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Consolidated Fuel-Reprocessing Program

NUCLEAR-FUEL-CYCLE COSTS

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ABSTRACT

The costs for the "back-end" of the nuclear fuel cycle, which were developed as part of the Nonproliferation Alternative Systems Assessment Program (NASAP), are presented. Total fuel-cycle costs are given for the pressurized-water reactor once-through and fuel-recycle systems, and for the liquid-metal fast-breeder-reactor system.

These calculations show that fuel-cycle costs are a small part of the total power costs. For breeder reactors, fuel-cycle costs are about half that of the present once-through system. The total power cost of the breeder-reactor system is greater than that of light-water reactor at today's prices for uranium and enrichment.

1. INTRODUCTION

Uranium resources are limited; therefore, the unused and bred fuel remaining in irradiated fuel assemblies must be recovered and recycled into reactors in order for nuclear power to have a significant contribution to long-term energy production. Forecasts of uranium availability and demand indicate that if the present system of light-water reactors (LWR) operating on the once-through fuel cycle (Fig. 1) is continued, there will be a shortfall in uranium resources sometime in the early decades of the next century.

Nuclear fission energy can make a significant contribution to the total energy supply over a period of several centuries through the use of breeder reactors. Less than 1% of mined uranium is used as fuel in the present LWR system. The balance of the uranium, the fertile material, is converted into fissile material (i.e., fuel) in the breeder reactor. This bred fuel can be recovered and recycled in what has come to be known as the "back-end" of the nuclear fuel cycle (see shaded area of Fig. 1). In the back-end of the cycle, irradiated fuel assemblies are removed from the reactor, briefly stored, and then sent to a reprocessing plant where the fuel is dissolved and purified and the ratio of fissile fuel to fertile material is

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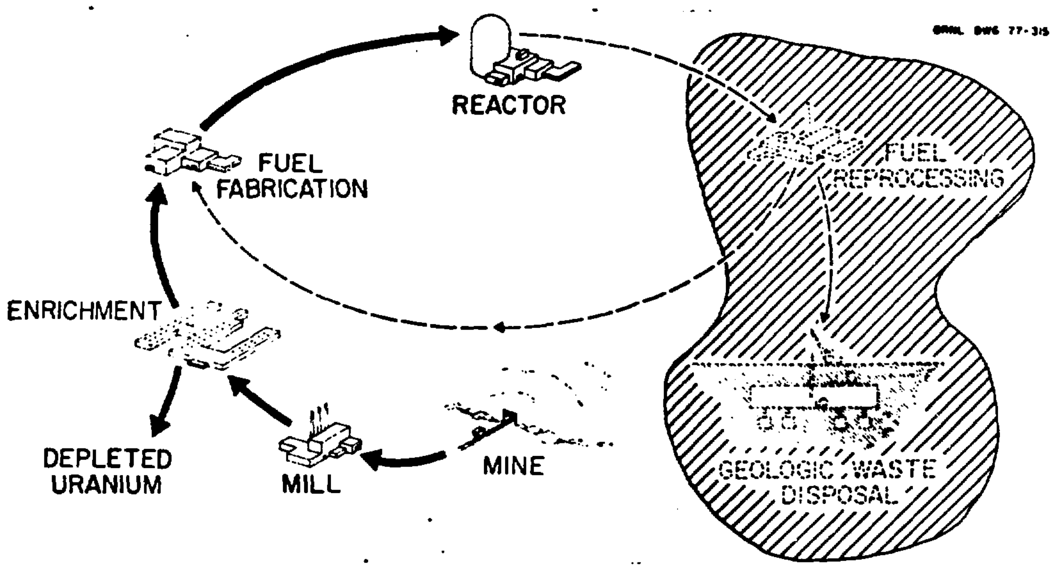

Fig. 1. The light-water reactor fuel cycle today.

adjusted. This material is refabricated into new fuel assemblies and reinserted into breeder reactors. The radioactive wastes from the processes are then collected and sent to a permanent repository.

The economics of the nuclear fuel cycle is an important consideration in making choices from prospective energy systems. This paper presents the costs of the back-end of the nuclear fuel cycle which were obtained by the Alternative Fuel Cycle Evaluation Program (AFCEP).[1] The AFCEP was initiated to compile information in support of the NASAP; NASAP was initiated to develop and coordinate a program of technical studies and analyses which would contribute to the International Nuclear Fuel Cycle Evaluation (INFCE). For the sake of completeness, costs of the front-end of the nuclear fuel cycle are developed and added to reactor costs. (The front-end of the cycle consists of those components connected by the solid arrows in Fig. 1.) Total power costs of once-through and closed fuel cycles are presented and compared.

2. ASSUMPTIONS AND METHODOLOGY USED IN CALCULATING COSTS

The components of the front-end of the nuclear fuel cycle – acquiring the ore and forming it into fuel as feed to a reactor – exist commercially. Hence, these costs are well known. The method used in this study consisted of obtaining current prices for each component (in terms of dollars per mass unit of heavy metal) from the literature and multiplying those prices by the equilibrium yearly amount of fuel required to sustain a reactor. This total cost was then divided by the number of kilowatt hours produced by the reactor during the year to obtain the mills per kilowatt hour cost of electricity. Carrying (i.e., inventory) charges are ignored in this calculation. A 1% loss of heavy metal was assumed during fuel fabrication or refabrication; a 1% loss was also assumed for reprocessing.

Reactor capital and operating costs were obtained from the NASAP studies.[2] Capital costs were converted to yearly costs by multiplying capital costs by a fixed charge rate typical of electric utilities, 16%. A capacity factor of 75% was assumed for reactors in all calculations of the amount of electricity produced.

The costs of the back-end of the cycle, which were developed by AFCEP, were revised for this paper, utilizing economic assumptions representative of government financing. This revision was made because it does not appear that private industry will undertake the closing of the nuclear fuel cycle at this time. The principal assumptions contained in this government-type financing are 100% debt, a 7.5% per year interest on debt, and zero taxes. The calculations assume a six-year design and construction period and a twenty-year plant operating lifetime. The on-stream efficiency of facilities was assumed to be 33% the first year of operation, 67% the second year, and 100% thereafter. Equipment replacement and maintenance charges were assumed as 5% of the initial equipment cost per year. The ACFAC (A Cash Flow Analysis Code) computer code[3] was used to calculate these unit costs. Application of the above assumptions yield a fixed charge rate of 11%. Capital costs were escalated at a rate of 10% per year; they are given in terms of December 1980 dollars.

In summary, current prices are used in developing costs for the front-end of the cycle. Calculations for reactor systems costs are based on electric utility financing and a 16% fixed-charge rate on capital; calculations of costs for the back-end of the nuclear fuel cycle utilized assumptions which yield a fixed charge rate of 11%. All costs are presented in terms of December 1980 dollars.

3. COSTS FOR THE FRONT-END OF THE CYCLE

3.1 Ore Requirements and Costs

Reactor designers determine the desired nuclear fuel characteristics by establishing the fissile material enrichment within the fuel, the design of the fuel assembly, and the amount of fuel loaded into a reactor. The reactor designs upon which these costs are based are those established by the ground rules of the NASAP. The amount of uranium ore required to fuel a reactor is obtained by working backwards from the amount required by a reactor. This calculation is done by subtracting the fissile content of the tail material of enrichment facilities from both the desired enrichment of the fuel and the naturally occurring fissile content in uranium, then dividing the former quantity by the latter. The amount of natural uranium required is obtained by multiplying this ratio by the amount of heavy metal fuel required as feed to the reactor.

These calculations indicate that the annual amount of ore required for a conventional 1000-MW(e) pressurized water reactor (PWR), if operating on the once-through fuel cycle, is 182 t (1.82×10^8 g). If the fuel cycle is closed and the unused fuel discharged from this reactor is recovered and reinserted, the uranium feed requirement is reduced to 98 t (9.8×10^7 g). Thus, this calculation indicates that uranium ore reserves can be extended by 46% through recovery and recycle of unused fuel discharged from reactors. A review of the literature indicates that other authors give values which range from 40 to 50%.

A small amount of uranium make-up material is required in breeder reactors because some uranium is converted into plutonium and some fissions. Also, some heavy metal is lost during reprocessing and recycle. However, this is a very small amount when compared to the ore requirements for nonbreeding reactors. (This contribution to fuel cycle costs is ignored in subsequent discussions.) This nation's stockpile of depleted uranium from enrichment facilities is sufficient to supply these make-up needs for many generations.

Calculations of the costs for the front-end of the nuclear fuel cycle are straightforward. The results of these calculations are given in Table 1 along with the cost of other components of the fuel cycle. Ore costs are calculated by multiplying the amount of U_3O_8 required by its cost, $88/kg U_3O_8 ($40/lb U_3O_8).[4]

3.2 Conversion

The ore is not in a form suitable for enrichment; it must be converted from U_3O_8 to UF_6.[5] The current cost for conversion is $5.5/kg U. Multiplying this unit cost by the amount of uranium required gives the total cost for conversion.

3.3 Enrichment

Once the uranium is in the form of UF_6, it is sent to a gaseous diffusion plant for enrichment. A charge for enrichment of $110/kg of separative work unit (SWU)[6] is assumed. Conventional formulas were used to calculate the number of SWUs required to increase the enrichment of uranium to the desired level.

3.4 Fuel Fabrication

Most commercial reactors operating today use pelletized fuel stacked within metal tube rods which are assembled into bundles. This well-developed process is used in several commercial plants to produce conventional LWR fuel assemblies. The cost for this component of the fuel cycle is $170/kg of fissile and fertile material.

4. COSTS FOR THE BACK-END OF THE CYCLE

Costs for those elements of the fuel cycle which follow the discharge of irradiated fuel from storage basins at the reactor site were compiled by the AFCEP. As noted in Sect. 2, these costs were recalculated for this paper to reflect economic assumptions characteristic of public financing. These assumptions yield a fixed charge rate of 11%.

4.1 Fuel Refabrication

The cost of fabricating fuel is primarily related to the facility operational philosophy. Present plants are contact-operated and maintained; however, this approach cannot be pursued when the fuel cycle is closed and plutonium is fabricated in fuel assemblies. Plutonium fuel refabrication requires alpha particle containment and gamma-ray shielding, which cannot be done properly using equipment and procedures developed for a conventional enriched uranium fuel fabrication facility. Personnel radiation exposure limits and fissile material safeguards will require highly mechanized equipment for remote operation and possibly remote maintenance. Thus, the cost of refabricating plutonium-containing material will be greater than that of fresh fuel fabrication.

Table 1 shows that the lowest fuel fabrication cost, which is 0.7 mills/kWh, occurs for the conventional once-through fuel cycle. For the closed fuel cycle case, it was assumed that plutonium-containing material, which is recycled into PWR's, was refabricated in remotely operated and contact-maintained plants ($340/kg of heavy metal); however, this recycled mixed uranium-plutonium oxide (MOX) fuel does not contain enough fissile material to sustain this reactor. Thus, it was assumed that the enriched fresh make-up fuel (UO_2) was fabricated in a conventional plant. The combined overall fuel fabrication cost for the PWR closed fuel cycle system is 0.92 mills/kWh. A similar procedure was followed for breeder reactors where plutonium fuel for the core region is refabricated in advanced facilities ($510/kg of heavy metal), but uranium-only assemblies for the blanket region are fabricated in conventional plants.

4.2 "Away from Reactor" Storage

Once-through fuel cycles do not involve recycle of unused fuel back into the reactor. Instead, they include the interim storage of irradiated fuel in water storage pools. This spans about five years of storage at the reactor site (contained in reactor costs) followed by storage in "away from reactor" (AFR) facilities for another period before it is shipped to a permanent geological repository. The cost of the AFR storage for the conventional once-through fuel cycle is estimated to be 0.29 mills/kWh ($70/kg of heavy metal).

4.3 Reprocessing

Reprocessing consists of a series of operations in which irradiated fuel assemblies are sheared and then dissolved in nitric acid. The resulting solution, after clarification, is treated by solvent extraction processes to separate plutonium and uranium from the fission products. The solution is then successively treated to selectively strip plutonium and uranium into separate aqueous streams. The resulting product streams are converted to an appropriate oxide for use in preparing pellets in a fuel refabrication plant, or uranium is returned to an enrichment facility for re-enrichment. The waste streams are solidified and suitably canistered for transfer to, and storage in, a federal waste repository.

The cost of reprocessing fuel is directly related to the type of fuel to be processed (170 to $250 and 210 to $290 per kg of heavy metal for pressurized water reactor and fast breeder reactors respectively). Three factors combine to make the recycle of breeder reactor fuel more costly than that of light-water reactor fuel: (1) the lower heavy metal content per breeder fuel assembly causes a greater redundancy and paralleling of equipment in the handling of intensive portions of the head-end of a reprocessing plant, (2) the higher fissile content introduces more difficult chemical and criticality problems throughout the process, and (3) residual sodium from the breeder reactor coolant circuit and shipping container must be removed. The range of reprocessing costs given in Table 1 reflect a number of opinions regarding the appropriate degree of conservativeness in the facility design and level of remote operation and maintenance required in reprocessing facilities.

4.4 Terminal Fuel or Waste Storage

An important part of any nuclear fuel cycle is the ultimate and final disposal of radioactive wastes. A commonly accepted approach at present is the construction and operation

Table 1. Fuel cycle costs (mills/kWh)

	Uranium ore (U_3O_8)	Conversion to UF_6	Enrichment	Fabrication/Refabrication	"Away from Reactor" Storage/Reprocessing	Terminal fuel storage or waste disposal	Transportation	Excess Pu product credit	Total
Pressurized water reactor (once-through)	2.5	0.13	2.1	0.70	0.29	0.24	0.17		6.1
Pressurized water reactor (recycle)	1.4	0.07	1.4	UO_2 0.37 MOX 0.55 } 0.92	0.69–1.00	0.24	0.28		5.0–5.3
Liquid-metal fast breeder reactor				Core 0.86 Blanket 0.47 } 1.33	1.17–1.54	0.46	1.01	(0.84)	3.1–3.5

of a geologic repository, which involves placing and sealing radioactive wastes in a deep, stable geologic formation. A geologic repository, which is similar to a mine, consists of access corridors and disposal rooms excavated deep within the formation. Various supportive structures are provided on the surface over the repository, and shafts are constructed to provide access from these structures to the disposal level. Waste-filled containers are unloaded from the carriers at the repository and prepared in surface facilities for descent to the mine level. The containers are lowered through a shaft to the disposal level and are transported to and placed in disposal rooms. As disposal rooms fill to their capacity, the original material (e.g., salt) is returned to the mine to backfill empty spaces in the disposal room to minimize eventual subsidence.

Table 1 indicates that the terminal storage charge for once-through irradiated fuel assemblies is about equal to that of the high-level-radioactivity and transuranium wastes from the light-water reactor fuel recycle (i.e., 57 and $59 per kg of heavy metal equivalents). The radioactive waste disposal cost from the breeder fuel recycle is slightly higher ($86 per kg of heavy metal equivalent) because of the larger land area required to disperse the higher radiation heat load, and also because a larger number of waste canisters must be handled each year.

4.5 Transportation

Radioactive materials in various physical and chemical forms must be transported between fuel cycle facilities located in diverse geographic areas. The variation in transportation costs (shown in Table 1) results primarily from differences in cooling requirements of the shipments and the number of units to be shipped. (Unit transportation costs are 40, 68 and $190 per kg of heavy metal for pressurized water reactor once-through, pressurized water reactor fuel recycle, and fast breeder reactor cases respectively.)

The sum of these fuel cycle components is also given in Table 1. The cost of recycling unused fuel back into conventional reactors is less than the present once-through fuel cycle system. The fuel cycle costs for breeder reactors are about half that of the present once-through light-water reactor fuel cycle. This results from the absence of costs for the front-end of the cycle (no ore, conversion, or enrichment requirement) and from an assumed credit for bred plutonium fuel. Charges for the back-end of the cycle (i.e., fuel reprocessing, refabrication, waste disposal, and transportation charges) are higher for breeder reactor than for light-water reactor systems.

5. TOTAL POWER COSTS

The capital and annual operating costs for 1-GW(e) pressurized light-water reactor systems were taken as $1.06 billion and $18.6 million respectively.[2] These costs are the same for both PWR once-through and closed fuel cycles because it is believed that the differences in reactor design, construction, and operation caused by recycling fuel will have only a minor impact on cost. It is generally acknowledged, however, that breeder capital and operating costs are higher than those for conventional light-water reactors. Values of $1.44 billion and $24.0 million were assumed for 1-GW(e) breeder reactor capital and annual operating costs respectively.[2] Reactor capital costs were converted to yearly costs by multiplying the capital costs by the 0.16% fixed charge rate. A 75% capacity factor was assumed for all reactors.

Reactor costs are presented in Table 2 along with fuel cycle costs to give the total cost of nuclear electrical power production. Even though the fuel cycle costs for breeder reactors are about half that of conventional reactors, the fuel cycle costs do not offset the much higher capital and operating costs of breeder reactors. The net cost of generating electricity with breeder reactors is about 20% higher than with conventional reactors at today's costs for uranium and enrichment. The use of breeder reactors, however, extends the use of fission nuclear energy to several centuries.

Table 2. Total nuclear power costs (mills/kWh)

	Reactor		Fuel cycle	Total	Ratio of total
	Capital	Operating			
Pressurized water reactor (once-through)	25.9	2.8	6.1	34.8	1.00
Pressurized water reactor (recycle)	25.9	2.8	5.2	33.9	0.97
Liquid-metal fast breeder reactor	35.0	3.6	3.3	41.9	1.20

Fuel costs are a small part of total power costs. This conclusion is fairly insensitive to changes in the economic assumption taken over a reasonable range. If closing the fuel cycle is considered to be a high-risk venture, thereby causing a fixed charge rate triple that of government-type financing to be used, the foregoing conclusion is still valid.

The break-even point, where the lower breeder reactor fuel cycle cost compensates for higher breeder capital and operating cost, occurs when the cost for uranium ore resources reaches \$275/kg U_3O_8 (\$125/lb U_3O_8). This assumes that credit for bred plutonium increases in the same proportion as ore costs; all other fuel cycle component costs remain unchanged. At this break-even point, conventional reactor systems have the same power costs as breeder reactor systems.

6. SUMMARY AND CONCLUSIONS

The cost of components for the back-end of the nuclear fuel cycle, developed as part of the NASAP, is presented after being revised to reflect government-type financing. These financial assumptions yield an 11% fixed charge rate. For the sake of completeness, ore requirements and costs for the front-end of the fuel cycle are also presented. Reactor costs were obtained from the literature and added to the fuel cycle costs to give the total cost of generating electricity with nuclear power.

Calculations show that the recovery of unused fuel in the discharged fuel assemblies and recycling the fuel into conventional light-water reactors extends uranium resources by 40 to 50%. Recovery and recycle causes a slight reduction in fuel cycle costs – from 6.1 to 5.2 mills/kWh for the once-through system.

The fuel cycle costs for breeder reactors are about half that of the present once-through system. This results from the absence of costs for the front-end of the cycle (no ore, conversion, or enrichment requirements) and from an assumed credit for bred plutonium fuel. Costs for the back-end of the nuclear fuel cycle (i.e., fuel reprocessing, refabrication, waste disposal, and transportation charges) are higher for breeder reactors than for conventional reactor systems.

Fuel cycle costs are only a small part (8 to 17%) of the total power costs, amounting to only 3.3 to 6.1 mills/kWh of the total 34.8 to 41.9 mills/kWh.

Even though breeder reactor fuel cycle costs are about half those of conventional reactor systems, fuel cycle costs do not offset the much higher reactor capital and operating costs. The net overall cost of the breeder reactor system is about 20% higher than that of conventional reactor systems. The break-even point, where lower breeder fuel costs offset higher capital and operating costs, occurs at \$275/kg U_3O_8 (\$125/lb U_3O_8). Although breeder reactors are not currently economically competitive, they may be introduced and extensively utilized because of the vast extension of domestic energy resources that are made possible through their use.

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