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Remarks by
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U. S. Atomic Energy Commission
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Plutonium and Other Actinides
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THE PLUTONIUM ECONOMY OF THE FUTURE

Introduction

Thirty years ago researchers at Berkeley were doing work which resulted in the discovery of a synthetic element which they named plutonium.

Today isotopes of that element are demonstrating their versatility in fundamental endeavors of our society. Today plutonium is providing energy to pace the human heart and thereby sustain life. Today plutonium is powering an experiment on the surface of the moon and thereby helping to advance human knowledge. Today plutonium is a partner with uranium-235 in the generation of over 1% of the electrical needs of this country, lighting our homes and energizing our industry, thus contributing to our economic growth and our general welfare.

Thirty years from now this same man-made element can be expected to be a predominant energy source in our lives. We believe we have the capability to develop a plutonium-fueled artificial heart which will reduce the disablement of tens of thousands of people. We are envisioning exploratory space missions to the outer planets as well as closer-in-earth-oriented space applications which can benefit from plutonium-based space power systems. On earth we expect that plutonium will be the fuel

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for over 50% of our total electrical energy needs. Since those needs are projected to be over 6 times greater than they are today, plutonium will then be fueling 3 times the amount of electricity now being produced today throughout the United States from all types of fuel - coal, gas, oil, hydro and nuclear.

This plutonium economy of the future is going to be a great deal larger than our present economy. The Gross National Product (GNP) of the United States was 932 billion dollars in 1969. The GNP is projected to reach nearly $1.5 trillion in 1980, $2.2 trillion in 1990 and $3 trillion in the year 2000. These estimates are in 1970 dollars, as are all other dollar estimates in these remarks. Electrical energy is basic to the growth of the economy, and without cheap reliable electric power such economic growth could not take place. Plutonium, as the key to electric energy production in the future, is thus a vital element of the overall economic well-being of this country.

Within the lifespan of a single generation this newcomer plutonium - born on a humble research budget and cradled in a cigar box - will have become the energy giant of the future. In this sense then, I wish to speak of plutonium as the energy cornerstone of our future economy and to speak of that economy as the plutonium economy of the future.

Plutonium as a Power Reactor Fuel

At the end of 1969 the total electric industry generating capacity of the United States was nearly 313 million kilowatts of which about 1.3% or some 4 million kilowatts was nuclear. Consumption in 1969 was over 1.3 trillion kilowatt-hours with nuclear generation representing about 1.1% of the total. The Federal Power Commission (FPC) has projected that installed capacity will reach 1.260 billion kilowatts in 1990 with the Nation's annual requirements reaching 5.83 trillion kilowatt-hours. In 1990 some 40% of the generating capacity is forecast by the FPC to be nuclear fueled.

Installed nuclear capacity will be doubling this year and about one-third of all new capacity presently planned is already scheduled to be nuclear. Both the existing and this new nuclear capability consists primarily of so-called LWR's - light water reactors - based on the enriched uranium fuel cycle. Plutonium is produced in the fuel as a by-product. A portion of that plutonium is consumed during the residence

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of the fuel in the reactor and contributes about one-third of the total heat output, with the remainder coming from the uranium. The residual by-product plutonium is then discharged with the fuel and available for reuse after chemical processing.

Recycling the by-product plutonium into future reactor cores can increase the actual utilization of its inherent energy content. The recycle plutonium displaces enriched uranium that would otherwise be required and substantially increases the fraction of the heat energy derived from plutonium. In such a case, because of continuing in-core plutonium generation, the spent fuel may contain two-thirds of the quantity of plutonium originally loaded in it. Such a system still requires substantial amounts of new enriched uranium if total system capacity is to expand to follow the growth of energy demand through time.

The next step in increasing the utilization of plutonium will require the successful development of a new reactor type - a fast breeder which generates more fissile plutonium than it consumes - with a breeding ratio, i.e. ability for self-sustaining fuel independence, large enough to allow penetration of the market and to follow the rising energy demand curve. This type of reactor which utilizes the energy inherent in uranium-238 is exemplified by the Liquid Metal Fast Breeder Reactor (LMFBR), the subject of an intensive Government-Industry cooperative research and development program, and the highest priority civilian program of the Atomic Energy Commission. Such a reactor will require only relatively small amounts of natural or depleted uranium (as the fertile material for plutonium breeding) and will derive about 80% of its energy output from plutonium while at the same time producing sufficient additional plutonium to provide fuel for new power plants. The remaining 20% of the energy output will come from the fast fission of uranium-238.

Obviously such a new reactor system does not arrive full-blown on the scene. There will undoubtedly be several generations of LMFBRs as there have been of LWRs. As breeders penetrate the market, plutonium can be released from the inventory of LWRs on plutonium recycle to provide initial plutonium fuel loadings for breeders. There may even be some anticipatory stockpiling of plutonium on the part of electric utilities as they commit their future system expansion to breeders. Such stockpiling will be limited by economic considerations, however, since the alternative use of plutonium recycled in LWRs also decreases power generation costs. Currently, the penetration rate of breeders into the economy is not expected to be limited by the availability of plutonium. Market acceptance is more likely to be paced by the more

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mundane and infinitely harder questions of the technical maturity and reliability of the new technology, the manufacturer's capability to deliver it at reasonable cost, and its overall economic attractiveness relative to competing energy sources. Thus the use of plutonium recycle in LWRs will provide, in effect, a plutonium stockpile in use which can be tapped as needed to provide the fuel base for the next step forward in energy independence.

The timing of breeder development is of critical importance. If our projections are realized, annual savings in national energy production costs in the tens of billions of dollars are at stake. This is many times the AEC's current annual budget for all civilian and military programs. Even when the time value of money is taken into account, as it should be, the more readily quantifiable economic benefits are valued in the billions today; and there are numerous additional benefits that cannot be so easily compressed into a dollar number. Continued discipline and dedication will be required to bring these projections to fruition. AEC's Cost-Benefit Analysis of the U.S. Breeder Program, published in 1969, indicated that delays in achieving the technical and economic objectives of the program introduce a cost penalty with a present value approaching a billion dollars per year of delay (and such estimates ignore the magnifying effects of escalation of costs in our economy).

Clearly, then, what we foresee can only be described as a technological revolution in our approach to energy production - a process that has already begun but yet has far to go. An attempt has been made to visualize this process of transition through computer-modeled studies of the future. I would like to draw on some of these studies, which were summarized in the Cost-Benefit report I mentioned a moment ago, to illustrate one possible sequence. The United States electric energy demand in this illustration is compatible with the FPC forecast for 1990 which I have described. Our projection must extend further into the future, however, to include at least one operating lifetime of breeders installed in the late 1980's. Hence this illustrative projection assumes an operating capacity (excluding about 20% extra capacity required for reserve) of 1.675 billion kilowatts generating 10 trillion kilowatt-hours in the year 2000 and 4.2 billion kilowatts capacity generating 24.2 trillion kilowatt-hours in the year 2020.

Now these are bold assertions and there are obviously substantial uncertainties about the future. Hence I wish to emphasize that they are illustrations and not predictions. (Actually, the majority of predictions about future energy use have proven to be too low, rather than the reverse).

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The concern for environmental effects from power production could result in a lower demand. So could lower population growth. On the other hand, many if not all of the environmental problems we now see require energy for their solution, regardless of our population level, and electricity may be the cleanest form of energy to use. Furthermore nuclear power is being designed to be an environmental good-neighbor. Indeed, I can think of no other energy system that has been so concerned, from its very inception, with the question of minimization and management of its waste products and early and continuing research on its effects upon the human ecology. The AEC has been conducting ecological studies of sites for nuclear installations for over 20 years - long before environmental questions had become major issues to the general public. Yet every advance in knowledge permits one to ask still another question. So I do not see an end to the need for continuing research on the environmental effects of nuclear energy - or any other technology. I do believe, however, that our headstart on care and concern for the consequences of this technology will be maintained and, on balance, permit nuclear energy to meet the power needs of the nation at lower economic and environmental costs than any other system now within our technical grasp.

1970-1980

To return to our illustration, we see nuclear power in the United States growing from its 1969 capacity and electric energy generation levels of 1% of the total to a capacity of about 150 million kilowatts at the end of 1980, generating over 1 trillion kilowatt-hours in that year. This represents about one-fourth of the generating capacity and one-third of the energy requirements of the country at that time. The Gross National Product will have increased from its 1969 level of $0.9 trillion to the projected 1980 level of $1.5 trillion. During this decade most reactors built will be LWRs although some thermal reactors of advanced type, such as high temperature gas cooled reactors (HTGR) operating on the thorium/uranium-233 fuel cycle, and LMFBR demonstration plants will also be built and operated.

Near term annual rates of recovery of plutonium from spent fuel will be about 500 kilograms; by the end of the decade the annual recovery rate will approximate 20,000 kilograms, a 40-fold increase. Cumulative production in the decade will exceed 80,000 kilograms of plutonium.

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There will be a temporary stockpile of plutonium in the early years, essentially a buildup in materials inventory, while a transition to the use of plutonium recycle fuel is in progress. By the end of this decade about one-fifth of the total energy will be generated from such fuel and essentially all available plutonium will be in use within the system.

With plutonium valued at about $10 per gram of fissile isotope content for thermal recycle (and assuming about 75% of the recovered plutonium to consist of fissile isotopes) the annual value of the recovered material will rise from under $4 million to an end of decade value of $150 million. The actual value of plutonium in the near term, after guaranteed purchase by the government is terminated, is uncertain. If it is then still in short supply for research and development needs, it may be worth more than $10. More likely, it will be worth less than $10 by virtue of having to initially absorb the one-time costs associated with establishing the recycle fuel fabrication capability and developing appropriate fuel management patterns. By the end of the decade, however, the transition is expected to be accomplished. Six hundred million dollars worth of plutonium is simply too valuable an asset to remain idle.

Two-thirds or more of the plutonium in recycle loadings will be recoverable from the spent fuel when additional plutonium generated during reactor operation is taken into account. Thus about 60,000 kilograms of recovered plutonium will be stored in-use in LWR inventory in 1980. As a result, about 45% of the total nuclear energy in 1980 and therefore about 15% of the total electrical energy will come from plutonium fission.

1980-1990

By the mid 1980's we expect to see the first generation of fast breeders becoming commercialized. In addition, if advanced thermal reactors on the thorium/uranium-233 fuel cycle are to make significant impact on the market, it will be in the 1980-1990 period. The projection that we shall use here assumes that they will and to this extent will compete successfully for a nuclear share of the market with LWRs and early design LMFBRs. Should this not occur, it merely means that our resulting extrapolations of the capacity of plutonium producing and consuming reactors have been conservative and that even larger quantities of plutonium will be in use than we shall now discuss. (Alternatively it is also possible that these advanced reactors may be operated on the uranium/plutonium fuel cycle instead of the thorium/uranium-233 fuel cycle, again making our illustration conservative.)

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By the end of 1990 the Gross National Product will have increased to $2.2 trillion from its 1980 level of $1.5 trillion. We hypothesize some 500 million kilowatts of nuclear capacity in 1990 generating well over 3 trillion kilowatt-hours annually. This represents about 40% of the capacity and 55% of the electric energy needs of the country at that time. Of the nuclear capacity, about 45% is expected to be LWRs with advanced reactors comprising 30% and LMFBRs comprising 25% of the total.

Plutonium recycle will come to an end as breeders use the available plutonium for their initial loadings. Annual recovery rates from LWRs will reach 60,000 kilograms of plutonium. A short-term pre-breeder stockpile, facilitating a rapid introduction of this reactor type, will reach its peak. Due to the more efficient use of plutonium in the LMFBR, the value of plutonium will rise, thus sharing some of the economic benefits of the breeder with its plutonium supplying partner, the LWR. The value of the last increment of plutonium available in the system may reach $20 per gram of fissile isotope in 1990 although the average value of the total plutonium inventory will be somewhat less. Thus annual LWR spent fuel may carry a plutonium value of over half a billion dollars. The material value of <u>all</u> of the plutonium fuel in existence in 1990 will be something like $6 billion. For comparison, in 1969 investor-owned electric utilities spent $3 billion for <u>all</u> fuel needs.

About 45% of the total nuclear energy in 1990 and therefore about 25% of the total electric energy will come from plutonium fission.

1990-2000

During the mid-1990's the LMFBR is expected to become the predominant nuclear power plant. By the year 2000 the Gross National Product will approximate $3 trillion. We hypothesize some 1.1 billion kilowatts of nuclear capacity at that time generating slightly less than 7 trillion kilowatt-hours annually. This represents about 65% of the operating capacity (exclusive of reserves) and 70% of the electrical energy needs of the country at that time. Of the nuclear capacity about two-thirds is expected to be LMFBRs with LWRs and advanced reactors splitting the remainder.

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Annual plutonium production from LWRs will decrease to about 35,000 kilograms by the end of the decade as their capacity utilization factor is decreased, reflecting the base-loading of the more economic breeders. Plutonium stockpiles will have long since been productively utilized. About the middle of the decade, breeders then in operation will be producing more plutonium then they are consuming - reaching an annual level of 80,000 kilograms by the year 2000 - not yet enough surplus to completely supply new capacity needs. Hence LWRs and their plutonium production will still be a vital part of the system.

As a result of increasing demand, the incremental value of plutonium production will continue to climb, perhaps reaching $25 a gram of fissile isotopes; but again, its average value will be somewhat less. Thus annual LWR and LMFBR spent fuel may carry a plutonium value of over $1.5 billion. The material value of all the plutonium fuel in existence in 2000 will approximate $18 billion.

Over 80% of the total nuclear energy in 2000 and therefore over 50% of the total electric energy could come from plutonium and uranium-238 fission according to these projections.

2000-2020

You will no doubt have noted that my remarks have grown briefer with each succeeding decade. I wish now to merely note that our studies have extended to the year 2020. By then, breeders are expected to saturate the electrical generation capacity and to readily produce plutonium in excess of system expansion needs. As a result, the plutonium inventory may be in an over-supply condition and therefore plutonium may become extremely inexpensive. Perhaps special reactor types will be designed solely to burn this very cheap fuel. Perhaps newer and better power systems such as the controlled thermonuclear fusion reactor will be beginning to compete in the energy market. If so, they will have to be even better systems then might otherwise be required because of the high standards of economic efficiency established by the LMFBR. In any event, this future economy, significantly larger and more complex than the one in which we now precariously survive, will have begun to be beyond our detailed understanding and acceptance, although not yet beyond our imagining.

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Significant Assumptions

We have also looked at how these results change under the effect of different assumptions. In general it appears that reasonable variations in the total nuclear capacity in the year 2000 are within a plus or minus 20% band. Of course, more drastic variations in the assumptions could alter this range somewhat. The content of this capacity, however, as between breeders and thermal reactors is more significantly affected by changes in assumptions. Factors tending to delay LMFBR penetration of the market, whether technical or economic, when combined with reduced energy demand, can decrease the capacity of breeders installed in 2000 by as much as one-third with compensating increases occurring in thermal reactor capacity. Conversely, if advanced thermal reactors do not establish a firm market position by the early 80's, correspondingly greater numbers of breeders can be built. Thus, while there is necessarily uncertainty as to the specific mix of reactor types in the future, because of the considerations noted, there is much less uncertainty with respect to the magnitude of the ultimate major role which nuclear power - regardless of type - will play in the electrical energy industry.

Plutonium-238 Production from Power Reactor Fuel

There are other aspects of this plutonium-based economy which I would now like to discuss. The first related matter is the potential availability of large quantities of plutonium-238, a special isotope of plutonium which is an attractive fuel for a number of uses including space and medical applications. Its value is based on the heat liberated by alpha particle decay rather than by fission.

One method of producing large quantities of plutonium-238 is by irradiation of neptunium-237 which is recoverable from spent uranium or uranium-plutonium fuel loadings. The neptunium-237 is formed during the power production cycle by neutron absorption of uranium-235 to form first uranium-236 and then uranium-237 with the latter decaying by beta particle emission to neptunium-237. An alternate route reaches the intermediate unstable uranium-237 by the (n, 2n) reaction on uranium-238. Subsequently the recovered neptunium-237 may be irradiated as a neutron target to form neptunium-238 which decays by beta particle emission to the plutonium-238 product.

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Plutonium-238 can also be obtained as a decay product of curium-242. Like neptunium-237, curium-242 is present, although to a much lesser extent, in spent reactor fuel and can be separated in chemical reprocessing. Curium-242 derives from neutron irradiation of plutonium fuel and its derivative americium during the power cycle. It has a 163 day half-life and decays by alpha particle emission to plutonium-238 which can be chemically separated in more isotopically pure form from the curium.

Another means of producing plutonium-238 is by the irradiation of americium-241. The latter, also a by-product of plutonium fuel as is curium-242, is similarly present in spent fuel. It can be irradiated in a neutron flux to produce americium-242 which decays to curium-242. The curium isotope then decays to "high purity" plutonium-238, as noted previously.

Depending on the use of the plutonium-238 the preferred production scheme is different since, during irradiation, impurity isotopes such as plutonium-236 which results from the (n, 2n) reaction on neptunium-237 are also produced. The content of the plutonium-236 must be limited when medical uses are contemplated since this isotope has highly energetic gamma ray emissions in its decay chain and the potential dosage to the user of the heat source device must be kept well within acceptable levels. Such plutonium-238 with a low content of plutonium-236 is often referred to as "high purity" plutonium-238.

The formation of plutonium-236 can be minimized by increasing the proportion of thermal neutrons in the reactor used for irradiation. Another but longer way of reducing plutonium-236 content is to allow plutonium-238 to age. The shorter half-life of plutonium-236 allows it to decay so that its concentration is reduced by about a factor of 10 in 10 years. While this method is time consuming and expensive as a specific production method, it nevertheless follows that plutonium-238 of ordinary isotopic purity will increase in purity while in use in applications where the plutonium-236 is not a problem. Thus additional high purity plutonium-238 can eventually be made available by recovery of aged plutonium-238 from such previous applications. Physical separation of plutonium-236 from plutonium-238 is also a possibility whose feasibility will undoubtedly receive more serious attention if relatively large amounts of "high purity" plutonium-238 are needed for proposed applications.

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Plutonium-238 for Space Applications

Plutonium-238 decays by alpha particle emission with an 87 year half-life and has a specific power of about one-half watt per gram. The most noteworthy use of a plutonium-238 powered radioisotope thermoelectric generator (RTG) has been as the power source (called SNAP-27) for the experimental package left on the moon by the Apollo 12 astronauts. Plutonium-238 was also the heat source which kept the Apollo 11 experiment package warm during the long lunar night. Plutonium-238 fueled RTGs are of particular interest as space electric power sources for missions requiring a long life and high reliability, where there are long periods of darkness or great distance from the sun, or where orientation or other problems tend to reduce the effectiveness of solar cells as an energy source. There are a significant number of space missions in the future which may have these attributes and which will therefore be powered by plutonium-238.

A series of Department of Defense navigation satellites, which have been named TRANSIT, will be used by all three military services and will continue in use for many years. The satellites will have a three to five year life so that there will be several launches per year to replace satellites when their orbit has decayed or equipment has passed its useful life. Each TRANSIT satellite is expected to use 30 watts of electric power produced by an RTG which will require about 1.5 kilograms of plutonium-238.

NASA's planetary science program will begin with the Pioneer missions. These are two flybys of the planet Jupiter to be launched in 1972 and 1973. The purpose of these missions is to photograph Jupiter and its moons, perform experiments on the atmosphere of Jupiter and measure meteoroid and radiation density between Earth and Jupiter. The Pioneer missions will require about 120 watts of electric power at the time of Jupiter encounter. If these missions are successful, they will represent a new capability which will lead into follow-on missions of data gathering spacecraft in and out of the solar ecliptic plane.

The so-called Grand Tour missions will be the most extensive of these follow-on missions. Successive pairs of spacecraft will be flown in 1977 past Jupiter, Saturn, and Pluto and in 1979 past Jupiter, Uranus, and Neptune. The encounter with the last planet on each mission occurs about 9 years after launch and at a distance of 30 astronomical units (that is 2.8 billion miles). Each Grand Tour mission will require about 400 to 500 watts of electric power at the outermost planet. These missions will require a total of about 75 kilograms of plutonium-238 in this decade, well within our capability to provide.

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Another planetary mission is the Viking program. Under this program NASA plans to launch vehicles in 1975 and 1977 which will land on Mars. These landers will gather scientific data on the Martian surface and atmosphere. Nuclear power is an absolute necessity for this mission because of the hostile Martian environment. Each of these vehicles would require about 2.5 kilograms of plutonium-238.

The very successful Nimbus weather satellite which already uses plutonium-238 is expected to be followed by the Unified Nimbus Observatory. This advanced weather satellite will gather more data and have a wider coverage than the present Nimbus. To be able to point very accurately at the Earth, the satellite should not also have to orient itself to the Sun for solar energy. Nuclear power solves this problem, since it does not require orientation, but nuclear power has not yet been chosen for the mission. Each of these satellites will require from 250 to 400 watts of electric power for a five year life and there will be three or four systems operating all the time. This program could require about 50 kilograms of plutonium-238 for the initial launches and about 16 kilograms a year thereafter.

A program which has high priority in NASA is the Manned Orbiting Laboratory. There will be several Skylab launches which will culminate in the Space Station and Space Base beyond 1977. These laboratories will have a whole host of experiments, many of which will have their own power sources and may be away from the laboratory. These experiments will also need heaters to keep the electronics and other equipment warm. The total power requirements for these laboratories and their experiments which will be provided by plutonium-238 systems is still unknown, but it will probably be several hundred watts.

Plutonium-238 finds another extremely important use in space as the power source for waste disposal. The heat from plutonium-238 decay serves to both produce bacteria-free drinking water from waste products and to incinerate the waste itself. The AEC has just successfully completed a 90-day test of a device to distill and filter water and has follow-on dual usage units for both water recovery and waste disposal under advance development.

There are missions still further in the future which are only concepts today but some of them will certainly come to pass. After the APOLLO manned lunar program comes to an end, exploration of the Moon may continue using robot vehicles. These vehicles will use radioisotope thermoelectric generators for propulsion and power for experiments. The electric power levels would be from 100 to 1,000 watts.

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The maintenance and servicing of space stations and NERVA engines in space may be done more easily and safely by robots than by man. Man has problems with work tasks exterior to a spacecraft and is subject to damage from micrometeoroids and radiation. A robot does not have these problems. Nuclear power would be an obvious candidate power system.

Looking down this admittedly very foggy road, I expect that hundreds of watts per year of plutonium-238 power sources will be needed in the seventies, kilowatts per year will be needed in the eighties and tens of kilowatts in the nineties. When system inventory and research and development needs are included, there could be a requirement for 10 to 20 kilograms or more of plutonium-238 per year in the seventies and early eighties and up to 100 kilograms per year in the nineties. Plutonium is going to be a very key element in the exploration and exploitation of space.

Plutonium-238 for Medical Applications

An important medical application for which plutonium-238 is being considered is a totally implantable artificial heart. Plutonium-238 is well suited for this role because of its non-penetrating, heat-producing alpha particle radiation, near absence of penetrating gamma radiation and almost ideal half life. An isotopically powered engine would operate the heart, providing the benefits of an implantable, long-life, highly reliable power system. A task force report to the National Heart Institute on the subject of cardiac replacement estimates that there could be 10 to 30 thousand potential candidates for cardiac replacement each year based on present medical statistics. This estimate is dependent upon the solution of the problem of immunologic rejection and the development of an artificial heart within the next five to ten years. The objective of the program is to produce an artificial heart which would restore mobility and remove limitations interfering with the individual's ability to function again as a useful member of society.

The present conceptual designs for isotopically powered heart engines call for a 30 watt heat source so that each artificial heart would contain about 54 grams of plutonium-238. The device should have an operating lifetime of at least ten years. Considering the magnitude of the medical-technological difficulties, we do not expect artificial hearts to be implanted in humans, even in early clinical procedures, until the latter part of this decade. After initial demonstration of their effectiveness,

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their use will undoubtedly grow gradually with acceptance by the public and medical community. In order to estimate the impact of this technological advance, we assume that 100 artificial hearts are implanted in the initial year of significant use and that thereafter the number doubles every year up to a steady state level of 10,000 per year. If this process begins in the eighties, it will not be until the end of this century that such a steady state is essentially reached. At that time about 90,000 people in the United States would have artificial hearts. This would also mean that there would be about 6,000 kilograms of plutonium-238 in artificial hearts. Thus, medical uses on earth could conceivably match space applications in terms of material requirements.

It is difficult to estimate what value should be assigned to isotope fuel in a device that prolongs the life of a recipient. The large scale of use would certainly permit the future cost to be significantly less than it is today. The recipient might only need to pay a rental charge since the isotope decays less than three-fourths of a percent per year. Also, considering the extent and difficulty of the medical procedures involved, their costs would most likely exceed the cost of the isotope. Accordingly we believe that the success of this application is not highly dependent on cost factors but more closely related to our ability to solve the difficult technological and medical problems which still remain.

One interesting aspect of isotopically powered hearts is that of having a large number of people in the general population carrying radioactive sources. Present AEC regulations require a license for the use of plutonium-238 in specific facilities. Obviously the concept of an artificial heart is inconsistent with present regulations so that new regulations would be required. The benefit that an artificial heart can bring to those suffering irreparable heart damage and the minimal risks to the general public involved should permit such issues to be resolved. Already similar problems were faced and solved when a recipient of an isotopic heart pacemaker powered by plutonium-238 wanted to go from France to Spain. The two governments quickly came to an agreement to permit the action even though international transportation of isotopes was involved.

<u>Transplutonium Isotopes</u>

In addition to the production of isotopic fuels, such as plutonium-238, this plutonium-based nuclear power economy will also result in the production of transplutonium elements. Isotopes of americium and curium

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will be the principal ones produced and recovered from spent reactor fuel. These isotopes result from the addition of several neutrons to the basic plutonium-239 fuel. The recycle of plutonium in LWRs enhances production of americium and curium since higher plutonium isotopes are continually built up in the recycle process.

The americium isotopes which will be present in spent fuel will be americium-241 and americium-243. Americium-241 decays by alpha particle emission with a 433 year half-life. One of its present uses is in americium-beryllium neutron sources. In about 35 percent of the alpha particle decays, a 60 Kev gamma ray is emitted. This gamma emission is useful in industrial measuring and gauging equipment. It also can be used to cause X-ray flourescence in elements in the middle of the periodic table, identifying their presence and relative amounts through observation of the energy and intensity of their characteristic X-rays. This makes possible a method of analysis for iodine in the diagnosis of thyroid disorders. Both americium-241 and americium-243 are potential target materials for neutron irradiation for production of higher isotopes. Americium-241 can be irradiated to produce curium-242 which decays to plutonium-238 as noted previously. Americium-243 can be irradiated in a neutron flux to curium-244 which is a target material for the production of still higher isotopes of very great interest such as californium-252.

Curium-242 and curium-244 are the principal curium isotopes found in spent fuel. Curium-242 was mentioned earlier as a source, following decay, of very pure plutonium-238. Curium-244 is an alpha particle emitter with an 18 year half-life. It has a specific power of about 2.65 watts per gram, about 5 times greater than plutonium-238. This makes curium-244 very attractive as a heat source for thermionic power systems. However, it has a higher radiation field due to neutrons from spontaneous fission. The technology of curium-244 applications in space is not nearly so advanced as that of plutonium-238. Nevertheless, the potential for significant use exists. The growing availability of curium isotopes in the future will undoubtedly lead to increased effort to assure that such potentials are developed and used as fully as possible.

Californium Applications

Californium-252 is distinguished by an interesting combination of two properties namely, a reasonably long 2.65 year half-life and a large neutron emission from spontaneous fission. These characteristics make californium-252 a neutron source of unique characteristics. As compared

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to present (α, n) neutron sources, a californium-252 source is smaller, is less radioactive and has smaller heat dissipation requirements. Californium-252 sources are compact and do not require elaborate control systems or power supplies as do reactors or machine neutron sources. Because of these characteristics, californium-252 will find uses in a variety of fields such as medicine, radiography, mineral exploration, and engineering.

Neutron irradiation of cancerous tissue is a promising approach in cancer therapy because it overcomes the radiation resistance of tumor cells lacking oxygen. An implantable californium-252 source can deliver a highly localized radiation dose without the undesirable radiation exposure from a reactor or accelerator and the immobile inconvenience of these latter two sources of neutrons.

There is also a possible medical diagnostic role for californium-252. It makes possible neutron activation analysis for diagnostic tests to determine the presence and quantity of elements. Also, short-lived radioisotopes could be produced by neutrons from californium-252 and used immediately without the losses normally occurring during shipment from a central irradiation facility to a using clinic.

Neutron radiography complements gamma and X-radiography by discriminating between many materials that are indistinguishable by the latter approaches. Neutron radiography is especially useful for nondestructive testing of thick heavy materials which gamma rays and X-rays do not penetrate well. Neutron radiography is also expected to be useful in medicine because it offers improved delineation of soft-tissue morphology and eliminates excessive bone contrast. Californium-252, as a source for neutron radiography, has the advantages of being transportable, if only relatively small sources are required, being a small point source and being inexpensive with a peak thermal flux 3 or 5 times greater than (α, n) sources of the same total fast neutron yield.

Neutron logging of wells and drill holes to measure the porosity of water-bearing or oil-bearing rocks is an important tool of geologists. Measurements made with californium-252 sources could be more representative than those made with plutonium-beryllium and americium-beryllium sources. The greater neutron intensity from californium-252 can permit a greater source-to-detector distance, also the well log would be less responsive to variations in borehole diameter and more sensitive to lithology. Californium-252 can be used also for on-the-spot analyses by neutron activation techniques in prospecting for precious metals and other elements of mining interest. It would be particularly advantageous in remote regions, especially on the ocean floor and possibly on other planetary surfaces.

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Availability of Isotopes

The first question that comes to mind when considering these possible applications for the various plutonium and transplutonium isotopes is "Will there be enough of these isotopes available to meet the needs?" The answer to that question is yes. Of course, production and application are a hand-in-glove situation. The need or incentive has to be there for production to be undertaken and there has to be production of material for developmental work and prototype devices to permit applications to mature.

Neptunium-237 is assumed to be separated from discharged power reactor fuel beginning in 1974, fabricated into targets and irradiated in reactors designed to enhance plutonium-238 production. Under this assumption plutonium-238 can be produced at a rate reaching 400 kilograms per year by the end of this decade with a cumulative production of nearly 1900 kilograms from this source supplementing current production of plutonium-238 by the AEC. If this program of recovering and irradiating neptunium-237 continues, plutonium-238 will be produced at an annual rate reaching 2500 kilograms per year by 1990, and over 17,000 kilograms total will be available including production from the previous decade. As nuclear power grows, the production rate of plutonium-238 will stabilize at about 2,000 kilograms per year. By the year 2000, over 40,000 kilograms could be available.

Clearly these potential production quantities are in excess of the needs associated with applications which we have discussed previously. Accordingly we see a significant untapped energy resource available to the economy which requires continued technological development for its full exploitation.

We have discussed the production of plutonium-238 from irradiation of recovered neptunium. In addition, "high purity" plutonium-238 could be recovered from the decay of curium-242 and produced from the irradiation of americium-241. Under such a program, a production rate of about 100 kilograms per year could be reached by 1980 with a total availability of over 400 kilograms of "high purity" plutonium-238. By 1990 an annual production rate of 700 kilograms per year could be reached with a cumulative availability then of about 4,200 kilograms. The production rate could increase to about 4,000 kilograms per year by the year 2000 with a cumulative availability of nearly 25,000 kilograms.

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Curium-244 will also be available from spent reactor fuel after the curium-242 has decayed to plutonium-238 and been chemically separated. By 1980, curium-244 could be produced at the rate of 40 kilograms per year with a total of nearly 100 kilograms being produced during the seventies. By 1990 the annual production rate could reach about 180 kilograms per year with cumulative availability at 1,200 kilograms. By the year 2000, with an annual production rate of 200 kilograms per year, cumulative availability could reach 3,000 kilograms.

Californium-252 is now being produced in relatively large-scale quantities by the AEC. Quantities up to milligrams of this material are being loaned to each of the interested potential users as part of a market evaluation program and some material will be offered for sale as well. To date some 25 private organizations are participating in the program and contracts are being negotiated with additional potential evaluators. Plans for continued large-scale production of californium-252 will depend upon the results of the current market evaluation program, including responses to the offer to sell. The AEC could produce a total of up to about 100 grams of californium-252 during this decade. By the end of the seventies we could reach a production rate of over 20 grams per year.

If market applications develop accordingly, californium could be produced at a higher rate. About 2 kilograms of californium-252 could be available by 1990 with a production rate of about 800 grams per year. By the year 2000 a production rate of about 3.5 kilograms per year could be possible with a cumulative availability at that time reaching 10 kilograms. Remember that this projection must be related to milligram quantities recently available, an increase of some 7 orders of magnitude.

Value of Spent Fuel

Based on these projections of quantities and usages of materials, the plutonium and transplutonium isotope content of spent fuel from civilian power reactors will have a very significant value. The worth of these isotopes will help to offset nuclear fuel cycle expenses with a resulting decrease in the cost of generation of electric power, if there is a market for them.

A paper by C. A. Rohrmann has made an appraisal of likely values for materials in reactor fuel discharges. He uses the value of the neutrons used in producing the isotope as the basis for the credit for the reactor operator. Using his appraisal of future prices, an estimate

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of the value of spent fuels can be made, assuming that the isotopes discussed would be recovered and used. As noted before, the value of the plutonium fuel recovered during the decade of the seventies is expected to be about $600 million. The value of the other isotopes in this fuel could reach nearly $900 million. We earlier estimated that the plutonium fuel recovered in the eighties could be worth $6 billion. The other isotopes, could have a worth of an additional $5 billion. Of course not all of this potential value will be realized if usage of these materials is lower than corresponds to their availability.

We should continue to bear in mind that by 1990, the United States could have a Gross National Product of about $2.2 trillion. The plutonium fuel recovered during the nineties will be worth something like $18 billion. The other isotopes recovered during this period could be valued at over $15 billion. This seems like a very large amount of money, and it is. But during this decade of the nineties, over 70 trillion kilowatt hours of electricity are expected to be generated and the Gross National Product in the year 2000 could easily be $3 trillion.

Closing Remarks

I want to reiterate that there are uncertainties in the assumptions that underlie the projections I have made. Despite these uncertainties there is no doubt that plutonium and transplutonium isotopes are going to be very important and valuable materials in our future. The amounts of these materials will grow from the laboratory quantities of thirty years ago to tons thirty years hence. They will contribute to all the myriad energy needs of our economy. They will fuel devices in remote or inaccessible locations with capacities in the range of tens of watts and higher. They will fuel large central power stations throughout the world with capacities in the millions of kilowatts. These materials will play a vital role in the life of our research institutions and in industrial and commercial activities. Their impact on the cost and hence per capita consumption of energy and the creation of new energy capabilities will affect the lives of all of us. Plutonium will become the basis for our electric power generation economy and therefore a prime factor in our total economy which is dependent on electric energy.

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The further challenge of these projections lies in the fact that their realization demands important human resources: creativity, energy, skill and dedication. There is another challenge involved that is both human and technological, that is to guide the changes we foresee with proper and intense concern for human safety and protection of the ecology on which human survival depends. As administrators and scientists, indeed as human beings, we have a deep responsibility to imagine and to build the future in human as well as technological terms. Thus I find the prospect of the next 30 years to be an exciting one. The challenges of the plutonium economy of the future will be immense. If our accomplishments can match our vision, however, the rewards and benefits will be equally immense both in their impact on our own lives and on the quality of life for future generations.

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