SOME FEATURES OF THE IMPACT OF A FUSION
REACTOR POWER PLANT ON THE ENVIRONMENT

by

J. E. Draley and S. Greenberg

Argonne National Laboratory

November 1972

Paper to be presented at the Texas Symposium on
the Technology of Controlled Thermonuclear Fusion
Experiments and the Engineering Aspects of Fusion
Reactors, Austin, Texas, November 20-22, 1972, and
to be Published in the Proceedings.

—NOTICE—

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

44

SOME FEATURES OF THE IMPACT OF A FUSION
REACTOR POWER PLANT ON THE ENVIRONMENT

by J. E. Draley and S. Greenberg

Argonne National Laboratory

SUMMARY

Although the design of fusion reactor power plants has not progressed to the point where their future environmental impact can be estimated accurately, it is possible to make certain comparisons with current and expected future fission plants.

Excepting tritium, there will be no direct radioactive products of the power-producing fusion process. This assures the absence of large amounts of long-lived radioactive substances that can be dispersed by accident or sabotage. It also avoids the concentration of large-Curie amounts of fission products at fuel reprocessing plants, with the relatively high release rates now encountered and the risk of large accidental releases at future reprocessing plants, where routine releases are expected to be low.

There will be relatively large inventories of tritium, about 760 grams (7.3×10^6 Curies) used in the operation of one 470 MWe D-T reactor. An additional 1250 grams (1.2×10^7 Ci) might be stored on site to allow short-term operation during malfunctions of the tritium separation system. Reactors based on other fusion reactions, for example, the D-D reaction, will have lower but still sizable inventories of tritium due to its production in side reactions. It appears feasible to design and operate a plant so that tritium stored at the plant site will not be released in the maximum credible accident, in which the operating plant inventory is released over a three-day period, together with reaction products of the lithium and potassium. The maximum

tritium dose at a site boundary would be about 45 mrem at average meteorology, ranging up to about 13 rem for rare and unfavorable meteorological conditions.

During operation, some of the tritium will be released to the environment. For the 470 MWe D-T reactor, this amount is estimated to be 2.6 Curies per day. This can be compared with releases of 11 Ci/day for current PWR's and 0.13 Ci/day for BWR's, both augmented by some 34 Ci/day at fuel reprocessing plants. For the more desirable, but probably further-into-the-future D-D reactor, tritium release rates might be lower than for the D-T reactor by a factor of the order of several thousand. This estimate is based on the expected elimination of tritium from the blanket, but with its continued production in side reactions and a corresponding loss through the containment structure. The significance of the D-T plant tritium release can be assessed in terms of the calculated ensuing dose rate; the 2.6 Ci/day leads to a calculated maximum individual off-site dose of 0.17 mrem/yr. This can be compared with a natural background dose of about 130 mrem/yr and the proposed 10 CFR 50, Appendix I, standard for light water fission reactors of 5 mrem/yr.

The bombardment of structural materials by neutrons will produce long-lived radioactive waste products in fusion reactors. If the currently-favored niobium is used for containment and structure, the volume of activated material requiring long-term storage will be substantially in excess of that produced in fission plants where stainless steel is largely the material of construction. After 5 years or more decay, the amount of radionuclides will be about the same as in waste fission products. Widespread dispersal of the low vapor pressure metal by accident seems essentially impossible.

In other respects, the impacts of D-T fusion plants and fission plants on the environment will be about the same. If high-efficiency direct-conversion

fusion plants can be developed, they will offer the prospect of substantially reduced rates of environmental pollution from the release of heat and chemicals used in cooling systems.

I. INTRODUCTION

At a time when environmental pollution is in the forefront of public attention and when the impact on the environment of every proposed nuclear power station is carefully evaluated, it is evident that it too is an important factor in considering the development of fusion power systems. The organization and general style of this statement is patterned after current detailed environmental statements by the Atomic Energy Commission related to the proposed issuance of nuclear station construction or operating licenses. Recently, an independent study¹ of the radiological impact of fusion has been published. It is largely based on the same fusion reactor design as used in this study. This statement considers the release and inventory of tritium and population doses therefrom in more detail than has previously been published.

In a number of categories, the impact of fusion plants is deemed to be the same as for fission or fossil plants. For such cases, no effort has been made to repeat descriptions that already exist in readily available public documents. Instead, simple statements of the equality or the similarity are made, or the items are omitted.

It is not possible for this statement to be as complete or as accurate as are those characteristically issued for fission plants because of the lack of a completely designed fusion plant. The conceptual design recently developed by A. P. Fraas² includes many of the features required to examine environmental impact, and it is used here as the reference design. It is evident that at this early stage the design has not been optimized in terms of maximum probable technical feasibility, minimum cost, and minimum impact on the environment. The compromises between these sometimes conflicting objectives will require a continuing evaluation for some time to come. In addition to the Fraas design,

an alternate is considered briefly, in Section IV-F, to indicate some of the types of variations that are possible. More general consideration of the environmental impact of fusion power plants, i.e., variations in the effects due to the substantially different characteristics of the several types of reactor plants, is not attempted because of the lack of needed design information and because it would impede clear presentation in the document.

II. THE NEED FOR POWER

The various projections of the national needs for power in the future have shown areas of disagreement, but all have agreed that energy needs will increase substantially during the years that would be required to develop fusion power systems. For example, the projection in Figure II-1³ shows an increase in total resources consumed of about 176% by the year 2000 and 363% by 2020, as compared to the 1969 consumption. Since a considerable fraction of the increased energy will be meeting the need for additional electric power, it is appropriate to examine the potential impact on the environment of not-yet-developed fusion central power stations.

Fig. II-1 Projected energy consumption³

III. THE SITE

In order to consider the effect of a power plant on the environment, it will be necessary to identify the environment in some detail. Evidently the radiation burden on people, flora, and fauna depends on their densities in the vicinity of the plant and the effects on such things as recreational facilities depends on their existence in the environs. To facilitate such evaluations, two specific locations have been chosen: the Bailly and Oconee Nuclear Stations. In both cases, a preliminary or a final detailed statement on the environmental considerations is available for reference. These were chosen, in addition to their availability, because they represent reasonably typical locations for a site near a big city and one in an area with a relatively low density of population.

Bailly (Site 1) is on the shore of Lake Michigan on a 350-acre site about 30 miles southeast of downtown Chicago. The Illinois-Indiana boundary is about 21 miles due west; Gary, Indiana is about 12 miles to the WSW; Michigan City, Indiana is about 13 miles to the ENE; and the Indiana-Michigan boundary is about 18 miles ENE. Population (1970) within a 50-mile radius is 7.9 million.

Site (2), Oconee, is in Oconee County South Carolina within 25 miles of the boundaries of the states of North Carolina and Georgia. Here at the southern reach of Appalachia, the Piedmont Hills join the Blue Ridge mountains to form the Piedmont Crescent of South Carolina. The largest city within 100 miles is Knoxville, Tennessee, 97 miles NW, with a population (1970) of about 175,000 while the nearest urban center is Anderson, South Carolina, 21 miles away, with a 1970 population of about 28,000. In the 0-10 mile radius, there were about 53,000 people in 1969; in the 0-20 mile radius, there were about 126,000 people.

IV. THE PLANT

A. Station Description

A schematic layout of the reference Plant is shown in Figure IV-1. The toroidal reactor is located in an evacuated (10^{-3} torr) cylindrical cell 200 feet in diameter by 90 feet high. The potassium turbines, potassium heat exchanger-steam generators, steam turbines and condensers, electric generators, and tritium removal and recovery system are located outside the reactor cell. The vacuum and cryogenic systems are contained in a building beneath the reactor cell, equipped to treat the contaminated exhaust of the vacuum system.

The cooling water intake and discharge structures will be designed, as for other plants, to minimize fish entrainment and other environmental disturbances, according to the standards in effect at the time of detailed design. Similarly, the choice of once-through or a closed cooling cycle (with cooling towers or lakes, or spray ponds to dissipate the heat) will be made at the time of detailed design and for the location selected.

B. Reactor and Electric System

The Reference Plant uses a toroidal steady-state fusion reactor operating on the D-T cycle to produce 1000 MW of thermal power, converted to 560 MW gross or 470 MW net electrical power. A 16% recirculating power requirement was assigned to the gross output given by Fraas² in accord with the average reported by Persiani, et al.⁴ for Tokamak reactors. The plant size was thought by Fraas to be of little importance in an evaluation such as this, because of only minor scaleup factors.

Except for the amount required for start-up, the tritium fuel is bred in a molten lithium blanket, in which graphite is present as a moderator. Heat

*ELECTRIC GENERATOR IS ASSOCIATED WITH EACH TURBINE.

Fig. IV-1 Power conversion and tritium recovery systems for D-T fusion power plant

produced in the blanket is used to boil potassium for operation of a potassium turbine-generator. After expansion through the turbine, the potassium vapor is condensed in a potassium-to-water heat exchanger, producing steam for operation of conventional turbine generators.

For all high-temperature portions of the system, molten lithium or potassium is contained in a niobium alloy such as Nb-1% Zr. In cooler portions of the system, stainless steel is utilized. Stainless steel steam generator tubes are clad with tungsten to minimize tritium effusion.

Material inventories in the Reference Plant² are:

Lithium in blanket	4.6×10^5 kg
Graphite in blanket	1.1×10^6 kg
Niobium in lithium system	1.4×10^5 kg
Potassium	1.0×10^4 kg

C. Effluent Systems

1. Heat

At full power operation, approximately 440 MW is dissipated to cooling water. This is of the order of 30% less than the heat dumped from current fossil-fueled or fission plants of equivalent output, although the use of higher efficiency thermal conversion seems available as a design option to all types of power plants. The cooling water transfers its heat to the air via a cooling tower [Site (1)] or to a lake by once-through condenser cooling water flow [at Site (2)].

2. Radioactive Wastes

Tritium is produced as necessary fuel for the plant and perhaps for sale to other reactors. Two approaches are considered for minimizing the release of tritium to the environment.

In the approach suggested by Fraas,⁵ most of the tritium is removed by cold trapping the potassium, to which lithium is added to aid in tritide precipitation. As calculated by Fraas and associates, such a system would result in a leak rate to the environment of approximately 6 mg/day,⁶ (equivalent to 2100 Ci/yr), if the steam boiler tubes were coated with tungsten or an equivalent diffusion barrier.

The approach developed here involves the use of an as yet unspecified technique (e.g., a hot diffuser wall) to maintain the tritium concentration in the lithium at a low (1.0 ppm by weight) value. Cold-trapping is not considered an effective method of removal of tritium from lithium because the estimated solubility,* by extrapolation of higher temperature data,⁷ is about 200 ppm at 200°C (14° above the melting point). In contrast, the solubility of hydrogen in sodium at the EBR-II cold trap temperature (the EBR-II cold trap is run at about the lowest practicable temperature) is approximately 0.05 ppm (by weight); the hydrogen content of EBR-II primary sodium is often close to this value.

The concentration (1 ppm tritium in lithium) used in the alternate approach is based on the assumption that it will be the minimum practicable atom fraction, limited by flow-rate and other kinetic factors. The atom fraction corresponds to 0.1 ppm hydrogen in sodium, about the average value maintained in the EBR-II coolant.

The concentration of 1 ppm tritium in lithium is the basis of calculation of the effusion rates and it is assumed that the permeation of tritium through the niobium alloy lithium-to-potassium heat exchanger (potassium boiler) is rapid enough to equalize the tritium activity in the

---

*

Used here as the concentration of hydrogen at which the hydride (or tritide) precipitates.

potassium and in the lithium. Using published Sieverts Constants for tritium in lithium⁸ and hydrogen in potassium,⁹ and estimating Sieverts Constants for tritium in potassium from the latter, ** the partial pressure of tritium will be about 2.5×10^{-7} torr in the lithium and potassium at 1000°C and 1×10^{-8} torr in the potassium at the estimated steam generator temperature of 575°C. For the estimate, it is assumed that the tritium concentration in the potassium does not change in traversing the closed circuit. The assumption is not strictly true. Some potassium vapor escapes from the turbine and tritium concentrations in liquid and vapor are not equal.

Tritium that enters the potassium can escape to the atmosphere via two routes:

(1) Leakage from potassium turbine shaft seals and casing, and potassium piping. It is probably feasible to have at least some of these components in an enclosure which is maintained at a negative pressure to minimize the escape of tritium. However, in the calculation presented below, it will be assumed that no containment structures surround these high-temperature potassium-containing systems. Despite compromises made in the calculated approximations, the overall result is hoped to be realistic; a calculated discharge rate which is too high at one location will perhaps compensate for a failure to include other sites of leakage.

(2) Diffusion from potassium to steam through the tubes of the steam generator. Two cases will be considered, (i) stainless steel tubes, and (ii) tubes clad with 0.3 mm thick tungsten. Although techniques exist to trap at least some of the tritium that enters the steam system, it will be assumed here at all of it escapes from the plant.

***

The Sieverts Constants, with concentrations in atomic units, were estimated to be the same for all hydrogen isotopes. It was also assumed that Sieverts Constants for potassium are equal to those for NaK (78 wt%K, Ref. 6).

The gas that escapes from the fuel-ash recirculating system and lithium blanket is collected by the reactor building vacuum system and trapped as HTO. Perhaps 80% of the tritium fuel is unburned in multiple passes through the reactor. It is assumed there is no accidental release of any of this tritium from the recirculating system to the environment, on the basis that all handling will be done inside the reactor cell so that leakage will be recovered.

Rates of the major tritium leaks have been calculated and are summarized in Table IV-1. Partial pressures of tritium in potassium as a function of temperature were obtained by fitting the values given earlier to an Arrhenius plot. Permeation rates were calculated using the data of Draley, et al.^{10*}

The value of tungsten liners for steam generator tubes is clearly shown. A major loss of tritium can occur in a steam generator with stainless steel tubes, whereas it is less than that calculated for the potassium piping when tungsten-clad steam generator tubes are used.

Presumably the steam blowdown will be added to the circulating water discharge in a plant with once-through cooling, or to the blowdown from a closed-cycle cooling system. Thus the tritium discharges for the reference plant with tungsten-lined steam generator tubes are 0.58 Ci/day to the water, and the remainder, 2.07 Ci/day, to the atmosphere.

At an operating concentration of 1 ppm tritium in lithium, the tritium inventory is 460 grams (4.4×10^6 Ci) in the lithium and 0.06 gram

---

*

Rate of permeation of stainless steel or other alloy by tritium, cc(STP)/hr =

$$10^{3.0 - \frac{3571}{T}} \sqrt{\frac{P_T}{760 \times 3}} \times \frac{\text{Area (cm}^2\text{)}}{\text{Thick. (mm)}}$$

TABLE IV-1

TRITIUM RELEASES

Source	Temp. °C ^(a)	P _T , torr	Thickness, mm	Area, cm ² ^(c)	Release cm ³ /hr Ci/da	
Potassium Piping	788	6.3x10 ⁻⁸	10.3	3.1x10 ⁵	0.066	2.0
Potassium Turbine	788	6.3x10 ⁻⁸	10.3	3x10 ³	6.6x10 ⁻⁴	0.02
Steam Generator (Stainless steel)	593	1.2x10 ⁻⁸	2.4	3x10 ⁷	2.16	66.7
Steam Generator (Tungsten clad)	593	1.2x10 ⁻⁸	0.3(w)	3x10 ⁷	0.0187	0.58
Potassium cold trap	532	7.8x10 ⁻⁹	7.1	3.1x10 ⁴	2.9x10 ⁻⁴	0.009
Reactor Cell	27	5x10 ^{-4(b)}	6.35	7.54x10 ⁸	7.0x10 ⁻⁵	0.002

(a) Where a temperature gradient exists, the arithmetic average is used.

(b) It is assumed that the cell is evacuated to a total pressure of 10⁻³ torr and that half of this is tritium.

(c) Areas based on following assumptions:

Potassium Piping - 100 ft of 12 in. pipe

Potassium Turbine - 1% of Potassium piping

Steam Generator - Fraas design

Potassium Cold Trap - 10% of Potassium piping

Cell - Cylinder, 25 m high x 60 m diameter.

(~540 Ci) in the potassium. The inventory in the steam-water system was estimated as follows.

The water inventory was prorated from one of the Zion Nuclear units¹¹ as $311,000 \frac{338^{**}}{1129^{\dagger}} = 93,100$ gallons. At steady state conditions, the rate of entry of tritium into the system is 210.8 Ci/yr (Table IV-1), or 22.0 mg/yr. This is the sum of four separate losses: in the steam blowdown, by diffusion through the condenser to the cooling water, by leakage from the turbine, etc., and with the non-volatiles in the ejector exhaust.

If the concentration of tritium, in grams T per gram H₂O is C, the tritium loss in the blowdown is estimated to be 1.85×10^{12} C mg/yr, using a Zion¹¹ -prorated average blowdown rate of $3.1 \frac{338 \text{ MW}}{1129 \text{ MW}} = 0.93$ gal/min.

For the diffusion loss, it was assumed, conservatively, that the pressure driving diffusion through the stainless steel condenser tubes (1.24 mm thick) was the vapor pressure of water at the estimated average temperature of 23.5°C. The area was prorated from the area of the EBR-II condenser tubes ($1.5 \times 10^7 \frac{338 \text{ MW}}{20 \text{ MW}} = 2.51 \times 10^8 \text{ cm}^2$). The rate of loss calculated in this way was 560 C mg/yr.

Leakage was taken as an average of 40 lb/min,¹² leading to a tritium loss of 2.1×10^7 C mg/yr. In the ejector output, the tritium is in the form of HTO, where the total water is that required to saturate 15 cubic ft/min of air¹² at an assumed trap temperature of 20°C. These parameters led to an ejector loss of 8.0 C mg/yr.

The blowdown loss is seen to exceed all others by a factor of the order of 10^5 . At steady state conditions, the concentration of tritium in

---

**

The gross electrical power produced by the steam turbine-generator in the Reference Plant.

†

The gross electrical power produced by the turbine-generator of one Zion Unit.

the steam system was calculated to be $22.0/1.85 \times 10^{12} = 1.2 \times 10^{-11}$ gm/gm H_2O . The tritium inventory would then be 0.004 gm, or 40 Ci.

The inventory of tritium in the recovery, processing, and injection systems can only be estimated very roughly in the absence of designs for these systems. Fraas has assigned a value of 300 grams for this quantity.²

Tritium inventories during operation of the plant are summarized in Table IV-2. In addition to the 760 grams shown in the table, some tritium will be absorbed in structural materials. Fraas² estimates 21 grams in blanket niobium. In addition, tritium probably will be stored for times of malfunction of the removal or processing system, and perhaps for possible need at other plants. Although this amount might be variable, it seems unlikely that more than 10 days consumption at full power (1.25 kg) will be stored. Depending on the nature of the malfunction, this supply might allow injection of fuel, and hence operation, for up to 2 days with the fuel recycle plan expected to be used in the Plant. The nature of the storage cannot be specified at this time but a selected tritide seems logical as it would not be released in the event of an accident.

The lithium blanket will become contaminated as the result of neutron- and charged particle-induced processes and corrosion. Thus, it will be necessary to purify the lithium continuously, and both liquid and solid wastes will result.

The potassium will become contaminated as a result of corrosion and (n, α) , (n, n', α) , (n, p) , and $(n, 2p)$ reactions. Continuous purification of potassium (to insure proper operation of the turbine and facilitate maintenance) will collect radioactive liquid and solid waste products.

TABLE IV-2

OPERATIONAL TRITIUM INVENTORIES

	<u>Conc., ppm</u>	<u>Inventory</u>	
		<u>Grams</u>	<u>Curies</u>
Lithium	1	460	4.4×10^6
Potassium	.010	0.10	530
Water-steam	1.2×10^{-5}	.004	40
Recovery, processing and injection systems		<u>300</u>	<u>2.9×10^6</u>
TOTAL		760	7.3×10^6

It is probable that some reactor components will not last the life of the plant. The failed components, together with components at the end of plant life, will be the major source of solid waste. In addition to the vacuum wall and blanket and potassium circuit components, the components of the recirculating fuel reprocessing system will be contaminated by activated products swept from the reactor chamber.

3. Chemical, Sanitary, and Other Wastes

Generation and release of these wastes will be the same as for other thermal power plants, so no detail is provided here.

D. Transportation of Fuel and Radwaste

After startup, no radioactive fuel will be transported to the plant; deuterium and lithium will be required at rates of 83 and 290 gms/day, respectively. Product tritium will be shipped from the plant at a rate determined by plant capability and/or the expansion of the D-T cycle segment of the industry. Solid wastes will be shipped intermittently from the plant. The greatest amount of material is likely to be the niobium blanket structural material, shipped at an average of about 4800 kg/yr if a 30-year life is realized.

E. Alternate Reactor System

A reactor operating on the D-D cycle would be more attractive than one on the D-T cycle because of the plentiful supply of deuterium already in existence and because the rate of release of tritium (produced by coincident nuclear reactions) would be reduced by a factor of 10^3 to 10^4 . Much of the power from the alternative reactor is assumed to be produced through high efficiency direct conversion, using charged particles. Nevertheless, a significant amount of power will be produced thermally, as a result of the branch-chain production of neutrons, which generate heat in an energy-conversion blanket.

In addition to the greatly reduced rate of tritium discharge, the higher generating efficiency will lead to decreased rates of discharge of heat to the environment. Assuming a direct conversion efficiency of 90%, that 45% of the system energy is converted thermally (in the blanket) to electricity at an efficiency of 56%, and a fractional circulating power of 0.5, and assigning a 10% loss of the circulating power to the environment, 16% less energy will be liberated to the environment than by the Reference Plant.

V. ENVIRONMENTAL IMPACTS OF PLANT OPERATION

A. Land and Water Use and Biological Impact

Alterations in land and water use are the same as for fission reactor power plants except where increased power conversion efficiencies may reduce sizes of cooling towers and cooling water intake and effluent structures. The release of tritium will probably lead to the establishment of exclusion zones around operating plants not much different in size than those around fission plants.

In this section, we are concerned with nonradiological effects on living organisms other than man. The chief effect of the plant on terrestrial life occurs during the construction phase. This effect is identical for fusion and fission plants, and therefore is not detailed here.

Plant operation affects aquatic life by causing mechanical damage as water is pumped through condensers, by the heating of water in the vicinity of the plant, and by the discharge of chemicals. Qualitatively, the effects of both types of plants are similar. The Reference Plant discharges about 0.92 MW into the cooling water for each electrical MW sold. This compares with about 2.0 MW/MW for current fission plants and 1.2 MW/MW for current coal plants (the coal plant also discharges about 0.3 MW/MW into the air via the stack). A considerable reduction in the heat discharged via the cooling water is accomplished through the use of the potassium topping cycle. There is no known reason known why liquid metal coolants, high-temperature containment materials such as niobium, and the potassium topping cycle could not all be used in fission or coal plants. Technological advances will be required for their use in any plant.

The choice might ultimately be made as an optimized decision based on the cost and reliability of power on the one hand and the importance of conserving

fuel and reducing environmental impact on the other hand. Less than a 10% reduction in the rate of heat discharged to cooling water seems fairly claimable for the Reference over future contemporary fission plants.

With the assumption that its circulating power loss is to the air, and that its thermal conversion loss is to the air and cooling water in the same proportion as in the Reference Plant, the alternate direct conversion fusion plant will discharge 0.67 MW into the cooling water for each electrical MW sold. The 25% reduction in heat discharged might be accompanied by a corresponding reduction of water flow rate. The environmental damage to the natural water might therefore be reduced by the order of 25%.

B. Radiological Impact

1. Significance of Tritium Releases

Releases of tritium to the environment are not expected to raise tritium to critical levels in man or his food chains. Tritium appears in the environment in overwhelming dominance as tritiated water (HTO) and the dose to man from it is strongly dependent on the local hydrologic cycle. An atmospheric source of tritium may contaminate a local landscape either by direct wet deposition or by exchange of tritiated water molecules of the atmosphere with ordinary water of soils, plants, animals, and surface waters. Once contaminated, soils, plants, and animals may carry tritium to man through ordinary food chain pathways. An example of such a pathway is the soil-plant-cow-milk-man food chain. The total dose to man from such a pathway depends on the turnover rate of tritium in each of the links of the pathway. In general, the turnover rate in the pathway as a whole depends on that of the slowest component. Tritiated soil water has been found to have turnover times ranging from 24 days in the tropics to 1.7 years in the desert. In temperate zone systems, turnover time for soil water in the rooting zone of plants may vary from 30 to 120 days, depending on location, soil type, and season of the year. Intrinsic turnover rates of plants, animals, and man are much faster.

Tritium is considered to be a low hazard isotope because of its low beta energy ($E_{\text{ave}} = 5.7 \text{ Kev}$) and relatively short half residence time in man ($t_{1/2} = 8\text{-}10 \text{ days}$). When the longer food chain residence times are considered, the conclusion that tritium is a low hazard isotope is still valid. Anspaugh et al.¹³ have calculated an anticipated dose to man from all avenues of exposure including foods, inhalation, and skin absorption. They assumed a steady concentration of 10^3 pCi per cubic meter to air in their calculations and concluded that men living in such an environment and deriving their food from it would acquire an annual dose of 3.7 millirem/year.

The data of Anspaugh, et al. indicate that when ecological pathways to man are considered, approximately 40% of the total dose to man from tritium comes from inhalation and skin absorption and 60% comes from meat, milk, and vegetables. Because of the extremely localized nature of tritium contamination around point sources, it is highly unlikely that an appreciable amount of the food of local residents will come from the contaminated area. Thus, in most actual situations, the food chain pathway will be less significant in delivering a dose to man than is indicated by Anspaugh.

2. Comparison with Fission System Releases

Some perspective on the 2.0 Ci/day tritium discharged in the air and 0.58 Ci/day discharged in the cooling water by the Reference Plant can be gained by comparing these amounts with the tritium discharged from fission plants in recent years (Table V-1). Assuming an 85% plant factor, the pressurized water reactors in Table V-1 averaged a tritium emission of 11 Ci/day in 1970, normalized for a 470 MWe output, while the boiling water reactors averaged 0.13 Ci/day, normalized for 470 MWe (all to the water).

The Reference Plant therefore might discharge about 4 times as much tritium into cooling water (19 times as much, total) as 1970 BWR's, but only

TABLE V-1

TOTAL ANNUAL LIQUID TRITIUM DISCHARGES (CURIES)¹⁴

	<u>1968</u>	<u>1969</u>	<u>1970</u>
<u>PWR's</u>			
Shippingport (90 MW)	35.2	20.0	1.71
Yankee (175)	1170	1230	1400
Indian Point-1 (265)	787	1100	410
San Onofre (430)	2353	3530	4780
Conn. Yankee (590)	1740	5100	7370
Robert E. Ginna (420)		1.26	106
<u>BWR's</u>			
Dresden-1 (200)	2.9	6.0	5.0
Big Rock Point (70.3)	34	28	53.6
Humboldt Bay (68.5)	6.6	<5	<7
LaCrosse (50)			19.8
Nine Mile Point-1 (500)			10
Oyster Creek (530)		5.1	22.2
<u>HTGR</u>			
Peach Bottom-1 (40)		40	--

1/19 as much tritium into cooling waters (1/4 as much, total) as 1970 PWR's (which use boron in the primary coolant).

The major part of the tritium in spent fuel from fission power plants is released at reprocessing plants. The Midwest Fuel Reprocessing Plant will reprocess about a metric ton per day of spent fuel, and release about 580 Curies per day of tritium. This is equivalent to about 34 Curies per day per net 470 MWe fission plant output.* The reference fusion plant would evidently be a minor source of tritium to the environment by comparison.

3. Maximum Individual Doses

The routine operation of the Reference Plant will result in the release of tritium to the atmosphere and the condenser cooling water. These releases will correspond to environmental concentrations which are a fraction of the maximum allowable concentrations specified in 10 CFR 20 for waterborne and airborne tritium, namely 3×10^{-3} $\mu\text{Ci/cc}$ and 2×10^{-7} $\mu\text{Ci/cc}$, respectively. The radiation doses resulting from exposures to these effluents were estimated using models and data presented in Publication 2 of the International Commission on Radiological Protection (ICRP).

The expected waterborne tritium release of 0.58 Ci/d represents an annual release of 180 Ci assuming a plant factor of 0.85. If the liquid effluent is released to the condenser cooling water discharge of 225,000 gal/min (scaled from the Zion Nuclear Power Plant¹¹) the annual average tritium concentration in the discharge would be 4.0×10^{-7} $\mu\text{Ci/cc}$. This concentration represents an annual total body dose of 0.067 mrem to an individual whose total daily water intake (2.2l) comes from this source.

---

*

Calculated using data in Reference 14, and present fuel burnup practice in commercial light water reactors.

The expected airborne tritium release of 2 Ci/d represents an annual release of 620 Ci, assuming the above plant factor. The gaseous effluent will be dispersed by atmospheric diffusion and mixing as determined by the meteorology of the site. Typically for North America at a distance of about 600 meters from the release point one can expect a maximum χ/Q of about 2×10^{-6} sec/m³. χ/Q is the ratio of the airborne concentration $\left(\frac{\text{quantity}}{\text{m}^3}\right)$ at some location to the release rate $\left(\frac{\text{quantity}}{\text{sec}}\right)$. Assuming the above χ/Q value, the annual release of 620 Ci would result in an annual average airborne tritium concentration of about 4×10^{-11} $\mu\text{Ci/cc}$. This concentration represents an annual total body dose of 0.10 millirem to an individual continuously exposed.

The maximum combined dose would thus be 0.17 mrem/yr, about one-thirtieth of the 5 mrem/yr allowed for light water reactors in 10 CFR 50, Appendix I.

4. Population Doses

To permit an estimate on the radiological impact the Reference Plant was sited at two locations and the potential radiation doses to residents within a 50 mile radius of the plant evaluated using conservative parameters relative to the meteorology, hydrology, and water-land use factors for individuals within the populations. The annual integrated population dose estimates (man-rem), the product of the annual radiation dose and individuals at risk, serves as a measure of the radiological impact.

Site 1¹⁶ was selected as representative of sites using a lake as the receiving water and near a large metropolitan area (with a 50 mile population 7.9×10^6). About 5.8×10^6 individuals within a 50 mile radius of the site obtain their drinking water from various lake intakes. Using the steady state diffusion model of A. Okubo¹⁷ the annual integrated population dose for the various intakes was computed to total 4.4 man-rem. The annual integrated population dose resulting from exposure to airborne tritium was computed, using an atmospheric diffusion model and the annual average site

meteorology, to be 0.28 man-rem. The combined annual integrated population doses from the above pathways is about 4.7 man-rem. For comparison, the natural background of 125 mrem/yr would result in an annual integrated population dose of about 990,000 man-rem to the 50 mile radius residents of Site 1.

Site 2¹⁸ represents a rural area (50 mile population 730,000 utilizing a river as the receiving water. Within fifty miles downstream of the site about 25,000 individuals derived their drinking water from the river. The annual integrated population dose to these individuals was computed to be 0.16 man-rem, based on an expected average river dilution of 10. The annual integrated population dose as the result of airborne tritium was computed to be 0.23 man rem. The combined annual integrated population doses from the above pathways is about 0.39 man-rem. For comparison, the natural background of 125 mrem/yr results in an annual integrated population dose of about 91000 man-rem to the 50 mile residents of Site 2.

The combined annual integrated population doses from exposure to the gaseous and liquid effluents of the plant at either sites are very small compared to the man-rem the population receives each year from the natural radiation background. Hence, no discernible radiological impact on individuals and the population is expected from normal operation of the Reference Plant.

5. Radiation Dose to Other Species

Since almost no living organisms are known to concentrate tritium¹⁹ and the specific activity is low, no species is likely to receive a dose known to have measurable effect.

C. Accidents

Typical environmental impact statements say little about large-scale accidental releases because these are handled separately in a safety analysis

report. In the present case, we shall examine the accident situation briefly because a rigorous accident analysis is not available.

1. Plant

Five separate accidental events are considered from the point of view of their effect on the plant and the resulting possible damage to the environment (and those living in it). No large-scale uncontrolled nuclear reaction is possible because of the limited amount of fuel present in the plasma (2 grams for the Reference Plant). For the same reason, there is relatively little radioactive fuel or fuel-related material available for dispersal in the event of a severe accidental release.

(a) An increase in magnet current due to faulty control would lead to some increase in magnetic field. The limit might be set by the temperature-field combination at which the magnet loses superconductivity (in which case, see next event). The increased magnetic field would compress the plasma ($n_1 \propto B^2$) and thus increase the specific reaction rate ($\text{Rate} \propto n_1^2$ or B^4).²⁰ Because of the reduced plasma volume, the total power would increase directly with the ion density, rather than with its square. The result might be severe damage to the reactor containment vessel and an increase in the blanket temperature. The magnitude of the damage from such a temperature surge can be estimated by observing that the adiabatic addition of half of the energy contained in 2 grams of fuel would increase the total blanket temperature by a calculated 100°C.

(b) If by loss of refrigerant or otherwise, the main magnet winding quickly lost its superconductivity, a large quantity of stored electrical energy (~330 MJ) might be released quickly. We have been told²¹ that through

judicious magnet and circuit design the rate of energy release can be limited so that serious explosive effects are prevented. Presumably the demonstration of this design will ultimately be required.

(c) If due to a malfunction, the rate of fuel injection is increased, there is no certain prediction of the result. At an injection temperature (20 keV) close to that of the plasma, it is perhaps most likely that increased reaction rates at injection points will lead to the so-called universal plasma instability due to the inhomogeneity before the excess energy leads to a significant effect. A more certain prediction will be required in the future. An accidental change in fuel composition would lead to a reduction in the rate of power production, since the 50-50 ratio is optimized for reactivity.

(d) A potassium to water/steam heat exchanger poses a special hazard.

In the worst case, a rupture of the heat exchanger would allow a massive injection of water and/or steam into the hot liquid and/or gaseous metal. This would lead to a rapid reaction, producing hydrogen gas and solid corrosion products (probably a mixture of potassium oxide, hydroxide, and hydride, judging from experience with the analogous sodium-water reaction). The most harmful potential effects are pressure surges, which upon contact with air would bring about hydrogen explosions. Loss of system security could lead to large-scale fires and release of the tritium contained in the blanket.

It is unlikely that all of the hot alkali metal(s) would react quickly because of the protective effects of the reaction products. In fact, the products could lead to a loss of coolant situation by blocking the coolant flow channels in or about the heat exchanger.

Small leaks in the heat exchanger can be expected to grow considerably larger, either by the rapid formation of new small holes in contiguous surfaces from jet impingement of reacting species, or by the slower formation of larger

corroded-through areas downstream of a seepage-type leak. In the former case, the new hole(s) would be small; in the latter case, some hours of warning would probably precede a massive reaction.

(e) Accidental loss of coolant flow, leading to brief continued heating at full power before shutdown would probably be less serious than the results calculated in (a), since almost 12 minutes full power operation would be required to burn 1 gram of fuel. The afterheat removal problem has been judged by Steiner and Fraas¹ to pose no serious hazard.

In the Reference Plant, the inventory of tritium dissolved in the lithium and potassium is 4.4×10^6 Ci. The inventory in the steam system is small (40 Ci); that in the recovery, processing, and injection systems is substantial at 2.9×10^6 Ci. Possibly an additional 10 days fuel supply (1250 grams or 1.2×10^7 Ci) will be in storage. It is assumed that the storage area will be sufficiently isolated and so designed that no substantial part of its contents could be discharged quickly to the environment by any conceivable accident.

The maximum credible accident is the release to the air, in a short time, of the order of minutes, of all the lithium, all the potassium, and all the tritium in actual service. Liquid metal fires are assumed, with the release of mixtures of nitrides, oxides, hydroxides, and hydrides of the liquid metals. For the sake of estimating the effect on the environment, it is assumed that the hot alkali metals will react (burn) at a constant rate with air and available moisture for a period of three days, thus producing reaction products containing 4.6×10^5 kg Li and 1.0×10^4 kg K. Although some of the discharged tritium would probably remain in the solid alkali metal reaction products dispersed by the fire, calculation of the result of the

accident is on the basis that the entire 7.3×10^6 Ci would be dispersed as gaseous HT or HTO.

Under rare and unfavorable meteorological conditions (e.g., a dead calm, of high stability, with a low inversion ceiling) this sort of accidental release of 7.3×10^6 Ci would lead to a dose at the 600-meter boundary of about 13 rem. This is well below the present 10CFR100 limit of 300 rem whole-body dose. And, of course, the probability of the accident occurring exactly during such a rare period of meteorological calm is negligibly small. With average meteorology the maximum dose at the boundary would only be about 45 millirem, i.e., about one-third of the annual background.

Another perspective on the matter can be gained from consideration of the present and anticipated ^3H releases from LWR-fuel reprocessing plants. Barnwell,²² for example, will release about 1×10^6 Ci/yr, i.e., the total dose* from normal operating releases there will equal that from the above Reference Plant accident, in somewhat above 7 years of normal operation.

As to dispersion into the environment, ^3H effective lifetimes range from about 3 to 6 years in North American watersheds. Taking the Mississippi basin as representative, a release of 7.3×10^6 Ci would add to the 3×10^5 Ci already present to raise the ^3H concentration from its present level of 300 pCi/L to about 7600 pCi/L in the first few months. However, this would decay with an effective half-life of about 5 years so that it would have dropped to about 330 pCi/L in 40 years. By contrast, the normal operation of MFRP ($\sim 200,000$ Ci/yr¹⁵) will have raised the level of ^3H in this basin to about 6000 pCi/L by the end of its 40 year expected operating lifetime.

---

*Note that doses are cumulative under ICRP rules, i.e., there is no dose rate effect.

VI. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES

The resources committed in construction and operation of the Plant are the same as those required for any large industrial facility with the exception of the deuterium and lithium. The deuterium supply is practically inexhaustible in terms of proposed uses. The known land-based lithium supply appears to be adequate for several thousand years of large-scale power production using the D-T cycle;²⁴ Gough and Eastlund²⁵ estimate many millions of years based on ocean reserves. Since there is little use of lithium in the present economy, no adverse effect is likely to result from large-scale diversion of the available lithium for power production. The use of niobium in plants such as the Reference Plant would not tax the anticipated supply of that metal.⁶

VII. SHORT-TERM USES AND LONG-TERM PRODUCTIVITY

In comparison with the long-term history of the sites and their environs, the expected useful life of the plant can be considered short-term. At the end of its useful life, it may be decided to dismantle the plant and restore the site as nearly as practicable to its pre-plant state. In this case, the effect of plant operation and construction will be comparable to a fission reactor. The absence of uranium, plutonium, and fission products may make it simpler (and cheaper) to accomplish the restoration. It seems more likely, however, that increased demands for power and resultant scarcity of suitable sites will result in continued use of the site for power generation.

VIII. COMPARISON WITH ALTERNATIVE POWER SOURCES

The major differences in environmental impact of the fusion reactor plant as compared to fission plants are: (1) the absence of fission products that can lead to the release of radionuclides on a continuous basis and that require fuel reprocessing plants where fission products are concentrated; (2) the presence of a greater amount of radioactivity in the form of activated structural material (assuming niobium blanket structures); and (3) rates of tritium release intermediate between those for current PWR's and BWR's. (It does not seem possible to claim for fusion reactors especially effective methods of reducing the rate of outleakage of tritium without allowing the use of the same methods in fission plants.)

Natural disasters, e.g., earthquakes, tornadoes, etc., cannot cause the release of fission products from fusion plants, and the fuel is not present in sufficient quantity to cause dispersion of plant components. The major effects of the maximum credible accident for the Reference Plant are large-scale tritium contamination and large-scale alkali-metal contamination.

The relationship between the problems in containing or storing the radioactive products of fusion and fission power plants is shown in Figure VIII-1. The activities of radioactive wastes are shown as a function of time after the retirement of the two fission plants and the two most important radioisotopes from the reference fusion plant, metastable Nb-93 and tritium. Bands have been used to indicate a basic uncertainty in the inventories of these substances. For only the first few years the fission products are present at higher (activity) levels than the fusion plant structural materials. Subsequently, the levels are about equal. Careful analyses of this sort that have been done in the past have shown that after long periods of times, when levels are low, the total

Fig. VIII-1 Activity of high level waste as a function of time for fission and fusion reactors

activity is characteristically provided by impurities. These have not been estimated for the fusion plant; it is believed that they would lead to a reduction in the rate of decline of the total radionuclides at long times and low activity levels. If a structural material with little induced activity were used in the Reference Plant instead of niobium, a substantial reduction in the need to store long-lived radioactive material would be affected.

Individual and population doses for fission and fusion reactors, normalized to a net electrical output of 470 MW, are given in Table VIII-1. The data for the fission reactors are taken from the environmental statements for fission plants at Sites (1) and (2). For the Reference Plant, doses were calculated as described in V-B. In all cases, the total radiation doses from the Reference Fusion Plant are considerably below those from the fission plants.

Table VIII-1

COMPARISON OF INDIVIDUAL AND POPULATION DOSAGE, PER 470 MWe

Plant	Dose to an Individual mrem/yr	Dose to Population (50-mile radius) man-rem/yr	
		Site 1	Site 2
Reference Fusion	0.17	4.7	0.39
Fission - Site (1) (BWR)	5.5	10.1	
Fission - Site (2) (PWR)	21.5	22.8	

IX. ACKNOWLEDGEMENT

This document could not have been written without helpful discussions or more substantial contributions from a number of people in Argonne's CTR Study Group and Environmental Statement Project. Among those especially helpful were V. A. Maroni, P. J. Persiani, J. R. Kline, K. Eckerman, and N. A. Frigerio.

REFERENCES

1. D. Steiner and A. P. Fraas, "Preliminary Observations on the Radiological Implications of Fusion Power," Nuclear Safety, 13, No. 5, pp. 353-362 (1972).
2. A. P. Fraas, "Conceptual Design of the Blanket and Shield Region of a Full Scale Toroidal Fusion Reactor," ORNL-TM-3096, to be published.
3. AET-8, "Reference Energy Systems and Resource Data for Use in the Assessment of Energy Technologies," Associated Universities, Inc., April 1972.
4. P. J. Persiani, W. C. Lipinski, and A. J. Hatch, "Some Comments on the Power Balance Parameters Q and c as Measures of Performance for Fusion Power Reactors," ANL-7932 (Argonne National Laboratory Report), June 1972.
5. A. P. Fraas, "Comparison of Two Tritium Removal Systems Designed to Minimize Contamination of Steam Systems in Full-Scale Thermonuclear Power Plants," ORNL-TM-2932, April 1970.
6. A. P. Fraas, et al., "Appraisal of the Potential Environmental Impact of Controlled Thermonuclear Reactors," June 1972 (unpublished report).
7. Charles E. Messer, et al., J. Phys. Chem., 62, 220 (1958).
8. V. A. Maroni, "Some Estimates of Tritium Permeation Rates in the Core of a D-T-Fueled Fusion Reactor," ANL-7948, June 1972.
9. E. T. Compere, et al., SNAP-8 Corrosion Program Summary Report, ORNL-3898, December 1965.
10. J. E. Draley, B. R. T. Frost, D. M. Gruen, M. Kaminsky, and V. A. Maroni, "An Assessment of Some Materials Problems for Fusion Reactors," 1971 Intersociety Energy Conversion Engineering Conference, SAE P-38, pp. 1065-1075.

11. Zion Station Final Safety Analysis Report, Vol. VIII, p. Q11.7-2, Commonwealth Edison Company, Amendment 15, September 1971, AEC Docket Nos. 50-295 and 50-304.
12. N. A. Frigerio, ANL, personal communication.
13. L. R. Anspaugh, J. J. Koranda, W. L. Robison and J. R. Martin, The Dose to Man Via Food-Chain Transfer Resulting from Exposure to Tritiated Water Vapor, In Press, Tritium Symposium, Las Vegas, Nevada, August 30 - September 2, 1971, Spons. Western Environmental Research Lab. of EPA and University of Nevada, Las Vegas.
14. ORP/SID 71-1, Radioactive Waste Discharges from Nuclear Power Facilities, October 1971.
15. Applicant's Environmental Report for Midwest Fuel Recovery Plant, Morris, Illinois, the General Electric Company, June 1971, AEC Docket No. 50-268.
16. Draft Detailed Statement on Environmental Considerations by the Division of Radiological and Environmental Protection, USAEC, Related to the Proposed Issuance of a Construction Permit to the Northern Indiana Public Service Company for the Bailly Generating Station Nuclear-1 (Docket No. 50-357), January 1972.
17. A. Okubo, "Review of Theoretical Models of Turbulent Diffusion in the Sea," TID-17342 (1966).
18. Final Environmental Statement on the Environmental Considerations by the USAEC Division of Radiological and Environmental Protection Related to the Proposed Issuance of an Operating License to the Duke Power Company for the Oconee Nuclear Station, Unit 1, Docket No. 50-269, March 1972.

19. J. E. Elwood, Ecological Aspects of Tritium Behavior in the Environment, Nucl. Safety, 12, 326-337 (1971).
20. See for example, D. J. Rose, ORNL-TM-2204, On the Feasibility of Power by Nuclear Fusion, Oak Ridge National Laboratory, May 1968.
21. C. Laverick, ANL, private communication.
22. J. L. Russell, A Review of the Actual and Projected Off-Site Doses at Fuel Reprocessing Plants, Paper in 17th Ann. Meet. Health Phy. Soc., June 1972, to be published.
23. L. W. Jones, "Liquid Hydrogen as a Fuel for the Future," Science, 174, 367-370 (1971).
24. E. J. Cairns, F. A. Cafasso, and V. A. Maroni, A Review of the Chemistry, Physics, and Thermal Properties of Lithium that are Related to Its Use in Fusion Reactors, in The Chemistry of Fusion Technology, D. M. Gruen, Ed., Plenum Press, N. Y., 1972.
25. W. C. Gough and B. J. Eastlund, "The Prospect of Fusion Power," Scientific American, 224, 50-64 (1971).