor dependent costs, so these two costs may independently vary over a period of time in relative importance. The labor dependent costs are entirely related to the

FIGURE 3. Variation of Fabricating Costs with Process Steps

fabrication process; this process may be separated into two major categories:

1) the preparation of the fuel material, blending, densification, crushing, and sieving, in which all the weight dependent costs, item 1 above, are included; and 2) loading the fuel into the cladding, together with the subsequent finishing steps, in which all the piece count dependent costs, item 2 above, are included. Item 3, above, refers to the indirect labor costs of the direct labor which is related to the sum of items 1 and 2.

Larger scale fabrication then may be expected to reduce these costs, through the economies of scale, lower wage and overhead rates in a manufacturing organization, and technological improvements. In the remaining sections of this report, costs are reported in \$/kg of oxide. These are the actual costs incurred at the time of fabrication under a laboratory scale rate of 50 kg of fuel per day.

COSTS WHICH VARIED WITH THE WEIGHT OF FUEL

Several shop costs were independent of fuel geometry and varied directly with the amount of fuel processed. These costs included the entire pneumatic impaction process and UO_2 preparation and fusion. The total cost for these processes was \$28/kg (Table II), distributed as \$8.71/kg UO_2 preparation and fusion costs and \$19.50/kg pneumatic impaction costs. The PRTR fuel data were used because the costs represent the most advanced usage of process and equipment as described in the next paragraph.

TABLE II.

VARIABLE FABRICATION COSTS PROPORTIONAL TO FUEL WEIGHT IN \$/100 kg FUEL (AS OXIDE)

<u>Uranium Costs</u>	<u>PRCF</u>	<u>EBWR</u>	<u>Saxton</u>	<u>PRTR</u>
Direct Materials -				
Arc Fusion	\$ 436	\$ 434	\$ 411	\$ 436
UO_2 Preparation	339	367	348	435
Total Uranium Costs	\$ 775	\$ 801	\$ 759	\$ 871
<u>Pneumatic Impaction Process</u>				
Blending and Loading	\$ 426	\$ 426	\$ 431	\$ 432
Double Canning	132	132	137	140
Pneumatic Impaction	297	288	298	217
Opening	191	195	200	195
Crushing and Sieving	870	1609	1699	975
Total Pneumatic Impaction Costs	\$1916	\$2850	\$2760	\$1959
Total Shop Costs	\$2791	\$3651	\$3519	\$2830

Several interesting processing effects can be seen in Table II. The decrease in pneumatic impaction processing costs brought about by the relocation and installation of additional heating furnaces is seen by comparing costs for the PRTR with the other fuels. The effect of processing equipment in the crushing and sieving operation is seen by comparing crushing and sieving costs. The PRTR and PRCF fuel were processed in one facility with better equipment arrangement and sieving facilities, while the EBWR and Saxton fuel were processed in another facility, requiring more manual operations. By comparing the PRTR and PRCF crushing and sieving costs, the additional cost of outgassing and sampling is seen in the PRTR fuel. The UO_2 preparation costs for the PRTR fuel are the most representative because these costs are based on a much larger quantity of material. During the time

studies of the EBWR and Saxton fuel, the UO_2 had already been prepared, so the UO_2 preparation costs for these fuels were based on the preparation of a comparatively small quantity of UO_2 for the PRCF fuel rods.

A detailed process step examination of each of the cost components in UO_2 preparation and pneumatic impaction processes showed that all of the components varied with weight or with a unit of constant weight with one exception, the loading of fuel into individual bottles for the vibrational compaction process. Bottling is a weighing operation in which cost varies with the number of weighings, i.e., bottles. However, this component of cost is small (~3%) and would only become significant for very small fuel rods. For the variation in cost to remain constant with weight, recycle and reject rates must be relatively constant, which implies consistent specifications on fuel properties between fuel designs.

UNIT COSTS WHICH VARY WITH PIECE COUNT

Within the size range limits of the Saxton fuel rod and the PRTR fuel rod, the unit cost for tubing preparation, vibrational compaction, finishing, and rework was nearly constant, independent of fuel weight. In addition to the cost of the fuel material, each fuel rod costs about \$50 to fabricate and about \$5/rod to assemble into a fuel array. The variation in finishing costs, (Table III), using the EBWR⁽⁵⁾

5. The EBWR finishing costs were recomputed from BNWL-131-B to eliminate (through technological advance) the end cap replacement step and include the same processing steps used in the Saxton and PRTR fuel rods.

as a base, is caused in the Saxton fuel by an increased cost to meet straightness tolerances and smaller batch sizes, imposed partly by criticality restrictions. The increased finishing cost in the PRTR fuel (\$5/rod) is caused entirely by increased labor costs required to assemble the fuel rods into a fuel element. Neither the Saxton nor EBWR fuel rods were assembled into the fuel array at this site. Detailed examination of the cost components for these processes show that each cost component varies with piece count or with a batch size that is uniform for a particular process step with the following exceptions. Batch sizes are limited in the etching and autoclaving steps by nuclear safety specifications for high plutonium concentrations; rework costs, which include work on both fuel rods and fuel materials, vary with both piece count and fuel weight. Since the relative cost of rework is small and the variation with piece count is predominant, all rework cost is included with piece count. The fuel assembly labor cost for the PRTR

TABLE III.

COSTS PROPORTIONAL TO PIECE COUNT

	(\$/fuel rod)		
	EBWR	Saxton	PRTR
Tubing Preparation	\$ 1.68	\$ 1.70	\$ 1.30
Vibrational Compaction	33.00	28.00	29.00
Finishing	15.00	20.00	23.00
Rework	<u>1.21</u>	<u>1.97</u>	<u>1.60</u>
Total Cost Proportional to Piece Count	\$51.00	\$52.00	\$55.00

fuel element varies primarily with piece count, for the assembly steps are performed on an individual rod basis. However, in other fuel designs assembly cost may vary on some other basis unique to the fuel design. The vibrational compaction costs may indicate a secondary effect of the length to diameter (L/d) ratio of the fuel rod; much higher L/d ratios may result in much higher vibrational compaction costs.

EFFECT OF TOTAL DIRECT PROCESSING COSTS

In the fabrication of plutonium fuel elements on the laboratory scale, the direct labor performed several functions classified as indirect (e.g., BNWL-131-D, p.8). On a larger scale of operations, some of this work would be performed by clerical workers. From observation, this indirect labor cost, item F in the cost model, is 1/4 of the total direct processing cost, or $F = 1/4 (A + B)$.

EFFECT OF PLUTONIUM ENRICHMENT

The PuO_2 preparation and the calculated plutonium nuclear materials cost vary directly with plutonium enrichment. These costs may be summarized on a \$/kg/% plutonium enrichment basis. The costs varying with plutonium enrichment are those that vary with the price of plutonium and those that do not. The use charge and losses vary with price, (Table IV), but the PuO_2 preparation (shop) cost, the conversion to oxide cost, and the scrap recovery cost for plutonium fuels do not vary with the

price of plutonium (Table V). The cost data used in Tables IV and V are rounded from calculations in a later section. From Tables IV and V an expression for the plutonium enrichment cost, C, may be derived:

$$C = \$8 + 0.3P$$

where C is in \$/kg oxide fuel/% PuO_2 enrichment and P is the price of fissile plutonium in \$/g.

TABLE IV.

COSTS RELATED TO PLUTONIUM ENRICHMENT THAT VARY WITH PRICE

	(\$/kg Oxide/% PuO_2 at \$10/g Pu)		
	EBWR	Saxton	PRTR
Use Charge	1	1	1
Losses:			
Processing	1	1	1
Conversion	<u>1</u>	<u>1</u>	<u>1</u>
	\$3	\$3	\$3

TABLE V.

COSTS RELATED TO PLUTONIUM ENRICHMENT THAT DO NOT VARY WITH PRICE

	(\$/kg Oxide/% PuO_2)		
	EBWR	Saxton	PRTR
PuO_2			
Conversion	4	4	4
Preparation	1	1	1
Reject Fuel	3	1	3
	<u>\$8</u>	<u>\$6</u>	<u>\$8</u>

EFFECT OF U^{235} ENRICHMENT

The calculated nuclear materials charges for uranium vary with the level of U^{235} enrichment in accordance with the AEC price schedule. Since the price schedule is nonlinear,

the charges vary in a nonlinear manner. For U^{235} enrichments of natural and below, the uranium nuclear materials charges, D, (\$/kg oxide fuel), Table VI, are nearly linear and may be expressed in the form:

$$D = \$2 + \$2 (\% U^{235}).$$

For uranium enrichments above normal, the nuclear materials charges would increase relatively with enrichment. An expression, similar to the above, may be derived for enriched uranium using appropriate price and processing schedules.

EFFECT OF FUEL DESIGN

There are some costs unique to the fuel designs. In the fuel designs studied only the cladding and hardware costs are included in this category, but specifications and tolerances could place other costs in this category. Specifications influence costs primarily through the number of processing and inspection steps required; tolerances influence costs primarily through the recycle and reject rates. In this study, which uses Zircaloy 2 cladding, costs varied from \$30/lb of Zircaloy for PRTR tubing to \$35/lb (Zircaloy) for EBWR tubing. Also, inspection and nondestructive testing costs varied widely between the PRTR and EBWR tubing. These costs for the EBWR tubing were very high and considered abnormal; Saxton tubing costs were inferred from these EBWR costs. The cost of pellets, springs, wire, end caps, end fittings, and end brackets all may be unique to the fuel design.

However, for similar fuel designs, such as the EBWR, Saxton, and PRTR Zircaloy clad fuel rods, an approximate relation between hardware cost and processing cost may be made. Each fuel rod contains two end caps,

TABLE VI.

URANIUM NUCLEAR MATERIALS CHARGES \$/kg Oxide			
Proportional to Price	EBWR (0.2 U ²³⁵)	Saxton Normal	PRTR Normal
Losses	0.3	0.7	0.6
Use Charge	0.1	0.5	0.5
Reject Fuel Charge	---	0.2	0.4
	0.4	1.4	1.5
(Not Proportional to Price)			
Conversion to UO ₂	2.1	1.9	2.0
(Natural and depleted uranium only)			

a spring, and a pellet; the cost of which is nearly the same for each fuel rod. In addition, some of the cladding fabrication costs vary with piece count, such as straightening, non-destructive testing, and cutting-to-length. The cladding cost is also related to rod size (fuel weight). The sum of the basic hardware costs then varies with both fuel weight and piece count, as does also total processing cost, (excluding plutonium oxide preparation). If cost information on cladding was lacking, an empirical relationship between processing cost and hardware cost, E, may be used for near-term estimating purposes. The relationship is $E \approx \$9 + B/3$. For smaller rods the proportion is less; for larger rods, it is more. Basic hardware includes those items that make up a fuel rod, but does not necessarily include direct materials required for assembly into a fuel array.

EFFECT OF DIAMETER AND LENGTH VARIATION ON FUEL ROD FABRICATION COST

The effect of length and diameter variations on fuel costs may be analyzed independently. Both diameter and length affect fabrication costs primarily through the unit weight of the fuel rod,

but the diameter also independently affects the unit cladding costs.

The effect of diameter, d , variation, assuming uniform cladding thickness, on fuel rod fabrication cost may be expressed in the following form:

$$K = A + \frac{H}{d} + \frac{B}{d^2}$$

where K = fuel fabrication processing cost in \$/kg

A = bulk fuel preparation cost in \$/kg

H = cladding cost expressed \$/kg of fuel. The weight of the cladding varies directly with fuel diameter, d , and cladding weight per unit weight of fuel varies inversely with the square of the diameter, or $\frac{Hd}{d^2} = H/d$.

B = fabrication cost in \$/kg of loading the bulk fuel into the jacket and completing the fuel assembly. Thus, for large diameters, the fabrication cost decreases approaching A .

As may be expected, fabrication costs increase rapidly as the fuel rod diameter decreases. The effect of diameter on fabrication cost (Figure 4) is shown for fuel lengths of 1, 2, and 3 meters (length affects the third term). In Figure 4, the following assumptions were used: The zirconium fabrication cost is constant with diameter at \$30/lb (of Zr), wall thickness is 0.075 cm, fuel density is 86% TD, and fuel rod fabrication cost, (B), is \$50/unit.

The effect of different levels of cladding cost and diameter on fuel fabrication cost (Figure 5) indicate that

cladding cost is relatively unimportant until the diameter decreases below 1 cm. In Figures 4 and 5, direct costs only are plotted. Experience indicates that cladding costs show a secondary variation with diameter, increasing with decreasing diameter, but this effect is neglected in Figures 4 and 5.

EFFECT OF LENGTH ON FUEL ROD FABRICATION COSTS

The effect of length, L , variations on fuel fabrication costs may be expressed in the following form:

$$K = A + H + \frac{B}{L}$$

where K , A , H , and B are defined above. Thus, the fabrication cost decreases for long lengths approaching $A + H$, i.e., the cost of preparing the powder by the pneumatic impaction process, A , plus the cost of the cladding, H . The effect of length on fabrication cost (Figure 6) is shown for diameters of 1/2, 1, and 2 cm (diameter affects the cladding cost). Other parameters are the same used in Figure 4.

NUCLEAR MATERIALS CHARGES

Nuclear materials charges include: the costs of converting the nuclear materials to the desired oxide form, losses, scrap recovery and fuel leasing. These charges, which are only partly controllable by the fuel fabricator, become significant in the differential cost analysis of plutonium enriched and enriched uranium fuel designs. Generally, plutonium fuel costs will increase less rapidly with enrichment than enriched uranium costs because of the unit value of U^{235} ; hence, all associated nuclear

FIGURE 4. Effect of Diameter on Fuel Fabrication Cost at Selected Fuel Lengths.

FIGURE 5. Effect of Diameter on Fuel Fabrication Cost at Selected Cladding Costs.

FIGURE 6. Effect of Length Variation on Direct Fabrication Cost at Selected Fuel Diameters

materials charges increase with enrichment, whereas the unit value of fissile plutonium remains constant. All nuclear material costs are expressed in \$/kg oxide; metal cost equivalents may be obtained by dividing the oxide cost by 0.88.

The variable shop costs for fabricating plutonium fuel rods for the EBWR, Saxton, and PRTR were determined to be \$198, \$252,⁽⁶⁾ and \$113/kg of fuel (as oxide), respectively.⁽⁷⁾ The shop costs were those variable costs incurred by the fabrication group working under AEC contract. The nuclear materials charges are added to these costs to obtain the complete variable costs associated with the fabrication process. For each of the fuel designs the nuclear costs were computed using the related fabrication experience on losses, reject rate, and fabrication cycle times. The nuclear materials costs for plutonium are calculated at \$10/g fissile, the assumed value as a thermal reactor fuel. In Table I, the total variable costs including nuclear materials of fabricating the EBWR, Saxton, and PRTR fuel rods are summarized; the nuclear materials costs were derived from calculations in the succeeding sections.

URANIUM COST CALCULATIONS

All depleted and normal uranium requirements are assumed to be obtained

as UF_6 under existing AEC price schedules. This assumption penalizes the natural uranium cases slightly, approximately 10% of uranium nuclear materials costs, but the overall affect on fabrication cost is less than 0.5% of the fabrication cost. It is further assumed that both depleted and normal uranium usage will be financed at 4 3/4% interest rate equivalent to the use charge for enriched uranium. These assumptions have the advantage of a uniform basis from which to make comparisons at all levels of uranium enrichment, and particularly between plutonium enriched and enriched UO_2 conversion costs.

CONVERSION COST

The conversion of UF_6 to UO_2 is taken at \$2.10/kg uranium for depleted and normal uranium with a loss of 1/2%, according to the formula and assumption used by Collins.⁽⁸⁾ The general formula for conversion cost per 100 kg (UO_2) of finished fuel is:

$$100 \left[\frac{(\% UO_2 \text{ fuel})}{100} \right] (0.88) \left[1 + (\% UO_2 \text{ lost and rejected}) \right] \times \$2.10.$$

Substituting for EBWR fuel: (98.5% UO_2); processing losses and reject, 10.5%, arc fusion losses, 1.5%, conversion losses, 0.5%.

$$100 \left[\frac{(0.985) (0.88)}{2.10} \right] \left[(1 + 0.125) \right] = \$205/100 \text{ kg fuel.}$$

6. Corrected from \$255 in BNWL-131-C; the interposition of two numbers in the plutonium preparation step resulted in an error of \$3/kg.

7. BNWL-131, Parts B, C, and D.

8. Collins, G. D. *Comparative Study of PuC-UC and PuO_2 - UO_2 as a Fast Reactor Fuel, Part II*. GEAP-3880, pp. 29. General Electric Company, San Jose, California. November 15, 1962.

By the same method, the conversion costs for the Saxton fuel rods are \$186/100 kg and the PRTR fuel rods are \$198/100 kg.

CHARGES FOR UO₂ LOSSES

Losses occur in conversion, 1/2%, in arc-fusion, 1 1/2%, and in fabrication. The general formula for the charges for losses per 100 kg of fuel is:

$$\frac{\text{kg U lost}}{100/\text{kg Fuel}} \times \text{Uranium Value in } \$/\text{kg}$$

Substituting for the EBWR: where depleted uranium is valued at \$2.50/kg: $100 (0.985) (0.88) (0.125)^* (\$2.50) = \$27$. Similarly, for the natural uranium cases with uranium valued at \$23.60/kg, the cost of uranium losses for the Saxton fuel is \$70/100 kg, and for the PRTR fuel the losses are \$57.

USE CHARGE FOR UO₂

A uranium processing cycle of 145 days (Figure 7) is assumed. The use charge for uranium is calculated as follows:

$$\text{use charge} = w \quad t \quad v \quad u$$

where: w is weight of uranium including recycle, scrap and losses

t is the processing cycle

v is the uranium value

u is the use charge rate

Substituting, the use charge per

100 kg EBWR fuel is:

$$100 [(0.985) (0.88)] [(1.406) (\frac{145}{365}) (\$2.50) (0.0475)] = \$6.$$

Similarly, for the Saxton and PRTR fuels the use charge is \$49 and \$53, respectively.

CHARGES FOR REJECT UO₂

It is assumed that the uranium portion of the reject fuel can be reprocessed to (metal) UO₂ for \$6/kg. The scrap recovery of impurity laden oxides is estimated at \$4/kg, and conversion to UO₂ at \$2/kg. The charge for reject UO₂ per 100 kg of fuel are calculated for the Saxton fuel as follows:

$$100 [(0.936) (0.88)] (0.044) (\$6) = \$22.$$

Similarly, for the PRTR fuel the cost is \$40. Since under the given assumptions it is uneconomic to recover the depleted uranium in the EBWR fuel, the reject EBWR uranium was included in the losses.

PLUTONIUM COST CALCULATIONS

CONVERSION COSTS

Conversion cost is the cost of converting plutonium nitrate to oxide. This cost is assumed to be \$0.45/g PuO₂,⁽⁹⁾ which was the cost of purifying and converting plutonium metal to oxide. In the EBWR, Saxton, and

* Reject fuel is included with the losses in the EBWR fuel, because the value of the depleted uranium is assumed to be less than the cost of recovery.

9. Burnham, et al., op. cit., used \$0.3/g for the conversion cost which they assumed will prevail at the larger capacities of future reprocessing plants. We used \$0.45/g to be consistent with the earlier reports in this series.

UO₂ Preparation (145 day cycle)

PuO₂ Preparation (65 day cycle)

FIGURE 7. Estimated Cycle Times

PRTR fabrication processes, PuO₂ was prepared by converting plutonium nitrate to metal, vacuum remelting to remove fluorine, and oxidizing the metal to PuO₂. It is believed that the conversion to metal and vacuum remelting steps will not be required. Available facilities that are operated principally for metal production required this route to obtain PuO₂ free from fluoride contamination. If the conversion to metal step was required, costs would increase \$1.50/g according to current AEC price schedules. A 1% loss is assumed in the conversion process. The conversion cost is included in the direct material cost in Parts A, B, C, and D of this report series.

CHARGES FOR PLUTONIUM PROCESSING LOSSES

The plutonium processing losses (as metal) for the EBWR, Saxton,

and PRTR fuels were calculated to be 9.22 g, 69.6 g, and 7.75 g, respectively, per 100 kg of oxide fuel.

The charges for plutonium losses are proportional to price and are obtained by multiplying the losses by the unit charge for plutonium. These charges are made for plutonium values of \$10/g, \$30/g, and \$43/g fissionable in Table VII.

TABLE VII

PROCESSING LOSS CHARGES PER 100 kg FUEL

	Price of Fissile Plutonium		
	\$10.00/g	\$30.00/g	\$43.00/g
EBWR	85	252	365
Saxton	640	1920	2750
PRTR	71	214	306

CHARGES FOR PLUTONIUM CONVERSION LOSSES

The conversion losses are calculated separately to distinguish them from shop losses. The conversion losses are assumed at 1% of the quantity of plutonium nitrate converted into plutonium oxide. The calculations, made similar to processing losses, are

TABLE VIII.CONVERSION LOSS CHARGES PER 100 kg FUEL

	<u>Price Fissile Plutonium</u>		
	<u>\$10.00/g</u>	<u>\$30.00/g</u>	<u>\$43.00/g</u>
EBWR	131	395	565
Saxton	555	1668	2390
PRTR	173	518	744

USE CHARGE FOR PLUTONIUM

The use charge is calculated at 4 3/4% using a fabrication cycle of 65 days (Figure 7), or twice the minimum fuel fabrication cycle. This is a two-bin inventory system in which the average fuel spends half time in storage and half time in fabrication. The quantity of plutonium used in calculating

shown in Table VIII for selected values of plutonium.

the use charge is the sum of the plutonium in the finished fuel, the recycled fuel, the reject fuel, and losses. The use charges are calculated (Table IX) at plutonium costs of \$10/g, \$30/g and \$43/g fissile.

TABLE IX.PLUTONIUM USE CHARGES PER 100 kg FUEL

	<u>Price of Fissile Plutonium</u>		
	<u>\$10.00/g</u>	<u>\$30.00/g</u>	<u>\$43.00/g</u>
EBWR	139	416	596
Saxton	555	1665	2385
PRTR	175	526	754

CHARGES FOR PLUTONIUM IN REJECT FUEL

It is estimated that the cost of recovery of plutonium from reject fuel is \$5/g plutonium. On this basis the recovery costs per 100 kg oxide fuel are \$520 for the EBWR fuel, \$900 for the Saxton fuel, and \$555 for the PRTR fuel.

DISTRIBUTION

<u>Number of Copies</u>		<u>Number of Copies</u>	
1	<u>ALKEM</u> 7501 Leopoldshafen Karlsruhe, Germany W. Stoll	4	<u>Battelle Memorial Institute</u> W. F. Heenan D. L. Keller S. W. Porembka (2)
5	<u>Argonne National Laboratory</u> C. H. Bean J. H. Handwerk J. H. Kittel R. Macherey J. F. Schumar	1	<u>Brookhaven National Laboratory</u> D. H. Gurinsky
1	<u>Associazione Euratom-CNEN</u> <u>Per I Reattori Veloci</u> Via Mazzini 2 Bologna, Italy F. Pierantoni	1	<u>Centre d'Etudes Nucleaires de</u> <u>Cadarache</u> Poite Postale No. 1 Saint-Paul-Lez-Durance, France Dr. B. Defreyn
7	<u>Atomic Energy Commission, Wash.</u> <u>Division of Reactor Development</u> R. Grube (3) J. M. Morrissey J. M. Simmons J. M. Valance M. J. Whitman	1	<u>Combustion Engineering, Inc.</u> J. C. Tobin
1	<u>Atomic Energy Research</u> <u>Establishment</u> Chemistry and Metallurgy Branch Fuels Development Branch Chalk River, Ontario, Canada J. A. L. Robertson	274	<u>Division of Technical Informa-</u> <u>tion Extension</u>
4	<u>Atomic Energy Research</u> <u>Establishment</u> United Kingdom Atomic Energy Authority Harwell, Didcot, Berks, England P. Murray (3) L. E. Russell	4	<u>Douglas United Nuclear, Inc.</u> T. W. Ambrose L. E. Kusler J. T. Stringer DUN File
1	<u>Atomics International</u> B. R. Hayward	1	<u>European Atomic Energy Community</u> 51-53 Rue Belliard (Euratom) Brussels 4, Belgium Pierre Kruys
2	<u>Atomic Power Development</u> <u>Associates</u> 119 First Street Detroit 26, Michigan W. H. Jens A. A. Shoudy	1	<u>General Electric Company, APD</u> Special Purpose Nuclear Systems Operation P. O. Box 846 Pleasanton, California J. E. Van Hoomissen
		2	<u>General Electric Company,</u> <u>Cincinnati</u> W. Briskin J. McGurty
		5	<u>General Electric Company,</u> <u>Pleasanton</u> L. P. Bupp E. A. Evans A. N. Holden B. Weidenbaum

Number
of Copies

- 6 General Electric Company,
Richland
T. W. Evans
M. Lewis
M. C. Leverett
C. H. Shaw
E. A. Smith
GETA File Copy
- 5 General Electric Company,
San Jose
W. E. Baily
K. Cohen
M. F. Lyons
T. J. Pashos
E. L. Zebroski
- 2 Isochem, Inc.
H. H. Hopkins
R. Y. Lyon
- 1 Kerr-McGee Indus. Inc.
Oklahoma City, Oklahoma
Harold Lambertus
- 1 Knolls Atomic Power Laboratory
W. K. Barney
- 5 Los Alamos Scientific Laboratory
R. Baker
M. Bowman
H. Hessing
D. MacMillan
R. Spence
- 2 NASA Lewis Research Center
A. F. Lietzke
N. T. Saunders
- 3 Richland Operations Office
P. G. Holsted
R. K. Sharp
Technical Information Library
- 1 Transuranium Institute (Euratom)
Karlsstrasse 42-44
Karlsruhe, Germany
H. M. Mattys

Number
of Copies

- 3 Union Carbide Corporation (ORNL)
R. M. Carroll
T. F. Connally
J. L. Scott
- 1 United Aircraft Corporation
Research Laboratory
East Hartford, Connecticut
G. H. McLafferty
- 1 University of Arizona
Nuclear Engineering Dept.
Tucson, Arizona
Monte V. Davis
- 1 University of California,
Livermore
Dr. James Hadley
- 1 University of Michigan
College of Engineering
Ann Arbor, Michigan
W. Kerr
- 3 U. S. Atomic Energy Commission
Brussels, Belgium
C. F. Shank
- 2 Westinghouse Bettis Atomic
Power Laboratory
J. Belle
B. Lustman
- 4 Westinghouse Electric Corp.
Robert Allio
A. A. Bishop
A. Boltax
N. R. Nelson
- 1 Wright Air Development Center
AF Materials Laboratory
Wright-Patterson AFB,
Dayton, Ohio
S. W. Bradstreet

Number
of Copies95 Battelle-Northwest

F. W. Albaugh
H. J. Anderson
R. J. Anicetti
E. R. Astley
W. J. Bailey
R. J. Baker
R. E. Bardsley
A. L. Bement
C. H. Bloomster (40)
C. A. Burgess
J. B. Burnham
S. H. Bush
J. J. Cadwell
P. D. Cohn
R. E. Dahl
G. M. Dalen
F. G. Dawson, Jr.
D. R. de Halas
D. E. Deonigi
R. F. Dickerson
K. Drumheller
E. A. Eschbach
S. L. Fawcett
J. C. Fox

Number
of Copies

P. L. Farnsworth
M. D. Freshley
S. Goldsmith
W. L. Hampson
H. Harty
R. J. Hennig
J. P. Keenan
G. A. Last
W. R. Lewis
R. J. Lobsinger
L. G. Merker
J. E. Minor
R. E. Nightingale
H. M. Parker
R. S. Paul
W. D. Richmond
W. E. Roake
R. K. Robinson
R. E. Sharp
R. C. Smith
H. A. Taylor
O. J. Wick
H. R. Wisely
F. W. Woodfield
H. H. Yoshikawa
Technical Publications (2)
Technical Information Files(5)