Health Physics Aspects of Fusion Power

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ABSTRACT

Fusion reactor technology is presently in conceptual and early developmental stages. Concomitant with hardware development, potential health and environmental impacts must be evaluated. This evaluation is necessary to ensure that technologists have pertinent information available such that adequate consideration is given to health and environmental problems. Problem areas attendant to tritium, activation products, and magnetic fields associated with fusion reactor systems are discussed.

INTRODUCTION

Major efforts are under way to use fusion reactors to produce electrical power. As these reactors are developed, sufficient awareness must also be developed of health and environmental problems likely to be encountered. Design of fusion reactors has not yet progressed to a point where these impacts can be estimated accurately; however, anticipated problem areas can be identified.

Considerations emphasizing the need for beginning the evaluation of potential problem areas at this time are that technologists need to have guidelines established to serve as a basis for design criteria. Also, prior to construction of a controlled thermonuclear reactor (CTR), the preparation of an Environmental Statement (ES) will require a compilation of site-specific information and an understanding of the technological operations of the facility to assess health and environmental effects.

Most of the assessment techniques developed to evaluate environmental impacts for fission reactors are also applicable to fusion reactors. The major differences of fusion reactors compared with fission reactors are:

1. the absence of volatile fission products and transuranic elements;
2. a greater amount of neutron-induced radioactivity in the form of activated structural material;
3. larger tritium inventories and potentially greater amounts of tritium released; and

4. high magnetic fields when magnetic
confinement is used.

Numerous articles have discussed health and environmental aspects of fusion power. For the most part, these have been written by workers closely associated with either basic research and development of fusion systems or the conceptual engineering design of CTRs. This paper presents an up-to-date picture of the health physics problems associated with tritium, activation products, and magnetic fields attendant to CTR systems.

APPROACHES TO FUSION POWER

Break-even fusion power conditions, as defined by the Lawson criterion,¹ involve containing a plasma of positive ions at a temperature of approximately 10^8 °K (10 keV) with a product of ion density and confinement time of about 10^{14} sec/cm³. Two different approaches are being studied to attain these necessary conditions.¹⁻³ The first of these involves an inertial confinement scheme in which the reactants are maintained in a pinhead-sized pellet and elevated to fusion temperatures by irradiation with lasers. In this scheme, the pellet is heated so quickly that a significant fraction of the fuel burns before thermal disassembly of the pellet terminates the reaction; the heating will require the use of lasers more powerful than any now existing. A second approach uses magnetic confinement to contain the plasma reactants while they are heated to temperatures necessary to sustain a fusion reaction. The magnetic field approach is then divided into two general classes on the basis of the configuration of the containment field: the magnetic mirror systems (e.g., Yin-Yang),⁴ and the toroidal systems (e.g., theta-pinch and tokamak).⁵⁻⁷

The United States, Europe (under Euratom), Japan, and the Soviet Union sponsor the major programs aimed at the commercial development of fusion power. The long-range magnetic confinement plans of these countries as of 1975 are shown in Fig. 1.⁸ Recently, suggestions to revise the U.S. magnetic confinement program have emerged due to scheduling difficulties.⁹ These suggestions include cancelling the

Fig. 1. Major world fusion plans.

Experimental Power Reactor I (EPR-I) and upgrading the present Tokamak Fusion Test Reactor (TFTR) facility to demonstrate the generation of tens of MW(e) that was originally envisioned for EPR-I. Results from studies of plasma physics obtained at the Technology Test Assembly with Plasma (TTAP) and results from an intense radiation damage facility are incorporated into the design of an experimental power reactor, scheduled to be built by 1990. A fusion demonstration plant is planned for operation by the late 1990s.

At present, the United States and Germany are the only countries giving major emphasis to designs for laser-driven CTRs. The development within the United States formerly came through Energy Research and Development Administration's (ERDA's) Division of Military Applications, and until recently, little public information was available. The new ERDA Division of Laser Fusion now controls the development of laser fusion. A recent Federal classification guide governing information on laser pellet implosion processes has resulted in declassification of almost all information on laser fusion physics relevant to power generation and related experiments. The timetable for laser CTR power generation is not significantly different from the magnetic confinement program.

At present, there is uncertainty as to which reactor concept will be used to demonstrate fusion power production commercially. However, there is general agreement that the first generation CTRs will use deuterium and tritium as fuels in the reaction:

The threshold fuel (plasma) temperature for break-even with reaction (1) is approximately 10 keV. This reaction has a substantially higher potential for ignition and a lower threshold temperature than other fusion reactions, which require temperatures greater than 50 keV. Deuterium is easily obtained from ordinary water, but tritium is present in nature only in minute quantities. However, difficulty in obtaining tritium can be overcome by breeding it from lithium; the neutron capture reactions are:¹⁰

This can be accomplished in the CTR by using a lithium blanket surrounding the plasma.

Some of the major components of a toroidal reactor can be seen in Fig. 2, where a cross-sectional view of the University of Wisconsin Tokamak I (UWMAK-I) torus is presented.¹¹ An artist's rendition of the UWMAK-I conceptual CTR power plant is presented in Fig. 3.¹¹ Only the principal features are included in these figures, so this reference design is only one of a series and serves as a basis for design calculations.

ORNL-DWG 76-9803

Fig. 2. Cross-section view of UWMAK-I fusion reactor.

1. PLASMA	6. Li PRIMARY SYSTEM (ONE FOR EACH OF 12 MODULES)	11. HOT CELL REPAIR AREA
2. TOROIDAL FIELD COIL (12)	7. Na SECONDARY SYSTEM (ONE FOR EACH OF 12 MODULES)	12. MAGNET SHIELD
3. RETRACTABLE DIVERTOR COIL (18)	8. DIVERTOR Li PRIMARY SYSTEM	13. BLANKET
4. TRANSFORMER COIL (10)	9. DIVERTOR Na SECONDARY SYSTEM	14. DIVERTOR COLLECTION AREA
5. EVACUATED PRIMARY CONTAINMENT BUILDING	10. TURBINE-GENERATOR BUILDING	15. MOTORIZED MODULE SUPPORT VEHICLE
		16. AUXILIARY EQUIPMENT AREA

Fig. 3. UWMAK-I power plant building.

TRITIUM

Radiological and Biological Aspects of Tritium

Tritium decays by beta emission to ^3He , with a half-life of 12.3 years. The beta particle, which has a maximum energy of 18 keV, is nonpenetrating (range in tissue is approximately 0.1 mm). For this reason, the external radiation hazard to man from tritium is negligible. The maximum permissible body burden is 1 mCi, and the average biological half-life for ingested tritiated water is 9.5 days.¹² The maximum permissible concentration in air $[(\text{MPC})_a]$ for tritiated water vapor is $5 \times 10^{-6} \mu\text{Ci}/\text{cm}^3$; the $(\text{MPC})_a$ for tritium gas is 400 times greater.

Retention of tritium is dependent on the chemical form in which it enters the body. In addition to ingestion, tritiated water vapor can enter the body easily through the skin, and almost 100% of the tritiated water inhaled into the lungs diffuses into the bloodstream. Since tritium mixes rapidly with body fluids, the whole body is irradiated. In contrast, intake of elemental tritium (gas) through dry skin is negligible, and when inhaled, only 1.6% is absorbed into the bloodstream, with the remainder being exhaled.¹³ According to Pinson and Langham,¹⁴ after inhalation of HT and HTO, equivalent rates of tritium appearance in the body fluids of man occurred when the specific activity of HT in air was about 15,000 times greater than that of the HTO.

Tritium Inventories for Fusion Reactors

Large quantities of tritium will be present in various parts of a CTR, including the fuel storage and processing system, the fuel injection system, the plasma recovery system, and the breeding blanket and reprocessing systems. For a 470-MW(e) tokamak plant,¹⁵ the operational inventory of tritium is estimated to total 760 g, corresponding to 7.3×10^6 Ci (1 g = 9600 Ci). Estimates of tritium inventories for several subsystems, requiring potassium as the coolant used to remove heat from a lithium blanket, are listed in Table 1. In addition to the operational inventory, the reactor will contain up to 10 kg per 1000 MW(e) of tritium in storage. Tritium inventories for various reactor designs are presented in Table 2.¹⁶

An important aspect of tritium fuel is that only the initial fuel charge will be transported to the CTR plant. Subsequent tritium fuel will be produced and handled in a closed cycle at the power plant. After startup, only the nonradioactive materials, that is, deuterium and lithium, are required to continue the supply of fuel for the plant.

Tritium permeates heated metal walls rapidly and can diffuse from the blanket-coolant system by three routes: (1) from the blanket into the plasma vacuum chamber (a recovery system will collect this tritium and recycle it as fuel); (2) outward through all reactor materials into the reactor hall; and (3) from the coolant system into the steam system. In some designs, the main source of tritium contamination in the working environment will be the leakage of tritium from coolants (potassium) through turbine shaft seals and casings and from the

Table 1. Operational tritium inventories for a 470-MW(e) reactor

Source	Concentration (ppm)	Inventory	
		Grams	Curies
Lithium	1	460	4.4×10^6
Potassium	0.010	0.10	960
Water-steam	1.2×10^{-5}	0.004	48
Recovery, processing, and injection sys- tems		<u>300</u>	<u>2.9×10^6</u>
Total		<u>760</u>	<u>7.3×10^6</u>

Table 2. Tritium inventories

Reactor design	Net power [MW(e)]	Tritium inventory in blanket and coolant (Ci)	Tritium inventory plant (Ci)
<u>Tokamaks</u>			
ORNL ^a	520	3.8×10^6	5.8×10^7
PPPL ^b	2000	3.8×10^6 ^c	5.4×10^7
UWMAK-I ^d	1500	3.8×10^7	$9.4 - 14 \times 10^7$
Theta-Pinch ^e	4100 ^f	9.3×10^6	5.7×10^7
Mirror (Yin-Yang) ^g	200	9.6×10^6	1.9×10^7

^aOak Ridge National Laboratory (ORNL) reference design.

^bPrinceton Plasma Physics Laboratory (PPPL) reference design.

^cIn salt processing system.

^dUniversity of Wisconsin Tokamak (UWMAK) reference design.

^eArgonne National Laboratory-Los Alamos Scientific Laboratory Theta-Pinch reactor reference design.

^fDepends on duty cycle; therefore, can be lowered or varied.

^gLawrence Livermore Laboratory Fusion reference reactor design.

pipng for the coolant. Successful containment of tritium will likely require that most of these components be enclosed within a second containment, which would be maintained under an inert atmosphere or at a negative pressure to minimize any tritium escape. Almost all of the tritium diffusing into the steam system will be oxidized, and small amounts of the tritiated water will be lost to the environment.

Surface Contamination

The adsorption of tritium onto the reactor structural materials will present a complex contamination problem in fusion reactors; tritium will diffuse into and contaminate all surfaces. Fraas¹⁷ has estimated that the niobium inner structure for a fusion reactor alone will absorb approximately 21 g (2.0×10^5 Ci) of tritium. Since it is unlikely that all maintenance and disassembly operations can be accomplished remotely, the contaminated surfaces may be a source of occupational exposure. Decontamination efforts will be complicated because tritium permeated into surfaces cannot be removed as easily as most particulate contaminants.

Tritium Instrumentation

Due to its low beta energy, the detection of tritium is difficult, especially in the presence of other radionuclides and radiation fields. Tritium-monitoring systems for the nuclear fission industry are being improved continuously, and these systems will be applicable to the monitoring programs at thermonuclear reactors. Ionization monitors with gamma compensation¹⁸ and scintillation counters¹⁹ have been developed to assay tritium in air, and plastic and liquid scintillator systems²⁰⁻²² are available to measure tritium

in flowing water. Tritium gas and tritiated water vapor are distinguished by the application of water-bubbler, silica-gel, or freeze-out techniques;¹³ however, for low tritium concentrations these procedures may require periods of an hour to a day for collection and analysis. The most common approach for the detection of surface contamination is the smear test. A modified proportional counter²³ has also been developed to monitor surface contamination.

Sophisticated bioassay techniques will be required at all CTR installations. An automatic HTO-in-urine analyzer with a sensitivity of 1 $\mu\text{Ci/liter}$ has been developed at the Chalk River Laboratory.²⁴ This system includes a urinal attached to a liquid scintillation analyzer. Samples are metered automatically, and the HTO activity is measured and recorded in about 2 min. Although use of this system represents an ex-post-facto method for monitoring tritium intakes, it is the most useful method available for monitoring tritium exposures. In addition, this technique will also function as a sensitive indicator of changes in the tritium air concentration in the occupational environment.

A survey of tritium instrumentation²⁵ has revealed that little additional research will be required for CTR application. Most of the improvements needed are for portable instruments. For example, a real-time portable monitoring system to detect levels of tritium near the $(\text{MPC})_a$ in the presence of air activation products is needed in addition to a reliable portable instrument to indicate, on a real-time basis, whether tritium is in the elemental or oxidized form. Finally,

the effects that magnetic fields will have on all instrumentation requires documentation.

Protective Clothing

Clothing for protection against tritium will be required in much of the reactor environment during normal operation. Double containment and the maintenance of low tritium inventories in all but the storage facilities will help insure low atmospheric tritium levels in the working environment, and presently-available clothing will be adequate for most situations that may occur. A glove of 0.36-mm neoprene can offer a protection factor up to 340.¹³ At present, polyvinyl chloride appears to be the most popular material for plastic suits; a "sandwich suit," consisting of a pair of wet cotton overalls (50 mg/cm²) sandwiched between two plastic suits, provides the greatest protection. The protection factor²⁶ for this suit when exposed to HTO was measured to be greater than 1900. However, additional protective clothing research is needed to develop a membrane that is less permeable to tritium oxide than polyvinyl chloride but will still give the worker mobility and comfort. Several factors point to the importance of continuing development in protective clothing: (1) recent discussion within radiation control organizations about lowering occupational exposure limits; (2) the requirement that a CTR plant have a high degree of operational reliability, necessitating maintenance during operation under potentially adverse conditions; (3) the provision of economically based alternatives to multiple containment schemes; and (4) the necessity of having adequate protection for accident response.

Tritium Releases to the Environment

Due to the permeation characteristics, tritium will escape from the structural containment into the environment. Draley and Greenberg¹⁵ have calculated expected tritium releases for a 470-MW(e) tokamak fusion reactor (see Table 3). The efficacy of lining steam generator tubes with tungsten as a tritium barrier is illustrated in this table. For this system, only 2.6 Ci of tritium are predicted to be released to the environment daily. This level is compared to releases of 11 Ci/day for current pressurized-water reactors (PWRs) and 0.13 Ci/day for boiling-water reactors (BWRs),¹⁵ both normalized for a 470-MW(e) output. In addition, both PWRs and BWRs are augmented by some 34 Ci/day at fuel reprocessing plants per net 470 MW(e) of fission plant output.¹⁵

For the Princeton Plasma Physics Laboratory (PPPL) reference design, a loss rate of about 7 Ci/day is calculated.¹⁶ However, in this design, a copper barrier is used in the heat exchanger tubes to keep tritium loss down to this level; without the copper barrier, the leakage would be about 20 Ci/day.¹⁶ The estimated tritium release from the Yin-Yang mirror design is 0.2 Ci/day;¹⁶ this low value is attributed to a sprayed layer of Al_2O_3 on the heat exchanger tubes to limit tritium leakage to the steam generator. For the Al_2O_3 layer to be effective, it must remain crack-free, and this may be difficult since the steam generator tubes will undergo significant thermal cycling.

At present, there are no generally applicable standards regulating the release of tritium to the environment other than

Table 3. Tritium releases for a 470-MW(e) reactor

Source	Release (Ci/day)
Potassium piping	2.0
Potassium turbine	0.02
Steam generator	
Stainless steel	(66.7)
Tungsten clad	0.58
Potassium coldtrap	0.009
Reactor cell	0.002
Total	<hr/> ~ 2.6

Federal and Agreement State regulations governing occupational and public radiation exposures. Present regulations for light-water reactors (LWRs) limit the radioactivity released in gaseous effluents so that the dose equivalent to an individual in an unrestricted area does not exceed 5 mrem/year to the whole body or more than 15 mrem/year to the skin. For liquid effluents, the upper limit is 3 mrem/year for the whole body and no more than 10 mrem/year to any organ.²⁷

Tritium Management and Strategy

Perhaps the single most important health and safety issue associated with CTRs is that of tritium management and strategy. Reference designs for CTR power plants¹⁶ have indicated a loss rate of only 0.2 to 8.2 Ci/day. However, neither the economic nor the engineering feasibility for such low projections appears to be well demonstrated at this time.

A detailed analysis of the various subsystem concepts (storage, injection, blanket, recovery, etc.) should be undertaken to minimize the potential hazard of tritium to the worker, the local public, and the global population. Several alternate designs of each major subsystem have already been suggested. Each subsystem is a potential source of tritium release, and design differences are reflected in exposure implications to the occupational worker and the general public, both during normal operation and under accident conditions. These differences must be identified and analyzed prior to commitment to a final design.

ACTIVATION PRODUCTS

During normal operation of a fusion reactor, tritium will most likely be the major radionuclide present in reactor effluents and the working environment. Under abnormal conditions, during major maintenance periods, or after normal shutdown and subsequent dismantling, other radioisotopes (the activation products created from the transmutation of structural and containment materials) may be the major radionuclides to contend with. Depending on the relative quantities and forms of these materials that could be released, information must be accumulated on their environmental transfer and metabolism in humans such that adequate assessments can be made of the potential radiological impact of the materials.

A D-T fusion reactor will be neutron-intensive; the initial containment, the coolant, and the breeder blanket will all be subjected to intense high-energy neutron fluences. Calculated neutron fluences at the initial containment wall are given in Table 4 for several magnetic-confinement schemes.¹⁶ In addition to alteration of the mechanical and physical properties caused by transmutations, the inner wall materials will also experience swelling due to the production of He_2 and H_2 gases in the metals²⁸ and will require periodic replacement. Structural design and material selection will dictate the frequency for replacement; estimated replacement intervals for different CTR schemes are presented in the last column of Table 4. and a list of proposed materials used in CTR schemes is summarized in Table 5.¹⁶

Table 4. Blanket - first wall fluence and replacement rate

Reactor design	14-MeV neutron wall load (MW/m ²)	14-MeV neutron current (n cm ⁻² sec ⁻¹)	Total flux (n cm ⁻² sec ⁻¹)	Total fluence at replacement (n/cm ²)	Replacement interval (years)
Tokamaks					
ORNL	0.44	1.95×10^{13}	1.48×10^{14}	3×10^{22} ^a	10
PPPL	1.76	7.3×10^{13}	8.65×10^{14}	1×10^{23} ^a	5
UWMAK-I	1.25	5.5×10^{13}	4×10^{14}	3×10^{22}	2
Theta-Pinch ^b	6.66	2.97×10^{14}	2.71×10^{15}	8.5×10^{22} /year	2
Mirror (Yin-Yang)	1.5 average 1.9 peak	7.1×10^{13}	5.2×10^{14}	unknown	NA

^aDesign assumes load factor for plant to be 60% for ORNL and 75% for PPPL.

^bAveraged over 3-sec reactor cycle and a 100% load factor for plant.

Table 5. Blanket - choice of coolant and materials^a

Reactor Designs	Coolant	Structural material	Breeding material	Moderating material
Tokamaks				
ORNL	Li	Nb-1% Zr	Li	C, Li
PPPL	He	PE-16 ^b	FLIBE ^c	FLIBE ^c
UWMAK-I	Li	316 stainless steel ^d	Li	Li, C
UWMAK-Ia	He	316 stainless steel	Li	Li, C
Theta-Pinch	Li	Nb-1% Zr	Li	Be, C, Li
Mirror (Yin-Yang)	Li	Stainless steel	Li	C, Li

^aSintered aluminum product, vanadium, and vanadium-10% titanium have also been suggested.

^bNimonic PE-16 approximate composition: 43% Ni, 35% Fe, 17% Cr, 3% Mo, 1% Ti, 1% Al.

^cFLIBE = a eutectic mixture of the salts LiF and BeF₂.

^dType 316 stainless steel approximate composition: 62% Fe, 1% Si, 18% Cr, 14% Ni, 3% Mo, 2% Mn.

Alternate Structural Materials

The list of CTR materials presented in Table 5 was developed from the different conceptual magnetic confinement schemes currently under evaluation.²⁸⁻³² Sintered aluminum product (SAP) and V-10% Ti have also been suggested for use as the first wall.^{33,34} (Sintered aluminum product is composed of pure aluminum that is strengthened by the addition of 5 to 10 wt % Al_2O_3 finely dispersed throughout the aluminum matrix.)

A multiplicity of nuclear reactions is possible for energetic neutrons (14 MeV) reacting with CTR materials (illustrated in Table 6 for ^{93}Nb). Reaction cross sections for 14-MeV neutrons³⁵ and the half-lives of resulting radionuclides are given. A list of possible activation products from the types of reactions with the inner wall materials listed in Table 5 is composited in Table 7. For simplicity, radionuclides with a half-life less than 30 days (with the exceptions of $^{92\text{m}}\text{Nb}$ and ^{51}Cr) and second-order transmutations are not listed.

A common feature of activated blankets in various conceptual designs is that the total inventory of radioactivity increases rapidly after startup. For example, the radioactivity of the UWMAK-I 5000 MW(t) stainless steel blanket reaches 10^9 Ci within 2 hr after startup and 4×10^9 curies after two years of operation.¹¹

The activity generated in the niobium structure of a tokamak is calculated to be approximately $9000 \text{ Ci MW(t)}^{-1} \text{ year}^{-1}$ for the principal activation product, $^{93\text{m}}\text{Nb}$. For a stainless steel blanket, the activity is of the same order of magnitude as niobium and the ratio of activity produced in an Nb-1% Zr wall compared to a type 316

Table 6. Fourteen-MeV neutron reactions with niobium

Reaction	14-MeV neutron cross section (barn)	Activation product	Half-life
$^{93}\text{Nb}(n,n)$	2		
(n,n')	0.87	^{93m}Nb	13.6 years
$(n,2n)$	1.09	^{92m}Nb	10.16 day
(n,γ)	0.0005	^{94}Nb	2×10^4 years
(n,p)	0.003	^{93}Zr	1.5×10^6 years
(n,α)	0.009	^{90}Y	64 hr

Table 7. Summary of activation products

Structural Material	Activation product ^a	Half-life
Nb-1% Zr	⁸⁹ Sr	52.7 days
	⁹³ Zr	1.5 x 10 ⁶ years
	⁹⁵ Zr	65.5 days
	^{92m} Nb	10.16 days
	^{93m} Nb	13.6 years
	⁹⁴ Nb	2 x 10 ⁴ years
	⁹⁵ Nb	35 days
Nimonic alloy (PE-16)	²⁶ Al	7.4 x 10 ⁵ years
	⁴⁵ Ca	165 days
	⁴⁹ V	330 days
	⁵¹ Cr	27.8 days
	⁵³ Mn	1.9 x 10 ⁶ years
	⁵⁵ Fe	2.60 years
	⁵⁹ Fe	45.6 days
	⁵⁸ Co	71.3 days
	⁶⁰ Co	5.263 years
	⁵⁹ Ni	8 x 10 ⁴ years
	⁶³ Ni	92 years
	⁹¹ Nb	≈ 10 ⁴ years
	^{92m} Nb	10.16 days
	⁹⁴ Nb	2 x 10 ⁴ years
	⁹⁵ Nb	35 days
	⁹³ Mo	> 100 years
	⁹³ Zr	1.5 x 10 ⁶ years
	⁹⁵ Zr	65.5 days
	⁹⁹ Tc	2.12 x 10 ⁵ years
Stainless steel (type 316)	⁴⁹ V	330 days
	⁵¹ Cr	27.8 days
	⁵³ Mn	1.9 x 10 ⁶ years
	⁵⁴ Mn	303 days
	⁵⁵ Fe	2.6 years
	⁵⁹ Fe	45.6 days
	⁵⁷ Co	270 days
	⁵⁸ Co	71.3 years
	⁶⁰ Co	5.263 years
	⁵⁹ Ni	8 x 10 ⁴ years
	⁶³ Ni	92 years
	⁹¹ Nb	≈ 10 ⁴ years
V-20% Ti	⁹³ Mo	> 100 years
	⁹⁹ Tc	2.12 x 10 ⁵ years
Aluminum	⁴⁹ V	330 days
	⁴⁵ Ca	165 days
	⁴⁶ Sc	83.9 days
	²⁶ Al	7.4 x 10 ⁵ years

^aActivation products listed do not take into consideration impurities present in the listed structural material.

stainless steel wall is slightly higher.²⁸ With the use of vanadium, the radioactivity inventory is greatly reduced.³¹

A more important aspect concerning the structural materials is the quantity of residual activity present after plant shutdown. For example the use of niobium will result in substantial amounts of long-lived ^{93m}Nb (13.6 years) and ^{94}Nb (2×10^4 years).^{30,31} With vanadium, the inventory of activation products is several orders of magnitude less, but niobium is a typical impurity in vanadium. Activities for type 316 stainless steel and V-20% Ti are comparable while operating; but V-20% Ti has only two long-lived activation products, while type 316 stainless steel has several. If a SAP (made with 99.99+ wt % aluminum) is used, the residual activity may be many orders of magnitude less than if niobium or stainless steel were used.³⁴

From the viewpoint of minimum long-term radioactivity, aluminum and vanadium appear to be particularly promising. But, the use of aluminum as SAP in CTR materials is unlikely because it does not have the good high-temperature properties possessed by either stainless steel or refractory metals,³³ and its chief disadvantage is its low ductility.³⁴ Some aluminum alloys are more promising,³⁶ such as the high copper alloy ALCOA 2219 (6.3% Cu, 0.3% Mn, 0.06% Ti, 0.1% V, and 0.18% Zr). However, even small amounts of alloying elements or impurities in aluminum alloys can have a large effect on the long-term radioactivity. The induced radioactivity for a wide range of aluminum alloys has been compared with other CTR structural materials on the basis of a two-year operation.³⁶ When compared to type 316

stainless steel, the activities for aluminum alloys are calculated to be a factor of 5 less at shutdown and two orders of magnitude less at one week and beyond (greater than 300 years).

Alternative structural materials that meet the engineering requirements imposed by the large fluences of energetic neutrons should be identified. Unalloyed materials were considered for blanket materials (Table 7), but alloyed materials will be used in practice.³⁴ All structural materials will have trace quantities of impurities that will increase the inventories of activation products.

Potential Biological Hazard

In evaluating the potential impact from activation products, knowledge of the quantity of radioactive material in a fusion reactor is desirable; however, such information by itself is of little value in assessing the radiological impact on man. In past articles,^{1,28,30,33} a biological hazard potential (BHP) has been used to demonstrate quantitative differences between fission and fusion reactors using alternative structural materials. The BHP is defined as the activity of a radionuclide produced in the reactor divided by the $(MPC)_a$. The BHP essentially becomes a measure of the maximum possible biological impact in the event of an accident, assuming all of the activity is released in a form available for human intake. Using the BHP as a yardstick for design engineering may be appropriate, but it is not adequate to use the BHP in evaluating environmental impacts. An assessment of the radiological impact from activation products depends on the quantities and forms (physical and chemical) of a release, environmental transport, and metabolism in

humans. All of these factors must be taken into account to perform a realistic hazard assessment.

Exposure Pathways

Workers may be exposed to radiation from CTR-activated materials during normal operation, disposal and/or recycle of CTR materials, and abnormal or accident situations. In the latter case, members of the public may also be exposed.

Most routine and preventive maintenance and dismantling operations will be accomplished remotely. The radiation fields for some fusion reactor designs are calculated to be several megarads per hour,³⁷ within the reactor interior and this may be a major source of occupational exposures during disassembly or reactor repair.

As a result of accidents, significant quantities of radioactive material could be released in the form of aerosols. In a suggested worst case, a rupture of a potassium-to-water/steam heat exchanger would allow a massive injection of water and/or steam into a hot liquid or gaseous metal.³⁸ This would lead to a rapid reaction, producing hydrogen gas. The most harmful effects would be pressure surges, which, on contact with air, could cause hydrogen explosions and the release of activated products from the coolant systems. (This could also lead to large-scale fires and the release of tritium contained in the reactor.)

Niobium is reported to burn, emitting white smoke, when exposed to air at 800°C.³⁹ This implies that niobium particles could be dispersed into the environment during an accident. Niobium (or other structural metal) would be closely associated with a large quantity of

lithium, and oxidation of the structural metal could occur only after most of the lithium had burned.

Waste Management

Vogelsang et al.²⁸ have estimated that the inventories of activation products in a CTR will be the same order of magnitude as the fission and activation products produced in a comparable liquid metal fast breeder reactor (LMFBR) during the period 1 to 100 years after shutdown. Figure 4 compares residual radioactivity in the UWMAK-I and the LMFBR for several suggested first wall materials. Although not shown, the radioactivity of the high nickel-based alloy (PE-16) and the stainless-steel systems are about the same.³³ (For the interested reader, the components contributing to the residual radioactivity for Nb-1% Zr and V-20% Ti used in a reference theta-pinch design are deconvoluted and shown in ref. 40). For the various CTR designs, the dominant isotopes leading to the major portion of the radioactivity for several time periods after shutdown are tabulated in Table 8. This table is based on a two-year operation and a wall loading of 1 MW/m².³³

In a typical CTR, there will be approximately 250,000 kg of activated structural waste material to be disposed of annually.³⁷ One solution would be the long-term storage of these structural materials; however, this may not be a viable solution to the problem because certain structural materials for use in the fusion reactor are of strategic importance.¹ The use of refractory metals such as niobium or vanadium may mean that our nation will be almost entirely dependent on foreign sources for these metals.^{1,41} Thus the United

Fig. 4. Decay of radioactivity following shutdown of fusion reactors based on the UWMak-I CTR design. The figure on the left is a comparison using different suggested structural materials for a ten-year operating time, except for aluminum as SAP in the BNL design, for which the operating time is two years. The figure on the right is a comparison of the UWMak-I with an equivalent LMFBR.

Sources: W. F. Vogelsang et al., *Nucl. Technol.* 22, 376 (1974).
 R. W. Conn et al., *Nucl. Technol.* 26, 391 (1975).

Table 8. Radioactivity density in the first wall of different CTR designs as a function of time

Tokamak Design (first wall material)	Time after shutdown									
	1.7 hr		2 years		20 years		200 years		2000 years	
	Dominant isotopes	dis sec ⁻¹ cm ⁻³	Dominant isotopes	dis sec ⁻¹ cm ⁻³	Dominant isotopes	dis sec ⁻¹ cm ⁻³	Dominant isotopes	dis sec ⁻¹ cm ⁻³	Dominant isotopes	dis sec ⁻¹ cm ⁻³
UWMAK-I (type 316 stainless steel)	⁵⁵ Fe	0.964 x 10 ¹²	⁵⁵ Fe	0.570 x 10 ¹²	⁵⁵ Fe	0.594 x 10 ¹⁰	⁶³ Ni	0.369 x 10 ⁸	⁵⁹ Ni	0.169 x 10 ⁶
	⁵¹ Cr	0.420 x 10 ¹²	⁵⁴ Mn	0.449 x 10 ¹¹	⁶⁰ Co	0.180 x 10 ¹⁰			⁵³ Mn	0.253 x 10 ⁵
	⁵⁴ Mn	0.223 x 10 ¹²	⁵⁷ Co	0.151 x 10 ¹¹	⁶³ Ni	0.134 x 10 ⁹				
	⁵⁷ Co	0.897 x 10 ¹¹	⁶⁰ Co	0.173 x 10 ¹¹						
	⁶⁰ Co	0.222 x 10 ¹¹								
	⁵⁸ Co	0.316 x 10 ¹²								
	⁵⁶ Mn	0.401 x 10 ¹²								
ORNL (Nb-1% Zr)	^{92m} Nb	0.678 x 10 ¹³	^{95m} Nb	0.903 x 10 ¹⁰	^{93m} Nb	0.378 x 10 ¹⁰	⁹⁴ Nb	0.174 x 10 ⁹	⁹⁴ Nb	0.164 x 10 ⁹
	⁹⁰ Y	0.915 x 10 ¹¹	⁹⁴ Nb	0.175 x 10 ⁹	⁹⁴ Nb	0.175 x 10 ⁹				
	^{95m} Nb	0.729 x 10 ¹¹								
PPPL (PE-16)	⁵⁵ Fe	0.103 x 10 ¹²	⁵⁵ Fe	0.618 x 10 ¹¹	⁵⁵ Fe	0.645 x 10 ⁹	⁶³ Ni	0.199 x 10 ⁸	⁵⁹ Ni	0.818 x 10 ⁵
	⁵¹ Cr	0.646 x 10 ¹¹	⁵⁴ Mn	0.193 x 10 ¹⁰	⁶⁰ Co	0.937 x 10 ⁹			⁵³ Mn	0.186 x 10 ⁴
	⁵⁴ Mn	0.957 x 10 ¹⁰	⁵⁷ Co	0.802 x 10 ¹⁰	⁶³ Ni	0.725 x 10 ⁸				
	⁵⁷ Co	0.476 x 10 ¹¹	⁶⁰ Co	0.901 x 10 ¹⁰						
	⁶⁰ Co	0.116 x 10 ¹¹								
	⁵⁸ Co	0.161 x 10 ¹²								
	⁵⁷ Ni	0.948 x 10 ¹⁰								
BNL (Al)	²⁴ Na	0.567 x 10 ¹²	²⁶ Al	0.184 x 10 ⁶	²⁶ Al	0.184 x 10 ⁶	²⁶ Al	0.184 x 10 ⁶	²⁶ Al	0.184 x 10 ⁶

Source: R. W. Conn, T. Y. Sung, and M. A. Abdou, "Comparative Study of Radioactivity and Afterheat in Several Fusion Reactor Blanket Designs," Nucl. Technol. 26, 391 (1975).

States may be forced to recycle metals used in the fusion reactors. Such recycling would increase the potential for exposure of personnel, as well as members of the general population. Presently, structural and containment materials for decommissioned fission reactors are not recycled.

Status of Metabolic Data

Some dosimetric data are available on the activation products listed in Table 7. Much of this information has been prepared in accordance with work currently being performed at Oak Ridge National Laboratory (ORNL) for the International Commission on Radiological Protection (ICRP).

There are deficiencies in the dosimetric data. For example, very little metabolic data for aluminum is reported in the literature, and these data were obtained from studies on rats. Consequently, the metabolic model for humans had to be based on information obtained experimentally for gallium, which is in the same classification in the periodic chart. Based on these data, the uptake fraction is estimated to be approximately 10^{-3} ; however, this is lower than the uptake indicated for aluminum in the Reference Man Report.⁴²

The situation is much the same for niobium. There is little data on the metabolism of niobium in man. A recent study of Furchner and Drake⁴³ compares the metabolism of niobium in the mouse, rat, monkey, and dog. Their studies showed preferential retention in bone, with bone having a tenfold higher concentration compared to the whole-body average. The Furchner and Drake data were used in the derivation of a retention equation for use in dosimetric evaluations. The animal

studies⁴³ indicate a gastrointestinal (GI) absorption of 1% or less; however, calculations using the observed urine excretion levels in humans point to a possible GI absorption of 60%.⁴⁴ Thus the incorporation of radioactive niobium into the food chain could be a significant exposure pathway.

In general, little human data are available, and in some cases, little animal data are available for many of the other elements of potential importance in fusion power. Because of these limitations, the dosimetric data for some activation products should be used with discretion.

MAGNETIC FIELD EFFECTS

All fusion concepts not utilizing inertial confinement rely on magnetic fields to retain the plasma. Estimates of the field strengths have been made for the reference CTR power plant designs, and detailed calculations and field pattern plottings are available for the UWMAK-I.¹¹

For this tokamak design, a toroidal field is produced by the main magnetic field coils, and a poloidal field is produced by the plasma current, divertor coils, and transformer coils. The toroidal field is in the plane of the torus, with the strength varying from 10,000 G in the area near the reactor to less than 1 G at a distance of 50 m. The poloidal field, on the other hand, will radiate both vertically and horizontally from the torus, and at a distance of 500 m, the magnetic field strength will be 1 G. (For comparison, the magnetic field strength of the earth is about 1/2 G.) Some personnel may be exposed to poloidal fields as high as 70 to 450 G outside the reactor area in the transport and hot-cell regions; other workers near the building could be subjected to field strengths of 1 to 70 G for long periods of time. Fusion reactor sites are expected to have exclusion boundaries at a distance of about 0.5 mile (800 m). Therefore, at the site boundary, public exposures to magnetic fields from CTRs will be similar to that from the earth's natural field.

At present, it is not possible to assess with any certainty the potential occupational hazards resulting from exposures to these magnetic fields; however, exposures to magnetic fields have occurred

with some frequency. Operators of the calutrons in the electromagnetic uranium isotope separation process in Oak Ridge were exposed to fields of at least hundreds of gauss for long periods of time. Additionally, other laboratories and installations have been involved in experiments or production activities where intermediate fields were regularly encountered by the worker. Many of these situations exist at present; however, the authors are unaware of any literature describing adverse effects subsequent to these exposures. In the past few years, human exposures to localized high-field strengths have occurred during therapeutic procedures,⁴⁵ and no permanent adverse effects are reported.

The first documented effect in man that has been consistently reproducible is the visual sensation called phosphenes.⁴⁶ When the head is placed in an alternating magnetic field, light flashes, believed to be an indirect effect due to induced electric currents, are seen. The effect subsides immediately after withdrawal from the field and is not observed for the case of static fields.⁴⁷

The experience of workers in various physics laboratories in the United States who were exposed to fields up to 20,000 G for up to 15 min, accidentally or during the course of their work, indicates that man can tolerate short exposures to high magnetic fields without apparent ill effects. While no aftereffects were reported,⁴⁸ taste sensations and mild tooth pain have been experienced by some workers.

There are no sound physical models available to describe the cause-and-effect relationships for most of the observed biological effects of magnetic fields. Much of the data from small animals have

been generated with ill-defined experimental conditions, and many of the adverse effects are observed at high fields. Although some experimental exposures to high magnetic-field intensities have produced no detectable change, others have found changes after exposures to low field strengths. Additional studies are needed to explain the highly variable and nonreproducible results reported in past experiments.

Although no protective regulations are known to exist in any country, two sets of recommendations are reported: one developed in the United States and the other developed in the Soviet Union. A set of safety standards for human exposure to magnetic fields is recommended by the board of directors at the Stanford Linear Accelerator Center.⁴⁹ These standards, presented in Table 9, reflect the results of animal experiments and observations of personnel at the Center who were exposed to magnetic fields. A second set of standards, reported by Novitskiy et al.,⁵⁰ is based on a Soviet study by A. M. Vyalov of 1500 occupationally exposed workers who spent up to 60% of the workday with their hands in magnetic fields from 350 to 3500 Oe and their heads in fields of 150 to 250 Oe. A number of general symptoms are reported, such as headache, fatigue, low blood pressure, and decreased red blood cell count. Specific effects include sweating of the palms, high skin temperature, subcutaneous edema, and shedding of skin of the palms. The safety standards recommended by Novitskiy are given in Table 10. The two sets of standards for whole-body exposures are of similar magnitude for

Table 9. Safety standards for magnetic fields recommended by the
Stanford Linear Accelerator Center

	Extended periods (hr)	Short periods (min)
Whole body or head	200 G	2,000 G
Arms and hands	2,000 G	20,000 G

Table 10. Safety standards for magnetic fields recommended by
A. M. Vyalov^a

	Field (Oe)	Gradient (Oe/cm)
Whole body	300	5-20
Hands	700	10-20

^aThe gauss (G) is the unit of magnetic induction or flux density. The oersted (Oe) is the unit of magnetic field strength. In a vacuum (and for all practical purposes in air) magnetic induction is numerically equivalent to field strength. (The different choice of units is not thought to have ideologic significance.)

exposures of long duration. The lower value for the hand exposure in the Vyalov standard is probably a result of the above-mentioned hand symptoms.

A brief summary of the literature on biological effects of magnetic fields has recently been made by Mahlum,⁵¹ with special emphasis on identifying necessary areas of research pertinent to the CTR program. A more complete list of references is presented in that report.

CONCLUSIONS

With the creation of the Energy Research and Development Administration, the development of energy technologies other than fission has been brought into sharper focus. One alternative that has promise in the future is the use of fusion energy for electrical power generation. However, tradeoffs and potential deleterious effects to man and the environment are associated with this technology. With the present conceptual CTR designs utilizing deuterium and tritium as fuel, it is possible a spectrum of health physics problem areas can be identified. Qualitatively, many of these areas are similar for fusion and fission reactors: (1) tritium releases and monitoring; (2) creation of activation products; and (3) waste disposal of long-lived radionuclides. Quantitatively, tritium releases and inventories of radioactive products are calculated to be of the same order of magnitude for fusion reactors as for fission reactors. Radioactive materials can also be released from CTRs during accidents or abnormal events. In addition to the areas mentioned above, a relatively unexplored aspect unique to confinement CTR designs is the exposure of workers to elevated magnetic fields. No Federal regulations exist governing such exposures.

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