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The 1966 Annual Lecture
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Dr. Glenn T. Seaborg, Chairman
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NUCLEAR POWER - TWO YEARS AFTER GENEVA

I am especially pleased to have been asked to give the 1966 Annual Lecture of the British Nuclear Energy Society, and honored to join the ranks of those who have spoken to you in previous years. This platform has seen and heard a distinguished group of men - Lord Sherfield, whom I know as my good friend Sir Roger Makins; Dr. Sigvard Eklund, the Director General of the International Atomic Energy Agency; Dr. W. Bennett Lewis, Senior Vice President of Atomic Energy of Canada, Limited; and Sir John Cockcroft, one of the truly outstanding British scientists and a real pioneer in nuclear energy.

In considering a subject for this evening's address, I naturally reviewed the topics of the Society's previous annual lectures. On this basis I was encouraged by some of my associates to speak on the nuclear power program in the United States - a reasonably simple and relatively non-controversial subject for me. But I know full well that when one gets a few thousand miles away from the United States its immediate nuclear power plans and program are

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not the most exciting thing one might talk about. Going contrary to the good advice I received, I thought it might be more appropriate for me to broaden my perspective this evening and consider nuclear power from a more international viewpoint. I recognize the risks entailed when one quotes facts and figures about someone else's nuclear program. However, I have tried to do my homework accurately and hope that we will be in agreement on most of the ideas I would like to present.

During the next hour I plan to build upon the summing-up statement I gave a little over two years ago at the close of the Third Geneva Conference on the Peaceful Uses of Atomic Energy and attempt to review worldwide energy needs and resources, more specifically those of nuclear energy, to examine the current status of reactor technology and finally to take a look at what lies ahead of us in the development of more advanced nuclear power reactors.

For the most part, I will rely on published figures relating to the performance and economics of the various reactor types. As a result of this, I will have to give some unintentional slight to the Soviet Bloc developments since it is difficult to transpose their economics into those with which we are generally familiar.

The analytical approach I shall use for the most part this evening is a rather simple and straightforward one. In almost every instance I will consider reactor systems and their concomitant economics in terms of one variable - that is, a one dimensional analysis and a very simple one at that. I considered for a while trying to present a more precise, detailed and technological exposition, but soon realized that my time would be insufficient this evening to discuss the matter so fully.

I wish to make one further caveat - and that relates again to the facts and figures I shall be presenting this evening. Each number is not meant to be statistically significant to the seventh digit. In fact, I have intentionally rounded many of them off in order that no one will decide to make a significant programmatic decision on the basis that one reactor type was said to be a tenth of a mill more or less costly than another reactor type in tonight's address. By the way, I hope you will also bear with me in my use of mills and American dollars rather than their British equivalents. I believe that if I attempt tonight to translate the

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currency at the same time that I am interpreting the technology involved, we will all be more confused than enlightened by the end of the evening. With all this as a prelude, let me strike boldly forth to the substance of my talk - "Nuclear Power - Two Years After Geneva."

Before one can discuss the future of power with any realism one must first talk about people - people in terms of population and the ever-growing pressure of population. This is a subject of overwhelming importance today, and I am sure that you are all familiar with the information in the first figure (#1) showing the exponential growth of the world's population projected to the year 2000. The curve on this graph bears a simple but most relevant message - that between the year 1960 and the year 2000 - within the lifetimes of many of those in the audience - the world's population will about double. It will rise from three billion or 3,000 million, to six billion, or 6,000 million people. Now if all the other aspects of civilization as we know it were to remain the same and proportionally each individual consumed the same amount of energy tomorrow as today, the energy demand should also double.

But we know that this will not be the case and the second figure (#2) shows the actual situation. This graph of past and projected annual worldwide energy consumption covers the same period as the previous population curve. The previous curve, normalized to the worldwide energy consumption curve at the year 1950, has also been included for comparison's sake. This makes obvious the fact that the consumption of energy by individuals does not have a constant value. In highly technological societies such as the United States and the United Kingdom, there has been and will be a significant increase in energy consumption per capita. In the emerging nations, however, there probably will be a startling increase. The consumption of energy in these countries today is almost nil compared to what it might be tomorrow. It is difficult to comprehend fully the energy demands of a world of double today's population, all of whose people enjoy living standards approaching those of the people of the U.K. and the U.S.A. Think of the magnitude of energy that may be required some day if we were to air-condition much of Africa and the sub-continent of Asia and heat population centers that will be growing up in sub-Arctic regions. What would it mean to provide the power required to transport people and materials to the remote parts of the globe to satisfy the needs of an ever-expanding population, and provide sufficient power and fresh water for home, industry, and agriculture? Imagine the future energy needs involved in growing, processing and distributing food, from land and sea, for a world population double that of today - and demanding an adequate diet for all. These are only a few of the energy challenges we face.

Now recognizing the great importance of energy for future global social and economic well-being - perhaps for our very survival - let us talk about one important form of energy - electricity. The past and projected worldwide annual electricity production is represented in the next figure (#3). Again, the worldwide annual energy consumption as shown in the previous figure has been normalized to the worldwide electricity production curve at the year 1950 and projected to the year 2000. I believe it is particularly evident that electricity will provide an even greater fraction of the energy consumed by man in the ensuing decades than it does today. This should not be a surprising fact when one realizes that many parts of the world are just being ushered into the Electric Age. Further, electricity is a particularly easily managed form of energy - simply transported by wire, conveniently and economically generated in large blocks, and capable of being produced from a number of independent energy sources - that is, hydro, fossil fuels, or the heat generated from nuclear fission. It is electricity produced by this last means that I would like to turn to next and examine in some detail.

In general, the future of nuclear electric power looks bright indeed, but we who are in this field know that we have many obstacles to overcome and that much hard work remains ahead of us to make the most of the atom's great potential power.

When we look at the nuclear electrical production throughout the world from the year 1950 to the turn of the century, as seen in the next figure (#4), again we see a familiar pattern of rapid exponential growth. In this case because of the newness of this energy source - nuclear generating capacity was clearly zero in 1950 - the annual worldwide electricity production curve has been normalized to the worldwide nuclear production curve at the year 1970. It is generally agreed that nuclear energy will take an ever-increasing share of the electrical generating capacity until the turn of the century, when essentially all new electrical power plants to be built are predicted to be nuclear power plants. I should observe that the United Kingdom is somewhat ahead of this time scale and leading the world substantially at present in its installation of nuclear capacity.

This then brings us to the importance of nuclear power - a point of which I am sure many of you are already acutely aware. As I indicated before, a rapidly expanding global population, its increasing appetite for energy and the satisfaction of an increasingly larger share of this energy appetite by electricity make nuclear electric power a key element in the future well-being and progress of man.

Assuming continued improvements in nuclear power technology, very large-size plants, and the absence of certain financial restraints, nuclear power has the potential for a significant reduction in the cost of electricity. A reduction large enough to cause rather dramatic changes in energy utilization is foreseen by some. There is no doubt that large-scale, very low cost sources of energy will determine more than any other single resource the availability and cost of other basic resources such as food, water, and industrial materials. With very low cost power, desalted water would be a reality. Our nitrogenous fertilizers and many of our basic chemicals would be produced by new routes and from raw materials such as water, air and coal. Electricity would widely be used to reduce most ores to metals. The world of tomorrow will certainly be far different from that of today if these promises of very low cost nuclear power do come true.

There are, I might add, other obvious advantages to nuclear power today. It is a clean source of power and does not add to the burden of pollution in the air. It is relatively independent of geography because of the extreme compactness and long life of nuclear fuels and therefore nuclear power plants can be constructed far from their sources of raw material - uranium and thorium ores - without a significant economic penalty. And finally, it lends itself well toward generation in large blocks of power so that enormous, very economical, central power stations can be built.

But if nuclear energy is actually to be used in this very important role it must be capable of meeting at least two criteria. First, it must be economic wherever it is used. Otherwise nuclear power stations will not be built in any significant numbers. Second, sufficient reserves of nuclear fuel must be available to provide the enormous amounts of energy which will be required - not only through the year 2000, but also beyond, as our energy consumption ever increases.

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Turning now to the present status of nuclear power in the world, let me point out that the types of reactors being constructed throughout the world today are being built for current and near-term economic use and their design does not in general take into consideration the long-term future resources of nuclear fuel. At present this long-term concern is really not a necessary condition of reactor construction because nuclear energy represents but a minor fraction of the annual global energy consumption and uranium resources are ample to meet near-term requirements.

The main thrust of today's reactor types is, of course, economics, and there is justification for this. As is generally known, the current reactor types have achieved economical competitiveness - remarkably so in countries such as the United States. In fact, in my tenure as Chairman of the U.S. Atomic Energy Commission I have witnessed a remarkable evolution of nuclear power. When I first took office the entire program was questioned on the ground that the expenditures of vast sums of public funds seemed to be for naught - that nuclear power would not be economic for several decades to come. Today I find some people at the other extreme beginning to question whether any additional government funding of advanced nuclear power programs is necessary, since so many nuclear power plants are being sold by the nuclear industry that the industry has reached the point of being self-supporting. In the United States alone, firm commitments for the construction of nuclear power plants went from 2,000,000 kilowatts in 1963-64 to 5,000,000 kilowatts in 1965 to 15,000,000 kilowatts for the first nine months of 1966. A similar increase in reactor construction is expected to occur in other countries.

Here in the United Kingdom, for example, the second Nuclear Power Program adopted by your Government in 1965 planned a program of 5,000,000 kilowatts of nuclear generating capacity during the period 1970-75. As a result of selection of the AGR, this program was increased from 5,000,000 to 8,000,000 kilowatts by the end of 1975.

The French civil program, as another example, is the largest in Continental Europe. According to the French Government's "Fifth Plan" (the V Plan), the French foresee 2,500,000 to 4,000,000 kilowatts installed from 1966 to 1970 utilizing gas cooled, graphite moderated and natural uranium fueled plants of 500,000 kilowatts or more. At the present time, about 1% of France's electrical energy is of nuclear origin; by 1970, it is expected to reach 5%; and by 1975, 12%.

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The installation of nuclear power in Japan is expected to total from 4,300,000 to 5,300,000 kilowatts by 1975, and approximately 10,000,000 kilowatts by 1980. Seven central stations are in various stages of planning in Japan, with two plants now operating. Sweden also plans a long range construction program of six nuclear power plants totalling 2,500,000 kilowatts of power by 1978. In the Federal Republic of Germany, two plants are now producing electricity, two are being built, and plans are going forward on several others. It is apparent that nuclear power will have a rapid growth in Germany during the next decade. Canada, India, Italy, Switzerland, and Spain also have substantial nuclear power plans.

One of the reasons given for this abrupt change in events has been the ability of the electric producers to begin utilizing very large blocks of electrical generation. As a result, it has become possible to take advantage of the savings incurred through scaling nuclear power plants to very large sizes, as can be seen in the next figure (#5). Some measure of these savings is obvious if we compare the three current types of nuclear power reactors - the light water reactors (LWR), both pressurized and boiling water, and the gas cooled reactor, specifically the advanced gas cooled reactor (AGR), and the heavy water moderated and cooled and natural uranium fueled reactor (CANDU). The unit costs reflected by these examples are those for the capital costs associated with construction and exclude the investment required in fuel. From these curves, and in particular from the light water reactor curve, one can see that while a 200 megawatt light water plant might cost $200 a kilowatt to construct, a 1000 megawatt plant would cost only about $120 per kilowatt to construct. Another well-known point brought out by this chart is the fact that the AGR and CANDU reactors, which have relatively inexpensive fuel costs, are somewhat more expensive to construct than the light water reactor which conversely has a somewhat more expensive fuel cost. I should also add that these cost data represent the unit construction costs for these reactors in the country of their development. The heavy water reactor costs are those for construction of a reactor in Canada. The light water reactor costs are those for construction in the United States, and the AGR costs for construction are those for the United Kingdom. I felt it somewhat beyond the scope of this evening's address to attempt to place these on any more of a common basis, and in essence, redo the rather extensive and detailed efforts contained, for example, in the Dungeness-B Evaluation Report.

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A similar caveat applies to the next figure (#6) which compares in tabular form the three reactor types for which data were given in the previous figure, at a common size of 1000 electrical megawatts. This table shows both a capital cost component and an operating cost component. The relationship just mentioned a moment ago between light water reactors with relatively low capital cost and high operating cost, and the AGR and CANDU reactors with relatively high capital cost and low operating cost, is again clearly evident. In these data, fuel inventory charges are set forth in the fuel working capital component of capital cost rather than in the fuel component of operating cost.

Certainly, all three reactor types are economically competitive in specific areas of the world. One has only to note that they are being contracted for and that they are being built. And, I might add, in considerable number.

Now, from an international perspective what determines whether a nation will build one or another of these reactor types? One of the most important factors in the decisional process leading to a choice of reactor type is the cost of money to be borne by the operator, or, more broadly, the fixed charge rate applied by the operator of the facility to convert capital costs into annual fixed charges. This rate can vary widely from country to country. The fixed charge rate does, of course, include many factors - the largest of which for private financing is usually the cost of money (i.e., interest rate). Other factors include depreciation, which varies depending on the period of plant amortization chosen, the provision for interim replacements, insurance and taxes.

There clearly is no unanimity on this matter, as shown in the next figure (#7). This figure presents the fixed charges in mills per kilowatt hour for various fixed charge rates for each $100 per kilowatt investment. Here you can see that in Canada, with an annual fixed charge rate commonly applied there, $100 per installed kilowatt would amount to about 1.0 mill per kilowatt hour in fixed charges. In the United Kingdom, this figure would be about 1.4 mills; in the United States, about 1.7 mills per kilowatt hour and in Japan about 2.0 mills per kilowatt hour. When one realizes the effort given to reducing the operating cost a few tenths of a mill - especially those costs associated with the fuel and fuel cycle - you can see how significant the country-to-country variation in the fixed charge rate can be. This

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variation can lead to power cost differences as much as one mill per kilowatt hour for every $100 of investment. And even a one-tenth mill increase per kilowatt hour is not an inconsequential increase. At today's level of electric power generation, this would cost the world on an order of an additional $350,000,000 per year and by the year 2000 the added cost of one-tenth mill per kilowatt hour would have risen to $3,400,000,000 per year. In the extremes noted in the figure, the fixed charges vary almost by a factor of two in going from Canada to Japan - that is, go from 1 to 2 mills per kilowatt hour for every $100 per kilowatt of investment.

The next figure (#8) amplifies the importance of the previous figure. It illustrates the total generating cost, including both the operating cost, which is independent of the fixed charge rate, and the total capital cost including the fuel working capital, which is of course dependent on the fixed charge rate. This has been done for each of the three current reactor types, again based upon a thousand megawatt generation station. I believe this makes clear why the heavy water moderated and cooled reactor and the AGR appear more economic in countries where fixed charge rates are low, and why the light water reactors appear more economic in countries like the United States, where the fixed charge rates are higher. Again I must mention that these curves are for construction and operation of these reactor types in their respective countries, and their accuracy is probably not sufficient to fix the cross-over point of the two curves in the figure as precisely as is shown. I would imagine that if one were to construct a light water reactor and an AGR reactor in some third country the economic difference represented by the distance between these AGR and light water curves might not be anywhere as large as indicated.

I am sure you have realized that up to this point I have been treating in an overly simplified way the economics of nuclear power using only one variable - that of the fixed charge rate. Obviously the real world is far more complex than this and there are many other variables or uncertainties which must be taken into account in any decisional process. Some of these variables, such as construction cost due to variation from country to country in the cost of labor or materials, have a tendency to balance themselves out somewhat from one reactor type to another. Others do not. Of those that do not, one important variable is the price of uranium - the basic fuel for these reactors. This will affect both the operating cost, which is independent of the fixed charge rate, as well as the capital cost. In the latter case, the price of uranium is reflected in the working capital tied up in fuel inventory.

So far during this evening's presentation I have assumed a fixed price of uranium equal to $8 per pound of U_3O_8. This has been a general level which has been attained through extensive national and international procurement of uranium ores over the past decade. Recently, prices a few dollars below the $8 level have been negotiated due to the temporary surplus of uranium ore supplies. However, if one views this question of uranium ore resources from a long-term viewpoint the price will probably slowly escalate as the higher grade ores are consumed and as the general cost of labor and materials increases. For the present moment the figure of about $8 a pound of U_3O_8 is a fair and perhaps a somewhat conservative one not likely to change drastically for the next decade.

Nevertheless, a careful examination of the current reactor types from the viewpoint of the future abundance or scarcity of natural uranium supplies - as reflected in their market price - is an obvious next step. In the next figure (#9) we have such an analysis for the current reactor types. As you can see, the chart shows the change in generating cost as a function of the price of natural uranium, assuming that any new fissionable material produced is recycled as future fuel and that the fixed charge rate on working capital is a sort of average value of 10 per cent. The sensitivity of the generating costs of light water and advanced gas cooled reactors - both of which are fueled with slightly enriched uranium - to increases or decreases in the price of natural uranium is obvious. While a short-term reduction in the price of natural uranium to say $5 per pound for U_3O_8 may reduce the operating cost of these reactors by 2/10ths of a mill per kilowatt hour and that of the heavy water reactors by perhaps 1/10th of a mill, the potential long-term increase in price will assert an economic penalty, particularly on the AGR and light water reactors. As you can see, if the price of natural uranium were to double, both the light water and advanced gas cooled reactors would effectively have their electric generation cost increased by 5/10ths of a mill. The heavy water moderated and cooled reactor fueled with natural uranium is, from a neutron physics viewpoint, a more efficient machine. It utilizes one of the best neutron moderators known - heavy water - and as a result gets more energy out of a given quantity of fuel. In a sense, if one did no further development beyond the current types of reactors, the heavy water reactor would appear more and more competitive as the price of natural uranium increased. There are some advocates of this latter reactor type who because of this substantive point argue that further reactor development is really not essential for some time to come.

This fact focuses attention on the question of what degree of urgency must be given to this matter of increasing uranium prices. For, this should have a direct effect on the future planning and programs leading to the development of advanced and improved reactors. As an extreme - if the world could be assured that from here to the turn of the century the price for U_3O_8 would remain at today's level - there might be considerably less pressure and urgency for the development through government sponsorship of newer and more efficient reactors. Nonetheless there would remain some important incentives for the continued development of newer reactor types which might promise to be more economical than the current round of reactors. In the United Kingdom, this has been exemplified in the progress from the magnox reactors to the advanced gas cooled reactors.

To obtain some appreciation of the time scale which should be factored into these programmatic decisions the next figure (#10) shows the known and estimated uranium resources. I have shown these uranium resources as millions of tons of U_3O_8 as well as the related megawatts of nuclear generating capability. My figures are based on the assumption of sufficient fuel for a 30-year lifetime for nuclear power plants of the current light water and advanced gas cooled reactor types. Combining the information presented on this chart with that on the earlier one (Figure #4) showing a very rapid exponential growth of nuclear power generating capability, one can predict that the known or estimated worldwide ore resources costing $10 per pound or less are sufficient to supply about 300,000 megawatts of nuclear generating capability, which will be contracted for, with the consequent commitment of the indicated amount of uranium, by 1980. If one considers uranium ore resources of $15 per pound or less, the reserves, both known and estimated, are sufficient for about 550,000 megawatts of nuclear power stations, a capacity which will be reached by about the year 1985. Using uranium ore resources of $30 per pound or less, the reserves are sufficient for about 1,000,000 megawatts of nuclear power, which will be reached by about the year 1990. A very important fact, shown by this present chart, is that there are enormous resources of uranium available if one is not limited by cost of the ore.

I might also add a word of warning about these figures. They do not reflect the increased activity during the past months toward new uranium exploration, in the United States, Canada and elsewhere. They represent the facts as we know them today. I am certain, however, that additional ore supplies will be found, in similar fashion to the new fossil fuel resources found yearly, and that this figure represents a conversative view of things.

In addition to these resources of uranium ore, vast quantities of thorium ore will be found - quantities similar in magnitude to that of the uranium ores. Thorium can also be considered a nuclear energy resource although it itself is not fissionable. Thorium-232, the isotope of thorium found in these ores, like the non-fissionable isotope uranium-238 which is the very abundant isotope of uranium found in nature, can be converted to useful fissionable form by nuclear transmutation. As you know, in the case of uranium-238 the small fraction of the naturally fissionable isotope uranium-235 provides the fission reaction neutrons which, when captured by uranium-238, cause it to undergo a transmutation eventually leading to plutonium-239 - an isotope which is fissionable. Similarly, thorium-232 upon capturing a neutron can be transmuted to uranium-233, another fissionable isotope. Thus plutonium-239 and uranium-233 are the keys to unlocking the vast energies stored in uranium-238 and thorium-232.

Unfortunately, the current reactor types do not take full advantage of this situation. In the case of the light water and advanced gas cooled reactors, for every atom of uranium-235 consumed only about 5/10ths or 6/10ths of an atom of plutonium-239 is produced (conversion ratio of 0.5 to 0.6). The heavy water moderated and cooled reactor is somewhat more efficient and, in this case, for every one atom of uranium-235, something of the order of 7/10ths to 8/10ths of an atom of plutonium-239 is produced (conversion ratio of 0.7 to 0.8). The data shown in the figure (#10) are based on the assumption that the megawatts of nuclear generating capacity capable of being supported by a given level of fuel resources are produced by the light water or AGR reactors, reactor types which have a lower efficiency than the CANDU reactors, or the advanced reactors which I shall describe, in utilizing the total energy contained in uranium.

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We presently know that it is quite feasible to increase the efficiency of utilization of our uranium ore resources. The heavy water moderated and cooled reactor and certain advanced reactors which I shall discuss in a moment indicate one direction in which to proceed. Increasing the thermal efficiency of nuclear power plants is another direction. In general terms it appears readily possible to more than double the energy which can be extracted from a pound of uranium by going to reactors with higher conversion ratios than the currently available light water and AGR reactors. I refer to the near breeders. The effect of this increased efficiency is reflected in the fact that with the installation of these near breeder reactors in place of the current reactors the period of use of the known uranium ore resources can be extended for about a decade. The actual effect of near breeder reactors is even more dramatic since some of these would utilize the thorium-uranium-233 fuel cycle to supplement and replace the uranium-plutonium-239 fuel cycle. But whatever fuel cycle is in fact used, near breeder reactors must provide improved nuclear efficiencies in order to make a significant contribution.

The next figure (#11) shows one way of utilizing the gains to be obtained by increasing the efficiency of the conversion or breeding ratio of the reactor. This curve assumes a 0.4% loss in each recycle of fuel and a burnup of 18,000 MWD/ton for each irradiation cycle. The recycle losses and burnups of course can vary considerably from reactor type to reactor type. You can see from this that the current reactor types with conversion ratios of 0.5 to 0.6 utilize only a few per cent of the energy locked in the nuclear fuel, assuming recycle of all fissionable material produced in the reactor. This chart shows the obvious incentive for getting near or into a breeding regime. By breeding I mean - as many of you know - a reactor where more fissionable fuel is produced from the fertile uranium-238 or thorium-232 than is consumed in the fission chain reaction. This figure shows that if one gets to a conversion or breeding ratio of 1.1 or greater, tremendous gains can be obtained. Rather than utilizing only a few per cent of the energy present in the nuclear fuel, more than 50 per cent can be usefully harnessed. This fact also means that even though the current reactors inefficiently utilize the uranium and thorium fuels, these fuels are not wasted. The large fraction of uranium-238 and thorium-232 not consumed in these reactors can serve eventually as fuel for future breeder reactors.

This has an immediate compound effect. Assuming one is able to build economic breeder reactors, the nuclear generating capacity capable of being ultimately fueled with today's low cost ore resources is greatly increased. Second, the high efficiency of these reactors means that they should be less sensitive to increases in the future costs of nuclear fuel.

Unfortunately, as we all know, government life and service are not as simple as to permit one to say "let there be a breeder reactor and lo there is a breeder reactor." There are many real scientific and technological hurdles which must be crossed. In addition there are other types of advanced reactors - near breeders - which for the near-term have considerable economic promise. If one looks about the world today one can see several types of advanced reactors, including breeder reactors, under intensive development. The next figure (#12) shows the projected capital and generating costs of several types of near breeder and breeder reactors. As you can see in this illustration, I am paralleling the earlier figure in which I considered the current reactor types. I have broken these newer reactor concepts into three broad categories. The first one is characterized by the near breeder reactors, the High Temperature Gas Cooled Reactor (HTGCR) or the advanced gas cooled Dragon reactor, and the heavy water moderated organic cooled reactor (HWOCR) or the heavy water moderated, boiling light water cooled reactor (HWBLW) somewhat parallel to the steam generating heavy water reactor (SGHWR) here in the U.K., with conversion ratios of .8 to a little less than 1.0. The second and third categories represent two general categories of fast breeder reactors - low gain breeder reactors with a conversion or breeding ratio of 1.1 to 1.25 and a specific power of about 0.25 Mwe/kg of fissionable fuel, and high gain breeder reactors with a breeding ratio of 1.4 and a specific power of about 0.33 Mwe/kg. For these combinations of breeding ratio and specific power, the low gain breeder has a long doubling time and the high gain breeder a short doubling time. The low gain breeder can perhaps be characterized by the sodium-cooled, UO_2-PuO_2 fueled, fast reactor while the higher gain breeder reactor cannot now be as clearly characterized although it is surely more exotic.

Figure #12 reflects our conjectures today that the breeder reactors, representing a somewhat more difficult technology than the near breeder types, will be more expensive to construct. The near breeder reactor types, after all, are built on technology closer at hand. Further, you can see that the operating costs of the low-gain breeder and the near breeder reactors based on present uranium fuel prices are not too different.

I should also add a word about two lesser known contenders in this reactor derby. For some years the Oak Ridge National Laboratory in the United States has been carrying on an extensive research and development program on a Molten Salt Reactor Project. This high temperature thermal breeder reactor utilizes thorium-uranium-233 in a homogenous fuel cycle. At present a 7500 thermal kilowatt reactor experiment is in successful operation. A high temperature thermal breeder reactor of this variety would not only be an efficient reactor with very low fuel cycle costs but would also require a smaller nuclear fuel inventory than a fast breeder reactor, further improving its economics. If all goes well with this Molten Salt Reactor Project it may have a profound effect on our future planning.

Another reactor under active development is the Seed and Blanket Reactor (the Light Water Breeder Reactor). This reactor program is aimed at the development of a thermal breeder reactor in the light water reactor system. The concept utilizes the thorium-uranium-233 fuel cycle and holds the promise common with other breeder reactors of extending our nuclear fuel resources significantly. It has the unique advantage that it is based on the well established light water reactor technology.

But this evening, for the sake of simplicity, let me focus attention on the better known near breeder reactors and breeder reactors.

If one takes the hypothetical figures for these reactors - and I stress that they are based largely on conjecture since we have yet to build or even firmly announce our plans to build a 1000 electrical megawatt unit of any of these types - and plots them against the variation in the fixed charge rate, one obtains the results indicated in the next figure (#13). At the present prices of uranium fuels, this chart indicates that these near breeder and breeder reactors, from a simple economic viewpoint, have considerable potential in those countries where the fixed charge rate is say less than 10 per cent. This is because they all promise to have remarkably low operating costs reflecting efficient fuel cycles. This also indicates that there is some incentive for developing these advanced reactors regardless of whether the price of uranium should increase - for they may be more economical than current types.

Of importance from a national and worldwide viewpoint is the built-in insurance policy which one can purchase with these near breeder reactors and breeder reactors. This insurance policy is reflected in the insensitivity of the total generating cost to the price of natural uranium as the next figure (#14) shows. You can see here that doubling the price of natural uranium increases the generating costs of the near breeder reactors about 2/10ths of a mill per kilowatt hour or less and that of the fast breeders perhaps 1/10th of a mill or even less. The fast breeder reactor, in fact, may prove so efficient that ore costing $100 per pound of U_3O_8 or more, available in virtually unlimited quantities, could still be used without a sizeable economic penalty. I should also observe that the curve for the near breeder reactors, while markedly different from that for the light water and advanced gas cooled reactors of the current round, is not too different from the heavy water moderated and heavy water cooled reactor. However, as you recall, the latter reactor type suffers from a high capital cost at this point in its development. Also a most important point is that near breeder reactors like the HTGR and Dragon and others would utilize the thorium-uranium-233 fuel cycle, thus increasing the reactor's conversion ratio since uranium-233 is the most favorable nuclear fuel from this respect in a thermal neutron reactor. As a result, the demands placed upon our ore resources would be less because of the increased efficiency of these reactors using the thorium-uranium-233 fuel cycle.

One other important consideration that must be borne in mind in analyzing the future trend of reactor development and its impact on nuclear fuel resources and the economy of electric power generation is the specific power of these future reactors. The specific power, that is, the power generated per kilogram of fuel placed in the reactor, can perhaps be viewed more simply in terms of the inventory of fuel required by a given size reactor. The higher the specific power, the lower the inventory. A low inventory has the effect of lowering the generating costs because the fuel carrying charges are less; that is, less capital funds are tied up in fuel inventory. Further, considering a breeder reactor economy, a smaller reactor inventory affects the doubling time - that is, the time required before a breeder reactor could refuel a carbon copy of itself. Also a smaller reactor inventory in any type of nuclear plant means that the resource requirements are less. Therefore, there is considerable incentive to develop near breeders and breeder reactors with high specific power and therefore low fuel inventory requirements.

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There is one further complexity that I feel should be considered even in this simplified treatment of nuclear power. It is, in a sense, a kinetic consideration. The growth of the annual electric consumption and that of nuclear electrical power will be rapid indeed for the next several decades. This poses a most interesting dilemma. If nuclear power is to satisfy these growing requirements to a larger and larger extent, great demands will be placed on our nuclear fuel resources even if a low-gain fast breeder reactor is developed. The reason here, in the most simplified fashion, is that if electrical requirements are doubling - say every ten years - and one has a fast breeder reactor which can produce new fuel at a doubling rate of 20 years - one would still have to continue to mine new uranium ores to make up the difference between that supplied by the breeder reactors and that required by the expanding power system. As time goes on, and as these requirements accrue in magnitude, it is conceivable that very expensive ores would have to be used.

This presents a possible continuing economic problem for some years in the future. But one could avoid this situation if it should prove possible to construct high-gain fast breeder reactors. I will not attempt this evening to give any specific qualities of this machine other than its breeding ratio of 1.4, its specific power of 0.33 Mwe/kg, and its doubling time, which would be less than ten years, perhaps seven years. A reactor with this short a doubling time, less than ten years, could meet the requirements placed upon the nuclear system by the growing electrical demand and seemingly always remain in a reasonably comfortable economic position.

My next figure (#15) attempts to illustrate this graphically in another manner. The doubling rate for electrical power demand in the world has, in fact, been about ten years and on this graph one can see the effects of a low-gain fast breeder reactor and those of a high-gain fast breeder in terms of the requirements placed on the uranium ore resources. In essence, a reactor economy dependent upon low-gain breeders requires ten to twenty times more ore than an economy based on high-gain breeders.

In summary then, for a breeder reactor to catch up with and maintain a prescribed total power growth rate, it is necessary that the doubling time of the breeder reactor be, or eventually become, as short as that of the power growth. It is interesting to note, as shown in the next figure (#16) that, in more quantitative terms, the amount of fuel that

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must be supplied to the breeder system to accomplish this mission is proportional to mf(T) where m is the specific inventory of nuclear fuel (reciprocal of the specific power), T is the breeder doubling time, and f is a function increasing with T whose form depends upon the power growth curve.

To give one further glimpse into the economic complexity of this situation before I conclude, consider what might happen in the oversimplified case where the demand for electric power slowed down appreciably and one had an entire economy of reactors of the high-gain breeder type. At this point there would be a plethora of fissionable material with insufficient consumers for power uses. On a free market basis, the bottom would drop out of the market and the price of fissionable material - either plutonium-239 or uranium-233 - would sink very low. At this point, there would obviously be an economic incentive to build reactors to simply burn and thereby consume this excess material without producing new fissionable material. This assumes that these burner reactors could be simpler reactors than the breeder variety and therefore constructed at somewhat less cost. Interestingly enough, the current generation of reactors could be considered to be just such burner reactors as could some of the advanced types. What I mean to imply by this is that any future reactor economy will probably be a mixed reactor economy. We will probably always have several types of reactors, with new reactor construction determined, among other factors, by the projected rate of growth of electric power demands, the price of natural uranium, and the price of bred fissionable material at the time the decision to go ahead with a reactor unit is made.

In closing, let me return to a point I illustrated just a moment ago, the plethora of fissionable material. Whether or not near breeder reactors and breeder reactors are, in fact, developed, built and operated, significant amounts of fissionable materials, expecially plutonium, will be bred throughout the world. And, as you know, plutonium can be used as the explosive ingredient of nuclear weapons. The last figure (#17) summarizes the cumulative quantities of plutonium that would be produced by the year 1980 and the year 2000. Astonishing amounts indeed. This plutonium will be produced throughout the world by 1980 - if our projections are correct - at the rate of more than 100 kilograms a day! In other words, material will be produced over the face of the globe sufficient for the potential production of a substantial amount of the world's electrical power - or, alternatively, sufficient for tens of nuclear weapons a day.

In the light of this, there are some who would say that the only rational course is to bring an abrupt and complete halt to the development of nuclear power here and now; that the price we pay for a little additional energy is much too high for the risk of nuclear annihilation, and that no adequate means of control can be developed to insure, in fact, that these nuclear fuels will not be misused.

But most of us know that such thinking is not fully realistic. Even in the early days of nuclear development, while there were some who felt we could hold back all our information and discoveries on this new form of energy, thus keeping others from obtaining nuclear weapons, most of us knew that it was only a matter of time before other countries could achieve a nuclear capability independently of the United States, the USSR, and the United Kingdom. The major secret of the atomic bomb was, of course, that it worked - and this had been revealed to the world. Many countries of the world had their own supplies of natural uranium and, perhaps more importantly, their own scientists. We also considered that if we failed to cooperate in sharing our peaceful nuclear technology and nuclear materials, there would be other countries which might be willing to provide nuclear materials and technology without a firm assurance as to their eventual peaceful end use.

Choosing, therefore, a more positive and constructive approach, the task has thus become not a matter of forbidding the further spread of nuclear science, but rather one of helping one another to develop the peaceful uses of nuclear energy under conditions which assure the peaceful use of the nuclear equipment and materials which are supplied.

An organization already playing a very significant role in guaranteeing that the peaceful atom will remain peaceful throughout the world is an agency whose existence is hardly known to the general public. This organization is the International Atomic Energy Agency (IAEA) with its headquarters in Vienna and its current membership of 96 nations, with three additional member nations about to be admitted. We have in the work of the International Atomic Energy Agency perhaps the forerunner of a fully international safeguards and control system. The essence of this system lies in the right to inspect facilities and materials supplied through international agreement. Such inspections are carried out by IAEA international inspection teams at those facilities whose countries have agreed to put them under international safeguards. Unfortunately, not all member countries of the IAEA have placed their facilities under such inspection arrangements yet. I am pleased to say that the United Kingdom has placed one of its large power reactor stations under IAEA safeguards inspection, as has the United States.

In addition to its present activities relating to the inspection of reactors, the IAEA has recently considered and developed appropriate safeguards and controls for chemical reprocessing plants to assure that none of the materials separated and purified in these plants are diverted to non-peaceful uses.

I am hopeful that the future will show a continued increase in the application of these IAEA safeguards and controls and that eventually we may have a worldwide system of safeguards and controls under which all nations will be able to develop and share the peaceful atom free from the fear of a potential nuclear threat.

In conclusion - and I regret that I do not have an appropriate chart or graph to illustrate this point - it has been a great pleasure for me to come to London to address the British Nuclear Energy Society. The fact that your country leads the world in the use of nuclear power to generate electricity, I believe, speaks well for the effectiveness of your Society in bringing Great Britain the remarkable advantages of the peaceful atom. Your highly successful nuclear programs devoted to peaceful endeavors should serve as an inspiration to many countries. We in the United States are proud to have been your partner in the development of nuclear energy since its earliest days. We look forward to a continued and growing era of cooperation with you as together we seek to further develop and make available to all men those benefits of nuclear energy which will promote peace and progress throughout the world.

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