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RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

ECONOMICS OF THE H.T.G.C.R. FUEL CYCLE

PART 2. FUEL CYCLE COST STUDIES

by

R. W. HUBERY
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ABSTRACT

The use of beryllium oxide as a moderator in a high temperature gas-cooled pebble bed reactor system which has been under study by the Commission incurs penalties due to its relatively high cost and the difficulty of reprocessing the fuel. This report examines the basic open and closed fuel cycles for such a system and defines the parameters affecting the cost of each cycle. Analytical relationships are developed for each cost component to facilitate calculations over a wide range of reactor design variables. This approach is of value during initial optimisation studies on a reactor concept.

Calculations based on a 200 MWe design show that, using optimistic assumptions, recycle of spent fuel would be economically attractive for installed capacities greater than 800 MWe.

PREFACE

The following list details a series of reports dealing with the fuel cycle of the High Temperature Gas Cooled Reactor. This report (AAEC/E179) is the second of the final group of reports dealing with The Economics of the H.T.G.C.R. Fuel Cycle.

Laboratory Development of the Grind-Leach Process for the H.T.G.C.R. Fuel Cycle

Part 1. Dissolution of Urania-Thoria Fuel Particles in Nitric Acid Solutions, by M.S. Farrell and S.R. Isaacs. AAEC/E143.

Part 2. Dissolution of Beryllia in Nitric Acid Solutions, by M.S. Farrell, S.R. Isaacs and M.E. Shying. AAEC/E154.

Part 3. Comminution of Beryllia Matrix Fuels, by M.G. Baillie and R.W. Hubery. AAEC/E162.

Part 4. Leaching and Dissolution of Beryllia-Based Fuels, by M.E. Shying, E.J. Lee and M.S. Farrell. AAEC/E180.

Development of Solvent Extraction Processes for the H.T.G.C.R. Fuel Cycle

Part 1. Design of a Flowsheet for the Recovery of Actinides, by M.G. Baillie and R.K. Ryan. AAEC/E139.

Part 2. Solvent Extraction of Thorium and Uranium from Beryllium Nitrate Feeds by Tri-n-Butyl Phosphate, by R.C. Cairns, M.G. Baillie, B.J. Fox and R.K. Ryan. Industrial and Engineering Chemistry, Process Design and Development Quarterly. In Press.

Part 3. Chemical Data for the Extraction of Actinides and Fission Products from Aqueous Beryllium Sulphate Solutions using Amines, by J.J. Fardy, M.S. Farrell and D.G. Pinchbeck. A.A.E.C. report in preparation.

Economics of the H.T.G.C.R. Fuel Cycle

Part 1. Pre-design Cost Study of Fuel Cycle Facility, by J.R. May and J.M. Devine. AAEC/E175.

Part 2. Fuel Cycle Cost Studies, by R.W. Hubery and M.G. Baillie. AAEC/E179.

CONTENTS

1. INTRODUCTION

The fuel selected for the High Temperature Gas-Cooled Reactor system recently studied by the A.A.E.C. was a dispersion type oxide fuel with a beryllia matrix. A number of important nuclear advantages accrue from the use of beryllia in a homogeneous system (Roberts 1964) but it is a relatively expensive material and the fuel is difficult to reprocess.

Fuel cycle costing methods have been developed elsewhere to suit the economic and technical situation in particular countries and a noteworthy trend towards standardisation of methods is apparent for conventional reactor systems. The Guide to Nuclear Power Cost Evaluation (U.S.A.E.C. 1962) and the Euratom Economic Handbook (Willems et al. 1966) give suitable methods for evaluating the cost of nuclear power including the portion of that cost attributable to the fuel cycle. However these "standard" approaches require considerable redrafting for application to an advanced reactor system of the type considered here. Variations from standard practice must be introduced to account for moderator recycle, a more complex fissile species than is normally encountered, combined reprocessing, reconversion, and refabrication in a single facility, "smeared" inventories in the recycle case, and the lack of physics data on the approach-to-equilibrium phase which prevents application of the present worth method of costing.

In this report a method of fuel cycle cost evaluation is set out which is more easily applied to dispersion fuelled advanced converter thorium systems without major modification. The approach is essentially that of the fuel processor rather than the reactor operator.

The aim of this work was to establish general relationships applicable to dispersion fuelled thorium systems, and then to establish minimum fuel cycle costs, for both open and closed cycles for the H.T.G.C.R. system by using optimistic data.

Costs are expressed in Australian currency units throughout the report.

2. BASIS FOR COSTING THE FUEL CYCLE

The alternative fuel cycle schemes for an integrated system comprising reactor installation and common fuel supply and/or recycling facilities are shown in Figure 1. The open cycle route is the so-called "throw-away" fuel scheme in which raw materials are purchased at their world market value and spent fuel is discharged to a fuel storage facility. However, fuel elements disposed of in this way are not regarded as thrown away in the literal sense. In fact it appears likely that fuel discharged from any currently proven reactor type will be reprocessed when the economic environment has changed and it is possible to justify recovery of its valuable constituents. (See "Evaluation of the Break-even Point" in Section 4.1).

The remaining scheme in Figure 1 is the closed cycle or recycle case in which recovered fuel material is combined with fresh make-up fuel to maintain normal supply to the reactor complex.

The components of the total fuel charge for each operating method are as set out in Figure 1.

When comparing these two schemes it must be realised that significant differences may appear between methods of operating the reactors used in each system. This is particularly true of the optimum fuel burn-up, which will normally be different in each cycle. When open cycle fuel is used the limitation on burn-up is due to reactivity or materials problems only, minimum costs being achieved at the maximum possible burn-up. Recycled fuel, on the other hand, involves a more difficult optimisation problem because of the complex relationship between burn-up and recycling costs. This is particularly evident in the case of make-up costs which may pass through a minimum at a relatively low burn-up. Depending upon the magnitude of the various cost components, this effect may result in a low burn-up optimum point for the entire system.

3. EVALUATION OF H.T.G.C.R. REFERENCE DESIGN

The reference H.T.G.C. pebble-bed reactor design described by Ebeling and Hayes (1967) is a nominal 206 MWe unit cooled by carbon dioxide gas flowing upward through a slowly recirculating bed of fuelled pebbles. The fuel elements are beryllia spheres of 3.5 cm diameter containing a uniform dispersion of $(Pu,Th)O_2$ particles of 150 to 200 μ diameter.

The two methods of fuel management proposed for this system were those outlined in Section 2. The basis for costing each cycle is now examined in more detail.

3.1 Open Cycle

It is assumed that all the reactors installed in the system under study would be fuelled by the same fabricator and that each reactor would carry its own permanent storage of spent fuel elements. Consequently no shipping charge for fuel disposal is applicable for this system. The shipping charge for fabricated fuel elements may also be neglected since it is very small for distances less than 1000 miles (see Section 3.4).

The cost of nuclear raw materials for use in these cycles has been assessed and a conservative set of projected costs selected. (See Table 1).

The cost of fabricating fuel elements from the raw materials has been examined by Silver and Wright (A.A.E.C. Unpublished) and the relevant fabrication costs applicable to this study are shown in Figure 2 as a function of throughput. These costs show little variation with throughput at capacities greater than 200,000 kg per year, corresponding to about 2000 MWe of installed H.T.G.C. reactors of the reference design.

At two points in the cycle, inventory or storage charges are introduced. These are simple time-dependent charges on the money outlaid on fuel and are calculated at the standard rate of interest on capital. In the case of the reactor inventory charge, the value of fuel is taken as the mean value of the fuel during its passage through the reactor complex (see Appendix 1).

Following disposal of the spent fuel elements, a zero value is assigned. It is apparent from Figure 1 and Appendix 1 that this assumption results in a negative value of fuel after discharge from the reactor.

The basic parameters used in assessing open cycle fuel costs are listed in Table 1. Further details of assumptions and calculations involved are given in Appendix 1 and the cost components for various system sizes are listed in Table 2. The fuel cycle costs assessed in this way are shown in Figure 3 as a function of system size.

3.2 Closed Cycle

Operation of a closed fuel cycle is an important objective for system planning because of the enhanced utilisation of both fissile and fertile reserves compared with that possible under open cycle conditions. The basic concept for the closed fuel cycle H.T.G.C.R. is a group of reactors close to common fuel handling facilities. This system is assumed to operate under equilibrium conditions, entirely unaffected by external considerations, being fed with make-up material at a fixed cost and producing power at a fixed price throughout its design life.

The application of inventory charges within this cycle is much more difficult than for the open cycle. The conventional approach is the establishment of a fuel cost before shipping to the reactor site and a spent fuel credit on discharge. However for this system at its present stage of development no core data for the approach-to-equilibrium phase of reactor operation are available. Consequently it is not possible to follow the first and subsequent fuel charges through the system to arrive at a realistic credit for spent fuel. As a result, inventory charges throughout the system cannot be allocated in the usual way but must be "smeared" over the entire system. Thus the value of the total fuel held up in the integrated reactor/recycle system is taken as the basis for the charging of a system inventory against the power produced from that system. This procedure is believed to be the only reasonable alternative to setting a value on spent fuel which can only be arbitrary in the absence of physics data on the early recycle cores.

A scrap value may be assessed for fuel remaining at the end of the system life but the actual value would depend on whether or not systems capable of accepting this kind of fuel were in existence at the time.

The combination of reprocessing and refabrication functions into a single costing component in Figure 1 is made necessary by the need for remote refabrication facilities in a Th232/U233 cycle. Both the high toxicity of U233 and the buildup of high-energy gamma emitting decay products of the U232 impurity always present in this fuel, make integration of these activities desirable for the present optimistic assessment. Moreover, because this integration is a fundamental design philosophy rather than a mere grouping of separate activities on a particular site, it is impossible to apportion costs realistically to either reprocessing or refabrication sections. Thus the conventional breakdown of reprocessing and refabrication costs yielding basic fissile material costs for recycle calculations is not possible in this system.

The supply of make-up materials to this cycle is necessary for two reasons. In the first place, true breeding in the sense of obtaining core recovery factors significantly greater than unity does not appear possible with this reactor concept, and secondly it would be necessary to bleed uranium and plutonium from the system to control the build-up of unsuitable higher isotopes. Both of these points have been discussed by Bicevskis et al. (1966) who suggested the arbitrary use of a 5 per cent. bleed of the fissile elements to offset the latter problem. Hence, although reprocessing losses of less than one per cent. would be feasible using the flowsheet envisaged for this purpose, the higher loss rate is assumed in these calculations.

The value of core recovery factor used in this study was taken from Bicevskis (1966) as 0.875 for a burn-up of 1.0 fissions per initial fissile atom. This assumes equilibrium core operation, recycle of U233, and fissile make-up with plutonium.

The most important charge associated with this cycle is that incurred within the reprocessing and refabrication facility. This charge is based on a cost estimate by May and Devine (1967) for an integrated recycle facility of 300 kg per day design capacity. The method of applying this estimate and scaling it for other throughputs is given in Appendix 2.

The basic parameters used in assessing closed cycle fuel costs are listed in Table 1 and details of assumptions and calculations involved are given in Appendix 2. The cost components for various system sizes are listed in Table 2 and plotted in Figure 3.

3.3 Costing Units

The examination of trends in fuel cycle cost components can give misleading results unless useful units are chosen for comparisons. Consider, for example, the assessment of the charge associated with reprocessing and refabrication of fuel. Appendix 2 sets out the general equation:

$$C = K_1 T^{K_2} \quad \$ \text{ per kg} \quad ,$$

which relates unit cost to plant throughput. K_1 and K_2 are normally constants over a restricted range of plant throughputs and K_2 is invariably fractional and negative (that is, $0 > K_2 > -1$). Inspection of this relationship indicates that unit cost <u>decreases</u> with throughput for $K_2 < 0$. Now Appendix 3 indicates that throughput varies inversely with burn-up, and consequently unit cost expressed in $ per kg (which <u>decreases</u> with throughput) must <u>increase</u> with burn-up. However by changing the units to power cost in cents per kWh it can be seen from Appendix 2 that the cost component C_R varies with burn-up according to the relationship:

$$C_R \propto (\text{F.I.F.A.})^{-K_2-1}$$

and hence always <u>decreases</u> with burn-up for $K_2 > -1$.

This kind of problem is not confined to recycling plant charges but it illustrates the importance of considering all factors in the fuel cycle in terms of their effect upon power costs.

3.4 Shipping Charges

The assumption that shipping charges are negligible in the open cycle case and not applicable for fully integrated closed cycle operation is satisfactory for the present estimation of fuel cycle costs.

However Salmon (1966) details a method of estimation of shipping costs for active and inactive fresh fuels, active spent fuels, and inactive basic fuel materials. Some approximate charges applicable to the present system for return trips of 1000 miles each way are:

Inactive fresh fuel – \$0.50 per kg ($\sim$ 0.001 ¢/kWh)

Active fresh fuel – \$1.50 per kg ($\sim$ 0.003 ¢/kWh)

Active spent fuel – \$2.50 per kg ($\sim$ 0.005 ¢/kWh)

These estimates are much less than those given in The Guide to Nuclear Power Cost Evaluation (U.S.A.E.C. 1962) and, as stated above, have been neglected for the present study.

3.5 Comparison with Other Costing Methods

In comparing this present assessment with the "standard" methods set out by Euratom and the U.S.A.E.C. (see Section 1) two points should be noted.

In the first place, and using the conventional terminology, the following cost items have been included in the calculations:

- All initial fuel purchases including raw materials, conversion and fabrication.
- All reprocessing, reconversion, and refabrication charges for recycled fuel.
- All storage charges before and after irradiation, and during recycling.
- All fuel consumption and loss charges which appear as make-up charges in the closed cycle.

Secondly, because of the choice of an integrated system and the simplifying assumptions associated with it, the following conventional charges do not apply:

- All shipping costs to and from reactors in both cycles (see Section 3.4).
- All fuel credits.
- All use charges, since private ownership is assumed.

4. DISCUSSION OF RESULTS

Many independent factors contribute to the cost of reactor fuel, and some of them cannot be accurately defined at this stage. Many will remain indeterminate until a definite reactor construction and siting plan is established. The results of any evaluation at this preliminary stage must therefore be treated as indicative of trends only.

4.1 Evaluation of Break-even Point

From Table 2:

$$C_O = 0.161 + C_F \quad ,$$

and $$C_C = 0.048 + C_R \quad ,$$

since only the fabrication and reprocessing/refabrication charges depend significantly on throughput. From Appendices 1 and 2 expressions for C_F and C_R can be obtained in terms of throughput or installed generating capacity, and hence:

$$C_O = 0.161 + 0.00147\ e^{5.55\ P_T^{-0.104}} \quad ,$$

and $$C_C = 0.048 + 23.3/P_T^{0.77} \quad .$$

These expressions are sufficiently accurate for use in analytical studies of fuel cycle economics provided the ground rules as set out in this report are applicable.

It is of some interest to evaluate the point on the cost versus capacity curve at which fuel recycle can be undertaken at the same cost as open cycle operation. This can be obtained from Figure 3 or by evaluating P_T in the above equations when $C_O = C_C$. The break-even point occurs at 800 MWe, which corresponds to about four H.T.G.C. reactors of the reference design.

In practice the change from open to closed cycle operation may be made at a different point to that calculated above, depending on the expected system size and growth rate.

For a potentially large and rapidly expanding power system more economic power production over a long period would be achieved by delaying the commencement of fuel recycle beyond the theoretical break-even point. In this way a large stock of spent fuel would be accumulated which could provide the entire feed for a high capacity plant for a considerable time. Thus the desirable economics of reprocessing and refabrication at a high throughput could be utilised earlier in the life of the system.

On the other hand, a small system consisting of four or more reactors with no prospects of early expansion, could use its accumulated fuel stock to enable recycling to be carried out at a high load factor before the completion of the last reactor in the series.

4.2 Usefulness of Results

The evaluation of fuel cycle costs as carried out in this report is not intended to give quantitative results for universal application. The data upon which the calculations are based are, in many instances, neither reliable nor complete because of the preliminary nature of the entire H.T.G.C.R. feasibility study. However, the approach outlined is believed to be of general application in dispersion fuelled thorium systems where optimisation or comparison studies within a single fuel cycle type are contemplated, especially in the early stages of an evaluation.

It is important to realise that this simple approach, which does not differentiate between the effect of charges at different times in the cycle lifetime, is quite unsuitable for comparison of generating systems which differ materially in their costing structure and in the timing of various events within them. These conditions are best handled by normalising all costs over the system lifetime using the present worth technique.

5. CONCLUSION

For the H.T.G.C. pebble-bed reactor system, the general fuel cycle cost relationships developed in this report indicate that when using optimistic assumptions the nominal break-even point between open and closed cycles is 800 MWe. This corresponds to an installation of about four reactors of the A.A.E.C.'s reference design.

Although the absolute values of fuel cycle costs computed here are not intended for comparison with other generating systems, it is of interest to note that the lowest fuel cycle cost which might be considered feasible is about 0.1 cents/kWh for a recycle system based on an installed capacity of 3000 MWe.

6. ACKNOWLEDGEMENT

Acknowledgements are due to Dr. R.C. Cairns, Head, Fuel Cycle Development Section, whose initial suggestions helped set the ground rules for this work.

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APPENDIX 1

OPEN FUEL CYCLE COSTS

1. Raw Materials

The cost equation developed here is the basis for calculating all make-up and inventory charges.

1.1 Fissile Material

The initial pure fissile material in a new core is m grams. The total fissions per core $= \frac{m}{M_1} \times 6.021 \times 10^{23} \times \text{F.I.F.A.}$

Thus the energy produced (at 200 MeV/fission) $= \frac{m}{M_1} \times 6.02 \times 10^{23} \times \text{F.I.F.A.} \times 200 \times 1.6 \times 10^{-13}$ watt-sec.

But the energy produced by a reactor of P MWe $=$

$$\frac{P \times 10^6 \times \text{Life} \times \text{LF} \times 365 \times 24 \times 3600}{\eta_c} \text{ watt-sec.}$$

Therefore $m = \frac{P \times \text{Life} \times \text{LF} \times M_1 \times 1.637}{\text{F.I.F.A.} \times \eta_c}$ g of pure fissile material,

and the unit cost of fissile raw material $=$

$$\frac{P \times \text{Life} \times \text{LF} \times M_1 \times 1.637}{\text{F.I.F.A.} \times \eta_c} \times \frac{C_1}{F_C} \times \frac{1}{P \times \text{Life} \times \text{LF} \times 87600}$$

$$= \frac{1.87 \times 10^{-5}}{\text{F.I.F.A.} \times \eta_c} \times \frac{C_1 M_1}{F_C} \text{ cent/kWh,}$$

where F_C is the weight fraction of fissile isotopes in the fissile raw material.

1.2 Fertile Material

For a homogeneous fuel with a nominal fuel concentration of 1 : X2 : X3 = fissile atoms : fertile atoms : moderator atoms, the total weight of pure fertile material required per core is:

$$\frac{X2 \times M_2}{M_1} \times \text{weight of pure fissile material per core.}$$

This is made up of fertile raw material (for example Th232) or fertile components of raw materials used primarily to supply fissile isotopes (for example Pu). The weight of fertile material incorporated with the fissile fractions is given by:

$$\text{Wt. of fertile} = \text{wt. of pure fissile} \times \frac{1 - F_C}{F_C} .$$

Thus the weight of fertile raw materials is given by the weight of pure fertile material required, less the weight available from fissile raw material.

Hence

$$\text{Wt. of fertile raw material per core} =$$
$$\text{Wt. of pure fissile material} \left(\frac{X2 \times M_2}{M_1} - \frac{1 - F_C}{F_C} \right) ,$$

and thus the cost of fertile raw materials is given by:

APPENDIX 1 (continued)

unit cost of fertile raw material =

$$\frac{P \times Life \times LF \times M_1}{F.I.F.A. \times \eta_c} \times \frac{1.637}{1000} \left(\frac{X2 \times M_2}{M_1} - \frac{1 - F_C}{F_C} \right) \times C_2 \times \frac{1}{P \times LF \times 87600 \times Life}$$

$$= 1.87 \times 10^{-8} \times \frac{M_1 \times C_2}{F.I.F.A. \times \eta_c} \left[\frac{X2 \times M_2}{M_1} - \frac{1 - F_C}{F_C} \right] \text{ cents/kWh.}$$

1.3 Moderator

In the same way as fertile material the cost of moderator can be expressed as

$$\frac{1.87 \times 10^{-8}}{F.I.F.A. \times \eta_c} \times C_3 \times M_3 \times X3 \text{ cents/kWh.}$$

1.4 Total Raw Materials Cost

In practice the inclusion of fertile material in the calculations is found to contribute less than 0.002 cents/kWh in long burn-up systems and consequently may be omitted for all but the most rigorous assessments. In all calculations in this work it is neglected.

Total raw materials cost:

$$C_{RM} = \frac{1.87 \times 10^{-5}}{F.I.F.A. \times \eta_c} \left(\frac{C_1 \times M_1}{F_C} + \frac{C_3 \times M_3 \times X3}{1000} \right) \text{ cents/kWh .}$$

2. Raw Materials Inventory

The total hold-up time in storage, fabrication, and shipping is taken as T_{RM} years. Then the charge on this inventory is given by

$$I_{RM} = C_{RM} \times i \times T_{RM}$$

$$= \frac{1.87 \times 10^{-5}}{F.I.F.A. \times \eta_c} \times i \times T_{RM} \left(\frac{C_1 \times M_1}{F_C} + \frac{C_3 \times M_3 \times X3}{1000} \right) \text{ cents/kWh .}$$

3. Fabrication

The cost of fabrication of fuel elements can be assessed for any given system and a relationship established between cost and throughput. Some estimates of fabrication costs at different plant throughput have been made by Silver and Wright (A.A.E.C. Unpublished). Between the limits 40,000 to 250,000 kg of fuel per year these costs can be correlated by:

$C = e^{8.82\ T_y^{-0.104}}$ $ per kg (T_y = throughput in kg per year), and converting to power cost units (Appendix 3):

$$C_F = 1.87 \times 10^{-8} \frac{R}{F.I.F.A. \times \eta_c} \times e^{8.82\ T_y^{-0.104}} \text{ cents/kWh.}$$

It can be shown (Appendix 3) that plant throughput can be represented by:

$$T_y = \frac{P_T \times LF \times R}{612 \times F.I.F.A. \times \eta_c} \text{ kg per year at a given core load factor.}$$

APPENDIX 1 (continued)

Hence

$$C_F = 1.87 \times 10^{-8} \frac{R}{F.I.F.A. \times \eta_c} \times \exp\left[8.82\left(\frac{P_T \times LF \times R}{612 \times F.I.F.A. \times \eta_c}\right)^{-0.104}\right] \text{cents/kWh} .$$

4. Reactor Inventories

Fuel held up in the reactors and their related storage facilities must be charged at the normal capital rate. The total hold-up time is the sum of:

Fuel storage time	T_S	years.
Core lifetime	Life	
Cooling time	T_C	

Now the value of the fuel decreases as it passes through the reactor complex from the inlet value V to the discharge value V_D . This decrease is assumed to be linear and the inventory charge is based on the mean value:

$$\frac{V + V_D}{2} \text{ cents/kWh} .$$

Since $V = C_{RM} + I_{RM} + C_F + C_{TF}$,

and $V_D = -(C_{TD} + C_D)$, (see Figure 1)

the mean value becomes:

$$\frac{V + V_D}{2} = \frac{1}{2}\left[C_{RM} + I_{RM} + C_F + C_{TF} - C_{TD} - C_D\right] \text{cents/kWh} .$$

Hence the reactor inventory charges are given by:

$$I_R = \frac{V + V_D}{2} \times i\,(T_S + \text{Life} + T_C) \text{ cents/kWh} ,$$

$$= \frac{i}{2}\left[C_{RM} + I_{RM} + C_F + C_{TF} - C_{TD} - C_D\right]\left[\frac{6.12 \times 10^5 \text{ F.I.F.A.} \times \rho_f (1-C)}{R \times PD \times LF} + T_S + T_C\right]$$

cents/kWh .

5. Spent Fuel Disposal

The assumption is made in this report that disposal facilities, provided in association with each reactor, are sufficient to handle all the fuel discharged during its lifetime. Both capital and operating charges incurred by this facility are assumed to be costed as part of the reactor complex and no inventory charge is payable on spent fuel, which is assumed to be valueless. The high cost of shipping spent fuel to disposal point is also eliminated by this approach.

However a charge is made for the cost of canning the fuel elements on discharge. This is taken as being constant at \$D per kg, which, on conversion to power cost units, becomes:

$$C_D = 1.87 \times 10^{-8} \times \frac{R}{F.I.F.A. \times \eta_c} \times D \text{ cents/kWh} .$$

For the stage of the development of the concept a value of D = \$3/kg as used by Bicevskis, Hesse and Mercer (1966) appears to be satisfactory.

APPENDIX 2

CLOSED FUEL CYCLE COSTS

1. Raw Materials Make-up

In general, make-up material = material charged × (1 − recovery fraction). For the specific case of fissile material the recovery fraction required is the product of the nuclear recovery fraction and the reprocessing fissile recovery fraction. This latter term allows for rejection of any part of the fissile content of discharged fuel during processing either by unavoidable losses or deliberate fissile bleeding which might be necessary to control the build-up of higher isotopes.

Application of these qualifying terms to the raw materials cost equation results in the expression:

$$C_{MU} = \frac{1.87 \times 10^{-5}}{F.I.F.A. \times \eta_c} \left(\frac{M_1 \times C_1}{F_C} (1 - RF \times F_1 \times A) + \frac{M_3 \times C_3 \times X_3}{1000} (1 - F_3) \right) \text{ cents/kWh,}$$

where C_1 and F_C refer to the make-up fissile material and M_1 is the mean value for make-up and recycled fissile material. The factor A accounts for the varying nuclear worth of fissile species in discharged fuel relative to unburnt fuel.

2. Make-up Inventory

The total hold-up time in the make-up material stockpile is T_{MU} years. Hence $I_{MU} = C_{MU} \times i \times T_{MU}$ cents/kWh.

3. Reprocessing and Refabrication

It is assumed in this calculation that the unit costs associated with recycling facilities can be related to throughput by a relationship of the form:

$$C = K_1 T_y^{K_2} \text{ \$ per kg } (T_y = \text{throughput in kg per year}).$$

For the present purpose a base plant of 300 kg per day (87,600 kg per year) capacity was selected and its associated annual fixed and operating costs assessed (May and Devine 1967). This plant was then scaled with throughput according to the above relationship with $K_2 = -0.77$ (based on estimates of Culler 1963). Estimated capital cost of a 300 kg per day plant is $30,000,000.

Annual Fixed Cost, assuming 10 year life at 6 per cent. per annum and capital recovery by sinking fund = $4,076,000.

Estimated Annual operating costs = $3,100,000.

Therefore the Total Annual Cost = $7,176,000.

Unit Cost = $81.92 per kg of fuel.

By substitution in $C = K_1 T^{K_2}$:

$K_1 = 81.92 \times 87{,}600^{0.77} = 6393 \times 81.92 = 5.237 \times 10^5$, and hence the cost equation is:

$C = 5.237 \times 10^5 \times T^{-0.77}$ \$ per kg.

Appendix 3 shows that:

$$\text{Power Cost} = \frac{\$}{kg} \times 1.87 \times 10^{-8} \times \frac{R}{F.I.F.A. \times \eta_c} \text{ cents/kWh},$$

and

$$T_y = \frac{LF \times P_T \times R}{612 \times F.I.F.A. \times \eta_c} \text{ kg per year.}$$

APPENDIX 2 (continued)

Therefore:

$$C_R = 1.87 \times 10^{-8} \times \frac{R}{F.I.F.A. \times \eta_c} \times 5.237 \times 10^5 \left[\frac{LF \times P_T \times R}{612 \times F.I.F.A. \times \eta_c}\right]^{-0.77} \text{ cents/kWh,}$$

$$= \frac{1.636}{P_T^{0.77}} \left[\frac{R}{F.I.F.A. \times \eta_c}\right]^{0.23} \text{ cents/kWh.}$$

4. Cycle Inventory

The cost of raw materials necessary to fill the cycle together with the charges accrued in storage, fabrication, and shipping to the reactor constitute a large proportion of the start-up capital necessary to bring the system into operation. Interest due on this capital should be charged at the normal rate and capital recovery effected by means of a sinking fund operating over the design life of the system. Due allowance should be made for a scrap value on the fuel remaining in the cycle at the end of this period.

From Figure 1 the initial value of fuel comprising a single reactor core entering the closed cycle from an external source is:

$$V = C_{RM} + I_{RM} + C_F + C_{TF} ,$$

and the final value or scrap value at the end of the system life is V_S. Hence the sinking fund charge on the non-recoverable capital is:

$$C_{SF} = (V - V_S) \frac{i}{(1+i)^n - 1} \text{ cents/kWh. core (n = system life in years),}$$

and the interest payable on the initial capital V is:

$$C_I = V \times i \text{ cents/kWh. core.}$$

Therefore the inventory charge on fuel in the cycle is given by:

$$I_C = \frac{V \times i (1+i)^n - (V_S \times i)}{(1+i)^n - 1} \text{ cents/kWh. core.}$$

Now the amount of fuel circulating in the closed cycle at equilibrium is given by:

$$\text{Total number of cores} = \frac{\text{Total cycle hold-up time}}{\text{core life}} .$$

The cycle hold-up time is the sum of:

Fuel storage time	T_S	years.
Core lifetime	Life	
Cooling time	T_C	
Recycling time	T_R	

Hence the number of cores $= 1 + \frac{T_S + T_C + T_R}{Life}$.

Therefore the capital charge on the fuel cycle inventory is:

$$I_C = \left[1 + \frac{T_S + T_C + T_R}{Life}\right] \left[\frac{(C_{RM} + I_{RM} + C_F + C_{TF})(1+i)^n - V_S}{(1+i)^n - 1}\right] \times i \text{ cents/kWh,}$$

APPENDIX 2 (continued)

with the proviso that C_{RM} , I_{RM} , C_F , and C_{TF} must be calculated at the burn-up applicable to closed cycle operation.

APPENDIX 3

MISCELLANEOUS RELATIONSHIPS

1. Calculation of Core Life

Lifetimes are normally expressed in this report as years of actual operation at a given core load factor. When expressed in days a load factor of unity is assumed.

Now 1g of fuel contains:

$$\frac{M_1}{M_1 + M_2 \times X2 + M_3 \times X3} = \frac{M_1}{R} \text{ g of fissile oxide.}$$

(M_1 is a mean value for the core).

$$\text{Number of fissions} = \text{F.I.F.A.} \times \frac{M_1}{R} \times \frac{6.02 \times 10^{23}}{M_1} \text{ fissions per g of fuel at full burn-up.}$$

$$\text{Therefore the energy released (200 MeV per fission)} = \frac{200 \times \text{F.I.F.A.} \times 6.02 \times 10^{23}}{R} \text{ MeV/g}$$

$$= \frac{19.26 \times 10^{12} \times \text{F.I.F.A.}}{R} \text{ watt-sec/g.}$$

$$\text{Also, the energy released} = \frac{P \times 10^6}{\eta_c} \times \frac{\text{Life} \times LF \times 365 \times 24 \times 3600}{W_C \times 10^3}$$

$$= 3.15 \times 10^{10} \times \frac{P \times \text{Life} \times LF}{W_C \times \eta_c} \text{ watt-sec/g,}$$

$$\text{and hence, since} \quad W_C = \frac{P \times \rho_f (1-c) \times 10^3}{\eta_c \times PD} \text{ kg,}$$

$$\text{the life} = 6.12 \times 10^5 \times \frac{\text{F.I.F.A.} \times \rho_f (1-c)}{R \times PD \times LF} \text{ years.}$$

2. Conversion of Fuel Cost to Power Cost

Conversion of fuel cost to power cost may proceed as follows:

(a) For fuel cost in \$/core

$$\text{cents/kWh} = \frac{\$}{\text{core}} \times \frac{\text{cores}}{\text{kWh}} \times \frac{\text{cents}}{\$}$$

$$= \frac{\$}{\text{core}} \times \frac{100}{P \times 10^3 \times LF \times 365 \times 24} \times \frac{1}{\text{Life}}$$

$$= \frac{\$}{\text{core}} \times \frac{100}{P \times 10^3 \times LF \times 365 \times 24} \times \frac{R \times PD \times LF}{6.12 \times 10^5 \times \text{F.I.F.A.} \times \rho_f (1-c)}$$

$$= \frac{\$}{\text{core}} \times 1.87 \times 10^{-11} \times \frac{R \times PD}{P \times \text{F.I.F.A.} \times \rho_f (1-c)}$$

(b) For fuel cost in \$/kg of fuel entering the reactor

$$\text{cents/kWh} = \frac{\$}{\text{kg}} \times \frac{\text{kg}}{\text{core}} \times \frac{\text{cores}}{\text{kWh}} \times \frac{\text{cents}}{\$}$$

APPENDIX 3 (continued)

$$= \frac{\$}{kg} \times \frac{P\ \rho_f\ (1-c)10^3}{PD \times \eta_c} \times 1.87 \times 10^{-11} \times \frac{R \times PD}{P \times F.I.F.A. \times \rho_f (1-c)}$$

$$= \frac{\$}{kg} \times 1.87 \times 10^{-8} \times \frac{R}{F.I.F.A. \times \eta_c} \quad .$$

3. Calculation of Fuel Throughput

Calculation of fuel throughput considers the mean fuel flow rate in the cycle at a given core load factor:

$$T_y = \frac{W_C}{Life} \times \frac{P_T}{P}$$

$$= \frac{P_T \times \rho_f\ (1-c) \times 10^3}{PD \times \eta_c} \times \frac{R \times PD \times LF}{6.12 \times 10^5\ F.I.F.A. \times \rho_f\ (1-c)}$$

$$= \frac{P_T \times LF \times R}{612 \times F.I.F.A. \times \eta_c} \quad \text{kg per year at the given load factor.}$$

$$T_D = \frac{4.48 \times 10^{-6}}{F.I.F.A. \times \eta_c} \times P_T \times R \quad \text{kg per day (design rate)} \ .$$

APPENDIX 4

SYMBOLS USED IN FUEL CYCLE COST EQUATIONS

A	=	fissile worth factor	
C_1	=	cost of fissile material (unfabricated)	$ per g
C_2	=	cost of fertile material (unfabricated)	$ per kg
C_3	=	cost of moderator (unfabricated)	$ per kg
c	=	core voidage fraction	
C_D	=	open cycle spent fuel disposal charge	cents per kWh
C_F	=	fabrication charge	cents per kWh
C_{MU}	=	closed cycle raw material make-up charge	cents per kWh
C_R	=	closed cycle reprocessing and refabrication charge	cents per kWh
C_{RM}	=	open cycle raw material charge	cents per kWh
C_{TD}	=	shipping charge for open cycle fuel en route to disposal	cents per kWh
C_{TF}	=	shipping charge for open cycle fuel en route to reactor	cents per kWh
C_{TP}	=	shipping charge for closed cycle fuel en route to reprocessing and refabrication	cents per kWh
C_{TR}	=	shipping charge for closed cycle fuel en route to reactor	cents per kWh
D	=	cost of canning spent open cycle fuel	$ per kg
F_1	=	fractional fissile recovery from reprocessing and refabrication	
F_2	=	fractional fertile recovery from reprocessing and refabrication	
F_3	=	fractional moderator recovery from reprocessing and refabrication	
F_C	=	weight fraction of fissile isotopes in fissile raw material	
F.I.F.A.	=	fissions per initial fissile atom	
i	=	fractional interest rate	
I_C	=	closed cycle inventory charge	cents per kWh
I_{MU}	=	closed cycle raw materials make-up inventory charge	cents per kWh
I_R	=	open cycle reactor inventory charge	cents per kWh
I_{RM}	=	open cycle raw material inventory charge	cents per kWh
Life	=	actual core life at a given load factor	years
LF	=	fractional load factor for reactor operation	
m	=	initial fissile material in a new core	g

APPENDIX 4 (continued)

M_1	=	molecular weight of fissile component	
M_2	=	molecular weight of fertile component	
M_3	=	molecular weight of moderator	
n	=	system lifetime	years
P	=	net power output from a single reactor	MWe
P_T	=	total system installed capacity	MWe
PD	=	thermal power density in the core	MW per m^3
R	=	$M_1 + M_2 \times X2 + M_3 \times X3$	
RF	=	recovery fraction = $\frac{\text{fissile discharged}}{\text{fissile charged}}$	
T_C	=	total hold-up time for fuel in a reactor cooling pond	years
T_D	=	design rate of fuel supply to reactors	kg per day
T_{MU}	=	total hold-up time for closed cycle raw materials make-up	years
T_R	=	total hold-up time for closed cycle fuel between cooling pond and reactor storage	years
T_{RM}	=	total hold-up time for open cycle raw materials in storage, fabrication, and shipping	years
T_S	=	total hold-up time for fuel in a reactor storage facility	years
T_y	=	actual mean rate of fuel supply to reactors	kg per year
V	=	value of open cycle fuel entering reactor fuel storage	cents per kWh
V_D	=	value of open cycle fuel leaving the reactor cooling pond	cents per kWh
V_S	=	scrap value of closed cycle fuel in the system at the end of its design life (n years)	cents per kWh
W_C	=	weight of an initial core	kg
X2	=	fertile/fissile atom ratio	
X3	=	moderator/fissile atom ratio	
η_c	=	overall fractional net station efficiency	
ρ_f	=	fuel density averaged over the fuel elements	g per ml

TABLE 1

H.T.G.C.R. FUEL CYCLE COSTING DATA

(a) Parameter	Units	Open Cycle	Closed Cycle	(a) Parameter	Units	Open Cycle	Closed Cycle
c		0.4	0.4	n	yr	n.a.	50
C_1	$ per g	10	10	P	MWe	206	206
C_2	$ per kg	10	10	R		43,633	41,000
C_3	$ per kg	16	16	RF		0	0.875
D	$ per kg	3	n.a.	T_C	yr	0.33	0.33
PD	MW per m^3	11	11	T_{MU}	yr	n.a.	0.33
F_1		0	0.95	T_R	yr	n.a.	0.17
F_3		0	0.80	T_{RM}	yr	0.33	n.a.
F_C		0.83	0.83	T_S	yr	0.17	0.17
F.I.F.A.		1.4	1.0	V_S	cents per kWh	n.a.	C_{RM} (b)
i	per yr	0.06	0.06	X2		8	23.6
LF		0.8	0.8	X3		1,650	1,380
M_1		271	266	η_c		0.40	0.40
M_2		264	264	ρ_f	g per ml	3.14	3.14
M_3		25	25	A		1.0	1.0

n.a. = not applicable

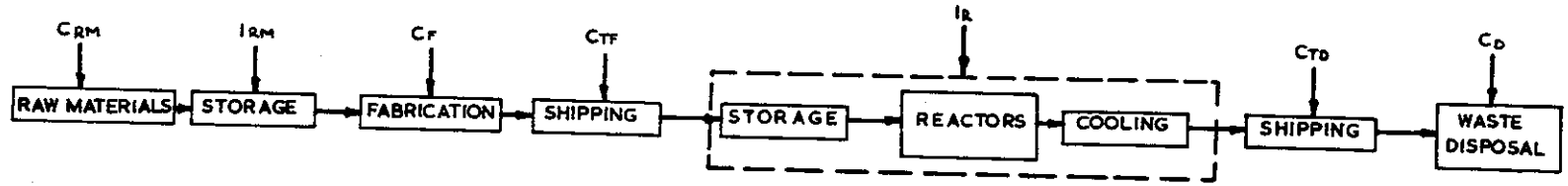
(a) For definitions of all parameters, see Appendix 4

(b) See Figure 1

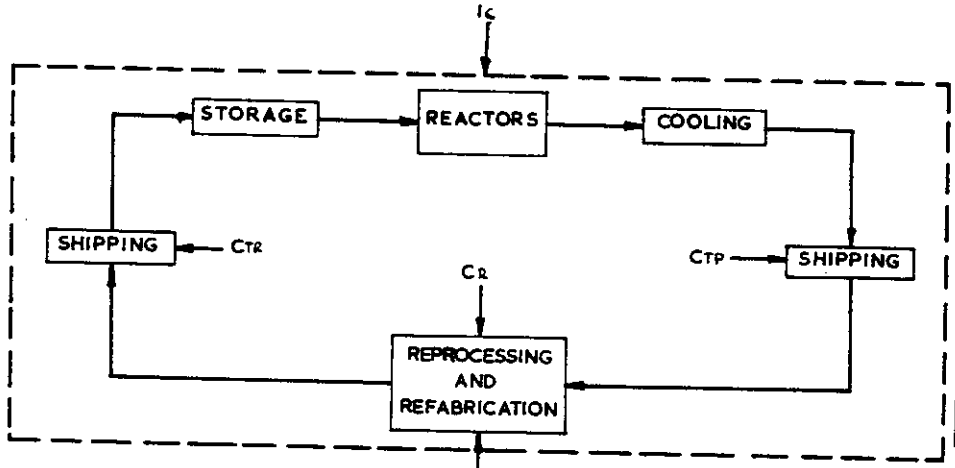
TABLE 2

FUEL CYCLE COSTS FOR SEVERAL SYSTEM SIZES (cents/kWh)

Cost Component (See Figure 1)	Installed Capacity of 206 MWe Reactors (MWe)			
	206	618	1442	3090
C_{RM}	0.132	0.132	0.132	0.132
I_{RM}	0.003	0.003	0.003	0.003
C_F	0.034	0.024	0.019	0.016
I_R	0.023	0.022	0.021	0.021
C_D	0.004	0.004	0.004	0.004
Open Cycle Fuel Cost C_O	0.196	0.185	0.179	0.176
C_{MU}	0.031	0.031	0.031	0.031
I_{MU}	0.001	0.001	0.001	0.001
C_R	0.385	0.165	0.086	0.048
I_C	0.017	0.016	0.015	0.015
Closed Cycle Fuel Cost C_C	0.434	0.213	0.133	0.095



OPEN CYCLE



CLOSED CYCLE

FUEL CYCLE COST COMPONENTS

OPEN CYCLE	C_o	CLOSED CYCLE	C_c
RAW MATERIALS	C_{RM}	MAKE UP MATERIALS	C_{MU}
STORAGE	I_{RM}	STORAGE	I_{MU}
FABRICATION	C_F	REPROCESSING AND REFABRICATION	C_R
SHIPPING TO REACTORS	C_{TF}		
REACTOR INVENTORIES	I_R	SHIPPING TO REACTORS	C_{TR}
SHIPPING TO DISPOSAL	C_{TD}	SHIPPING FROM REACTORS	C_{TP}
DISPOSAL	C_D	CYCLE INVENTORY	I_C

FIGURE 1. BLOCK DIAGRAM SHOWING FUEL CYCLE COST COMPONENTS FOR AN H.T.G.C.R. FUEL CYCLE

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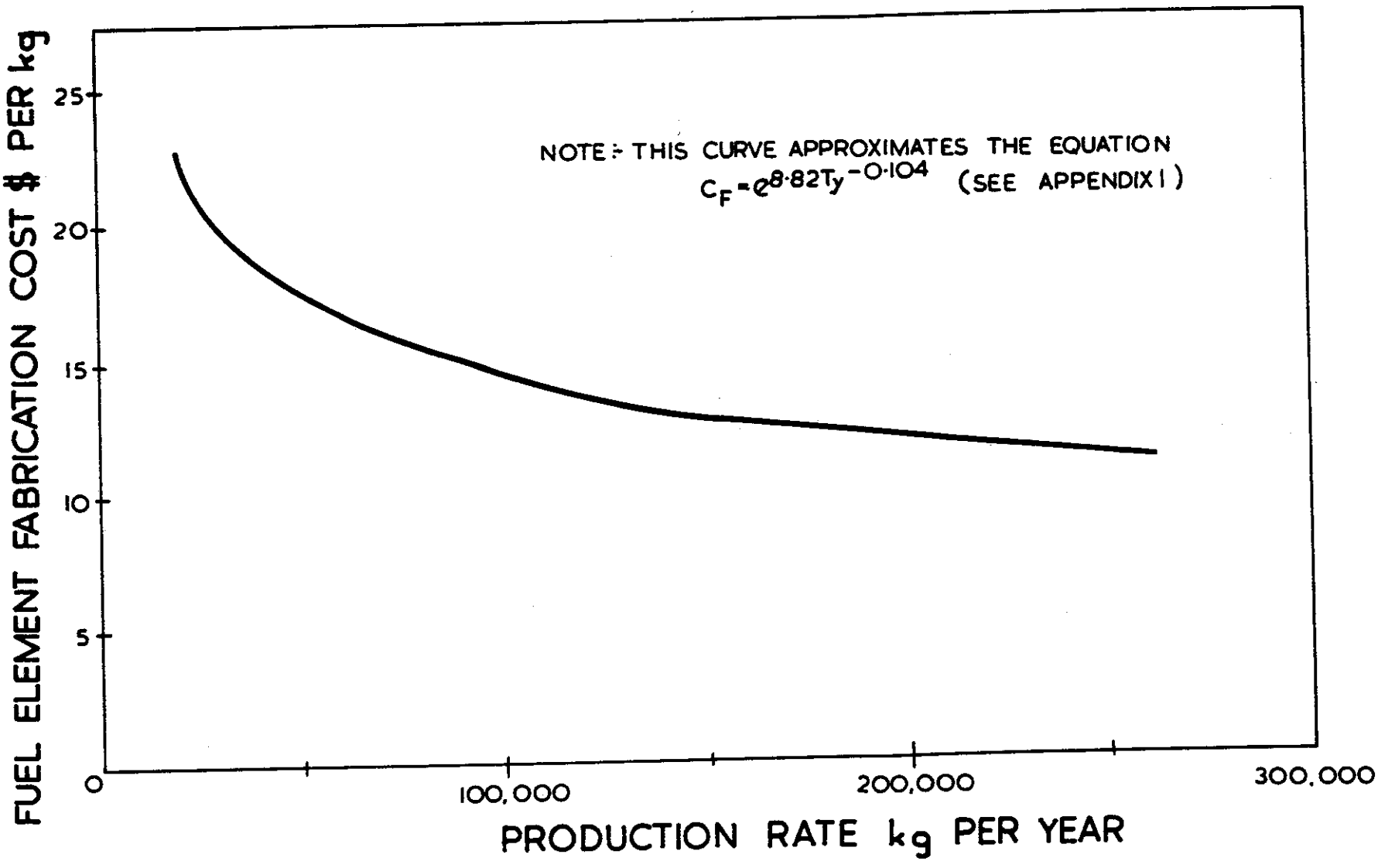

FIGURE 2. COST OF FUEL FABRICATION FOR THE H.T.G.C.R.

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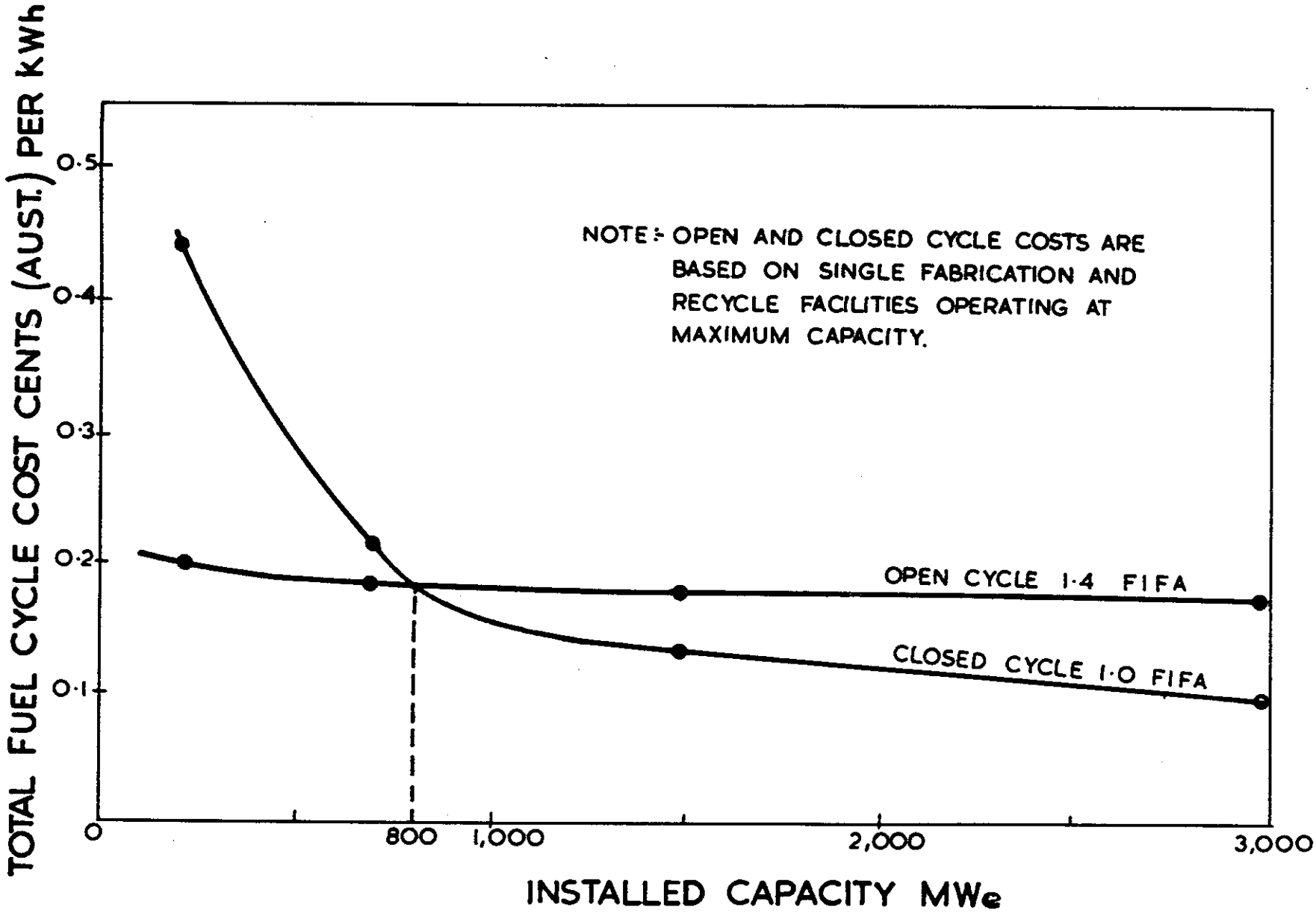

FIGURE 3. COMPARISON OF FUEL CYCLE COSTS FOR THE H.T.G.C.R.

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