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RODCOST
A PROGRAM FOR CALCULATING
THE COST OF FABRICATING
UO₂ AND PuO₂-UO₂ FUEL RODS
AS A FUNCTION OF DESIGN

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FUEL RODS AS A FUNCTION OF DESIGN

By

G. L. Simmons, B. M. Cole and J. B. Burnham, Jr.

Engineering Analysis Section
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FUEL RODS AS A FUNCTION OF DESIGN

ABSTRACT

A description is given of a computer code that calculates the cost of fabrication of fuel elements for both pressurized and boiling light water reactors. A one tonne per day plant and vibratory compacted fuel are assumed. Cost relations are developed based on the work of Burnham et al.⁽¹⁾ Information is given to allow the use of this code as a subroutine in a larger program.

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AUTHOR'S NOTE

This program was written to be used as part of a fuel cycle optimization chain of computer codes. With this in mind a number of simplifying assumptions were made. For example, the cost of end caps was assumed to remain constant with rod diameter.

The most detailed cost data was used as a basis for the calculations. This does not include, however, some of the newer processes currently under development by the Materials Department. Thus, such calculations as the fabrication costs of fuel as a function of density are valid only for the process studied. An entirely different cost relationship would be expected in a process specifically designed to fabricate low density fuel.

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INTRODUCTION

Reactor core design is influenced by the cost of manufacturing fuel elements and the variation of this cost with such parameters as rod size and fuel enrichment. Also, the value of recycled plutonium in light water power reactors is dependent on the fabrication penalty that one must pay in order to manufacture plutonium fuel rods. Thus, in making a recent study of the plutonium value in BWR's and PWR's, it was necessary to develop sufficient information to evaluate the cost of fuel element fabrication as a function of fuel density, rod diameter, fuel enrichment, plutonium value, extra enrichments in an assembly, etc.

Burnham, et al⁽¹⁾ have studied the cost of fabrication of oxide fuel assemblies in a one tonne per day plant. In order to utilize the extensive research into fuel element fabrication costs performed in that study, equations have been derived which express those costs as a function of fuel element design.⁽²⁾

The user of this code should be aware of some of the assumptions used in the program. In some instances they may limit the applicability of the results; in other cases a correction factor may have to be used to make the results meaningful for the particular conditions under study. The basic assumptions are:

- vibrational compacted oxide fuel
- one tonne per day oxide throughput
- constant clad thickness to pin diameter ratio
- UO_2 enrichment from natural to 5%
- pin diameter greater than 0.300 inches should be used
- fabrication costs only, no profit -- see reference (1)

Cost Equations

This code performs calculations of the rod fabrication cost as a function of rod diameter, rod length, U-235 enrichment, Pu enrichment, fuel density and extra enrichments per assembly. The change in cost associated with each of these parameters is obtained by varying the applicable cost components. Many process steps are unaffected by changes in rod diameter. Others have fixed and variable components. The cost of extra enrichments in an assembly is obtained by assuming that separate manufacturing lines are added in the process steps where this is necessary. The costs of these extra lines increase proportionally to the number of extra enrichments.

Direct Material Costs*

A formula has been developed for the cost of zircaloy tubing as a function of rod outside diameter with the ratio of wall thickness to tube diameter held constant. Here the ratio of wall thickness is changed somewhat from that given in Reference 1. The cost of end caps is assumed constant and the cost of the assembly hardware is assumed constant for a particular reactor type. The fuel component of the direct material cost includes the cost of conversion of U_3O_8 to ceramic grade UO_2 and in the case of enriched uranium the conversion of UF_6 to UO_2 ; for mixed oxide fuels the cost for converting $Pu(NO_3)_4$ to PuO_2 is included. Also, all shipping and insurance charges are included in the direct materials cost. The resulting formulae are:

	$\frac{PuO_2 - UO_2^*}{UO_2}$	$\frac{UO_2}{UO_2}$
Tubing - (T)	$(6.7703 OD - 0.5859) TL$	Same
End Caps - (EC)	1.072	Same
Assembly - (A)	8.547 (+3.00 for BWR)	Same
Fuel - (F)	$308.5 WP + 5.615 WU$	6.83 WU

* All costs are in dollars per rod.

OD is the outside diameter in inches.

TL is the tube length in feet.

WP is the weight of PuO_2 per rod in kg.

WU is the weight of UO_2 per rod in kg.

The total direct materials cost (DM) per rod is then

$$DM = T + EC + A + F$$

* The same terminology and assumptions used in Ref.1 are maintained for all cost components.

Labor and Rework Labor

The labor cost is divided into two components, one variable the other fixed. The former refers to that labor associated with rod preparation and handling. Obviously the cost of welding closures will go up as the number of rods increases. The labor in oxide preparation, though, is independent of the size of rods loaded and remains fixed.

	<u>PuO₂-UO₂</u>	<u>UO₂</u>
Variable - (DLV)	4.568 RF	3.676 RF
Fixed - (DLF)	7.307	5.748

RF = total weight of oxide loaded per rod in kg/2.1111

The total labor and rework labor cost (DL) per rod is

$$DL = DLV + DLF$$

Building and Equipment

This component has been divided into two components as in the preceeding item. The relations are

	<u>PuO₂-UO₂</u>	<u>UO₂</u>
Variable - (BEV)	3.413 RF	3.229 RF
Fixed - (BEF)	0.737	0.543

The total cost per rod for building and equipment is then:

$$BE = BEV + BEF$$

Indirect Manufacturing Expense

	<u>PuO₂-UO₂</u>	<u>UO₂</u>
Variable - (IMEV)	5.957 RF	5.274 RF
Fixed - (MEF)	9.528	8.427

The indirect manufacturing expense in total per rod is given by:

$$XI = IMEV + IMEF$$

Use Charge and Nuclear Losses

These items are proportional to the value of the fuel material.

The cost of U₃O₈ has been held constant at \$8.00/lb. A linear enriching charge has been assumed over the range of interest.

	<u>PuO₂-UO₂</u>	<u>UO₂</u>
Use Charge - (UC)	3.514 UR VX	3.436 RF UR UV
Nuclear Losses - (XL)	5.0 RF PV	4.977 RF UV

Where

$$UR = \text{use rate of interest}/4.75\%*$$

$$UV = \frac{\text{value of uranium actually used}}{\text{value of uranium at 3\% enrichment}*} = \frac{23.5 + (\% \text{ enrichment} - 0.711)}{246}$$

$$VX = \frac{10160.0 \text{ WP (Fraction of Pu Fissile)}}{475.12} \frac{\text{Pu Value}}{10} + (18.25 \text{ WU})$$

The total use charge plus nuclear losses per rod is then

$$UCNL = UC + XL$$

* Note normalization to Reference 1.

<u>Ordinary Losses</u>		
	<u>PuO₂-UO₂</u>	<u>UO₂</u>
Ordinary Losses - (XO)	0.6509	0.451

<u>Fixed Manufacturing and Non-Manufacturing Cost</u>		
	<u>Pu₂-UO₂</u>	<u>UO₂</u>
Fixed Manufacturing and non-manufacturing - (FM)	4.872 RF	4.706 RF

Working Capital

This item is dependent upon the working capital interest rate and all of the previously discussed items except, of course, use charge which is calculated independently. For both PuO₂-UO₂ and UO₂ fuel rods these costs are identical.

$$\text{Working Capital} - (\text{WC}) = (\text{CM} + \text{DL} + \text{BE} + \text{XI} + \text{XO} + \text{XL}) 0.01422 \text{ FI}$$

$$\text{Plant Interest} - (\text{FI}) = \text{Plant interest rate}/12\%$$

Total Rod Cost

The total cost per rod is then the sum of all the above items.

Extra Enrichments for a Fuel Assembly

As previously indicated, to produce fuel rods of different enrichments for one fuel element it becomes necessary to add parallel manufacturing lines for certain process steps. This procedure is used in order to minimize the amount of cleanup and decontamination associated with the production of a fuel assembly with rods of more than one enrichment. To achieve this end,

we have assumed that only a few items in the manufacturing line must be duplicated. The increase in the affected cost components, due to the addition of one extra enrichment per assembly, are given in Table I. Note that as expected, the penalty for making extra enrichments with plutonium fuel is less than with uranium fuel. It should be noted that these are incremental costs and the absolute cost of plutonium bearing rods is usually higher than uranium rods.

TABLE I

PERCENT INCREASE OF COST COMPONENTS FOR ONE EXTRA ENRICHMENT

	<u>$\text{PuO}_2\text{-UO}_2$</u>	<u>UO_2</u>
Direct Labor	25.5	35.5
Building and Equipment	19.6	28.4
Indirect Manufacturing	18.6	41.6
Working Capital	10.0	34.8

RODCOST: Use of The Code

The program is used as a subroutine and is called by the FORTRAN statement

```
CALL RODCST (OD, TL, TD, PUV, WPPU, WIR, FIR, FPU, EU235, III,  
            JJJ, NPA)
```

OD = Rod outside diameter in inches

TL = Rod length in feet

TD = Fraction of fuel theoretical density

PUV = Plutonium value in \$/gm fissile (Pu-239 and Pu-241)

WPPU(1) = Plutonium weight fraction that is Pu-239

WPPU(2) = Plutonium weight fraction that is Pu-240

WPPU(3) = Plutonium weight fraction that is Pu-241

WPPU(4) = Plutonium weight fraction that is Pu-242

WIR = Working capital interest rate, fraction

FIR = Fuel interest rate, fraction

FPU = Weight fraction of plutonium in the total amount of fuel

EU235 = Weight fraction of U-235 enrichment

III = 1 - mixed oxide - PWR fuel element

2 - mixed oxide - BWR fuel element

3 - uranium oxide - PWR fuel element

4 - uranium oxide - BWR fuel element

JJJ = Number of extra enrichments per assembly

NPA = Number of fuel rods per fuel assembly

Page 11 through page 15 is a FORTRAN listing of the program.

Page 16 contains the output for an example problem with the following input values.

OD	.402
TL	11.0
TD	.886
PUV	10.0
WPPU(1)	.69
WPPU(2)	.16
WPPU(3)	.11
WPPU(4)	.04
WIR	.12
FIR	.0475
FPU	.0288
EU235	.00711
III	1
JJJ	0
NPA	234

Figures 1 and 2 give examples of changes in fuel rod fabrication costs as a function of the number of extra enrichments, the fraction of theoretical density, and the outside diameter of the tubing using the input parameters specified above where applicable.

REFERENCES

1. J. B. Burnham, et al, "Comparative Cost of Oxide Fuel Elements," BNWL-273, Vol. 1, 2 and Appendix, July 1966.
2. Private communication, J. B. Burnham, Jr.
3. Private Communication, P. Loizzo and G. L. Simmons.
4. P. Loizzo and G. L. Simmons, unpublished data.

SUBROUTINE RODCST(OD,TL,TD,PUV,WPPU,WIR,FIR,FPU,EU235,III,JJJ,NPA)

FUEL FABRICATION COSTS FOR UO2 AND PUO2 FUEL RODS FOR
BOILING AND PRESSURIZED WATER REACTORS

```
DIMENSION WPPU(4)
WT=OD/18.27272
VOL=((TL*12.)*(3.1415927/4.)*(OD-2.*WT)**2)*16.387
ROFUEL=((10.12*FPU)+(1.-FPU)*10.97)*TD
G0235=ROFUEL*VOL*(1.-FPU)*EU235
G0238=ROFUEL*VOL*(1.-FPU)*(1.-EU235)
G0239=ROFUEL*VOL*FPU*WPPU(1)
G0240=G0239*WPPU(2)/WPPU(1)
G0241=G0239*WPPU(3)/WPPU(1)
G0242=G0239*WPPU(4)/WPPU(1)
TOTALO=VOL*ROFUEL
C1=G0235
C2=G0238
C3=G0239
C4=G0240
C5=G0241
C6=G0242
C7=TOTALO
TW=C7/1000.
GM235=G0235*.88015
GM238=G0238*.88148
GM239=G0239*.88192
GM240=G0240*.88235
GM241=G0241*.88278
GM242=G0242*.88321
TOTALM=GM235+GM238+GM239+GM240+GM241+GM242
C8=GM235
C9=GM238
C10=GM239
C11=GM240
C12=GM241
C13=GM242
C14=TOTALM
DN235=GM235*.6023/235.
DN238=GM238*.6023/238.
DN239=GM239*.6023/239.
DN240=GM240*.6023/240.
DN241=GM241*.6023/241.
DN242=GM242*.6023/242.
C15=DN235/VOL
```

```
C16=DN238/VOL
C17=DN239/VOL
C18=DN240/VOL
C19=DN241/VOL
C20=DN242/VOL
A2=OD-2.*WT
A5=NPA
NA5=A5
A3=1000./ (A5*TW)
NA3=A3
A4=WT
A6=OD
NA7=JJJ
A8=TL
A9=WIR*100.
A10=VOL
B1=8.
B2=PUV
B3=FIR*100.
B4=TW*1000./VOL
RF=TW/2.1111
UR=FIR/.0475
AJJJ=JJJ
FI=WIR/.12
WP=TOTALO*FPU/1000.
WU=TOTALO/1000.-WP
IF (III.GE.3)WU=VOL*TD*.01097
GO TO (1,2,3,4),III
1=PUO2UO2PWR 2=PUO2UO2BWR 3=UO2PWR 4=UO2BWR
C 1 DM=(6.7703*OD-.5859)*TL+1.077+308.5*WP+5.615*WU+8.547
GO TO 5
2 DM=(6.7703*OD-.5859)*TL+1.077+308.5*WP+5.615*WU+11.547
5 DL=7.307+4.568*RF
IF (JJJ.GT.0)DL=AJJJ*.2452*DL+DL
BE=.737+3.413*RF
IF (JJJ.GT.0)BE=AJJJ*.1959*BE+BE
XI=9.528+5.957*RF
IF (JJJ.GT.0)XI=AJJJ*.1855*XI+XI
FPF=(WPPU(1)+WPPU(3))* .8815
VX=((10160.*WP*FPF*PUV/10.)+(WU*18.25))/475.12
UC=3.514*UR*VX
XL=5.*VX
XO=.6509
FM=4.872*RF
GO TO 7
3 DM=(6.7703*OD-.5859)*TL*1.077+6.83*WU+8.547
```

```
GO TO 6
4 DM=(6.7703*OD-.5859)*TL*1.077+6.83*WU+11.547
6 DL=5.748+3.676*RF
  IF(JJJ.GT.0)DL=AJJJ*.355*DL+DL
  BE=.543+3.229*RF
  IF(JJJ.GT.0)BE=AJJJ*.284*BE+BE
  XI=8.247+5.274*RF
  IF(JJJ.GT.0)XI=AJJJ*.416*XI+XI
  UV=(.00235+.971*(EU235-.00711))/ .02457619
  UC=3.436*RF*UR*UV
  XL=4.977*RF*UV
  XO=.451
  FM=4.706*RF
  TW=WU
GO TO 7
7 WC=(DM+DL+BE+XI+XL+XO)*.01422*FI
  IF(JJJ.GT.0.AND.III.LE.2)WC=AJJJ*.0995*WC+WC
  IF(JJJ.GT.0.AND.III.GE.3)WC=AJJJ*.348*WC+WC
  TC=DM+DL+BE+XI+UC+XL+XO+FM+WC
  D1=DL/TW
  D2=DL
  D3=D2*A5
  D4=(6.7703*OD-.5859)*TL/TW
  D5=(6.7703*OD-.5859)*TL
  D6=D5*A5
  D7=XI/TW
  D8=XI
  D9=D8*A5
  D10=1.072/TW
  D11=1.072
  D12=D11*A5
  D13=FM/TW
  D14=FM
  D15=D14*A5
  D16=8.547/TW
  IF(III.EQ.2.OR.III.EQ.4)D16=11.547/TW
  D17=8.547
  IF(III.EQ.2.OR.III.EQ.4)D17=11.547
  D18=D17*A5
  D19=BE/TW
  D20=BE
  D21=D20*A5
  D22=(308.5*WP+5.615*WU)/TW
  IF(III.GE.3)D22=6.83*WU/TW
  D23=308.5*WP+5.615*WU
  IF(III.GE.3)D23=6.83*WU
```

```

D24=D23*A5
D25=WC/TW
D26=WC
D27=D26*A5
D28=UC/TW
D29=UC
D30=D29*A5
D31=XL/TW
D32=XL
D33=D32*A5
D34=XO/TW
D35=XO
D36=D35*A5
E1=TC/TW
E2=TC
E3=E2*A5
WRITE(6,1000)
1000 FORMAT(1H1/1H ,11X,104H      ** FUEL FABRICATION COSTS FOR UO2 AND P
1UO2 FUEL RODS FOR BOILING AND PRESSURIZED WATER REACTORS **      //)
      IF(III.EQ.1)WRITE(6,1010)
1010 FORMAT(33H0IDENTIFICATION      PWR  PUO2-UO2      //)
      IF(III.EQ.1)GO TO 1045
      IF(III.EQ.2)WRITE(6,1020)
1020 FORMAT(33H0IDENTIFICATION      BWR  PUO2-UO2      //)
      IF(III.EQ.2)GO TO 1045
      IF(III.EQ.3)WRITE(6,1030)
1030 FORMAT(33H0IDENTIFICATION      PWR  UO2              //)
      IF(III.EQ.3)GO TO 1045
      IF(III.EQ.4)WRITE(6,1040)
1040 FORMAT(33H0IDENTIFICATION      BWR  UO2              //)
1045 WRITE(6,1050)
1050 FORMAT(1H0,22HFUEL PLANT INFORMATION,43X,20HFUEL ROD INFORMATION )
      WRITE(6,1060)A2,NA3,A4,NA5,A6,NA7,A8,A9,A10
1060 FORMAT(1H ,27H  PLANT THROUGHPUT (OXIDE),9X,11H1 TONNE/DAY,11X,2H
1 ,8X,17HINSIDE DIAMETER ,F8.3,7H INCHES /4X,20HNUMBER OF ASSEMBL
2IES,6X,18, 8H PER DAY,13X,2H ,8X,14HWALL THICKNESS,3X,F8.3,7H 'IN
3CHES /4X,14HNUMBER OF RODS,12X,18, 13H PER ASSEMBLY,8X,2H ,8X,17
4HOUTSIDE DIAMETER ,F8.3,7H INCHES /4X,21HEXTRA ENRICHMENTS ,11X
5, 12,13H PER ASSEMBLY8X,2H ,8X,11HTUBE LENGTH,6X,F8.3,5H FEET /4X
6,26HWORKING CAPITAL INTEREST ,F8.3,8H PERCENT,13X,2H ,8X,13HLOAD
7ED VOLUME 4X,F8.3,3H CC )
      WRITE(6,1070)B1,B2,B3,B4
1070 FORMAT(1H0,25HFUEL MATERIAL INFORMATION /4X,20HPRICE OF YELLOW CAK
1E,6X,F8.3,12H $/LB (U3O8) /4X,19HPRICE OF FISSILE PU,7X,F8.3,15H $
2/GM (NITRATE)/4X18HFUEL INTEREST RATE,8X,F8.3,8H PERCENT /4X,15HSM
3EARED DENSITY,11X,F8.3,6H GM/CC /)

```

```

      WRITE(6,1080)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,
      1C16,C17,C18,C19,C20
1080 FORMAT(1H0,50X,18H * FUEL ASSAY * //
      129X,4HU235,9X,4HU238,9X,5HPU239,8X,5HPU240,8X,5HPU241,8X,5HPU242,8
      2X,5HTOTAL //25H GRAMS OF OXIDE PER ROD ,7(1PE13.5),/25H GRAMS OF
      3METAL PER ROD ,7(1PE13.5) /25H NUCLIDE DENSITY AT/BR CM,7(1PE13.5
      4))
      WRITE(6,1090)
1090 FORMAT(1H0, / 51X,19H* COST COMPONENTS */
      1/26X,11H$/KG(OXIDE),5X,18H$/ROD $/ASSEMBLY,19X,11H$/KG(OXIDE),
      25X,18H$/ROD $/ASSEMBLY )
      WRITE(6,2000)D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14,D15,
      1D16,D17,D18,D19,D20,D21,D22,D23,D24,D25,D26,D27,D28,D29,D30,D31,
      2D32,D33,D34,D35,D36,E1,E2,E3
2000 FORMAT(1H0,16HLABOR AND REWORK,6X,3F12.2,9X,8HTUBING ,3F12.2,/
      123H INDIRECT MANUFACTURING,3F12.2,9X,8HEND CAPS,3F12.2,/
      223H FIXED MANUFACTURING ,3F12.2,9X,8HASSEMBLY,3F12.2,/
      323H BUILDING AND EQUIPMENT,3F12.2,9X,8HFUEL ,3F12.2,/
      423H WORKING CAPITAL ,3F12.2,/
      523H FUEL USE CHARGE ,3F12.2,/
      623H NUCLEAR LOSSES ,3F12.2,/
      723H ORDINARY LOSSES ,3F12.2,//
      862X,14H TOTAL COST = ,3F12.2,/
      964X,10H***** )
      RETURN
      END

```

** FUEL FABRICATION COSTS FOR UO2 AND PUO2 FUEL RODS FOR BOILING AND PRESSURIZED WATER REACTORS **

IDENTIFICATION PWR PUO2-UO2

FUEL PLANT INFORMATION

PLANT THROUGHPUT (OXIDE)	1 TONNE/DAY
NUMBER OF ASSEMBLIES	2 PER DAY
NUMBER OF RODS	234 PER ASSEMBLY
EXTRA ENRICHMENTS	-0 PER ASSEMBLY
WORKING CAPITAL INTEREST	12.000 PERCENT

FUEL ROD INFORMATION

INSIDE DIAMETER	.358 INCHES
WALL THICKNESS	.022 INCHES
OUTSIDE DIAMETER	.402 INCHES
TUBE LENGTH	11.000 FEET
LOADED VOLUME	217.736 CC

FUEL MATERIAL INFORMATION

PRICE OF YELLOW CAKE	8.000 \$/LB (U308)
PRICE OF FISSILE PU	10.000 \$/GM (NITRATE)
FUEL INTEREST RATE	4.750 PERCENT
SMEARED DENSITY	9.698 GM/CC

* FUEL ASSAY *

	U235	U238	PU239	PU240	PU241	PU242	TOTAL
GRAMS OF OXIDE PER ROD	1.45807+01	2.03615+03	4.19605+01	9.72998+00	6.68936+00	2.43249+00	2.11154+03
GRAMS OF METAL PER ROD	1.28332+01	1.79482+03	3.70058+01	8.58525+00	5.90523+00	2.14840+00	1.86130+03
NUCLIDE DENSITY AT/BR CM	1.51060-04	2.08607-02	4.28308-04	9.89521-05	6.77803-05	2.45575-05	

* COST COMPONENTS *

	\$/KG(OXIDE)	\$/ROD	\$/ASSEMBLY		\$/KG(OXIDE)	\$/ROD	\$/ASSEMBLY
LABOR AND REWORK	5.62	11.88	2778.97	TUBING	11.13	23.49	5497.45
INDIRECT MANUFACTURING	7.33	15.49	3623.78	END CAPS	.51	1.07	250.85
FIXED MANUFACTURING	2.31	4.87	1140.29	ASSEMBLY	4.05	8.55	2000.00
BUILDING AND EQUIPMENT	1.97	4.15	971.27	FUEL	14.34	30.28	7084.46
WORKING CAPITAL	.68	1.43	334.53				
FUEL USE CHARGE	1.66	3.50	818.84				
NUCLEAR LOSSES	2.36	4.98	1165.11				
ORDINARY LOSSES	.31	.65	152.31				
				TOTAL COST =	52.25	110.34	25819.02

FIGURE 1

Fuel Rod Fabrication Costs (\$/Rod) as a Function of Design Parameters

FIGURE 2

Fuel Rod Fabrication (\$/Kg oxide) as a Function of Design Parameters

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