NUCLEAR ELECTRIC POWER

Economics of the Conversion of Nuclear Energy to Electricity

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I. INTRODUCTION

This paper discusses the economics of producing electricity from nuclear energy. The economic data presented are intended to indicate the current and near-term situation in nuclear economics, without displaying undue optimism or pessimism. In addition, the subject matter are also for the purpose of providing you with a better understanding of the economics of nuclear power in general. The input data used in this paper are from a multitude of sources and in many cases, the data were subjected to interpretation by the author. I wish to also make the qualification that the specifics that go into determining the economic performance of nuclear electric plants are changing rapidly with time. Hence, you are cautioned that certain portions of this paper are subject to obsolescence and it is to be understood that the data and information presented represent the situation based on what we think we know today, as seen from the authors point of view. There are a number of factors currently prevalent in the field of nuclear power which make economic evaluations and analyses difficult. The nuclear industry is relatively new and a sufficient base of operations is just beginning to be established. There are reasons to believe that the size of the nuclear industry will increase rapidly with time. Several authoritative growth projections indicate that annual rates of nuclear fuel throughput and new plant construction will increase more than ten-fold in the decade 1970 to 1980. These factors introduce major complications in choosing realistic cost input data to use in economic computations. This is one of the primary reasons why estimates of future economic performance of nuclear electric plants vary widely.

In the U.S., economically competitive nuclear electric power has not yet been produced. However, it is expected that several large nuclear electric plants now under construction will demonstrate that they are competitive in their particular circumstances. It will be a few years however before this is borne out. Thus, one must look into the near future in order to speak of economic nuclear power. For this reason, it is important that the underlying technical, economic and operational assumptions which go into nuclear power cost estimates be spelled out with a reasonable degree of clarity. This paper attempts to provide a general appreciation of nuclear electric plant economics - it presents data on the currently estimated economic status and provides a general indication of what we might expect as more advanced reactor concepts are brought into being. In going about this endeavor, the following sequence of presentation will be followed:

- Current program
- Fuel cycles, flowsheet, material and energy balances
- Methodology of Economic Computations
- Specific Economic Estimates
- Analysis of Fuel Costs

Current Program

Historically, the AEC has carried out a broad base program of reactor development involving many reactor types. The scope of this past and current effort can be well appreciated by Table I which lists the nuclear plants presently committed, under construction or operable.

TABLE 1

NUCLEAR ELECTRIC PLANTS PRESENTLY COMMITTED, UNDER CONSTRUCTION, OR OPERABLE
(In the U.S.)

PRESSURIZED WATER	EMW NET	DATE CRITICALITY
Shippingport	100	1957
Yankee	175	1960
Indian Point	255	1962
Saxton	3	1962
San Onofre	375	1966
Malibu	463	1968
Haddam Neck	463	1967
BOILING WATER		
EBWR	4	1956
Dresden	200	1959
Big Rock Point	73	1962
Elk River	20	1962
Humboldt Bay	67	1963
Pathfinder	59	1964
Bonus	16	1964
La Crosse	50	1965
Oyster Creek	515	1967
Nine Mile Point	500	1968
WATER COOLED GRAPHITE MODERATED		
NPR	800	1965

GAS COOLED	EMW NET	DATE CRITICALITY
Peach Bottom	40	1965
EGCR	22	1965
SODIUM GRAPHITE		
Sodium Reactor Exper.	6	1957
Hallam	75	1962
HEAVY WATER		
Carolinas Virginia	17	1963
ORGANIC COOLED		
Piqua	11	1963
FAST SODIUM COOLED		
Fermi	61	1963
EBR-II	17	1963

TOTAL ABOVE (THROUGH 1968)

Operable by End 1964	1159 EMW
Under Construction	3228 EMW
TOTAL	4387 EMW

Data as of Dec. 31, 1964

Recently, the AEC has been reducing the number of reactor concepts under active development. The present AEC civilian nuclear power program is focused on the development of advanced thermal reactors and fast breeder reactors, leaving further improvement of the conventional light water reactors to industry.

The primary technical incentives for the development of these reactor concepts are listed in Table 2.

TABLE 2

TECHNICAL REASONS FOR ADVANCED THERMAL REACTORS AND FAST BREEDER REACTORS

1. Achieve the timely introduction of advancing technology into the growing nuclear complex, with attendant cost reductions.

2. Reduce the requirement for fissile material mined from the ground, thereby extending the availability of nuclear resources.

3. Permit the use of higher cost nuclear fuel resources while still producing low cost energy, thereby expanding the resource base.

Fuel Cycles

Besides the various choices for structure, coolant and moderator combinations, nuclear reactors can operate with various combinations of fissile and fertile materials although certain reactor types are logically oriented towards particular fissile/fertile species.

The heavy elements of interest as nuclear fuels are shown in Table 3.

TABLE 3

NUCLEAR FUELS

Fissile	Fertile
Uranium 233	Thorium 232
Uranium 235	Uranium 238
Plutonium	

The naturally occurring nuclear fuels are thorium, uranium 238 and uranium 235. Thus, of the fissile isotopes, only U235 is naturally occurring, found in concentrations of 0.711 wt.% in natural uranium. The other two fissile isotopes, U233 and plutonium (isotopes 239, 240, 241 and 242) are produced through the capture of a neutron by thorium and uranium 238, respectively. The technology of the U235 - U238 fuel system is better established than that of other systems. Extensive fuel cycle development is in progress on the plutonium-uranium and the U233 - U235 - thorium systems. Studies are in progress on other combinations of fissile/fertile species.

Under certain conditions, it is possible to produce more fissile isotope than is consumed. This occurs when sufficient excess neutrons released during fission are captured in a fertile isotope, converting it to fissile. Such a process is referred to as "breeding". All reactors are inherently capable of converting fertile material to fissile. The extent to which they do this depends on a number of factors. These include the concentration of the fissile and fertile isotopes, the number of neutrons released per fission (a function of the isotope and the incident neutron energy), and the probability of the neutron released by fission being captured by a fertile isotope rather than being lost through leakage or capture in non-fuel materials. If the above conditions are favorable, the reactor can produce more fissile isotopes than it consumes. If the above conditions are less favorable, the reactor will still regenerate a certain fraction of the fissile isotope consumption.

Figure 1 indicates the overall flowsheet for a slightly enriched uranium fueled converter reactor with plutonium recycle. (See Figure 1, end of text).

Mass and Energy Balances - Reactor

Figure 2 indicates a mass and energy balance of a single irradiation cycle of a pressurized light water reactor, typical of some large plants currently under construction. (See Figure 2, end of text).

For this particular example, the heat was produced from the various isotopes as follows:

TABLE 4

Distribution of Heat Production by Isotope

Isotope	% of Heat Produced
U235	60
U238	5
Plutonium	35
	100

The conversion ratio, grams fissile produced per gram fissile consumed is 0.62.

Thus, in consuming 30.3 grams of fissile material by neutron absorption (25.7 grams of which fissioned), 18.1 grams of new fissile material was produced.

On an input-output basis, 30 grams of fissile material was fed to the reactor, 25.7 grams of material was fissioned and 19.1 grams of fissile material was discharged.

Mass and Energy Balance - Nuclear System

In providing the U235 for the reactor feed, the system flow sheet for this example looks about as shown in Figure 3 (See this Figure at end of text).

Thus, in this example, 4.1 Kg of fresh natural uranium is required to replenish the U235 consumed in each Kg of fuel throughput of the reactor. If the plutonium were recycled, the fresh natural uranium requirement would drop to around 2.4 Kg. Under this recycle condition the mass balance indicates that of the total natural uranium fed to the uranium enriching plant, about 1.1% of it actually is fissioned, most of the other 98.9% ending up in the enriching plant tails stream. This is one reason why we are working on advanced converters and breeders - to increase the fraction of mined uranium that is fissioned. Please note however that the 98.9% that is currently set aside is not lost. It can be reintroduced to the system at some future date as a fuel for breeder reactors.

I don't wish to leave the idea with you that in the above case example, there was not a significant quantity of heat released. The 24 MWD/KgU corresponds with releasing 900 million BTU per pound of uranium charged to the reactor.

II. METHODOLOGY OF COMPUTING ENERGY COSTS

The following discussion is not intended as a complete treatise on computing nuclear energy costs, but rather, it highlights the method employed in this paper.

Capital Costs

The capital costs set forth in this paper are intended to represent the total cost of acquiring an operable plant to a typical private utility company. These costs include plant equipment required through the point of supplying electric power to the main transformer but exlude the transformer cost and equipment beyond the transformer. This total cost includes the direct construction cost of the nuclear plant and includes indirect costs such as general and administrative expenses, architect engineer and nuclear engineering fees, plant startup cost, contingencies, escalation, taxes, and interest during construction. These indirect costs generally amount to 25 to 40% of the direct construction costs.

Fuel Cost

The individual items identified in a standard fuel cost presentation are generally as follows:

TABLE 5

Nuclear Fuel Cost

	M/KWH
Direct Charges	
Fabrication	XX
Uranium Consumption	XX
Spent Fuel Recovery (Chem. Processing & Shipping)	XX
Plutonium or U233 Credit	(XX)
Uranium Use Charge (if applicable)	XX
Subtotal, Direct	XX
Fixed Charges	
Working Capital	XX
Total Fuel Cost	XX

Most of the fuel costs given in this paper are for the condition where the nuclear fuel material is privately owned. For privately owned fuel, the item labeled "Working Capital", includes the investment charges in the fuel materials, and the uranium use charge entry is not used.

In addition, it includes other investments in the fuel cycle, based on a cash flow analysis and assuming that fixed charges on the fuel cycle investment are 10%/year on the net investment. A more complete discussion of fuel costing methodology is contained in a paper I presented at the Third United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, August 31 - September 9, 1964, paper A/CONF. 28/P/247.

Operation, Maintenance and Insurance

Operation and maintenance costs are based on estimates of manpower, supplies and materials required to operate the reactor. Insurance costs are based on $60 million of third party liability insurance at a premium of $260,000/year plus $500 million federal indemnity at a premium $30 per thermal megawatt per year.

Fixed Charge Rate

Plant capital investment is charged against electricity generation through the use of an annual fixed charge rate. For example, the capital cost in dollars is multiplied by the fixed charge rate in %/year to give dollars per year. Dividing this by the KWH produced per year and converting dollars to mills, one gets the capital charges in M/KWH.

The annual fixed charge rate varies from one utility to another. For investor owned utilities it generally runs between 10 and 15%/year. For public utilities and cooperatives, it runs around 7%/year.

Capacity Factor

The plant capacity factor is the actual KWH production over a period of time divided by the KWH production that would have occurred if the plant had operated 100% of the time at its rated capacity; usually expressed as a percentage.

Nuclear electric plants have low incremental operating costs which favors operating them as base load plants. In this paper, an 80% capacity factor is generally used in the economic computations.

Total Generating Cost

The total energy cost is thus made up as follows:

TABLE 6

Total Generating Cost

Capital Charges	M/KWH
Plant	XX
Fuel Working Capital	XX
Fuel	XX
Operation, Maintenance and Insurance	XX
Total	XX

III. SPECIFIC ECONOMIC ESTIMATES

This section deals with the estimated economic performance of several types of nuclear electric plants. These include:

TABLE 7

Reactor Types Included

- Light Water Cooled and Moderated, Producing Saturated Steam (LWR)
- Heavy Water Moderated, Organic Cooled (HWOCR)
- High Temperature Gas Cooled, Graphite Moderated (HTGR)
- Sodium Cooled Fast Breeder Reactor (FBR)

For the light water reactors, data on capital costs is included in the discussion. For the other reactors, the discussion is limited to fuel costs.

A. LIGHT WATER REACTORS

As indicated earlier, most of our operating experience with nuclear electric plants is with the light water reactors - boiling and pressurized. The technology is to the point where manufacturers are making fixed price contracts with warranted plant and fuel performance available to utility customers.

1. Capital Costs

The capital cost of steam-electric plants, whether they use fossil or nuclear fuels, varies significantly throughout the country. While the size of the plant is important, there are many other factors which affect the capital cost. Foremost among these are the local site and labor conditions (including weather considerations) and the plant specifications desired by the individual customer. These and other lesser factors give rise to substantial differences in capital cost of electric plants. It is important that one appreciates that these differences exist. Nevertheless, specific plant capital cost data are of interest and if there are an adequate number of data points one can gain an insight of the cost situation.

Cost data for a number of light water nuclear electric plants are shown in Figure 4. (See this figure at end of text) The ordinate is the unit capital cost in $/KW (net) and the absicca is the station size. The date of completion (criticality) of each plant is in parenthesis. Two points are indicated for each plant, the points being interconnected by a straight line. The upper point is the unit cost of the initial warranted plant rating. The lower point is for the expected rating (or stretch rating). A few words regarding this overcapacity or stretch are in order. Since there is not yet a great deal of experience with nuclear power plant design and operation, the reactor manufacturers are deliberately conservative in selecting the values of the individual limiting conditions which go into determining a plants capacity. After the plant is placed into operation, the plant operator can set about actually establishing the plants capability. The over-capacity that can be realized will depend on several factors including the amount of conservatism incorporated in the reactor core design, the design versus warranted output and the capability of the steam piping and turbine generator system. The piping and turbine generator system can be closely designed to meet a certain design capability. It is the nuclear reactor portion of the plant where the design conservatisms are incorporated. Hence, in many plants now under construction, the piping and turbine generator side of the plant is being designed for higher power capability than the warranted reactor rating.

The dotted line on this slide is based on the price list published in the fall of 1964 by a large manufacturer of boiling water reactors. These costs are based on a turnkey built plant and I've added 20% to the published turnkey price to allow for customer costs. The customer costs generally run less than 20%.

Oyster Creek - Capital Cost

The very detailed analysis published in 1964 by the Jersey Central Power and Light Company for their Oyster Creek Nuclear Station has attracted a lot of attention, both in and out of the nuclear industry. To my knowledge, this is the most comprehensive analysis of the expected economic performance of a nuclear plant over a

30 year life ever published. The analysis was very detailed and most of the input economic and operational parameters were changing with time, to reflect what these people anticipated for the future. The salient capital cost data for this plant are given in Table 8.

TABLE 8

OYSTER CREEK NUCLEAR STATION

CAPITAL COST DATA

Single cycle boiling water reactor

Turnkey built plant

Total capital cost, including customer costs but excluding escalation: $66.4 million ($58.5 million excluding customer costs)

Plant Rating:

Initial guaranteed.	515 MW (net)
Expected.	640 MW (net)

Unit Capital Cost:

At Initial Rating	$129/KW (net)
At Expected Rating.	$104/KW (net)

2. Fuel Costs

Fuel costs in a nuclear electric plant decline with time. This is due to several factors. First of all, the initial core loading of a reactor is usually designed for a lower goal exposure than is the replacement fuel. This is due to limits on holding down initial reactivity. The other reason is that the cost of the manufacturing operations will decline with time - partly due to technologic improvement and partly due to increased volume of business mentioned earlier. Recently the Atomic Energy Act was revised at the request of the AEC to permit private ownership of nuclear fuels. Prior to this legislation, ownership of the fuel was retained by the government and it was leased to customers. Carrying charges on leased material (usually called "use charges") are at the rate of 4-3/4%/year on the value of the material on hand.

With the new legislation, enriched uranium can now be either leased or purchased and after 1972, must be purchased. For reactor operators, the new legislation includes the following important milestones. As of January 1, 1969, the Commission will provide a uranium enriching service (fuel enriched through this service would be privately owned). As of Jan. 1, 1971, no additional enriched uranium will be distributed by the government by lease. Also, as of July 1, 1971, the guaranteed purchase of plutonium by the government will terminate. As of January 1, 1973, all material out on lease must be purchased.

Near Term Fuel Costs

The typical technical and economic bases and estimated near-term fuel cost of a light water reactor is given in Tables 9 - 11. The data used are intended to apply to a nuclear electric plant that could become operational around 1968-1969.

TABLE 9

Technical Bases for Fuel Cost

Large Light Water Reactor

(Heat Rate 10,900 BTU/net KWH)

	1st Core	Replacement Fuel
Initial enrichment, % U235	2.0	2.4
Discharge enrichment, % U235	0.83	0.85
Kg uranium discharged per Kg U charged	0.976	0.969
Plutonium discharged, grams per initial KgU		
Total Pu	6.3	7.3
Fissile Pu	4.4	4.9
Fuel Exposure		
MWD/KgU	16.5	22.0
Millions of BTU/KgU	1350	1800
Net eMWH/KgU	124	165
Fuel Specific Power, Thermal MW/MTU	15.5	18.5
Average Fuel Residence time in Core, Full power years	2.9	3.3

NOTE: U is uranium, MWD is thermal megawatt days of energy, MTU is metric tons uranium and eMWH is electric megawatt hours.

TABLE 10

Economic Assumptions for Fuel Cost

Large Light Water Reactor

	1st Core Average	Early Replacement Fuel
Fabrication Price $/KgU	100	85
Post Irradiation Shipping $/KgU	6	6
Natural Uranium Price, $/lb U_3O_8	8	6
Separative Work Cost, $/KgU	30	30
Cascade Tails Assay, % U235	0.253	0.281
Pu Credit, $/g fissile 1/	9	9
Chemical Processing, $/KgU	38	38
Ex-core Inventory Holdup Time, Years	1	1
Uranium Carrying Charges, %/year	4-3/4	10
Working Capital Charges, %/year	10	10
Plant Capacity Factor, %	80	80

1/ $9/gram is used in both columns since this is the estimated fuel value with U_3O_8 priced at $6/lb. In this connection, most of the plutonium produced by the first core is not discharged until after the assumed change in enriched uranium prices.

TABLE 11

FUEL COST

Large Light Water Reactor

80% Capacity Factor

	Cents per million BTU 1st Core	Cents per million BTU Replacement	Mills per net KWH 1st Core	Mills per net KWH Replacement
Direct Charges				
Fabrication	7.4	4.7	.81	.52
Uranium Consumption	8.5	7.6	.92	.83
Spent Fuel Recovery	3.3	2.4	.35	.27
Plutonium Credit	(2.9)	(2.4)	(.32)	(.27)
Uranium Use Charge	1.4	-	.16	-
Sub-total	17.7	12.3	1.92	1.35
Fixed Charges				
Working Capital	1.6	4.0	.18	.43 1/
Total Fuel Cost	19.3	16.3	2.10	1.78

1/ For the replacement fuel, the working capital charges are allocated as follows:

	M/KWH
Fabrication	0.13
Uranium Consumption	0.30
Spent fuel recovery	(0.07)
Plutonium Credit	0.07
	0.43

3. Operation, Maintenance, and Insurance Cost

For a 1,000 MW single unit nuclear electric plant, the annual operation and maintenance cost is around $1.6 million. This includes a total operating staff of around 75. The nuclear insurance would run something less than $360,000/year.

For an 80% plant capacity factor, these two items amount to:

O+M	0.23
Ins.	0.05
O+M+I	0.28 M/KWH

4. Total Generating Cost

The total generating cost of a typical 1000 MW light water reactor, based on the data presented above, would run about as shown in Table 12. These costs are representative of what one might expect of the early years of operation of a light water reactor entering service in the late sixties. It should be noted however, that these costs have not yet been demonstrated and it will be several years before we have the facts at hand to clearly back up these expectations.

TABLE 12

TOTAL GENERATING COST

1000 MW LIGHT WATER REACTOR NUCLEAR ELECTRIC PLANT
(after several years operation)
80% C.F.

	$/KW	$/KW-Yr.	¢/10^6 BTU	M/KWH
Capital Charges				
Plant (@ 12%/yr.)	120	14.4	-	2.06
Fuel (@ 10%/yr.)	29	3.0	-	0.43
Fuel	-	-	12.3	1.35
Oper. Maint. & Ins.	-	2.0	-	0.28
Total				4.1

NOTE: $/KW-Yr., ¢/$10^6$ BTU, and M/KWH are equivalents, not additive

B. ADVANCED THERMAL REACTORS

- Heavy Water Moderated, Organic Cooled -

- High Temperature Gas Cooled -

These two reactor concepts have the capability of breeding. For the present and near term, their operation will undoubtedly be optimized for minimum generating cost and this will lead to conversion ratios of less than unity. The current AEC program includes plans to construct a prototype thorium fueled high temperature gas cooled reactor and a uranium fueled heavy water moderated, organic cooled reactor. Both these prototypes will probably be around 300 MW in size. The AEC also plans to construct a seed blanket reactor prototype. This prototype is expected to demonstrate the interesting ability to breed in a light water reactor. This reactor concept is not discussed in this paper since it is outside my area of cognizance.

The fuel cost data presented below are idealized in the sense that it is assumed that fuel throughput rates are equivalent to an installed capacity of 15,000 MW (for the purpose of estimating processing charges). Also, it is assumed that the technology presently under development will be successful and that no real bottlenecks are encountered. So please bear in mind that these cost data are estimates and the technical characteristics of these reactors will not really be firmed-up until the prototypes have operated. At this point in time, the following data are to be considered as being speculative. They indicate what is potentially attainable if the development programs are largely successful; and if each reactor system is constructed in large quantity such as to realize large annual fuel throughput rates.

TABLE 13

BASES FOR FUEL COST

Large Heavy Water Reactor (Organic Moderated)

(Uranium Fuel Cycle - Sell plutonium)

Technical Bases	
Initial enrichment, % U235	1.20
Discharge enrichment, % U235	~0.05
Plutonium discharged, g fissile/KgU	4
Fuel Exposure	
MWD/KgU	20
10^6 BTU/KgU	1640
net eMWH/KgU	158
Net thermal efficiency, %	33
BTU/net KWH	10340
Fuel Specific Power, Thermal MW/MTU	24
Fuel residence time in reactor, full power years	2.2
Refueling	On-line
Economic Bases 1/	
Fabrication, $/KgU	40
Natural Uranium, $/lb U_3O_8	6
Separative work, $/KgU	30
Spent fuel recovery	30
Plutonium credit, $/fissile Gram	9
Working Capital Charges, %/year	10
Ex-core inventory holdup, years	1
Plant capacity Factor, %	80
Annual fuel throughput, MTU/year (for 15,000 MW)	660

1/ Fuel throughput rate and unit costs based on 15,000 MW installed capacity

TABLE 14

FUEL COST

LARGE HEAVY WATER REACTOR NUCLEAR ELECTRIC PLANT
(Equilibrium Cycle)
80% C.F.

	Cents per million BTU	Mills per net KWH
Direct Charges		
Fabrication	2.4	0.25
Uranium Consumption	3.4	0.35
Spent Fuel Recovery	1.8	0.19
Plutonium Credit	(2.2)	(0.23)
Sub-total	5.4	0.56
Fixed Charges		
Working Capital 1/	1.2	0.12
Total Fuel Cost	6.6	0.68

NOTE: Charges for heavy water (investment and losses) amount to about 1.9¢/10^6 BTU or 0.2 M/KWH. Charges for organic makeup amount to about 1¢/10^6 BTU or 0.1 M/KWH. Thus the fuel cost plus special charges on heavy water and organic amount to about 8.8¢/10^6 BTU or 0.91 M/KWH.

1/ The working capital charges are allocated as follows:

	M/KWH
Fabrication	0.05
Uranium Consumption	0.07
Spent fuel recovery	(0.04)
Plutonium Credit	0.04
	0.12

TABLE 15

BASES FOR FUEL COST

High Temperature Gas Cooled Reactor
(Thorium Fuel Cycle - recycle U233)

Technical Bases

Initial enrichment, % U235 + U233 in U + Th	3.1
Discharge enrichment, % U235 + U233 in U + Th	2.5
Kg U + Th discharged per Kg charged	0.94
Fuel Exposure	
MWD/KgU + Th	52
10^6 BTU/KgU + Th	4260
Net eMWH/KgU + Th	550
Net Thermal efficiency, %	44
BTU/net KWH	7760
Fuel specific power, thermal MW/MTU + Th	29
Fuel residence time in reactor, full power years	5
Fraction of core replaced per refueling	1/6

Economic Bases 1/

Fabrication, \$/KgU + Th	110
Natural uranium, \$/lb U_3O_8	6
Thorium, \$/lb ThO_2	5
Separative work, \$/KgU	30
Spent fuel recovery, \$/KgU + Th	110
U233 value, \$/g U233	11
Working capital charges, %/year	10
Ex-core inventory holdup, years	1
Plant capacity factor, %	80
Annual Fuel throughput, MTU + Th/year (for 15,000 MW)	190

1/ Fuel throughput rate and unit costs based on 15,000 MW installed capacity.

TABLE 16

FUEL COST

LARGE HIGH TEMPERATURE GAS COOLED REACTOR NUCLEAR ELECTRIC PLANT
(Equilibrium Cycle)
(80% C.F.)

	Cents per million BTU	Mills per net KWH
Direct Charges		
Fabrication	2.6	.20
Uranium Consumption	1.8	.14
Spent Fuel Recovery	2.6	.20
Sub-total	7.0	.54
Fixed Charges		
Working Capital 1/	5.0	.39
Total Fuel Cost	12.0	.93

1/ The working capital charges are allocated as follows:

	M/KWH
Fabrication	0.07
Uranium Consumption	0.39
Spent Fuel Recovery	(0.07)
	0.39

According to these data, the HWOCR has a projected fuel cost of about 0.7 M/KWH and the HTGR about 0.9 M/KWH. The HWOCR has some extra charges for heavy water and makeup of organic coolant degradation that do not apply to the HTGR. The sum of these extra charges -- based on 10%/year investment charges on heavy water, 0.5% heavy water loss per year, organic makeup rate of 4000 lbs. per eMW per year; and costs of $20/lb heavy water and 17 cents per pound organic -- amount to 0.2 M/KWH on the heavy water and 0.1 M/KWH on the organic. Therefore, the sum of fuel cost plus special material charges for the HWOCR is about one M/KWH. Thus the HWOCR and HTGR are very close together on the basis of fuel cost plus special material charges.

The light water reactor described previously, if evaluated on the basis of computing fuel cycle unit costs according to the throughput rate for 15,000 MW, has an estimated fuel cost (direct plus fixed charges) of 1.4 M/KWH.

C. FAST BREEDER REACTORS

Most of the effort on high gain breeder reactors centers around the sodium cooled fast breeder reactor, fueled with plutonium. This reactor offers promise of attaining a reasonably high breeding gain and a reasonably short doubling time.

It appears that for many years to come, the requirement for natural uranium mined from the ground will be determined by the amount of fissile material required for inventory buildup and fuel makeup. A high gain breeder reactor offers the interesting prospect of eventually making the nuclear complex self-sufficient on fissile material at which time the system can be sustained on the fertile fuels - U238 and thorium. This will permit utilization of most of the latent energy of fission contained in our nuclear resources.

The design characteristics of fast breeder reactors are less well defined than the reactors previously discussed. However, a number of conceptual design studies have been made so there is some indication of how they may perform. The following tables provide preliminary estimates of the bases for and resulting fuel cost of a fast breeder reactor.

TABLE 17

BASES FOR FUEL COST

SODIUM COOLED FAST BREEDER REACTOR NUCLEAR ELECTRIC PLANT
(1100 eMW net, 44% net thermal efficiency)

	Core	Blanket	
Technical Bases		Axial	Radial
Power, thermal MW	2170	35	295
Initial Loading, MTU + Pu	23.7	8.0	57.1
Initial concentration, Kg fissile Pu/Kg (U+Pu) in	0.156	0	0
MT(U+Pu) discharged per MT(U+Pu) charged	0.893	0.995	0.992
Discharge concentration, Kg fissile Pu/Kg (U+Pu) out	0.141	0.020	0.048
Fuel Exposure, MWD/initial KgU+Pu	100	4.8	7.6
Fuel Residence Time, full power years	3.0	3.0	4.0
Fuel fraction replaced per refueling	1/6	1/6	1/8
Economic Bases			
Fabrication, $/KgU+Pu	190	190	50
Spent fuel recovery, $/KgU+Pu	120	55	40
Plant Capacity factor %	----------	80	----------
Plutonium Credit, $/fissile gram	----------	10	----------
Working Capital Charges, %/year	----------	10	----------
Ex-core inventory holdup, years	----------	1.0	----------

TABLE 18

FUEL COST

SODIUM COOLED FAST BREEDER REACTOR

	Core	Blanket	Total
	M/KWH		
Fabrication	0.16	0.12	0.28
Pu Consumption	0.27	(0.75)	(0.48)
Spent Fuel Recovery	0.10	0.07	0.17
Subtotal	0.53	(0.56)	(0.03)
Working Capital	0.56	0.24	0.80
Total	1.09	(0.32)	0.77

IV. ANALYSIS OF FUEL COST

This section discusses several important aspects of nuclear electric plant fuel costs.

Uranium Pricing

In the U.S., enriched uranium is produced by the gaseous diffusion process. If one makes a few simplifying assumptions, the cost-enrichment relationship is as follows:

$$C\ (X_i) = F\ (X_i)\ C_f + \Delta(X_i)\ C_\Delta \qquad \text{.............(1)}$$

Where: $C(X_i)$ = Unit cost of uranium of enrichment X_i, \$/KgU

$F(X_i)$ = Kg natural Uranium feed required to produce 1 Kg of uranium at enrichment X_i.

C_f = Unit cost of natural uranium feed to the diffusion plant, \$/KgU as UF_6.

$\Delta(X_i)$ = Separative work required to produce 1 Kg of uranium of enrichment X_i from natural uranium, Kgs U

C_Δ = Unit cost of separative work, \$/KgU

The feed requirement per Kg of product is:

$$F(X_i) = \frac{X_i - X_w}{X_f - X_w} \qquad \text{.............(2)}$$

Where: X_i = product material enrichment

X_w = diffusion plant tailings enrichment

X_f = natural uranium enrichment (0.711%)

The separative work requirement is:

$$\Delta(X_i) = \phi(X_i) + W\phi(X_w) - F\phi(X_f)$$

Where: $\phi(X_j) = (2X_j - 1)\ \ln \frac{X_j}{1-X_j}$

W = Kgs diffusion plant tailings per Kg product

F = $F(X_i)$ defined previously

For any particular ratio of feed to separative work cost, there exists a certain optimum tailings enrichment which will result in minimum product cost (any product enrichment). The tailings enrichment, X_w, is determined by taking the first derivative of the cost equation (1) with respect to X_w, setting it equal to zero, and solving for X_w. That is, solve for X_w in the equation:

$$\frac{dC(X_i)}{dX_w} = 0 \qquad \text{.............(4)}$$

The current USAEC schedule of charges for enriched uranium is based on a natural uranium feed charge of \$23.5/KgU as UF_6 and a separative work charge of \$30/KgU. For this ratio of feed to work cost, the optimum tailings enrichment computed from equation (4) above is 0.253% U235 in Uranium.

Makeup of Fuel Cost

Table 19 indicates the makeup of the direct fuel cost of the light water reactor described in Table 12, but on a plutonium recycle mode of operation. The costs are allocated to the discrete production operations which were previously set forth in the flowsheet of Figure 1.

TABLE 19

DISTRIBUTION OF FUEL COST COMPONENT CHARGES

Light Water Reactor with Plutonium Recycle
(See Table 9 for Design Data)

	%of Direct Fuel Cost
Mining, milling, refining	20
Conversion U_3O_8 to UF_6	2
Enriching	23
Fabrication	36
Spent Fuel Recovery	19
	100

NOTE: This cost allocation compares with the flowsheet shown in Figure 1.

Minimized Fuel Costs

One of the interesting characteristics of nuclear fuel cycles is that there exists a certain optimum fuel exposure to obtain minimum fuel cost. This is mostly due to the increase that results in nuclear fuel investment charges as the design fuel exposure is increased. This in turn is due to the increased fissile loading required to attain high fuel exposures. The optimum fuel exposure depends on the combined effect of all of the individual cost inputs to the fuel cost computation.

A typical set of fuel cost versus fuel exposure curves are given in figure 5 (see this figure at end of text).

V. CONCLUSIONS

The nuclear industry is relatively new and is just beginning to show positive signs of getting underway. Much research and development is in progress. These conditions contribute towards causing specific levels of economic performance of nuclear electric plants to change rapidly with time. Thus, one must be closely connected with the nuclear power field in order to keep abreast of the situation.

Since 1960, twelve nuclear electric plants have entered service but only one of them can be called reasonably large. Small nuclear plants demonstrate technology well, but because they are small, cannot demonstrate economic competitiveness. Thus, we are in a position today where we think nuclear plants can be built which will be economic but we don't have any in hand at the moment. In the period 1966 through 1968, five large nuclear electric plants are scheduled to enter service. It will be most interesting to closely follow their progress and performance to see if our predictions will indeed be realized.

Figure 1

Uranium Flowsheet
Nuclear Electric Plant and Supporting Operations

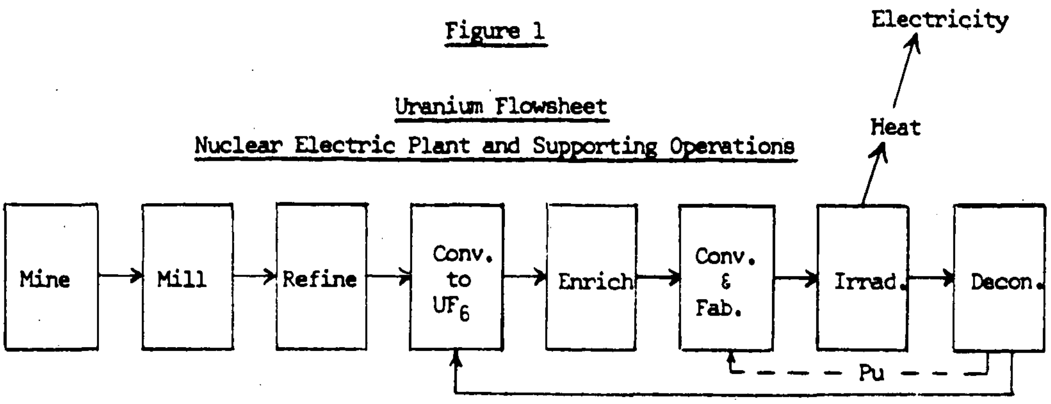
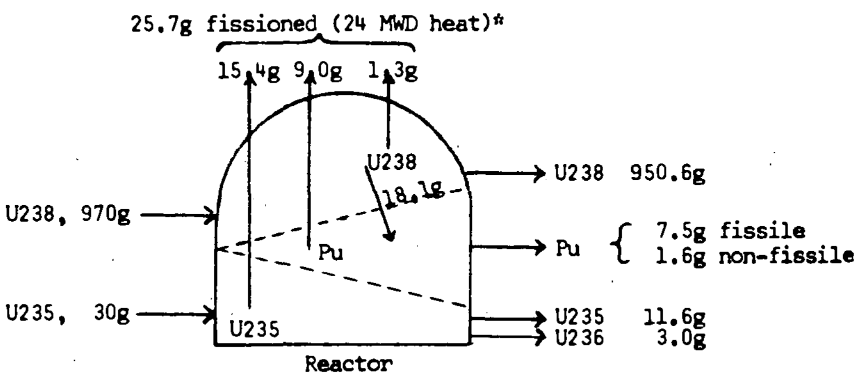


Figure 2

Mass and Energy Balance Around Reactor
(one irradiation cycle)



* 0.023 grams mass converted to energy ($E=MC^2$)

Figure 3

Mass Balance Around Nuclear System
(Non-Pu Recycle)

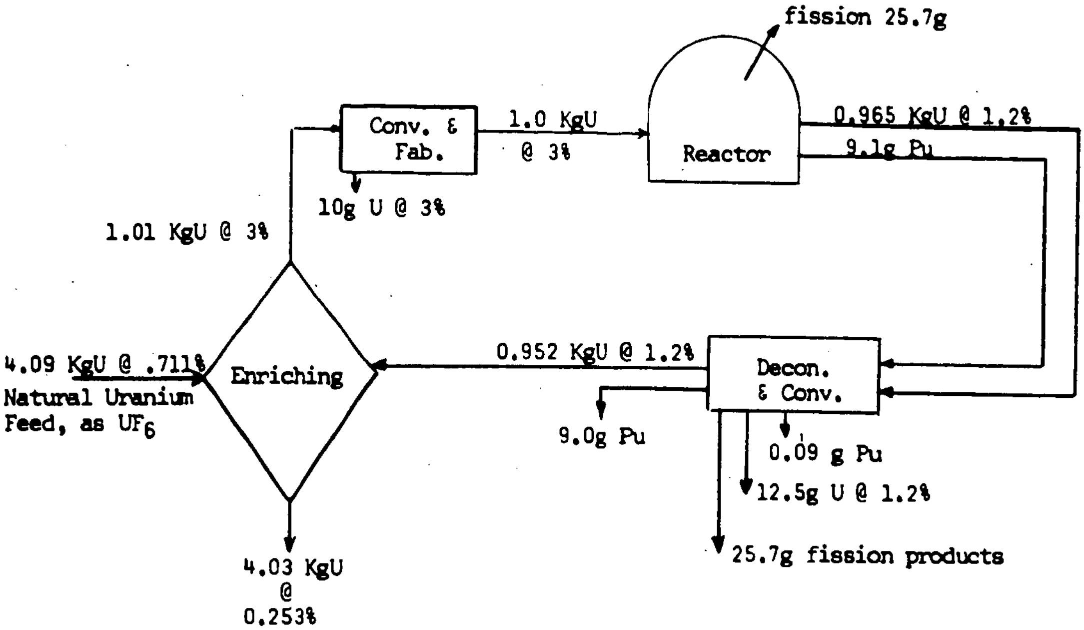


Figure 4

Trends in Capital Cost
Light Water Nuclear Electric Plants

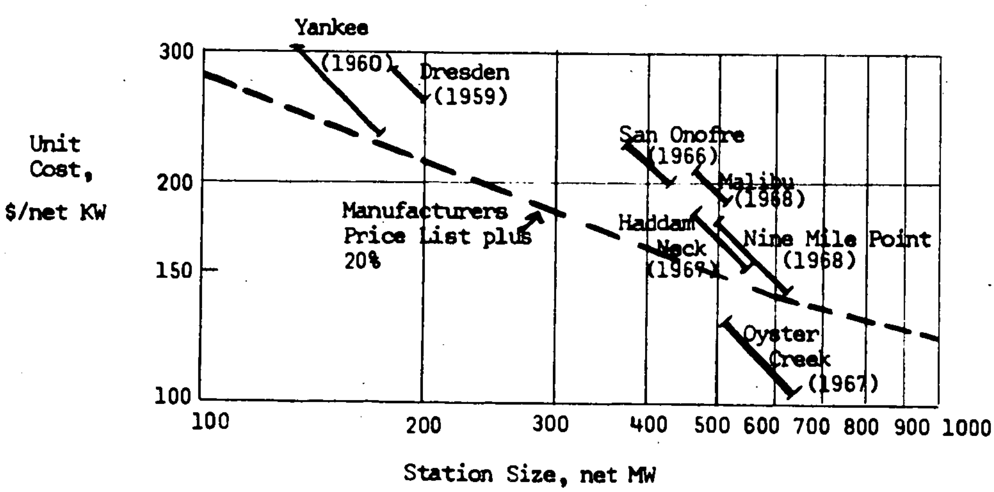


Figure 5

ILLUSTRATIVE EXAMPLE

Fuel Cost Versus Design Fuel Exposure

Light Water Reactor