NUCLEAR FISSION AS A SOURCE OF POWER*

By J. R. MENKE

1. Introduction

THE announcement of the atomic age on August 6, 1945 at Hiroshima brought to a close its scant fifty-year period of gestation. Civilization is thus presented by the new era with significant new problems: we may classify these problems in three groups as the enlightened use of:

1. Atomic bombs and energy by the military,
2. Nuclear research tools by science,
3. Fission energy as power by industry.

The first class, enormously important in its negative, dangerous aspects implies political problems portending "one world or none." May that portent be a good one. The second class holds forth all the promise of new insight into medicine, biology, chemistry, and physics. In these fields a new "one world" could achieve prosperity. This paper will deal with the third, possibly least important class, the effect of atomic energy on the cost of power. Such discussion is a necessary preliminary step to any analysis of the total economic effect of atomic energy and of the policies that might maximize its benefits to society. The economic problems of nuclear energy and the need for adequate policy have in fact been recognized in the atomic-energy bill passed by the Congress.[1]

The examination of the effect of nuclear fission, a source of atomic energy, on the cost of industrial power will constitute the problem of this paper. At present the only feasible agency for making use of atomic energy is the pile. It will be valuable here to give a brief, functional description of such a pile within the limits of security.

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* Cowles Commission Special Paper, No. 1. Numbered references in square brackets refer to items in Bibliography at the end of this paper.

The author wishes to state that the paper was substantially completed in June, 1946, and declassified in June, 1947. This accounts for the absence of reference to the report prepared under Dr. Charles A. Thomas and published in the latter half of 1946 on behalf of the United States representative to the United Nations Atomic Energy Commission. Data from this report have been used in the analysis by Sam H. Schurr (*American Economic Review*, Vol. 37, May, 1947, pp. 98–108) to be circulated as Cowles Commission Special Paper No. 2. (See also Philip Sporn's discussion, and Schurr's reply, *ibid.*, pp. 110–117.)—MANAGING EDITOR.

[1] The Atomic Energy Act of 1946 [1] states that "Research and experimentation in the field of nuclear chain reaction have attained the stage at which the release of atomic energy on a large scale is practical. . . . It is reasonable to anticipate, however, that this new source of energy will cause profound changes in our way of life."

The bill provides specifically for: "A report to the President . . . stating the Commission's estimate of the social, political, economic and international effects of such use . . . and recommendations for . . . supplemental legislation."

2. Description of a Pile

2.1. In general usage the term "pile" means a lattice of fissile material, such as uranium 235, with moderator, shield, controls, and other necessary appurtenances arranged to give a controlled fission chain reaction. It is not considered within the scope of this report to give more than an economic viewpoint.[2]

In one functional respect a pile is similar to a hydro-electric plant with its many products such as energy, water for irrigation, flood control, navigation, fish propagation, etc. It is even more similar in an economic sense to a chemical plant with its many products which can be sold or fed back into the production processes.

A pile may be considered as a source of three things:

A. Energy:
  a. heat,
  b. other local radiations;
B. New fissile material such as plutonium;
C. Other radioactive elements.

Dependent upon the design, a pile can be built to emphasize the production in useful form and amount of any or all of these products.

2.2. We will consider the composition of the input (cost) first, and, later, each of the products separately, both qualitatively and quantitatively.

Input: A. Materials:

a. A certain amount of fissile material, say uranium 235.

b. About an equal amount of a cheap and relatively plentiful fertile material such as uranium 238, the more abundant isotope in natural uranium, as more fully discussed below.

c. Other materials such as moderators, coolants, and chemicals for purification.

B. Labor:
  a. For operation of pile and heat engine.
  b. For maintenance.
C. Fixed Costs:
  a. Interest on investment.
  b. Depreciation and insurance of plant.
  c. Overhead for supervisory personnel.
  d. Taxes.

While all the input costs may be important, we shall keep in mind the unit of input of one pound of, say, uranium 235 for the discussion of products which follows.

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[2] Sources giving descriptions of piles from different viewpoints are references [2], [3], [4], [5], [6], [7], and [7a].

2.3. A. At present the pile can be considered as a source of commercial energy only in the form of heat. It is this heat energy that is thrown away at Hanford in such enormous quantities because it is available only at a small temperature difference relative to the cooling water. Nevertheless, this heat will undoubtedly become available in a useful form in the future, that is, with a usefully large temperature difference.[3] In the generation of heat the pile is analogous to a furnace used to burn coal and heat water in a steam-boiler power plant, or to a furnace used to supply process heat in any industry.

Local radiations, a form of energy, such as X-rays, might conceivably be used on the spot for industrial or medical purposes. But it is not likely that they will assume economic importance in the near future.

B. A new fissile element such as plutonium is more difficult to recognize as an economic good. The difficulty lies in the fact that it has two uses:

a. Military, for bombs;

b. Economic, as fuel for piles.

Strictly speaking, it has two values, the first of which is very difficult to measure. By assuming extreme values for the military demand we can avoid this difficulty.

C. The other radioactive elements, the fission fragments, have utility in research and probably in other limited-demand fields. If, for instance, the problem of the photosynthesis of organics can be solved with radioactive tracers as tools of research, then the available amount of food and energy can be increased enormously. While these radio-elements have enormous usefulness as research tools, it is not likely that they will quickly become products of economic importance in themselves.

2.4. The above qualitative description of the pile product can be pictured as coming from a plant such as that shown schematically in Figure 1. Figure 2 is added directly under Figure 1 to show the degree of similarity of a pile power plant and an ordinary coal-burning power plant.

It will be seen that the diagrams are identical on the right-hand sides. There is no important difference between the systems that make use of heat from the pile and heat from the coal furnace. This similarity enables us later to estimate the cost of operation and maintenance of that part of the pile system from published data on steam power plants.

The quantitative question now arises: how much product for a unit input, one pound of fissile material?

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[3] Reference [4]; especially paragraph 4.10, 6.32, 6.41, 8.54; and Reference [7].

2.5. Products: A. Energy. The amount of energy released in a typical fission process is well discussed in the literature. Smyth in his official report said that roughly 200 million electron volts of energy are released in every fission. This is equal to about 10 million kilowatt-hours of heat per pound of uranium 235 or plutonium fissioned.[4]

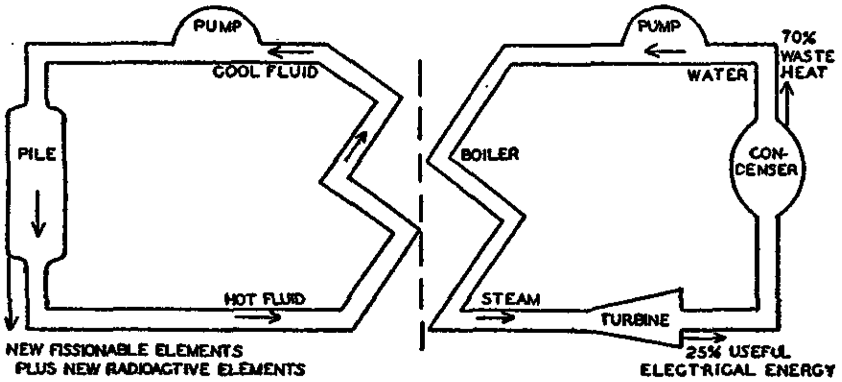

FIGURE 1.—Pile-steam electric power plant, schematic.

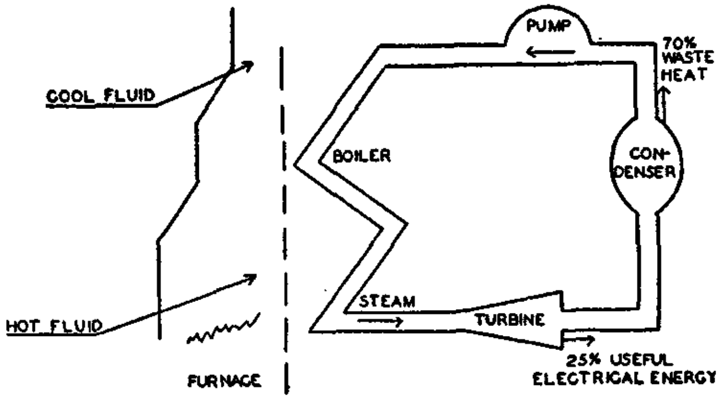

FIGURE 2.—Coal-steam electric power plant, schematic.

2.6. B. New Fissionable Elements. The amount of new fissile elements formed per pound of uranium burnt (fissioned) is now held secret. However, references are made in the literature that permit a useful approximation to be made. Two early references may be cited that estimate the number of neutrons emitted per fission: Szilard and Zinn

[4] There are references in the literature which estimate 11.4 million kilowatt-hours per pound [2] and [6], probably too high.

[10] about 2.3 neutrons per fission; and v. Halban, Joliot, and Kovarski [11] about 3.5 neutrons per fission. Two later but less definite references can also be cited: Smyth [4] about one to three neutrons from fission process; and Wigner [5] about two neutrons per fission. These results are summarized in Table 1. The diagram, Figure 3, from Smyth [4] illustrates the fission process well.

TABLE 1

NEUTRONS PER FISSION

Source	Date	Estimate
[10]	1939	about 2.3
[11]	1939	about 3.5
[4]	1945	between 1. and 3.
[5]	1946	about 2.

Let us choose the latest published estimate, two neutrons per fission, for our purposes. It is, also, reasonably close to the average published estimate. These neutrons are either:

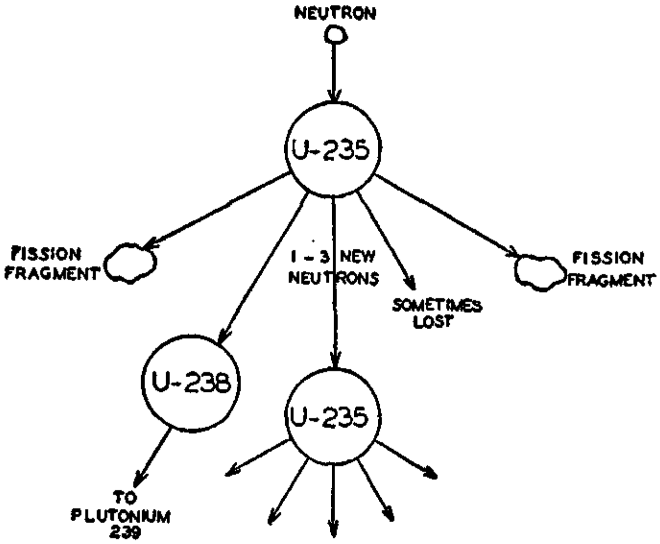

FIGURE 3.—Fission process.

a. wasted,
b. used in the "chain" reaction to cause the next fission, or
c. used to make plutonium.

If the number of effective neutrons, N, is as small as one, then the chain reaction will just continue producing energy, but without producing any new fissile element, until it has "burnt" up too much fissile material to maintain its "critical" size. Since it is known that the pile at Hanford did produce plutonium, it is apparent that N, the effective number of neutrons per fission, can be made greater than one.

If N is equal to two, then the chain reaction will continue and will in addition produce as much new fissile material as it burns old.

If N is more than two, then the chain reaction will continue, will replenish what it burns, and will in addition create some new fissile material left over to "sell." One can, of course, also "sell" the new fissile material that might have been used to replenish the pile. The pile would then eventually burn itself out again, slowly or quickly, depending only upon the amount of fissile material built into it and upon the rate at which this is burnt.[5]

Two effective neutrons per fission as assumed here will, therefore, yield about one pound of *new* fissile element for each pound of uranium 235 burnt.

2.7. Products: C. New Radioactive Elements. For each pound of uranium 235 that undergoes fission we will get almost one pound of

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[5] In this regard the safeguarding of resources must also be considered. The optimum use of available supplies of uranium and thorium requires long-range planning. Dr. Szilard [8] before the Senate Committee on Atomic Energy testified: "With your permission, I will assume that the quantity of fissionable substances which can be produced might be expected to increase from year to year in geometrical progression . . . the time in which the production would double might be less than 1 year and might be more than three years . . . the years from 1946 to 1949 or from 1946 to 1958 ought to be considered as 'the building-up period.' During such a period it might not be advisable to divert any substantial quantities of the fissionable substances for the purpose of being 'burned' in order to produce electrical power. After such a 'building-up period,' however, there is no reason why we should not 'burn' up some 20 tons of fissionable material per year and produce electrical power at the rate of about 15,000,000 kilowatts." Also see J. A. Wheeler [3] for description of these regenerative processes: "The other possible outcome is more favorable to economy of raw materials. In every day of operation in which we destroy 1 kg. of fissionable material we synthesize from an inert substance more than 1 kg. of new fissionable material say, for example, 1.1 kg. In this case we leave 1 kg. of the new product in the plant to make up for the losses of the day and remove the other 0.1 kg. to help start up a new pile; or, if necessary to help make atomic bombs. In case we can achieve this outcome, there is no need for us to supply new fissionable material to our plant from the outside except to get it started. After it is in operation we could even feed it as raw material uranium from which all of the active constituent, U^{235}, has been extracted, although it would be cheaper to use natural uranium. The plant itself will convert the inactive uranium to fissionable material for use in the chain reaction. Evidently we have only to design a plant with sufficiently good regeneration characteristics in order to use for power purposes all the uranium, not merely the rare constituent U^{235}."

new radioactive elements. The fission fragments are the new radioactive elements and weigh within a few per cent of the original unbroken nucleus.

A list of elements suggested by the Smyth Report [4] as found in the normal fission chain reaction is given in Table 2.

TABLE 2

FISSION PRODUCTS

Mass Numbers 83–115		Mass Numbers 127–154
Selenium		Antimony
Bromine		Tellurium
Krypton		Iodine
Rubidium		Xenon
Strontium		Cesium
Yttrium	more abundant fragments	Barium
Zirconium		Lanthanum
Columbium		Cerium
Molybdenum		Praseodymium
*Masurium		Neodymium
Ruthenium		*Illinium
Rhodium		Samarium
Palladium		Europium
Silver		Gadolinium
Cadmium		
Indium		
Tin		

* Names not definitely assigned

Other elements [3], [9] can be activated by subjecting them to the tremendous neutron bombardment available in the pile. However, these elements use up neutrons that would otherwise cause fission (produce power) or make plutonium. They are thus not the normal consequence of the chain reaction.

2.8. To recapitulate, then, for *each pound of fissioned* (burnt) *uranium 235* together with one pound of ordinary uranium we get:

a. about *10 million kilowatt-hours* of energy in the form of heat,
b. about *one pound of new fissile element* (e.g., plutonium),
c. about *one pound of new radio-elements.*

$$1.\,\text{lb.}U^{235} + \sim 1.\,\text{lb.}U^{238} \cong 10. \times 10^{6}\ \text{kw-hrs.} + \sim 1.\,\text{lb.}Pu^{239} + \sim 1.\,\text{lb. radio elements.}$$

More complete descriptions of piles and pile operation, but from different points of view, are given in the literature from which this description is taken.

3. Resources

3.1. Only if the total amount of nuclear energy available in metals at mineable concentrations is significantly large is it worth while to consider the cost.

Uranium and thorium are the most likely primary, natural sources of nuclear energy for the reasonably foreseeable future. Both elements are metals of moderate abundance in the earth's crust. Roughly, the two metals, taken together, are as abundant, let us say, as lead. However, they do not occur in well-segregated ore bodies like lead, silver, and gold. They are of an ubiquitous nature, being found in many igneous, and sedimentary rocks, almost always in very low concentration [12], [13], [14], [15], [16], [17].

3.2. Information available before 1941 [23], [24], [25], [26], [27], [28] indicates that the then known "commercial deposits" of uranium contained about *10^8 pounds* of metal. These deposits are mainly situated: in the Belgian Congo, at the copper mines in Haut Katanga; in Canada, at the Great Bear Lake; and in the United States, in Colorado and Utah. "Commercial deposits" might be defined as greater than one-per-cent concentration in the ores mined before 1941. Goldschmidt [19] suggests that about 4 parts per million of the earth's crust is uranium. If we estimate that one-third of the earth's area, 6×10^7 square miles, is available, then 4 parts per million represents a total of about *10^{16} pounds* of uranium in a 3-mile deep layer. (The earth's crust weighs about 3×10^{13} pounds per cubic mile.) The deepest mines are now about one mile deep; the deepest holes, oil wells, are about three miles deep.

There is, therefore available to the world somewhere between 10^8 and 10^{16} pounds of uranium. The demand for energy in the world and in the United States in 1940 has been estimated [19], [20], [21], [22], and is shown in Table 3.

Table 3

Energy Demand

	United States	World
Coal	$500. \times 10^6$ kw.	$2000. \times 10^6$ kw.
Petroleum products	300.	500.
Natural Gas	100.	100.
Water Power	10.*	25.
Total	$900. \times 10^6$ kw.	$2600. \times 10^6$ kw.

* This value is inconsistent with U. S. Bureau of Mines' figures [18] which give about 130×10^6 kw. which is corrected for an arbitrary efficiency.

World fuel consumption in all forms recently is therefore equivalent to about 2×10^6 pounds of uranium per year. The full utilization of uranium 235 and uranium 238 which goes to make plutonium is assumed here [29], [30], [31], [32]:

$$\frac{2600 \times 10^6 \times 8.6 \times 10^3}{10.3 \times 10^6} = \frac{\text{kw.} \times \text{hours/year}}{\text{kw-hrs./pound U}}$$
$$\cong 2 \times 10^6 \text{ pounds U/year.}$$

It will be seen then that even the minimum figure of 10^8 pounds of uranium is a significant reserve of energy, more than is available in proven petroleum reserves (equivalent to less than 10^7 pounds of uranium) but much less than is available in coal reserves (equivalent to more than 10^{11} pounds of uranium); see Table 4.

TABLE 4.
WORLD RESOURCES
(In terms of uranium)

	Available
Minimum Uranium	about 10^8 pounds
Petroleum	less than 10^7 pounds
Coal	more than 10^{11} pounds

The minimum amount of uranium available alone constitutes a significantly large reserve of power and consequently warrants further economic study as a source of power.[6]

3.3. Thorium is probably a source of power of similar magnitude to uranium. While many of the published studies of thorium date back to 1910–1915 when it was widely used as thoria in Welsbach incandescent gas mantles, a general estimate can be made from these old and incomplete data. Sands that contain the mineral monazite are found in three important localities: in the province of Travancore on the southwest tip of the Indian Peninsula, in Brazil, and in the United

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[6] Estimates of mineral reserves must be accepted in the proper light. Uranium and thorium are only recently (within less than, say, forty years) in great demand and figures quoted above are only from information available before 1941.

The testimony of R. E. Wilson of the Standard Oil Company (Indiana) before the Special Committee Investigating Petroleum Resources, U. S. Senate, October 3, 1945 can be repeated here with value in the discussion of mineral reserves:

"The unfortunate experiences of our sober and highly regarded U. S. Geological Survey makes any group reluctant to undertake projections except with many reservations—in 1918 the Survey estimated the total crude (oil) reserves underlying the country to be around 6,500,000,000 barrels and most contemporary geologists were inclined to concur. Actually we have since that time produced 25 billion barrels and have today proven producible reserves of more than 20 billion barrels, a total already seven times that estimated by the survey."

In 1918 oil had been an article of commerce for fifty years.

States, in North Carolina, and Virginia [33], [34], [35], [36], [37], [38], [39].

Indications are that the larger sand deposits in Brazil and Travancore contain in 0.5–1.0% concentration between *10^7* and *10^8 pounds* of thorium. Estimates by geochemists of the concentration of thorium in the earth's crust, about 11.5 parts per million, taken for the same part as was considered before, yield a total of *10^{16}–10^{17} pounds* as an upper limit for the total thorium available. Thorium, then, is also a a significantly large reserve of power.

Goldschmidt [20] suggests that both uranium and thorium belong to a "silicon" group of rock-forming minerals, that is minerals that do not separate out of a silica-high solution. This theory is consistent with the large over-all abundance of the two minerals and with the general rarity of rich segregated ore bodies. However, one might argue instead that the search for the two minerals is new and incomplete.

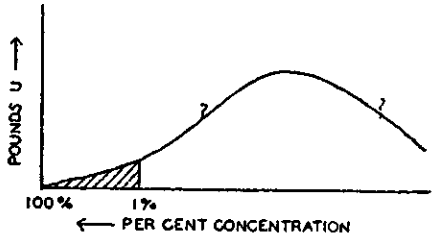

Figure 4.—Reserves as a function of concentration.

3.4. To conclude the consideration of our first factor in the cost of nuclear power, the relative importance of the total amount available, we will look more closely into the availability of the totals delineated in Sections 3.2 and 3.3. Ideally, we should know the function, indicated in Figure 4, that gives the amount of material available to the world at each concentration of metal in the ore. Dr. Clark Goodman [20a] of the Massachusetts Institute of Technology was able to approximate this function for the United States. In the rough terms in which such estimates must be made, Table 5 gives some of his results together with cost estimates made by the author.

Table 5

Reserves and Costs

Concentration	Pounds of metal in U. S.	Cost per pound of metal
1.0% and higher	10^7	
0.1%	10^8	$ 5.
0.01%	10^9	$ 50.
0.001%	10^{10}	$500.

The cost estimate has been obtained as follows: The product of the 1937 price of many metals with the concentration of metal in marginal mines gives an average figure of about 0.5 cent per pound of ore. Since the work involved in each case was common to any type of underground mining it is not surprising that nearly a constant figure resulted. Clearly no answer is given here to the question as to the range of concentrations at which the economic limit of mining will be found. That is a proper subject for a detailed future study. At least it is clear that the amount available is indeed significant.

4. Effect of Atomic Energy on the Cost of Power

4.1. The effect of atomic energy on the cost of power can be examined by considering the following factors:

a. the present cost of power and its variation with coal price,
b. the anticipated cost of nuclear power,
c. the probable future cost of nuclear power,
d. other factors beside cost that determine the feasibility of power plants.

Let us now examine the first problem, the present cost of power.

In comparing the cost of producing electrical power by nuclear fission and the cost by coal-burning, steam-electric plants, a word of warning is needed. No implication is meant here that uranium will *substitute* for coal. Coal will retain its value as a chemical, e.g., in the reduction of ores and in the synthesis of organics. Furthermore, coal will retain a strong position as a fuel, both because of the enormous coal reserves and because of an awakening technology.

The similarity shown in Section 2.4 permits a more direct comparison than do the other forms of utilizing energy. It will be convenient to consider the cost to the generating plant of the electric power produced "*at the bus-bar*" [40], [41], [42], [43], [44], [45]. This means that costs of the generating station, both fixed and direct, will be considered. However, the costs of transmission, distribution, and customer relations (meter reading and bill collecting) will not be considered. These latter categories represent about ⅔ of the domestic consumer's bill.

4.2. What then, is the cost of electrical power at the bus-bar? Data compiled from the sources given above indicate that coal-steam electric power costs from 0.4 to 1.5 cents per kilowatt-hour in representative plants in the United States and, in comparison, that hydro-electric power costs from 0.05 to 0.4 cent per kilowatt-hour. Sales *revenue* for both forms in the United States for 1940–44 averaged between 1.7 and 1.5 cents per kilowatt-hour. The difference is represented mostly by the distribution costs. Large consumers pay very little more than the bus-bar costs for power; representative data for them are given in Table 6 [40], [41].

TABLE 6

BUS-BAR COSTS OF POWER

Consumer Plant Type	Power Source & Remarks	Cents/kw-hr.
Aluminum (Aluminium Co. of Canada, Ltd.)	Shipshaw, Quebec hydro At least partly subsidized by U. S., Canada, & Grt. Britain on capital costs (interest & depreciation) $\backsim 10^6$ kw Saguenay R., Quebec [40]	0.05–0.06
Aluminum (Aluminum Co. of America)	Niagara, TVA, Bonneville 8 private hydro-plants: $\backsim 0.5 \times 10^6$ kw. from private; and $\backsim 0.1 \rightarrow 0.5 \times 10^6$ kw. from public power plants. Private plants have been rapidly depreciated. [40]	0.13–0.15
Aluminum (Reynolds and Bonneville—Metals & other hydro Defense Plant Corp. plants) [40]	hydro	0.2–0.25
Aluminum Seven other more or less "uneconomic" (war) plants for aluminum production	*various [40]	0.3–0.9
Sodium, chlorine, fused alumina, silicon carbide, calcium carbide, etc.	Niagara hydro [41]	$\backsim$0.35
Ferro-alloys, zinc refining [41]	*various	0.3–0.5
Copper refining, electrolytic [41]	*various	$\backsim$0.7 and up to 1.5

* various = hydro and coal-steam.

The higher cost figures indicated represent coal-steam power. In these industries the costs are unusually low because of the high load factor (ratio of average demand to plant capacity), in some cases approaching 100 per cent compared to about 50 per cent or less for average utilities. Less than ¼ of the installed capacity in these industries is for coal-steam plants; the aluminum industry, in fact, cannot compete at present with power costs of more than $\sim$0.3 cent per kilowatt-hour.

4.3. Since we have chosen to use coal-steam electric power in comparison with atomic power, let us examine a breakdown of such a plant's costs. Table 7 below represents values for a very efficient (thermal) plant running at a higher-than-average load factor. The national average for thermal efficiency was 0.21 in 1940 and 0.44 for load factor in the same year. These values were chosen in order to compare the better present practice with a new development.

TABLE 7

BUS-BAR COSTS OF COAL-STEAM ELECTRIC PLANT
(Typical of Better Plant) 1944
Cents per kilowatt-hour

	Load Factor = 0.5		Load Factor = 1.0	
I. Direct Costs				
1. Fuel cost at mine ∽0.12 + transport & handling ∽0.18	0.3		0.3	
2. Labor	0.05		0.05	
3. Maintenance & other supplies	0.04		0.04	
Subtotal		0.39		0.39
II. Fixed Costs				
1. Overhead, administrative and general	0.06		0.03	
2. Taxes (& franchise costs)	0.13		0.065	
3. Interest	0.08		0.04	
4. Depreciation (& reserves for obsolescene)	0.08		0.04	
5. Insurance	0.01		0.005	
Subtotal		0.36		0.18
Total cents/kw-hr.		→0.75		→0.57

Assumptions:

1. Plant investment = $120 per kw. of capacity,
2. Thermal efficiency = 0.26 = (1 lb. coal/kw-hr.),
3. Coal price = $6/ton delivered,
4. Fixed cost total = 12% of plant investment,
5. Correction for "power factor" of 0.9 has been made.*

* Power factor is not the same quantity as load factor; a value between 0.8 and 0.9 is normal for plant power factor. See any text on technical electricity.

Thus, fuel represents 40 per cent of the total bus-bar cost with 0.5 load factor. If the same plant were run at a load factor near unity, the total cost would be about 0.6 cent per kilowatt-hour and fuel would represent about 50 per cent of the total.

Fuel costs may, of course, be very much higher in localities remote from sources, coal being as high as $12 per ton at some seaports. The effect of different coal prices on power costs is indicated in Table 8.

TABLE 8

COST OF POWER WITH DIFFERENT COAL PRICES
(cents per kilowatt-hour)

Coal Price	Load Factor = 0.5	Load Factor = 1.0
$ 4. per ton	0.65	0.47
6. " "	0.75	0.57
8. " "	0.85	0.67
10. " "	0.95	0.77
12. " "	1.05	0.87

This table has been calculated using the same assumptions as above.

4.4. Remembering the similarity of piles and coal-steam plants, Section 2.4, we can now make a first approximation of a *lower limit* to the cost of pile power, the second question in our consideration. Let us assume that the pile replenishes itself (Section 2.6), and let us also neglect the purification costs, so that our fuel cost is zero. Then, if we further assume that the capital and other operating costs are similar to those of the coal-steam plants, we can see that the total power cost will be reduced by, say, 0.3 cent to *about 0.3* to *0.5* cent per kilowatt-hour. These values lie between hydro-electric costs and the fuel-plant costs, as shown in Table 9.

TABLE 9

ROUGH COMPARISON OF POWER COSTS

		cents/kw-hr.
	1. Hydro	0.05→0.4
(first approx.)	2. Nuclear	0.3 →0.5
	3. Coal-steam	0.4 →1.5

Because of the costs neglected, this will later prove to be an underestimate of the cost for the near future. It will be necessary to examine further the simplifying assumptions made above.

4.5. We shall now try to estimate in more detail the probable future cost of nuclear power.[7] If we postulate a plant of reasonable size, say 100,000 kw., we can examine a breakdown of probable costs. Such an analysis is intended merely as an illustration. We have assumed here that the fuel costs will occur only as fixed charges on the original investment. We will then examine the remaining costs; the other fixed costs, and labor, maintenance, and miscellaneous materials. In a fairly arbitrary manner we will estimate all purification and reprocessing costs to be 0.1 cent per kw-hr.

The cost of all the equipment *except* the pile itself may be estimated

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[7] The author has assumed a greater degree of development than was assumed in the preparation of the Thomas report (*Scientific Information Transmitted to the United Nations Atomic Energy Commission by the United States Representative,* Vol. IV, "Nuclear Power," September 5, 1946, 6 pages). The latter report was based upon a modification of the existing Hanford installation and contained an estimated cost of 0.8 cents per kw-hr. at 100% load factor.

from data on the cost of steam-electric plants. If we use the same basis as before, or $120 per kilowatt capacity and remember that we save the expense of a furnace, about 25 per cent of total plant up to the bus-bar, then we have for such a plant:

$$0.75 \times \$120 \text{ per kw.} = \$90 \text{ per kw.}$$

It is much more difficult to estimate the cost of the pile with its fissile charge. While the cost of present-day piles is much higher, the author has estimated that a reasonably achievable goal for this cost is in the neighborhood of $100 per kw. Furthermore, a first approximation to this task has been given in a study entitled "Nuclear-Energy Potentialities" by Wagner and Hutcheson of the Westinghouse Electric Corporation released in August, 1946. They give two estimates to indicate the probable range: $60 per kw. and $120 per kw. respectively. Taking the latter, more conservative figure we get a total investment of about $210 per kw. of electric capacity. Then the fixed-charge cost per kilowatt-hour can be estimated by using the over-all fixed percentage developed in Section 4.3, about 12 per cent.

To the above fixed costs may be added an allowance for labor and maintenance similar to that given in Section 4.3 equal to about 0.09 cent per kilowatt-hour. Total estimated nuclear power costs are shown in Table 10.

TABLE 10

NUCLEAR POWER COSTS
(near future, say, 5–10 years)
(cents per kilowatt-hour)

	Load Factor = 0.5	Load Factor = 1.0
I. Direct Costs:		
Labor, Maintenance,	0.09	0.09
Reprocessing Costs	0.10	0.10
II. Fixed Costs:		
Fissionable Materials in Pile	0.34	0.17
Auxiliaries & Secondary Machinery	0.24	0.12
Total	0.77	0.48

No great accuracy can be assigned to the values given. Probably ±50 per cent is the best that should be claimed for these early figures. As more is learned and as more available information is released it should be continuously refined. It will be seen that a large part of the estimated cost is represented by the fixed charges on the investment in plant.

The costs projected above are estimates made in the beginning developmental period of new and rather complicated processes. Necessarily the solution of many technical problems is assumed here. These solutions will properly take time, one can estimate something like five years, optimistically, or longer.

For the more distant future it should be noted that almost one-half of the total cost is represented by fixed costs on the fissile materials. As this investment cost becomes less and less, owing to improvements in the synthesizing and separating processes, this item in the power cost will be reduced. Moreover, see footnotes under Section 2.6. It could be hoped that a rate of, say, 0.3 cent per kilowatt-hour might be achieved in, perhaps, ten to twenty years of further active development.

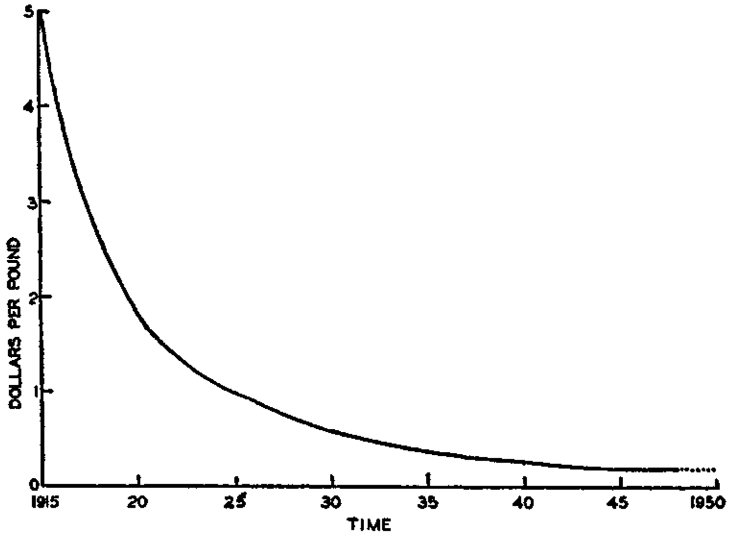

FIGURE 5—Price of magnesium for period of development [19], [29], [47].

A pattern is shown for magnesium prices in Figure 5 from 1915 to date showing the typical asymptotic approach to a final low level.

4.6. Other criteria of atomic-energy plants beside cost also determine their feasibility. In the selection of a site for any power plant, the climate, transportation, and maintenance facilities are important considerations. For most ordinary plants the availability of good water supplies and firm foundations are extremely important. Atomic-energy plants have similar problems and requirements. The particular problems will depend as much on the system that receives and converts the pile heat, the heat engine, as they will depend on the pile.

For instance, a good water supply would be of paramount importance in a pile, steam-turbine system but of negligible importance in a pile, gas-turbine system. While it would be futile to set down here the engineering requirements peculiar to the piles, one might mention such obvious necessities as freedom from earthquake shocks and floods. These criteria may rule out regions where such energy may, otherwise, be produced economically.

Furthermore, for many years the pile will require a high caliber of supervisory personnel. Remote regions are not likely to attract and keep the necessary ability.

Considerations of employee and community health and safety will continue to command attention until such plants are well established.

The anticipated power demand, the load factor, will help to determine the feasibility of a pile installation. The high original cost will weigh heavily against any installation to serve a sporadic demand.

The enormous convenience of handling such a concentrated fuel is very important. Localities remote from water power and cheap coal can be served with power. In aluminum manufacture, for instance, it might cost more to transport bauxite in certain cases to the power site than to buy the power itself. The emancipation from the problem of transporting fuels in bulk will argue strongly for the feasibility of many pile installations.

Finally, military and political expediency will also contribute strongly to such decisions.

4.7. There are, of course, other forms of demand for energy than the coal-steam example given in Section 4.4.

Rough estimates for the United States for 1940–1943 have been made [18], [19], [21], and are shown in Table 11.

TABLE 11

ESTIMATED ANNUAL DEMAND FOR ENERGY, UNITED STATES, 1940–1943

Category*	Amount
1. For Power Production (all forms)	340×10^6 kw. of heat energy
2. Nonindustrial Heating	200
3. Industrial Heating and Other	360
Total	900×10^6 kw.

* Power production for electric power plants, automobiles, and locomotives has been included. Retail deliveries of coal were used to estimate the nonindustrial heating.

About $\frac{1}{6}$ or $53. \times 10^6$ kw. of the heat energy used for power production comes out in useful form. Of this useful energy about $23. \times 10^6$ kw. is generated in the form of electricity, $\frac{1}{3}$ by hydro-electric plants and almost $\frac{2}{3}$ by coal-burning, steam-electric plants [42]. This $\frac{2}{3}$ fraction, or about 15×10^6 kw., a representative figure for, say, 1940–1944, equivalent to about 5×10^4 lbs. U per year, has served us as a useful form for comparison in Sections 4.4 and 4.5.

A useful table, Table 12, has been compiled by Lincoln Gordon for the National Resources Planning Board and published in 1943, data referring to 1936–1939 (also see [41]):

TABLE 12

COST OF POWER IN INDUSTRIAL PRODUCTS

Industry	Consumed kw-hrs. per Dollar Value of Product
Calcium carbide	74.5
Ferroalloys made in electric furnaces	51.3
Aluminum	51.2
Electrolytic zinc	45.0
Magnesium	33.4
Electrolytic caustic soda and chlorine	23.1
Cement	14.0
Reclaimed rubber	12.1
Pulp good	11.7
Ice	11.0
Other Industries	less than 10.0

The importance of the fuel cost to the small consumer of electrical power is much less than that indicated in Section 4.4. He must bear the additional distribution and customer-relations costs. Fuel costs represented between 7 and 13 per cent of the consumer's dollar between 1937 and 1944.

The importance of the fuel cost is large, however, for both industrial and nonindustrial heating. The high-temperature heat for certain industries (such as smelting and working metals) is not at present a feasible pile product. The upper temperature limits are defined by the properties of the materials of construction, such as strength and resistance to corrosion. However, lower-temperature process heat is a feasible pile product. In many cases this heat is gotten by industry at low cost as a by-product of power production. Heat as such is a difficult commodity to transport over any great distance. Nonindustrial heat sales (building and home heating) from piles would be limited to concentrated groups of consumers such as exist on Manhattan Island and buy heat (in the form of steam, N. Y. Steam Co.) from central heating plants. Nevertheless, large amounts of such heat are practicable outlets for pile energy and should be studied.

5. *Summary*

Taking into consideration the low cost of fuel transportation for a unit of energy, we have estimated the cost of power made by nuclear fission processes. We have in addition shown that important amounts of resources are available.

However, these early estimates can only be valuable if they are continually revised with our growing fund of knowledge of nuclear engineering.

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(on leave of absence from Kellex Corporation)

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