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CENTRAL FILES NUMBER
CF-59 - 2 - 57

DATE: February 20, 1959 COPY NO. 22

SUBJECT: The Nuclear Fuel Cycle: Prospects for Reducing Its Cost

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Abstract

Nuclear fuel cost of 1.25 mills/kwh would make nuclear power competitive with conventional power in low-cost coal areas if capital and operating costs can be brought to within about 10 percent of those of coal-fired plants. Substantial decreases in fuel fabrication cost are anticipated by 1970; other costs in the fuel cycle are expected to remain about the same as at present. Unit costs and irradiation levels that would be needed to give a fuel cost of 1.25 mills/kwh are believed to be attainable by 1970.

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THE NUCLEAR FUEL CYCLE: PROSPECTS FOR REDUCING ITS COST

1.0 Summary

If nuclear power is to compete with power from coal, nuclear fuel cost must be reduced below the cost of coal in order to offset the probable higher capital and operating costs of the nuclear plant. Fuel cost can be reduced by increasing plant thermal efficiency and fuel irradiation level, and by reducing unit costs in the fuel cycle.

Fabrication of fuel elements, including conversion of UF_6 to final fuel material, is one of the high-cost steps in the fuel cycle. It seems likely that this cost can be decreased to a fraction of present levels through better fuel element design and more efficient production techniques. The costs of the other steps in the fuel cycle, of which the largest are spent fuel re-enrichment and reprocessing, probably will not decrease significantly by 1970.

If the capital and operating costs of nuclear plants can be brought to within 10 percent of those of coal-fired plants, a nuclear fuel cost of 1.25 mills/kwh would make the nuclear plant competitive with low-cost coal. Reductions in unit costs alone will not be enough to give 1.25 mills/kwh fuel cost. Average irradiation levels will have to be upwards of about 15,000 Mwd/tonne in order to achieve this goal. To get such irradiation levels with low enrichment fuel, the fuel will have to be rearranged in the reactor quite frequently—once per year or oftener—in order to maintain reactivity. This means that a good fuel-charging machine will be required. Obviously also, the fuel elements themselves must be capable of standing up under such irradiation.

To achieve low fuel cost by 1970, efforts should be concentrated on development of (a) improved fuel element designs, (b) improved techniques for producing fuel elements, and (c) efficient fuel-charging machines.

2.0 Introduction

It has often been stated that if nuclear power is to compete with power from coal, nuclear fuel cost must be reduced substantially below coal costs. The reason is that capital and operating costs are expected to be higher than those for coal-fired plants. If nuclear power is to cost the same as or less than power from coal, therefore, it must be because the nuclear fuel is cheaper than coal.

Right now nuclear fuel cost exceeds the cost of even the highest-priced coal in the United States. Drastic reductions are necessary if it is to compete in low-cost coal areas.

The purpose of this paper is to examine nuclear fuel costs to see what they are and how they can be reduced. To avoid getting too far into the future, the discussion is concerned primarily with the period 1970. A constant value of the 1958 dollar is assumed.

3.0 The Fuel Cycle

Nearly all of the power reactors in being or planned for early construction in the United States use the U^{235}-U^{238} fuel cycle. A relatively few reactors will use other combinations of fissionable and fertile materials, such as enriched uranium and thorium or natural uranium and plutonium.

In this paper, the discussion of fuel cycles is confined largely to the U^{235}-U^{238} cycle for three reasons. First, more is known about this cycle than the others. Second, it is likely to be the most widely used during the period covered here. Third, most of the things that will reduce costs for the U^{235}-U^{238} cycle will do the same for other cycles.

The U^{235}-U^{238} cycle is shown schematically in Fig. 3-1.

Spent fuel discharged from the reactor is sent to storage, where it is held for 3 or 4 months prior to shipment to a chemical processing plant. There plutonium and uranium are separated from each other and from fission products and clad material. Plutonium is sold to AEC. Recovered uranium in the form of uranyl nitrate solution is converted to uranium hexafluoride, which is fed to a gaseous diffusion plant. In the diffusion plant, the uranium is enriched in U^{235} content to the level required for the reactor. The re-enriched uranium hexafluoride next is converted to the form used in the reactor; for most power reactors, uranium dioxide is the fuel material. Finally, the fuel is fabricated into fuel elements.

4.0 Typical Fuel Cycle Cost

In order to have a basis for discussion of fuel cycle costs, the estimate for the ORNL Gas-Cooled Reactor (GCR-2) is presented in Table 4-1; this may be regarded as fairly representative of the U^{235}-U^{238} cycle. The estimate was developed by TVA in a review of this reactor design.[1]

The fuel cost for a coal-fired plant of similar size (225 Mw electric) in a low-cost coal area such as the Tennessee Valley would be about 1.8 mills/kwh.[2] If a total power cost of 6 mills/kwh is assumed, and if it is further assumed that the capital and operating costs of the nuclear plant can be brought to within 10 percent of those of the coal-fired plant, then a fuel cost of 1.25 mills/kwh would make the nuclear plant competitive.

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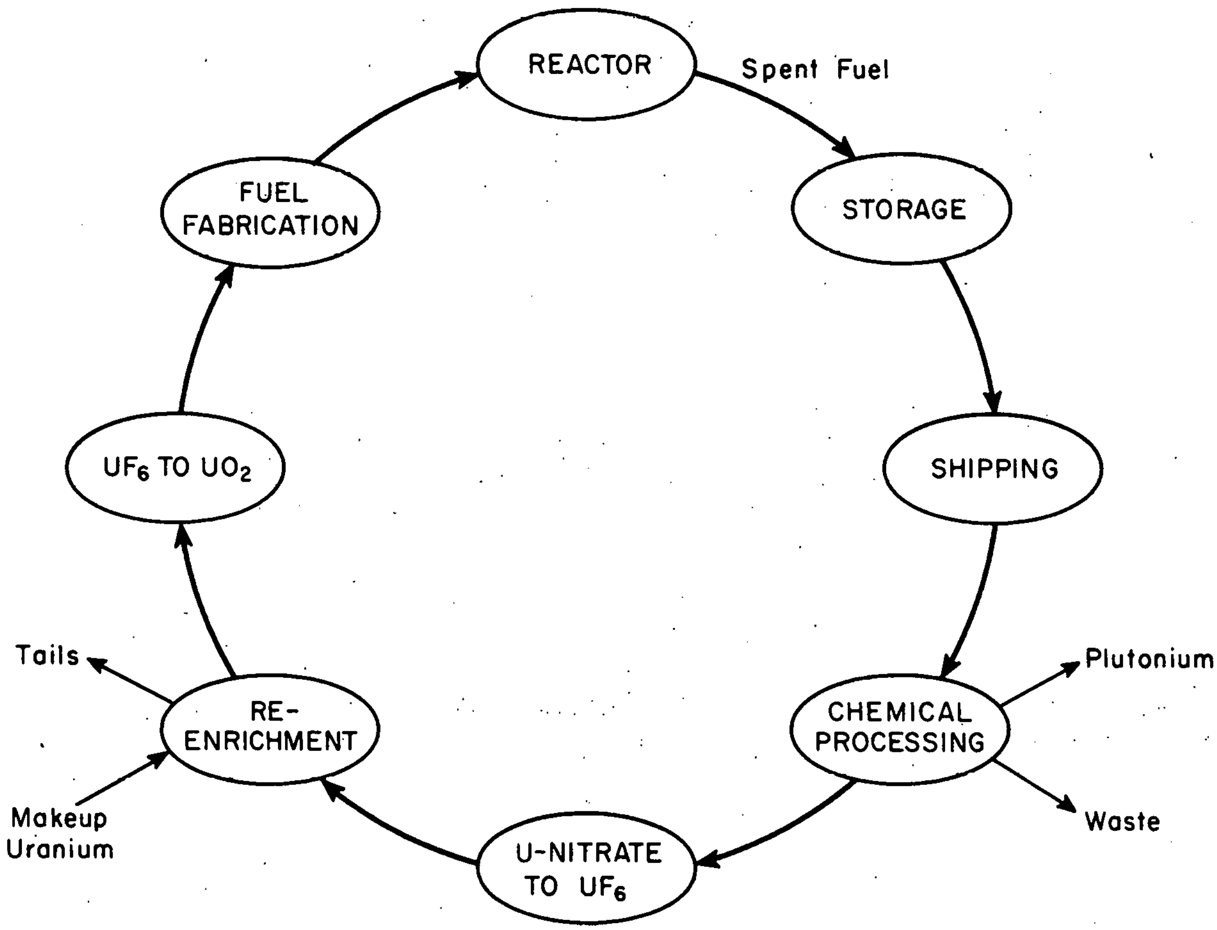

Fig. 3-1. The U^{235}-U^{238}, slightly enriched Uranium fuel cycle.

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Table 4-1

Estimated Fuel Cycle Costs for ORNL Gas-Cooled Reactor

(Based on 7400 Mwd/tonne U and 32.8% net thermal efficiency.)

	Cost, $/kg U	Cost, Mills/kwh
Storage and shipment of spent fuel	3	0.05
Chemical processing	22	0.37
Conversion, U nitrate to UF_6	6	0.10
Re-enrichment minus plutonium credit	58	1.02
Conversion, UF_6 to UO_2 powder	26	0.46
UO_2 pellets	8	0.14
Fabrication of replacement fuel elements	16	0.28
Out-of-pile inventory	7	0.12
	146	2.54

5.0 Ways in Which Fuel Cost Can Be Reduced

The equation for determining fuel costs in terms of mills/kwh indicates the ways in which these costs can be reduced.

$$\text{Cost, mills/kwh} = \frac{\text{unit cost, \$/kg U x kg U/yr x } 10^3 \text{ mills/\$}}{\text{irradiation level, kwd/kg U x kg U/yr x 24 hr/day x Th Eff}}$$

It is apparent that fuel cycle costs can be reduced by decreasing the unit costs of the various steps, by increasing irradiation level, and/or by increasing plant thermal efficiency. The amount of fuel handled annually does not affect fuel cycle cost except insofar as it affects unit cost.

Thermal efficiency is determined by reactor and fuel element design. Once these have been fixed, this factor in the equation is set. The maximum irradiation level for the fuel (reactivity lifetime) also is established by reactor and fuel design. Reactivity lifetime, in general, increases with increased fuel enrichment, increased fuel inventory, decreased poison fraction, and decreased moderator temperature. Continuous fuel loading give maximum reactivity lifetime, and mixed loading gives a higher lifetime than simple batch loading. Figure 5-1 shows the effect of irradiation level on the fuel cycle costs of the ORNL Gas-Cooled Reactor.

The ideal fuel element has sufficient integrity to remain intact over the entire reactivity lifetime. It need not have a lot of excess strength; this would be undesirable if it added to the cost of the fuel.

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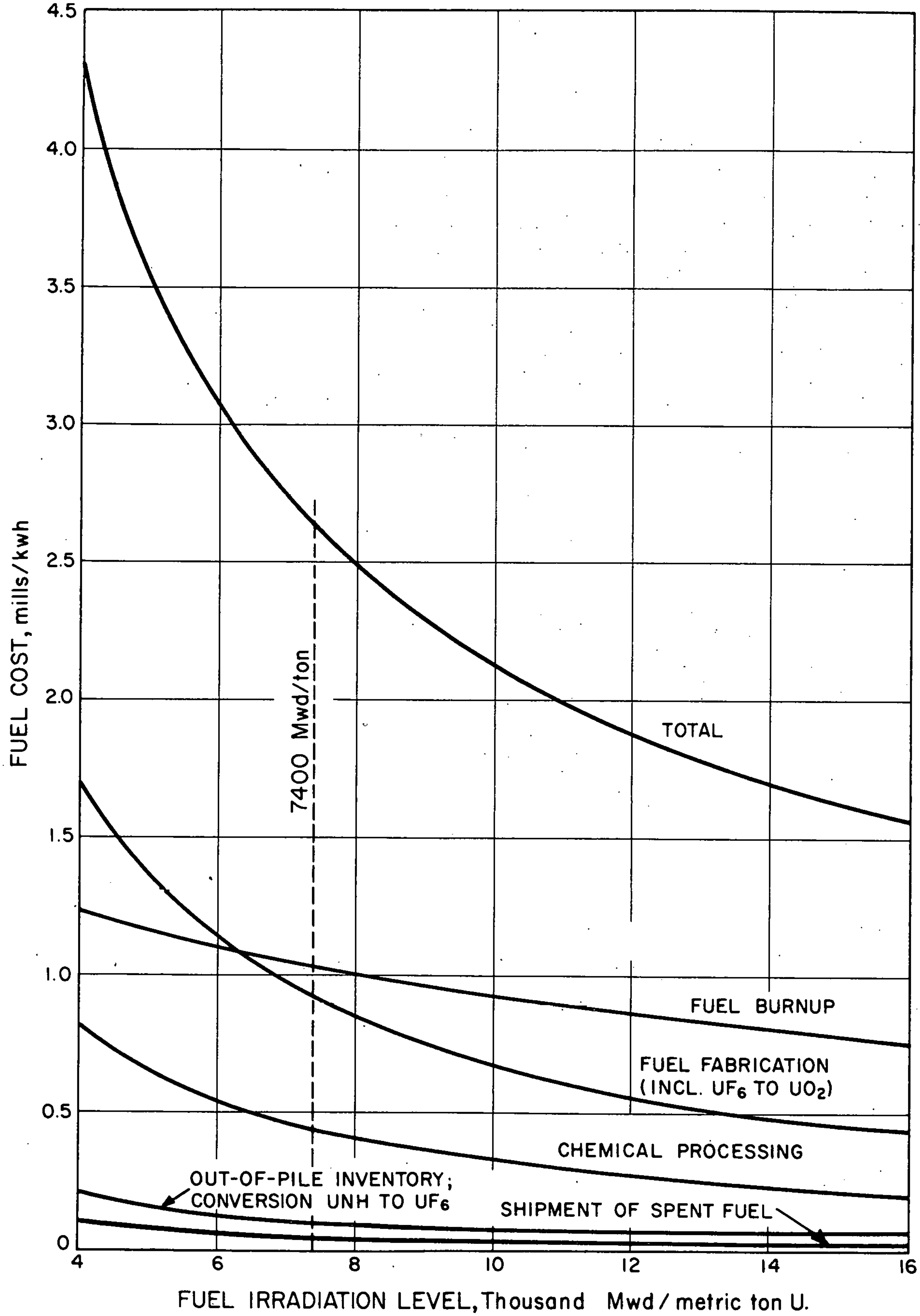

Fig. 5-1. Variation of fuel cost with fuel irradiation for the ORNL GCR-2.

Other than providing fuel elements of adequate integrity, those concerned primarily with the fuel cycle cannot contribute much toward reducing fuel cycle costs through increased thermal efficiency and irradiation level. Fuel cycle people are concerned mainly with the unit costs of the operations they carry out. These unit costs are discussed next.

6.0 Unit Fuel Cycle Costs

Unit costs can be reduced by (a) improved technology and, (b) increased volume of business. It is believed that, for the period to 1970, the volume of business will have a greater effect on unit costs than will technological advances. Nonetheless, it is very important that efforts be directed toward improving the technology of the various steps in the fuel cycle.

Each of the steps in the fuel cycle is discussed below from the standpoint of the possibilities of reducing its cost.

6.1 Storage of Spent Fuel

Spent fuel is stored for a period of about 90 to 120 days in order to (a) allow fission product activity to decay, (b) allow neptunium-239 to decay to plutonium-239, and (c) allow uranium-237 to decay. Decay of U^{237} governs the time of storage; in 120 days this activity is low enough that the uranium, after separation from fission products and plutonium, can be handled directly. In this time, fission product activity is reduced by a factor of 50 to 100; this reduces problems in shipping the spent fuel to the reprocessing plant.

The cost of storage is made up of amortization of equipment, uranium inventory charges, and operation and maintenance costs. For the ORNL-GCR-2,[1] these costs amount to about 0.06 mills/kwh. This is not included in the first item of Table 4-1, since storage equipment costs are included with other capital items, inventory charges are included in the last item in Table 4-1, and operation and maintenance costs are included with operation and maintenance for the entire plant.

The design of storage facilities presents no unusual problems. Fuel elements are usually stored in water-filled canals; the water provides shielding and serves to remove heat generated by radioactive decay.

The use of spent fuel elements as a radiation source might be a source of revenue, if a customer for the radiation can be found. This revenue could reduce spent-fuel storage cost, and perhaps even provide a small credit to this item. Other than this possibility, no reduction in storage cost is anticipated.

6.2 Shipment of Spent Fuel

It is unlikely that any one reactor station will be large enough to support its own chemical processing facility for many years to come. Spent fuel, therefore, must be shipped to a central processing plant. The fuel is shipped in heavy lead-shielded containers equipped with means for cooling the fuel en route.

The spent fuel carriers may weight 15 or more times as much as the fuel contained in them; their cost will be in the neighborhood of 50-75 cents/lb. Thus, a carrier capable of holding 1 tonne of fuel would cost more than $15,000. To minimize uranium inventory charges during shipment, a number of carriers would be needed; for the GCR-2, it was estimated[2] that 14 would be the optimum number of carriers for shipping 28 tonnes of U annually.

Shipping cost for the GCR-2 was estimated[2] at about 0.05 mills/kwh, not including cost of carriers; carrier cost is included with other capital items. The shipping cost figure was based on shipment over a distance of 2700 miles (to Hanford, Washington from a site in east Tennessee) at a round-trip rate of $5.30/100 lb. The estimate is very uncertain because freight rates on this type of shipment have not been established.

Shipping cost will depend on the distance the fuel is to be shipped, and upon the rates that can be negotiated with railroads and truck lines. Container costs are closely tied to the price of lead. The direction shipping cost will take in the future is not known. It is likely, however, it will be but a small fraction of the total fuel cycle cost.

6.3 Chemical Processing

In chemical processing, the fuel is dissolved and is treated by solvent extraction to separate fission products and clad material from the uranium and plutonium, and to separate these elements from each other. Alternatively, clad material may be removed chemically or mechanically before the fuel is dissolved.

Solvent extraction will be the dominant processing method during the period to 1970. The volatility and pyro processes need a lot of development before they can come into widespread use.

Chemical processing is one of the costlier items of the fuel cycle. The figure in Table 4-1 of 0.37 mills/kwh, corresponding to $21.40/kg U, is based on AEC's chemical processing charge formula. For batches of 8 tonnes or more of slightly enriched uranium, the base charge is equal to $15,300 times the number of short tons U plus 8. To the base charge is added a charge equal to 1 percent of the value of the uranium and plutonium recovered to take care of process losses.

The AEC processing charge at present is considerably below the charge that a private company would have to make for a similar service, considering the small volume of business to be handled over the next few years. C. E. Guthrie[5] has estimated that in order to reprocess spent fuels for 0.35 mill/kwh (at 8000 Mwd/tonne irradiation level), a 6 tonne/day plant operating at capacity would be required. An installed nuclear power capacity of 48,000 Mw heat would be needed to keep the plant busy. This power level might be attained by 1968-1973, depending on whose predictions are chosen.

AEC has stated that it would get out of the reprocessing business when private industry was ready to do the job at a "reasonable" price. "Reasonable" could, presumably, mean something above the AEC price — say, 10 or 20 percent. It is improbable that a private processor would enter the business before about 1968. The first processor probably would have the field to himself for a few years at least, and would not have the pressure of competition to induce him to reduce his charges. It may be concluded, therefore, that no decrease in chemical processing charges can be anticipated by 1970. Instead, an increase of about 20 percent might be forthcoming. After 1970, competition might lead to a reduction in processing charges.

6.4 Plutonium Credit

Until such time as it becomes technically and economically feasible to recycle it to the reactor, plutonium will be sold to AEC. AEC has announced that it will pay $30/gram of plutonium metal (of the isotopic grade that will be produced in power reactors) until June 30, 1963. Not many power reactor owners, however, will be able to take advantage of this attractive price. Although AEC's intentions regarding the price after that date are not known, it is generally assumed that the price will drop to $12/gram. The latter figure was used in arriving at the plutonium credit for the fourth item in Table 4-1.

It is difficult to set a figure for the true value of plutonium. The $12/gram figure was arrived at through a comparison of the fuel value of plutonium-239 with that of uranium-235 for one particular initial enrichment and irradiation level. A different figure would be developed with a different set of reactor conditions. The isotopic analysis of the plutonium also has a considerable effect on its fuel value.

The plutonium credit figure is for plutonium metal. The cost of converting the plutanyl nitrate recovered in the processing plant must also be paid for by the reactor owner. The AEC suggests a cost of $1.50/gram Pu for this conversion. Since each kg of recovered U contains around 5 grams Pu, this amounts to about $8/kg U. The conversion cost might be reduced to about one-third—say, $3/kg U—in large-scale plants.[6]

Unless the government fixes a price of $12/gram of plutonium, it is believed that plutonium credit is more likely to decrease below $12/gram after June 30, 1963 than it is to increase. The net result, of course, would be an increase in fuel cycle cost.

6.5 Conversion of Uranyl Nitrate to Uranium Hexafluoride

Conversion of the uranyl nitrate solution discharged from the chemical processing plant includes the steps of (a) evaporation and calcination to produce UO_3, (b) reduction with hydrogen to UO_2, (c) treatment with anhydrous

HF to produce UF_4, and (d) treatment with fluorine to yield UF_6.

In the absence of commercial facilities, AEC has announced it would carry out the conversion in its facilities. The charge for the service will be $5.60/kg U for enrichments under 5 percent.

The capital required for a plant to carry out this conversion would be much less than a spent-fuel reprocessing plant. It is possible, therefore, that private processors would undertake this operation within a few years. Competition may be expected sooner for this conversion step than for the reprocessing step. Conversion costs of around $3/kg U[6] may be achieved by 1970.

6.6 Re-enrichment

The recovered uranium may be re-enriched to the initial U^{235} content by blending with highly enriched uranium, by blending with partially enriched uranium, or by feeding the recovered uranium to a gaseous diffusion plant. The latter method has the advantage that some of the U^{236} in the recovered material is removed in the gaseous diffusion plant. Blending with partially enriched uranium may have some advantage in cost.[8] For a given irradiation level, re-enrichment cost varies directly with initial enrichment. It is advantageous, therefore, to design the reactor system for minimum enrichment.

It is very unlikely that gaseous diffusion plants will be owned by private companies in the foreseeable future, if ever. Enriched uranium prices, therefore, will continue to be set by the government. It is not known in which direction these prices will go in the future. The present price schedule is based only on the U^{235} content, and is not affected by the U^{236} content. The presence of U^{236} increases the cost of the gaseous diffusion operation, so it seems likely that someday AEC will take U^{236} content into account in the pricing of uranium, thereby increasing the cost of re-enrichment.

6.7 Conversion of Uranium Hexafluoride to Uranium Dioxide

The conversion of UF_6 to UO_2 includes the steps of (a) hydrolyzing the UF_6 in water, (b) adding ammonium hydroxide to precipitate ammonium diuranate, (c) filtering the diuranate and calcining to U_3O_8, and (d) reducing the U_3O_8 with hydrogen to form UO_2.

This is one of the high-cost steps in the fuel cycle. The cost appears to be reducible. Quotations received by TVA[2] averaged $22/kg U and ranged from $14 to $29/kg U for this step. These prices were for a quantity of about 135 tonnes U; the figure of $26 given in Table 4-1 is for 28 tonnes, the amount replaced annually. The prices are not too surprising when it is considered that present operations are carried out on a small scale by batch methods.[7] With larger scale operation using continuous methods, substantial cost reductions should be attained by 1970. Opinions differ as to the amount of the reduction; one source[6] predicts $10/kg U, another[11] looks for future costs of $2.50-$5.50/kg U for slightly enriched uranium.

UO_2, of course, is not the only possible fuel for reactors. Other compounds or alloys of uranium may become the preferred materials in the future. Conversion costs for these materials, too, will be affected by the scale of operations and by the processing method. Without knowing what the final material may be, one may hazard a guess that conversion costs would be about $10/kg U or less by 1970.

6.8 Pelletizing Uranium Dioxide

Quotations to TVA[2] on pellet manufacture ranged from $2 to $20/kg U and averaged $7/kg U. At the present time, costs at about the middle of this range seem reasonable, due to low production rate and batch processing methods. Costs of $2/kg U by 1970 do not seem improbable.

6.9 Clad Manufacture and Assembly of Fuel Elements

Clad manufacture and assembly of fuel elements is the largest cost item in the fuel cycle for most reactors. In the case of the ORNL-GCR-2 stainless-clad elements it was surprisingly small, ranging from $10 to $30/kg U,[2] not including UO_2 cost. Considering AEC's proposed guarantees to Euratom,[9] it is likely that fabrication costs in the neighborhood of $70/kg for stainless-clad elements are more in line with present conditions (taking cost of converting UF_6 to UO_2 pellets at $30/kg U, and assuming that the published figure of $100/kg includes this conversion). Zirconium-clad elements, at present, cost around $30 to $40/kg U more than stainless-clad elements.[9] This difference will doubtless decrease as the consumption of zirconium increases and as techniques for producing and fabricating it are improved, but there will always be some disparity.

One reason present fabrication costs are high is that production is low. There is not enough business to warrant investment in automatic machinery to mass-produce fuel elements. Designs for fuel elements are not standardized, and are not particularly well adapted to mass production. By 1970, however, the demand for fuel elements will be much greater than it is now, and quite probably reactor designers will have settled on fewer types of elements. It is perhaps not too much to expect that fabrication costs equal to the lowest quoted to TVA on the GCR-2 elements—$10/kg U—may be achieved by 1970. The cost of cladding with zirconium might drop to around $20/kg U by then.

Fuel elements may or may not get simpler in design. If fuel inventory costs should increase for some reason, there would be even more of an incentive than there is now to get the maximum amount of heat out of a given quantity of fuel. This would tend to make fuel elements more complicated.

6.10 Out-of-Pile Inventory

The reactor owner must pay a rental charge on all the uranium he holds whether it is in or out of the reactor. The in-pile inventory charge is a fixed cost, and is usually included with annual charges on capital investment.

Out-of-pile inventory is generally regarded as a fuel cycle cost item, and it is so treated here.

Out-of-pile inventory cost is affected by (a) the amount of fuel in the reactor, (b) the enrichment of the fuel, (c) the irradiation level to which the fuel is exposed (which determines the discharge rate of the fuel), (d) the time the fuel is held outside the reactor, and (e) the rental rate for the fuel.

Factors (a), (b), and (c) are fixed by reactor design. Factor (e) is controlled by AEC. Factor (d) can be controlled to some extent by the reactor owner and those he hires to reprocess, convert, and refabricate his fuel.

The annual rental charge of 4 percent of the value of the fuel is very favorable to the reactor owner. The rate is little more than the cost of money to the federal government. If the cost of money to the government were to increase, the rental charge could be expected to increase as well.

Inventory costs would increase sharply if the government decided to sell enriched uranium instead of renting it. Then the annual charge would be more like 12 than 4 percent, depending upon the rate of return the reactor owner expects on working capital.

It is unlikely that the federal government, in its efforts to promote nuclear power, would do anything to markedly increase the cost of nuclear power. Quite probably the only increases that will be made in the factors directly controlled by the government--uranium and plutonium prices and rental rates--will be those brought about by inflation.

6.11 Total Unit Costs

Table 6-1 shows a comparison between estimated present unit fuel cycle costs for a GCR-2 and those postulated for 1970. These figures indicate that a reduction in unit costs of 20 to 25 percent may be achieved. Nearly all of the reduction is obtained in the steps comprising fabrication of replacement fuel elements. The total of the rest of the steps in the fuel cycle is about the same.

If the savings shown in Table 6-1 were realized, the GCR-2 would have a fuel cycle cost of 2 mills/kwh at an average irradiation level of 7400 Mwd/tonne. To reduce this to 1.25 mills/kwh, a large increase in irradiation level would be needed. Figure 5-1 shows that net fuel burnup cost imposes a floor in the neighborhood of 0.75 mill/kwh at high irradiation levels. With a total unit cost, not including burnup, of $59 (112-53), an irradiation level of 15,000 Mwd/tonne U would give 1.25 mills/kwh. Such an irradiation level can be attained with 2 percent enriched fuel by a mixed fuel-loading procedure (see Fig. 2.39 of reference 1).

Table 6-1

Estimated Present and Fugure Unit Fuel Cycle Costs
For ORNL Gas-Cooled Reactor

Item	Unit Cost, $/kg U	
	Present	1970
Storage and shipment of spent fuel	3	3
Chemical processing	22	26
Conversion, U nitrate to UF_6	6	3
Re-enrichment minus plutonium credit[a]	58	53
Conversion, UF_6 to UO_2 powder	26	10
UO_2 pellets	8	2
Fabrication of replacement fuel elements	16	10
Out-of-pile inventory	7	7
Total	146	112

[a]At an irradiation level of 7400 Mwd/tonne U.

The irradiation level required for 1.25 mills/kwh fuel cost varies with initial enrichment of the fuel. The 15,000 Mwd/tonne figure applies to the 2 percent enrichment of the GCR-2 fuel. For low-enrichment fuels (below about 3 percent U-235), the unit costs of most of the steps in the fuel cycle are almost independent of enrichment; criticality considerations keep them from being completely independent of enrichment. However, re-enrichment cost increases and plutonium credit decreases with increasing enrichment. Thus, to achieve a particular fuel cycle cost, a higher irradiation level must be attained with, say, a 3 percent enriched fuel than with a 2 percent enriched fuel.

7.0 Other Fuel Cycles

7.1 Pu^{239}-U^{238} and U^{233}-Th^{232} Cycles

A quantitative comparison between the costs of either of these fuel cycles and of the U^{235}-U^{238} cycle cannot be made at this time. Qualitatively, it appears that chemical reprocessing and conversion costs will be roughly the same for each of the three cycles. Fabrication costs probably will be highest for the U^{233}-Th^{232} cycle and higher for the Pu^{239}-U^{238} cycle than for the U^{235}-U^{238} cycle. This means that if the Pu^{239}-U^{238} or the U^{233}-Th^{232} cycles are to compete successfully with the U^{235}-U^{238} cycle by 1970, differences in fabrication costs must be offset by lower fuel burnup costs. Over the long range, say, by year 2000, it may become necessary to adopt one or both of the alternate cycles in order to extend supplies of fissionable and fertile materials.

8.0 Needed Emphasis in Research and Development

It was brought out above that if an average irradiation level of about 15,000 Mwd/tonne (for 2 percent U-235 fuel) can be attained and if total fuel fabrication costs can be reduced to about $22/kg U, fuel costs of the order of 1.25 mills/kwh could be attained. Research and development that will lead to attainment of these goals should be emphasized.

Development effort on fuel charging machines is needed in order to achieve high irradiation levels. Irradiation levels of the required order cannot be attained with simple batch loading of the fuel; a mixed loading procedure must be employed. Complete relocation of the entire fuel charge and replacement of part of the charge will be required at frequent intervals, perhaps annually. To minimize reactor downtime, an efficient, reliable fuel charging machine will be required. Beyond this, a machine that could remove and relocate fuel while the reactor was in operation would further increase reactivity lifetime and reduce reactor downtime.

The fuel element should be capable of standing up without failure during its entire reactivity lifetime; earlier failure is costly and could be catastrophic. Work to develop fuel integrity, therefore, should be emphasized. It appears that UO_2 pellets can withstand irradiation to as high as 25,000 Mwd/tonne U without damage.[10] What is needed, then, is a metallic or ceramic container for the fuel that will stand up under the effects of such irradiation levels. It should be realized that in order to attain a particular average irradiation level, peak levels must be several thousand Mwd/tonne higher.

A third important area for study is the development of fuel element manufacturing techniques, in both the chemical and mechanical phases. Lower cost methods are needed for carrying out chemical conversions such as UF_6 to UO_2. Pelletization and sintering operations need to be mechanized. Designs for fuel elements that lend themselves to mass production are needed. Required also are the mass-production machines themselves.

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