ECONOMIC ASPECTS OF ATOMIC ENERGY AS A SOURCE OF POWER[1]

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The possible use of fissionable substances as a new and important source of energy gives rise to a number of economic questions. This paper deals in a very general way with two sets of questions: those related to the comparative costs of producing energy from atomic fuels and other sources; and those related to the economic consequences which might follow the introduction and use of atomic fuels. The discussion is built around examples which illustrate each of the questions considered.

I. *The Comparative Costs of Power from Atomic and Non-atomic Sources*

Energy is developed in the atomic pile in the form of heat. The heat produced might possibly be consumed directly in a variety of industrial and nonindustrial uses requiring either low- or high-temperature heat. In the light of what is known of current research on peacetime applications of atomic power, it is probable that the earliest important use of the heat produced in the pile will be in the generation of electricity. It is for this reason that such estimates as have been made of the cost of energy from atomic sources have been for the generation of electric power. This paper, similarly, is limited to a discussion of atomic energy as a source of electric power.

Electricity is at the present time generally produced most cheaply in large hydroelectric developments.[2] One important factor to notice in connection with water power is that it exists only where natural conditions permit, and that it is not considered economically feasible to transmit the electricity produced beyond a radius of about three hundred miles.[3] The cost of electricity based on a fuel such as coal is generally higher than for hydroelectric power, but such fuels are very widely used because they can be transported to the power station, wherever located. The transportation of ordinary fuels is, however, costly; for example, each two hundred miles of coal transportation by rail adds about one mill per kilowatt-hour to the cost of electricity so

[1] The author wishes to express his thanks to Jacob Marschak and Edward Boorstein for their many helpful suggestions which have been incorporated in this paper.

[2] For data supporting this generalization see Lincoln Gordon, "Power and Fuels" in *Industrial Location and National Resources* (National Resources Planning Board, December, 1942).

[3] J. P. Watson, "Potential Waterpower in the United States" in *Energy Resources and National Policy* (National Resources Committee, January, 1939).

that generating costs in a power station located four hundred miles from a coal mine might be greater by about 30 per cent than in a station at the mine mouth, as a result of the cost of coal shipment on railroads.[4] When we consider that one pound of atomic fuel yields about as much energy as two and a half million pounds of coal it is clear that, by ordinary standards, the cost of transporting atomic fuel will be infinitesimal. As a result nuclear power costs will for similar plants be fairly uniform throughout the world.

What, then, are the costs of producing atomic power? The most authoritative publicly available estimate of costs is that derived by a group working at Oak Ridge under the direction of Dr. C. A. Thomas,[5] Vice-President of the Monsanto Chemical Company. According to this study a power plant based on atomic fuel could generate electricity at a cost of about eight mills per kilowatt-hour, if operated at 100 per cent of capacity. Because of the nature of their demand, power stations normally operate at no more than about 50 per cent of capacity; we have, therefore, reconstructed the Thomas figure on the basis of operations at 50 per cent of capacity, and have derived an estimated cost of about ten mills per kilowatt-hour.

A lower cost for atomic power was derived by a group working under the direction of Professor Condliffe at the University of California.[6] They estimated that the same general type of plant as was assumed by the Thomas group might produce electricity for as little as four mills per kilowatt-hour, operating at about 45 per cent of capacity. This compares with a cost of about ten mills in the Thomas report.

Both estimates are surrounded by a wide area of uncertainty because the future cost both of constructing atomic plants and producing fissionable materials can be estimated only within broad limits. Despite the uncertainties, it is possible to isolate one factor which may account for at least part of the difference between them. Thus, the estimate of the Thomas group is for a plant with a capacity of 75,000 kilowatts, while the California estimate is for a plant of 500,000 kilowatts. The California study indicates that a large part of the investment in an atomic power plant would be for special instruments and controls, and that their costs would not vary in the same proportion as size of plant. As a result, the larger plant assumed in the California study might be expected to produce electricity at a substantially lower cost than the smaller plant assumed in the Thomas report.

[4] Based on data in I.C.C. *Reports*, Vol. 69, p. 18; *Electrical World*, December 2, 1939, "Fourth Steam Station Cost Survey"; and John Bauer and Nathaniel Gold, *The Electric Power Industry* (Harper, 1939).

[5] *Nuclear Power*, Scientific Information Transmitted to the United Nations Atomic Energy Commission by the United States Representative, Vol. IV, September 5, 1946.

[6] "Atomic Energy, Its Future in Power Production," *Chemical Engineering*, October, 1946.

The two estimates may, therefore, be taken to suggest that the cost of generating electricity in atomic power plants may be somewhere between four mills and ten mills per kilowatt-hour, or possibly somewhat beyond this range. Table I summarizes our estimates of electric

TABLE I

ESTIMATED COSTS OF GENERATING ELECTRICITY IN SELECTED REGIONS OF THE WORLD, 1937 AND 1947, COMPARED WITH ESTIMATED COSTS OF ATOMIC POWER

	Average Generating Costs in Mills per Kilowatt-Hour[a]		Cost of Atomic Power in Mills per Kilowatt-Hour
	1937	1947	
Thomas Report			8.0-10.0[b]
California Report			4.0[c]
Argentina			
Coastal regions	9.0	16.0	
Inland regions	10.0 -11.0	17.0 -18.0	
China			
Mining regions	6.5 - 7.0	—	
Other regions	7.0 - 9.0	—	
Great Britain	7.25	9.5	
Hungary	9.25	—	
India			
Mining regions	6.5 - 7.5	—	
Other regions	7.5 -10.0	—	
Soviet Union[d]			
Ural region	6.5	—	
United States[e]			
At mines	5.50- 6.25	5.75- 6.75	
Near mines or on developed waterways	6.50- 7.25	7.00- 8.25	
Far from mines, accessible by rail	7.50- 8.75	8.50- 9.50	

[a] In order to place all electricity costs on a comparable technological base, we do not show data on actual generating costs since these would be influenced by the condition of the plants in operation. Instead we have estimated electric generating costs from the cost of fuel in the various regions, assuming the same relationship between fuel costs and generating costs as would obtain in a modern 100,000 kilowatt plant operating with a 50 per cent load factor. (Based on data in *Electrical World*, December 2, 1939, "Fourth Steam Station Cost Survy," and Bauer and Gold, *op. cit.*) All coal prices include cost at mine and transportation charges. Transport costs from mines to consuming regions estimated from representative railway, river, and ocean freight charges.

[b] Assuming 75,000 kilowatt plant. Lower cost based on 100 per cent load factor; higher cost estimated by us for 50 per cent load factor.

[c] Assuming 500,000 kilowatt plant and 45 per cent load factor.

[d] Data on mining costs could not be found for this region; hence United States mine price was used.

[e] Coal plants only. Generating costs estimated on basis of standard relationship described in footnote *a*. Earlier figures relate to 1938 and are based on data on actual fuel costs for plants in operation in that year. Figures for 1947 are preliminary estimates derived by us from general information on current coal prices and freight rates.

generating costs for selected regions in 1937, a prewar normal year, and 1947, in those cases where data are available. The regions have been chosen to represent varying patterns of energy resources occurrence and use.

For every region covered the costs of electricity are within or above the range of atomic power costs we use. This could be taken to indicate that atomic plants of a size assumed in the California study could produce electricity more cheaply than some of the power stations currently in operation in all countries. However, such stations would probably be so large that few, if any, locations could absorb the electricity produced, considering the feasible limits of transmission. For example, a 500,000 kilowatt plant, which is the size assumed in the California study, produces enough electricity to satisfy an industrialized region of about one million population. As estimated coal-electricity costs approach the upper limit of the range of atomic costs, or go beyond it, this qualification becomes less important, for this can be taken to indicate that even more moderately-sized atomic power plants might produce electricity more cheaply than coal plants.

The highest and lowest level of generating costs in the countries covered in Table I are for Argentina and the United States respectively. This is to be expected since Argentina is an outstanding example of a country poor in energy resources which must import fuel from extremely distant sources of supply, while the United States is an outstanding example of a country with abundant fuel resources. Nevertheless, even in the United States costs approach the upper limit of the range of atomic costs in certain parts of Minnesota, South Dakota, and Wisconsin. Costs throughout Argentina in 1937 were in the neighborhood of the upper end of the range of atomic costs; currently, costs throughout Argentina are considerably beyond the highest estimate of atomic costs, as a result of the world-wide shortage of coal and shipping. If postwar normal electricity generating costs in Argentina are somewhere between costs in 1937 and 1947, the savings which might be possible through the use of atomic energy appear to be considerable.

Other regions with generating costs approaching the upper end of the range of atomic costs and therefore exemplifying places where atomic power may be economically feasible, are Hungary and areas remote from coal mines in India and China. Hungary uses domestically-mined fuel for the generation of electricity and the high costs are explained by the fact that the fuel is poor in quality and costly to mine. In China and India the level of electric generating costs in regions remote from energy resources is relatively high as a result of coal transportation; the highest costs in India are above those in China because mines are more highly localized in India.

The position of Great Britain differs from that of the other regions covered. It has traditionally been an important producer and exporter of coal, and there are few regions in that country remote from sources of energy. This condition was reflected in moderate costs of electricity as shown in Table I for 1937. However, generating costs are considerably higher in 1947 than they were in 1937 as a result of increases in the costs of mining coal between the two years. In part these increases have resulted from temporary dislocations brought on by the war; in part, there has been a long-run tendency towards increasing costs in the British coal industry as a result of an insufficient degree of mechanization and modernization of coal mines to counteract the decline in the grade of coal resources. Whether coal costs will fall in the future, and by how much, will depend on the success the British have in carrying through modernization of their coal industry; if they do not experience a high degree of success, atomic energy may prove to be a cheaper source of electricity than coal.

The Ural region of the Soviet Union typifies still another situation. The cost of generating electricity in this region is estimated at a level about midway between the two estimates of atomic costs, which suggests that the use of atomic power may be of questionable economic benefit. The relatively low level of costs results from the current use of locally mined coal and lignite for electric power generation.[7] There is evidence, however, that any substantial expansion of electrification in this region would require that coal be sent from other parts of the Soviet Union. We estimate that such additional amounts of electricity would cost between nine and nine and a half mills per kilowatt-hour—a level not far below the upper end of the range of atomic costs. Atomic energy might provide the additional power at a lower cost.

Before concluding the analysis of the comparative costs of power from atomic and non-atomic sources, two additional factors which might favor the position of atomic power should be considered. The estimates of atomic power costs are for a technology on the threshold of development. Great declines in cost may be possible in the future as a result of advances in techniques of constructing and operating piles, and of producing fissionable materials. Electricity based on coal represents an established technology which probably will not undergo radical change to nearly the same extent.

The second factor to consider is that for such countries as China, India, Great Britain, and the Soviet Union, the saving involved in introducing atomic energy cannot be assessed merely by comparing the current level of costs of producing power from atomic and non-atomic sources. To a certain extent expanded electrification in each of these countries would require considerable investment of capital in the development of energy resources: England may be able to buy cheaper

[7] In addition, as noted in Table I, in the absence of data on actual mining costs in this region, we were forced to fall back on estimates based on United States experience. Actual costs in the area, therefore, may be higher than the costs we show. Similarly, the estimated costs of electricity based on coal shipped from other parts of the Soviet Union may be too low.

electricity in the future at the cost of large-scale investment in the modernization of coal mines; China, India, and the Soviet Union may be able to expand electrification through hydroelectric development or by the development of new coal mines and the modernization of old ones. Atomic energy, either alone or in conjunction with other energy resources, might possibly offer a faster route to expanded electrification or one requiring a smaller total investment of capital.

II. *Economic Effects of the Use of Atomic Energy*

On the basis of the comparative costs of producing electricity from atomic and non-atomic sources, it appears possible that atomic fuels may replace or supplement existing sources of power in some parts of the world at an early date. The affected regions will not necessarily be areas remote from existing energy resources as can be seen from the fact that atomic energy may prove cheaper than coal in a country like Great Britain. The figures presented above are, however, purely suggestive and it would be incorrect to draw any hard and fast conclusions with respect to specific areas from them. As a result, our discussion of the economic effects of the use of atomic energy is not limited to the specific areas for which data are shown above. We consider, first, the savings which might be involved in replacing fuels currently used in the generation of electric power by atomic energy; and, second, the unique developmental possibilities opened up by atomic power.

The total saving in an economy such as our own as a result of the use of cheaper fuel in electricity generation may be seen from the following over-all figures. The amount of fuel consumed in the United States in 1942 for the generation of electricity by central stations was about 80 million tons of bituminous coal equivalents.[8] If we assign an average value of $6.00 per ton of coal equivalents at the power station, we get a total value of about 500 million dollars for fuel consumed by the electric utilities. This figure could be increased to include fuel consumed by certain industrial establishments in the generation of their own power, and it would still come to no more than a fraction of 1 per cent of our total national income of about 150 billion dollars. Thus, if all the fuel currently used in the generation of electric power were replaced by a fuel which costs nothing, the savings in our economy would be very small. The savings per unit of electricity would be greater for countries in which fuel costs are higher than in the United States, but few of these countries are power-based to anything like the same extent as the United States.

[8] J. M. Gould, *Output and Productivity in the Electric and Gas Utilities* (National Bureau of Economic Research, 1946), p. 163.

Obviously, however, this type of calculation does not provide a measure of the full economic effect to be expected from the possible cheapening of power through the introduction of atomic energy, nor is it even a measure of the major economic effect. For the major economic importance of the cheapening of power in any part of the world is to be found not in the cost-reducing effects, as such, but in the growth in economic activities which may result therefrom. In one sense the large-scale development of hydroelectric power by the TVA merely reduced the cost of power in the Tennessee Valley, but we do not think of this saving as a full measure of the economic effects of TVA, because the principal effect of cheap power has been to expand the economic life of the region. The domestic demand for electricity has grown as a result of cheaper rates, and has brought with it the extended wiring of homes, the introduction of new electrical appliances in the home and on the farm, the proliferation of service activities related to electrification, etc. Cheap power also encouraged greater industrialization by making new combinations of productive factors economically feasible. The industries developed in the first instance as a result of the availability of cheap power have been electroprocess industries which, in turn, have served to attract a variety of secondary industries. These developments and many more tended to reinforce one another and merge in a general process of growth.[9]

Similar developments on a varying scale could occur elsewhere as a result of the cheapening of power. The number of areas opened up to this kind of development by atomic energy are very much greater than with other energy resources because it is not bound to a specific site in the manner of water power, nor is it costly to transport in the manner of ordinary fuels. Thus, one of the great promises of atomic energy lies in the development of regions remote from other energy resources. In such cases the important effect is to be sought in the pervasive influence of power in the economic development of an entire region as in the Tennessee Valley, rather than in the savings involved in substituting one source of power for another.

We must note, too, that our calculation of the over-all savings involved in the possible cheapening of power obscures the differential importance of atomic energy in the development of specific industries. It is to be expected that in an advanced economy such as our own, the impact of atomic power will be felt largely through its effects on the important energy-consuming industries. Costs in such industries might be reduced substantially either through the use of cheaper power in present locations; or through the location of production in new

[9] David E. Lilienthal, *TVA: Domocracy on the March* (Harper, 1944).

centers in which atomic fuel is brought to raw materials, which, in the past, had to be shipped to fuel for processing; or through a combination of the two causes. Examples of industries in which location of production, costs of production, or both could be affected by the advent of atomic power include the electroprocess industries such as aluminum, ferroalloys, and chlorine; and important heat consuming industries such as metal smelting, cement, glass, clay products, and pulp and paper.

To illustrate specifically the type of development which could result from the use of atomic power, we consider its possible significance for aluminum, an important electroprocess industry. Table II presents data on those components of costs in the production of aluminum which might be affected by atomic power.

Since power accounts for roughly 20 per cent of the cost of pig aluminum, it is clear that a substantial reduction in total costs could be achieved through reductions in power costs. Because their power requirements are so great, aluminum reduction plants have located themselves close to sources of cheap power. The plants covered in Table II obtain power at an average cost of less than two mills per kilowatt-hour from nearby hydroelectric power stations. Atomic power plants may be able to match these low costs at some time in the future, but it is questionable that they will lower electricity costs even further. It may be concluded from this fact that costs in the aluminum industry, as presently constituted, probably would not be seriously affected by the advent of atomic power.

However, another extremely important element in aluminum costs is the transportation of bauxite and alumina. The Alcoa plants covered in Table II derive their aluminum from bauxite mined in Dutch Guiana. The bauxite is shipped to an ocean port in the United States (in this case Mobile) for the first stage in the reduction process: the conversion of bauxite to alumina. If the bauxite is shipped dry, approximately 1.7 tons are required per ton of alumina. The alumina produced in Mobile is then shipped to plants close to cheap power for the last stage in the production of the metal: the electrolytic reduction from alumina to aluminum. Two tons of alumina must travel to these plants for each ton of aluminum produced. In total, therefore, the cost of transporting 3.4 tons of bauxite from Dutch Guiana to the United States and 2 tons of alumina from Mobile to aluminum plants in various parts of the country is included in the cost of producing a ton of aluminum.

The transportation of aluminum raw materials which enters into the cost of producing aluminum results from the need to bring raw materials to cheap power. Under present circumstances, it would be even more costly to bring power to raw materials since roughly 10 pounds of coal would be required to produce sufficient power for the reduction of 1 pound of aluminum, while only 3.4 pounds of bauxite need be shipped to power. The relationship between the weight of raw materials and the weight of fuels required per ton of aluminum could, however, be completely reversed by atomic fuels, one pound of which yields

TABLE II

COSTS OF POWER AND TRANSPORTATION OF BAUXITE AND ALUMINA IN THE ESTIMATED AVERAGE POSTWAR COST OF PIG ALUMINUM IN ALCOA PLANTS[a]

	Cents per Pound of Pig Aluminum	Per cent of Total Cost
Power for electrolytic reduction of aluminum (9 kilowatt-hours per pound of metal)	1.73	19.6
Transportation of bauxite and alumina	1.24	14.0
a. Bauxite, from Dutch Guiana to Mobile, Alabama	0.55	6.2
b. Alumina from Mobile to electrolytic aluminum plants	0.69	7.8
Other costs	5.87	66.4
Total cost	8.84	100.0

[a] Source: Adapted from data in "Aluminum Plants and Facilities," *Report of the Surplus Property Board* to the Congress, September 21, 1945.

enough energy to produce 250,000 pounds of aluminum. Thus, 1 pound of atomic fuel could be shipped to bauxite instead of shipping close to 1 million pounds of bauxite to power.

The size of the cost reductions which might result from bringing power closer to aluminum raw materials may be judged from Table II. For example, if aluminum reduction works could be based on cheap power at Mobile, a saving of close to 8 per cent in production costs would be effected, all other factors being equal; and if an integrated aluminum works could be based on cheap power in Dutch Guiana, a saving of 14 per cent in costs could result.

Clearly such a calculation does not provide a basis for undertaking the development of aluminum production at new locations; the availability of other raw materials, the adequacy of the labor supply, and the cost of transportation to possible markets are among the other economic factors which would have to be considered. It does, however, illustrate the type of economic factors which may come into play in determining the aluminum industry's structure if cheap power can be made available, wherever needed. Perhaps atomic power will reduce power costs at Mobile, Dutch Guiana, or other places sufficiently to encourage the development of new productive activities. This would result not only in a quickening of economic activity in the regions affected but also in reductions in the cost of aluminum production which might prove important in awakening new demands for aluminum and its products throughout the world.

In discussing the economic effects of atomic energy, the following points have emerged: Measured purely in terms of the savings involved in substituting atomic fuels for other fuels in the generation of electricity, the economic importance of atomic energy does not appear to be great. However, this calculation neglects the fact that historically the cheapening of power has been of major importance in economic growth, a factor which transcends in importance the savings involved in the substitution of one fuel for another. In this connection, it was noted that the unique mobility of atomic fuel renders it ideal for the purpose of providing cheap power in regions remote from other energy resources. Finally, it was stressed that even in regions with abundant fuel resources, atomic energy might have important implications for the major energy-consuming industries. Such industries could experience reductions in production costs either through the cheapening of power, or, as may be possible with aluminum, through the development of production at new locations in which atomic fuel is brought to raw materials which had previously to be shipped to other sites for processing. It was suggested that this could have a double-edged importance, resulting both in economic expansion in the regions affected and in the growth of demand for those products whose costs had been reduced.

III. *Concluding Remarks*

To this point in the discussion we have considered two main topics: the cost of producing atomic power, and the economic effects of the use of atomic power. Both were discussed on the assumption that economic factors would be allowed full sway in determining the manner in which this new force will be exploited. However, the enormous military importance of atomic explosives renders the exploitation of atomic energy inescapably subject to noneconomic considerations. This is true whether there is international control or not. In either case political considerations will take precedence over purely economic goals.

If the nations of the world do not agree on the international control of atomic energy, it is likely that an atomic arms race will occur. Under such circumstances it is probable that atomic power will result, if at all, only as a by-product of the production of atomic explosives. The cost of power will in this case be arbitrarily determined and will depend on the size of the military subsidy. The choice of areas in which atomic power will be made available will be determined by security considerations, and might be completely unrelated to the relative urgency of the need for power.

International control of atomic energy could also have serious economic implications. It is possible that the control plan which governs the development of the world atomic energy industry may impose restrictions with respect to the design of atomic piles as a security measure.[10] The existence of this type of institutional rigidity could result in higher costs of atomic power than if there were complete freedom of choice with respect to plant design. Furthermore, security considerations might dictate a severe limitation on the size of the world atomic energy industry—and its distribution—in order to minimize the dangers from diversion of materials or seizure of plant.[11] This factor could operate to vitiate, in part, the important possibilities of atomic power in expanding economic life in regions remote from other energy resources, and in encouraging new industrial locations through the availability of cheap power, wherever needed. Whether, and how severely, political forces will limit the economic benefits of atomic energy, time alone will tell.

[10] For example, the Acheson-Lilienthal plan for the international control of atomic energy provides that certain plants (producing approximately one-half of the total world output of atomic power) shall be designed in such a way that they will not be able to produce new fissionable substances.

[11] This consideration has been stressed in certain materials submitted by Mr. Baruch to the United Nations Atomic Energy Commission. See, for example, *Technological Control of Atomic Energy Activities*, Scientific Information Transmitted to the United Nations Atomic Energy Commission by the United States Representative, Vol. VI, October 14, 1946.

Lewis N. Dembitz; Philip Sporn; Sam H. Schurr; Jacob Marschak

DISCUSSION

LEWIS N. DEMBITZ: Mr. Coale's paper makes it clear that we do not have any answers yet to the problem of reducing this country's vulnerability to atomic bombs. Only a start has been made toward mapping out the problem.

The question whether or not this country should undertake a great defensive program and if so, what lines the program should follow and how the related economic problems should be solved, involves a job of tremendous magnitude for the economist. I should like to emphasize also that the whole subject will require continuing study for as far into the future as one can see. Regardless of what decisions are made in the next year or two—whether they lead to the conclusion that a full-scale defensive program should be initiated along some particular lines, or to the conclusion that no such program should be initiated for the present—in either case the decision will have to be under continuing review and subject to change at any time in accordance with new developments. One of the most serious dangers to be avoided is the danger of becoming too firmly committed to a defense program based on 1947 or 1948 considerations, and then being attacked in some future year—say 1970—when our defensive system is obsolete.

The problems of defense against bombing may appear to lie primarily in the fields of military science, industrial engineering, and the natural sciences rather than the field of economics, and I should like to point out that economic questions are more thoroughly involved than might be apparent at first sight. For example, let us assume that analysis from the military and technological viewpoints has indicated that we must assure a certain continuing supply of steel products during any prospective war in order to assure surviving the war. We might assure this supply perhaps by building a number of small steel plants in widely-scattered locations; or perhaps by building or rebuilding our large steel plants with such rugged construction that nothing except an almost direct hit would seriously affect them; or perhaps by arranging for large stock piles of semifinished steel to be stored near every steel consuming industry; or perhaps by making plans so that most of the vital steel products could in extreme emergency be made out of substitute materials; or by some combination of these methods. Assuming that all these methods are physically feasible, it is, of course, an economic problem to determine which is preferable, considering the extent to which each would call upon abundant or expansible resources, and thus involve a minimum in real cost to our economy, or the extent to which scarce resources might be required. The decision as to which of these methods is to be used will of course be intertwined with decisions as to transportation facilities, as to the locations of steel consuming industries, and so forth. These decisions in turn are dependent not only upon military and technological considerations but also upon the relative economic costs that different decisions would involve. Thus, the entire plan of defense will have to be developed on the basis of a thoroughly intertwined complex of economic and other considerations. The objective is a complete co-ordinated plan that will be adequate from a military view-point and for which the total real cost to the economy will be kept within reasonable limits.

In one sense the designing of a plan of defense is an even more difficult task than the laying out of an industrial system would be, because the plan of defense must not only produce a production system that will work; it must also produce a large number of subsidiary production systems each consisting of the original system minus some part assumed to be destroyed, such that each of these subsidiary systems will also work.

The costs of a plan of defense might be met largely out of the public treasury, or they might be met largely by requiring each enterprise in a strategic industry to stand the costs of reducing the vulnerability of its own operations. In the latter case, where each company has to adopt less efficient production methods or less efficient locations or has extra expenses for plant construction or for excess plant maintenance, this would be reflected directly in higher costs—meaning higher prices for its products. Regardless of how the program is financed, our economic system would have to adjust to a lower efficiency of production, which leads to the questions how far this could be offset, and the standard of living maintained, by increased efficiency in other directions or by more thorough use of our manpower and other resources. Thus the economist will be called on to state whether we can effectuate a given plan of defense without a reduction in the national standard of living that might be intolerable in peacetime.

A most important question is the extent to which the capital investment required by such a plan can be timed in a contracyclical manner so as to minimize the real cost. Decisions on timing, however, will have to be based largely on noneconomic considerations—such as how long it is considered safe to defer a given protective measure for the purpose of reducing its economic cost.

It is clear that all aspects of our national life are liable to be affected by this defense problem, and it therefore seems essential that the problem be made the subject of widespread intelligent thought and discussion. Some kinds of information will, of course, have to be surrounded by a high degree of secrecy, but many kinds ought to be widely publicized. One reason is that when the time comes to consider the appropriations or other legislative measures that would be needed to put any thoroughgoing plan of defense into effect, a well-informed public opinion will be needed to back up such measures, or possibly to back up their legislators in opposing the adoption of unsound or hysterical measures. An even more important reason for publicity, I think, is this: the main purpose of any preparedness program is not to prepare for war but rather to prevent war, by convincing any potential attackers that the United States is prepared to withstand any possible attack. Thus, subject to the obvious requirements of security for some kinds of information, there will be much room for intelligent public discussion, of kinds in which economists should be prepared to take a leading part.

PHILIP SPORN: The possibilities of generating electric power by nuclear piles more economically than by presently used means warrant a full-scale and thorough investigation to determine the economic aspects of the new means at the earliest moment the necessary data for that purpose become available. From that standpoint Mr. Schurr's paper is to be welcomed. Also Mr. Schurr's basic approach of considering the subject on the assumption that economic factors would be allowed full play in determining the manner and—the addition is mine—the location in which this new force will be exploited, can be highly commended.

But having said this much it is necessary to go further and ask: Are the necessary data for making an investigation of the economic aspects of nuclear power available? I hardly think so. For what have we actually to guide us as a base for such an evaluation? So far as I know we have but two small bits of general information of so approximate a nature as to make difficult its classification even as a "guesstimate." I refer, of course, to the Thomas report which is well known, and to the Condliffe report which is mentioned by Mr. Schurr and referred to subsequently as the California Report, which I have not had an opportunity to go over.

The Thomas report in particular has been widely quoted on its estimated figure of cost of energy at 100 per cent load factor of 8 mills per kilowatt-hour. Less widely quoted, in fact hardly mentioned, is this full observation concerning a possible commercial power pile:

> A number of changes in design and operating technique would be necessary. *An extensive research and development program would be required to solve the problems which will arise. These problems appear difficult but not insurmountable.* The complete nuclear power plant would include not only the pile itself, but all of the auxiliary equipment and installations needed to operate a continuous thermal power plant.
>
> While no such plant has ever been built or even designed, it is felt *probable* that a large stationary nuclear power plant could be built. Based on prices now current, a plant designed along the lines indicated and producing 75,000 kilowatts could be built in a normal locality in the eastern United States for approximately $25,000,000. On the assumption that the plant would operate at 100 per cent of capacity and that interest charges on the investment would be 3 per cent, the operating cost of the plant would be approximately 0.8 cents per kilowatt-hour.

Please note the many qualifying statements in this short, two-paragraph quotation from the Thomas report.

It may be that the California report contains data of a more positive nature but I doubt it, again because of the lack of fundamental data. To the best of my knowledge the Oak Ridge experimental power pile is somewhere in the design or design-completed stage. But it is a safe guess that the first pile is not going to be a 75,000 kilowatt pile and that as a thermal plant it will leave a great deal to be desired as far as economy and efficiency are concerned. That is said in no critical spirit. I am merely giving the designers credit for acting on the principle that it is well to learn to walk before starting to run a race. But with all this glaring gap in our technological line of knowledge and with almost no actual experience on costs, or even engineering cost estimates, it seems to me that an economic study becomes almost impossible and one is forced back on broad generalization and speculation. That, it seems to me, is what the author really has been forced to do in substance and perhaps the paper should be discussed from that standpoint. But the author has also attempted to take in more territory than that and it may, therefore, be pertinent to point out some of the errors introduced by generalized treatment.

For example, he makes a statement that energy at the present time is generally most cheaply produced in hydroelectric developments. Without qualifications such a statement is obviously incorrect. Volumes have been written on the competitive cost of hydroelectric energy and steam-electric energy and the discussion still continues. Some hydroelectric developments have produced very cheap energy, but so have numerous thermal plants. Similarly, volumes will probably be written on the subject of the cost of atomic energy versus the cost of other forms of energy. We have made a beginning and the discussion will probably continue just as the discussion of hydroelectric energy versus steam-electric energy will continue. Until it is possible to get into a specific case with the necessary engineering data on costs available, an objective discussion of the economic aspects of atomic energy will be out of the question.

The author appears to assume that an atomic energy plant consists of nothing but an atomic pile, although the conception today—I admit that it may change as we go along—is that nuclear fuel would merely be substituted for the conventional fuel in a boiler where steam will be generated and the steam used through steam turbines similar to those in current use. This means that an atomic plant cannot be located anywhere. The subject of condensing water must be considered. It is true that the gas turbine may come into the picture. But where coal is as plentiful and generally cheap as in the United States, the gas turbine has been able to find few enthusiastic backers.

In Table I there are given some figures on the cost of steam power in various sections of the world compared with the cost of atomic power, the latter being estimated both on the basis of the Thomas report and on the basis of the California report. The Thomas report actually does not go into details of arriving at a figure of 8 mills but with the knowledge that a nuclear pilot plant has been estimated at a cost of $333 per kilowatt, and that interest charges on investment have been calculated at 3 per cent, a reasonable breakdown can be constructed. Carrying out such a calculation I arrive at a figure of cost of energy at 50 per cent load factor of 12.8 mills instead of 10 mills used by Mr. Schurr. The California figure is based on a 45 per cent load factor operation. Unless the Thomas figures for capital cost are totally out of line it seems hard to visualize how a figure of 4 mills could be developed. However, leaving these figures with no more than this comment, I should like to make this observation about the remainder of the figures in Table I.

As to the figures for foreign countries, I wonder how authentic they are, how up to date they are, and what kind of technical performance on the exisiting power facilities they represent? My point is: If they represent, as I am sure in many cases they are bound to—and I base this on knowledge gathered by personal observation in some of the foreign countries,—performance of plants technically obsolete by modern standards, there is not any point in comparing them with performance expected out of a nuclear plant, the physics of which has just barely been born and the technology of which has not begun to be developed.

As to the American figures, I can speak with more authority and make this observation that while the level of values used in Table I is somewhere near right, the figures are sufficiently off to cause one to pause before making any rigorous comparisons with figures on nuclear energy. For example, the cost of energy at the mouth-of-mine is given in Table I by the figures 5.75 to 6.75 mills per kilowatt-hour. Using a cost per kilowatt figure of $120 and again the figure of interest of 3 per cent, with corresponding figures for depreciation, taxes, and maintenance utilized in the breakdown of the Thomas figures, and using a cost of fuel of 12½ cents per million B.T.U. (about $3.50 a ton for high grade coal) and a thermal performance of 10,000 B.T.U. per kilowatt-hour, I arrive at a figure of total cost at 100 per cent load factor of 3.22 mills per kilowatt-hour and at 50 per cent load factor of 5.89 mills. I do not comment at this point upon the qualifications that have to be made with regard to the practicality of operating any plant at either of those two load factors but nevertheless the basis of calculation is the same as that used in the breakdown of the Thomas figures. With the cost of coal at $7 (26 cents per million B.T.U.) and the cost of a power plant at $133 per kilowatt, I arrive at a figure for 100 per cent and 50 per cent load factor respectively of 5.12 and 7.14 mills per kilowatt-hour. These are not so very far apart from figures given in Table I but it seems to me that a ratio of 8.0 to 3.22 is an entirely different affair from a ratio of 8.0 to 6.75.

The whole trouble with the figures is that we are attempting to compare fairly precise figures that are determinable with engineering accuracy on ordinary fuel burning plants with figures arrived at on the basis of very broad estimates for nuclear plants where we not only have almost no knowledge on cost of capital facilities but no really reliable figures on the cost of the nuclear fuel itself. And again to point up what I have already stated I think we are going to arrive at bad concepts of what the relative economics of competitive factors are if we merely compare expected performance of nuclear plants with the average performance as it exists in the United States today. Thus the average performance of thermal plants in the United States in the year 1945 showed a figure for fuel requirements of 16,900 (1.3 kilowatt-hour) B.T.U. per kilowatt-hour of electric energy. This represents a thermal efficiency of 20.2 per cent. The most efficient straight steam-electric plant in the United States is the Twin Branch Station, with which the discussor has been associated both in design and operation. This plant operates with a performance of 10,200 B.T.U. per kilowatt-hour, or an efficiency of 33.13 per cent. However, the discussor also has just completed the design of two new stations, one to be located in Indiana and another to be located in West Virginia, each of which will show a thermal performance of 9,250 B.T.U. or a thermal efficiency of 36.9 per cent. This is almost double the thermal efficiency of the average performance for the year 1945 in the United States. Because a nuclear power plant, when and if it becomes technologically feasible, will not only utilize if not a weightless at least a freightless fuel, at the expense, however, of a much higher capital cost, it is particularly important not to treat this phase of the problem too broadly. For while a thermal power plant using nuclear fuel will be affected to some degree by the efficiency of the thermal cycle, such effect will be minor relative to the effect improved thermal performance will have on a power plant using more conventional fuels. This I am sure needs no further elaboration but does need stressing.

I have gone into all this detail in order to bring home this point more effectively. If we are not going to go astray in our discussions of the economics of nuclear energy, it is necessary to compare new technology with new technology and, therefore, nuclear plants which may represent the latest technology should under no circumstance be compared with anything but the best that can be obtained with existing technology. But to do that it will be necessary that we first get more reliable information on the investment and probable operating costs of nuclear plants. This appears to me to be impossible until the technology of such plants is further developed.

Even though I find a number of points on which to differ, I shall not, because of lack of time, attempt to go into a detailed discussion of the second phase of the author's paper treated under the heading of "Economic Effects of the Use of Atomic Energy." I would, however, like to make one observation on the treatment of the possibilities that nuclear energy might open up to produce aluminum where the bauxite is mined. I very much question whether the minor gains in the saving of transportation costs would be enough to swing a decision to locate an appreciable percentage of the aluminum capacity required by the United States, say, to Dutch Guiana, if we consider the security angle and the increased jeopardy to such security that such a move might entail.

In all of this I hope I have not given the impression that I undervalue the possibilities of nuclear energy and its development in the future. If nuclear energy will give us more economical power than we can obtain by the use of our hydroelectric resources and particularly our fuel resources, then it certainly should be developed, although obviously it will find application first in locations and in countries that are not so richly endowed as we are with economical normal fuel resources. The possibilities that nuclear energy appears to offer are unquestionably pregnant with the greatest economic significance and those possibilities need to be explored and developed, particularly since it now appears that the most fruitful peacetime application will be in the field of electric power generation. But until we have built the pilot plant at Oak Ridge and perhaps another one after that, and perhaps one plant of a capacity say somewhere between 10,000 and 100,000 kilowatt rating, I am fearful that we will not have the knowledge necessary to carry out an effective economic study of nuclear energy for use in electric power generation and any such study carried out before then is bound to be more or less a speculation.

Finally I want to underscore the author's concluding remarks; i.e.,. that the enormous military importance of atomic explosives renders the exploitation of atomic energy inescapably subject to noneconomic considerations and unless full and effective international control is developed political and national security considerations will take precedence over purely economic goals. Perhaps even as the author states, these considerations will become dominant even though we have international control.

One more point that might be appropriately made here. Except in the United States of America, there is a world-wide shortage of electric power. In the United States we are more fortunate, perhaps because of greater foresight or the better job that we did in balancing our production during the war, or merely because our electric power industry was more fully developed. Throughout the world, however, programs for expanding electric power facilities are going on. In the United States, for example, generation facilities are being expanded by some 7,000,000 kilowatt of capacity. So far as I know none of those entrusted with the responsibilities of supplying their respective countries with adequate power resources, whether in the United States, Great Britain, France, Switzerland, or Russia, to name only a few of the countries, is retarding a developmental program based upon using existing energy sources in order to take advantage of the proposed newer methods of generation by nuclear energy. It is to be hoped that, while keeping their eyes and minds open and on the alert and where possible co-operating in the development of more economical sources of energy, if such seems attainable, they will still not neglect their responsibilities for keeping the economic systems of their respective countries from suffering under the crippling handicap that results when adequate supplies of electric energy are unavailable. To paraphrase Voltaire, "We must continue to cultivate our garden with the tools we have today."

Sam H. Schurr: There can be no disagreement with Mr. Sporn's point that the data on the costs of atomic power are not precise and must remain more or less vague until such time as atomic power plants are constructed. The essential difference between us seems to be that Mr. Sporn believes that the lack of precision in our knowledge renders economic analysis impossible at this stage, while I feel that analysis can and does result in the clarification of several important points.

Thus it seems to me relatively unimportant that the limits of the estimated range of atomic costs may have been incorrectly placed at 4 mills and 10 mills, and that the upper limit of the range should perhaps be 12.8 mills. For I conceive that the important point with respect to current estimates of the cost of atomic power is that they are in the neighborhood of coal-steam-electricity costs in various parts of the world. It appears, therefore, that even though we cannot calculate exact figures on atomic costs, we can nevertheless state that atomic energy will provide a fairly cheap source of power in certain places, judged by conventional standards. It seems to me that this information is of great importance when coupled with the known fact that atomic fuel is practically weightless and can, therefore, be brought to any region of the world at infinitesimal transportation costs.

Apart from this basic disagreement, Mr. Sporn has criticized the analysis on the grounds that it does not compare atomic costs with costs based on the best modern coal-steam plant technology. He states that, particularly for foreign countries, our coal-electricity costs may be based on plants technologically obsolete by the latest standards. This is not so; see footnote *a* of our Table I.

The nature of the performance of the assumed plant on which all of our estimates of the cost of coal-steam electricity are based may be judged from the figures used by Mr. Sporn. To test the accuracy of our estimated costs for the United States, he has derived electricity costs based on coal prices comparable to the prices used by us, for a plant with a thermal performance of 10,000 B.T.U. per kilowatt-hour—a performance somewhat better than the Twin Branch Station which Mr. Sporn considers the most efficient steam-electric plant in the United States. He finds, on this basis, that our figures are "somewhere near right." To cite a specific example: for power stations at the mine mouth, he derives a kilowatt-hour cost of 5.89 mills, while in Table I we show a range of 5.75-6.75 mills. I consider the two estimates sufficiently close to justify the statement that our estimates of coal-steam costs are based on an assumed plant which represents the best modern practice in the United States. Let me stress again that this plant has been used by us to estimate electricity costs in all regions included in Table I, and that the difference in coal-electricity costs shown in that table are due entirely to variations in the cost of coal in the several regions covered.

I believe part of the difference between Mr. Sporn and myself is that from his standpoint the difference between 5.89 mills on the one hand and the range of 5.75-6.75 mills on the other is significant. Possibly decisions with respect to contracts for the construction of steam power plants have been made on margins as narrow as this. This analysis is, however, not designed to yield results of sufficient precision to serve as a basis for investment decisions (an undertaking which would, in any case, be somewhat premature with respect to atomic power). Rather its purpose is to provide a perspective for the judgment of the possible economic importance of atomic energy in various parts of the world. For that purpose small differences in cost are of considerably less importance, for they are lost in the rather broad range of coal-electricity costs in the world as a whole.

As information on atomic costs becomes more precise, it is to be hoped that analyses of the economic importance of atomic power will be brought into sharper focus. I believe, however, that even on the basis of information currently available sensible economic judgments can be made.

JACOB MARSCHAK: The secular trends favoring or impeding the development of electricity based on fission must be considered on the supply (or cost) and on the demand side separately.

The supply price of atomic power relative to the supply price of power from coal and waterfalls will depend on: (1) the trend of price of coal in old industrial areas (Britain) due to exhaustion of better mines and to increased adverse mobility of mining labor; (2) the relative speed of technical improvement in nuclear fission and its auxiliary processes on the one hand, and the utilization of coal (including recent attempts at coal gasification), oil (growing use in locomotives), and water power (increasing transmission distances) on the other.

The demand for atomic power will depend on: (1) improvements in electric furnaces and kilns; (2) the speed of exhaustion of easily reducible higher-grade ores, especially near world's industrial markets or water power (United States, Scandinavia); (3) the speed of developing—by loans and policing measures—of remote centers of demand for electricity: ore deposits (South Africa, South America, Siberia), old settlements (interior China, India), new settlements (airfields, new harbors and irrigation projects)—the "developing" being understood to cover not only the building of mills, houses, and highways but also education, and especially satisfactory policing from the point of view of the interested political power.

The economic effect on the United States would be mostly an indirect one, through the competition of and added exports (of goods, services, and personnel) to new development areas of the globe rather than through any significant cheapening of electricity at home.

The connection between atomic economics and world politics is thus due not only to the technical relation between atomic energy and weapons but also due to the role that atomic energy may play in the different speed of development in various areas (especially in the backward areas).