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Balanced Program Plan
Volume X: Fusion

Analysis for Biomedical and Environmental Research

June 1976

Prepared for the Division of Biomedical and Environmental Research, Energy Research and Development Administration, under Contract No. E(45-1):1830

Battelle
Pacific Northwest Laboratories

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BALANCED PROGRAM PLAN
VOLUME X: FUSION

ANALYSIS FOR BIOMEDICAL AND ENVIRONMENTAL RESEARCH

F. P. Hungate
Fusion BPP Coordinator

Prepared for the Division of Biomedical and Environmental Research, Energy Research and Development Administration, under Contract No. E(45-1):1830

June 1976

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Richland, Washington 99352

FOREWORD

Development of the Balanced Program Plan was initiated in the spring of 1975 by the Assistant Administrator for Environment and Safety, Dr. James L. Liverman and organized by Dr. Raymond Cooper, Division of Biomedical and Environmental Research. The goal was a redefinition of research efforts and priorities to meet ERDA's requirements for a program of health and environmental research to support the development and commercialization of energy technologies.

As part of the Balanced Program planning effort the major ERDA-supported multidisciplinary laboratories were assigned responsibility for analyzing the research needs of each of nine energy technologies and describing a research program to meet these needs. The staff of the Division of Biomedical and Environmental Research was assigned the task of defining a research program addressed to each of five biomedical and environmental research categories (characterization, measurement and monitoring; physical and chemical processes and effects; health effects; ecological effects; and integrated assessment and socioeconomic processes and effects) applicable to all energy technologies. The first drafts of these documents were available for a workshop in June 1975 at which the DBER staff and scientists from the laboratories developed a comprehensive set of program recommendations.

Pacific Northwest Laboratory was assigned responsibility for defining research needs and a recommended research program for fusion and fission technologies. This report, Volume X, for fusion was prepared by Dr. Frank P. Hungate with input from the staff of the Pacific Northwest Laboratory, other multidisciplinary laboratories, and DBER. This report also reflects the discussions at the Workshop in June 1975.

W. J. Bair
Manager
Environmental and Safety Research Program

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BALANCED PROGRAM PLAN FOR FUSION TECHNOLOGY

INTRODUCTION

In this draft planning document for health and environmental research needs relevant to the development of fusion technology, we have attempted to integrate input from the participating laboratories on the basis of the King-Muir study categories. A significant difficulty has been the current uncertainty about which of the several proposed fusion technologies will prove practical for industrial application. Present estimates indicate that technology verification may not be achieved until about 1990, with demonstration CTRs in place by about 2000 and commercial power production escalating thereafter.

This draft will undoubtedly require substantial revision to further define areas now covered only generally and, of course, to keep pace with technological developments. An obvious deficiency in the program units is the incomplete identification of typical environmental problems, such as effects from heat dissipation, construction, mining, milling, etc. We have stressed the issues that we feel are most important to fusion.

The general description covers only those concepts and features that we consider important to an understanding of possible and probable effects of thermonuclear reactors on health and the environment.

Appendixes are included which reflect our understanding of three areas of special interest: materials requirements, effects from magnetic fields, and tritium effects.

A GENERAL DESCRIPTION OF NUCLEAR FUSION

Nuclear fusion is a process in which nuclei of light elements are combined, with a net release of energy that is manifested as kinetic energy of the particles released in the reaction.

Nuclear fusion requires temperatures of hundreds of millions of degrees so that the kinetic energy of the colliding nuclei is sifficient to overcome the electrostatic potential barrier that normally separates them. At such high temperatures, neutral atoms cease to exist and the negatively charged electrons and positively charged hydrogen nuclei exist as a mixture of ions called a plasma.

The primary difficulties in achieving conditions suitable for fusion are in attaining high plasma temperatures and in holding large numbers of nuclei in sufficiently close proximity for a long enough time that useful numbers of fusions occur.

Two quite different basic approaches are being pursued to achieve fusion. One approach uses intense magnetic fields to force the plasma particles together, thereby heating them and isolating them in a vacuum for a sufficient length of time and in adequate concentrations that a useful percent of the nuclei fuse. With magnetic isolation of the plasma, fusion may occur over prolonged periods during which energy is carried from the fusing plasma by neutrons and helium nuclei and transported to collector systems that are meters distant from the plasma.

The second approach uses pulsed lasers to compress and rapidly heat pellets of fuel. The pellets are injected into a vacuum chamber and fusion occurs instantaneously (within fractions of a nanosecond), producing intermittent releases

of energy as pellets are injected. Intervals between pulses are dictated by the capability of the lasers to recharge and discharge such large energy pulses. Lasers capable of delivering the energy required are not yet available.

The immediate products of nuclear fusion are newly formed, stable atomic nuclei and neutrons. The neutrons dissipate their energy in containment materials and, in so doing, activate and damage the containment materials, resulting in radioactive species that constitute a potential hazard to health and the environment. Furthermore, the fuels showing the greatest potential for early use are stable deuterium and radioactive tritium, with the latter being produced as well as used during operation of the fusion reactor. The potential for tritium release into working areas and into the environment is high.

THE CONTROLLED THERMONUCLEAR REACTOR AS AN ENERGY SOURCE

Energy production in excess of consumption by fusion has so far been demonstrated only in uncontrolled releases, i.e., fusion bombs. The idea of utilizing fusion bombs for power production, as in the Pacer concept, is not included in this planning document, however, since this approach is entirely different from the more usual projected means for deriving power from fusion. Many more years of research and development are necessary to demonstrate the practicality of controlled fusion for power generation and to develop the equipment and systems needed for a competitive power plant. Such a plant, the controlled thermonuclear reactor (CTR), is expected to be introduced commercially shortly after the year 2000. Much of the information about health and environmental implications of CTRs will derive from research done for fission plants. However, research on health and environmental effects critical to fusion plant design should be initiated in the near future in support of the CTR program.

The fusion-fission concept is worthy of mention as a possible intermediate step toward fusion. It involves utilizing the energetic neutrons from fusion reactions in a blanket region containing fissile or fertile materials. The potential applications of fusion-fission systems are: a) to provide electrical power, b) to alleviate constraints in fission systems by the production of fissile fuels or the transmutation of radioactive wastes, or c) combinations of the above. The possibility of the hybrid reactor further emphasizes the importance of research related to fission for ultimate needs in fusion.

Several conceptual CTR power plant designs are being considered. Modes of plasma confinement for each of the sponsoring laboratories are as follows:

Magnetic Confinement	
Tokamak	Princeton Plasma Physics Laboratory Oak Ridge National Laboratory University of Wisconsin Brookhaven National Laboratory
Theta Pinch	Los Alamos Scientific Laboratory
Mirror	Lawrence Livermore Laboratory (LLL)
Fusion-Fission Hybrid	LLL/Pacific Northwest Laboratories
Inertial Confinement	
Wetted Wall	Los Alamos Scientific Laboratory
Blascon	Oak Ridge National Laboratory
Suppressed Ablation	Lawrence Livermore Laboratory

Although incomplete, this listing illustrates that a number of divergent approaches to CTRs are being developed, with no convincing evidence of either success or lack of success for any particular concept. CTRs of all types share the following features of general significance:

- likely consumption of large quantities of some materials potentially in short supply
- probable use of vast quantities of helium for cryogenics associated with large magnets and possibly as heat exchange material
- absence of criticality-type accident potential and minimal afterheat problem in case of loss of coolant
- infinite supply of low cost fuel.

FUNCTIONAL FEATURES OF A CTR

The functional portions of a CTR power plant are represented in Figure 1. There are two primary systems: one produces, confines and maintains the fusing plasma and the other captures the reaction products and converts the associated energy into electricity. In addition, a feedback system recovers unused fuel and materials in the unused plasma. A second feedback system is shown on the assumption that tritium will be used as one of the fuel materials. This tritium will be formed as a product of the interaction of 14 MeV neutrons with a blanket of lithium surrounding the reactor chamber.

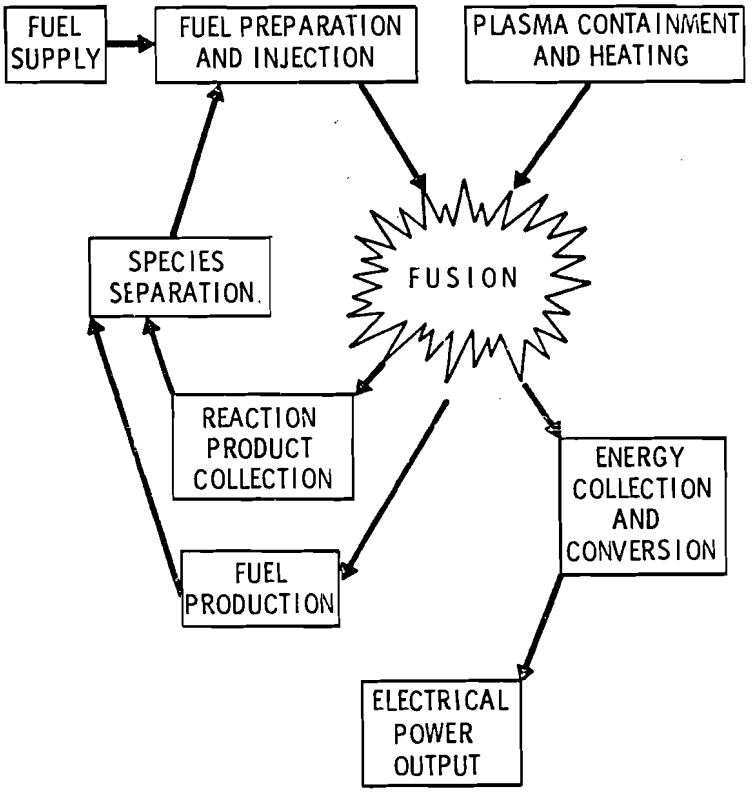

FIGURE 1. Functional Components of CTR Power Plant Systems

PLASMA CONFINEMENT

Magnetic fields have been the most thoroughly investigated means for confining high temperature plasma. Theoretically, they would allow fusion times measured in minutes or hours. The strength and geometry of these fields will depend on the reactor concept ultimately used. Patterns for two types of magnetic fields have been plotted for the University of Wisconsin's proposed Tokamak design for a 5000 MWe CTR. The main toroidal magnet will produce field strengths varying from 10,000 gauss in the area immediately surrounding the plasma containment hardware to <1 gauss at the outer edge of the reactor building (about 50 meters). The poloidal field will extend both vertically and horizontally from the torus, with field strengths >1 gauss at distances up to 500 meters from the fusion chamber. Thus, while some manipulations to reduce and control magnetic fields are possible, it seems likely that people working in the reactor building could be subjected to field strengths up to 500 gauss in CTRs using magnetic confinement unless special devices for field suppression are installed. Limited exposure would also be possible for other life forms, such as birds, in the vicinity of the reactor.

The technology for magnets of the size and strength needed for CTRs is being developed, and it seems likely that superconducting systems will be required. Large quantities (hundreds of tons) of helium and superconducting metals such as niobium, tantalum and tin would be used in the cryogenic systems. Yet another problem of magnetic confinement would be the extremely large electrical demand during cycle startup. This power need exceeds projections of power available from commercial power grids, and some form of local energy storage would be required.

In inertial confinement CTRs, a solid fuel pellet traversing the plasma chamber is imploded by laser energy to densities hundreds of times greater than that of the initial pellet. The imploded pellet is converted to a plasma in which fusion occurs within fractions of a nanosecond and the reaction ceases as the plasma flies apart. The near-instantaneous release of large amounts of energy requires attention to the possibility of blast effects. Neutrons deliver about three-quarters of the fusion-released energy to and into the containment wall and blanket of lithium. The remaining energy is delivered to the containment surface, primarily by the helium "ash." Protection of the containment surface is an important aspect of all CTR designs, and especially so for those using inertial confinement.

Blast effects from laser-induced fusion are expected to be slight for two reasons. First, the mass of matter transporting the energy is small (a million times smaller than that of a TNT explosion) and second, the neutrons carry most of the energy and dissipate this energy through a substantial volume of surrounding lithium and wall materials. (In contrast, energy from a TNT explosion would be delivered to the first surface contacted.) Much testing in a variety of containment systems will be required before the magnitude of effects (including vibration) from inertial confinement systems can be predicted.

All CTRs must have some containment material or structure surrounding the plasma. Due to damage to this structure from the neutrons and helium nuclei, the inner wall may have to be replaced every few years, and radioactive aerosolized fragments of the wall will undoubtedly be present in the recovered plasma. For example, it is estimated that the stainless steel liner in the 5000 MW Princeton Tokamak would contain 3×10^7 Ci of cobalt-60 ($T_{1/2}$ = 5.3 yr), 10^9 Ci iron-55 ($T_{1/2}$ = 2.6 yr)

and 3 x 10^6 Ci nickel-63 ($T_{1/2}$ = 92 yr). Some inertial containment designs incorporate a moving layer of molten lithium at the first wall to minimize damage. It is clear, however, that neutron activation of wall materials and of even more remotely located structures, such as the magnets, will lead to potential radiation hazards to the work force. Damage to wall materials may be exacerbated by the presence of lithium and other corrosive materials in the molten lithium blanket.

Research is now in progress to identify containment materials that will sustain minimal damage from the neutrons and helium nuclei produced during fusion. Containment materials having minimal activation products that would cause health and environmental hazards must also be developed in case replacement or decommissioning is required. It appears likely that the neutron-induced radionuclides will have reasonably short half-lives and low-energy emissions, so short-term storage and recycling of materials should be feasible ways of avoiding the storage problem now posed by the products of fission reactors. Less wall damage and a reduced need for replacement of the structural containment layer should result from using the fusion-fission hybrid, since orders of magnitude fewer 14 MeV neutrons would be involved than in a straight fusion CTR.

Special features of plasma confinement systems that could have important effects on health and the environment include:

- large magnetic fields (extending to hundreds of meters) at magnetic confinement reactors
- vibrations transmitted to the ground at inertial confinement reactors
- large quantities of high-level solid radioactive waste to be handled and stored if the containment layer shows need of replacement.

FUELS

Several fuel alternatives are theoretically attractive for reasons of efficiency or for their minimal health and environmental implications. However, due to the extreme plasma conditions needed to achieve fusion, it is likely that the fuel used in the first commercial reactors will be the one which poses the least stringent requirements--a mixture of deuterium (D) and tritium (T). While a D-D reaction would have advantages in that it would not require a radioactive fuel and would possibly produce less activation of containment materials, its reaction rate is less favorable than that of the D-T reaction by about two orders of magnitude. The D-T reaction can be shown as

deuterium + tritium → helium (3.5 MeV) + neutron (14 MeV)

with the 17.5 MeV of energy from the helium nuclei and neutrons being absorbed in a blanket surrounding the plasma. The thermal energy is then transferred from the blanket and used for power generation.

Natural supplies of tritium do not exist in economically recoverable amounts. However, sufficient quantities for startup operation can be produced in fission reactors and continuing supplies can be produced as a part of the CTR operation. This is achieved by surrounding the plasma with a blanket of lithium, which absorbs the neutrons and is converted to helium and tritium. Tritium produced in this blanket is recovered directly or indirectly from molten lithium as it is circulated for energy transfer to the power generating system. Typical inventories of tritium contained in the lithium blanket, in collection and purification equipment, and in storage are estimated to be about 6 kg (6×10^7 Ci) for a 2000 MWe generating plant, i.e., about equivalent to the global inventory of naturally-occurring T.

While this is a large amount, it is about the same curie amount as the ^{131}I present in a comparably sized fission plant, and the health hazard posed by tritium is substantially lower, curie for curie, than that posed by ^{131}I.

A feature that causes special concern about tritium is its ability to diffuse through metals, with the diffusion rates becoming very significant at temperatures above 300°C. Hundreds or even thousands of curies per year could be released; therefore, sophisticated tritium recovery and specially engineered heat transfer systems will be required for containment.

No special problems are anticipated from continuing use of deuterium as a fuel. Hundreds of tons of deuterium are now being produced in the U.S. each year with no apparent health or environmental consequences. With concentrations of 0.015% in natural waters and projected annual use rates in fusion reactors of 50 to 60 kg/1000 MWe, deuterium is an essentially inexhaustible fuel. For reasons of efficiency, deuterium would be produced at a site remote from the CTR and transported to the reactor area for storage and use. Since deuterium is produced by sequential distillation, energy use is high and appears to represent the major feature of concern. The present cost of D_2 is approximately $500/kg.

Special features of the D-T fuel cycle important to health and the environment include:

- potential for chronic release of substantial quantities of tritium (mostly as T_2 or TD or TH) during routine operation of the CTR
- possible accidental release of tritium in multikilogram amounts
- presence of 14 MeV neutrons (whose high energy poses special shielding problems) and formation of activation products.

Fuel Preparation and Injection

The manner in which the fuel (D + T) is prepared will depend on the type of reactor used. Rates of fuel use for a 2000 MWe plant are estimated to be 450 g T_2 and 300 g D_2 per day (i.e., equal numbers of atoms of D and T). Introduction of the fuel into a reaction chamber of magnetically confined design requires that the fuel be converted to a neutral gas or a neutral atom beam since the magnetic field would exclude all charged particles. Injection of solid pellets of fuel into the plasma has been proposed but the methods for achieving this are not yet defined. Glass encapsulation would be one means of confining the fuel in pellet form before injection into the laser-fired systems.

As with any system involving even small amounts of hydrogen, the potential for explosion would be present if oxygen were permitted to enter fuel-handling areas. This possibility seems remote since meticulous care in material purity will be required in all stages of fuel handling.

No special features of fuel preparation and injection appear to have important effects on health or the environment.

Fuel Production (T)

To economically produce tritium in amounts sufficient for operating fusion plants using D and T fuels, the tritium must be bred in a blanket of lithium surrounding the fusing plasma. The 14 MeV neutrons induce the reactions

$$^{7}Li + n \rightarrow {}^{4}He + T + n - 2.47 \text{ MeV}$$

in which T is formed without loss of a neutron by using up some of the energy of the 14 MeV neutron (i.e., endothermic reaction); and

$$^{6}Li + n \rightarrow {}^{4}He + T + 4.78 \text{ MeV}$$

in which thermal neutrons are consumed and T is formed in an exothermic reaction. The amount of T that can be produced cannot be precisely defined until 14 MeV neutrons are available. However, analyses of lithium nuclear cross-sections indicate that more than enough T can be produced to supply fuel for continuing operation. It has even been suggested that CTRs in populated areas use fuel produced in more isolated reactors to avoid the complications of T breeding and the associated higher inventory of T.

Molten lithium in the blanket circulates past heat exchangers to transfer energy into the power generating portion of the CTR. Tritium can be removed from the circulating lithium by a variety of techniques including molten salt entrainment, yttrium getters, or diffusion through stainless steel tubes. Such diffusion through metals poses a severe problem to CTR design because the tritium is also expected to diffuse through heat exchangers, which makes it vulnerable to ending up in the water or air used as the coolant in the turbines. Nominal leakage rates of one or more Ci/day are anticipated. Accidental releases could exceed this amount.

Two proposed designs use beryllium in multiton quantities in the tritium breeding cycle. Obviously the use of such a highly toxic material poses a potential problem to health and environment. However, the use of flibe (a eutectic mixture of LiF and BeF_2) allows the tritium inventory in the blanket to be held ten to a hundred-fold lower than in pure lithium blankets, and flibe is noncombustible. A lithium fire with release of tritium from the blanket material is postulated as the most serious accident potential in a CTR.

Special features associated with fuel production that could have significant effects on health and the environment include:

- routine handling of large quantities of lithium with the potential for fire and large releases of lithium and T
- heavy use of a rare element (Be) and possible release of beryllium fluoride if flibe is used in the breeding blanket.

Species Separation

Since only a small percentage of the fuel is used in each burn cycle, fuel recovery and removal of plasma contaminants (such as helium, protium, and radioactive ablated wall materials) will be a necessary feature of CTRs.

Gas permeation through metal membranes (silver-palladium on a ceramic support) at temperatures above 300°C provides one means for separating tritium and deuterium from each other and from other gaseous contaminants. Likewise, cryogenic fractional distillation could be used to separate individual species. Tritium obtained from the breeder blanket would also flow through the same or a similar purification process.

Special features associated with plasma recovery and reprocessing that have potential implications for health and the environment include:

- potential for chronic release of lithium
- potential for chronic release of beryllium and its fluoride
- accumulation, storage, and possible release of radioactive aerosols resulting from ion and neutron damage to the containment vessel.

ENERGY COLLECTION AND CONVERSION

Molten lithium metal is proposed as the primary coolant in all CTR designs except for the Princeton Tokamak, which uses flibe ($LiF-BeF_2$). Lithium is liquid at temperatures between 186°C and 1336°C and it has a relatively large capacity to dissolve all hydrogen isotopes. Since hundreds of tons of lithium will be in close contact with the walls of heat exchangers interfacing with the secondary coolant, diffusion of tritium through the successive heat transport systems poses the major means for chronic tritium release to the environment.

Intermediate heat transport materials between the primary coolant (lithium) and the turbine are proposed to minimize tritium release to the environment. This transport sequence will also minimize movement of radioactive materials eroding into the lithium from the plasma containment shell. Molten sodium, vaporized potassium and helium gas have all been proposed for this energy transport. Tritium trapping in such intermediate transport systems will be required to minimize release. Careful selection of the materials used in the heat exchangers will also help contain the tritium.

Standard steam turbines appear to be the most likely means of fusion's early use for conversion of heat to electric power. With temperatures approaching 600°C, efficiencies of about 40% are projected. Heat rejection to the environment will be unavoidable in CTR operation, as in any thermodynamic cycle.

Directly converting a part of the fusion energy by directing the movement of charged particles through a magnetic field (magnetohydrodynamic conversion) offers the promise of higher conversion efficiences and thus less heat loss.

However, direct conversion technology has yet to be developed, so this feature is not likely to be a part of early demonstration CTRs.

Hazardous features associated with fusion energy collection and conversion include:

- chronic T release
- release of waste energy to the environment
- possible metal fire, causing release of materials used in heat transport.

ESTIMATE OF INITIAL PROGRAM PRIORITIES

(100 Points Total)

CHARACTERIZATION, MEASUREMENT AND MONITORING - 10 POINTS

Since definition of source terms and characterization of the forms of release depend on an identified technology and since such identification is unlikely until after the period projected here, only certain specific objectives, such as real-time monitors for T, warrant immediate attention.

PHYSICAL-CHEMICAL PROCESSES AND EFFECTS - 30 POINTS

One particular feature warrants early investigation because of its commonality with fission and its probable involvement in fusion regardless of CTR design: T transit and rates of conversion to other compounds such as TOH. Available diffusion and conversion data must be analyzed to determine their adequacy for defining likely local and global concentrations of chemical forms of T. If the data are inadequate, supplemental research programs should be established.

HEALTH EFFECTS - 35 POINTS

Health effects from magnetic fields could affect CTR design. Early research is needed to establish whether magnetic fields of the magnitude projected for CTR work areas represent significant health hazards, including effects on electronic medical devices such as cardiac pacemakers. Current data are conflicting and confusing, and leave this question unanswered.

Leading candidates for containment materials (e.g., V, Nb, Ti) will produce radionuclides whose behavior in living

organisms has received little attention. Early studies are needed to establish their potential oncogenic effects and to permit time for later definitive tests before their extensive use in demonstration reactors.

Increased knowledge about effects on health from chronic exposure to concentrations of T would be valuable. Since such research would provide much needed information about possible effects of such exposure on occupational personnel, it is warranted despite its high costs.

ECOLOGICAL EFFECTS - 20 POINTS

Early study of biotic systems in which T is converted to TOH or other compound forms is necessary. A better understanding of the impact of low-level T effects on factors basic to the survival and function of organisms in ecosystems is also needed.

INTEGRATED ASSESSMENT - 5 POINTS

Since reasonably adequate means are now available and improved methods are being developed for assessing other technologies, efforts to develop techniques specific to fusion can be delayed. However, continuous efforts should be made to assure that adequate information on societal impacts of CTR technology is available and transmitted to the public.

PROGRAM UNITS

In the following pages program units are arranged sequentially by King-Muir Category and identified as follows:

C = Characterization, Measurement, Monitoring

P = Physical-Chemical Processes and Effects

H = Health Effects

E = Ecological Effects

I = Integrated Assessment

The technology time frame with which the program units are identified is:

Year 1980	Proof of Feasibility
Years 1990 - 2000	Demonstration CTR
Years 2000 - 2010	First Commercial CTR

Relative severities of problems are indicated by A, B, and C, defined as:

A. severe and requiring early action

B. severe but immediate action not required

C. less severe, or the potential severity not defined sufficiently to require early action.

PROGRAM UNIT TITLE: Personnel Exposure from Controlled Thermonuclear Reactor Waste Handling

Technology: Fusion (CTR)

King-Muir Category: Characterization, Measurement and Monitoring

Scope

Generally, waste handling problems for controlled thermonuclear reactors will be similar to those for a fission reactor. Cleanup of primary liquid metal coolant and replacement of highly radioactive mechanical reactor parts will be much the same for CTRs as for LMFBRs. The major differences will occur in the type and form of radioactive species present. The fast neutrons from the (D,T) reaction will produce an entirely different spectrum of radionuclides in the coolant and construction materials than that created by the primarily thermal neutrons in a fission reactor. Also, special precautions may be required for CTR coolant cleanup to handle the toxic Li, Be, and F compounds that will be present. Finally, the omnipresent tritium required for CTR operations is sure to appear in reactor waste operations. This program unit will 1) identify and assess the radiological implications of potential fast neutron activation products likely to appear in the process wastes, 2) examine and evaluate existing technology for measuring these radionuclides and the tritium, beryllium, lithium, and fluorine expected to be present, and 3) develop the complete technology required to measure and monitor the quantities and qualities of radiological or toxic materials appearing in the plant wastes.

Milestones

By 1980: Identify the fast neutron spallation products, the physical and chemical forms of Li, Be, and F, and

the quantities and forms of tritium for each proposed CTR design, that are anticipated to be present in process wastes, coolant cleanup, or in reactor parts requiring maintenance. Estimate the radiological and toxic implications of each of these. Examine and evaluate existing technology for measuring each of the pollutants anticipated to be present in the waste handling procedures.

By 1985: Optimize existing technology for application in monitoring specific processes or problems. Develop appropriate new technology for measuring and monitoring the radiological and toxic materials manifested in waste handling procedures in conjunction with evolving engineering requirements or proposals.

Program Unit Priority

Severity of Problem: A

The production of large quantities of radioactive spallation products in CTR components is a certainty. These will have to be dealt with in coolant cleanup and reactor maintenance. The toxic nature of the coolants themselves, along with the tritium in the coolants, adds to the health and pollution problem.

Extent of Problem: C

Waste handling risks and exposure will be limited to plant personnel.

Need for Information: A

It is necessary to identify and characterize each radioactive or toxic species anticipated to be present in reactor wastes as well as to monitor the quantities present in order to adequately protect plant personnel from unnecessary or inadvertent exposure.

Urgency: B

Actual monitoring capability will not be required until CTRs are operational. However, preliminary research is necessary to allow adequate time for development of appropriate technology.

Estimated Program Costs

1) Total program unit - $2 million
2) FY-1977 - $100 thousand

PROGRAM UNIT TITLE: Pollutant Release to the Environment from the Preparation of CTR fuels, Construction Materials, and Special Components

Technology: Fusion (CTR)

King-Muir Category: Characterization, Measurement, and Monitoring

Scope

Controlled thermonuclear reactors will require large amounts of hazardous substances for their operation. Large quantities of tritium and deuterium will be required for first-generation CTRs and, depending on specific design characteristics, hundreds of tons of Li, Be, and "flibe" (LiF and BeF_2) may be used. In addition, hybrid reactors will contain a blanket of fertile heavy elements such as uranium-238. By the year 2000, if CTRs are built in place of LMFBRs, the total U.S. domestic consumption of lead will increase more than threefold, and the consumption of lithium will increase nearly 100-fold. This program unit will estimate the amounts and forms of pollutants that may enter the environment from increased mining and refining of these or other materials and will develop the technology to measure and monitor releases of tritium and other hazardous materials used for startup operation.

Milestones

By 1980: Identify the major environmental pollutants from the mining, refining, and fabricating processes for all materials likely to require significant production increases. Evaluate possible release mechanisms and forms of potentially released tritium and other hazardous operating materials. Evaluate applicability and effectiveness of existing technology for monitoring hazardous materials or increased pollutant releases that would result from full development of a CTR program.

By 1985: Develop appropriate monitoring capability where adequate technology is not available. Evaluate proposed technology for reduction of releases and estimate release rates.

Program Unit Priority

Severity of Problem: A

Potential for release of hazardous or polluting materials is high.

Extent of Problem: C

Effects are likely to be localized and of concern in mining, production, and refining operations.

Need for Information: B

Major increases in production of lithium, beryllium, flibe, and perhaps other materials, must precede demonstration plants. The type and quantity of pollutants entering the environment during mining, milling, and production efforts is now uncertain, and such information should be available.

Urgency: B

Actual monitoring capability will not be necessary until material usage requires production. However, the technology must precede the requirements sufficiently to allow uninterrupted progress of CTR development.

Estimated Program Costs

1) Total program unit through 1980 - $3 million
2) FY-1977 - $0.2 million

PROGRAM UNIT TITLE: Releases of Radioactive and Nonradioactive Pollutants - Associated Personnel Health Hazards in Operation of CTRs

Technology: Fusion (CTR)

King-Muir Category: Characterization, Measurement, and Monitoring

Scope

The possibility of tritium loss to the environs exists in each phase of CTR operation: injection, burn, evacuation, recovery, power generation, and storage. Similarly, the loss of breeder blanket/coolant materials such as lithium, lithium-beryllium, flibe, or of heat exchanger materials with their burden of tritium and spallation products presents possible environmental pollution problems. In addition, radioactive spallation products from structural materials may accumulate in heat exchangers, energy generation systems, coolant cleanup systems, and vacuum systems, and thus pose a significant radiological health hazard to personnel. This program unit will 1) identify and characterize the possible radioactive and nonradioactive pollutants which may be produced in and released from fusion reactors, 2) optimize measurement technology for the various species involved, 3) develop suitable monitoring equipment capable of detecting these anticipated pollutants, 4) identify likely fast neutron reaction product concentration points and assess technology needs for reducing the radiological hazard from these pollutants, and 5) verify the adequacy of dosimeters and instrumentation for monitoring personnel exposures to neutrons.

Milestones

By 1980: Identify the pollutants and their chemical forms likely to be released from all operational steps including fuel recovery, energy conversion, and

loss of coolant (LOC) accidents. Identify possible radiological hazards from buildup of radioactive neutron spallation products.

By 1982: Evaluate the applicability of existing technology for the measurement and monitoring of each of these releases or hazards.

By 1985: Optimize current or develop new techniques for real-time monitoring of each potential pollutant release. Assess and evaluate techniques proposed for the reduction and control of releases or radiological exposure to personnel throughout CTR operation.

Program Unit Priority

Severity of Problem: A

The potential for continuous or accidental release of radioactive or toxic pollutants from CTR operation is high. Large quantities of radioactive residues from fast neutron reactions are certain to be generated.

Extent of Problem: B

Except in the case of LOC accident or fire, the widespread release of pollutants is not anticipated. Similarly, radiation exposure, other than from tritium, is anticipated to be confined to plant personnel.

Need for Information: B

It is necessary to identify each possible pollutant, its potential release or concentration points, and its potential effects on the environs and the populace, as well as develop appropriate technology for measuring and monitoring each species and reducing the probability or frequency of release.

Urgency: C

The technological capability for characterization, measurement, and monitoring of potential releases must precede development and operation; however, major demonstration projects are probably at least a decade away.

Estimated Program Costs

1) Total Program Unit - $10 million
2) FY-1977 - $0.5 million

PROGRAM UNIT TITLE: Possible Release of Tritium During Loss of Helium from Superconducting Magnets

Technology: Fusion (CTR)

King-Muir Category: Characterization, Measurement, and Monitoring

Scope

Controlled thermonuclear reactors operating on a magnetic confinement concept will use very large superconducting magnets. Although the magnetic fields generated will be much higher than any currently in operation, the technology required to monitor the fields at any location has already been developed. Some research on biological effects of high-strength magnetic fields and on methods of field reduction will be required. These large superconducting magnets will be cooled by liquid helium. Since the ash from the (D,T) fusion reaction is helium, and since the burned plasma must be reprocessed for tritium recovery, the helium ash could also be purified for use as magnet coolant. In addition, tritium diffusion through metals may result in tritium contamination of the liquid helium cryogen. This program unit will investigate the probability of helium recovery and use in terms of potential tritium content and its escape to the environs.

Milestones

By 1980: Determine solubility of tritium in liquid helium and evaluate the probable and possible tritium concentrations in magnet coolants.

By 1985: Develop and optimize technology for monitoring magnet coolant losses of both helium and tritium and for monitoring the tritium content of magnet coolants.

Program Unit Priority

Severity of Problem: C

The use of reprocessed helium ash could be economically advantageous. However, some tritium will probably be present in such recovered helium.

Extent of Problem: B

Loss of helium from magnet coolants could result in a loss from the plant proper and any tritium present in the helium could become widespread.

Need for Information: B

If helium ash is recycled, it will be necessary to develop technology for purifying it of tritium, and, in any case, the tritium content of the cryogen must be monitored as a safeguard in case of a LOC accident. The general solubility and behavior of tritium in liquid helium needs to be determined.

Urgency: C

On-line monitoring will not be required until a plant is operational, but the technology should be developed earlier to both monitor the coolant stream and purify the helium ash.

Estimated Program Costs

1) Total Program Cost - $0.4 million
2) FY-1977 - $25 thousand

PROGRAM UNIT TITLE: Distribution and Transport of Tritium Released from Fusion Reactors

Technology: Nuclear Fusion

King-Muir Category: Physical-Chemical Processes and Effects

Scope

This program unit seeks to define the hydrological, environmental, and global processes that influence the transport and distribution of tritium (T) released from fusion reactors. The research will focus on mechanisms that distinguish between HT and HTO transport and rates of oxidation between HT and HTO. The role of differential transport and hydrological cycling will be examined relative to potential hazards and dose commitments from tritium releases for both acute accidental and chronic conditions. A key consideration will be to quantitatively estimate the distribution of the tritium accumulation into the various compartments of the environment so that subsequent exposure conditions can be more accurately predicted.

Program Unit Priority

Severity of Problem: B

Basic concepts are already established; refinements in data are needed on micro and mesoscale transport problems, especially for HT transport.

Extent of Problem: A

Tritium exposures of global population groups may be limiting factors for fusion technology.

Need for Information: B

New data are needed on HT reactions in atmosphere and ecosystems. Refinements in data are needed on HTO transport.

Urgency: B

Studies are to proceed concurrently with development of fusion technology; research will provide feedback on required tritium containment in reactor plant.

Estimated Program Costs

1) Total - $15 million
2) FY-1977 - $1.0 million

PROGRAM TITLE 1: Determine, Using Appropriate Experimental Animals and Other Laboratory Model Systems, Qualitative and Quantitative Effects on Living Systems of Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 1.1: Determine Biologic Effects of High Magnetic Fields

Technology: Fusion

King-Muir Category: Health Effects

Scope

Although a number of studies have examined the response of biological systems to magnetic fields, many of the studies used rather large fields for limited periods and the results were highly variable and often not reproducible. Sufficient experimental data are not available for predicting the effects of prolonged exposure to high magnetic fields typical of the occupational situation in magnetic confinement CTR facilities. The scope of this program unit includes the study, in experimental animals and other laboratory systems, of behavioral, teratologic, mutagenic, physiologic, metabolic and pathologic effects of such fields, particularly as a result of long-term exposures. Additional studies will investigate the exacerbation of existing dysfunctions (e.g., subthreshold epileptiform brain activity), the synergistic effects of magnetic fields with radiation, and the consequences of exposure to patients with implanted electronic medical devices. The program also seeks to develop reliable theories on the mechanisms of interaction of magnetic fields with biologic materials.

Program Unit Priority

Severity of Problem: B

Workers in CTRs using poloidal fields can receive exposures to magnetic fields of hundreds of gauss.

Extent of Problem: C

Only occupational groups will be significantly exposed.

Need for Information: A

Existing information is inadequate or conflicting; reliable data are needed to establish exposure standards.

Urgency: A

Definition of design for initial demonstration CTRs is expected in the 1980s. If magnetic fields are shown to produce effects on workers, design selection will be significantly affected. Therefore, it is essential that suitable experiments and epidemiologic work be completed before 1985.

Estimated Program Costs

1) Total - $10 million
2) FY-1977 - $0.5 million

PROGRAM TITLE 1: Determine, Using Appropriate Experimental Animals and Other Laboratory Model Systems, Qualitative and Quantitative Effects on Living Systems of Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 1.2: Determine Biologic Effects of Long-Term Low-Level Neutron Exposure

Technology: Fusion

King-Muir Category: Health Effects

Scope

Depending on CTR biologic shield design, occupational personnel may be exposed to low-level neutron fluxes which may or may not produce subtle or delayed effects. This program is directed toward studies in experimental animals and other laboratory model systems to determine whether such radiation poses a credible risk and, if necessary, to aid in the revision of current human exposure standards. Determination of potential teratologic, mutagenic, and carcinogenic sequelae will be emphasized.

Program Unit Priority

Severity of Problem: B

Existing information is probably sufficient to permit adequate biological shield design if future modifications are not needed. However, most of that information deals with low-energy and thermal neutron exposures.

Extent of Problem: C

Only occupational groups will be exposed.

Need for Information: B

More knowledge is needed in the area of high-energy neutron interactions with biological systems and effects on these systems.

Urgency for Knowledge: C

Continuing studies of neutron effects relevant to both fusion and fission are needed to assure that all exposures can be properly handled.

Estimated Program Costs

1) Total - $5 million
2) FY-1977 - $0.1 million

PROGRAM TITLE 1: Determine, Using Appropriate Experimental Animals and Other Laboratory Model Systems, Qualitative and Quantitative Effects on Living Systems of Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 1.3: Determine Biologic Effects of Fuels and Fuel-Related Components Associated with Controlled Fusion Technology

Technology: Fusion

King-Muir Category: Health Effects

Scope

Several isotopic species may be considered as fuel components if one includes tritium breeders (lithium) and neutron multipliers (beryllium) in the CTR plasma blanket. Occupational and public health hazards arise from the large amounts of these materials in the production of power by nuclear fusion. CTRs that use flibe (LiF-BeF) as a tritium breeding blanket will have to process the flibe to recover the tritium. Such processing increases the potential for release of small amounts of BeF, and therefore the consequences of lifetime exposures to pragmatic levels of BeF and LiF must be evaluated, as well as consequences of acute exposures following accidental releases.

Potential health hazards posed by deuterium are probably minimal, although studies have shown biologic effects as a result of gross incorporation of deuterium oxide by animals. Tritium, on the other hand, represents a potential problem because: it is present in large quantities; it may unavoidably diffuse or leak from various components in the power plant facility; and its environmental conversion may result in the accumulation of readily incorporated tritium oxide and organic tritium compounds in the

atmosphere, water and food web. Whether such forms of tritium pose a human health hazard is controversial, and research--particularly in the areas of mutagenesis and teratogenesis--should be directed toward resolving that controversy.

Program Unit Priority

Severity of Problem: A

With the large curie amounts of T expected to be routinely released and the massive inventories that could escape under accidental conditions, public concern is inevitable. Extensive research at pragmatic T concentrations will be required to respond to this public concern by fully defining occupational and public safety.

Extent of Problem: A

Occupational exposure is of prime importance, but mass exposure to low levels of tritium appears inevitable. Accident situations will increase the magnitude of potential risk and of public reaction.

Need for Information: A

Although considerable information is available on toxicity of tritiated water, it is nevertheless inadequate to define the consequences of lifetime exposure to low levels.

Urgency: A

Research on long-term, low-level effects from tritium should begin immediately.

Estimated Program Costs

1) Total - $50 million
2) FY-1977 - $1.5 million

PROGRAM TITLE 1: Determine, Using Appropriate Experimental Animals and Other Laboratory Model Systems, Qualitative and Quantitative Effects on Living Systems of Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 1.4: Determine Biologic Effects of Radionuclides and Other Hazardous Materials Present and Produced in Fusion Reactor Wall, or in Other Areas, to which Humans May be Exposed

Technology: Fusion

King-Muir Category: Health Effects

Scope

Neutron interactions in blanket materials produce various effects, including atomic displacements, gas production (through n,α and n,p reactions), transmutation to different chemical species and post-shutdown release of "afterheat" through radioactive decay of activated materials. Radioactive material induced in the containment vessel becomes important because various mechanisms (sputtering, gas blistering, embrittlement, alloying) may necessitate periodic replacement of the vessel and cause activation products to be present in spent plasma and in the lithium blanket. Occupational personnel may be directly exposed and, in the event of accident, the public sector may risk exposure to activation products. Materials presently considered for first wall containment include stainless steel, vanadium, molybdenum, niobium, and graphite. Activation products from such materials must be assessed for their potential implications to health. Fast fission decay products should also be considered if the fission-fusion hybrid CTR becomes a likely candidate for early use. Immediate work on preliminary tests to evaluate potential oncogenicity in rodents is needed so that more

definite studies in longer-lived animals can be completed before startup of a demonstration CTR in 1990.

Program Unit Priority

Severity of Problem: A

Corrosion and spallation of wall materials will introduce radionuclides into the spent plasma recovery system and into the tritium breeding blanket, both of which are routinely treated for fuel recovery. Such treatment increases the potential for release as does wall removal and storage.

Extent of Problem: B

Except for accident conditions and waste storage problems, only occupational groups will be at risk.

Need for Knowledge: B

Little is known about the metabolism and fate of several of these materials. As with any material which could affect human health, knowledge of potential effects is necessary.

Urgency: B

Information should be obtained on the isotopes that are not well documented before operation of the first demonstration CTR. Early testing of metabolic behavior and of the potential of these radionuclides to exhibit oncogenic behavior at concentrations likely to occur in occupational persons is needed. If oncogenic behavior is observed in rodents, tests in longer-lived animals should be completed before 1990, when demonstration CTRs are projected to become operational.

Estimated Program Costs

1) Total - $8 million
2) FY-1977 - $0.25 million

PROGRAM TITLE 2: Assess Risk and Establish Exposure Standards for Humans Exposed to Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 2.1: Develop and Improve Methods for Extrapolating Dose-Effect Relationships in Laboratory Animals and Other Model Systems to Humans

Technology: Fusion

King-Muir Category: Health Effects

Scope

This program involves the use of experimental animals, organs, tissues, cells, and culture techniques with an emphasis on developing predictive models for extrapolation of data from laboratory systems to man. An interspecies comparative approach to dose-effect relationships will be required, as well as a comparison of whole-animal results with those obtained by cell and organ culture. Eventually predictive models applicable to long-term, low-level exposures to various combinations of agents and to delayed toxicologic effects must be developed.

Program Unit Priority

Severity of Problem: A

The value of all other laboratory data on health effects depends on the ability to extrapolate these findings to the human case.

Extent of Problem: Not applicable.

Need for Information: A

Finding suitable models, establishing mechanisms of action, and developing methods for extrapolation to man are problems of high priority in biological research.

Urgency: B

The quest for suitable experimental species and laboratory model systems is an ongoing and continuing long-range problem.

Estimated Program Costs

1) Total - Since this is a problem in common with other technologies, there is no way to identify costs specially identified with the fusion technology.
2) FY-1977 - $1.25 million

PROGRAM TITLE 2: Assess Risk to and Establish Exposure Standards for Humans Exposed to Hazardous Agents Associated with Controlled Fusion Technology

Program Unit 2.2: Establish and Conduct Epidemiological and Clinical Studies in Selected Population Groups to Evaluate Effects and Assess Risks of Exposure to Radionuclides and Other Hazardous Agents Associated with Controlled Fusion Technology

Technology: Fusion

King-Muir Category: Health Effects

Scope

This program emphasizes the quantitative evaluation of exposure risk and health effects in man produced by long-term, low-level exposure to hazardous agents associated with CTR operation. Periodic clinical examinations, including whole-body counting, of occupational personnel and selected local population groups will be conducted. In addition, a registry should be established to enable comparison of disease incidence and life span in occupational groups with populations remote to CTR facilities. Early studies of populations exposed to high magnetic fields will be required to supplement studies of such field effects in experimental animals, and to provide direct data on humans.

Program Unit Priority

Severity of Problem: A

Early work on magnetic fields is required since results of such work could affect CTR design. Magnetic fields from cyclotrons, acclerators, etc. should be examined for field strengths in areas occupied by workers, and the workers then surveyed.

Extent of Problem: B

Occupational groups are the major concern.

Need for Information: B

There is no known epidemiologic study of effects from magnetic fields on humans, and it would be difficult to identify possible parameters for such a study. However, the possibility of neurologic or behavioral effects, as well as other potential effects, needs careful evaluation. Combined effects from such factors as tritium and magnetic fields should also be studied to assure safe working conditions at CTRs.

Urgency: A

An epidemiologic study of effects on humans exposed to existing magnetic fields is needed immediately to supplement animal studies and make such studies more relevant to humans.

Estimated Program Costs

1) Total - $5 million
2) FY-1977 - $0.2 million

PROGRAM UNIT TITLE: Behavior of Nonradioactive Chemicals, Thermal and Magnetic Energy Likely To Be Released to the Environment During CTR Operation and the Ecological Significance of Such Releases

Technology: Fusion

King-Muir Category: Ecological Effects

Scope

CTRs will require large amounts of special materials such as lithium metal and flibe ($LiF-BeF_2$), Nb, V, and Pb. Although the ecological behavior of some of these elements is known in a qualitative sense, little is known about the quantitative aspects of large environmental release. This program will emphasize measurements of sublethal stress resulting from chronic releases during operation of CTRs and from related mining and manufacturing activities. Acute damage parameters must be identified to establish consequences of accidental releases. Thermal and chemical releases are not unique but their magnitude of involvement may require special attention. Effects of magnetic fields should be studied if the technology indicates that measureable forces operate outside the reactor building.

Milestones (Following Program Initiation)

Year 1: Estimate source terms based on literature and engineering calculations pursuant to design of laboratory and field experiments. Thermal effects studies should be coordinated with similar work for other energy sources.

Year 3: Identify biota and life stages most sensitive to lithium.

Year 6: Determine implications of acute exposure to Li in selected compartments of terrestrial and aquatic ecosystems.

Future: Evaluate other potential pollutant effects as CTR technology development dictates need for information.

Program Unit Priority

Severity of Problem: B

Releases of potentially toxic materials unique to CTRs may result from accidents as well as from their mining, refining and manufacture.

Extent of Problem: C

These materials will not likely become widely dispersed. Local concentrations of significance are more likely as a result of mining, refining, manufacturing, or accidental releases.

Need for Information: B

Little is now known about ecological effects from CTR candidate materials such as lithium, Be, V, and Nb. Protection of native life systems and of human health requires much improved knowledge of their behavior in biotic systems.

Urgency: C

Only lithium appears to have assured use in large quantities in CTRs. Work on Li should be initiated soon but other work can await further definition of materials requirements.

Estimated Program Costs

1) Total Program Unit - $5 million
2) FY-1977 - $0.2 million

PROGRAM UNIT TITLE: Determine Behavior of Neutron Activation Products Associated with CTR Operation, Determine their Effects on Ecosystems and Identify Potential Accumulation in Native and Agricultural Food Chains Leading to Human Consumption

Technology: Fusion

King-Muir Category: Ecological Effects

Scope

The highly energetic neutrons from fusion-induced radioactive products may include ^{26}Al, ^{51}Ti, ^{55}Fe, ^{60}Co, ^{49}V, $^{93,94}Nb$, and ^{53}Mn. Due to dissipation of low levels of these materials as aerosols during operation and during periods of containment wall replacement is probable. Although the ecological behavior of some of these materials is known from worldwide fallout sampling in a qualitative sense, quantitative measurements, especially from aerosol → biota → man are still needed.

Milestones (Following Program Initiation)

6 Months: Estimate source terms based on literature and engineering calculations pursuant to design of laboratory and field experiments.

Year 2: Estimate accumulation and retention in selected compartments of terrestrial and aquatic ecosystems.

Year 3: Determine trophic relationships and dose commitment to selected compartments in terrestrial and aquatic ecosystems.

Year 4: Determine implications of longer-term exposure to selected compartments of terrestrial and aquatic ecosystems.

Year 5: Synthesize accumulated information.

Program Unit Priority

Severity of Problem: B

Potential for release of some of these materials appears to be high.

Extent of Problem: C

Effects will be proximate to fusion reactors.

Need for Information: B

This information will be needed to assist in establishing limits for releases during plasma recovery and repurification as well as techniques required for containment wall replacement, storage, and reprocessing.

Urgency: C

Some delay is possible since containment materials have not yet been defined.

Estimated Program Costs

1) Total Program Unit - $5 million
2) FY-1977 - $0.1 million

PROGRAM UNIT TITLE: Determine Nature of Responses of Ecosystems to Tritium Released into Environment by Fusion Reactors and Determine Health Hazards Resulting from Transfer and Transformation Through Food Chains

Toxicology: Fusion

King-Muir Category: Ecological Effects

Scope

Chronic releases of tritium from CTRs are expected to occur by diffusion of the molecular species through heat exchangers and to be released with the air or water used for cooling. Those ecosystems in which tritium oxidation occurs need to be identified and oxidation rates determined so that local and global rates of conversion to the more biologically available tritiated water can be evaluated. Doses delivered to sensitive elements require a careful evaluation, particularly with respect to immunologic compromise, mutation, and species competition.

Milestones (Following Program Initiation)

Year 1: Estimate source terms based on literature and engineering calculations pursuant to design of laboratory and field experiments.

Year 2: Estimate accumulation and retention of tritium in selected compartments of terrestrial and aquatic ecosystems.

Year 4: Determine trophic relationships and dose commitments to selected compartments in terrestrial and aquatic ecosystems.

Year 6: Determine implications of longer-term exposure to selected compartments of terrestrial and aquatic ecosystems.

Year 5: Synthesize accumulated information.

Program Unit Priority

Severity of Problem: B

Released tritium will be primarily in atomic or molecular form and will constitute little hazard until oxidized. Biotic and abiotic systems converting tritium to water and to organic forms need to be identified and conversion rates established to better establish estimates of dose commitments. Specially sensitive biotic systems must be identified.

Extent of Problem: B

Full containment of tritium appears impossible and releases from CTRs will be much higher than from BWRs or PWRs. Worldwide distribution of tritium will occur. Higher local concentrations will occur if rapid oxidation of tritium takes place.

Need for Information: B

It is particularly important to identify conversion rates of tritium to the oxide, and to increase information about effects on sensitive aspects of the biota--such as the immune system.

Urgency: B

Substantial time remains to acquire the needed data for CTRs. However, this problem is not unique to fusion and specific problems now identified, such as effects of low doses of T on the immune system, need to be actively pursued.

Estimated Program Costs

1) Total Program Unit - $7 million
2) FY-1977 - $0.2 million

PROGRAM TITLE 1: Environmental and Health Impact Assessment

Program Unit 1.1: Determine Current State-of-the-Art for Evaluating Environmental and Health Effects from Fusion Energy Systems; Define Source Terms from Various Fusion Fuel Cycle Components; and Identify Major Data Inputs to Environmental Transport and Health Consequences Calculations

Technology: Fusion (CTR)

King-Muir Category: Integrated Assessment

Scope

Maintain contact with developing CTR technology. Source terms from the entire fusion energy cycle (including raw material extraction, pre-treatment processes, power plant operation, material transportation, and waste disposal) will be evaluated with state-of-the art technology to comprehensively estimate environmental and health consequences of fusion energy systems. Source terms evolving from CTR research will be used to rank problem importance and prioritize needed research.

Program Unit Priority

Severity of Problem: B

Liaison with CTR research needs to be maintained so early identification of potential health and environmental effects can be identified.

Extent of Problem: C

It would be premature to identify the extent of health and environmental effects at this time.

Need for Information: B

Coherent evaluation of potential effects will be required.

Urgency: C

CTR technology is still in an early exploratory stage.

Estimated Program Costs

1) Total - $0.25 million
2) FY-1977 - $75 thousand

PROGRAM TITLE 1: Environmental and Health Impact Assessment

Program Unit 1.2: Develop an Empirical Method for Ranking Source Terms; Evaluate and Develop Safety and Environmental Criteria for the Assessment of Environmental Impact of Fusion Energy Systems

Technology: Fusion (CTR)

King-Muir Category: Integrated Assessment

Scope

Develop list of expected guidelines and criteria for licensing fusion reactors, related materials supply, reprocessing, and waste disposal facilities; identify needed criteria that cannot be developed through adoption or modification of existing criteria.

Program Unit Priority

Severity of Problem: B

A coherent approach to identifying relative importance of source terms and applying them is needed.

Extent of Problem: C

Not yet established.

Need for Information: B

Potential implications of CTR technology must be analyzed by groups skilled in systematically evaluating health and environmental implications of new technologies.

Urgency: C

Source terms are not yet sufficiently identified to permit substantive development of new methods or testing of existing methods.

Estimated Program Costs

1) Total - $1 million
2) FY-1977 - $0.1 million

APPENDIX I

Some of the material requirements projected for CTR and LMFBR power plants are shown in Tables I through IV, which will be published in BNWL-2013, "Current Fusion Power Plant Design Concepts."

TABLE I. CTR Powerplant Material Requirements - Construction*
(Metric Tons)

Element	UWMAK-I[a] Nuclear Island[g]	UWMAK-I[a] Balance of plant[h]	UWMAK-I[a] Total	PPPL[b] Total	ORNL[c] Nuclear Island	Theta Pinch[d] Total	Mirror[e] Reactor and Convertor[i]	BNL Blanket[f] Blanket and Shield
Al	347	445	792	17				2488
B	1580		1580					5790
Be				875		50		189
C	446		446		1100	680	233	3138
Cr	5490	6199	11689	1658	36		7506	
Cu	7466	3259	10725	3264	450	9300	8810	
Fe	18872	95924	114796	11921	6424		24770	
He	58	80	138	117	1	1200		
Hg		3	3					
K					10			
Li	1700		1700	598	460	1600[j]	83	60[j]
Mn	607	608	1215	164			751	
Mo	579	22	601	288				
Na		17826	17826					
Nb	101	39	140	102	1000	3600		
Ni	4221	4484	8705	1547	28		4504	
Pb	20500		20500		5350		1272	
Sn				34		300		
Ti	52	20	72	17	642			
Y		5	5					
Zr		100	100	1	1			
Concrete		680,000	680000	32000	20000		38200	

TABLE II. CTR Powerplant Material Requirements - Average Annual Replacement Quantities* (Metric Tons)

Element	UWMAK-I[a]	PPPL[b]	ORNL[c]	Theta Pinch[d]	Mirror[e]	BNL Blanket[f]
Al	7.2					252
Be				10		1
C			110	140	11.	174
Cr	129.	39			6.3	
Cu	7.2			2		
Fe	445.	85			20.	
He				1		
Li				16		5
Mn	14.				0.6	
Mo	14.					
Nb			14	77		
Ni	100	94			3.8	
Zr			0.1			

*See Footnotes to Table I

a. Due to 316 SS replacement. 32% due to biannual replacement of inner blanket; 68% due to replacement of remainder of blanket every 10 years.

b. Due to Pe-16 replacement; one-fifth of blanket each year.

c. Replace blanket every 10 years.

d. Replace one-fifth of blanket modules each year.

e. Blanket life is not estimated in the design. 304 SS structure and first wall loading are similar to UWMAK-I. Table is based upon replacement schedule postulated by rough analogy to UWMAK-I. Replacement of inner 30 cm of blanket every 2 years; replacement of outer 70 cm of blanket every 10 years; 30 year plant life.

f. Replace one-third of blanket modules each year.

TABLE I. Footnotes

*In addition to the sources indicated in footnotes a, b, c, d, e, and f, the following powerplant designs were consulted but did not include information on material requirements:

J. Williams, T. Merson, F. Finch, F. Schilling, and T. Frank, "A Conceptual Laser Controlled Thermonuclear Reactor Power Plant," CONF-740402-P1, Proceedings of the First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, CA, April 16-18, 1974. (The "Wetted Wall" concept.)

A. P. Fraas, "Conceptual Designs of a Series of Laser-Fusion Power Plants of 100 to 300 MW(e)," presented at the 9th Intersociety Energy Conversion Engineering Conference, San Francisco, CA, August 26-30, 1974. (The "Blascon" concept.)

J. Hovingh, J. Maniscalco, M. Peterson, and R. W. Werner, "The Preliminary Design of a Suppressed Ablation Laser-Induced Fusion Reactor," CONF-740402-P1, Proceedings of the First Topical Meeting on the Technology of Controlled Thermonuclear Fusion, San Diego, CA, April 16-18, 1974. (The "Suppressed Ablation" concept.)

a. Review Draft, 5/9/75; B. Badger et al. (22 authors), UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design, Volume II, UWFDM-68, University of Wisconsin. Net Plant Output is 1475 MWe.

b. A Fusion Power Plant, R. G. Mills, Ed., MATT-1050, Princeton Plasma Physics Laboratory, 1974. Does not include requirements for small components such as valves, pumps, electrical equipment. Net Plant Output is 2030 MWe.

c. A. P. Fraas, Conceptual Design of the Blanket and Shield Region and Related Systems for a Full Scale Toroidal Fusion Reactor, ORNL-TM-3096, May 1973. Major components only. Net Plant Output is 518 MWe.

d. J. E. Draley, R. A. Krakowski, T. A. Coultas, and V. A. Maroni, An Engineering Design Study of a Reference Theta-Pinch Reactor (RTPR): Environmental Impact Study, LA-5336, ANL-8019, (joint report), Vol. II, March, 1975.

e. R. W. Werner, G. A. Carlson, J. Hovingh, J. D. Lee, and M. A. Peterson, Progress Report #2 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor, UCRL-74054-2, September 1973. As emphasized by the title, this design is for an experimental device of low power. Optimization for power production would be expected to introduce economics of scale reducing some of the material requirements per MWe. Covers blanket and shield, Cu for coils, 304 SS coil support structure and direct convertor structure. Superconductor for coils not included. Net plant output is 170 MWe.

f. J. R. Powell, Ed., "Preliminary Reference Design of a Fusion Reactor Exhibiting very Low Residual Radioactivity." BNL-19565, Brookhaven Nat'l Lab, December 1974. Net Plant Output is 1605 MWe.

g. Only construction materials included here (differs from tabulation in source). Tabulation includes all material within toroidal magnets, plus divertor and vertical field coils, injectors, and entire primary coolants.

h. Not including turbine, reheaters, control room, cooling towers and electrical switch gear. Not including tritium extraction equipment except yttrium.

i. These requirements were not developed in the design document. Blanket and shield requirements were calculated from the spherical shell neutronics model; coil requirements and materials for coil support and for the direct convertor structure were calculated from descriptions and dimensions, by G. A. Carlson.

j. Feedstock for ^{6}Li enrichment included.

TABLE III. Normalized CTR Powerplant Material Requirements - Construction*
(Metric Tons/MWe)

Element	UWMAK-I[a] Total	PPPL[b] Total	ORNL[c] Nuclear Island	Theta Pinch[d] Total	Mirror[e] Reactor and Convertor	BNL Blanket[f] Blanket and Shield	Reference Envelope* Maximum
Al	0.54	0.008				1.55	1.6[f]
B	1.07					3.61	3.6[f]
Be		0.43		0.012		0.12	0.4[b]
C	0.30		2.12	0.17	1.4	1.96	2.1[c]
Cr	7.92	0.82	0.07		44.		44. [e]
Cu	7.27	1.61	0.87	2.27	52.		53. [e]
Fe	77.8	5.87	12.4		146.		146. [e]
He	0.09	0.06	0.002	0.29			0.3[d]
Mg	0.002						0.002[a]
K			0.02				0.02[c]
Li	1.15	0.29	0.89	0.39	0.49	0.04	1.2[a]
Mn	0.82	0.08			4.4		4.4[e]
Mo	0.41	0.14					0.4[a]
Na	12.1						12.1[a]
Nb	0.09	0.05	1.93	0.88			1.9[c]
Ni	5.90	0.81	0.05		27.		27. [e]
Pb	13.9		10.3		7.5		13.9[a]
Sn		0.02		0.07			0.02[b]
Ti	0.05	0.008	1.24				1.24[c]
Y	0.003						0.003[a]
Zr	0.07	0.0005	0.002				0. [a]
Concrete	461.	15.8	38.6		225.		461. [a]

* See Footnotes to Table I

- Maximum quantities are from designs correspondingly labeled

TABLE IV. Normalized CTR Powerplant Material Requirements - Average Annual Replacement Quantities* (Metric Tons/1000 MWe)

Element	UWMAK-I[a]	PPPL[b]	ORNL[c]	Theta Pinch[d]	Mirror[e]	BNL Blanket[f]	Reference Envelope Maximum
Al	4.9					157.	157.[f]
Be				2.4		0.6	2.4[d]
C			212.	34.	66.	108.	212.[c]
Cr	87.	19.			37.		87.[a]
Cu	4.9			0.5			4.9[a]
Fe	302.	42.			118.		302.[a]
He				0.2			0.2[d]
Li				3.9		3.	3.9[d]
Mn	9.5						9.5[a]
Mo	9.5				3.7		9.5[a]
Nb			27.	19.			27.[c]
Ni	68.	46.			22.		68.[a]
Zr			0.3				0.3[c]

*See Footnotes to Table I and III.

Maximum quantities are from designs correspondingly labeled.

APPENDIX II

The following report summarizes our current information about effects from magnetic fields and indicates research needs in this area. This material was taken from the manuscript which later appeared as: Biomagnetic Effects: A Consideration in Fusion Reactor Development, (BNWL-1973) by D. D. Mahlum, February 1976.

BIOLOGICAL EFFECTS OF MAGNETIC FIELDS

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INTRODUCTION

Fusion as a power source is receiving increased attention. Several designs have been proposed and the feasibility of each alternative is being studied. As we move closer to a working design, we should note potential biological hazards associated with fusion reactor operation. The presence of large magnetic fields and the emission of tritium and lithium are some of the areas that need consideration.

This report summarizes results of a review of the current state of knowledge concerning biological effects of magnetic fields alone and in combination with ionizing radiation. The purpose of the review is to help identify areas requiring additional biomedical research for establishing guidelines for reactor design and operation.

Although this review has as its main focus an evaluation of the potential biological effects associated with operation of fusion reactors, those effects may also have implications for other situations. For example, bubble chamber operations, cyclotron maintenance, eventual use of levitated trains, space travel, and work around high-voltage systems may all result in exposure of people to fields greater than the geomagnetic background.

The references included in this review represent only a fraction of the literature available on biological effects of magnetic fields. The work by Busby (1), the volumes edited by Barnothy (2,3) and the English translation of the Russian work by Presman (4) as well as the bibliographies by Manganelli (5), and Davis, Pappajohn, and Plavinieks (6) provide additional and more detailed review material on biomagnetic effects.

Current fusion reactor concepts rely on the use of magnetic fields to confine high temperature plasmas. The magnitude and geometry of these fields will depend on the reactor concept ultimately employed. The Tokamak and Yin Yang configurations both have a large dipole field external to the biological shield. In contrast, the external magnetic field of the theta pinch design should be small because of effective cancellation of opposing field coil elements that leave only high order multipole moments. The laser implosion concept uses a modest divertor field to protect its inner wall.

The most extensive calculations and plots of magnetic field patterns have been performed for the Tokamak reactor as conceived in UWMAK-I and based on a 5000-megawatt thermal plant. Two types of magnetic fields are encountered in a reactor based on this concept, a toroidal field produced by the main toroidal magnetic field coils and a poloidal field produced by the plasma current, divertor coils, and transformer coils. The toroidal field is generated in the plane of the torus and the strength may vary from 10,000 gauss in the area surrounding the nuclear island to <1 gauss at the outer edge of the reactor building (about 50 meters). The poloidal field radiates both vertically and horizontally relative to the torus and requires a distance of 500 meters to reach <1 gauss.

Levels of ionizing radiation will limit access to parts of the reactor building; thus, there may be little likelihood of exposure to the toroidal field. However, poloidal fields of several hundred gauss may be encountered by people working in the transport and hot-cell regions. Conceivably, these fields could be as high as 70 to 450 gauss. Those people working in the region immediately surrounding the reactor building and associated facilities could be subjected to field strengths of 1 to 70 gauss for substantial periods. Beyond the horizontal plant boundaries, the field strength will have decreased to background so population exposures will not be involved. It is possible that some wildlife, particularly birds, could be exposed to field strengths in the same range as those encountered by people working in the region surrounding the reactor complex.

Certain strategies such as using a Mu metal liner in the wall of the reactor building or redesigning the transformer to balance currents may help reduce the field strengths outside of the reactor. On the other hand, higher field strengths may be produced if the resistivity of the plasma is lower than the presently used value or if different temporal factors are used.

POPULATIONS OF CONCERN

The general public will not be exposed to the magnetic fields used in fusion reactors. The major consideration in evaluating possible consequences of exposure of people to a high magnetic field is, therefore, directed toward

personnel working in the reactor and associated facilities. This group can then be considered in view of the likely makeup of its various subgroups: (1) male and female; (2) those with a potentially greater sensitivity to insult, (a) those with identifiable medical problems, (b) those with identifiable psychological problems, (c) pregnant women, and, (d) those with medical prosthetic devices.

Magnetic exposure of other biological material in the environment surrounding the fusion reactor will probably be of minimal consequence. An exception to this might be birds; evidence is accumulating that their navigation is at least partially governed by geomagetic information.

SUMMARY OF LITERATURE

Human

Interest in the biological effects of magnetic fields goes back perhaps thousands of years to the connections made between human health and the mysterious power of the lodestone. Present day interest in this area is indicated by the efforts of a number of investigators to correlate disturbances in the earth's magnetic field caused by solar flares with incidence of death (7), mental disorders (8,9), and catastrophic events (10). In any retrospective epidemiologic study, cause and effect relationships are difficult to establish and the situation with magnetic fields is no exception.

During the past hundred years a number of studies have been performed in an attempt to determine if man is capable of responding in some way to a magnetic field. Perhaps the first documented effect in man which was consistently reproducible was that of seeing light flashes when the head

was placed in an alternating magnetic field (11). This phenomenon known as magnetic phosphene has been studied in detail by a number of investigators and several hypotheses advanced to explain it. Barlow, Kohn, and Walsh (12) concluded that the retina was the probable locus of the effect and Valentinuzzi (11) developed a mathematical model to account for the excitation mechanism. Peterson and Kennelly (13) and Drinker and Thompson (14), using static magnetic fields of approximately 2500 gauss, reported no observable effect when the head was placed between the poles of the magnetic field.

Beischer, Grissett, and Mitchell (15) have examined the response of human volunteers to an extremely low frequency (ELF) alternating magnetic field (10^{-4} webers). The subjects were confined for a one-week period and exposed for either 10 or 22.5 hours at a time unknown to them. A large number of measurements were made, including body temperature, heart rate, respiration rate, blood pressure, electrocardiograms, effect of stress, short-term memory, psychological response, and extensive blood and urine analyses. The only significant change found was a transient rise in serum triglyceride levels after cessation of exposure.

In contrast to these well controlled experimental studies, there are a number of subjective studies which indicate that people exposed to magnetic fields experience a number of objectionable effects. Beischer and Reno (16) quoted results of the studies of Soviet workers who were engaged in the fabrication of permanent magnets. The Soviets reported both brady- and tachycardia and a decrease in arterial blood pressure. The workers exhibited increased irritability, fatigue, occasional dizziness, altered appetite

and headaches. Changes were found in the electroencephalograms, particularly during light stimulation. Hands were reported to exhibit a marbling pattern as well as itching, burning, and numbness. No estimate of field strength was reported in Beischer's discussion. Beischer also reported that placing the hand in a 120,000-gauss field resulted in a feeling of bitter coldness and aching of bones, along with a feeling as if ants were moving over the hands.

Friedman, Becker, and Bachman (17) exposed heads of patients to fields of 5-11 gauss modulated at either 0.1 or 0.2 cycles per second. Exposure to the 0.2 cycles per second field slowed the reaction time significantly. Exposure to a 0.1 c/s or a static field did not alter the reaction time. No consistent changes in EEG patterns accompanied the alterations in the reaction times (18).

The work of Cohen (19,20) is of interest when considering the possible response of man to a magnetic field. In two very careful studies, he was able to demonstrate that there are very small magnetic fields associated with normal physiologic functions of the human body. He observed a magnetic field component which was similar to the ECG component associated with ventricular depolarization and repolarization. He also has found magnetic fields at the surface of the scalp which appear to be produced by alpha rhythm currents of the brain.

Non-Human Primates

Data in non-human primates have been provided by Beischer and coworkers (21,22). They have exposed squirrel monkeys to fields of 20,000 to 100,000 gauss and studied changes in the electrocardiogram. Breathing rates and R-wave amplitude were unchanged but there was a decrease in heart rate, an

increase in sinus arrhythmia and an increase in the amplitude of the T-wave. Further investigation showed that part of the change in the electrocardiogram was due to an EMF generated by aortic blood flow.

There are various other studies with experimental animals and isolated organs or tissues which indicate that neurological, cardiac, and other muscular function can be affected by magnetic fields. However, the magnitude of the field required is usually quite large.

Growth and Development

Immature organisms often demonstrate an enhanced sensivitity to insults of various kinds including radiation, administration of toxic drugs and metals and a variety of environmental challenges. The biochemical and physiologic processes occurring during differentiation and growth often amplify the damage which has been produced, facilitating detection and measurement of alterations inflicted by an agent. Several studies have attempted to utilize this concept for studying biomagnetic effects. Windle (23) in 1895 reported an increased incidence of malformations in the chick after exposure to an ill-defined magnetic field. However, he found no developmental abnormalities when he used the silkworm. Perakis (24) found a retardation of development and an increased incidence of abnormalities of sea urchin eggs exposed to non-homogeneous fields of 8,800 or 43,000 gauss. A uniform field of 33,000 gauss appeared to have no effect. Beischer (25) also reported retardation of development of the sea urchin egg with a field of 140,000 gauss. Neurath (26,72) and Levengood (28) worked with frogs and salamanders, also providing evidence for an effect of magnetic fields on

development. Moreover, evidence for the importance of this stage of development was presented by Levengood. The fields used in these studies ranged between 6,300 and 17,700 gauss with large gradients.

Another study by Levengood (29,30), in which Drosophila pupae were exposed to approximately 150 gauss from a magnetic probe, showed that the development time was increased significantly. Moreover, when treated males were bred to untreated females, the offspring showed an increased development time; this characteristic was transmitted for 30 generations. In addition, the number of progeny from these crosses were fewer than from control matings. Treated females did not carry the trait for increased development time. The ability of a magnetic field to affect development in Drosophila was further documented by Tegenkamp (31) who found an alteration of sex ratio as well as other genetic changes. Mulay and Mulay (32) also reported abnormalities in Drosophila; these seemed to be non-genetic. Beischer (25), in contrast, found no effect of either homogeneous or non-homogeneous fields on Drosophila development.

Only a few studies have been made of developmental effects using mammals. Barnothy (33) reported that exposure of young mice to either a homogeneous or a nonhomogeneous field resulted in a decreased weight gain. The effect of the homogeneous field was greater than that of the nonhomogeneous field, although the differences were not great. Eisenlein, Boutell and Biggs (34), using large groups of mice approximately three weeks of age, found no effect of a magnetic field on weight gain over a period of 11 days. The field varied between 8,800 and 14,400 gauss.

An extremely low frequency (0.5 Hz) rotating field of 0.5 to 15 gauss was imposed on pregnant rats for various

periods during gestation (35). Offspring were found to have higher thyroid and testicular weights than the controls. A number of behavioral measures were also found to be altered in the magnetic-field-treated animals. No differences were found in eosinophil counts, adrenal weights, blood sugar, or body weights.

Behavioral Effects

There are various other pieces of evidence indicating that organisms are capable of responding to the presence of magnetic fields. Studies of behavior among nonmammalian animals indicate varying degrees of sensitivity and responsiveness to magnetic fields. A recent paper by Keeton in Scientific America (36) presents evidence which shows that some species of birds depend on geomagnetic input for navigational purposes. Keeton also refers to work which indicates that honey bees are sensitive to magnetic fields of a few gamma (10^{-5} gauss). These studies, along with those which show that a diverse array of organisms can respond behaviorally to magnetic fields, are important indicators of the ability of magnetic fields to affect some biological responses. Barnwell and Brown, and Brown (37,38) have shown that the directional movement of both planaria and snails can be influenced by placing them in a low-level magnetic field. The type of effect was also influenced by time of day and lunar position. Gottlieb and Caldwell (39) also found the behavior of snails to be influenced by imposition of a magnetic field. Again there was an interaction of time of day and month on the response to the field. The honey bee was also shown to respond to a magnetic field (40); their response tended to be a narcoleptic one in which they became

rigidly fixed at a point corresponding to maximum field strength. Several other studies (41-44) have shown behavioral changes for Diptera, electric fish, paramecium, and Drosophila when exposed to magnetic fields.

Experiments performed by Russell and Hedrick (45) indicate that mice allowed to choose between a low and high magnetic environment spent more time in the lower field. However, when the number of trips from a neutral position were counted, more were made into the high field. The food and water consumption was also higher in the high magnetic field.

Persinger (46) found that rats exposed prenatally to a low-frequency, rotating magnetic field exhibited decreased activity in an open-field test than did the controls. Persinger and Pear (47) also used a suppressed response paradigm to test prenatally-exposed rats and found them to be more easily suppressed than were the controls.

These varied studies indicate that a diverse array of organisms can respond behaviorally to a magnet field. These data along with those reported for the human are important in that they show the ability of a magnetic field to affect certain biological responses.

Other Effects

The effect of magnetic fields on biological systems has been studied in a variety of ways. Hematologic studies have been reported by a number of investigators (48-51) and the results vary from a marked effect on leukocyte levels as found by Barnothy and coworkers (48) to no effect as reported by Eiselein, Boutell, and Biggs (34). Neither group found an effect of a magnetic field on erythrocyte levels. Hackel (50), however, using an in vitro test system, found an

enhancement of erythrocyte agglutination when the reaction took place in a magnetic field. A very interesting study by Murayama (51) showed that sickled erythrocytes placed in a static field became oriented with their long axes perpendicular to the field.

Pathologic changes in the tissues of animals have been reported by Barnothy and Sumegi (52), Kholodov et al. (53) and Friedman and Carey (54). Barnothy and Sumegi (52) reported marked changes in the adrenals of mice after exposure to a 9000-gauss field for 13 days while Kholodov et al. (53) found severe brain lesions in rabbits in their study. Friedman and Carey (54) ascribed the results of the latter studies to an endemic infection found in rabbits. However, they also presented evidence that the effects of the infection were exacerbated by the magnetic field.

There have been many attempts to treat various diseases with magnetic fields and varying degrees of success have been reported. One of the most interesting studies was that of Pautrizel et al. (55) who found that mice and rats could be protected against Trypanosoma infection by treating the animals with a magnetic field. This protective effect appeared to be mediated through the humoral immune system.

Radiation + Magnetic Field

Consideration must be given to effects of combined exposures of organisms to magnetic fields and radiation since personnel working in fusion reactors will have the potential for exposure to both.

Forssberg (56) in 1941 reported the results of an experiment to study the combined effects of magnetic fields and x-radiation on the survival and development of Drosophila.

He found that exposure of Drosophila eggs to 165 R while in a magnetic field resulted in a higher mortality than from radiation alone. The magnetic field, in many experiments increased the mortality by about 17%.

Amer and Tobias (57), on the other hand, found that exposure of the flour beetle, Tribolium confusum, to a magnetic field protected against radiation-induced wing abnormalities. Exposure to a magnetic field also protected against temperature-induced abnormalities (58). Their results suggested that the protective effect of the magnetic field was equivalent to cooling the organism about 1.5°C/8000 gauss. They therefore examined the effect of a magnetic field on liquid crystals which undergo changes in coloration with changes in temperature. They found that application of a 6300-gauss field resulted in a gradual change in color from blue to orange, the same as the change observed when the temperature of the liquid crystal is lowered (59).

Barnothy and Barnothy (60) have also studied the effect of magnetic fields on survival of mice after irradiation. They found an enhanced survival if mice were first exposed to a magnetic field and then irradiated. They ascribe the protective effect to an increased leukocyte concentration found after exposure to a magnetic field.

Sikov (61) performed a number of studies to examine the effect of simultaneous exposure to mice to radiation and magnetic fields. He found some suggestion that there was an interaction of the two agents when certain parameters were examined. The effects of the magnetic fields were not great, and were somewhat inconsistent. It should be noted, however, that only acute exposures (30 minutes) were used so that the time available for interaction of the field with the organism was very limited.

GENERAL EVALUATION

Studies of the possible biological effects of magnetic fields should emphasize field strengths below 750 gauss since it seems unlikely that any significant exposures to higher fields will occur. However, use of higher fields will undoubtedly be necessary to fully define the experimental systems studied. It would also appear that the field will be static but nonhomogeneous. The organisms which are apt to encounter significant fields are humans (working personnel) and birds. The exposure to lower animal forms and plants should be of little significance since the field will be limited to the reactor area.

A number of studies have been performed to examine the response of biological systems to magnetic fields. Many of these have employed rather large fields for limited periods and have not used adequate numbers of experimental subjects for good statistical analysis. The results have been highly variable and often nonreproducible.

Various biological parameters have been studied in animals exposed under many experimental conditions to magnetic fields ranging from a few gauss to 140,000 gauss. The systems studied have included electrical activity of the brain and heart, blood composition, growth and development, genetic defects, tumor growth, and function of enzymes. In addition, several attempts have been made to correlate human behavioral patterns with naturally occurring changes in the earth's magnetic field. A substantial proportion of the many studies reported in the literature have been unable to detect any change in biological structure or function even after exposure to high intensity fields. Others have found significant changes after exposure to even low-strength fields.

Changes in the electrical activity of the brain and heart have been found after exposure of humans, monkeys, rabbits, and pigeons to fields of 500 to 91,000 gauss. There have also been a number of field studies in which correlation has been made between changes in magnetic field and behavior. Documentation has been fairly extensive in these areas although more information is obviously needed.

Some investigations have obtained results which suggest that preexisting lesions may be exacerbated in the presence of magnetic fields while other studies suggest that changes are due to nonspecific stress. These are important areas for further study since people with certain extant medical problems might form a sensitive subpopulation which should be identified.

The genetic effects of magnetic fields have been studied primarily in lower organisms, houseflies, and flour beetles. Changes in mortality and induction of wing abnormalities have been reported. In at least one study, there appeared to be some synergism between the effects produced by irradiation and magnetic field exposures.

Evidence for an influence of magnetic fields on growth and development has been presented from studies on frogs, salamanders, fruit flies, sea urchins, and mice. Of the various studies reported, most have been performed at field strengths above 2500 gauss and the results have varied markedly from no effect to complete prevention of development, depending upon the laboratory performing the study.

There are reports of changes in several other biological parameters as a result of exposure to magnetic fields. Although many of the results are controversial, they do provide guidelines for design of more definitive experiments in the future.

REFERENCES

1. Busby, D. E. Biomagnetics. Considerations relevant to manned space flight. National Aeronautics and Space Administration, Washington, DC, NASA-CR-889, 63 pp. 1967.
2. Barnothy, M. F. (ed.). Biological effects of magnetic fields. Vol. 1, Plenum Press, New York, NY. 324 pp. 1964.
3. Barnothy, M. F. (ed.). Biological effects of magnetic fields. Vol. 2, Plenum Press, New York, NY. 314 pp. 1969.
4. Presman, A. S. Electromagnetic fields and life. Plenum Press, New York, NY. 336 pp. Translated from Russian by F. L. Sinclair and edited by F. A. Brown, Jr. 1970.
5. Manganelli, L. A. Biomagnetism: an annotated bibliography. The George Washington University Medical Center, Biological Sciences Communication Project, Washington, DC. 187 pp. 1972.
6. Davis, L. D., K. Pappajohn, and I. M. Plavinieks. Bibliography of the biological effects of magnetic fields. Fed. Proc. 21 (5, Part II): 1-38, 1962.
7. Dull, T. and B. Dull. Correlations betwen disturbances in terrestrial magnetism and frequency of deaths. Deutsch Medizinische Wochenschrift 61: 95, 1935.
8. Friedman, H., R. O. Becker, and C. H. Bachman. Geomagnetic parameters and psychiatric hospitals admissions. Nature 200: 626-628. 1963.
9. Friedman, H., R. O. Becker, and C. H. Bachman. Psychiatric ward behaviour and geophysical parameters. Nature 205: 1050-1052, 1965.

10. Poumailloux, M. Repercussions humaines de l'activité solaire interne. Cah Call. Med. Hosp. Paris 10: 1201-1214. 1969.
11. Alexander, H. S. Biomagnetics -- the biological effects of magnetic fields. Am. J. Med. Electronics 1: 181-187, 1962.
12. Barlow, H. B., H. I. Kohn, and E. G. Walsh. Visual sensations aroused by magnetic fields. Am. J. Physiol. 148: 372-375, 1947.
13. Peterson, F. and A. E. Kennelly. Some physiological experiments with magnets at the Edison Laboratory. New York Med. J. 56: 729-732, 1892.
14. Drinker, C. K. and R. M. Thompson. Does the magnetic field consitute an industrial hazard? J. Indust. Hygiene 3: 117-129, 1921.
15. Beischer, D. E., J. D. Grissett, and R. E. Mitchell. Exposure of man to magnetic fields alternating at extremely low frequency. NAMRL-1180. Naval Aerospace Medical Research Laboratory, Pensacola, FL. 1973.
16. Beischer, D. E. and V. R. Reno. Magnetic fields and man: where do we stand today? In: A. M. Pfister (ed.), AGARD Conference Proceedings N. 95, Part III, Special Biophysical Problems in Aerospace Medicine. Aerospace Medical Panel Specialist Meeting, Luchon, Franc, September 30 - October 1, 1971. pp. C12-1 - C-12-7.
17. Friedman, H., R. O. Becker, and C. H. Bachman. Effect of magnetic fields on reaction time performance. Nature 213: 949-950, 1967.
18. Becker, R. O. The effect of magnetic fields upon the central nervous system. In: Biological Effects of Magnetic Fields (M. F. Barnothy, ed.). Vol. 2, pp. 207-214. Plenum Press, New York, NY. 1969.

19. Cohen, D. Magnetic fields around the torso: production by electrical activity of the human heart. Science 156: 652-654, 1967.
20. Cohen, D. Magnetoencephalography: evidence of magnetic fields produced by alpha-rhythm currents. Science 161: 784-786, 1968.
21. Beischer, D. E. J. C. Knepton, Jr. Influence of strong magnetic fields on the electrocardiogram of squirrel monkeys (Samimisi sciureus). Aerospace Medicine 35: 939-944, 1964.
22. Beischer, D. E. Vectorcardiogram and aortic blood flow of squirrel monkeys (Saimiri sciureus) in a strong superconductive magnet. In: Biological Effects of Magnetic Fields. (M. F. Barnothy, ed.). Vol. 2, pp. 241-259. Plenum Press, New York, NY. 1969.
23. Windle, B. C. A. On the effects of electricity and magnetism on development. J. Anat. Physiol. 29: 346-351, 1895.
24. Perakis, N. On the physical chemistry of the sea urchin egg and its development in a magnetic field. Bull. d'Histologic Appliquee 18: 115-132, 1941.
25. Beischer, D. E. Survival of animals in magnetic fields of 140,000 De. In: Biological Effects of Magnetic Fields. (M. F. Barnothy, ed.). Vol. 1, pp. 201-208, Plenum Press, New York, NY. 1964.
26. Neurath, P. W. High gradient magnetic field inhibits embryonic development of frogs. Nature 219: 1358-1359, 1968.
27. Neurath, P. W. The effect of high-gradient, high-strength magnetic fields on the early embryonic development of frogs. In: Biological Effects of Magnetic Fields. (M. F. Barnothy, ed.). Vol. 2, pp. 177-187. 1969.

28. Levengood, W. C. A new teratogenic agent applied to amphibian embryos. J. Embryol. Exp. Morphol. 21: 23-31, 1969.
29. Levengood, W. C. Cytogenetic variations induced with a magnetic probe. Nature 209: 1009-1013, 1966.
30. Levengood, W. C. Morphogenesis as influenced by locally administered magnetic fields. Biophys. J. 7: 297-307, 1967.
31. Tegenkamp, T. R. Mutagenic effects of magnetic fields on Drosophila melanogaster. In: Biological Effects of Magnetic Fields. (M. F. Barnothy, ed.). Vol. 2, pp. 189-206. Plenum Press, New York, NY. 1969.
32. Mulay, I. L. and L. N. Mulay. Effect on Drosophila melanogaster and S-37 tumor cells; postulates for magnetic field interactions. In: Biological Effects of Magnetic Fields. (M. F. Barnothy, ed.). Vol. 1, pp. 146-169. Plenum Press, New York, NY. 1964.
33. Barnothy, J. M. Growth-rate of mice in static magnetic fields. Nature 200: 86-87, 1963.
34. Eiselin, J. E., H. M. Boutell, and M. W. Biggs. Biological effects of magnetic fields -- negative results. Aerospace Med. 32: 383-386, 1961.
35. Ossenkopp, K.-P., W. T. Koltek, and M. A. Persinger. Prenatal exposure to an extremely low frequency -- low intensity rotating magnetic field and increases in thyroid and testicle weight in rats. Developmental Psychobiol. 5: 275-285, 1972.
36. Keeton, W. T. The mystery of pigeon homing. Scientific American 231: 96-107, 1974.
37. Barnwell, F. H. and F. A. Brown, Jr. Responses of planarians and snails. In: Biological Effects of Magnetic Fields. M. F. Barnothy (ed.). Vol. I, pp. 263-278. Plenum Press, New York. 1964.

38. Brown, F. A. Effects and after-effects on planarians of reversals of the horizontal magnetic vector. Nature 209: 533-535, 1966.
39. Gottlieb, N. D. and W. E. Caldwell. Magnetic field effects on the compass mechanism and activity level of the snail Helisoma duryi endiscus. J. Genetic Psychol. 111: 85-102, 1967.
40. Caldwell, W. E. and F. Russo. Exploratory study of the effects of an A.C. magnetic field upon the behavior of the Italian honeybee (Apis mellifica). J. Genetic Psychol. 113: 233-252, 1968.
41. Becker, G. On the orientation of Diptera according to the geomagnetic field. Third International Biomagnetic Symposium, (abstract), pp. 9-11. 1966.
42. Kogan, A. B., I. N. Goltseva, L. I. Dorojkina, and T. S. Sachava. Changes in the motion pattern of Paramecium caudatum under the influence of a static magnetic field. Third International Biomagnetic Symposium, (abstract), p. 12. 1966.
43. Wehner, R. and Th. Labhart. Perception of the geomagnetic field in the fly Drosophila melanogaster. Experentia 26: 967-968, 1970.
44. Werber, M., R. M. Sparks, and A. C. Goetz. The behavior of weakly electric fish (Sternarchus albifrons) in magnetic fields. J. Gen. Phychol. 86: 3-13, 1972.
45. Russell, D. R. and H. G. Hendrick. Preference of mice to consume food and water in an environment of high magnetic field. In: Biological Effects of Magnetic Fields. M. F. Barnothy (ed.). Vol. II, pp. 233-239. Plenum Press, New York, NY. 1969.
46. Persinger, M. A. Open-field behavior in rats exposed prenatally to a low intensity-low frequency, rotating magnetic field. Develop. Psychobiol. 2: 168-171, 1969.

47. Persinger, M. A. and J. J. Pear. Prenatal exposure to an ELF-rotating magnetic field and subsequent increase in conditioned suppression. Develop. Psychobiol. 5: 269-274, 1972.

48. Barnothy, J. M., M. F. Barnothy, and I. Boszormenyi-Nagy. Influence of a magnetic field upon the leucocytes of the mouse. Nature 177: 577-578, 1956.

49. Barnothy, M. J. Hematological changes in mice. In: Biological Effects of Magnetic Fields. M. F. Barnothy (ed.). Vol. I, pp. 109-126. Plenum Press, New York, NY. 1964.

50. Hackel, E. Magnetic field effects on erythrocyte agglutination. Vox Sang. 9: 60-64, 1964.

51. Murayama, M. Orientation of sickled erythrocytes in a magnetic field. Nature 206: 420422, 1965.

52. Barnothy, M. F. and I. Sumegi. Abnormalities in organs of mice induced by a magnetic field. Nature 221: 270-271, 1969.

53. Kholodov, Y. A., M. M. Alexandrovskaya, S. N. Lukanova, and R. A. Chizhenkova. Effects of a constant magnetic field on the nervous tissue structures. Third International Biomagnetic Symposium, (abstract), pp. 37-39, 1966.

54. Friedman, H. and R. J. Carey. The effects of magnetic fields upon rabbit brains. Physiol. Behavior 4: 539-541, 1969.

55. Pautrizel, R., A. Priore, F. Berlureau, and A.-N. Pautrizel. Stimulation, by physical means, of the defenses in the mouse and in the rat against experimental trypanosomiasis. Comp. Rend. Acad. Sci., Ser. D. 268: 1889-1892, 1969.

56. Forssberg, A. Some experiments in irradiating Drosophila eggs with roentgen-rays and γ-rays in a magnetic field. Acta Radiologica 21: 213-220, 1940.

57. Amer, N. M. Modification of radiation injury with magnetic fields. Rad. Res. 19: 215, 1963.
58. Amer, N. M. and C. A. Tobias. Analysis of the combined effect of magnetic fields, temperature, and radiation on development. Rad. Res. 25: 172-173, 1965.
59. Amer, N. M. and C. A. Tobias. A possible explanation for the effects of magnetic fields upon biological systems. Rad. Res. 31: 644, 1967.
60. Barnothy, M. F. and J. M. Barnothy. Biological effect of a magnetic field and the radiation syndrome. Nature 181: 1785-1786, 1958.
61. Sikov, M. R. Personal communication.
62. Young, J. R., B. F. Gore, D. D. Mahlum, J. A. Strand, R. C. Thompson, and J. K. Soldat. Information Requirements for Controlled Thermonuclear Environmental Statements. BNWL-1883. 1975.

TABLE A-I

Information Requirements for the Assessment of Environmental Effects of Magnetic Fields*

1. The magnetic field patterns for the several reactor concepts.
2. Behavioral, physiological and morphological consequences of exposure of mammals to 1- to 500-gauss fields, particularly prolonged exposures.
3. Behavioral, physiological and morphological consequences of exposure of avian species to 1 to 200 gauss fields.
4. Consequences of combined exposure of mammals to magnetic fields up to 500 gauss and to several radionuclides likely to be encountered in fusion reactor plants, particularly tritium.
5. Consequences of exposure of people with implanted electronic medical devices to magnetic fields of 0.1 to 500 gauss.
6. Sensitivity of people with extant medical problems, recognized or subclinical, to exposure to magnetic fields, alone or in combination with radionuclides or other stresses.
7. Effects on plant systems.
8. Effects of magnetic field gradients vs constant field.
9. Effects of magnetic fields on differentiation and on the development of embryos and fetuses.
10. Development of acceptable and testable hypothesis for interaction of magnetic energy with biological material.

* From Ref. 62.

APPENDIX III

Much attention has deservedly been given to tritium as a factor of concern for CTR operation. A brief summary of environmental and health effects from tritium was included in BNWL-1883, Information Requirements for Controlled Thermonuclear Reactor Environment Impact Statements, January 1975. This material is included here to assist in identifying the relative importance of tritium as a problem to health and the environment.

TRITIUM

Tritium is an isotope of hydrogen, which is the simplest element and probably the most studied and best understood of all elements. Tritium oxide, the compound of principal hazard concern, is water, which must be the most studied and best understood of all compounds. One would therefore expect that we should be able to predict with some assurance the behavior of tritium in the biosphere. This is certainly true of tritium oxide, but it is less true of elemental hydrogen, which plays no essential role in mammalian biological processes and has therefore received much less study than has water. Compounds of tritium, other than the oxide, may also present special problems that must be considered in terms of their specific biological behavior.

It is, therefore, of primary importance to be able to identify the source terms. Are we to expect releases in the form of elementary tritium gas, either HT or T_2? Will the releases be in the form of water, either HTO or T_2O, gaseous or liquid? May we expect significant quantities of tritium compounds other than the oxide? These questions must be answered before one can speak quantitatively of radiation hazard. In the absence of answers to these questions, one must consider all possibilities. The ensuing discussion will therefore separately consider the hazard potential of elemental tritium, tritium oxide, and other compounds of tritium. Preceding these discussions, information is presented on the occurrence and the biohazard of all forms of tritium.

Separate discussions are presented on the terrestrial, aquatic and human effects of tritium. A brief description of tritium detection methods is also included.

GENERAL CONSIDERATIONS

Sources and Occurrence of Tritium

Tritium is produced under natural conditions within the atmosphere by interaction of cosmic energy with nitrogen and oxygen. Nir et al. (48) have concluded that the natural production rate resulted in a total equilibrium inventory in the biosphere of approximately 69 megacuries of tritium. Jacobs (49) has estimated the natural annual production to be 4-8 megacuries. Most of this naturally produced tritium ($\sim$ 90%) is in the hydrosphere consisting of the oceans and other water bodies.

Tritium was also released to the biosphere during the period of atmospheric testing of nuclear weapons and devices. Eriksson (50) estimated that approximately 1700 megacuries of tritium were produced in tests through early 1962. This amounted to nearly 25 times the steady-state inventory from natural sources. A 3-year half-time of tritium in the stratosphere was estimated for such weapons-produced tritium; however, more recent findings suggested the residence half-time is on the order of 10 days (51).

The recent trend of using nuclear fission as an energy source for electrical power generation has also served to release increasing amounts of tritium to the environment. Peterson et al. (52) indicated that a 100 MWe boiling water reactor (BWR) will release from the reactor coolant between 10-20 curies of tritium per year. The projected release of T from an 800 MWe pressurized water reactor (PWR) appears to be about 400 curies per year. Based on the projected nuclear power economy for the United States and the free world, the rate of production of fussion-produced tritium will exceed the rate of production of natural tritium by 1990 (49).

It is expected that even greater quantities of tritium will be produced and circulated throughout the CTR; and, as at the PWR and BWR plants, tritium is expected to escape from the plant both in gaseous and liquid effluents. The quantity may be orders-of-magnitude greater than for either fission design.

Tritium Detection

Tritium is not detected by traditional techniques of gross radioactivity analysis. Because tritium occurs in the environment primarily as tritiated water (HTO), it is usually evaporated during the procedures to prepare samples for radioactive analysis. Also, due to the low energy of the beta particle emitted during decay, it is not detected by conventional gross beta counting methods or on-line plant monitors. As a result, special analytical techniques such as liquid scintillation counting must be applied to measure tritium.

Liquid scintillation counting of tritium permits rapid analysis of aqueous samples since automated sample changers can be conveniently applied. The sensitivity that is achieved is considered satisfactory, although it is not competitive when compared to the proportional counter.

One of the more serious limitations of scintillation counting is the difficulty of incorporating aqueous samples into scintillator solvents at the temperatures required for acceptable counting efficiencies (53). A partial solution to this problem is attained by use of emulsions having a high water content. Quenching is another disadvantage of scintillation counting (54) but is also partially solved by preparing emulsions (53). Corrections for quench can also be facilitated by using both internal or external standards, by adding increments of sample to the counting vial and

extrapolating to zero sample weight, or by applying corrections on the basis of spectral drift when a dual-channel analyzer is used (54). Quench due to color of the sample can be reduced by decolorizing using charcoal filtration, chemical bleaching, or distillation (54).

For biological samples, the tritium present in tissue water is conveniently removed by lyophilization or vacuum distillation. This fraction is often referred to as tissue-free water tritium (TFWT). The dry residues resulting from the lyophilization process are then combusted to determine tissue-bound tritium (TBT). The water of combustion is trapped in a liquid scintillator that has a low freezing point and is then analyzed as above.

A combustion technique after methods developed by Kelly et al. (55) generally is used. A dry sample, total weight less than 300 mg, is placed in a platinum basket in a closed, oxygen-filled, 2-liter flask. Ignition is made with an electrical current or spark. The water is frozen on the bottom of the flask which has been placed in a bath or dry ice, chloroform, and carbon tetrachloride for 1/2 hr. The ice is dissolved with a 20 ml of toluene phosphor solution containing 20% ethanol, and an aliquot of 15 ml is used for counting.

An additional method employed is based on trapping of water of combustion without freezing (56). Combustion takes place with a flame ignited by an electrically heated combustion basket in a preheated combustion chamber. Combustion is controlled by regulating the oxygen flow and the temperature of the combustion basket. After combustion, oxygen is displaced from the system by nitrogen purge. All liquids and the final counting vial are maintained in a nitrogen atmosphere, eliminating the problem of oxygen quench. The

Tri-Carb Sample Oxidizer is based on this approach. The additional feature that trapping the water without freezing provides greater ease in dissolving combustion products into an appropriate solvent system, directly in a scintillation counting vial. Also, there is little memory effect, and clean-up is rapidly conducted. Sample size is unlimited with this method; tissues ranging in weight from 100 mg to 1 or 2 g are easily handled.

An additional application of the sample oxidizer is also the separation of tissue-free water tritium (TFWT) and tissue-bound tritium (TBT). The aqueous portion is vaporized to comprise the first sample containing TFWT. The residue is then combusted to obtain the second sample containing TBT.

BEHAVIOR OF TRITIUM UPON RELEASE TO THE ENVIRONMENT

Because of a possible increase in the release of tritium resulting from CTR development and operation, there is need for additional information on the behavior of this nuclide in natural systems. This will enable assessment and prediction with assurance of both the potential impact and dose commitment to natural populations including man. However, relatively few studies to date relevant to this need have been undertaken. The existing information can be summarized as follows:

Terrestrial Considerations

Jacobs (49) indicated that, in general, tritiated water is expected to behave as ordinary water in the ground, except for a slight difference in vapor pressure. However, water associated with minerals may have various degrees of mobility, depending upon the nature of the association. In a water saturated formation, the greater fraction of water

will exist as ordinary water that occupies the interparticle spaces. This water was considered freely mobile and its velocity of movement dependent upon pore size. In addition to this fraction, loosely bound water of hydration was found on the mineral surface (57). This fraction was considered to be in equilibrium with the environment after a short time and was removable at temperatures below 400°C. A second phase of adsorbed water required a much longer time to attain equilibrium and was vaporized at 200 to 500°C. Finally, a third phase required a very long time or hydrothermal alteration for exchange and was only removed at temperatures ranging between 500 to 1100 °C. This latter phase consisted primarily of structural hydroxyl groups.

Jacobs (49) furthermore reported that the impact of all such adsorbed phases on tritium behavior in the ground was dependent on two factors: 1) the relative amounts of these phases compared with free water in the pores, and 2) conditions under which adsorption and desorption occurred. The relative amounts of each adsorbed phase increased as the moisture content decreased; and, as such, tritiated water may be expected to move more slowly through a very dry soil than through a moist soil. If tritiated water is deposited under conditions of high temperature, i.e., nuclear detonation, exchange with the structural hydroxyl groups will occur. Since a high activation energy is required to initiate exchange, subsequent replacement of this fraction must be considered to be slow under normal conditions.

Koranda (58) found the mineral-bound tritium of soil at the Pacific Proving Groups to be very high. The concentration in free water in the soil was 60 tritium units*; the concentration in bound water was 3.7×10^5 tritium units. The soil consisted of almost entirely $CaCO_3$ and $Ca(OH)_2$.

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*A tritium unit is one atom of tritium per 10^{18} atoms of hydrogen.

In a saturated fraction, nearly all the tritiated water will exist in the interparticle pores, and its movement will depend upon the dispersive characteristics of the formation. Nakayama and Jackson (59) reported that the diffusion coefficient for tritiated water in soil was nearly constant for a range of volumetric water contents between 10 and 40%. Below 10%, the diffusion coefficient increased rapidly with a maximum at 4% water content, suggesting gaseous diffusion of water vapor through the larger interparticle pores. Below 4% water content, the diffusion coefficient decreased rapidly, suggesting the influence of adsorbed phases.

Gorham and Hofstetter (60) studied the penetration of tritium of atmospheric origin in bog peats and lake sediments of the Red Lake wetlands in northern Minnesota. They found that tritium in surface bog peats exhibited nearly the same concentration as in atmospheric precipitation which was still appreciably enriched from nuclear weapon testing. Past input pulses from recent testing were not preserved in the peat profile. The pattern of subsurface decline suggested that most of the modern precipitation rich in tritium was removed rapidly by evapotranspiration and by lateral runoff within the surface 1.5 m of the 3.5 m thickness of little-decomposed peat at the crest of the raised bog. However, some tritium of weapons origin did penetrate down to the discontinuity between surface material and the well-decomposed bog peat, presumably by molecular diffusion.

In profundal lake sediments, Gorham and Hoffstetter (60) found the influence of enriched precipitation from the early 1960s to be largely transitory and of only major significance in sediment depths of less than 1 meter. Again some penetration below this depth occurred and was likely attributable to molecular diffusion.

Jordan et al. (61) studied the movement of tritium as HTO through the soils of montane tropical rain forest in eastern Puerto Rico and determined that HTO moved downward through the soil in a wave-like pulse, maintaiinng a nearly symmetrical distribution. They concluded that the residence half-time of HTO in the soil was longer than that in vegetation and air when input to each compartment was instantaneous. Since, in the environment, HTO movement into vegetation and air was not instantaneous but was found to be dependent upon HTO movement out of the soil, it was concluded that residence half-time in soil was a rate-limiting step in the transfer of HTO through soil and air.

Koranda and Martin (62) obtained a similar finding working in a desert ecosystem. They found a direct correlation between the tritium concentration in grazing animals and in the soil.

Jordan et al. (61) studied the movement of tritium through a old-field ecosystem. They determined that a pulse of tritium moved downward through the soil as a function of the amount of rainwater entering the soil above the pulse. Concomitant with downward penetration, the peak was found to broaden and flatten due to diffusion. The pulse became immobile if the upper soil dried out to the extent that rain-water did not penetrate to the depth of the pulse peak. Concentrations of tritium in vegetation equaled concentrations in soil water at the depth at which the plants were taking up water. Loss of tritium from the system occurred by evapotranspiration and deep drainage.

Cline (63) investigated the uptake of HTO by the red kidney bean, Phaseolus vulgaris, and determine that uptake occurred rapidly over the first few hours, but equilibrium between plant water and that of the nutrient medium was not attained over the 72-hour duration of exposure. The rate and degree of incorporation were correlated with metabolic activity.

Raney and Vaadi (64) conducted similar experiments on the movement and distribution of HTO in tissue water of shoots of sunflower, Helianthus annus, and tobacco, Nicotina rustica. The distribution of tritium in plant organs with roots in tritiated water was followed as a function of time. During a 12-hour period, concentrations of tritium approached equilibrium with the concentrations of tritium in the nutrient solution. The approach to equilibrium was much slower in the terminal nodes and internodes that were still elongating and in leaf tissue still expanding. The tritium concentration in the leaves of intact plants growing in tritiated water did not reach an equilibrium with the external medium over a protracted period. Although the veins equilibrated in a manner similar to that of the stem, the interveinal tissue did not reach equilibrium with the major veins, the stem, or the nutrients' solution. It was demonstrated that the lack of equilibrium in interveinal tissue was attributed to exchange of tritium between the leaf and the atmosphere by transpiration.

Thompson (65,66) studied metabolic turnover rates of tritium in higher animals. In mice, he demonstrated the biological half-life of tissue-free body water to be approximately 1.1 days. The curve of loss of tritium from the tissue-bound fraction was resolvable into components of 9 and 90-day half-life, which were shown to be of comparable tritium-binding capacity. The biological half-life of tissue-free body water in the rat was found to be 3.3 days. All organs and tissues sampled, with the exception of blood, demonstrated components which depurate tissue-bound tritium with a biological half-life of 80 days or longer. Evidence was presented which suggested that these longer-lived components represented a significant proportion of the total metabolically replaceable hydrogen.

In subsequent studies, Thompson and Ballou (67) separated protein and lipid fractions from various tissues of rats sacrificed 4 and 8 months after administration of tritium oxide. The concentration of bound tritium in these fractions was determined and a biological half-life calculated. Collagen fractions demonstrated half-lives of 300 days or longer, and lipid fractions were obtained with half-lives as long as 300 days. The highest concentration of tissue-bound tritium, 4 months after administration, was found in brain lipids.

In yet other studies, Thompson and Ballou (67) exposed mature female rats to constant levels of tritium oxide, mated them after 6 weeks' exposure, maintained the exposure conditions over intrauterine development and nursing of the progeny, and then maintained the progeny on an identical exposure level for an additional 6 months. The progeny were then removed from the contaminated environment and sacrificed at intervals, and selected tissues were analyzed to determine the tritium concentration of their tissue-free water and tissue-bound fractions. In those animals sacrificed immediately after exposure, most tissues sampled yielded tissue-bound values of 20 to 30% of the concentration of the tissue-free water during exposure. The authors interpreted this to mean that 20 to 30% of the organically bound hydrogen (both freely exchangeable and firmly bound) was derived from the tissue-free water.

In more recent studies, Evans (68) found the same tritium concentration in the tissue-bound fraction as in the tissue-free water fraction from seven tissues of 52 deer killed on the Savannah River Nuclear Site. His interpretation was that sustained exposure to tritiated body water would result at equilibrium in labeling of all organic molecules

equal to that of the tissue-free water on a per gram hydrogen basis. He concluded therefore that the body burden due to continuous low-level exposure to tritiated water would be 1.4 or 1.5 times greater than that predicted by current models. It was assumed that the deer studied by Evans (68) received tritium as tritiated organic molecules in their forage.

Koranda et al. (62) reported similar results based on analysis of tritium in the tissue-free water and tissue-bound residues of 95 kangaroo rats from the elevated tritium environment of the Sedan Crater at the Nevada Test Site. Tritium activity in the lyophilized residues of six organs based on per gram hydrogen averaged 1.5 times as high as that measured in the tissue-free waters. They concluded after extrapolating their data to man in a situation of continuous low-level exposure that the body burden and concomitant dose would be approximately 1.8 times that predicted by current models. The kangaroo rat subsists on dry forage without any free water. It is again assumed that the exposed animals derived most or all of their tritium from ingestion of tritiated forage, and that tritium in their tissue-free water was derived mainly from catabolism of the tritiated molecules.

Moghissi et al. (69) and Barth et al. (70) investigated tritium kinetics in goats and reported a residence half-life of approximately 4 days in lactating, and approximately 8 days in nonlactating animals. In related studies of tritium turnover in the blood of cows, Potter, et al. (71) reported values of 12.5 and 65 days for short and long components, respectively. Moghissi et al. (72,73), in studies of the human, demonstrated a two-component exponential loss rate

with a half-life of 21-33 days for the short component and 280-550 days for the long component.

Aquatic Considerations

Isotopic discrimination against incorporation of tritium into plants is well documented (74, 75). Rosenthal cultured the alga, Chlamydomonas reinhardti, in tritiated water and determined a marked isotopic discrimination against incorporation of tritium into organic molecules. Tritium in the cell fluid, however, tended to equilibrate with that in the external environment. Some published results also suggest discrimination in favor of retention once tritium is incorporated (75).

Foster (76) investigated tritium oxide absorption and retention in the body water of salmon fry, Onchorhynchus tshyawytscha, mayfly nymphs, Callibaetis spp., and snails, Radex japonica, maintained in a tritiated environment for 24 hours. After removal to an uncontaminated environment, the organisms were sampled at intervals ranging from 1 minute to 8 hours. Half-life values of approximately 10 minutes for snails, 20 minutes for mayfly nymphs, and 24 minutes for salmon fry were calculated.

Stewart et al. (77) studied tritium accumulation in two species of snails, Lymnaea reflexa, and Helisoma trivolvis, and the leopard frog tadpole, Rana pipiens. It was found that the tissue-free water of the snails approached equilibrium with the environmental HTO in approximately 6 hours. Tissue-free water tritium in tadpoles exceeded environmental levels in 3 hours. The final equilibrium level was 1.11 times greater than the environmental level. Tissue-bound tritium attained equilibrium in the snails in approximately 5 days but was not observed to reach equilibrium in tadpoles in 10 days when the experiment was terminated.

Strand et al. (78) studied the accumulation and retention of tritium in embryonic and larval rainbow trout, Salmo gairdneri. For embryos exposed to tritiated water, a rapid uptake over the first 1 to 2 days was demonstrated, followed during the ensuing 27 to 28 days of exposure by maintenance of essentially equilibrium levels. The tissue-bound tritium accounted for approximately 20% of the total label in each egg, a level not exceeded as measured over the duration of exposure. Both tissue-free water and tissue-bound fractions, after transfer to uncontaminated water, eluted rapidly with estimated half-times of ∿ 1.0 and ∿ 2.0 hour, respectively. A slower component of the tissue-free water fraction persisted for ∿ 17 days, as determined in hatched fry. The slow component of the tissue-bound fraction, for comparison, persisted at approximately 0.5% of the initial bound equilibrium level at 17 days.

The tissue-bound tritium of water fleas, Daphnia galeata; fairy shrimp, Eubranchipus vernalis; snails, Lymnaea reflexa and Helisoma trivolvis; and northern chorus frog tadpoles, Pseudacris triseriata; was found by Rosenthal and Stewart (75) to be derived chiefly from the consumption of tritiated forage. However, tissue-free water tritium was derived mainly from the external environment. They also determined that approximately 1/3 of the intracellular-bound tritium in snails was not exchangeable.

Harrison and Koranda (79) studied the tritiation of aquatic animals in an experimental freshwater pool. They found that in the tissue-free water of clams, Anodonta nuttalliana; crayfish, Astacus spp.; goldfish, Carassius auratus; cattail, Typha angustifolia; and filamentous algae, Pithophora spp., tritium increased to 95% of the level in

the pool water and remained at that level for the duration of the experiment. Tissue-bound tritium had a higher concentration in plants than in animals and the highest value was observed in algae. In the animals, the organically bound tritium was highest in the visceral organs and lowest in calcified tissues. In the viscera, tissue-bound tritium increased to approximately 60% of the concentration of tissue-free water tritium. In muscle tissue it increased to a maximum of 30% of the concentration in tissue water over a period of 90 days.

Strand et al. (80) conducted similar studies in a simulated aquatic ecosystem containing mussel, Anodonta californiensis; crayfish, Pacifastracus trowbridgi; carp, Cyprinus carpio; cattails, Typha spp.; and filamentous algae, undetermined species. Tritium as HTO was introduced continuously for 8 months in the replacement water at a concentration of 1 μCi/liter. The system was maintained on uncontaminated replacement water for an additional 8 months to determine the rate of elimination of tritium from the system. A rapid uptake of tritium during the first 2 days was demonstrated in all biota sampled. In mussel, crayfish, and carp, the concentration of the tissue-free water approached 90% of the tritium level in the pond water within 2 days of the introduction of the isotope and remained at that level for the ensuing 8 months of exposure. Emergent vegetation attained no more than 70% of the concentration of tritium in the pond water; filamentous algae exceeded 90% of the pond concentration. The concentration of tissue-bound tritium varied with time and type of tissue. Maximum concentration was reached in 5 months, accounting for 7 to 21% of the total label in mussel, crayfish and carp. In emergent vegetation, the concentration ranged between 4 and 12%. The tissue-bound fraction for algae compared closely with that observed in animal tissue.

Upon termination of the uptake experiment, Strand et al. (80) determined that loss of tritium from the pond water occurred exponentially; and at the end of the first month, less than 10% of the initial concentration remained. Most tissues eluted rapidly and trace activities were measured in mussel, crayfish, and carp at the end of the first month. Emergent vegetation and algae demonstrated significantly slower rates of turnover and retained between 30 and 40% of their initial label throughout this period. Even after 8 months in uncontaminated replacement waters, activities retained in plant materials exceeded 10% of the original concentration.

Van Hook and Deal (81) studied the transfer of HTO from water to watercress to crickets and determined that adult crickets reached tritium concentrations less than unity, $\sim$ 0.19. They concluded that other factors such as food habits and developmental stage were as important as simple diffusion from environmental concentrations in accounting for the degree of tritiation observed.

Conclusions and Research Needs

In summary, tritium released to the environment in the form of tritiated water behaves as ordinary water throughout the hydrosphere and is readily metabolized by both terrestrial and aquatic biota.

Although most biochemical reactions discriminate against the incorporation of tritium in favor of protium, the possibility of some concentration should not be overlooked. Available information indicates that the isotopic effects of tritium in most exchange reactions is negligible. Data from studies of both acute and chronic exposure conditions generally supports the hypothesis that there occurs no significant

concentration above that of environmental concentrations in water or forage at any level of the food chain, although data on complex terrestrial and aquatic food chains or food webs is not yet available. Moreover, the data currently available suggests that in most ecosystems, tritium concentration tends to become more dilute at levels of greater organization within the food chain or food web.

It is known that a fraction of tritium accumulated as tritiated water becomes organically bound; that is, exchanges with hydrogen bound in organic molecules. The rate and extent of incorporation are dependent upon metabolic activity of the organism. On this basis, the highest concentration of organically bound tritium would be expected in tissues and population segments which are in formative or growth stages at the time of exposure. Furthermore, as exposure duration increases from acute to chronic situations, tritium concentrations are shown to approach equilibrium levels with a single tritium-to-hydrogen ratio common to all parts of the hydrogen pool. Organic binding would not be expected to result in significant bioaccumulation of tritium from tritiated water, because water is approximately as hydrogen rich ($\sim$ 11% by weight) as any compound of the biological organism ($\sim$ 10% by weight). However, exposure pathway may influence the extent of organic binding. Recent evidence indicates that enhanced binding may result from ingestion of tritiated foodstuffs.

Tritium loss, both from tissue-free water and the tissue-bound fraction, is dependent upon metabolic activity. Hence, processes favoring accumulation and incorporation also favor its depuration. Tritium which is organically bound demonstrates a longer half-time, but it would appear to constitute a small fraction of the total tritium label.

From the above compiled literature review, it is apparent that relatively few studies have been conducted on the cycling of tritium through either the abiotic or biotic compartments of natural ecosystems. Furthermore, there exists little information on the behavior of this radionuclide in temperate climates paramount to assessment and prediction of the potential environmental effects and dose commitment to natural populations. For both acute and chronic releases of tritium, current estimates of concentration factors and turnover rates in the various compartments need confirmation. To more fully understand the relationship between the concentrations of tritium in these different compartments, a more detailed analysis of both the sources of tritium and variations in concentration are required. Temporal and spatial variations must be followed and trophic relationships need additional study. Although little concentration of tritium by either terrestrial or aquatic biota has been demonstrated and there exists little evidence to indicate that biomagnification of tritium occurs, release of larger quantities of tritium to the environment increases the justification for additional research to confirm available information.

RADIOLOGICAL SIGNIFICANCE OF TRITIUM ISOTOPE EFFECTS

A basic question that arises in any consideration of tritium metabolism is whether tritium may be assumed to behave like protium, i.e., like normal hydrogen. Because the tritium atom is three times as heavy as the protium atom, isotope effects are observed which are much larger than those normally encountered with other elements. This subject was recently reviewed by Weston, who concluded that, "it is apparent that large kinetic isotope effects are often

found for tritium-labeled compounds. In tracer experiments utilizing tritium, observed rate constants could easily differ by an order of magnitude from those for the analogous unlabeled compound. If tritium from a source of HTO at constant specific activity is incorporated into a biological system by irreversible chemical reactions, it will be discriminated against, and the tritium level in the biological system will remain lower than that of the source. Conversely, kinetic isotope effects in the back-exchange to remove tritium after incorporation will favor retention of tritium in the biological system" (82).

Relative Biological Effectiveness of Tritium Beta Radiation

Tritium is a pure beta-emitter of very weak energy--18.6 keV maximum. The linear energy transfer (LET) of such weak betas is higher than that of more energetic beta, X-, or gamma radiation, and a considerable experimental effort has been devoted to determining whether this higher LET is reflected in an increased relative biological effectiveness (RBE). These studies were reviewed in 1968 by Bennart, who concluded "that a value of QF different from unity for either tritium or other β-emitters is hardly justified" (83). The International Commission on Radiological Protection in its 1959 report on Permissible Dose for Internal Radiation used an RBE (or QF) value of 1.7 for tritium (84); however, this value was reduced to unity in 1969 (85), a value concurred in by the National Council on Radiation Protection and Measurements (NCRP) (86). More recently there has been further evidence presented to justify a value higher than unity but in no case greater than 3 (87,88).

The induction of gene mutations by tritium in mice is being studied at Oak Ridge National Laboratory (89,90). The most recent report from these important studies presents the

following conclusion concerning the tritium-induced mutation rate in mouse spermatogonia: "If our present estimated dose to the testis could be taken as a reliable guideline, then the mutation frequency observed would represent approximately twice that expected from external gamma radiation delivered at low radiation dose rate. However, in view of the various uncertain factors and the sample size, a relative biological efficiency (RBE) of 1.0 for the tritium radiation relative to external gamma radiation is not exceeded. A very high RBE dose already appears to be excluded" (90).

Conclusions and Research Needs

Although rather large isotope effects occur in individual chemical reactions, the overall effects in biological organisms seem relatively small, as has been discussed by Shtukkenberg (91). Several comparisons of tritium and deuterium incorporation in rats (92,84) and algae (85) have demonstrated such effects, which have been small, and the discrimination has been against tritium. It therefore seems reasonable to assume that tritium will behave like ordinary hydrogen, and that the error introduced by such an assumption will be on the side of this presumed behavior (will overestimate the effects of tritium) in long-term, many-generation studies with experimental animals exposed to various regimens of tritium exposure.

Thus, while there is clearly some uncertainty as to the appropriate RBE for tritium, the subject has received considerable study and for both somatic and genetic effects the uncertainty is probably no greater than a factor of two.

Extensive studies over the past 30 years have demonstrated no unique behavior of tritium in the biosphere that would not have been predicted with due consideration for physico-chemical form of the principle compound type. Moreover,

such experimentation has failed to produce effects data significantly different from those which might have been predicted from a general knowledge of the effects of ionizing radiation. However, this is not to say that the effort over the last 30 years has been wasted, or that further research is not required. In no area of radiation research do we possess sufficient information that suggest experimental validation of predicted values is not required.

In general, the biological consequences of low-level irradiation have become an important consideration in all environments. State-of-the-art knowledge, as it would relate to tritium or other common radionuclides, is concerned mainly with somatic effects. Relatively few studies have been conducted, directed at assessment of potential genetic effects, particularly under conditions of chronic exposure. When considering the environment, we are not primarily concerned with individual organisms, but first with populations; more sensitive parameters of radiation effects on individuals, populations, and communities need to be developed. Longer-term or chronic studies on factors such as rates of growth, morphological abnormalities, onset of maturity and reproductive capacity need to be undertaken. Chromosome investigations under both laboratory and field conditions should be extended, and the somatic and genetic consequences of such changes on populations, communities, and ecosystems should be evaluated.

Because of the often conflicting nature of the present experimental data on the effects of low-level chronic irradiation on the developing embryo, additional studies should be established under rigorously controlled experimental conditions. The effects of other environmental stress factors such as temperature, oxygen, other pollutants, and disease need to be studied and expanded to include the interaction of these factors with radiation effects.

Measurements of absorbed dose should become standard practice in experimental work. In field areas subject to contamination, investigations should be initiated to determine the radiation regime in the environment. Such data should be closely correlated with measurements of concentration of radionuclide in order that the historical radiation regime can be determined.

HUMAN HAZARDS OF TRITIUM

The effects of tritium on man are considered in terms of hazards from 1) elemental tritium, 2) tritium oxide, and 3) tritium compounds other than the oxide.

Elemental Tritium

Hydrogen gas is not metabolized by man nor is it soluble to a significant degree in body fluids or tissues. As a consequence, 99.9% of inhaled tritium is rapidly exhaled by rats (93,94); and an even lower retention is reported for humans (94). Absorption of tritium gas through the skin has also been shown to be of minor hazard significance (95). The radiation dose resulting from the brief residence of inhaled tritium in the lung and its slight solubility in body fluids can be readily calculated; it is considerably smaller than the dose resulting from inhalation of the same amount of tritium in the form of the oxide. Thus, the ICRP-recommended occupational maximum permissible concentration for elemental tritium in air, (MPC), is 2 c 10^{-3} $\mu Ci/cm^3$ 400 times higher than the MPC for tritium oxide in air, 5 x 10^{-6} $\mu Ci/cm^3$ (84).

Releases of elemental tritium would therefore be of much less concern than releases of tritium oxide, providing one could be assured that the elemental tritium was not converted to the oxide by environmental processes. The

conversion of tritium to the oxide in air by either oxidation or exchange processes is slow, even in the presence of metal catalysts. Eakins and Hutchinson recently reviewed the literature in this area. Reported studies led them to conclude that "in a room completely lined with platinum, one of the best catalysts for conversion of elemental tritium to tritiated water, it would take about 4 years for half the elemental tritium at an initial concentration of 10 $(MPC)_a$ to be converted to tritiated water" (96).

Further studies of environmental conversion of tritium to tritium oxide are needed. Certain micro-organisms are capable of oxidizing hydrogen (97); their presence in the gastrointestinal tract has been indicated as the probable reason for the slight retention which does occur when animals inhale tritium (93). Whether they might significantly influence the fate of tritium in the biosphere should be determined. The loss of tritium to the upper atmosphere, out of reach of biological systems, should also be quantified.

It is, in any case, important to establish the extent to which the original source term consists of elemental tritium and the degree to which it remains in this form, since it is so much less hazardous in this form. Because of uncertainties in this area, it has been common radiological protection practice to assume that any measured tritium is tritium oxide. This places a severe and unnecessary restriction on exposure limits if, in fact, the exposure can be proved to be to tritium gas.

Tritium Oxide

Assuming the absence of a significant isotope effect in its reactions with biological materials, the metabolic behavior of tritium oxide and its consequent radiological

hazard are quite accurately predictable. This is notably true for the case of truly chronic exposure, where all the water of the biosphere, including that incorporated in the tissues of man, will attain an approximately equal concentration of tritium. This is an extreme situation which will never be quite attained, since tritium will not be injected into the biosphere at an absolutely steady rate and some of the equilibration half-times may be long in comparison to the half-life of tritium. For the case of man, however, tritium oxide, whether inhaled, ingested, or absorbed through the skin, is quickly and totally absorbed and equilibrated with body water (94,98-100). Since body water is quite uniformly distributed throughout most tissues, a quite uniform total-body radiation dose is delivered by the tritium in body water. The skeleton, because of its low water content, is relatively spared.

One must also be concerned about the incorporation of tritium, from body water, into the organic compounds of the body through synthetic or exchange processes. Assuming no isotope effect, such incorporation can increase the total-body radiation dose from tritium by no more than about 50%, the maximum set by the ratio of organically bound hydrogen to body-water hydrogen. Whether tritium incorporated into organic compounds might exert some unusually toxic effect is another question, which will be considered later.

For the case of non-chronic exposure, the evaluation of radiation doses is somewhat more complex since equilibrium levels will not be attained. However, the rates of turnover of body water and of the various organic components of the body have been extensively studied. The information available can be used to obtain good estimates of the total-body radiation exposure resulting from an acute intake of tritium oxide (101,102).

What is not so easily determined is the radiation dose to very limited regions of the body, whose dimensions may be small relative to the uniformity of hydrogen distribution within tissues or compounds. This is the problem encountered with exposure from specific tritium-labeled compounds, which will be discussed in the next section.

Tritium Compounds Other Than the Oxide

In a uniformly tritiated environment, about half the human tritium intake would be in the form of tritiated organic compounds in food. Most of this organically bound tritium would be converted within the organism to tritium oxide, by oxidation or exchange; but some tritiated organic compounds would be incorporated directly into body tissues. Other tritiated organic compounds will be formed within the body by exchange or synthetic processes. By these two routes, all hydrogen-containing compounds in the body will incorporate tritium. This organically bound tritium will add perhaps 50% to the total-body dose from body-water tritium, but will it have any special effect because of its molecularly incorporated state?

Two possibilities exist for enhanced effect: 1) a transmutation effect due to conversion of a hydrogen atom to a helium atom, and 2) an enhanced radiation effect due to origin of the beta ray within the molecule. Such effects might be particularly critical for tritium incorporated in DNA or other vital molecules within the cell nucleus.

This problem has been extensively studied and recently reviewed (103,104). Although a somewhat controversial subject, there now appears to be agreement on the following conclusions: "The effects of intracellular tritium are overwhelmingly due to beta irradiation of the nucleus. Transmutation effects do not produce a measurably increased effect under most conditions and are detectable, if at all,

only under highly specialized laboratory conditions" (194). Further, "The origin of tritium beta tracks in, or their close juxtaposition to, the DNA molecule does not appear to enhance the degree of somatic effect" (104). This latter conclusion appears reasonable since, "Every part of the cell nucleus lies within one tritium beta range of some part of a chromatid, and the nucleus contains no sizeable contiguous 'insensitive' volume of a radius exceeding the effective range of tritium beta rays" (104).

Acute exposures might seem to present special problems. Concern has been expressed for the case in which a developing female fetus is exposed to elevated body-water levels during the period of oocyte formation; tritium incorporated in these germ cells would be retained until ovulation and this might constitute a special genetic hazard (105). Osborne, however, has estimated that in such a circumstance, less than 0.2% of the initial dose rate to the nucleus originates from tritium incorporated in DNA, and that it would be 30 years before the initial dose from body water was equaled by the cumulative dose from DNA-incorporated tritium (106).

It would thus appear quite certain that tritium incorporated into organic compounds poses no substantially increased hazard beyond that accounted for by its contribution to total-body dose.

Conclusions and Research Needs

The human metabolic behavior of tritium and the radiobiological consequences of this behavior are probably better understood than is the case for any other radionuclide. The chronic radiation exposure from environmentally dispersed tritium, in whatever form, is essentially a total-body exposure. Uncertainties in the individual parameters involved in

converting measured intake to estimated dose equivalent are probably no larger than a factor of two. A factor of ten should encompass the total uncertainty in this estimate.

The primary experimental deficiencies would seem to lie in the area of large-scale, multigeneration demonstration experiments. This would predictably add little to our present knowledge of basic principles but would be reassuring in view of the exposure of world populations that will result from tritium release.

REFERENCES

48. A. Nir, "On the Interpretation of Tritium "Age" Measurements of Groundwater," J. Geophys. Res. 69:2589-2595, 1964.

49. D. G. Jacobs, Sources of Tritium and Its Behavior upon Release to the Environment, AEC Critical Review Series, TID-24635. U.S. Atomic Energy Commission, Division of Technical Information, 90 p, 1968.

50. E. Eriksson, "An Account of the Major Pulses of Tritium and Their Effects in the Atmosphere," Tellus, 17(1):118-130, 1965.

51. J. J. Koranda, J. R. Martin and L. R. Anspaugh, The Significance of Tritium Releases to the Environment, Lawrence Radiation Laboratory, Livermore Rept. UCRL 73546, 1971.

52. J. T. Peterson, J. E. Martin, C. L. Weaver and E. D. Harward, "Environmental Tritium Contamination from Increasing Utilization of Nuclear Energy Sources," Environmental Contamination by Radioactive Materials, International Atomic Energy Agency, Vienna, Austria, pp. 36-60, 1969.

53. C. G. Bell and F. N. Hayes, eds., Liquid Scintillation Counting, Pergamon Press, Inc., London, 1958.

54. E. Rapkin, "Liquid Scintillation Counting 1957-1963: A Review," Int. J. Appl. Radiat. Isotop., 15(2):69-87, 1964.

55. R. G. Kelly, E. A. Peets, S. Gordon and D. A. Buyske, "Determination of ^{14}C and ^{3}H in Biological Samples by Schoniger Combustion and Scintillation Techniques," Anal. Biochem., 2:267-273, 1961.

56. N. Kaartinen, A New Oxidation Method for the Preparation of Liquid Scintillation Samples, Technical Bulletin No. 18, Packard Instrument Company, 9 p., 1969.

57. P. Joergensen and I. Rosenquist, "Replacement and Bonding Conditions for Alkali Ions and Hydrogen in Dioctahedral and Trioctahedral Micas," Norsk. Geol. Tidsokr., 43:497-536, 1963.

58. J. J. Koranda, "Preliminary Studies of the Persistence of Tritium and ^{14}C in the Pacific Proving Ground," Health Physics 11:1445-1457, 1965.

59. F. S. Nakayama and R. D. Jackson, "Diffusion of Tritiated Water in Soils," Soil Sci. Soc. Amer. Proc., 27(3):255-258, 1963.

60. E. Gorham and R. H. Hofstetter, "Penetration of Peat Bogs and Lake Sediments by Tritium from Atmospheric Fallout," Ecology, 52(5):898-902, 1971.

61. C. F. Jordan, J. R. Kline and D. S. Sasscer, "Tritium Movement in and Old Field Ecosystem Determined Experimentally," Proc. Third National Symposium on Radioecology, Oak Ridge, TN, pp. 199-203, May 10-12, 1971.

62. J. J. Koranda, J. R. Martin and R. W. Wikkerink, Biological Half-Life Studies of Tritium in Animals with a Chronic Exposure at Sedan Crater, Lawrence Radiation Laboratory, Livermore Rept., UCRL-70914, 1969.

63. J. F. Cline, "Absorption and Metabolism of Tritium Oxide and Tritium Gas by Bean Plants," Plant Physiol., 28(4): 717-723, 1953.

64. F. Raney and Y. Vaadia, "Movement and Distribution of THO in Tissue Water and Vapor Transpired by Shoots of Helianthus and Nicotina," Plant Physiol., 40(1):378-382, 1965.

65. R. C. Thompson, "Studies of Metabolic Turnover with Tritium as a Tracer, I Gross Studies on the Mouse," J. Biol. Chem., 197(1):81-87, 1952.

66. R. C. Thompson, "Studies of Metabolic Turnover with a Tritium as a Tracer, II Gross Studies on the Rat," J. Biol. Chem., 200(2):731-743, 1953.

67. R. C. Thompson and J. E. Ballou, "Studies of Metabolic Turnover with Tritium as a Tracer, IV Metabolically Inert Lipide and Protein Fractions from the Rat," J. Biol. Chem., 208(2):883-888, 1954.

68. A. G. Evans, "New Dose Estimates from Chronic Tritium Exposures," Health Physics, 16:57, 1969.

69. A. A. Moghissi, R. Lieberman, M. W. Carter and J. E. Ragnier, "Biological Half-Life of Tritium," Health Physics, 21: 57-60, 1971.

70. J. Barth, R. E. Stanley and A. A. Moghissi, "Biological Half-Life of Tritium in Goats," Health Physics, 22(4): 396, 1972.

71. G. D. Potter, G. M. Vattuone and D. R. McIntyre, "Metabolism of Tritiated Water in the Dairy Cow," Health Physics, 22(44):405-409, 1972.

72. A. A. Moghissi, M. W. Carter and R. Lieberman, "Long-Term Evaluation of the Biological Half-Life of Tritium," Health Physics, 21:57-60, 1971.

73. A. A. Moghissi, M. W. Carter and E. W. Bretthauer, "Further Studies on the Long-Term Evaluation of the Biological Half-Life of Tritium," Health Physics, 23:805-806, 1972.

74. D. Weinberger and J. W. Porter, "Incorporation of Tritium Oxide into Growing Chlorella phrenoidose Cells," Science 117:636-638, 1953.

75. G. M. Rosenthal and M. L. Stewart, "Tritium Incorporation in Algae and Transfer in Simple Aquatic Food Chains," Proc. Third National Symposium on Radioecology, Radionuclides in Ecosystems, Oak Ridge, TN, pp. 440-444, May 10-12, 1971.

76. F. R. Foster, Tritium Oxide Absorption and Retention in the Body Water of Some Aquatic Organisms, HW35917, USAEC-GE, Richland, WA, pp. 98-103, 1955.

77. M. L. Stewart, G. M. Rosenthal and J. R. Kline, "Tritium: Discrimination and Concentration in Freshwater Microcosms," Proc. Third National Symposium on Radioecology, Radionuclides in Ecosystems, Oak Ridge, TN, pp. 452-459, 1971.

78. J. A. Strand, W. L. Templeton and E. G. Tangen, "Accumulation and Retention of Tritium (Tritiated Water) in Embryonic and Larval Fish, and Radiation Effect," Proc. Third National Symposium on Radioecology, Radionuclides in Ecosystems, Oak Ridge, TN, pp. 445-451, May 10-12, 1971.

79. F. L. Harrison and J. J. Koranda, "Tritiation of Aquatic Animals in an Experimental Freshwater Pool," Proc. Third National Symposium on Radioecology, Radionuclides in Ecosystems, Oak Ridge, TN, pp. 425-434, May 10-12, 1971.

80. J. A. Strand, W. L. Templeton and E. G. Tangen, "Fixation and Long-Term Accumulation of Tritium in an Experimental Aquatic Environment," Pacific Northwest Laboratory, Annual Report for 1971, BNWL-1650, Vol. 1. - Life Sciences, Part 2 - Ecological Sciences, 1.13-1.14, 1972.

81. R. Van Hook and S. L. Deal, "Tritium Uptake and Elimination by Tissue-Bound and Body-Water Components in Crickets (Acheta domestions)," J. Insect. Physiol., 19:681-687, 1973.

82. R. E. Weston, "Kinetic and Equilibrium Isotope Effects of Tritium Substitution," Tritium, A. A. Moghissi and M. W. Carter, eds., Messenger Press, Las Vegas, pp. 289-303, 1973.

83. J. Vennart, "The Quality Factor for Low-Energy β-Emitters," Health Phys., 14:541-548, 1968.

84. International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation, Oxford, Pergamon Press, 1959.

85. International Commission on Radiological Protection, "Progress Report from ICRP," Health Phys., 17:389, 1969.

86. National Council on Radiation Protection and Measurements, Basic Radiation Protection Criteria, Report No. 39, 1971.

87. H. A. Johnson, "The Quality Factor for Tritium Radiation," Tritium, A. A. Moghissi and M. W. Carter, ets., Messenger Press, Las Vegas, pp. 231-239, 1973.

88. Y. I. Moskalev, V. F. Zhuravlev, A. G. Istomina, I. K. Petrovich and D. A. Kazbekova, "Relative Biological Effectiveness of Tritium," Tritium, A. A. Moghissi and M. W. Carter, eds., Messenger Press, Las Vegas, pp. 240-244, 1973.

89. R. B. Cumming, W. L. Russell, E. M. Kelly and M. F. Walton, "Tritium-Induced Mutation Rate in Postspermatogonial Stages of Germ Cells in the Mouse," Biology Division Annual Progress Report for Period Ending June 30, 1973, ORNL-4915, Oak Ridge National Laboratory, p. 98, 1973.

90. W. L. Russell, R. B. Cumming, E. M. Kelly and M. F. Walton, "Tritium-Induced Mutation Rate in Spermatogonia of the Mouse," Biology Division Annual Progress Report for Period Ending June 30, 1973, ORNL-4915, Oak Ridge National Laboratory, p. 99, 1973.

91. Y. M. Shtukkenberg, "Physical Properties of Isotopes of Hydrogen," Tritium Oxide, Y. I. Moskalev, ed., Moscow, Atomizdat, translated as AEC-tr-7298, pp. 6-20, 1968.

92. R. C. Thompson and J. E. Ballou, "Studies of Metabolic Turnover with Tritium as a Tracer III. Comparative Studies with Tritium and Deuterium," J. Biol. Chem., 206:101-107, 1954.

93. G. N. Smith, R. J. Emerson, L. A. Temple and T. W. Galbraith, "The Oxidation of Molecular Tritium in Mammals," Arch. Biochem. Biophys., 46:22-30, 1953.

94. E. A. Pinson and W. H. Langham, "Physiology and Toxicology of Tritium in Man," J. Appl. Physiol., 10:108-126, 1957.

95. C. W. DeLong, R. C. Thompson and H. A. Kornberg, "Permeability of Excised Mouse, Rat, and Human Skin to Gaseous Tritium," Radiation Res., 1:214-217, 1954.

96. J. D. Eakins and W. P. Hutchinson, "The Radiological Hazard from the Conversion of Tritium to Tritiated Water in Air by Metal Catalysts," Tritium, A. A. Moghissi and M. W. Carter, eds., Messenger Press, Las Vegas, pp. 392-399, 1973.

97. G. N. Smith and R. O. Marshall, "Fixation of Molecular Tritium by Bacterial Suspensions," Arch. Biochem. Biophys., 2:395-405, 1952.

98. E. A. Pinson, "Water Exchanges and Barriers as Studied by the Use of Hydrogen Isotopes," Physiol. Rev., 32:123-134, 1952.

99. I. G. Campbell, D. F. White and P. R. Payne, "The Uptake of Tritium-Labelled Water Vapour by the Mammalian Lung," Brit. J. Radiol., 24:682-684, 1951.

100. C. W. DeLong, "The Percutaneous Absorption of Water Vapor," Science, 114:397, 1951.

101. W. S. Snyder, B. R. Fish, S. R. Bernard, Mary R. Ford and J. R. Muir, "Urinary Excretion of Tritium Following Exposure of Man to HTO- a Two Exponential Model," Phys. Med. Biol., 13:547-559, 1968.

102. J. W. Croach, "Theoretical Radiation Dose to the Human System from Assimilated Tritium," Health Phys., 24:17-22, 1973.

103. L. E. Feinendegen, Tritium-Labeled Molecules in Biology and Medicine, Academic Press, New York, 1967.

104. L.E. Feinendegen and V. P. Bond, "Transmutation versus Beta Irradiation in the Pathological Effects of Tritium Decay," Tritium, A. A. Moghissi and M. W. Carter, eds., Messenger Press, Las Vegas, pp. 221-231, 1973.

105. E. P. Radford, "Statement of Concern," Environment, 11:18-27, 1969.

106. R. V. Osborne, "Permissible Levels of Tritium in Man and the Environment," Radiation Res., 50:197-211, 1972.

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