ENVIRONMENTAL ASPECTS OF FUSION POWER PLANTS*

A. P. Fraas
Associate Director
Reactor Division

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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INTRODUCTION

One phase of the AEC-CTR program of the past year has been an effort to evaluate the possible environmental impact of fusion reactor power plants.¹ The point of departure for this work was the set of thermonuclear reactor designs summarized in a companion paper by Fred Ribe.² These designs have been examined from the standpoint of requirements for critical materials, reactor safety problems, capital and operating costs, and the environmental implications of low cost fusion energy if it were available. This paper summarizes the results of that effort coupled with earlier related work.^{3,4}

MINERAL RESOURCE REQUIREMENTS

FUEL SUPPLY

One of the prime reasons for the development of fusion reactors is the tremendous supply of fuel available. With the breeder reactor it is estimated that the world's reserves of uranium will supply fuel at the high level of energy consumption anticipated for the year 2000 for a period of around one million years. However, if fusion reactors prove viable, there is sufficient deuterium in the world's oceans so that, if half of it were extracted, it would supply the entire world's total energy requirements at 15 times the projected rate for the year 2000 for a period greater than that for which the sun is expected to last. The supplies of lithium in proven terrestrial reserves are sufficient to supply the world's entire energy requirements from the D-T reaction at the rate projected for the year 2000 for around 200 years, and it is anticipated that much larger amounts of lithium in terrestrial deposits could be found if the market developed.⁵ It should be noted that, whereas for most minerals the proven reserves only run 10 to 20 years at the current rate of consumption, for lithium the proven reserves run about 2000 years at the current low rate of consumption. In addition to terrestrial deposits, there is enough lithium in the world's oceans to fuel the world's total energy economy for a million years.⁶ Certainly by that time we ought to have been able to develop a D-D fusion reactor.

It is important to note a number of striking advantages with respect to the fuel supply situation for a D-T reactor. In the first place, every nation in the world has access to water and could build its own heavy water plant with a modest capital investment. Lithium supplies are plentiful and it would be easy to stock-pile sufficient lithium to last for many decades without a serious capital investment in the stockpile. As a consequence, international tensions arising from competition for energy supplies would be enormously alleviated. Further, if a fuel supply adequate for some years were provided in a power plant, the power plant would then be unaffected by strikes in the mines or transportation system, floods, war, or other factors which currently present problems in supplying fuel to central stations. In addition, there would be no strong incentive for criminals to try to hijack fuel shipments because their value would not be very great, and the opportunities would be rare. The fuel materials would not lend themselves to the construction of a nuclear weapon and hence would not tempt saboteurs, hijackers, or kooks.

There would be no land despoilment associated with the extraction of deuterium from water, and the amount of water processed by the isotope separation plant would be a trivial fraction of the water employed in the economy of any country. The land despoilment associated with the removal of lithium from terrestrial deposits would be trivial because the quantities would be small. Actually, in the U.S. a single hot spring in Nevada is pouring out dissolved lithium at a rate such that it could fuel the entire U.S. economy if we had a fusion reactor system.⁵

STRUCTURAL AND COOLANT MATERIALS

The amounts of the various materials required for each of the different types of fusion reactor of Ref. 1 are summarized in Table 1. This was prepared in an effort to determine the extent to which

there might be a shortage of critical materials if one were to have a full-blown fusion reactor economy. Perhaps the most important point that developed from an analysis of Table 1 was that it would be desirable to avoid the use of beryllium in the blanket of a fusion reactor because known reserves of beryllium ore do not appear to be sufficient to provide the amount required for a world-wide fusion reactor economy. Thus metallic lithium is clearly to be preferred as the blanket material to breed tritium in D-T reactors. The next most critical material appears to be niobium which is required for the superconducting material in the magnets of some of the proposed designs as well as in the blanket structure of those designs that contemplate the use of a lithium blanket operating at temperatures above around 500°C. The known world reserves of niobium appear to be about sufficient for a power plant system that would provide all of the world's energy at the level estimated for the Twenty First Century and employ a reactor with niobium-tin superconducting magnets and a niobium blanket structure. However, it does appear that there is sufficient niobium in manganese nodules found on the deep sea floor to give perhaps 100 times as much niobium as is present in proven reserves of terrestrial deposits.⁷ Further, it seems likely that attractive superconductors not requiring niobium will be developed, and that vanadium might be used in the blanket structure rather than niobium, but this will require extensive research and development work. Molybdenum could be employed if means could be found to solve the problems associated with the embrittlement of molybdenum in weld zones. It should be noted that either of these materials, and vanadium in particular, would reduce the amount of activity in the structure. It should be noted also that the activated structure of a fusion reactor will differ from the fission product wastes of a fission reactor in that it could be recycled if — as seems likely — techniques could be developed to refabricate it in remote handling facilities. If this could be done, it would serve to ease the supply situation and essentially eliminate the problem of long-lived radioactive waste disposal.

Helium for cooling the superconducting magnets may be a problem. The reserves of the U.S. natural gas deposits are clearly limited, and will be largely consumed by the year 2000. Helium can be obtained from the atmosphere as a by-product in the production of N_2 , O_2 , A, and Ne, but the market for these products is only a few percent of the production rate if the current He consumption rate is to be met by taking He from the atmosphere. As a consequence, it is estimated that the price of He will rise to 30 to 100 times its present price, i.e., ~\$3.50/ft³ versus the present \$3.50/100 ft³. If this proves to be the case, the cost of the He inventory for the cryogenically-cooled magnets of the reference CTR would be about \$1,000,000, an acceptable amount. If a new superconducting material can be developed to operate at, say, 20°K, liquid hydrogen might be used and He would not be needed. However, it would probably still be worthwhile to use helium to avoid the explosion hazard associated with hydrogen.

Perhaps the next most critical material would be copper; where large amounts of copper would be required, as in the theta-pinch system, it would probably be best to design for aluminum rather than copper conductors.

The amounts of other critical materials such as nickel and chromium are comparable to the amounts required in conventional coal-fired power plants, hence fusion reactors should not present any special problems in these areas.

SAFETY ASPECTS OF FUSION REACTORS

The foremost question in the minds of the public in considering the possible environmental impact of any type of nuclear plant is concerned with the possible release of radioactivity. This in turn entails two major problem areas; namely, the routine release of trace amounts of activity, and the possibility of an accident in which a large amount of activity might be released in a single incident. Any attempt to appraise either of these possibilities requires a detailed examination of a reference design because the problems are in large measure dependent on the detailed design of the plant. Although there are major differences between the various concepts, a good insight into the safety problems inherent in fusion reactor plants can be gained by examining a typical plant design. Thus, a representative design, the ORNL tokamak of the first column in Table 1, was used as the Reference Controlled Thermonuclear Reactor, or Reference CTR. The detailed design report on this reactor and related analyses served as the basis for an appraisal of the reactor safety problems of a typical full-scale plant.^{8,9,4}

It must be emphasized that the nuclear power plant designer will go to great lengths to assure the safety of the general public, hence the differences between various types of nuclear plant will lie primarily in the difficulties and costs inherent in getting the requisite high degree of safety. It is important to differentiate between accidents that affect the public and those that simply represent a loss to the plant operator. Engineered safeguards must deal with both classes, but the main

concern here is with those that might affect the public. For purposes of this paper consideration is given first to small leaks and routine emissions, and then to the possibilities of major accidents.

TRITIUM LEAKAGE

The principal radiological hazard problem in fusion reactor design is posed by tritium. Even if a D-D reaction is employed, a certain fraction of the reactions will produce tritium and the equilibrium concentration of tritium in the charge recirculated through the fuel injection system will run at least 10% of the level that will prevail in a D-T reactor.⁹

The tritium leakage rate to be expected is heavily dependent on the design of the system. This is particularly true because tritium tends to diffuse through hot metal walls at a substantial rate, hence high temperature elements of systems that contain tritium should be surrounded by a tightly sealed cold wall. In the reference design of Fig. 1, for example, the lithium blanket is surrounded by the cold wall of the magnet shield so that any tritium diffusing through the walls of the blanket would simply go into a region surrounded by cold walls. A more serious problem is posed by tritium diffusion from the lithium in the blanket through the tube walls of the potassium boiler into the potassium of the potassium vapor cycle. Fortunately, tests of elements of a zirconium hydride fueled, NaK-cooled reactor system indicate that it should be possible to remove the tritium from the potassium by adding a small amount of lithium to the potassium and cold trapping lithium tritide from a bypass stream of tapped-off condensate leaving the potassium condenser.^{10,11} With this approach it appears possible to hold the tritium concentration in the lithium to roughly 1 to 10 ppm irrespective of the type of reactor, the total lithium inventory, or the tritium generation rate, and this characteristic appears typical of what might be expected for any of the reactor systems. Thus, the tritium inventory in the lithium system will be primarily a function of the total lithium inventory irrespective of the type of reactor or the power output.

An appraisal of the leakage characteristics that have been experienced with high temperature liquid metal and molten salt systems indicates that the tritium leakage can be kept to something of the order of 0.006 g/day. This would amount to a tritium leakage rate to the atmosphere of 60 curies/day if no effort were made to take advantage of a secondary enclosure and process the atmosphere in that enclosure to remove tritium and thus inhibit tritium leakage from that enclosure to the atmosphere.³

The second principal avenue for tritium leakage in the system of Figs. 1, 2, and 3 would be from the potassium vapor condenser to the steam system. Data in the literature indicate that a diffusion barrier might be employed in the steam generator tubes to inhibit this leakage rate.¹¹ This would be a most desirable step because, if the rate of leakage of tritium into the steam system can be kept to a sufficiently low level, there will be no need for concern about activity in the steam system or leakage of that activity to the atmosphere. Estimates indicate that the diffusion rate of tritium into the steam system might be held to 0.0015 g/day, a probably acceptable value. Note that there is a strong incentive to do this because otherwise it would be necessary to sequester the water in the steam system. It would be too expensive to employ an isotope separation process to remove the tritium from the water because AEC tolerances call for a concentration less than 3% that of that for deuterium in sea water.

LIQUID METAL LEAKS

An obvious cause for concern is a leak of lithium into the plasma region. If this occurs, even a small amount of lithium leaking into the plasma will quench the fusion reaction because the amount of lithium will be large relative to the roughly 1 g of deuterium and tritium in the plasma. This will occur because the increased loss via Bremsstrahlung radiation from the lithium atoms and/or conduction cooling will chill the plasma below the ignition temperature.

The probability of a lithium leak will be low because the pressure in the lithium blanket will differ from that in the plasma region by only about 1/10 of an atmosphere, and hence both the pressure stresses and driving force for a leak will be small. Further, the blanket has been designed to keep all of the thermal stresses well within the elastic range both during normal operation and in the course of any of the transients that have been envisioned, and this should minimize the probability of a crack induced by thermal strain cycling.¹²

The initial design of the reference fusion reactor envisioned the use of a magnet shield that consisted of water and lead in a titanium tank. While the probability of lithium coming in contact with the water in this shield seemed exceedingly low, it was decided that with relatively little increased cost the water could be replaced with graphite or a metal oxide such as alumina or magnesia.

The presence of water in the shield can be avoided completely by employing helium rather than water as the shield coolant. The energy deposition in the magnet shield as a consequence of nuclear and thermal radiation and thermal conduction will represent only about 0.25% of the total reactor output. Analysis indicates that the shield can be cooled easily with helium at about ten atmospheres. Thus, with the lithium blanket cooled by potassium, the designer can eliminate the possibility of a substantial energy release from a lithium-water reaction.

If a leak develops in the potassium condenser-steam generator of the reference design considered here (see Fig. 3), the steam jetting into the potassium condenser will react with the potassium to form potassium oxide and hydrogen. Inasmuch as the potassium condenser will have a large vapor volume space available, there will be plenty of space for the hydrogen, and no explosion or even large increase in pressure will occur.⁹ (This situation is completely different from that in a liquid metal-heated boiler in which there is little or no free volume on the liquid metal side into which the hydrogen from the reaction can expand.) As the hydrogen builds up in the condenser, it will block the flow of potassium vapor into the condenser and produce a back pressure on the potassium turbine. Only a few pounds of steam leaking into the condenser would produce an unmistakable change in the turbine back pressure which would be obvious to an operator or could be used to trip a warning signal. If a large steam leak were to develop as a consequence of a burst type of failure, the inherent nature of the inlet orificing of the reentry tube boiler contemplated (see Fig. 4) is such that vapor rather than water would be injected into the potassium region, and as a consequence the rate of injection would be relatively low — about 4 lb/sec per ruptured tube.¹³ In the design analyzed, this would lead to an increase in the pressure in the condenser at a rate of about 1 psi/sec, or about 60 psi/min. This would be easily and reliably detectable, and could be the basis for closing valves in the feed water supply line. To protect against the contingency that no action might be taken, a rupture disc should be provided to blow off at perhaps 40 psia.

INVENTORY OF RADIOACTIVE MATERIALS

The inventory of volatile radioactive material is one of the most important factors to be considered in appraising the requirements for engineered safeguards for a nuclear power plant. This in turn means that the tritium inventory, particularly the active inventory in the liquid metal system, is the most vital consideration because it will be the only volatile activity in a fusion reactor. If the tritium inventory can be kept to the level estimated for the reference design, calculations indicate that even under the extreme hypothetical assumption that the entire inventory would be released up a stack in a single burst the maximum dose to anyone downwind would be only a few rem under normal atmospheric conditions.¹⁴

The only substantial inventory of radioactive material other than tritium will be that in the blanket structure, and the bulk of this activity will be in the region close to the first wall. This material will be solid metal and refractory so that it could not be readily dispersed, and the activity level will be low enough so that no special cooling would be required.⁸

The above discussion was based on the Reference CTR design of Figs. 1, 2, and 3 and their associated analyses. Other designs might yield substantially more or less favorable values. For example, although the laser-fusion system is much less well defined at this stage than the tokamak, it may be noted that the amount of activated material in the structure of the ORNL design for a laser-fusion reactor would be reduced by a factor of about 1000 relative to the Reference CTR because it would not employ a metal wall between the plasma and the lithium. On the other hand, the amount of activated structure in some of the laser-fusion systems that have been proposed would be higher than the Reference CTR by a factor of as much as 100. Amounts of activity in the structural material in some magnetically confined plasma machines would also be much higher than that indicated here for the reference design. Thus, one must be careful in any attempt to generalize other than to say that the inventory of radioactive material in a fusion reactor will be heavily design-dependent, and in at least some designs it can be kept to relatively low levels.

MAJOR ACCIDENTS

A common cause for concern is the abrupt release of a substantial amount of energy via nuclear reactions. In this case the only fuel that could possibly react would be that actually inside the plasma region, i.e., about 1 g. If all of the energy obtainable from fusion of all of the fuel charge could be dumped into the blanket in a few seconds, the average temperature of the lithium would rise about 15°C, a minor perturbation. Plasma physics considerations indicate that a dump of such magnitude is impossible. Alternatively there is the possibility that relatively local areas of the vacuum wall could be strongly heated by interaction with a malfunctioning plasma. Such an interaction could heat the surface of the wall and release a mixture of adsorbed fuel atoms and contaminants whose

combined effect would act to quench the reacting plasma. There is also the possibility that energetic beams of runaway electrons could be generated by some instability in the plasma. These beams might produce intense heating of the vacuum wall over a small area sufficient to produce local melting. Such action could burn a hole in the vacuum wall. (Melting of tungsten limiters, presumably by runaway electrons, has been observed in present tokamaks.) Clearly, the probability of such plasma malfunctioning must be made extremely low before one can consider the plasma physics to be sufficiently in hand to yield a practical system. In any event, local wall burnout would at worst cause a lithium leak into the plasma but would not cause an accident affecting the public. The low total available energy in the fuel charge and the low probability of liberating more than a small fraction of it in a fault situation are major factors in the inherent safety of fusion reactors.

Another possible source of an abrupt release of energy is the magnet. There are two major fault modes.¹⁵ First, in a high current density coil a transition from super to normal conduction could progress over the total conductor volume in a time short compared to the overheat in the conductor. The rate of stored energy dissipation is usually taken care of by the insertion of an external load resistor. If, somehow, the resistor is not cut-in, the temperature of the coil assembly would rise to about room temperature while evaporating and venting the liquid helium with no damage to the coil. There is satisfactory experience with this type of quench fault. Second, in a time interval of perhaps 2 min, at low current densities in a coil the quench might not spread rapidly and a load resistor could easily be inserted automatically in a time interval of about 2 min to drive the current down, thus preventing local heating which could damage the conductor. A third possible fault mode is the breaking of a conductor in the coil. This would lead to further damage of the coil by arcing and probably a quench as before. In the latter two cases proper design can insure that an accident would be very unlikely, and that, in any case, the damage would be limited to the coil itself.

One of the most difficult types of accident with which the designer must cope in nuclear plants is posed by afterheat. The study of this problem for the reference CTR indicates that it is possible to evolve a design in which the afterheat will be so low that the reactor will be virtually unaffected by a loss of coolant accident. An analysis of the consequences of a complete loss of coolant in both the blanket and the shield region of the reference CTR indicate that all of the afterheat could be removed by thermal radiation and conduction with a temperature rise of no more than about 100°C in the high temperature zone during the first week after the outage even if no action whatsoever were taken by the plant operating personnel.⁹ It should be noted that these data are for a blanket structure built of niobium. If stainless steel were employed, the afterheat would be reduced by a factor of about 2 relative to that of niobium, or, if vanadium were employed, the afterheat immediately following shutdown would be reduced by a factor of about 4. Further, if vanadium were employed, the afterheat would fall off much more rapidly than with the niobium.⁹

CAPITAL COSTS

Any cost estimate for a full-scale CTR power plant at this stage inherently involves many uncertainties, but an attempt was made to get some idea of capital costs by making estimates for several CTR's for which design drawings are available.³ The power plant was divided into two major portions, i.e., the relatively conventional power conversion system, for which cost estimation is relatively straightforward, and the "nuclear island." The special equipment in the latter is not only unconventional in many respects, but it is not yet clear just what will be required.

The first step in making the cost estimates was to prepare Table 2 which summarizes the amount and costs of the materials and equipment used in the primary plasma containment, reactor, and reactor auxiliary systems. The material quantities have been taken from drawings or estimated. The unit prices listed for these materials are representative of those currently being paid on one-time orders for a wide range of laboratory research equipment. For example, the prices for the superconductors are representative of current large order prices for the conductor itself and of the unit winding and structure costs for the Baseball II magnet. Thus, if plasma physics work proceeds as anticipated, these unit costs may be within ~20% of those to be expected for the first versions of CTR power plants. The greatest uncertainties in the cost of the reactor auxiliaries lie with the injection systems and the theta-pinch reactor energy switchgear. Not only is the injector research work still some distance away from the reactor requirements, but there are major uncertainties in the energy with which the ions will have to be injected. The switchgear cost for the theta-pinch reactor was based on an estimated cost of \$2 to 7 million for similar equipment which has been designed for two synchrotrons for 1 to 2 sec switching of 100 to 1000 MJ. This requirement is for 10 msec switching of 200 GJ. The range of cost is probably \$100 to 200 million for development and fabrication. In addition, the costs projected for the theta-pinch reactor are heavily dependent on the permissible wall heat loading, and this will depend on the development of an insulator for the inner wall of the blanket

vessel where radiation damage limitations will be severe because of uncertainties in radiation damage effects.

Maturing of the fusion reactor industry will bring the advantages of production techniques, remove design uncertainties, and should reduce the reactor costs over the values given in the bottom line of Table 2. Of course, not all of the reactor types considered in Table 2 will yield systems that will be as attractive as the conceptual designs. However, it seems likely that development of at least one of these systems will proceed without running into plasma physics problems that will be responsible for major increases in costs. It appears that values on the order of \$200/kW(e) seem reasonable for the nuclear island of a fusion reactor. Thus, if the plasma physics problems can be resolved in a fashion such that there are no truly major increases in costs over those envisioned for one of the above designs, even a factor of two increase in the costs of some of the novel components would not be too serious because the bulk of the costs appear to come in areas where reasonably good cost estimates can be made on the basis of experience already in hand. For example, the vacuum pumps, the cryogenic refrigeration equipment for the superconducting magnets, the superconducting magnets themselves, the building, and the bulk of the power plant equipment required for conversion of the heat into electricity are all items for which fairly good to good cost data are available. In estimating the cost of the balance of the system (such as the heat exchangers), the weight of the materials required, the number of feet of weld seam, and the number of tube-to-header joints were estimated, and conventional cost estimating procedures for nuclear components were applied. Thus, it appears likely that the capital costs for a fusion reactor plant ought to be roughly the same as for a fission reactor plant.

If one turns from capital charges to fuel costs, the situation becomes very favorable indeed. The cost of deuterium is about \$150/lb and the cost of lithium is about \$10/lb. On this basis, and with rather generous allowances for handling costs, it appears that the fuel cost would run only about 0.006 mills/kWhr, or roughly 1% of the fuel cost projected for fission reactors.

GENERAL ENVIRONMENTAL EFFECTS

AIR AND WATER POLLUTION

For the plant design proposed, there would be essentially no air or water pollution because tritium leakage could be kept to an extremely low level. If one makes an effort to be quantitative, the data given in a previous section on local contamination of the environment can be applied to appraise the general contamination of the biosphere. An insight into the problem is given by an analysis that considered the amount of tritium released from a world-wide complex of power plants having the characteristics of the reference design. This would, under the conservative assumptions made in that study, be 4.4×10^7 curies/yr for a total power output of 6×10^6 MW, i.e., about the estimated world requirement for electric power in the year 2000.³ This tritium would react with oxygen to form water, much of which would mix with the water circulating in the earth's biosphere. The half life of tritium is about 12 yr while the half life for mixing in the earth's circulating water is less than 5 yr. The earth's circulating water is taken to include the water in the oceans to a depth of 75 meters.¹⁸ It happens that the rate of exchange of tritium between the atmosphere and the upper 75 meters of the oceans has been measured, and appears to give an equivalent mixing time of about 25 yr. Nonuniform mixing in the earth's atmosphere will further tend to give a higher concentration of tritium in the 30° to 50° north latitude band in which the greater portion of the tritium would be released. Thus, surface water in this region may have a tritium concentration perhaps 50 times that which one would expect if the tritium were uniformly mixed throughout the atmosphere and upper 75 meters of the seas. On this basis the resulting specific activity in the surface water in the U.S. would be less than 1.4×10^{-6} microcuries/cm³. Inasmuch as there seems to be little tendency to concentrate tritium in plants or animals (the half life of tritium in the human body is only 12 days) the tritium concentration in plant, animal, and human tissues would have about the same specific activity, i.e., less than 1.4×10^{-6} microcuries/cm³. The resulting dose to the human body would be less than 0.25 mrem/yr, or 1/500th of the dose from natural radioactivity.

THERMAL POLLUTION

The power conversion system contemplated would have a high thermal efficiency (about 55%) and this would reduce the waste heat rejection to the environment by approximately a factor of 2 with respect to the best current coal-fired steam plants. This would give low thermal pollution effects. It should be noted that work currently under way on a fossil fuel-fired potassium vapor topping cycle should also give a similarly high efficiency and low waste heat rejection.

ULTIMATE SYSTEM

In view of the rapidly dwindling reserves of fossil fuel and the very attractive prospects for a fusion reactor system as outlined above, it seems in order to look well into the Twenty First Century and examine the possibilities for basing the entire energy economy of the world on fusion reactors. It is particularly important to consider the implications of nearly zero fuel costs for this means that the incremental cost of off-peak power will be almost negligible. To appraise these possibilities it is interesting to examine Table 3 which presents the energy requirements for the U.S. as projected for the year 2000. Note that, of the electrical power requirements, about 25% will go for residential use and the balance for commercial and industrial applications. Note further that there is a large demand for heat at low temperatures, i.e., up to say 400°F. This suggests that one might operate the fusion reactor plant in such a way as to reject its heat at perhaps 300 or 400°F so that the resulting heat could be transported in the form of superheated water to industrial and domestic consumers.¹⁷ This would serve to reduce the amount of waste heat rejection to the environment by a large factor, a most desirable objective, and would supply low temperature heat at very low cost. That this is practicable is indicated by the fact that there are already over 100 district heating systems operating in the U.S., and both increased fuel costs and anti-pollution measures are now increasing the incentive to employ such systems.¹⁷

It is proposed to build the plant of Fig. 2 so that the peak temperature in the thermodynamic cycle would be about 1800°F, and this would make the cycle efficiency relatively insensitive to a heat rejection temperature of 300 or 400°F. (Clearly, a good thermal efficiency could not be obtained if the peak temperature in the thermodynamic cycle were only 500 to 600°F. The cycle efficiency is essentially proportional to the ideal Carnot cycle efficiency.) Of course, there would be a problem in balancing the electrical and heat loads on the power plant if this were done. However, it also appears that one might use a portion of the waste heat from the power plant for either desalting sea water or distilling sewage, and the mismatch between electrical and heat loads could be taken care of by providing fairly large reservoirs of water so that the heat load for the distillation processes could be interruptable. It might be mentioned at this point that, if about one-third of the heat rejected from the thermodynamic cycle of the proposed power plants were employed to distill sewage, it would be possible to distill 100% of the domestic sewage in the United States. If the provisions for doing this could be incorporated in new plants when they were installed, the incremental capital cost has been estimated to be only of the order of \$25 per capita. Inasmuch as the fuel cost would be negligible, this appears to be an eminently practical as well as desirable objective, and would provide a fine way to utilize waste heat during off-peak load conditions.

If we turn back to Table 3, it can be seen that a large amount of high temperature heat is required in the steel industry. However, this could be supplied in the form of electricity. It should be mentioned that even now it is economical to smelt iron electrically by adding only sufficient powdered coal to carry off the oxygen; a plant is now under construction in Mobile, Alabama, to reduce iron ore from Venezuela by this process; to make cast iron sewer pipe. High temperature heat for other metallurgical and ceramic processes, of course, could also be supplied electrically.

Another major requirement for energy is posed by our transportation system. Approximately 10% of the petroleum currently employed in our transportation system goes into diesel locomotives. An obvious means of eliminating this would be to electrify our railroads. This appears to be economically attractive, but will require a large capital investment.¹⁸ Automotive requirements present a more difficult problem. Fortunately, work on high energy batteries is progressing in a very encouraging fashion and it appears that, by going from lead-acid storage batteries to perhaps a lithium-sulfur cell of the type under development at the Argonne National Laboratory, it will be possible to get about 10 times the energy storage capacity per pound of battery as currently obtained from lead-acid batteries.¹⁹ Thus, the practical cruising radius of a vehicle could be increased from perhaps 40 miles to several hundred without overloading the vehicle with batteries. This approach would have the additional advantage that it would lead to a large electrical load at night for recharging the batteries. (See Table 3.)

If we go to an energy economy that depends entirely on fusion power plants for both electrical and heat supplies, it will be essential that each urban center have a multiplicity of power plants to provide redundancy in case of a forced outage. This in turn implies that each urban area ought to have at least three fusion reactor plants, and thus the reactors ought not be too large. A study of the projected electrical power requirements for urban complexes in the year 2000 as a function of the population size indicates that on this basis it will be necessary to have fusion reactor plants of no more than 500 Mw(e) per unit if we are to supply 75% of the U.S. urban areas with all of their heat and electrical energy from fusion power plants.²⁰ It should be noted that over 75% of the U.S.

population currently lives in cities of more than 100,000, and the fraction of the population living in these urban areas is continually increasing.

The distance to which one can pipe heat in the form of superheated water and do it economically appears to be around 20 miles.¹⁷ Thus, the advantages to locating an electrical power plant in a metropolitan area include both a reduction in electric transmission line costs and the practicality of rejecting the waste heat to a district heating system. It appears possible to obtain excellent reactor safety characteristics in a fusion reactor, hence siting in metropolitan areas appears acceptable. Thus, it may be inferred that, if heat can be made available as cheaply as appears possible with a fusion plant, there will be a very strong incentive indeed for industries and domestic consumers to make use of heat from a district heating system. The principal barrier to doing this will be the cost and legal and political difficulties associated with installing the complex of hot water mains required to accomplish it. However, high fossil fuel costs coupled with such limitations as those on air pollution and strip mining are likely to provide the necessary incentive.

SUMMARY

A review of the material presented above indicates that there is indeed a tremendous incentive to develop fusion power, and, if plants of the type envisioned can be developed, they should provide the basis for essentially eliminating air, water, and thermal pollution as well as most of the land despoilment currently associated with mining operations for power plants. The power resulting from this type of plant should be cheap and the fuel reserves adequate for the life of our sun. In short, from the long range point of view the development of fusion power plants appears to be eminently worthwhile.

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TOROIDAL FUSION REACTOR (1000 MW)

Fig. 1. Conceptual design for a Toroidal Fusion Reactor.

Fig. 3. Flow diagram for the potassium-steam binary-vapor-cycle power conversion system.

Fig. 4. Section through a reentry tube for the potassium condenser-steam boiler of the reference CTR.

Table 1. Data for CTR Reference Designs.

	ORNL Tokamak	PPPL Tokamak	LASL Q Pinch	LIL Mirror	ORNL Laser	LASL Laser	LLL Laser	Notes
Reference Design	ORNL-TM-3096	-	LA-KC-72 234-A	UCNL-7288J	ORNL-TM-3231	LA4858MS Vol.1	Freeman et al APS Mfg. 11/71	a. r_p = plasma radius
Major Radius, m (R)	1000	5700	3500	FT 1250 D ³ He 1720	150	2025	~ 200	b. r_c = expander collector radius
Minor Radius, m (r)	520	1640	1750	500	500	625	~ 100	c. pressure vessel diameter
Thermal Efficiency, %	52	40	50	40	41	41	~ 50	d. from ten modules
Water Flow, m ³ /s	Torus R=10.5m r=3.5m	R=9m r=2m	R=56m r=1.3m	$r_p=3m^a$ $r_c=20m^b$	$r_p=4m^a$ $r_c=150m^b$	4m sphere ^c	2m sphere ^c 1m sphere ^c	e. average during 1 ms pulse, 1 ms pulse per sec
Magnetic Field in Plasma, kG	24.5	64	150 ^v	42	70	0	0	150
Plasma Wall Load, MW/m ²	0.69	4.50	3.5 ^h	1.3	0.5	13	10 ^{4d} - 10 ^{5f}	~ 50
Surface area, m ²	1450	800	670	430 ^w	200 ^w	11.4	π	π
Heat flux, W/cm ²	0.25		.3 ^g	0.1 [*]	0.1	25	1.0	thin
Plasma Volume, m ³	2120	720	101	170 ^w	52 ^w	5.2	4.2	0.5
Blanket Material Structure	Nb	SS	Nb	Nb	SS	Nb	SS	k. low but not determined. No breeding required.
Reflector	Graphite	Fiberglass	Graphite	CH ₄	H ₂ O	Li	Li	Li-LiD
Shielding	Li	Helium	Li	Li	H ₂ O	Li	Li	Li-LiD
Activity after 1 year ⁿ , curies	7 x 10 ⁷			10 ⁹	10 ⁴	3 x 10 ^{9d}		m. One year at full power
Tritium inventory, g				1000	k			n. See also Scien- tific American June, 1971.
Deuterium inventory, g	375	300	35		20			p. Coolant is 50% enriched lithium. Shield is normal lithium
Plasma coolant, g	0.2	.5			0.1			
Neutron system, g	300	7600	35		100			
Major Wall Heat Inventories, Metric Tons								
Blanket	143	0	132	200	110			q. Plus 1.1 cm ³ Al ₂ O ₃
Reflector	360	0	725 ^p	130	20			r. No detail design
Shielding	0	0	33		0			s. Material to shield field is normal plasma
Blanket	200	8800	2500	1000	3000	25		
Reflector	200	0	560		10			
Shielding	1		600		0			
Blanket	450	0	5100		0			
Reflector	1300	800	1000	500	490	0		
Shielding		1200	0		240	0		
Blanket	1100	0	520	400	0			
Reflector	5000	350	350		100			
Shielding	0	0	1000	210	750	0		
Blanket		1200						
Reflector		2000	5000	200	400			
Shielding		5000	1000	20	10			

TABLE 2. THERMONUCLEAR ISLAND PROTOTYPE COST SUMMARY

BASIC PLASMA REACTOR SYSTEMS		ORMAK R=10.5m, r=3.5m		Ø FINCH R=56m, r=30cm		FRANKTON TOKAMAK R=9m, r=2m		LLL DT MIRROR R ₀ =80m ⁽¹⁾ , r=3m ⁽²⁾		ORNL LASER		LASI & LLL LASERS		NOTES
NOMINAL FIRST WALL FLUX IN MW/M ²		520 ± 0.6		440 TO 4200 ⁽³⁾ ± 0.17 ⁽⁴⁾		1840 ± 4.5		500 ± 13		36 ± 13		1000 ± ~50		
- BASIC MATL -		3/Kg	NETRIC TONS	3/M	NETRIC TONS	3/M	NETRIC TONS	3/M	NETRIC TONS	3/M	NETRIC TONS	3/M	NETRIC TONS	3/M
Al-12	60	143	86	132	8			200	12	110	66			(a) He extracted from the atmosphere - \$500 PER KG (b) 80 METRIC TONS (1" = .0254 CM) IS GIVEN WEIGHT FOR 113 METRIC TONS OF LITHIUM TUNGSTATE (c) THE 25 A-25 RINGS ARE NOT EXPANDED TO BE 250 METRIC TONS OF 2500 IN DIAMETER (d) TIME AVERAGE (e) ENERGY DENSITY OF 10 ¹⁴ WATTS/M ² (f) 100 METRIC TONS OF LITHIUM TUNGSTATE (g) 100 METRIC TONS OF LITHIUM TUNGSTATE (h) 100 METRIC TONS OF LITHIUM TUNGSTATE (i) 100 METRIC TONS OF LITHIUM TUNGSTATE (j) 100 METRIC TONS OF LITHIUM TUNGSTATE (k) 100 METRIC TONS OF LITHIUM TUNGSTATE (l) 100 METRIC TONS OF LITHIUM TUNGSTATE (m) 100 METRIC TONS OF LITHIUM TUNGSTATE (n) 100 METRIC TONS OF LITHIUM TUNGSTATE (o) 100 METRIC TONS OF LITHIUM TUNGSTATE (p) 100 METRIC TONS OF LITHIUM TUNGSTATE (q) 100 METRIC TONS OF LITHIUM TUNGSTATE (r) 100 METRIC TONS OF LITHIUM TUNGSTATE (s) 100 METRIC TONS OF LITHIUM TUNGSTATE (t) 100 METRIC TONS OF LITHIUM TUNGSTATE (u) 100 METRIC TONS OF LITHIUM TUNGSTATE (v) 100 METRIC TONS OF 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SYSTEMS		R=10.5m, r=3.5m		R=56m, r=30cm		R=9m, r=.2m		R _c =50m, r=.3m ^(f)				
TOTAL FIRST WALL FLUX IN MW/m ²		520 ± 0.6		4200 ^(a) ± 0.87 ^(a)		1840 ± 4.5		500 ± 1.3		56 ± 13		
— BASIC MATL —		kg	NETRIC TONS	# M	NETRIC TONS	# M	NETRIC TONS	# M	NETRIC TONS	# M	NETRIC TONS	# M
AS-12		60	143	8.6	132	8			200	12	110	6.6
Li		9	460	4.1	1780 ^(a)	32 ^(a)			100	.9	20	2
Be		100			33	7						
STAINLESS STEEL		15	200	30	2500	38	2500 ^(a)	132	1000	15	25	4
Fe		12	200	2.4	560	7					10	1
He		10 ^(a)	1		600	6	81	.8				
Cu		10	450	4.5	5100	51						
NaTe ^(dd)		VARIES	1300 ^(a)	32	200 ^(a)	12	800 ^(a)	47 ^(a)	500 ^(a)	59		
Nb ₂ Sn ^(dd)		VARIES					1200 ^(a)	237 ^(a)				
GRAPHITE		2.50	1100	2.8	530	1			400	1		
Al		.60	5350	3.2	380	.2	350	.2				
Al		7			1000	7			210	1.4	100	.66
FLiBe		8					1200	96				
Ni		1.50										
K		2.20	10	—								
STRUCTURAL STEEL		2	6300 ^(a)	12.6	12K	24	5000	10				
INSULATORS	LUMP SUM					5		5 ^(a)				
CONCRETE		.12	20K	2.4	5200	.6	2300	.3	25K	3		
SUB TOTAL FOR BASIC MATL —				15.6		195.8		441.9		92.3		7.4
3 / KW FOR BASICS			242		45 TO 450		240		185		132	
— REACTOR AUXILIARIES — ^(f)												
HELIUM REFRIG. SYSTEM			4		30		8		2.6			
INJECTION SYSTEM			20		—		20		13.0			
TRITIUM RECOVERY SYSTEM			6		8		10		6			
POWER SUPPLIES			—		—		SEE INVERTERS & RECTIFIERS		—			
CONTROL & INSTRUMENTATION			2		5		4		2			
PUMPS & COMPRESSORS			—		—		SEE OTHER		—			
HEAT EXCHANGERS			2		2 TO 20		SEE OTHER		1			
LASER & OPTICAL SYSTEM			—		—		—		—		~50 TO 2K	
DT PELLET SYSTEM			—		—		—		—		~.5 TO 2	
INVERTERS & RECTIFIERS			.1		—		15		2.0			
VACUUM SYSTEMS			1.3		1		7		.3			
TRITIUM ³ M PER K ^(a)			1		1		7.3		1			
FINITE WALLING DEPT.			10		10		10		10			
DIAGNOSTIC VESSEL			10 ^(a)		20 ^(a)		20		30			
—			—		~150 ^(a)		50 ^(a)		—			
—			56.4		227 TO 245		151.3		67.9			
—			122		103.6 TO 119		503.2		160.2			

CONCEPTUAL DESIGN ONLY

- (1) He EXTRACTED FROM THE REACTOR VESSEL @ 300 PER K³
- (2) 60 METRIC TONS LI³ @ 30 PER K³ AS GIVEN IN REACTOR DESIGN 1130 METRIC TONS LI³ 600 METRIC TONS 25% WHERE DURING REACTOR COST ESTIMATED TO BE 200 PER K³ ON BASIS OF 3000 PER K³
- (3) 100.25 PER K³ HELIUM FOR REACTOR VESSEL COOLING WITH EXP. COST
- (4) TIME AVERAGE
- (5) ENERGY DENSITY 100% REACTOR VESSEL ARE INCLUDED
- (6) COOLING FLUIDS OF REACTOR VESSEL
- (7) 100% OF REACTOR VESSEL ARE INCLUDED
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- (100) 100% OF REACTOR VESSEL ARE INCLUDED

TABLE 3
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

^aThis column gives the electrical energy — the thermal energy input to the plants generating electricity will be several times as great.