

THE FACTS OF ATOMIC POWER DEVELOPMENT: SOME ASPECTS OF NUCLEAR POWER ECONOMICS*

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I

Before discussing the economics of atomic power development, it seems desirable that fundamental concepts and terminology be established and defined in terms comprehensible to the nontechnical reader. Accordingly, this discussion will be prefaced by a brief description of the fission process and the type of mechanical gadgetry which accompanies its commercial utilization.

In the production of electrical energy today, we customarily use such fossil fuels as coal, oil, and gas, from which, by chemical reaction with the oxygen of the air, heat energy is released. This heat energy is used to boil water and produce steam. The steam, in turn, is passed through a turbine, the rotating shaft of which is coupled to a generator which produces electricity for transmission to consumers.

Where nuclear fuels—uranium and plutonium—are used, the pattern is quite similar. Significant changes, in fact, are found only in the steam generating unit—reflecting the fact that heat energy is here released not as a result of a chemical reaction, as is the case with fossil fuels, but as a result of a nuclear reaction called fission, in which the basic elemental characteristics of the atom are changed.

Briefly, fission is that reaction in which a neutron strikes the nucleus, or center of a fuel atom, causing it to split into two separate atoms. As the rupture occurs, heat energy is released, and two to three new neutrons are emitted. These neutrons may then go on to split other fuel atoms, initiating a chain reaction.

Since the neutrons emitted when an atom is split may be captured by non-fissionable material or lost to the surrounding atmosphere, one of the basic requirements for an atomic reactor is that sufficient fissionable fuel—in nuclear terminology, a critical mass—be present so that at least one neutron per fission is captured by another fuel atom. If this occurs, a chain reaction will ensue and a sustained amount of heat energy be released. This requirement of a critical mass is one of the most important concepts affecting atomic power economics. Since the critical mass exceeds the daily fuel requirement about a thousandfold, and since the cost of nuclear fuel is about \$9,000 per pound, a substantial fuel inventory charge must be borne as part of the cost of producing electricity.

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When the fuel atom splits, the resultant new atoms are called fission products. They also will capture neutrons but will not themselves split. Accordingly, if they continue to remain in the fuel, ultimately fewer neutrons will strike fuel atoms and the chain reaction will cease. As a result, the nuclear fuel must be removed from the reactor periodically to remove the fission products and/or add new fuel. Unlike coal, for example, another shovelful of nuclear fuel cannot be thrown into the reactor and be permitted to burn to ash. The effect of fission products, thus, is another basic concept which directly affects atomic power economics, in that fuel reprocessing facilities and operating charges become an important part of the cost of producing electricity.

Another important concept affecting atomic power economics is the effect of a fertile material. Two elements—thorium and one of the isotopes of uranium—although they are not themselves fissionable, are transmuted, on the capture of neutrons, into fissionable fuel. They are known as fertile materials, and can either be mixed with the fuel (in which case, the term internal conversion is applied) or placed around the fuel (in which case, they are called blankets). The presence of a fertile material can affect atomic power economics in that it can lengthen the time between fuel processing periods, thereby decreasing the annual costs for fuel handling, fabrication, and reprocessing; and it can also effect the production of new material which, after removal from the reactor, can be used for a continuous supply of new fuel or can be sold at a premium price for special uses, such as weapons.

These three concepts are the important features of nuclear fuels that affect the operating costs of atomic power plants. Other concepts primarily affect capital costs. After heat energy is released from the nuclear fuel, it must be harnessed to boil water and produce steam. Without going into detail, it is evident that this could be done in innumerable ways. Basically, however, the structure in which the reaction occurs—the reactor—must meet the following specifications:

1. The fuel must be subdivided by some means that allows the heat from the fissioned atoms to be transferred to some other medium.
2. The fuel must be supported in its critical configuration so that a chain reaction may occur. Since structural materials capture neutrons without producing fission, it is desirable to use them in as small amounts as feasible, consistent with the demand for support or rigidity; also, since many of the so-called conventional structural metals have a comparatively high affinity for neutrons, the use of many less conventional structural metals is indicated.
3. The fission products, which are highly radioactive, as are other materials which capture neutrons, must be contained so that they are not dispersed outside of the reactor.
4. An adjustable means to control the speed of the chain reaction must be incorporated in the reactor so that the heat release may be equated with the demand for electricity from the plant.

5. Surrounding the reactor, there must be biological shielding to protect the operators from nuclear radiations produced by the neutrons; and around the entire plant there must be either sufficient uninhabited land or a secondary container to protect the public from radioactivity in the event of a reactor failure.

The nuclear fuel, its structure, the reactor, the shield, and associated equipment and controls necessary to produce steam constitute the steam generating unit; and it is this unit alone that is new to power-producing technology. The basic design problem of the atomic power plant manufacturer today, then, is to select, from the multitude of ways to meet the basic requirements, a practical design for a nuclear-fueled steam generating unit that can be built with sufficient integrity, yet at a minimum cost.

II

Evaluation studies of experimental atomic power plants indicate that five design approaches, described in Table I, have today advanced to the stage where commer-

TABLE I

ATOMIC POWER PLANT DESCRIPTIONS

Type of Plant—Pressurized Water

Being Developed Commercially by The Babcock & Wilcox Co. for Consolidated Edison, near Peekskill, New York.

Brief Description—

Enriched uranium fuel† and thorium fertile material, as the metal, are suspended in a pressure vessel filled with water. The water serves as a moderator* for the neutrons involved in the chain reaction. This same water, pressurized to prevent boiling, is circulated past the fuel and fertile material to transfer the heat energy. As it leaves the reactor it is passed through a heat exchanger-boiler where steam is produced. This steam is then passed through a separate oil-fired superheater. Finally, the steam at 1000° F. is put through a turbine-generator where the energy is converted to electricity.

Type of Plant—Boiling Water

Being Developed Commercially by General Electric Co. for Commonwealth Edison and associates, near Chicago, Illinois.

Brief Description—

Slightly enriched uranium fuel† or enriched uranium and thorium, as the metal, are suspended in a pressure vessel partially filled with water, which serves as a moderator*. In this reactor, the pressure is not maintained as high as in the pressurized water reactor, so that the water boils in the reactor. The steam produced in the reactor is then passed directly to the turbine-generator. Some feature such as a flash boiler or feedwater temperature control is used in conjunction with this reactor to control the amount of sub-cooling in the reactor-boiler. Controlling the sub-cooling regulates reactor power. Saturated steam at 600 psi, 486° F., is used to operate the turbine-generator producing electrical energy.

Type of Plant—Sodium-Graphite

Being Developed Commercially by North American Aviation Co. for Consumers' Public Power District of Columbus, Nebraska.

Brief Description—

Slightly enriched uranium fuel† or enriched uranium and thorium, as the metal, is suspended through channels in a large structure of graphite. The graphite is the moderator* for this reactor. Liquid sodium is pumped through the channels past the fuel and fertile material. The energy released from fission is transferred to the sodium, which then passes through a superheater and steam-generator producing steam at 825° F. This steam is used in a turbine-generator set to produce electricity.

Type of Plant—Aqueous Homogeneous

Being Developed Commercially by Foster Wheeler Corporation; also more recently by Westinghouse Electric Corp. for Pennsylvania Power & Light Co.

Brief Description—

Enriched uranium† is dissolved in a heavy water solution. The heavy water serves as both the moderator* and heat transfer medium. This fuel solution is pumped through a pressure vessel which has a configuration that will allow a chain reaction to occur. The heat is released directly in the fuel solution. This solution is then circulated to heat exchanger-boilers where the heat energy is used to boil water producing saturated steam at 600 psi, 486° F. A slurry of thorium is also circulated, either as a separate blanket system or integral with the fuel solution. The heat release in this system is also used to produce steam. The combined steam sources are used to operate a turbine-generator set.

Type of Plant—Fast Breeder

Being Developed Commercially by Atomic Power Development Associates for Detroit Edison and associates, near Detroit, Michigan.

Brief Description—

Enriched uranium† with natural uranium as blanket material—all in the metallic form—are suspended in a vessel which contains liquid sodium. This reactor has no moderator*. Therefore, the physical principles and kinetics are different than in the thermal reactors. Nevertheless, from an engineering viewpoint, this reactor is similar in that the sodium is circulated past the fuel elements where the heat energy released by fission is transferred to the sodium. The sodium then flows through heat exchanger-boilers where steam at 730° F. is produced. The steam, again, is used to operate a turbine-generator set.

* The moderator is usually some light element, such as hydrogen, heavy hydrogen, or graphite, which reduces the kinetic energy of the neutrons after they are released from fission and before they are captured by the fuel. As the neutrons are reduced in energy, there is a greater probability that the surrounding fuel will capture them to produce new fissions. As a corollary however, there is also a greater probability that the structural material will capture them. A reactor using a moderator is called a thermal reactor because the energy of fission neutrons is reduced to an energy which is in equilibrium with the thermal vibrations of the constituent atoms. New fissions are produced using thermal neutrons. A reactor without moderating material is called a fast reactor because the neutrons are used at the high energies, or while they are still fast.

† Enriched uranium refers to uranium enriched in the fuel isotope, U-235. Since natural uranium has only .7% U-235, the balance being constituted of nonfissionable U-238, it is often advantageous thus to increase the U-235 concentration.

cial development appears to be imminently feasible. It is the intent of the writer to present some of the cost data developed by manufacturers of these plants and to discuss the factors which may modify these presently estimated figures. Secondly, the writer hopes to point out some of the limitations that must be acknowledged in extrapolating the cost data of this interim period in the history of atomic power development. And lastly, some comparisons will be drawn concerning the competitive position of nuclear and fossil fuels.

CAPITAL COSTS

The broad range of estimated capital costs, as set forth in Table II, is attributable to many factors. Apart from inherent physical differences among the plants and the varying amount of work that the AEC has already undertaken with respect to each, one of the most significant of these factors is the fact that in each case, the manufacturer has adopted a different method of writing off developmental costs. From AEC experience, as well as from experience in more conventional industries, it is not improbable that the developmental costs of a new plant may be one hun-

TABLE II
ESTIMATED CAPITAL COSTS

Type of Plant	Size (In Kilowatts)	Capital Cost (In thousands of dollars)	Cost per Kilowatt
Pressurized Water.....	236,000	\$55,000	\$233
Boiling Water.....	180,000	45,000	250
Sodium-Graphite:			
Uranium fuel.....	75,000	22,500	300
Uranium-thorium.....	100,000	26,500	265
Aqueous Homogeneous.....	100,000	21,000	210
Fast Breeder.....	100,000	45,000	450
Conventional Coal.....	100,000	16,566	166

dred per cent or more of the actual construction costs. Accordingly, charging these costs in their entirety to the first plant certainly does not indicate what might be the cost of other plants of the same type, if we can expect more to be built in the near future. Therefore, perusal of the estimated capital costs of these first plants may be misleading unless one has some estimate of the developmental costs included and a measure of the amount by which they may be decreased as subsequent plants are built. These data are difficult to obtain, however, since their determination is governed by internal company policy and since changes in reactor technology are occurring so rapidly that no concise approach to the proration of developmental costs can be formulated at present. In addition, manufacturers have had to build new facilities or extend existing ones, hire new personnel, and reorganize their working arrangements, and the extent to which these factors have contributed to the costs of first plants cannot accurately be determined.

TABLE III
ESTIMATED OPERATING COSTS
(In Mills per Kilowatt-Hour)

Type of Plant	Capital Charges (at 16%)	Labor and Maintenance	Fuel* Inventory	Fuel† Operating	Total
Pressurized Water.....	5.4	1.0	0.2	2.0	8.6
Boiling Water.....	5.7	0.8	0.2	1.7	8.4
Sodium-Graphite:					
Uranium fuel.....	6.9	2.0	0.45	2.0	11.35
Uranium-thorium.....	5.8	1.5	0.5	1.5	9.3
Aqueous Homogeneous.....	4.8	2.0	0.2	1.2	8.2
Fast Breeder.....	10.0	1.0	0.5	-0.2‡	11.3
Conventional Coal.....	3.8	0.6	negligible	3.0	7.4

*Fuel inventory charges are based on the existing price policy of the AEC.

†The fuel operating charge includes charges for fuel and fertile material fabrication, fuel and fertile material handling, reprocessing, and the purchase of new material to replace that which has been burned up or lost in the process. If the reactor produces new fissionable material, any credit for the sale or recovery of that material is deducted from the charges listed.

‡Since the fast breeder can produce high-grade fissionable material in excess of that needed for fuel, the credit for sale at a premium more than exceeds the fuel operating charges. A breakdown of charges and credits is as follows: fuel operating charges 5.6 mills, credit for sale of new fissionable material 5.8 mills. This condition would be drastically changed if the premium price for high-grade fissionable material were canceled or reduced.

In order to arrive at some figures that will indicate the magnitude of cost reductions necessary to render nuclear fuels competitive with fossil fuels, the effects of capital and operating costs will be separated by making certain arbitrary assumptions. The possibilities for reduction in each of these categories can then be discussed as they apply to the plants now under design.

Let us assume, then, that operating costs will remain the same, as estimated in Table III. Further, let us assume that atomic power will become competitive when total production charges are brought below eight mills per kilowatt hour. It is now possible to calculate the magnitude of the reductions in capital costs necessary to produce power at a cost nearly competitive with the power produced from fossil fuels. Reductions in operating costs would lower electrical production charges still further so that a definitely competitive position would be established. Table IV summarizes these calculations.

Examining Table IV in the light of a convenient cost breakdown for atomic power plants, the percentage capital cost reduction necessary to make these plants

TABLE IV
THE DIFFERENCE BETWEEN ALLOWABLE AND ESTIMATED CAPITAL COST

Type of Plant	Revenue Available for Capital Charges (In mills per kw-hr)	Equivalent Capital Cost	Estimated Capital Cost	Difference
		(In Thousands of Dollars)		
Pressurized Water.....	4.8	48,889	55,000	6,111
Boiling Water.....	5.3	41,841	45,000	3,159
Sodium-Graphite:				
Uranium fuel.....	3.55	11,576	22,500	10,924
Uranium-thorium.....	4.5	20,560	26,500	5,940
Aqueous Homogeneous.....	4.6	20,150	21,000	850
Fast Breeder.....	6.7	30,200	45,000	14,800

competitive can also be calculated. Since some components of the atomic power plant are rather conventional it would be unreasonable to assume that much developmental cost will be encountered in those areas. Accordingly, for our purposes, an atomic power plant may be divided into three major components: site and structure, steam generating plant, and steam-electric conversion plant. An average cost breakdown, applicable to all power plants, would be:

	<i>Atomic</i>
Site and Structure	25%
Steam Generating Plant	40%
Steam-Electric Plant	35%

Assuming, then, that the cost of structures and steam-electric plant will not be greatly changed by continued development, as they are quite similar to conventional equipment, the percentage capital cost reductions in the steam generating plant that

TABLE V
NECESSARY COST REDUCTION IN STEAM GENERATING UNIT

Type of Plant	Reduction Necessary	Estimated Cost Appropriated to Steam Generator	Percentage Reduction Necessary
	(In thousands of dollars)		
Pressurized Water.....	6,111	22,000	28%
Boiling Water.....	3,159	18,000	18%
Sodium-Graphite:			
Uranium fuel.....	10,924	9,000	121%
Uranium-thorium.....	5,940	10,600	56%
Aqueous Homogeneous.....	850	8,400	10%
Fast Breeder.....	14,800	18,000	82%

would render atomic power competitive can be calculated. An analysis of these figures, as set forth in Table V, in the light of possible developmental costs attributed to the first plants, would seem to indicate that it is not unreasonable to expect that continued manufacture of atomic power plants will soon effect these reductions.

Another factor which must be considered in connection with the reduction of capital costs is the possibility of increasing power output from the reactor by overcoming existing temperature limitations and increasing steam plant efficiency. A one per cent increase in power output with no increase in over-all capital cost would be equivalent to a two and a half per cent reduction in the capital cost of the steam generating unit in the example given. One cannot expect large gains to be effected in this way because of the extensive metallurgical advances that must be made before appreciable increases in temperature can be tolerated. But even as steam temperatures have increased in conventionally fueled plants over the past twenty-five years, so it seems not unreasonable to expect that continued improvements in atomic plant efficiency will similarly serve to reduce the cost of generating electricity from nuclear fuels.

Unfortunately, an analysis of this type is too general to afford specific conclusions regarding the economics of atomic power. Nevertheless, trends can be discerned and discussed with particular reference to each reactor type.

In the pressurized water reactor, the principal developmental item influencing capital costs is the investigation of alternate construction materials. Stainless steels are used for most of the primary component equipment today; but if it becomes evident from experience that carbon steels can be so used, substantial reductions in cost could result.

The boiling water reactor's major developmental problem concerns the connection of the steam plant to the turbine-generator. This problem is ramified by the requirements for controlling the reactor and keeping contamination in the turbine plant at a low level so that maintenance procedures can be simple. A satisfactory solution to this problem could markedly reduce the capital cost of this reactor. Moreover,

the steam pressure and temperature for these first reactors have been chosen conservatively, and experience may show that they can safely be increased and more power extracted per unit volume, thereby effectively reducing the capital cost per unit power output. The extent of these reductions, however, cannot be evaluated until more experience is gained.

The sodium-graphite reactor as well as the fast breeder reactor has a high capital cost today, a result of the large number of precision-machined parts required for the reactor complex. Only experience will show where the demand for strict tolerances can be relaxed or techniques improved and costs decreased. Also, since both of these reactors employ a liquid metal heat transfer medium, it seems likely that steam temperatures could be increased without adding substantially to reactor costs. And although the temperatures are, at present, limited by fuel metallurgy, the characteristics of new fuel alloys appear to permit this increase. Accordingly, if continued development substantiates the presently meager data, power output per reactor could be increased, appreciably lowering capital cost per kilowatt. In fact, preliminary estimates for the sodium-graphite reactor indicate that increasing the temperature to that indicated by these early experiments would reduce the effective over-all capital cost by approximately twenty-five per cent. This is equivalent to a sixty per cent reduction in the steam generating unit cost, as computed in Table V. Since it is greater than the fifty-six per cent reduction necessary when using uranium-thorium, increasing the temperature would make this reactor competitive.

Two major developmental problems are contributing to the capital cost of the aqueous homogeneous reactor; the fabrication of large components with the required quality control using corrosion-resistant material, and the design requirements for complete remote maintenance of the major components. This latter item is more important in the homogeneous reactor than in any of the others because the circulating fuel seriously contaminates all of the major pieces of equipment. As a result, special precautions must be built into the plant to permit maintenance under quite unusual conditions. Were it not for this problem, the aqueous homogeneous reactor could have a relatively low capital cost.

In all of these reactor types, the fabrication of new metals in the sizes and shapes required is adding considerable cost. As soon as sufficient manufacturing facilities and techniques are established, it would seem probable that capital costs will begin to decrease.

OPERATING COSTS

Up to this point, only the reduction in capital costs has been discussed as a means of achieving competitive atomic power—and, of course, it is the most effective means to this end since capital charges constitute the major component of the price of generated electricity. Nevertheless, some marked reductions in the cost of atomic power may be achieved in the area of operating costs. From Table III, it may be observed that the important operating cost is the fuel operating charge, which is composed of three interrelated charges—fuel fabrication, reprocessing, and replacement

of burned or lost fuel. The factors influencing these costs are too numerous and complex to treat in detail here, but, in general, the following major approaches are being taken to minimize them:

1. Judicious nuclear design using special fuel alloys which minimize radiation damage can lengthen the time that each fuel element can stay in the reactor, thus reducing annual charges for fuel fabrication and reprocessing.
2. Continued modification of fuel element design so that mass production techniques can be utilized to reduce fuel fabrication costs.
3. Careful selection of fuel alloy materials and reprocessing techniques which are compatible can reduce the number and cost of the steps necessary to separate the fission products from the fuel.
4. Continued investigation of the properties and characteristics of fuel in liquid form could lead to the elimination of the need for metallurgical fabrication and make reprocessing a simpler operation.

Relating these approaches to the specific reactor types being discussed, it appears that in the pressurized water and boiling water reactors, the problem is essentially the same. The relative incompatibility of water and uranium has forced the designers to use fuel alloys which are more difficult to fabricate and reprocess. Further, costs are high because of the inability to recover the waste material from the fabrication operation in an economical manner. Processes and techniques to reduce the amount of waste or to recover it economically would, thus, result in decreasing the fuel operating charges. Also, the use of thorium as a fertile material in these fuel elements would markedly extend the length of time that an element could stay in the reactor. Metallurgical problems, however, must be overcome before the combination of thorium-uranium will be an economic fuel element. Satisfactory solutions to these problems could, however, reduce fuel operating costs in these reactor types by a factor of two or more.

In the sodium-graphite reactor, the problems are similar, although the compatibility of sodium and uranium is better than that of uranium and water. This characteristic could lead to the development of a fuel element that might still have a long life, but be somewhat easier to process. Fabrication costs are still quite high, however, and the presence of sodium, which reacts violently with water, further increases handling costs when aqueous processing is used. An alternate type of processing and modified fabrication techniques may reduce this fuel operating cost.

The peculiar characteristics of a fast breeder reactor require that a larger amount of fissionable material be processed than would need be for the same power output in a thermal reactor. Accordingly, fuel operating costs will be relatively high until an alternate to aqueous processing is developed. Pyrometallurgical processing seems to afford a solution, provided it can be operated remotely with sufficient control. Successful development of a process of this type could reduce the fuel operating charge for a fast breeder reactor to a fraction of today's estimates.

The aqueous homogeneous reactor promises lower fuel operating costs than any of the other reactors discussed. The fuel is in a convenient form for handling and needs no metallurgical fabrication. Changes in the chemical form will need to be effected, however, and these operations, though well-known, become somewhat costly when they must be done by remote means. Continued improvement in the process techniques may lower fuel operating costs of this reactor, but the reduction will probably not be as marked as in the solid fuel reactor types, as these costs are already estimated to be comparatively low.

III

During this interim period in the history of atomic power development, any discussion of costs necessitates a number of intuitive or educated guesses. To sort out the multitudinous factors influencing costs is almost an analytic impossibility. It is encouraging, however, that the price tags being placed on the first atomic power plants being commercially produced bring the electrical production charges to a level almost competitive with fossil fuels. It would seem that as a multiplicity of similar plants are built and operating techniques improved, nuclear fuels will achieve a competitive position with fossil fuels—especially in those areas where fossil fuel costs are high.

Besides the reactor types discussed, recent announcements by the AEC seem to indicate that two other design approaches are also reaching the stage where commercial development may become feasible. These are the liquid metal homogeneous reactor and the organic moderated reactor. To date, however, there has been no prototype experience with either, and, accordingly, the economics of their operation is still quite vague. But preliminary studies would seem to indicate that the technological improvements which have led to their development may also be reflected in economic improvements.

The acid test for any atomic power plant is actual operating experience. Therefore, until these first commercial plants are installed and operated for a reasonable period of time, no one will know to what extent design modifications are feasible or how the various economic factors influence the actual costs. That private industry is willing to share with the AEC a large part of the developmental costs of these first plants, however, would seem strongly to indicate that competitive atomic power is not far ahead.

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