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ENVIRONMENTAL AND TECHNOLOGICAL IMPLICATIONS OF A
THETA-PINCH FUSION POWER PLANT

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ANL -ENG/CTR Technical Memorandum No. 17

Presented at the Workshop on Fusion
Reactor Design Problems, Culham
Laboratory, Culham, England
January 29 - February 15, 1974

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ENVIRONMENTAL AND TECHNOLOGICAL IMPLICATIONS OF A THETA-PINCH FUSION POWER PLANT*

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INTRODUCTION

World-wide demands for energy are at an all-time high and increasing. Although the United States leads in use of energy per capita, other nations are also demanding more. Much of this demand is for energy in the form of electricity. This demand comes at a time when fossil energy reserves are becoming more difficult to discover and extract, and there is a simultaneous public demand for a cleaner environment. This supply-demand situation intensifies the search for alternate energy sources. As a result, fission, fusion, solar, geothermal, and other energy sources, are being intensely developed to replace declining amounts of fossil fuels.

For the near-term, fission energy, along with processed coal, offers increased supply, but with increased cost and environmental impact. Work is currently underway to alleviate price increases and to reduce atmospheric pollution from these two sources. Longer range possibilities include solar energy and thermonuclear fusion. Both of these sources offer boundless energy, but scientific and engineering feasibility and their environmental impact have not been adequately examined. This paper summarizes the work of a cooperative effort between Los Alamos Scientific Laboratory and Argonne National Laboratory, which was initiated to investigate these problems for the Theta-pinch fusion power plant.

Fusion power has much to recommend it as an ultimate energy source. Advocates have maintained that the fuel is unlimited and can be obtained virtually cost-free from the sea. Zero emission, no noxious by-products, urban siting, and small land despoilment, have been claimed. More realistic assessments of the environmental impact of fusion have shown these claims to be exaggerations, but accurate and quantitative assessment has been limited by lack of detailed plant designs upon which to base their study. In this void, environmental impact studies have relied heavily upon rules of thumb for tritium leakage and radiation-waste accumulation. The potential for accident has been highly subjective and impossible to predict.

*For discussion at the Workshop: Fusion Reactor Design Problems
Culham Laboratory, Culham, England; January 29-February 15, 1974

The conceptual design made by LASL/ANL begins to fill the need for data needed to evaluate both environmental impact and scientific and engineering developments required to build a fusion power plant. Although this plant design is quite detailed and enables a very realistic assessment of environmental impact and needed technological developments, it must be cautioned that it is only one iteration, and an early one at that. Already it can be seen that the design could be improved relative to waste problems, size, etc. Thus the environmental assessment which follows is based upon a point-design plant, and the effects are easily altered by design changes.

There are so many possible alternatives that parametric design studies are now underway to examine effects of such basic changes as the torus diameters, magnetic fields, duty cycles, etc., on the plant operation and its environmental impact. Another design study will investigate use of present-day technology and materials for fabrication of a Theta-pinch power plant. Other systems-type studies will examine the possibility of minimizing radioactive waste and explore other alternatives to find their impact upon the environment and the technological development required to implement the design. These parametric studies may result in a design considerably different than from discussed here.

ENVIRONMENTAL EFFECTS

A major environmental effect of a fusion power plant is the leakage of tritium. Tritium is considered a "low-hazard" isotope because it is a low-energy beta emitter and the half-life of tritium ingested in the human body, either by breathing or drinking, is short. However, there is another as yet inconclusively examined danger from tritium. Foods grown in a tritium environment may allow tritium to replace hydrogen in some carbohydrates. Because of this potential indirect hazard, measures were taken to prevent tritium escape from the reference power plant.¹ Tritium is also a valuable fuel and there is an economic incentive to capture tritium for subsequent use as fuel.

In the reference design² most of the tritium escapes via the steam power plant. Tritium which migrates from the lithium coolant through the intermediate sodium coolant and thence to the steam (see Fig. 1) must be considered essentially lost. The tritium quickly comes to equilibrium with the water, either as HTO or T₂O and its separation or removal does not appear economically attractive.² A method has been reported³ to remove tritium from deuteria. A cursory examination of this process indicates that it is probably not applicable to the reference plant. There, the tritium concentration in the deuteria is about one Ci/g. while in the Theta-pinch plant, the concentration is lower by three to eight orders of magnitude.

A comprehensive mathematical model was developed to "map" the tritium in important power-plant components. This model is used not only to estimate the loss of tritium to the environment, but also calculates the hold-up of tritium in the structure, heat exchangers, plumbing, and processing equipment. Properties which determine the solubility and permeating rate of hydrogen through structural materials, as well as details of the calculational model, are given by Maroni in Ref. 1.

Fig. 1. Heat exchanger, power plant schematic flow diagram
Theta-pinch fusion power plant.

Tritium Loss Via Steam Power Plant

The partial pressure of tritium in the lithium (10^{-10} Torr) is limited by the lower practical limit of the molten-salt lithium extraction process specified for the plant. No provision was made for tritium removal from the sodium. Thus the partial pressure of tritium in sodium should reach, but not exceed, 10^{-10} Torr. Other pertinent design values used in calculation of tritium migration toward the steam are shown in Fig. 2. The results of a series of calculations, with and without a copper diffusion barrier in the sodium/steam heat exchanger, are summarized in Table I. The copper layer is a good barrier to tritium migration if the continuity of the laminated structure is maintained. To allow for imperfect fabrication and partial failure, the calculations include cracks and delamination of the copper layer amounting to a sizable fraction (1.0%) of the total area. Portions of the primary heat exchanger are not amenable to insertion of a copper diffusion barrier (flanges, weldments). These areas are estimated to be $\sim 0.01\%$, or considerably less than 1% of total heat-exchanger area.

Table I
SUMMARY OF CALCULATIONS FOR TRITIUM LEAKAGE FROM THE
SODIUM/STEAM HEAT EXCHANGER

Na/Steam Heat Exchanger Wall	Daily Tritium Leakage to Steam System	
	grams	Curies
With 2.5 mm-thick copper layer (99% effective)	6×10^{-4}	6
Without copper layer	10^{-2}	100

These calculations indicate the extreme design dependence of the tritium leakage. The lithium blanket coolant was processed to obtain the very low tritium concentration, and then diffusion barriers were used to prevent excessive permeation of tritium into the steam system. Other losses in the plant were minimized by use of contiguous networks of barriers (both metal and ceramic) both in parallel and in series around tritium containing systems (see Fig. 3). As mentioned, the plant was not optimized in any manner, and it may well be that the expense of such measures to prevent tritium losses are not justified. On the other hand, other steps could be taken to reduce the tritium leakage still further if required. For instance, Maroni⁴ indicates that if helium is used as the intermediate heat-exchange fluid, tritium losses to a steam system is lowered by about a factor of 7 with the same heat-transfer area between helium and steam. Even though design options do exist to control tritium leakage over wide limits, the design presented here indicates minimal leakages are obtainable.

The Theta-pinch plant described in Ref. 2 rejects its waste heat to a flowing body of water, e.g. a river. If all of the tritium lost to the

Li/Na Heat Exchanger (622-814K)

Na/Steam Heat Exchanger (533-543K)

Total Area = 37 000 m²

Total Area = 40 000 m²

* Symbols

H = Protium

T = Tritium

S = Quantity of dissolved H or T

ϕ = Rate of permeation of H or T

P = Partial pressure of H or T

FIG. 2 TRITIUM DISTRIBUTION AND LEAKAGE PROFILE
 (Blanket/Heat Transfer/Energy Conversion Section)

Fig. 3. Perspective view of conceptual Theta-pinch power plant.

steam is eventually discharged, via leak collection and steam generator blow-down, to the condenser cooling water, the tritium concentration in that condenser cooling discharge would be equivalent to 3.3 nanocuries/liter. Three microcuries per liter of drinking water is allowed by the International Commission on Radiological Protection⁵. Alternatively, the steam system may be considered "closed," e.g. most leaks and blowdown captured, processed, and returned to the system, such that very little water from the power conversion system is lost; the tritium concentration will build up the system. However, if influx is limited to six Curies per day, the steady-state radioactivity of the water in the steam system would be only 30,000 Ci. This corresponds to 7,000 $\mu\text{Ci}/\text{l}$. After 20 years the system has reached 65% of steady state.

Should the plant be located such that cooling water is not available, and either dry or wet cooling towers must be used for waste heat disposal, the tritium escaping into the steam may eventually be discharged to the atmosphere, either by venting through a separate stack or through the air side of the cooling tower. Calculations for two typical sites (Bailly, Indiana and Oconee, South Carolina) indicate that maximum annual average dosage for an individual may be as high as 1 mrem/yr¹. This calculation ignores fallout due to precipitation and may be more hazardous to growing crops in the vicinity.

Tritium Leakage from Other Systems

Another pathway to the environment includes leakage from the plasma chamber, the vacuum, fuel/ash processing, coolant processing, and heat-exchange equipment. These tritium containing components are designed to be double-walled tritium barrier material, with a helium gas purge in the jacket. Further, they are located in helium purged rooms which are lined with barrier material. This loss can be made arbitrarily small if sufficient barriers are placed in series and if doors and other joints are properly sealed. To estimate this leakage, a value often used for fission reactor containment is used, along with estimated tritium concentration in helium purge gas in the plant. The rule of thumb, one part per thousand per day⁶ along with a tritium concentration in the helium purge of 4.3×10^{-8} Torr (pressures as low as 10^{-15} are believed³ possible), gives a total plant loss of 0.11 Ci/day, which is small compared to that lost via the steam. These calculations are detailed further in Ref. 1.

Radioactive Waste, Resource Usage and Transportation

The blanket first wall represents the most crucial and failure-prone component of the plant; the intense neutron flux will couple with the cyclic stresses induced by thermal and flow transients to reduce module lifetime. After long-term (~ 5 yrs) exposure to radiation, the blanket structural material will need to be replaced. This "spent" structure will be radioactive and must be handled remotely. Based on an estimated lifetime of five years, the amount of material to be stored or disposed of is 9 kg/MWe-yr. Depending upon initial purity, it may be possible to recycle blanket materials after some years of "cooling." In view of the rapidly growing use of automation in the metals industry, remote handling and recycling of this material may

eventually prove practical and economical. Remote recycling repair would eliminate the need for extremely long-term storage of radioactive wastes and would remove some of the long-lived activity by further transmutation during reuse in the fusion blanket (see Table II).

The decay of the Nb activity with time after removal from the blanket is given by Refs. 1 and 7. This structure is initially placed in a hot cell for several weeks before long-term storage. The normalized activity values, e.g. 5.1 Ci/wt at shutdown, 10^{-1} Ci/wt after one year, were calculated for a five-yr (in-reactor) lifetime in the first wall region. A five-year lifetime represents an optimistic allowable total flux of 5×10^{23} . This may be an order of magnitude higher than available materials can withstand without embrittlement, swelling, or excessive transmutation. If much shorter lifetimes are found allowable, it may be necessary to reduce the wall loading of the reactor to attain lifetimes on the order of several years. It should be noted that if a total wall flux of 5×10^{23} is allowable, this represents a total material neutron wall loading of 29 MWe-yr/m². Molybdenum (TZM) and vanadium alloys (V-Ti) represent reliable alternatives to Nb as a structural metal⁷ and may reduce radioactive waste. The amounts of dissolved tritium in the structural metals (Nb) (the S_T 's in Fig. 2) are small considering the volumes of these materials.

The salt contactor processing system used to remove tritium from the lithium coolant is also an effective lithium purification system. In addition to the hydrogen isotopes, it will remove the isotopes of carbon, nitrogen, and oxygen on a continuing basis. Furthermore, radioisotopes of boron, sulfur, silicon, or phosphorus, which are initially present in the lithium or blanket materials exposed to the lithium, will also be removed by the purification system. However, no more than one ppm of each of these isotopes would be expected. Larger amounts of calcium, potassium, and sodium are expected in the initial lithium charge, but these impurities should be removed during the start-up operation of the plant and before a significant radiation problem is incurred.

Constituents and impurities of the blanket materials in contact with the lithium, e.g., iron, nickel, chromium, niobium, tantalum, hafnium, and tungsten, will also be removed during the processing step and will eventually require disposal. Experience over many years operation with a similar liquid-metal system on the EBR-II indicates that the accumulation of these materials is not significant (amounting to tens of liters per year). An estimate of the amount of impurities to be collected over a 20-year plant lifetime can be obtained from the estimated niobium corrosion rate of 0.4 mil/yr.¹ This corrosion rate includes neutron sputtering effects.

Thermal Effects - Land Despoilment

During normal operation, approximately 2 MW is dissipated into the cooling water or cooling tower air for every 1 MW of electricity generated. This high value of reject heat is a result of the choice of a very conservative, low-temperature power plant (thermal efficiency ~40%). The waste heat from a fusion plant is, like all other power plants, dependent upon the maximum

thermal-conversion temperature. If advanced energy-conversion cycles using high temperatures are used, the waste heat is reduced, regardless of the heat source used. The use of direct conversion of a portion of the fusion energy to electricity helps to balance electrical (recirculating power) losses unique to a fusion plant.

Land despoilment is also little different from other heat sources. There is little likelihood that a fusion plant will be anymore acceptable in an urban site (thus reducing need for transmission lines) than fission or fossil plants. (Solar and geothermal-source plant sites are even further restricted.) The amount of land required for the plant and land required for fuel/structure mining seems similar for fusion, fossil, or fission-fueled plants.

Transportation of Fuel and Radioactive Waste

After start-up, no radioactive fuel will be transported to the plant; deuterium and lithium isotopes will be required at rates of 970 and 3360 gms/day, respectively. Product tritium will be shipped from the plant at a rate determined by plant capability and/or the extent to which the DT cycle is used in a growing fusion economy. Tritium is currently routinely shipped in DOT-approved, double-wall shipping containers in ten-gram lots.

An impact which has not been generally acknowledged is the large amount of materials needed for construction and operation of a fusion plant. Shown in Table III are estimates of the material requirements for the conceptual Theta-pinch power plant. These numbers are preliminary, and perhaps optimistically low, since they are based upon a five-year blanket lifetime.

Table II

RADIOACTIVE WASTE

	5-Yr Lifetime 10 ⁶ kg/yr
Niobium	0.7
Be	0.1
C	0.14
Cold Trap	0.3

Table III

RESOURCE REQUIREMENTS

	One Plant		World* Resources
	Const. 10 ⁶ kg	Oper. 10 ⁶ kg/Yr	
Li (Nat)	1.6	.016	10 ⁵
Nb	3.6	.08	6,000
Be	0.05	.01	1,000
Cu	9.3	.002	10 ⁶
He	1.2	.001	29,000

In the third column of Table III is an estimated world resource of these materials. It is seen that available resources appear adequate for projected fusion power plants except possibly for niobium and/or beryllium. Even if these reserves do prove to be accurate, the Theta-pinch concept is not dependent upon the particular materials, and substitution could be made. It should be noted that although the amount of lithium used is very small (3360 gm per day), most of it is lithium 6, and requires considerably more natural lithium. This factor is considered in Table III.

The environmental impacts described above will have implications for a fusion economy. Based upon the design described in Ref. 4, it is seen that the tritium leakage is very small (six Curies per day for 4000 MW) and its global consequence small; however, local contamination could become significant. The major loss of tritium is found to be from the steam power plant, since it cannot be effectively removed from the working fluid. Other tritium losses from the plant, however, can be made very small.

Radioactive waste from the plant is relatively easier to handle compared to some volatile fission fragments from a fission plant, but there is more waste mass for disposal. These wastes include corrosion products from the lithium coolant processor, niobium structure, beryllium, and carbon moderators, and perhaps copper wastage from the compression coils.

Accidents or Unusual Occurrences

Possible accidental incidents which could occur with the Theta-pinch plant are discussed in Ref. 1. The maximum credible accident would be a rupture of the lithium coolant system with subsequent fire and release of its contained tritium and corrosion products. Such an accident postulated the simultaneous rupture of eight lithium piping systems, failure of the lithium dump valve systems, rupture of eight sets of three concrete walls, in series, a source of moisture to ignite the lithium, and no corrective action taken over a period of some weeks while the lithium smolders. The probability of such simultaneous malfunctions certainly borders on the incredible. Any portion of the above accident would be costly and very inconvenient from a plant operation standpoint, but the external effects should be tolerable. Other, less severe accidents during operation are discussed in Ref. 1, and their effects will be totally contained within the plant.

TECHNOLOGICAL REQUIREMENTS

In addition to the environmental impact, another objective of the joint ANL-LASL work was to delineate technological problems which would need solutions before the successful demonstration of a Theta-pinch power plant. Some problems were obvious in the beginning of the study, and others arose as a result of probing more deeply into the design.

Energy Storage

A feature of the pulsed Theta-pinch power plant is the need for energy storage. Between plasma burns, the compression field magnetic energy must be stored. Other fusion reactors also require energy storage, but the pulses are slower. The Theta-pinch cycle is reminiscent of a Diesel cycle,⁸ wherein

the energy for compression on the next stroke is stored in either a flywheel or in additional pistons in different portions of their cycle. In the reference design, 100 gigajoules are stored in a superconducting magnetic energy-storage device described in Ref. 2. It is essential that the energy-storage device be very efficient, since in the reference design the energy-storage requirement from cycle to cycle is approximately twice the thermal output of the plant. With an overall efficiency of about 40%, it is seen that if 20% of the energy is lost in storage, the net output of the plant would be zero, neglecting other losses. Another serious consideration in the superconducting energy-storage device is the energy required to "pump" the heat (energy) loss from the superconducting temperature. Refrigeration at 4°K currently requires on the order of 500 watts power for each watt refrigeration. Carnot refrigeration requires about 75 watts per watt. At 50% of Carnot efficiency, the amount of energy which can be dissipated in a superconducting energy store is less than 0.13%. This puts very stringent design requirements on such a device. This problem is intensified by the heat loss into the cryogenic energy store from the normal (room temperature) copper compression coil leads. Although means may exist to reduce this loss, it is estimated that the heat leak into the cryogenic coils from their leads will be 8 megajoules per pulse.

Gas Blanket

In addition to containment of plasma while the reaction proceeds to produce significant fusion energy, it must also be demonstrated that the plasma can be handled during cooling and ash removal. In Tokamaks, this is accomplished by a divertor. In the Theta-pinch, a "gas blanket" is interposed between the very hot plasma and the chamber wall to allow a cooling time while the plasma energy is gradually conducted to the first wall (and thence to the coolant). The plasma cooling time determines the temperature difference between the plasma/insulator and insulator/metal interface. In the reference design, a cooling time of one sec gave a temperature difference across the 3 mm alumina insulator of 40°C. This temperature difference is inversely proportional to the insulator thickness and directly proportional to its conductivity. The insulator thickness was determined by the dielectric strength and the number of segments as well as the implosion heating voltage.

If cooling time is to be minimized, the insulator must have high values of allowable stress, dielectric constant and thermal conductivity, but low values of coefficient of expansion and elastic modulus. Shorter cooling times can also be attained by lower plasma energies, implosion heating voltages, torus radius, or more blanket segments. Since all of the latter parameters are under the control of the designer (but subject to other constraints), it appears that it may be possible to considerably reduce the plasma cooling time from one second used in the reference design. This plasma cooling time, along with removing the partially burned plasma and cooling the first wall, determines the time between pulses. These factors are further discussed in Refs. 8, 9, and 10.

Another facet affecting the gas blanket which was not resolved during the design study is the requirement for plasma wall stabilization from the $\times 1$ -0 fields. The requirements are not accurately known at this time but early

consideration indicated only minor problems involved in incorporating them into module geometry. However, this requires the gas blanket to have a non-cylindrical geometry with unknown effects.

In the reference design, it is difficult to isolate the plasma from the gas purged from the torus from the previous pulse. Thus, when the implosion heating occurs on succeeding pulses, the gas previously purged from the torus will rush back into the plasma chamber to fill the void between the plasma and the torus wall. The gas pressure may not reach equilibrium before the ignition point is reached, but there is a heat loss to the neutral gas tending to extinguish or prevent ignition of the plasma. This does not appear to be a serious effect, but its magnitude is now under study at ANL and LASL. There is also a possible beneficial effect if the on-rushing gas blanket protects the plasma from wall atoms sputtered or desorbed during the compression process.

Coils, Leads, and Switches

The technology of switching, circuitry, and construction of the implosion heating and compression coils is not sufficiently advanced to permit final design of these electrical systems. Although most of the more obvious problems were resolved in the coil design, it is not clear that all effects have been properly mitigated. Interaction between the very rapid transients of the implosion heating coil and the surrounding compression coil, Joule losses in both coils and their leads, and required coil inductances for rapid rise and proper decay time, were considered, but additional experiments and calculations are required to verify that the proposed design will operate as expected. Interactions with other parts of the module, such as the lithium manifold, the shield liner, and external wiring circuits, also need investigated.

The design of the circuit to provide the fast-rising IH field is complicated by the presence of the compression coil. The design study for the implosion heating experiment at LASL¹¹ considered several alternatives for the .1 microsecond risetime circuit. These included variations of transmission-line circuits, coaxial water lines, lumped circuit-delay lines, and pulse-forming networks. The transmission line systems have the disadvantage of bulk and the lumped constant-delay line was felt to be too costly. The pulse-forming network selected may be suitable for reactor use since the space limitation and cost were considered. However, the mating of the criss-cross IH coil design to any specific generator has not been studied. This question will be addressed with increasing force as the design of the staged Theta-pinch experiment proceeds at LASL.

For the compression coil, a strong advantage of the inductive energy store with transfer by variable inductance is the absence of switches from the circuit. However, the inertial energy associated with the rotation of the magnets² implies long rise-times. In addition to the demands on plasma stability thus incurred, the scaling of the inertial energy with stored energy leads to the specification of small storage units and a corresponding cost penalty.

The alternative to transfer by variable inductance is the use of a switch in the superconducting circuit and a transfer capacitor, which must handle one-half of the energy. A very attractive, but unproven, possibility exists in the use of homopolar generators² for this function. Whatever the capacitor is, the circuit must contain switches and the viability of the scheme will require the development of switches with acceptably low losses.

The need to maintain the current may be met with transformer coupling or a crowbar circuit. The former has a tendency for inefficient energy transfer and the latter suffers from the aforementioned switch losses. Additionally, the use of a crowbar circuit would require that the current be interrupted at full flow to return the energy to the store. In practice, this is extremely difficult.

First Wall - Blanket

Problems with the blanket and first wall are primarily concerned with materials. These were addressed in Ref. 12. The first-wall metal insulator composite undergoes thermal stress variation during each cycle and thermal fatigue may limit wall lifetimes. Further, neutron radiation damage, high-energy particle impact, and other radiation also limits the first wall and structural portions of the blanket lifetime. Corrosion does not appear to be a severe problem, but as discussed later, residual impurities from the tritium removal process may affect the corrosion rate. Another major development area is the fabrication of these parts. The plant construction appears feasible, but neither economic analyses nor manufacturing engineering has been applied.

Because of the expected short lifetimes, means for quick and easy replacement of the blanket and first wall must be developed. A modular approach is used such that modules may be easily removed and replaced. Finally, cooling of the first wall and the blanket is not a severe first-order problem, but more information on the effect of both steady state and transient magnetic fields upon liquid metal at flow transitions is needed.

First Wall

A particularly crucial problem for the reference power plant is the insulator used on the first wall. Alumina was selected as a reference insulator, but does not have all the desirable insulator properties discussed earlier. The major uncertainties regarding the effectiveness and lifetime of this insulator include thermal stresses, the bond between the insulator and the metal substrate and the bulk and surface radiation effects. Numerical values expected for the first wall in the reference plant are shown in Table IV (Ref. 12). It is seen that shock heating voltage, the thermal fatigue, swelling and blistering problems, pose limits to the first-wall lifetime, and considerable development work on the insulator/metal composite is required.

The metal chosen for the first wall and other structural portions of the blanket was a niobium alloy. As mentioned in the environmental section, this may be a poor choice because of limited world resources of the ore. Further, the activation of this metal results in considerable long-lived

Table IV

SUMMARY OF FIRST-WALL RESPONSES

(Burn Time ~0.100 sec, Plasma Cooling Time ~1.0 sec, Duty Cycle, ~3.0 sec)

Fusion neutron (14.1 MeV) current	8.91×10^{14}	n/cm ² /pulse	Metal (Nb)	(a)	atm
Total neutron flux	9.03×10^{15}	n/cm ² /pulse	isothermal (300→800 K)	0	atm
Bremsstrahlung flux (0.5-1.0 Å)	71.62	J/cm ² /pulse	during burn	0	atm
Average energy density in			during plasma cooling	-200	atm
Insulator			pumping differential	-600	atm
neutron	156.3	J/cm ³ /pulse	Rate of		
gamma	63.5	J/cm ³ /pulse	Average atom displacement		
bremsstrahlung	1432.4	J/cm ³ /pulse	Al ₂ O ₃	~100 ^(b)	dpa/yr
total	1652.2	J/cm ³ /pulse	Nb	120	dpa/yr
Metal			Average helium production		
neutron	23.6	J/cm ³ /pulse	Al ₂ O ₃	.56	atm %/yr
gamma	183.4	J/cm ³ /pulse	Nb (maximum)	197	ppm/yr
bremsstrahlung	286.4	J/cm ³ /pulse	Hydrogen production		
total	493.4	J/cm ³ /pulse	Al ₂ O ₃	0.33	atm %/yr
Temperature transients in			Nb	680	ppm/yr
Insulator	Inside	Outside	Neutron transmutation		
during burn	310	250	Al ₂ O ₃	0.80	atm %/yr
during plasma cooling	75	60	Nb	0.73	atm %/yr
total	385	310		0.97	atm %/yr
average	350				
Metal					
during burn	250	220			
during plasma cooling	40	30			
total	290	250			
average	270				
Stresses induced in					
Insulator (Al ₂ O ₃)	(a)	atm			
isothermal (300→800 K)	0	atm			
during burn	+570	atm			
during plasma cooling	+1370	atm			

^aThese stresses are based on assumption of zero stress at 800°K^bEstimated by extrapolation of neutron spectral results calculated for other materials.

radioactive waste. Other refractory metals (except vanadium), however, are probably not much better in this respect. Further, niobium and vanadium are very good getters for such impurities as oxygen, nitrogen, and carbon. Thus extreme care is required to protect these metals from the atmosphere and other sources of these elements. Finally, although development of fabrication procedures for refractory alloys (particularly niobium) have advanced recently, the requirements for extreme cleanliness and quality control may prove excessive for near-term practicality. The use of high nickel alloys is limited by the corrosion resistance to lithium at high temperatures. Further, because of the differing coefficients of thermal expansion, the use of an alumina insulator is unlikely with stainless steel-type nickel alloys.

Modular Construction

Because of the high-wall loading that is possible with the Theta-pinch concept, some effort has been made to design the modules so that they may be quickly and efficiently changed.⁸ Figure 3 illustrates module transport casks, module storage and supply areas, and provisions for changing modules by use of an interlock chamber, without seriously disturbing the vacuum. The modules are designed to be completely independent so that one may be removed without disturbing adjacent modules. These infant efforts begin to show the type of design development needed. In the Theta-pinch module (Fig. 4), connections have been designed for good accessibility and the vacuum purge line is not disturbed during module change.

A possible design deficiency of this arrangement which has not yet been adequately evaluated is the possibility of neutron streaming between modules. This space has been minimized consistent with magnetic field non-uniformity and vacuum pumping requirements and there is overlap between module to prevent direct streaming. Even so, it is not clear that the neutron leak through these gaps will be detrimental to tritium breeding. The additional heat load at the shield surface at these points is not a serious problem.

Magnetic Effects

One of the advantages of a pulsed plasma cycle is that the magnetic field is off for a large part of the cycle and, during that time, a liquid-metal coolant can flow unimpeded by magnetic forces. Heat transfer can thus occur by convection rather than by pure conduction. The effects of a steady (i.e. not pulsed) magnetic field on the heat transfer at the first wall has been adequately discussed and wall loadings less than two or three MW/m² are easily attainable with liquid-metal coolant.^{13,14} This limit is primarily due to allowable stresses in the coolant channels. High stresses are caused by the high pressure losses involved in pumping (across strong magnetic fields) the lithium flow required to remove the first wall and blanket heat load. Heat-transfer rate (e.g. coefficient), even though limited to laminar flow, is seldom the limiting effect of the magnetic field.

In the conceptual design of the Theta-pinch plant, the total first-wall loading (thermal power/wall area) is 11 MW/m². To examine this high wall loading, two one-dimensional heat-transfer programs were used to find the temperature variation with time on the first wall at both LASL and ANL.⁸

Fig. 4. Theta-Pinch Fusion Power Plant Module.

These results (see Table IV) show that the cycle time could be reduced perhaps to as short as two seconds if cooling were the only consideration. This would allow a total wall flux of about 15 MW/m^2 , which is certainly adequate. Thus, to first order, the magnetic field does not severely limit the heat transfer in the Theta-pinch design.

However, the liquid-metal flow patterns, particularly during the field transients, are not at all clear. This is particularly true in transition regions such as bends, area changes, channel entrance and exits, and transitions from flow parallel to flow perpendicular to the magnetic field. The effects of such unusual flow upon heat transfer could be very serious in causing first-wall cooling nonuniformities or "hot spots."⁸ Since the flow paths and geometries are complex, it appears that the problem will require experimental study. Further, the effects of the pulsed field on coolant channel stresses needs further examination.

External Systems

These systems, consisting of the biological shield, the power conversion equipment and the tritium separation and barrier systems will not preclude the successful attainment of a fusion power plant. However, it will be necessary that these systems undergo some development to fulfill their function without excessive capital or operational costs. The tritium separation systems are in the early stage of feasibility demonstration and considerably more development is required. The problems with the power conversion system are similar to those for any other power plant except that the Theta-pinch is a pulsed heat source. These thermal pulses must be smoothed before reaching the steam turbine or other prime mover. Also, the niobium blanket and liquid-metal coolant may cause corrosion problems in the heat exchangers. Like all power-conversion machinery, higher temperatures are required for higher thermal efficiencies, and higher temperatures bring additional materials development problems.

Power Plant

The reference plant uses a conventional steam turbine energy conventional system. State and flow parameters are shown in Fig. 1.

Because of the pulsed nature of the plant, thermal inertia is used to maintain relatively steady steam conditions at the turbine inlet. During a three-sec cycle, the sodium temperature decays about 3°C . If smaller variations are required, increases in the sodium or lithium inventory can be made. Increases in the sodium inventory are preferable because the tritium concentration in the sodium is so very low (0.2 wppm).

The pulsed temperature rise during the burn portion of the cycle limits the allowable maximum power plant temperature. For instance, for a potassium turbine inlet temperature of 1000°C , the maximum first-wall temperature would be about 1350°C during the very short burn portion of the cycle. This wall temperature increment above coolant temperature is independent of

duty cycle time. Thus, a pulsed cycle (at least with long times between pulses) will result in higher (300°C for the reference plant) maximum wall temperatures for a fixed turbine inlet temperature.

The use of niobium structure and lithium coolant poses corrosion problems in the intermediate heat exchanger (see Fig. 1). In the RTPR, this problem has been mitigated by the use of bi-metal construction (Fig. 2) of the primary heat exchanger, but such construction may prove to be either impractical or expensive. If the steel barrier on the niobium is omitted or violated, it would be expected^{15,16} that mass transfer of carbon, nitrogen, and oxygen from the steel portions of the sodium loop via the sodium to the niobium would result in excessive oxidation, carburization, and nitriding of the niobium in contact with the sodium. Further, if stainless steel is used in contact with the lithium in the secondary heat exchanger, not only would excessive corrosion of the stainless steel occur, but carbon, oxygen, and nitrogen would be transported to the niobium in the blanket. This corrosion problem, as well as those involving impurities introduced during tritium removal will need extensive study.

Tritium Systems

In a breeder plant, one of the more important auxiliary systems is that which removes the tritium bred in the lithium blanket. In the reference plant, a molten salt contactor was suggested. Recent experiments at ANL¹⁷ indicate that adequate separation of LiT from lithium can be accomplished by contacting about 20 to 50% of the total lithium inventory with an equal volume of a molten lithium halide salt every hour. This leads to relatively small flow rates and contactor equipment. However, practical problems include the effect of small amounts of dissolved salt in the lithium on neutronics, and corrosion in the blanket, development of materials of construction for the contactor that are compatible with both lithium and the salt, and demonstration of methods for removing the tritium and other impurities, e.g. oxygen, carbon, nitrogen, etc., from the salt phase.

The separation of hydrogen isotopes from the residual ash, gas blanket, and plant purge gases, does not seem to be a severe problem. For the ash and gas blanket, cryogenic distillation is proposed but the number of stages required to adequately remove protium and helium from the reinjected fuel has not been accurately determined. The plant purge gas used to collect trace amounts of escaped tritium will be purified by the addition of oxygen or fluorine to the hydrogen isotopes and collected by desiccants or molecular sieves. Chemical reactions with such very low concentrations of hydrogen may require catalytic surfaces, hot filaments, etc., but the residual oxidizer must not be allowed to contact hot niobium surfaces.

Finally, barriers to tritium migration, both in high-temperature portions of the plant (blanket, heat exchangers), and for peripheral systems at room temperature, need to be investigated. Bonded metal composites, e.g. copper, aluminum, or gold interlayers and/or ceramic coating, appear viable for this task but more development is required.

CONCLUSIONS

The environmental effects of this conceptual design were evaluated and found to be little different from other electrical power plants in most regards. Exceptions include a very small release of tritium, a low-hazard isotope, and relatively large amounts of radioactive material which must be either stored on site for eventual reprocessing or permanently discarded. These radioactive materials are nonvolatile and should not pose a difficult disposal problem, although some of the material may remain radioactive for hundreds of years. Natural resources required to build and operate the reference plant are not excessive except perhaps in the case of niobium and beryllium. The accident, sabotage, etc., problems of the plant are very minimal and although accidents can be postulated which would be inconvenient and costly within the plant, the probability of sizable impact on the surroundings is so as to be incredible.

Major technological efforts will be required to refine and optimize the plant design. The need for very efficient and rapidly pulsed energy-storage systems and a composite insulator/metal first wall is most critical. Other development problems are foreseen for all of the systems, but many apparently viable and practical solutions are perceived. These later problems are of an economic and optimization nature. Even the requirements of the energy storage and composite first wall materials can be considerably alleviated by design alternatives.

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