Conf-740213--1

THE ENVIRONMENTAL IMPACT OF FUSION POWER*

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Paper prepared for presentation at the
American Association for the Advancement of Science, 140th Meeting

San Francisco, California
February 24 - March 1, 1974

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE, 140th MEETING

The Environmental Effects of Fusion Power

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Building 9102, P.O. Box Y
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8:30 a.m., February 27, 1974
San Francisco Hilton, Parlor 1

AAAS Section on Physics (B)
Fusion Power

San Francisco Hilton

RELEASE TIME
At time of Presentation

This paper considers the possible environmental effects of fusion power assuming as a typical model a conceptual design for a full-scale fusion power plant. The appraisal indicates that such a system would yield plentiful, cheap power for all of the world's energy requirements and provide fine solutions to most of our environmental pollution problems if the uncertainties in the plasma physics can be resolved in the fashion that current experiments lead one to expect.

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Introduction

Developments of the past six months have shown how vitallv important a role energy plays in our economy and society. Although the bulk of the current public clamor is concerned with how much gasoline people can have today or next week, we really should be much more concerned with the availability of energy 10, 30, or 100 years from now. Many feel that the most promising of all the long-range approaches appears to be fusion power; there is enough deuterium in the world's oceans to provide all of the world's energy requirements at 10 times the level projected for the year 2000 for longer than the sun will last. Further, the product of the fusion reaction is helium which is not radioactive and hence the problems of fission product disposal will be avoided. These are clearly excellent, but not necessarily sufficient justification for an aggressive fusion reactor development program, hence the next step is to attempt a comprehensive appraisal of the potential environmental impact of a fusion reactor assuming that the plasma physics problems can be solved satisfactorily.

Fuel Supplies

The fuel supply situation differs not only with the type of fusion reactor but also with the major choices made in the design of a power plant.

As will be emphasized repeatedly in the course of this paper, design choices have enormous effects on all phases of the potential environmental impact of a fusion reactor system. In the first place, with respect to fuel resources one finds that, as mentioned above, the supply of deuterium available appears to be more than adequate for as long as the sun is expected to last. However, if a D-T reaction is employed because it presents much less difficult plasma physics and engineering problems, the limiting consideration then becomes the resource used to produce the tritium because there is no significant supply of naturally occurring tritium. Although a D-T reaction yields only one neutron, tritium can be bred by n, 2n reactions if either lithium or beryllium is used to slow down the 14 MeV neutrons released by the D-T reaction. Taking the projected energy consumption for the year 2000 as the base, supplies of lithium appear adequate for something like 1,000,000 yr, whereas supplies of beryllium would not be adequate to build even an initial set of reactors designed to take care of a modest fraction of the world's energy requirements. It may be noted that the energy available from the known lithium reserves is of the same order as from the known reserves of uranium assuming successful development of a fast breeder reactor.

The cost of the deuterium and lithium for a D-T fuel cycle will run roughly 0.006 mill/kWhr, i.e., less than 1% of the current cost of the uranium for a fission reactor. This very low cost would make it possible for a utility to buy a 20 yr supply of fuel if they chose for a capital investment of less than $1,000,000 for a 1000 MW(e) plant, i.e., a small fraction of the total capital investment in the power plant. This would make their fuel supply completely independent of strikes in mines or transportation systems, international crises, floods, and the like. Further, inasmuch as the fuel cycle can be handled entirely within the plant boundaries, there will be very little movement of fuel in the transportation system and consequently almost no opportunity for hijacking the fuel. Further, inasmuch as it is highly doubtful that an amateur could ever make a weapon of deuterium, tritium, and lithium, there would be no problem with the threat of fanatics hijacking material and threatening a city or a nation with a nuclear weapon. Practically all nations have access to sea water, and both deuterium and lithium could be obtained from that source so that international competition for particular pieces of geography with rich energy resources would be eliminated. This should help enormously to ease international tensions.

Energy Requirements

It is interesting to examine the projected energy requirements for the U.S. for the year 2000 as summarized in Table 1. It is clear that a large fraction of the energy will be required in the form of relatively low temperature heat for industrial processes and heating buildings. This implies that power plants should be built to produce electricity while rejecting the waste heat from their thermodynamic cycle at a sufficiently high temperature so that it can be used in district heating systems. In this connection it should be mentioned that there are over 100 district heating systems in use in the U.S. in the central portion of major cities, and that the bulk of the city of Munich including 2 km^2 of single family residences makes use of the waste heat

Table 1. U.S. Energy Requirements in the Year 2000

Application	Electricity (10^{15} Btu/yr)[a]	Heat (10^{15} Btu/yr)	Total (10^{15} Btu/yr)
Residential	5.0	19.5	24.5
Commercial	12	15.5	27.5
Industrial			
Food, paper, chemicals (T < 400°F)	2.7	19	21.7
Steel	1.3	12	13.3
Ceramics	0.6	5	5.6
Miscellaneous	4.0	21	25
Subtotal	8.6	57	65.6
Transportation		48	48
Total	25.6	140	165.6

[a]This column gives the electrical energy - the thermal energy input to the plants generating electricity will be several times as great.

from their electric power plants for building heating and industrial process heat (up to temperatures of about 160° C). The Munich system includes large tanks for storing superheated water so that they can accommodate diurnal variations in the ratio of electrical to heat loads. This arrangement has proved eminently successful and enables them to utilize nearly 90% of the energy available in their fuel. Note that this approach largely eliminates the problem of waste heat rejection to the environment from municipal electric power plants. Although district heating systems in the U.S. ordinarily do not supply industrial process heat, they are beginning to; Dow Chemical has recently made arrangements with the Consumers Power Company in Midland, Michigan, to draw a large amount of process heat from a new nuclear electric power plant. Looking into the future, it appears likely that the incremental cost of low temperature heat in off-peak hours will be sufficiently low for fusion power plants that at a capital cost of ~$100/ inhabitant it would be practicable to distill all of the domestic sewage of a metropolitan complex.

High temperature industrial process heat for metallurgical and ceramic processes is a major energy consumption item. The bulk of this heat is currently obtained from fossil fuels, but in most cases it would be better to make use of electric heat if the cost were competitive. This would be particularly attractive if the cost of producing the electric energy were as low as it appears likely to be with fusion power, and it would certainly greatly ease the problems of minimizing air pollution. Of course, if this approach were followed, the requirements for electric energy would be much greater than projected in Table 1. Similarly, a large amount of energy is required for transportation. Studies indicate that not only would it be quite possible to electrify our railroads, but, if the capital investment were made, the operating costs would be reduced not only for energy but also for maintenance. Further, if high energy batteries can be developed for automotive service, this would eliminate the need for fossil fuels in that area, and would eliminate automotive exhaust as our principal air pollution problem. Thus, all of the major energy requirements of Table 1 could be satisfied with a fusion power plant system except for aircraft fuel. With cheap electric power the latter could be made by the electrolysis of water to produce hydrogen that could be used directly as aircraft fuel if liquefied, or it could be combined with coal to produce hydrocarbon fuels. These steps would largely eliminate land devastation and air pollution, but they would require huge capital investments in central stations, and systems of hot water mains.

Closely associated with the matter of the amount and kind of energy required is the type of location in which the bulk of the requirements will fall. Over 75% of the population of industrialized countries and over 85% of the energy requirements fall in urban areas with populations of 100,000 or more.[1] Thus, it is highly desirable to locate future nuclear plants in urban areas to minimize the land areas required for transmission lines, the losses in transmission lines, and to facilitate the use of waste heat from the thermodynamic cycle for district heating systems and industrial processes. Studies indicate that hot water can be piped economically for 20 miles or more, but there is a strong capital cost incentive to place the heat source as close as possible to the load center. This in turn implies that fusion reactor power plants should capitalize on their ability to operate without a large inventory of radioactive fission products, and should be designed for locations in urban centers. This makes the fission-fusion symbiosis concept with its large inventory of fission products quite unattractive. Here again one is confronted with a design choice. Inasmuch as combining a fission reactor with a fusion reactor is attractive only if fusion reactor capital costs fall in a relatively narrow range where the fusion reactor would be sub-marginally competitive economically, it appears to the writer that at best the extra costs associated with the extra complexities and safety problems of combining fission and fusion plants will largely offset what might at first appear to be a small cost advantage. Others going to the opposite extreme have suggested that it would be possible to make use of two types of fusion reactor, one designed to breed tritium and the other to serve simply as a burner. The advantage claimed for this arrangement is that the burners (about 25% of the total) could be located in metropolitan areas with a minimum inventory of tritium whereas the breeders (representing about 75% of the system capacity) would be located at some distance from the metropolitan areas so that most of the radiological hazard associated with the tritium would not be in a population center. However, this approach ignores the greatly increased probability of a tritium release as a consequence of an accident in the course of transporting the tritium, nor does it take account of the fact that the requirements for energy in the form of heat are roughly equal to those for electricity, and hence one would like to place the bulk of his power plants, i.e., around 85% of them, in the metropolitan areas where both the heat and the electricity are required. The latter approach would obviate the need for both transmission lines and long pipe lines, both of which entail important environmental and capital cost penalties.

Reactor Safety Considerations

The safety aspects of a nuclear power plant are extremely design-dependent. Conceptual designs for full scale fusion power plants have differed by as much as a factor of 10^5 in the amount of induced activity in the structure as a consequence of differences in the choice of geometry and materials for the breeding blanket region surrounding the plasma. To simplify this discussion the conceptual design for a 1000 MW(t) tokamak shown in Figs. 1 and 2 was chosen as the reference design for the purposes of this paper and all subsequent estimates are based on this design.[2] This design satisfies all of the plasma physics and engineering conditions insofar as it has been possible to envision them. The lithium blanket of this reactor is contained in niobium and is designed to operate at 1000°C. The heat generated in the blanket is removed by boiling potassium which is expanded through a turbine, condenses at about 550°C, and gives up its heat to a conventional steam cycle.

Tritium

Extensive experience in the analysis of the radiological hazards of fission reactors has shown that by far and away the most important factor affecting the safety of a nuclear plant is the hazard associated with the possible accidental release of volatile radioactive material. In examining fusion reactors one finds that the inventory of volatile radioactive material and the ease with which it might escape inadvertently are both heavily dependent on the design. Fortunately, tritium is one of the least harmful of the radioactive isotopes.[3] This stems in part from the fact that the radioactive decay of the tritium leads to the emission of a beta particle with an average energy of only 6 keV which is much less serious than either a hard gamma or an alpha particle. Even more important, tritium does not tend to be concentrated in living tissue. In man, for example, half the tritium ingested as

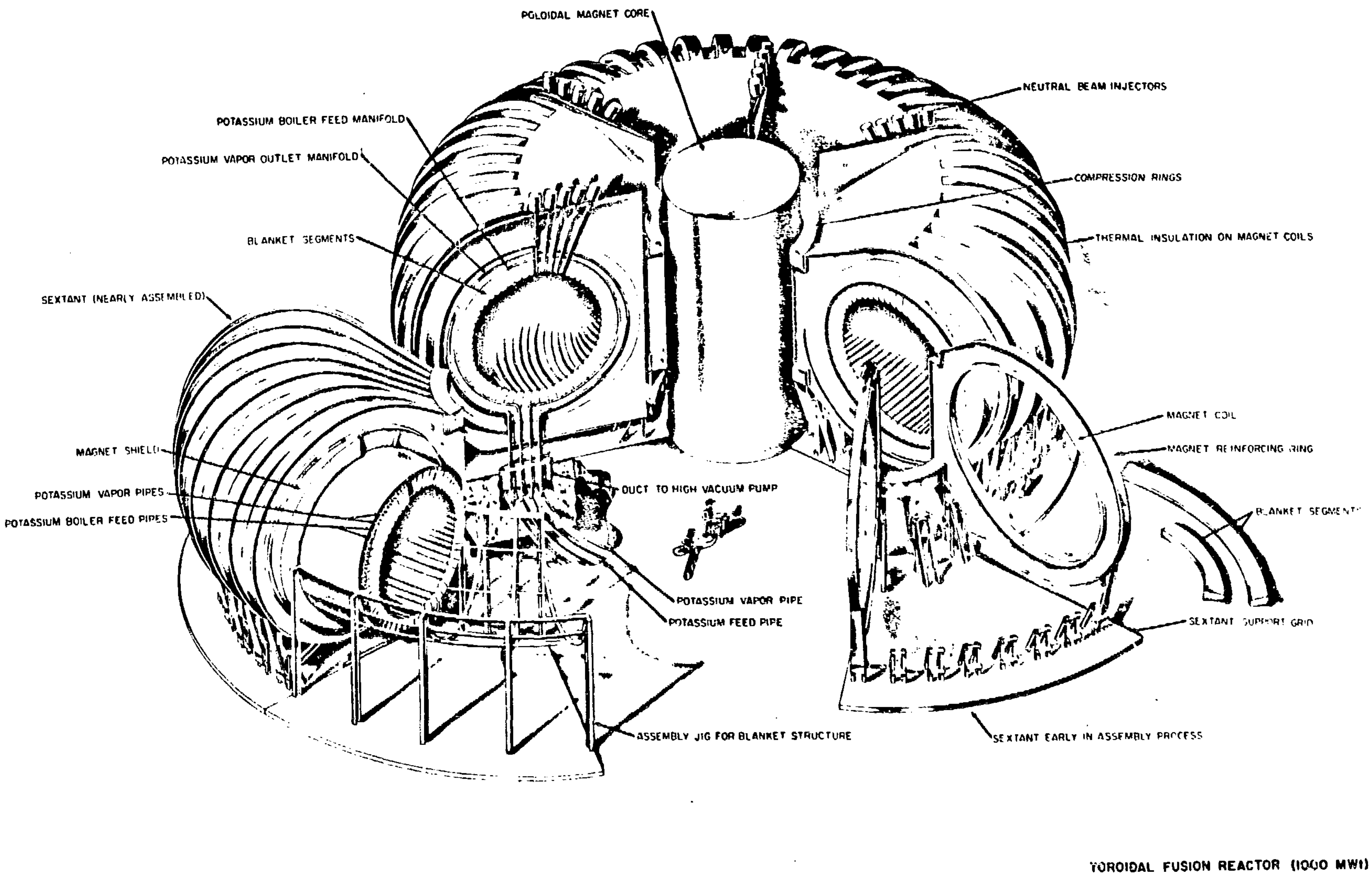

Fig. 1. Conceptual design for a 1000 MW(t) tokamak fusion reactor used as the reference design for environmental impact studies. The minor and major diameters of the wall enclosing the plasma region are 7 m and 21 m respectively.

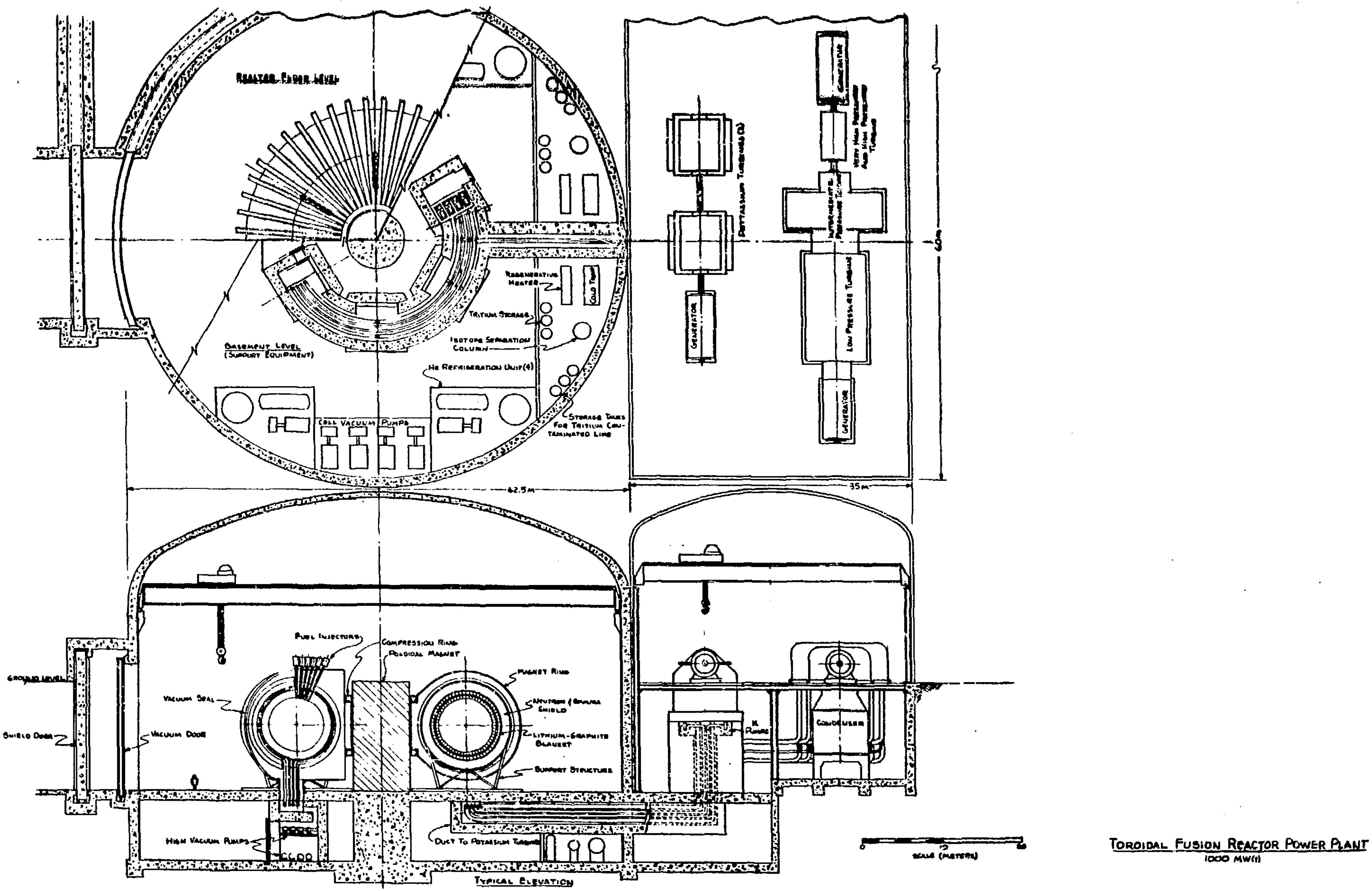

Fig. 2. Conceptual design of a power plant based on the reactor of Fig. 1.

water is rejected from the body within a week whereas the half-life of tritium is 12.3 yr. As a consequence of these factors, in a fusion reactor of the type considered as the reference design for illustrative purposes the biological hazard potential represented by the tritium inventory is more than a factor of a million lower than that represented by the radioactive iodine in a fission reactor of similar output.[4] From this standpoint the 1000 MW(t) fusion reactor of Figs. 1 and 2 would be equilavent in radiological hazard potential to a fission reactor having a power output of about 1 kW(t), and the latter has been readily accepted in urban areas. It must be emphasized that achieving a low tritium inventory is dependent on the designer choosing a blanket and tritium removal system that will make it possible to breed and yet maintain a very low tritium inventory.

A second major consideration associated with the tritium is the question of an uncontrolled release of the tritium. The probability of a serious release depends in part on the partial pressure of the tritium in the blanket system. In the lithium blanket of the reference design considered here the partial pressure of the tritium both in the lithium blanket and in the potassium circuit employed to remove and utilize the heat deposited in the blanket will be of the order of 10^{-6} torr because of the strong affinity of Li for T, and hence the tendency to diffuse through metal walls, particularly those in the heat exchanger between the power conversion system and the environment, will be very low. The low partial pressure also would inhibit the release of tritium if a leak developed in the blanket. If, on the other hand, a helium system is employed for cooling the blanket for example, and the tritium is transported from the blanket to the tritium recovery system by the helium system, basic mass balance considerations show that the partial pressure of the tritium in the helium will be quite high, and hence the tendency of tritium to diffuse through the system and heat exchanger walls to the environment or escape in the event of a leak will be much increased. As this implies, the probability of environmental contamination is very much dependent on the designer's choice of materials for not only the blanket and tritium removal system but also for the power conversion system. Studies at ORNL favor the use of a metallic lithium blanket rejecting its heat to an intermediate potassium system and removal of the tritium by cold trapping lithium tritide from the potassium (to which a small amount of lithium would be added to facilitate this operation). The choices that went into the selection of this system stemmed from considerations outlined above of which many were chosen to minimize possible contamination of the environment.

Strict attention to the above considerations when evolving a design can yield a major payoff by reducing the problems associated with reactor safety. The conceptual design of Fig. 1, for example, is estimated to entail an active inventory of tritium of about 400 g (i.e., the tritium circulating in the lithium blanket, the potassium vapor cycle, and the tritium recovery systems). If one takes as a hypothetical upper limit for an accident an incident that would cause the complete release of all of this tritium, analyses indicate that, assuming a building vented through a 100 m stack, on a normal day the maximum dose that anyone would get on the ground downwind of the reactor would be limited to a few rem, about 10% of the maximum dose generally considered acceptable for such a severe accident.

Afterheat

A major factor affecting the probability of an inadvertent release of tritium to the environment is the amount of afterheat associated with activated structure. This, again, is heavily dependent on the designer's choice of the materials for the blanket and the quantity of structural material required. It seems quite possible to reduce the amount of structure in the blanket to a few volume percent so that even with one of the more severely activated structural materials such as the niobium used in the design of Fig. 1, the afterheat can be kept sufficiently low so that little or no increase in temperature in the blanket would occur even if all of the heat removal systems were to become inoperative. Thus, there would be no danger of a meltdown of the type that has been hypothesized for some fission reactors. Instead, the minor losses of heat through thermal radiation and thermal convection of air in the room would suffice to keep the reactor temperature from rising appreciably, and hence no conceivable chain of events could result in general melting of the blanket structure to produce a major release of the blanket coolant and hence a major release of tritium.

Activated Structure

The amount of long-lived activity in the activated structure of the blanket is important not only because of afterheat considerations but also because it will affect maintenance operations. Analyses indicate that any material that might be used for the blanket structure of a reactor would contain sufficient impurities so that the level of activity in the structure would be too great to permit contact maintenance. Experience indicates that, inasmuch as remote maintenance will be required, it makes relatively little difference from the maintenance standpoint whether the amount of activity is large or small provided it is not large enough to present a heat removal problem. Thus, if the volume fraction of the blanket in the form of structure can be kept to a few percent, a wide range of structural alloys ranging from stainless steel to titanium would be satisfactory from the maintenance standpoint.

The principal problem that appears to be associated with long-lived activity in the structure of a fusion reactor is that of waste disposal. Fortunately, it appears that the activated structure of a fusion reactor differs fundamentally from the fission products of a fission reactor in that it could be reprocessed with remote handling equipment and refabricated for another reactor. Of course, this probably would not be done until the material had had an opportunity to decay for perhaps 10 to 50 years. Although remote fabrication techniques would certainly require more expensive fabrication processes than would otherwise be the case, they ought to be quite feasible and economically viable by the time the problem arises 50 to 100 years from now. If this course were followed, the quantity of radioactive waste requiring disposal would be very small indeed. Even if this course were not followed, the amount of radioactivity in the waste would be a factor of ~100 lower for the reference design than for fission reactors, and this waste would not contain any long-lived alpha emitters (the most objectionable isotopes). No cooling of the material would be required in the course of shipment other than thermal convection of the surrounding air, thus eliminating a possible mechanism for dispersal of the radioactive material.

Explosions

The designer of fission reactors must go to considerable trouble to assure that under no circumstances could a sequence of events occur that might lead to a nuclear explosion. For the reference design fusion reactor, the total amount of deuterium and tritium present in the plasma would amount to only about 1 g. It is easy to show that even if all of this were to undergo fusion reactions instantaneously (an event that is considered inconceivable), the resulting energy release would lead to only a minor increase in the temperature of the blanket, and would in no way disturb the integrity of the containment of the radioactive material.

Reactor Integrity

Virtually all of the non-volatile activity in a fusion reactor and most of the active inventory of tritium will be contained by the structure of the blanket, and hence the integrity of this region is a vital consideration. The blanket integrity is heavily dependent on the choice of structural material. Unfortunately, a whole complex of boundary conditions must be met when attempting to choose a structural material. (See Table 2.) The first of these is that the material be weldable so that a hermetically sealed system can be obtained

Table 2. Design Limitations for the Principal Candidate for the Structural Material of a Full-Scale Fusion Reactor

Limitation	Stainless Steel	Nb-1%Zr	Molybdenum	Vanadium	Titanium
Maximum operating temperature, °C	500	1000	1100	850	800
Materials compatibility peak temperature with Li	500	>1100	>1100	?	800
Peak temperature with k, °C	850	>1100	>1100	?	>800
Permissible H_2O and O_2 partial pressure in ambient gas at maximum operating temperature, torr	>100	$<10^{-7}$	$<10^{-3}$	$<10^{-8}$	$<10^{\ 8}$
Maximum temperature for creep strength >1000 psi for 1% creep in 10^5 hr, °C	850	1100	1300	?	~750
Sputtering ratio for 20 keV deuterons		0.001	0.01	?	0.014*
Permeability coefficient at maximum operating temperature, cm^3 (STP)·mm/hr·cm^2·$atm^{1/2}$	0.02	200	0.001	200	~200
Ductility after irradiation in a fission reactor, %	~5% after 2.5 to 3×10^{22} nvt at 450°C	5% after 2.5 to 3×10^{22} nvt at 425°C	0% after 2.5 to 3×10^{22} nvt at 425°C	20% after 4 x 10^{20} nvt at 550°C	
Weldability	Excellent	Excellent	Poor	Good	Good
Afterheat from induced activity 1000 hr after shutdown, W/MW(t) of reactor output	1	2	0.05	0.001	~0.001

*He^+ ions with Ti target at 50°C.

both to keep contaminants out of the plasma and to contain the tritium generated. The second is that this structure should operate at a high temperature, for (as indicated later) unless this is done the thermal efficiency of the power plant will be low and there will be a serious waste heat disposal problem with its consequent adverse environmental effects. At first thought aluminum would be a good candidate because it has been chosen for numerous test reactors such as the MTR because its induced activity is much less than for most structural materials. However, no one has built a viable power reactor of aluminum because it loses strength so rapidly with an increase in temperature that it is not practicable to get a sufficiently high reactor temperature to give an attractive thermodynamic cycle. Attempts have been made both in the U.S. and Europe to design organic-cooled reactors using an aluminum material strengthened with dispersed aluminum oxide to permit its operation at a temperature of around 300°C. These efforts were abandoned because this aluminum-aluminum oxide material (called SAP) has virtually no ductility even before exposure to radiation, and it rapidly loses that small amount of ductility after a relatively small amount of fast neutron irradiation. In the complex structures required in fission reactors, and even more so in those of fusion reactors, substantial temperature variations must be expected, and these lead to severe local thermal stresses that can be accommodated only by either yielding or cracking. Cracking is unacceptable in reactor structures. The situation is a bit analogous to that of the use of glass in bridges. Glass is a plentiful, inexpensive, strong material, but it is brittle, and as a consequence no glass bridges have been built to the writer's knowledge. The reason is that one small stress concentration can lead to a crack, and the crack will lead to a catastrophic failure. An essentially similar situation holds in gas turbines. Extensive tests of gas turbine wheels made with ceramic blades or all-ceramic rotors were carried out in the latter 40's, but in every case at some point in the course of the test a failure occurred with catastrophic results. Although ceramic stator blades are currently again under consideration for gas turbines, this is a quite special application that entails much easier conditions to satisfy than those of a hermetically sealed structure whose leak-tightness must be preserved.

The principal candidates for the structure of a fusion reactor blanket appear to be stainless steel, niobium, vanadium, and titanium. All of these are weldable with good ductility in the weld zones. All but vanadium have been demonstrated to show good compatibility with liquid lithium at temperatures to over 500°C so that they provide a good heat source for a thermodynamic cycle. The niobium and stainless steel have the disadvantage that they would give a relatively large amount of residual activity, i.e., the amount envisioned in the previous discussion. Vanadium and titanium, on the other hand, would give amounts of long-lived induced radioactivity which would be down by a factor of 10 to 100 relative to the niobium or stainless steel. In terms of availability and processing technology the stainless steel is the leading contender, titanium alloys next, niobium third, and vanadium a poor fourth in the sense that relatively little experience has been gained with vanadium alloys either in fabrication or in service. In terms of the basic availability of mineral resources, titanium would be the leading contender. Niobium is a much less familiar material than stainless steel, but the ore reserves of niobium appear to be roughly equal to the known reserves of chromium, a major constituent of stainless steel.

Thermal Efficiency

About 85% of the energy from the D-T fusion reaction appears as heat in the blanket as a consequence of the slowing down and capture of the 14.3 MeV neutrons emitted in the reaction. The best way to convert this heat into electricity is via a thermodynamic cycle, and this raises the question of thermal efficiency. As indicated in the first part of this paper, an ideal way to meet all of the energy needs of our economy in the next century would be to employ fusion power plants that will produce electricity with a thermal efficiency of close to 50% while rejecting the waste heat from the thermodynamic cycle to a district heating system at 100°C to 200°C. If this can be accomplished, there will be a good balance between the electrical and heat loads of urban centers, and there will be little waste heat rejection to the environment associated with the production of electric power. Such an arrangement will also minimize the capital investment in the reactor, for that depends primarily on the thermal rather than the electrical output.

As shown by the classical demonstration of Carnot, the thermodynamic cycle efficiency depends primarily on the peak temperature in the cycle. For a given peak temperature the efficiency also depends on the degree to which the actual cycle approaches the ideal Carnot cycle. Figure 3 shows

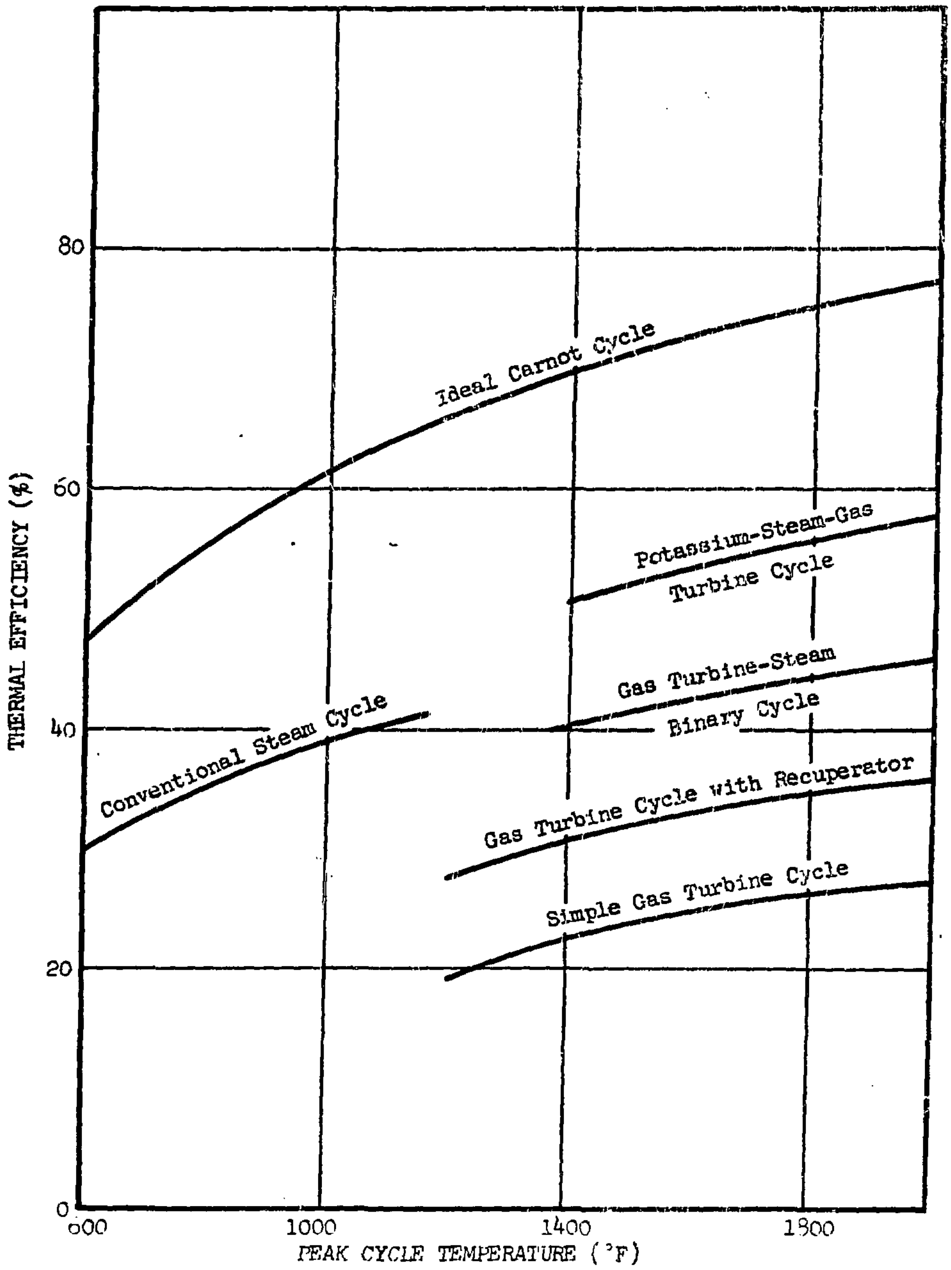

Fig. 3. Effects of peak cycle temperature on the thermal efficiency of a set of typical thermodynamic cycles with fossil fuel heat sources. Note that the efficiency of the Rankine cycles would be increased by ~5 points in a nuclear plant because heat losses to stack gases would be eliminated.

the consequences of these effects for the actual cycles that have been given serious consideration for use with a fusion reactor. The upper temperature limit for the conventional steam cycle is imposed by corrosion considerations while that for the potassium-steam binary vapor cycles is imposed by temperature limitations on the allowable stress in structural materials. Trace amounts of moisture or oxygen in helium tend to give serious corrosion of niobium or vanadium at temperatures above about 800°C, so this is likely to be the upper temperature limit for a helium gas turbine cycle. The pronounced difference in cycle efficiency between the gas turbine and Rankine cycles at any given temperature stems from the substantial pumping losses in the compressor for the gas turbine cycle.

As the peak cycle temperature is increased, the efficiency of electric power production becomes less sensitive to an increase in the temperature at which heat is rejected from the thermodynamic cycle for use in industrial processes and building heating. This effect is shown in Fig. 4, and emphasizes the importance of designing for a fusion reactor blanket temperature of at least 800°C.

Summary

In summary it may be said that, if the plasma physics problems are resolved along the lines currently expected, the designer of fusion reactors will be confronted with not only many more boundary conditions that he must meet but also many more degrees of freedom than prevail in the design of a fission reactor. The inventory of radioactive material will be heavily

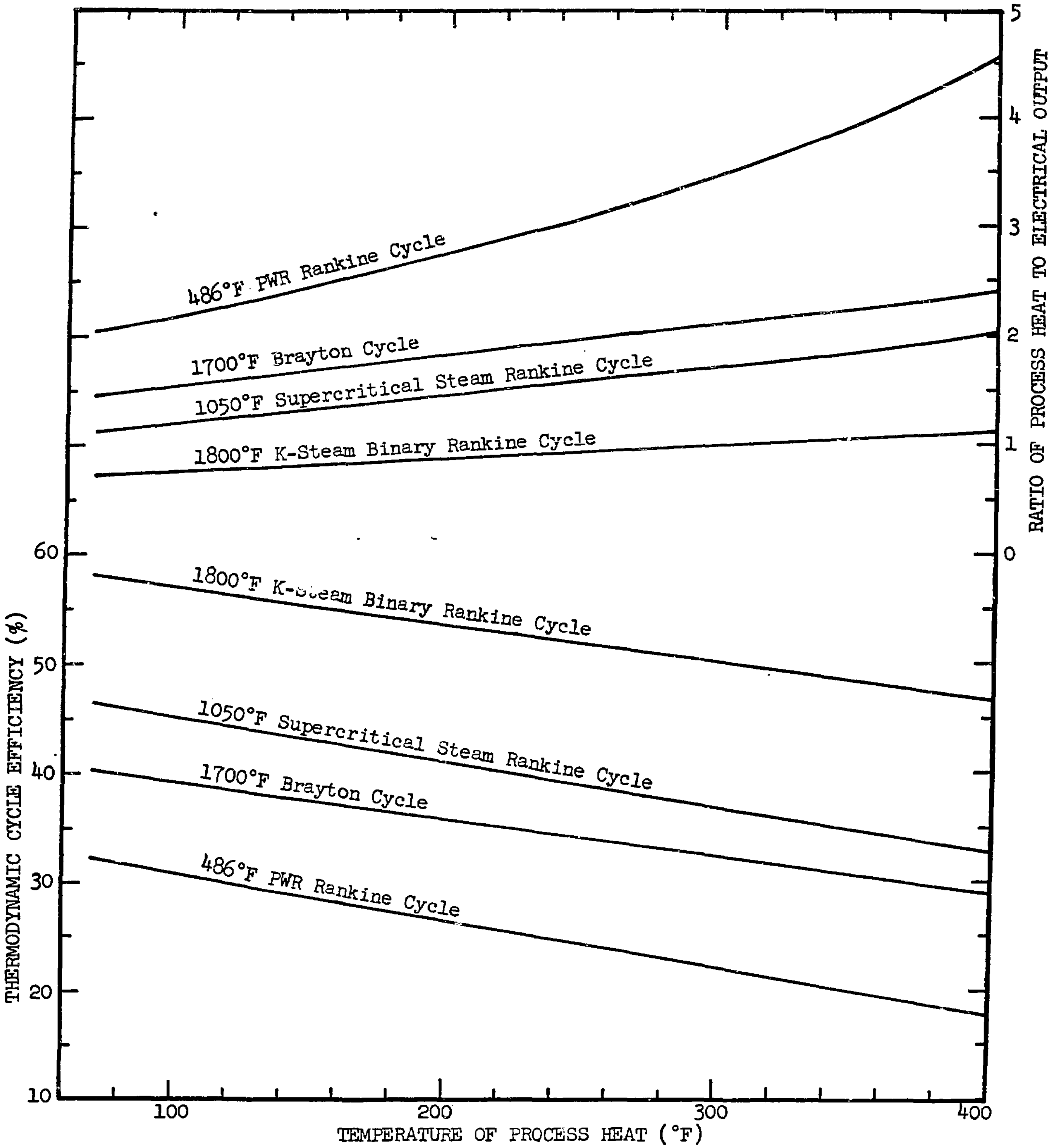

Fig. 4. Effects of process heat removal temperature on the over-all thermal efficiency of the cycle for electric power generation and on the ratio of energy to the process heat system to the energy to electric power for some typical thermodynamic cycles.

dependent on both the geometry of the structure employed and the choice of material, and by judicious design it can be kept small thus reducing both the afterheat and the radiological hazards problems to moderate values. It appears from design studies that by clever integration of the many systems involved, particularly the blanket, the tritium recovery, and the power conversion systems, and by a judicious choice of materials, it will be possible to obtain a nuclear power plant with an exceptionally high degree of integrity. The possibility of any accidental release of activity can be reduced to virtually zero, and even the amount of activity that might be released through an act of sabotage would in no sense be catastrophic. There would be very little radioactive waste, and none of it would be in the form of long-lived alpha emitters. The power plant could be located in urban centers where it could supply all of the energy requirements for heat and electricity including electric power for trains and automobiles. Hydrogen for aircraft fuel could be obtained by the electrolysis of water. The radioactive waste disposal problem would be minimal and the opportunity for fanatics to obtain material for clandestine weapons would be essentially nill. Whether or when this highly attractive situation can be achieved will depend on the success of the plasma physics investigations currently underway.

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