INFORMATION REQUIREMENTS
FOR CONTROLLED THERMONUCLEAR REACTOR
ENVIRONMENTAL IMPACT STATEMENTS

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

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PREFACE

As development proceeds for controlled thermonuclear reactors (CTRs), environmental impact statements probably will be written for both the overall development program and the major experimental facilities contained in that program. A major deficiency apparent during preparation of environmental statements for other programs has been a lack of fundamental information necessary for defining the nature and magnitude of environmental effects. This has resulted in impact estimates of questionable accuracy and in criticisms by opponents.

Preparation of an environmental statement for CTRs may require information currently not available and not scheduled for development. The need must be recognized early enough to permit development of that information prior to preparation of the environmental statements.

This document presents the results of an analysis of the proposed CTR designs to determine the potential environmental effects, the nature of the information needed for defining those effects, the availability of that information, and the general nature of the research necessary to obtain the information currently not available. It also includes an evaluation to determine if sufficient information is available to permit preparation of an environmental statement for the CTR development program at this time.

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SUMMARY AND CONCLUSIONS

The current CTR development effort in the United States was reviewed to determine the most probable designs and the general types of environmental effects for the first commercial thermonuclear reactors. This review revealed that most published designs probably would have the following common characteristics if they are selected for the first commercial reactors:

- The D-T fusion reaction
- A large 14 MeV neutron flux
- Lithium in the blanket region
- Large tritium inventories
- Large quantities of solid radioactive waste
- Standard electricity generation systems and the associated environmental impacts

In addition, the designs using magnetic confinement of the fusion plasma probably will have much larger magnets and stronger magnetic fields than currently are in use, and the designs using inertial confinement may have a vibration impact because of the frequent fusion ignitions.

Analysis of the reactor characteristics and the resultant environmental effects shows that many of the environmental effects will be similar to those being experienced at fission reactors. Consequently, ample technology is available or is expected to be developed to permit estimation of the size and importance of many of the effects. However, the analysis also identified five potential sources of unique environmental effects:

- Releases of large quantities of tritium during both routine operation and accidents
- Releases of large quantities of lithium during accidents
- Large magnetic fields at magnetic confinement reactors
- Vibration at inertial confinement reactors
- Environmental effects related to material procurement for construction and operation

Sufficient information is available to permit adequate prediction of the metabolic and radiological consequences of tritium releases. The metabolic and radiological effects of tritium probably are better known than for any other radionuclide. The primary deficiencies in our knowledge of tritium lie in environmental transport and in assurance that there are no unforeseen long-term effects. Large-scale, multigeneration demonstration experiments are needed to confirm our present knowledge of basic principles.

Ample information is available to permit prediction of the general environmental effects of lithium releases. A substantial amount of information concerning its characteristics and environmental effects is available from past industrial experience, and standards for normal low-level releases have been established. Additional research is needed to assure complete understanding of the effects on both terrestrial and aquatic ecosystems. However, the lack of all detailed information on lithium effects does not preclude ability to prepare an environmental statement at this time. Information is available to permit an order-of-magnitude estimate of the effects as needed for preparation of an initial program environmental statement. Ample time should be available for obtaining the additional information needed for preparation of the environmental statements for the first CTR prototypes.

The information needed for accurate prediction of the biological effects of chronic exposure to large magnetic fields is not available at this time. Large scale, multigeneration demonstration experiments may be necessary to obtain the necessary information. However, lack of this information does not preclude conducting an environmental analysis. Magnetic fields have relatively small impact regions. Because the fields affecting the general public are capable of reduction by proper building and equipment design, and by use of exclusion zones, the environmental impact on the general public due to magnetic fields is not expected to be significant. However, considerable research may be necessary to demonstrate that there will not be significant effects on plant employees.

Vibrations at laser-fusion facilities are expected to have a negligible environmental effect. Reduction of vibrations to a desirable level is possible by proper plant design, although the cost may be high. In addition, reduction of vibrations to an acceptable level for the reactor auxiliary systems, such as the lasers, turbine generators and instrumentation, should result in acceptable vibration levels for the general public.

Procurement of materials for construction of fusion reactors may cause unique environmental effects because of the significant increase in the quantities of materials used. This could result in a large increase in land alteration during mining of ores or storage of chemical wastes. It could also result in increased air and water pollution. No additional research is justified until the types and quantities of materials used are known. At that time, additional research may be justified if the environmental effects appear excessive.

In addition to defining environmental effects, an environmental statement must include a cost-benefit analysis plus discussions of: long-term losses vs. short-term gains, unavoidable adverse effects, irreversible and irretrievable commitments of resources, and alternatives. Sufficient information can be obtained from descriptions of the environmental effects in the statement itself and from the alternative energy systems described in the literature to permit preparation of these portions of the statement.

In conclusion, information appears to be presently available to permit preparation of an environmental statement for the fusion reactor program. Development of the reactors has progressed far enough that the general design and environmental effects of the initial commercial reactors can be estimated. Sufficient information appears to be available to permit estimation of all environmental effects except those due to magnetic forces and large lithium releases. In those two cases the impacts on the general public probably can be reduced to insignificance by use of large exclusion areas and by proper plant design.

The estimated environmental effects would at the present time be speculative because the reactor designs have not been developed far enough for the specific design of the initial commercial plants to be known. This is a normal situation for any development program in its initial stages and should not be considered a block to preparing an environmental statement. Detrimental environmental effects estimated on the basis of current technology would probably be larger than those that actually will occur because additional technology that becomes available before commercial fusion reactors are built will probably reduce the magnitude of detrimental effects.

INFORMATION REQUIREMENTS
FOR
CONTROLLED THERMONUCLEAR REACTOR ENVIRONMENTAL STATEMENTS

INTRODUCTION

The controlled thermonuclear reactor is being developed as a potential source of low cost electricity with a lower environmental impact than either fission or coal-fired powerplants. Additional advantages could include an unlimited supply of low cost fuel (the deuterium in the oceans) and a low potential for accidents affecting the general public.

The National Environmental Policy Act requires that a detailed statement be written for each major Federal action significantly affecting the quality of the human environment. This statement discusses the environmental impacts of the proposed action, the alternatives, the short-term uses of the environment, the maintenance and enhancement of the long-term productivity, and any irreversible and irretrievable commitments of resources.

Preparation of an environmental statement during the initial stages of a powerplant development program requires a comprehensive analysis to determine the potential effects of construction and operation of the proposed plant systems. Because the final designs for the powerplants are not known, the statement cannot be written for a specific plant design. Instead, all of the more promising plant designs must be considered on a conceptual basis in accordance with the state of development. For each of the more promising plant designs, potential effects on the environment are estimated by determining: 1) the materials that may be needed for constructing and operating the plant, 2) the physical alterations of the environment as a result of obtaining these materials, constructing the plant, operating the plant, and finally disposing of the plant at the end of its useful life, and 3) the effects of these physical alterations of the

environment on the human population. Whenever possible, the more promising plant designs are classified generically and the environmental effects are analyzed for each class rather than for each specific plant design.

Preparation of an environmental statement for a new activity such as construction of CTRs may require information not expected to be available unless an effort is made to develop that information. As a result, it is advisable to determine the information that must be developed well ahead of the time when the environmental statement must be prepared. This permits orderly development of that information prior to the time when needed and should provide much better information than would be available as a result of a more hurried, last-minute development schedule.

This document describes the information that should be developed prior to preparation of the environmental statement for the first commercial CTRs. The analysis was based on a five-step procedure consisting of: 1) determining the current concepts of the final designs of the fusion reactors being developed in the United States, 2) analyzing these several designs to determine the probable environmental effects, 3) determining the information needed in order to estimate these environmental effects, 4) determining the expected availability of that information, and 5) determining the development efforts needed to obtain the information not expected to be available.

The evaluation was based on the assumption that much of the information needed for determining the environmental effect of fusion reactors has been developed or will be developed for fossil and fission powerplants. Consequently, primary emphasis was placed on identifying causes of environmental effects that will be unique for fusion reactors.

After the information needed for writing an environmental statement for CTRs was determined, an analysis was made to determine if enough information currently is available to permit preparation of an adequate environmental statement.

This discussion is presented in five sections. The first section describes the expected role of the CTR, including a discussion of the possible size of the reactors as a guide to the magnitude of the impact at a reactor site. The second section describes the several types of CTRs currently being developed and analyzes those designs to determine the potential sources of environmental effects. The third section first briefly describes environmental statements. It then analyzes the potential environmental effects for CTRs to determine the unique environmental effects in comparison to fossil and fission powerplants. The fourth section analyzes these unique environmental effects to determine the availability of the information needed to describe the environmental effects and the general nature of the research needed to assure ability to describe the environmental effects. The fifth section determines the adequacy of the available information for preparing an environmental statement for the CTR program.

1.0 EXPECTED ROLE OF THE CTRs

The CTR has the potential of producing low cost heat and electricity by use of an unlimited source of fuel--the light elements such as deuterium in the oceans. It also has the potential for producing this energy with a much smaller environmental effect than either fission or coal-fired powerplants. Only very small amounts of long half-life radionuclides might be generated, and large quantities of gaseous pollutants (SO_2 , NO_x , etc.) would not be released. Higher thermal efficiencies (up to seventy percent for direct conversion concepts) could also result in a significant reduction in the quantity of heat released per unit of electricity produced.

The CTR is expected to be introduced commercially at about the end of this century. Many years of development are necessary to first demonstrate fusion at a practical power generation level and then develop the equipment and systems needed for a competitive powerplant.

By the time that CTRs are introduced, the electricity consumption in the United States is forecast to be several times the current level. As a result the largest power reactors may be several times as large as the current ones and the electricity supply systems probably will be large enough to accommodate reactors of 5,000 to 10,000 MWe size. The initial commercial fusion reactors may be of this size, and the later ones may be even larger. Such large sizes may be necessary to take advantage of economies of scale to obtain competitive electricity unit costs.

A desirable characteristic for CTRs is a low enough detrimental environmental effect that they can be sited close to, if not inside, large cities. This would reduce transmission costs and effects, and increase the reliability of electricity supply. Two operational modes may evolve for the CTR: 1) a breeder reactor, located in remote regions, which would generate large quantities of excess fuel, and 2) a burner reactor, located in or near cities, that would be designed to burn this excess fuel with minimum environmental effect.

Several roles in addition to electricity generation may evolve for the CTR. Typical examples are: 1) providing large quantities of high temperature heat for industrial processes, 2) providing particles that are catalysts for chemical reactions, and 3) producing desirable isotopes by irradiation of targets with low cost neutrons. The practicality of such roles will depend on the CTR designs that evolve and the costs for these special roles.

2.0 PROPOSED TYPES OF CTRs

Reactions which occur between light nuclei and liberate energy as a result of rearrangement of the nuclei are commonly called fusion reactions. In order for such reactions to occur, the interacting nuclei must collide with sufficient energy to overcome the repulsive forces between them. When the energy of collision is the energy of random thermal motions of the nuclei, the reaction is called thermonuclear. A controlled thermonuclear reactor, then, is a device for achieving the release of energy by thermonuclear fusion in a controlled manner.

The energy released in fusion reactions comes from a conversion of mass to energy--the mass of the products of the reaction is smaller than the mass of the colliding nuclei, and $\Delta E = (\Delta m)c^2$ as shown by Einstein. This energy is carried off primarily as the kinetic energy of the reaction product particles. The release, collection, and conversion of this energy to electricity is the function of a CTR powerplant.

Both charged particles (atomic nuclei) and uncharged particles (neutrons) can be produced in fusion reactions. Electric and magnetic fields can be used to direct the motions of charged particles and to extract electrical energy from them (direct conversion). Neutron kinetic energy, however, usually can only be collected as heat generated by collisions of the neutrons with material placed in a blanket around the chamber in which the neutrons are released. Conversion of heat energy to useful work (electricity) requires a heat engine operating in a thermodynamic cycle (e.g., steam turbine) and is accompanied by the rejection of waste heat to the environment.

2.1 GENERALIZED SYSTEMS DESCRIPTION

For the purpose of functional analysis, a CTR powerplant may be considered to consist of two complementary sets of systems--one set that produces, confines and maintains the fusing plasma, and one set that captures the reaction products, extracts their kinetic energy and ultimately

produces electricity. In addition, two feedback mechanisms probably will be necessary to reduce fuel cycle costs and radionuclide releases. First, unburned plasma will be collected, along with reaction products, for return to the plasma fuel system. Second, for deuterium-tritium, the fuel with the greatest likelihood of use in first generation CTRs, it is necessary to produce tritium via a nuclear reaction induced by neutrons from the fusion reaction. This tritium must also be returned to the fuel system. A diagram indicating the functional relations of the primary CTR powerplant systems is shown in Figure 1.

2.2 FUELS

In order for the rate of fusion energy production in a plasma to equal the rate of energy input to the plasma (breakeven), high values of plasma density and temperature are required. Due to the extreme difficulty of achieving adequate plasma conditions, it is quite likely that the fuel used in the first commercial reactors will be that with the least stringent plasma requirements--deuterium and tritium. The reaction and its products are

Fuels considered for powerplant use must be obtainable in large quantities at a relatively low cost per unit of electricity produced. While natural supplies of tritium which satisfy this criterion do not exist, it is possible to produce tritium from lithium via the reactions

Because the 14 MeV neutrons produced in D-T fusion exceed the 2.5 MeV threshold for the ${}^7\text{Li}$ reaction, it is possible for a fusion neutron to produce two tritons in lithium--by inducing the ${}^7\text{Li}$ reaction, which emits a secondary neutron, which induces the ${}^6\text{Li}$ reaction. Studies indicate that blankets can be designed for D-T fusion reactors which will breed tritium, producing more than enough tritium to fuel the fusion reaction.

FIGURE 1. Functional Relations of CTR Powerplant Systems

The presence of deuterium in water with an isotopic abundance of 0.015% ensures its availability, and large reserves of lithium exist in the United States. Production costs for deuterium and lithium are very low in relation to the worth of the power which can be generated from them. Thus, in addition to being the fuel in which fusion may be the easiest to achieve, deuterium and tritium bred from lithium satisfy the requirements for fuel for a large scale power industry.

A number of alternative reactions have been identified,⁽¹⁾ but they require harder-to-achieve plasma conditions. The reaction

is of interest but requires plasma kinetic temperatures much higher than the D-T reaction to achieve equivalent reaction rates.

The deuterium fuel for this reaction is universally available, and virtually inexhaustible. Hence it represents a possible longterm solution to the world's energy needs. This reaction is also of interest because tritium need not be bred in the blanket, and the 2.5 MeV neutrons produced are less penetrating, less damaging and cause less activation than the 14 MeV neutrons from the D-T reaction.

Each D-D fusion produces as a reaction product, either an ion of tritium or of ${}^3\text{He}$. The T ions may be consumed within the plasma via the D-T reaction. Furthermore, the ${}^3\text{He}$ ions may be likewise consumed via the reaction

The sequential reactions DD-DT and DD-D ${}^3\text{He}$ both release about 7 MeV per deuteron consumed, as opposed to the roughly 2 MeV released per neutron consumed by the D-D reaction. This additional energy release provides incentive for maximizing the rates of these secondary reactions in a fusing D-D plasma (at the expense of increased production of 14 MeV neutrons).

Fusion reactions which produce only charged particles are of interest since they may allow highly efficient direct conversion of particle energy to electricity. D-³He fusion is such a reaction. However, because the isotopic abundance of ³He (0.00013%) is two orders of magnitude smaller than that of deuterium it would have to be created by appropriate nuclear reactions. ³He production via the radioactive decay of tritium produced by neutron irradiation of lithium has been proposed.⁽²⁾

The reaction

is also a reaction producing only charged particles. Furthermore, the fuel has a low cost and is readily available. Recent studies⁽³⁾ have indicated that the ¹H-¹¹B reaction may be a candidate for use in advanced laser-ignited inertial confinement CRT's, although it is not expected to be useable in magnetic confinement CRT's because of the high reaction temperatures required.

In Figure 2, the thermally averaged reaction rates for several fusion fuels are plotted as a function of ion kinetic temperature.⁽⁴⁾ A range is indicated for the p-¹¹B reaction due to uncertainties in cross sections and other effects. The significant increases in plasma temperature necessary for achieving fusion in fuels other than deuterium-tritium are displayed in this figure.

The appeal of the alternative fuels lies in the long-term availability of fuel, reducing neutron production and eliminating the necessity to breed fuel through transmutation reactions. Advanced fuels show promise of decreasing the induced activation of blanket and structural materials, of reducing inventories and effluents of radioactive tritium gas, and of decreasing waste heat per unit of electrical power by allowing more efficient electrical generation via direct conversion. Achievement of any or all of these possibilities should reduce the environmental impact of fusion reactors (although the occurrence of some unforeseen compensating factor might prevent it).

FIGURE 2. Thermally Averaged Reaction Rates for Various Fusion Fuels.(4)

Since existing conceptual reactor designs assume the use of D-T fuel, and since CTRs using that fuel are expected to have a greater environmental impact than as-yet-undisigned CTRs using alternative fuels, this study assumes the use of D-T fuel and the need to breed tritium in the reactor.

2.3 PLASMA CONFINEMENT

Magnetic and inertial confinement schemes have been proposed to isolate plasmas with kinetic temperatures exceeding 10^8 K from surrounding physical systems. In the various magnetic confinement schemes proposed, helical charged particle motion along magnetic field lines is used to slow charged particle diffusion out of the reaction region. This is necessary to hold the plasma together during the period in which fusion reactions take place.

Magnetic field lines form closed loops. Consequently, unless a CTR plasma chamber is constructed to contain entire field line loops--as in toroidal machines--charged particles spiraling along field lines may escape confinement where the field lines exit the plasma chamber. However, a remedy for this problem exists in the form of magnetic "mirrors" which tend to reflect charged particles. Plasma confinement in both toroidal geometries and between magnetic mirrors is under study.

Interial plasma confinement is actually non-confinement. The thermonuclear plasma disassembles on a time scale determined by plasma particle velocities and collision rates--fractions of a nanosecond. (The release of large amounts of fusion energy during this brief period requires that considerable attention be paid to the containment of blast effects.)

Plasma creation, compression, and heating is accomplished by laser irradiation of a solid fuel pellet. Laser energy is coupled to the fuel via electromagnetic interactions. In fact, this coupling must be strong enough to cause plasma implosion to densities many hundreds of times that of the solid fuel pellet. Thus, the action-at-a-distance property of the electromagnetic interaction is of fundamental importance to both fusion confinement methods.

2.4 CONCEPTUAL POWERPLANT DESIGNS

The Federal Government is the primary sponsor of fusion research in the United States, with about 90% of the total effort managed by the ERDA.⁽⁵⁾ Of this, slightly more than half is managed by the Division of Controlled Thermonuclear Research, which supports a broadly based program of research, development, reactor technology and the magnetic containment programs. Most of the remainder of the government fusion program is managed by the Division of Military Application, in support of laser fusion research.

Most of the ERDA support is allocated to a few major laboratories. Research laboratories and the confinement schemes which are studied there are listed in Table 1.

TABLE 1. Major ERDA Fusion Research Efforts

<u>Laboratory</u>	<u>Confinement Schemes Studied</u>
Lawrence Livermore Laboratory	Inertial; Magnetic (mirror)
Los Alamos Scientific Laboratory	Inertial; Magnetic (theta pinch)
Oak Ridge National Laboratory	Magnetic (tokamak)
Princeton Plasma Physics Laboratory	Magnetic (tokamak)
Sandia	Inertial

In addition, smaller programs are supported at other ERDA laboratories, universities, and industrial sites.

In a recent report prepared for the Chairman of the USAEC⁽⁵⁾ the following objectives were identified for the fusion program.

Research

To conduct theoretical, computational, and experimental studies seeking the body of knowledge that predicts the behavior of thermonuclear fusion experiments and the operating characteristics of fusion reactors.

Development

To develop the technology necessary to perform fusion research.

Confinement Systems

To investigate, develop and establish the feasibility of low density closed (tokamak), high density closed (theta pinch), and open (mirror) magnetic confinement systems as a basis for practical fusion power generation.

Laser-Fusion

To investigate, develop and establish the feasibility of laser-fusion as a basis for practical fusion power generation.

Fusion Reactor Technology

To develop the engineering base, qualify materials, develop components and conduct engineering studies necessary for the design, construction and operation of prototype, demonstration, and commercial fusion power reactors.

In support of the Fusion Reactor Technology objectives, conceptual and reference designs for CTR powerplants have been prepared by various study groups, as identified in Table 2. The results of analyses of these conceptual and reference designs are presented in the remainder of this section. Major systems have been identified, their functions described, and systems diagrams have been prepared for each of the designs. In addition, a fusion-fission hybrid reactor designed jointly by Lawrence Livermore Laboratory and Battelle-Pacific Northwest Laboratory is similarly analyzed and described at the end of this section. With the exception of an external processing cycle for fission fuel, the generalized system description of Figure 1 is seen to be applicable to hybrid CTRs.

TABLE 2. Originators of Conceptual and Reference CTR Powerplant Designs

Magnetic Confinement CTR

Tokamak	University of Wisconsin Oak Ridge National Laboratory Princeton Plasma Physics Laboratory
Theta Pinch	Los Alamos Scientific Laboratory
Mirror	Lawrence Livermore Laboratory

Inertial Confinement CTR

Wetted Wall	Los Alamos Scientific Laboratory
Blascon	Oak Ridge National Laboratory
Suppressed Ablation	Lawrence Livermore Laboratory

It should be noted that these designs are generally the result of ongoing efforts. Some of the design documents lack complete descriptions of certain facets of the design, assuming the existence of the necessary systems or assuming the feasibility of a process. In such cases this is simply noted in the following descriptions. No attempt has been made to review the completeness of preceding efforts to justify or support such assumptions.

The expected duration of the thermonuclear burn, during which fusion reactions take place varies widely between the several magnetic confinement concepts. The mirror reactor burn is not expected to be time limited due to continuous plasma replenishment. Impurity buildup during the tokamak burn is expected to require refueling after burn times of many hundreds of seconds, or less. Plasma expansion will require termination of the theta-pinch burn after many tens of milliseconds, and pellet disassembly limits inertially confined thermonuclear burn to fractions of a nanosecond. Thus, significant differences are found in the systems supporting the fusion plasma among the various magnetic and inertial confinement schemes.

All of the designs are based upon the use of D-T fuel. Hence, each must handle the same reaction products and breed tritium from lithium. Nevertheless, properties of blanket systems are determined in part by thermonuclear burn duration and frequency and by space limitations, and significant differences do exist.

2.4.1 Magnetic Confinement Designs

The three magnetic confinement concepts are: tokamak, theta pinch, and mirror. Each is discussed here, and the powerplant designs based upon each concept are described.

Tokamak

A tokamak is a toroidal machine which contains entire magnetic field loops within its plasma chamber. While charged plasma particles spiraling about magnetic field lines are individually confined by a simple toroidal field, plasma instabilities (including gross motion of the plasma as a whole) require a more complex magnetic field structure for containment. Plasma stabilization requires that the circular field loops be distorted into helices. This is achieved by inducing a current in the plasma ring which creates its own magnetic field. The field lines produced by the combined effects are a nested set of helices whose pitch angles vary with radial position within the torus cross section. (A similar field configuration is used in stellarator machines. However, it is produced by helically wound coils, instead of plasma current. The tokamak is thus a simpler machine.)

An additional vertical field, perpendicular to the plane of the torus, is required to stabilize the radius of the plasma ring and to provide vertical stability, thus keeping the plasma centered in the toroidal plasma chamber. Consequently, tokamaks require magnetic circuits to produce toroidal and vertical magnetic fields, and to induce a high current (megamperes) in the plasma.

Three powerplant designs based upon the tokamak concept of magnetic confinement have been produced. The University of Wisconsin has devoted extensive efforts to a design starting with basic plasma requirements.⁽⁶⁾ A design has been developed at Oak Ridge National Laboratory starting from assumed plasma conditions,⁽⁷⁾ and Princeton Plasma Physics Laboratory has developed a design for which the descriptive document⁽⁸⁾ had not been issued as this material was compiled. Descriptions of each of these energy systems follow. (The description of the PPPL design is drawn from previously issued documents⁽⁹⁻¹²⁾ and discussions.)⁽¹³⁾

University of Wisconsin Tokamak. The design philosophy of UWMAK-I⁽⁶⁾ requires use of present-day technology capabilities invoking as little extrapolation as possible. (Thus stainless steel structural material is specified.) Reasoning from plasma scaling laws, cost optimization fixes the power output at 5000 MWt and the plasma chamber size as follows: torus major radius, 13 meters; minor radius, 5.5 meters. Figures 3 and 4 show the powerplant building and the reactor in cross section.⁽⁶⁾

The coils producing the UWMAK-I magnetic fields are of superconducting niobium-titanium. Included are the toroidal field coils, the air-core ohmic heating transformer coils, and the poloidal divertor coils.

An initial charge of D-T fuel gas is ionized and a plasma current established by the ohmic heating transformer coils. It is not expected that ohmic heating alone will lead to ignition. Further plasma heating (to ignition) by the injection of energetic beams of neutral atoms is to be employed. This is accomplished in a few seconds, after which the neutral beam injectors are shut down and plasma energy is maintained by alpha particle heating from the fusion reactions.

This technical diagram illustrates the exploded view of a mechanical assembly, likely a pump or engine component. The main body is shown in a cross-sectioned, exploded state to reveal internal components. The assembly includes a central shaft with multiple gears or impellers mounted on it. A large, curved, bowl-shaped component is positioned at the bottom, and a smaller, cylindrical component is at the top. Various bolts, nuts, and internal structural parts are labeled with circled numbers 1 through 16. The diagram is a black and white line drawing with hatching for shading.

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

FIGURE 3. UWMAK-7 Powerplant Building

FIGURE 4. Cross Section View of UWMAK-1 Fusion Reactor

The average confinement time of plasma particles is about 15 seconds, followed by escape and then collection by a double null magnetic divertor. Plasma density is maintained by fuel injection in the form of solid pellets of D-T. The fuel feed rate will be 8.4 kg T and 5.6 kg D per day. Impurity buildup in the plasma is expected to be slow.

It is possible that following ignition a "bootstrap" plasma current may be maintained by plasma processes. If so, impurity build up in the plasma will terminate the thermonuclear burn. If not, the plasma current must be maintained against resistive losses by increasing the field of the ohmic heating transformer coils. In the latter case, transformer coil capacity may limit the thermonuclear burn duration to about an hour and a half. Following the burn the plasma chamber is evacuated and refilled with fresh fuel gas. Initiation of another cycle begins within minutes of shutdown.

Power requirements of the ohmic heating transformer and divertor coils during cycle startup exceed projections of power available from commercial power grids. Some form of magnetic energy storage and transfer system is required.

Mercury diffusion pumps and cryopumps cooled by liquid helium maintain the vacuum in the reaction chamber. Two sets of cryopumps are used to allow periodic degassing. Gases recovered by the vacuum system are sent to a cryogenic distillation system for purification and return to the fuel system. External deuterium supply and tritium supply from blanket systems are planned.

Systems whose functions relate to production of the fusion reaction are:

- Superconducting magnets (all magnets)
- Fuel injection system (gas and pellet)
- Neutral beam injection system
- Magnetic energy storage and transfer system
- Plasma and divertor chamber vacuum system
- Used fuel cryogenic distillation system

- Liquid helium cryogenic system
- External deuterium supply
- Tritium supply from blanket lithium.

Energy collection and tritium production take place in a blanket located inside the magnet coils, adjacent to the plasma. Neutron moderation and capture are accomplished by liquid lithium metal contained in the Type 316 stainless steel structure and reflector.

Lithium is also the primary coolant for the blanket. It is circulated out of the blanket to exchange heat to an external sodium system. From this intermediate cooling system heat is exchanged to a steam turbine system.

The corrosion of stainless steel by lithium is dependent on impurity levels (particularly nitrogen). Furthermore, it is desirable to limit corrosion product transport and deposition. Consequently, a cleanup system is planned for hot trapping impurities in the lithium with a zirconium getter. A similar hot trap is also planned for the sodium system.

Tritium bred in the blanket lithium and trapped in flowing lithium in the divertors is removed by passing a portion of the lithium stream exiting from the heat exchangers through an yttrium extraction bed. Thermal regeneration of the extraction beds releases the tritium, which is then sent to the fuel system via the cryogenic purification system.

Particles and radiation which penetrate the blanket are to be attenuated by a shield protecting the superconducting magnets. A heterogeneous mixture of lead and boron carbide with stainless steel structure is specified. A heat removal system employing helium gas is specified for the shield.

Systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure and moderator
- Lithium primary coolant and tritium breeding system

- Sodium intermediate coolant system
- Lithium and sodium hot-trapping (Zr) systems
- Tritium getter (Yt) system
- Steam turbine system
- Shield for superconducting magnets
- Helium shield coolant system.

The functional relations between systems of the UWMAK-I tokamak powerplant are shown in Figure 5.

Oak Ridge Tokamak. An ORNL study⁽⁷⁾ addresses design of the blanket and magnet shield portions of a 1000 Mwt CTR, including related systems. Design of systems associated with the production of the fusion reaction is not addressed. Sizes, field strengths, and other critical parameters relating to plasma confinement are assumed using representative values based upon other Oak Ridge studies. The dimensions chosen for the toroidal plasma chamber are: major radius 10.5 meters; minor radius 3.5 meters. Figures 6 and 7 show a pictorial section view of the reactor and a cross section drawing of the powerplant.

The plasma is to be confined by a toroidal magnetic field produced by superconducting magnets. Vertical magnetic fields are to be produced by copper coils. An iron core is provided in the center of the solenoid. Subsequent studies show that extending the iron core to make a complete iron magnetic circuit is favored.⁽¹⁴⁾

Plasma fueling and heating is to be accomplished by neutral beam injection. The fuel feed rate is 0.6 kg of T and 0.4 kg of D per day. The thermonuclear burn lasts almost three minutes. It is terminated by impurity build-up when the helium content of the plasma reaches 10 percent. It is assumed that plasma losses will be small and that it will not be necessary to protect the blanket vacuum wall from escaping plasma particles by means of a magnetic divertor.

At the termination of the burn the spent plasma is cooled and neutralized. It blows down from the toroidal plasma chamber into the vacuum duct-plenum region, where it is cooled to near room temperature. It is then pumped out and sent to a distillation system for reclamation of the

FIGURE 5. Functional Relations Between Systems of the UWMAK-I Tokamak Powerplant

TOROIDAL FUSION REACTOR (1000 MWt)

FIGURE 6. Pictorial Section View of the ORNL Tokamak

FIGURE 7. Cross Section of ORNL Tokamak Powerplant

unburned fuel which is purified and recycled to the injection system. External deuterium supply and tritium supply from blanket systems are planned.

Systems whose functions relate to production of the fusion reaction are:

- Superconducting toroidal magnets
- Vertical-field coils (non superconducting) and iron core
- Neutral beam injection system
- Liquid helium cryogenic system
- Plasma chamber vacuum system
- Recirculating fuel purification (distillation) system
- External deuterium supply
- Tritium supply from blanket lithium.

Energy collection and tritium production take place in a blanket located inside the magnet coils, adjacent to the plasma. Neutron moderation and capture is accomplished by lithium and graphite contained in the niobium blanket structure.

Lithium is the primary coolant and is circulated within the blanket by MHD pumping. Heat exchange to an intermediate potassium binary system takes place within the outer blanket region. The potassium vapor is piped out of the reactor to a topping turbine, and is then condensed in a steam generator. The steam thus produced drives a turbine-generator.

Tritium bred in the blanket lithium is allowed to diffuse through the tubes of the heat exchanger into the potassium system. A small amount of lithium is dissolved in the potassium system's condensate tank. A side-stream of about one-fifth of the potassium system flow is sent through cold traps where condensed LiT is filtered out. Tritium released during regeneration of the Li getter is sent to the fuel system.

Particles and radiation which penetrate the blanket are to be attenuated by a shield to protect the superconducting magnets. Graphite followed by lead is specified, with inclusion of LiOH suggested.

Systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure and moderator
- Lithium primary coolant and tritium breeding system
- Potassium intermediate coolant system and topping turbine
- Tritium cold trap gettering system
- Steam turbine system
- Shield for superconducting magnets.

The functional relations between systems of the ORNL tokamak powerplant are shown in Figure 8.

Princeton Tokamak. The Princeton design philosophy is based upon the use of present technology and materials as far as possible. Power output is 5300 MWt, and plasma chamber dimensions are: major radius, 11 meters; minor radius, 3.6 meters. Figures 9 and 10 show section views of the reactor and powerplant.⁽⁸⁾

All magnet coils are of niobium-tin superconductor cooled by liquid helium. Included are coils which produce the toroidal, vertical, and poloidal divertor fields, and the transformer coils which produce and maintain the plasma current.

An initial charge of D-T gas is ionized by an rf discharge, and heated by plasma current induced by the vertical field coils. Plasma density and energy are then increased by injection of beams of neutral atoms of fuel gas, and ignition occurs. It is expected that plasma and "ash" will escape from the plasma following an average residence time of 3.9 seconds, during which a burnup of 8.7% is achieved. The single null poloidal divertor guides the escaping particles into an exhaust chamber for collection.

Plasma fuel replenishment is by the injection of pellets of solid D-T which ablate in the plasma. The fuel feed rate is 6.0 kg of T and 4.0 kg of D per day. A fundamental design assumption is that impurity buildup is controlled by plasma losses so as not to limit the duration of the thermonuclear burn.

FIGURE 8. Functional Relations Between Systems of the ORNL Tokamak Powerplant

FIGURE 9. Section View of the PPPL Tokamak

FIGURE 10. Pictorial Section View of the PPPL Tokamak Powerplant

Maintaining the plasma current is expected to require continuous change of the flux in the transformer coil. Consequently, the duration of the thermonuclear burn is limited by the capacity of the transformer coil to about one and one-half hours. This is followed by a 30 second pumpout, refilling with fresh fuel gas, and initiation of another cycle.

Escaping plasma ions collected by the magnetic field of the divertor are neutralized in collection chambers, and the neutral gas atoms are pumped from the divertor channel by vacuum pumps. Impurity removal is accomplished by cryogenic distillation, and the purified fuel is recycled. External deuterium supply and tritium supply from blanket systems are planned.

Systems whose functions relate to production of the fusion reaction are:

- Superconducting magnets (all magnets)
- Fuel injection system (gas and pellet)
- Neutral beam injection system
- Plasma and divertor chamber vacuum system
- Recirculating fuel purification (distillation) system
- Liquid helium cryogenic system
- External deuterium supply
- Tritium supply from blanket lithium.

Energy collection and tritium production take place in a blanket located inside the magnet coils. Neutron moderation and capture is accomplished in molten flibe (fluorine, lithium, beryllium, a eutectic mixture of the salts LiF and BeF₂) and in structural material of the Nimonic alloy PE-16 (43% Ni, 35% Fe, 17% Cr, 3% Mo, 1% Ti and 1% Al).

Heat is removed from the blanket by helium gas coolant, with heat transfer taking place throughout the blanket. The inner blanket wall is separated from the plasma by a radiation shield of tubes also cooled by helium. Heat is exchanged from the helium systems to a steam turbine system.

Molten flibe is continuously circulated from the blanket through a desorber where bred tritium, entrained as TF gas, is removed by helium gas sparging. Circulation of the gas through potassium fluoride beds yields KTF_2 from which tritium is chemically recovered and sent to the fuel system.

Particles and radiation penetrating the blanket are attenuated by a shield consisting of half a meter of concrete and iron. This shield protects the superconducting magnets during operation and limits radiation affecting maintenance personnel when the reactor is shut down.

Systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure and moderator
- Flibe tritium breeding system
- Helium coolant system
- Tritium recovery system
- Steam turbine system
- Shield for superconducting magnets.

The functional relations between systems of the PPPL tokamak power-plant are shown in Figure 11.

Theta Pinch

In a theta pinch device, a fast-rising magnetic field is used to heat and compress plasma to thermonuclear ignition conditions. The applied magnetic field induces currents in the plasma by transformer action which flow in the "theta" direction encircling the coil axis. Interaction of these currents with the rising magnetic field heats and compresses the plasma - hence, the "theta pinch".

Plasma shock heating and compression in theta pinch experiments have been accomplished simultaneously, using a single, one-turn magnet coil. However, it is believed that by use of separate, concentric coils, the functions of plasma implosion heating and compression can be separated

FIGURE 11. Functional Relations Between Systems of the PPPL Tokamak Powerplant

and staged. This is expected to reduce the necessary plasma compression, improving plasma stability and lowering costs.⁽¹⁵⁾ The physics and technology of theta pinch staging are presently under investigation at Los Alamos Scientific Laboratory. Separation and staging of plasma shock heating and compression are assumed in the design described below.

Los Alamos Theta Pinch. The Los Alamos Reference Theta Pinch Reactor (RTPR)⁽¹⁶⁾ is a toroidal machine, thus eliminating end losses. It operates in a pulsed mode, with a 0.1 second thermonuclear burn every 10 seconds. This yields a power output of 3600 MWt. The major radius of the plasma chamber is 56 meters; its minor radius is 0.5 meters. With an aspect ratio exceeding 100, the plasma chamber shape may be likened to that of a bicycle tire, in contrast to doughnut-shaped tokamaks having aspect ratios near 3. Figures 12 and 13 show cutaway views of a 2-meter-long RTPR module and of a conceptual RTPR powerplant.⁽¹⁶⁾

The pulsed operation of the RTPR is as follows. D-T gas contained within the plasma chamber is ionized, shock heated and compressed to fusion ignition by the application of strong, fast-rising magnetic fields. Following ignition, the deposition of alpha particle energy in the plasma causes plasma expansion. To prevent plasma-wall contact the burn is terminated by relaxing the magnetic containment field, allowing the plasma to expand into a layer of neutral D-T gas introduced along the wall. The plasma radius is then maintained constant by slowly relaxing the magnetic field, while the plasma is quenched and neutralized. Plasma energy is then transferred through the gas to the plasma chamber wall. Options available for refueling range from constant-pressure dilution of the gases remaining in the plasma chamber, to chamber evacuation followed by the introduction of fresh fuel.

Recycle of unburned D-T gas is achieved by removing impurities and ash from the exhaust gas by cryogenic distillation. External deuterium supply, and tritium supply from blanket systems are planned.

FIGURE 12. Cutaway View of a RTPR Module

FIGURE 13. Cutaway View of a Conceptual RTPR Powerplant

RTPR systems whose functions relate to production of the fusion reaction are:

- Plasma implosion heating coil and capacitor bank
- Plasma compression coil
- Compression coil energy storage and transfer system
- Fuel gas supply system
- Plasma chamber evacuation system
- Used fuel cryogenic distillation system
- External deuterium supply
- Tritium supply from blanket lithium

Energy collection and tritium production take place in a blanket located inside the magnet coils, adjacent to the plasma. The blanket receives 14 MeV neutrons and plasma radiation during the thermonuclear burn. In addition, it receives plasma kinetic energy transmitted from the quenched plasma through the neutral gas blanket following each burn. Direct conversion of charged particle energy is accomplished during the thermonuclear burn as the plasma, heated by the deposition of alpha particle energy, expands against a constant magnetic field.

Neutron moderation and capture in the blanket is accomplished by lithium, beryllium and graphite, with neutron multiplication by Be (n,2n) reactions. Neutrons are parasitically captured by niobium structural material and alumina (Al_2O_3) insulation, and they escape to the surrounding magnet coils. Incorporation of beryllium in the blanket for the purpose of neutron multiplication allows tritium breeding with a thinner blanket and a consequent reduction in the amount of energy which must be transferred to and from the magnet coils. (The magnetic energy which must be transferred to and from the compression coils for each pulse is roughly 1.8 times the fusion energy released per pulse.)

Thermal energy removal from the blanket is accomplished by pumping the (molten) lithium out of the blanket and through a heat exchanger. (Although

electromagnetic effects inhibit the flow of molten metal across magnetic field lines, the plasma compression field is zero for 90% of the cycle.) Heat exchange can be to an intermediate sodium system or to a potassium binary system in which potassium vapor drives a topping turbine. From either intermediate system, heat is exchanged to a conventional steam turbine system.

Extraction of tritium bred in the blanket lithium is accomplished by diverting a small portion of the lithium stream exiting from the primary heat exchanger through a molten salt contactor system. The greater solubility of LiT in the molten salt than in the lithium causes it to move preferentially with the salt when the liquids are separated by centrifugation. Either electrochemical or gas sparging techniques will then be used for liberation of the tritium from the molten salt. The molten salt contactor will also serve to remove a wide range of impurities from the lithium, including corrosion products and impurities which might react with structural materials.

Some neutron and gamma ray leakage from the blanket to and through the magnet coils is tolerated to minimize magnet coil size. An external concrete biological shield is provided to reduce radiation levels in areas adjacent to the reactor.

Systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure and moderator
- Lithium primary coolant and tritium breeding system
- Intermediate coolant (Na or K) system
- Steam turbine system
- Lithium cleanup-tritium separation system
- Biological shield

The functional relations between systems of RTPR powerplant are shown in Figure 14.

Mirror

A charged particle in helical motion about a magnetic field line experiences a retarding force as it moves into a region of increasing

FIGURE 14. Functional Relations Between Systems of the Los Alamos RTPR Powerplant

magnetic field. If this force is strong enough, the particle's motion along the field line will be stopped and the particle will be pushed back toward its source (the rotation about the field line remaining unchanged). This effect may be likened to reflection by a mirror - hence, a localized high-field region of a magnetic field may be termed a magnetic mirror. Charged particle confinement by trapping between two magnetic mirrors is called mirror confinement.

A charged particle whose direction of motion is close enough to the direction of the magnetic field line around which it spirals will penetrate a magnetic mirror. Consequently, for each magnetic mirror there exists a "loss cone" through which particles can escape. Because plasma particles are continually scattered into the loss cone by collisions, mirror confinement is inherently leaky.

Livermore Mirror. The Livermore Mirror CTR design⁽¹⁷⁾ envisions plasma creation and continuous replenishment of leaking plasma by the injection of energetic beams of neutral fuel atoms. These are ionized and trapped in the plasma. Plasma impurities, including helium "ash," are maintained at a low level by the dilution effect of continuous plasma replenishment combined with plasma loss through the mirrors. Consequently, the operating cycle for this mirror confinement CTR is not expected to be limited by the necessity for plasma refreshment, and continuous operation is projected.

The kinetic energy of leaking plasma particles represents a sizable power loss from the plasma, which must be made up by the neutral beam injectors. This power loss is sufficiently great that direct conversion to electrical energy of the kinetic energy of leaking plasma is required. Furthermore, the maintenance of plasma energy content by neutral beam injection requires that a sizable fraction of the electrical power generated be returned to the injectors. The reactor produces 1130 MWt, and generates 750 MWe, of which 430 MW is generated by direct conversion and 320 MW by the thermal cycle. The net plant output is 170 MWe.

Stability of plasma confined between magnetic mirrors requires a magnetic well - that is, a magnetic field having minimum strength in the plasma center. Such a field is achieved in the Livermore design by the "Yin-Yang" coil configuration shown in Figures 15 and 16.⁽¹⁷⁾ The plasma is confined in the central region between the superconducting coils, and leakage is selectively directed through one of the mirrors into an expander-collector structure which directs it to the direct convertor. This may be seen in the cross section view of Figure 16. As indicated on the figure, the radius of the magnet coils is 10 meters.

Recycle of unburned fuel is necessary, requiring collection of the leaked plasma. Plasma ions escaping through the magnetic mirrors are decelerated by an electric field in a direct convertor and neutralized on charge collector elements. The neutral gas atoms thus produced are then collected by the vacuum system. The system for purification of this unburned fuel is not defined. External deuterium supply, and tritium supply from blanket systems are planned.

Systems whose functions relate to production of the fusion reaction are:

- Superconducting magnets
- Neutral beam injection system
- Reactor and direct convertor vacuum systems
- Fuel gas purification system (undefined)
- Liquid helium cryogenic system
- External deuterium supply
- Tritium supply from blanket lithium.

Neutron energy collection and tritium production take place in a blanket located adjacent to the plasma, which consists of overlapping layers of stainless steel tubes containing lithium, and graphite. The lithium is the primary coolant. It is pumped through the tubes, which are directed along magnetic field lines to minimize MHD pumping losses. Heat exchange to a nonconducting intermediate coolant (immune to MHD

FIGURE 15. Cutaway View of the Livermore Mirror CTR

FIGURE 16. Cross Section Through the Livermore Mirror CTR and Direct Converter

pumping losses) takes place in the blanket. The intermediate coolant (helium is a likely choice) conveys the heat to a steam generating system.

Tritium is removed from the lithium by diffusion through the stainless-steel tubes to the vacuum system. Since the entire lithium flow system will be located in magnetic field regions, laminar flow is assumed. Consequently, tritium must diffuse through the lithium, as well as through the tube walls. Lack of data on attainable rates for this process is noted, as is the need for further design study to minimize tritium holdup in the lithium.

Particles and radiation which penetrate the blanket are to be attenuated by a shield which protects the superconducting magnets. Preliminary studies assume a composition of one-half lead and one-half kerosene.

Systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure and moderator
- Lithium primary coolant and tritium breeding system
- Charged particle direct conversion system
- Shield for superconducting magnets
- Nonconducting intermediate coolant system (undefined)
- Steam turbine system

The functional relations between systems of the Livermore Mirror CTR powerplant are shown in Figure 17.

2.4.2 Inertial Confinement Designs

Central to powerplant design based upon the inertial confinement concept is the assumption that ignition of a pellet of D-T fuel can be achieved by imploding and heating it with focused laser beams. (According to a recent report, some previously classified details of pellet design have been released.⁽¹⁸⁾ Among the pellets of interest are glass microspheres about 50 μm in diameter, containing D-T gas at 50 to 100 atmospheres pressure.)

The production of electrical power requires that the energy released in the pellet explosions be captured. Proposed powerplant designs employ

FIGURE 17. Functional Relations Between Systems of the Livermore Mirror CTR Powerplant

repeated pellet explosions, ignited in a central cavity in a containment vessel. The cavity is surrounded by a blanket to moderate the fusion neutrons and to breed tritium by capture in Li.

The fusion neutrons deliver roughly three quarters of the energy of the fusion pulses to the blanket, distributing it over a volume of material. The remainder of the energy is delivered to the containment surface as the kinetic energy of pellet debris and helium "ash," and as x rays. Several concepts have been proposed to protect this surface from the effects of very high rates of energy deposition. In the Wetted Wall concept⁽¹⁹⁾ a layer of liquid lithium coating the blanket wall is ablated by the blast energy and the vapor is blown down to a diffuser/condensor. In the Blascon concept⁽²⁰⁾ the cavity is a vortex in a swirling pool of molten Li, and no surface structure exists. In the Suppressed Ablation⁽²¹⁾ concept a liquid Li layer coats and protects the blanket wall, but is not ablated because energy fluxes are held sufficiently low. These concepts are described further in the following discussions. Other concepts which have been proposed, but not developed to the powerplant stage, include a dry-wall concept having an ablative inner blanket wall of carbon,⁽²²⁾ and a cavity having bare walls which are protected from the ionized plasma debris and helium ash by magnetic fields.⁽²³⁾ An outline of some of the engineering aspects of an inertial confinement CTR dubbed the Saturn reactor has been presented,⁽²⁴⁾ but is not addressed herein.

In describing the energy released in the fusion of a pellet, one may note that the energy release of chemical high explosive is about 2 MJ per pound of TNT. However, the blast effect of a fusion pulse will be much smaller than that of a TNT explosion for two reasons. First, the mass of fusion pellet debris carrying the blast is a million times smaller than the mass of debris from an equivalent TNT explosion; and second, most of the energy is carried by neutrons which penetrate material surfaces and interact with a distributed volume of material. Consequently, blast effects of fusion pulses will be more than 1000 times weaker than blast effects of TNT explosions of equivalent energy. However, the complexity of confinement

analysis may be indicated by noting that ablative blowoff from confinement surfaces can cause shock waves which amplify blast effects by orders of magnitude.

As has been noted, certain aspects of laser-fusion research have been classified due to weapons implications. For example, the Los Alamos study⁽¹⁹⁾ has a classified companion volume which discusses the problems of achieving laser-driven fusion.⁽²⁵⁾ Furthermore, the AEC has monitored all privately sponsored laser-fusion research in the United States.

Recent declassification of laser-fusion information has significantly assisted development of commercial CTRs.

Los Alamos Wetted Wall. This proposed concept⁽¹⁹⁾ assumes the existence of an appropriate high-power laser, laser beam transport system, fuel supply and purification system, and an appropriate D-T fuel pellet fabrication and injection system.

Systems whose functions relate to the production of the fusion reaction are:

- Laser system
- Beam transport system
- Fuel pellet fabrication and injection system
- Exhaust gas removal system
- Fuel gas purification system
- External deuterium supply
- Tritium supply from blanket lithium.

Neutron energy collection and tritium production take place in a blanket of lithium surrounding a cavity in which the laser-initiated fusion pulses are produced. The concept takes its name from an ablative coating of lithium which flows through the porous niobium cavity wall and protects it from the high fluxes of particles and radiation occasioned by the extremely short duration of the fusion pulses. Pressure pulses due to the fusion pulse, and to the rapid lithium ablation, are transmitted through

the thin cavity wall and through the lithium to a thick stainless steel pressure vessel deep in the blanket. The structure is shown in cross section in Figure 18.⁽¹⁹⁾

An energy release of 200 MJ per pulse is assumed in the 1.0 meter radius cavity. The design calls for cavity blowdown and evacuation to allow repetitive pulsing once a second (200 MWt average power). It is assumed that several such structures could be clustered and served by a single laser. A 2000 MWt powerplant, requiring ten cavities, is assumed in the design study.

Kilogram quantities of lithium are vaporized from the wetted cavity wall by each fusion pulse. Cavity blowdown of Li vapor and pellet debris takes place through a diffuser/condenser into a pool of liquid lithium sufficiently deep to absorb the kinetic energy of the products. Figure 19 details the condenser,⁽¹⁹⁾ which receives a significant fraction of the fusion energy.

Lithium is the primary coolant. It is circulated from the blanket and from the condenser pool to exchange heat with an intermediate coolant system. From the intermediate system heat is transferred to a steam turbine system for generation of electricity.

The primary coolant is purified of tritium (LiT) and condensable impurities by directing a sidestream from the heat exchanger outlet through cold traps. Tritium recovered by this process is purified and recycled to the fuel system.

Succeeding studies have also been carried out for this concept. A cost-based systems analysis has been reported;⁽²⁶⁾ and a design study for a 1000 MWe powerplant has been presented, in which 8 laser beams from a central laser facility are switched to serve 24 separate reactor cavities by means of a rotating mirror assembly.⁽²⁷⁾ Pulses of 100 MJ are produced inside each cavity at a frequency of 1.2 per second. Each 3.4 m diameter cavity produces 156 MWt, which is transferred through a sodium intermediate cooling system to a steam turbine system.

FIGURE 18. Cross Section and Flow Schematic of the Wetted Wall Laser-Pellet CTR

FIGURE 19. Diffuser/Condenser Concept for Cavity Blowdown in the Wetted Wall Laser-Pellet CTR

Systems whose functions relate to products of the fusion reaction are:

- Pressure vessel and blanket structure
- Lithium moderator, coolant and fertile material
- Lithium blowdown system
- Tritium extraction (cold trap) system
- Sodium intermediate coolant system
- Steam turbine system.

The functional relations between systems of the Los Alamos Wetted Wall laser-pellet powerplant are shown in Figure 20.

Oak Ridge Blascon. Fundamental to the Blascon concept⁽²⁰⁾ is the assumption that the initiation of fusion reactions in a pellet of D-T can be achieved by irradiation of the pellet by a single beam from an appropriate high-power laser. The existence of such a laser and a beam transport system is assumed, along with fuel supply, fuel purification, pellet manufacture, and pellet injection systems.

Systems whose functions relate to production of the fusion reaction are:

- Laser system
- Beam transport system
- Fuel pellet fabrication and injection system
- Fuel gas purification system
- External deuterium supply
- Tritium supply from blanket lithium.

Energy collection and tritium production take place in a swirling pool of molten lithium contained within a pressure vessel several meters in diameter. A vertical vortex created by the swirling liquid lithium forms a port into which fuel pellets are injected for laser irradiation and thermonuclear ignition. Radiation and particles, including unburned fuel and fusion products, are absorbed in the lithium blanket. The blast creates a shock wave to be contained by the pressure vessel. Attenuation

FIGURE 20. Functional Relations Between Systems of the Los Alamos Wetted Wall Laser-Pellet Powerplant

of this shock wave by the cushioning effect of bubbles entrained in the lithium is important to the confinement concept. It is estimated that fusion explosions every 10 seconds which yield an average energy release rate of 150 MWt could be contained in a steel sphere 4 meters in diameter having a wall thickness of 25 cm.

Creation of the vortex is accomplished by admitting the lithium (which is circulated as the primary coolant) tangentially into the pressure vessel and drawing it off centrally through the vessel bottom. Figure 21 shows a design sketch.⁽²⁰⁾ Heat transfer to an external cooling system driving a heat engine is envisioned.

Succeeding studies of this concept have been directed at establishing the feasibility of the blast containment concept⁽²⁸⁾ and at integrating groups of Blascon chambers into powerplant configurations of differing sizes.⁽²⁹⁾ Central to the latter study is a chamber 4 meters in diameter, pulsed every two seconds and yielding 200 MJ per pulse. Due to the reduction in pulse energy no significant fraction of the Li is vaporized, allowing a faster pulse rate. Blast forces are also reduced, and the chamber thickness has been reduced to about 5 cm. Blanket cooling is also addressed in this study, and an intermediate coolant system using NaK or a potassium binary cycle is proposed for transferring heat to a steam turbine system. Tritium will be allowed to permeate into either choice of intermediate coolant, where it will be gettered by a small amount of dissolved Li. Filtered cold traps will then collect precipitated LiT for decomposition and recycle of the T to the fuel system.

Systems whose functions relate to products of the fusion reaction are:

- Pressure vessel structure
- Lithium moderator, coolant and fertile material
- Tritium extraction system
- Intermediate coolant system
- Steam turbine system

FIGURE 21. Cross Section of the Blascon Pressure Vessel and Lithium Vortex

The functional relations between systems of the Oak Ridge Blascon laser-pellet powerplant are shown in Figure 22.

Livermore Suppressed Ablation. This preliminary design⁽²¹⁾ assumes the existence of appropriate laser and beam transport systems, each delivering 12 laser beams into one of 10 reactor cavities. The fuel pellets are to be hollow spheres, injected at a frequency of 10 per second by a helium gas gun. Fuel purification is not addressed. Protection of the reaction chamber inner wall from blast debris is achieved by a thin film of liquid lithium, as in the Los Alamos "Wetted Wall" concept. Here, however, the ablation of the Li coating is reduced to an insignificant level. One effect of this (though not the major effect) is that vacuum pumping requirements are greatly reduced.

Systems whose functions relate to the production of the fusion reaction are:

- Laser system
- Beam transport system
- Fuel pellet fabrication and injection system
- Exhaust gas removal system
- Fuel gas purification system
- External deuterium supply
- Tritium supply from blanket lithium

Neutron energy collection and tritium breeding take place in a blanket of liquid lithium surrounding the 4.4 m diameter reactor cavity. The niobium cavity is shaped like an icosahedron, as shown in Figure 23. The blanket inner wall is formed into pyramidal surfaces which are thinly coated with Li pumped by capillary action from the blanket. By thus increasing the first wall surface area, and simultaneously reducing the blast energy and debris, the energy flux to the lithium coating is held low enough to suppress Li ablation. Because ablative blowoff of Li is estimated to amplify blast effects a thousandfold, suppression of Li ablation is expected to allow containment of 7 MJ blasts by an Nb first wall 0.4 mm thick.

FIGURE 22. Functional Relations Between Systems of the Oak Ridge Blascon Laser-Pellet Powerplant

FIGURE 23. Conceptual Reactor Chamber and Service Assembly of the Suppressed Ablation Laser-Pellet CTR

Li is the primary coolant. It is circulated from the blanket through an undefined boiler heat exchanger. The heat energy is ultimately converted to electricity by an unspecified thermal convertor.

Removal of the tritium bred in the blanket Li is not discussed.

Systems whose functions relate to products of the fusion reaction are:

- Blanket structure
- Lithium moderator, coolant and fertile material
- Tritium extraction system
- Thermal convertor systems

The functional relations between systems of the Livermore Suppressed Ablation laser-pellet powerplant are shown in Figure 24.

2.4.3 Fusion-Fission Hybrid Design

The neutrons released in the D-T fusion reaction induce transmutation reactions in CTR blanket and structural materials. With the exception of the lithium reaction which breeds tritium, this is often regarded as a detriment. (Induced radioactivity and destruction of the structural materials often occur.) However, various possibilities exist for using fusion neutrons for beneficial purposes. Some examples⁽³⁰⁾ are: the transmutation of radioactive waste, the production of fissile fuel from fertile materials, and the multiplication of fusion energy by neutron-induced fission in a blanket incorporating fissile or fertile material. In this section a fusion-fission hybrid reactor designed as a self-contained electrical powerplant is described as an example of use of the neutrons for other purposes than the generation of tritium.

Livermore/Battelle Mirror Hybrid. As may be seen in Figure 25⁽³¹⁾ this reactor resembles the pure fusion, mirror CTR shown in Figure 15. However, due to the multiplication of fusion energy (17.6 MeV per fusion) by fissions in the blanket (200 MeV per fission), the plasma conditions in the hybrid are less stringent. More specifically, the required fusion rate in the plasma is reduced, due to the energy production

FIGURE 24. Functional Relations between Systems of the Livermore Suppressed Ablation Powerplant

FIGURE 25. Pictorial Section View of the Livermore/Battelle Mirror Hybrid CTR, Showing the Plasma, Magnets, and Fissile Blanket

in the blanket. While the dimensions of the "Yin-Yang" magnet coils and the outer containment structure of this reactor are the same as for the pure fusion, mirror CTR (10 m coil radius, 16 m containment radius), the strength of the magnetic field required to contain the plasma is reduced. Reduced plasma conditions are also reflected in reduced plasma volume, allowing a 2 meter thick, fission blanket in place of the 1 meter thick blanket in the pure fusion design.

The fusion portion of this system operates similarly to the pure fusion, mirror CTR, with continuous replenishment of leaking plasma by energetic beams of neutral fuel atoms. However, due to the improved energy multiplication of the fission blanket, direct conversion of leaking plasma energy to electricity is no longer necessary. Instead, the ions deposit their energy as heat in an undefined collector where they are neutralized and removed by the vacuum system for purification and recycle. Even so, less than one quarter of the electrical power generated is used by reactor systems, and a net power output of 660 MWe is predicted for a thermal power generation of 2045 MW.

Systems whose functions relate to production of the fusion reaction are:

- Neutral beam injection system
- Superconducting magnets
- Liquid helium cryogenic system
- Reactor vacuum system
- Fuel gas purification system
- External deuterium supply
- Tritium supply from blanket lithium.

Energy collection and multiplication take place in the fission blanket surrounding the plasma. The heart of the blanket is a section of a modified High Temperature Gas-Cooled (fission) Reactor lattice. The fuel rods consist of carbide-coated UO_2 microspheres in a carbon binder; the moderator is graphite, and channels are provided for helium coolant. Next to the

plasma is a region of plates of depleted UO_2 , clad with stainless steel, in which fast-neutron induced fission of ^{238}U occurs, and considerable plutonium is produced. Overall Pu breeding is achieved - for each fusion source neutron, a Pu atom is produced. Between the uranium region and the fuel lattice is a layer of lithium, canned in stainless steel; a similar layer is located on the outer surface of the lattice. The lithium captures thermal neutrons leaking from the fission lattice, breeding tritium. (By so doing, the inner lithium layer also inhibits fission of the ^{239}Pu produced in the depleted UO_2 region.) A radiation and thermal shield is located between the fission blanket and the superconducting magnets.

Fission fuel and canned lithium must be discharged for processing in external systems. The fission fuel will be processed offsite; the lithium processing system is undefined. The helium coolant system will exchange heat to a steam turbine system.

Due to the reduced fusion rate necessary to achieve a given blanket power in this reactor, material damage and activation by fusion neutrons are reduced. Also, much less Li is used in the blanket. Consequently, the blanket inventory of tritium is reduced even at the higher concentrations required for periodic, rather than continuous, extraction from the Li.

Mirror Hybrid systems whose functions relate to the products of the fusion reaction are:

- Fixed blanket structure, moderator and fission fuel system
- Lithium tritium breeding system
- Helium coolant system
- External tritium removal from lithium
- External fission fuel processing system
- Shield for superconducting magnets
- Steam turbine system

The functional relations between systems of the Livermore/Battelle Mirror Hybrid powerplant are shown in Figure 26.

FIGURE 26. Functional Relations Between Systems of the Livermore/Battelle Mirror Hybrid Powerplant

2.5 SUMMARY OF CONSTRUCTION MATERIAL REQUIREMENTS

CTR powerplants are expected to be capital and material intensive when compared with fission reactor powerplants, due to complex structure and low power density. In Table 3 the material requirements for various CTR designs are compared with those of a liquid metal fast breeder reactor powerplant. It should be noted that several of the CTR designs have evolved considerably since these tabulations were prepared; all will doubtless change in the future. Thus, the table indicates spread and order of magnitude at best.

2.6 CTR SYSTEMS CATALOGUE

Comparison of the descriptions of various powerplant concepts reveals that both the differences and the similarities are notable. Regarding the similarities, many of the systems are common to several of the concepts. (Steam turbine generation of electricity, for instance, is common to all.) Consequently, to eliminate redundancy in the analysis of these concepts for their environmental effects, a functionally-based catalogue of systems is presented. System materials and effluents are identified, as required by system function.

2.6.1 Confinement Systems

The two CTR confinement systems are magnets and pressure vessels.

Magnets

All magnetic confinement CTR concepts require large, high field-strength magnets. In addition, inertial confinement schemes utilizing magnetic protection of cavity walls have also been suggested. A variety of magnet types have been suggested, having both superconducting and normal windings. Cryogenic stability in superconducting magnets requires a low resistance shunt to the superconductor material in the event of transition to the normal conducting state. Therefore, large quantities of non-superconducting electrical conductors (copper and aluminum) are required in all magnetic confinement CTR designs. In addition, significant

TABLE 3. Material Requirements for CTR and LMFBF Powerplants

Material	Material Requirements (metric tons per 1000 MWe)						
	U.W. (32) Tokamak	ORNL (33) Tokamak	PPPL (33) Tokamak	LASL (33) Theta Pinch	LLL (33) Mirror	ORNL (33) Laser	LMFBF (34)
Nb	46	275	0	75	400	1964	
Li	950	885	0	414	200	357	
Be	0	0	0	19		0	
SS	9130	385	4783	1429	2000	446	2180
Ti	24	385	0	320		179	
He		2		343		0	
Cu	3250	865	0	2914		0	695
Superconductor (see components)							
Nb-Ti in Cu		2500	435	571	500	0	
Nb-Sn in Cu		-	652	0		0	
Graphite	0	2115	0	303	400	0	
Pb	10940	10288	190	223		1786	46
Al	36	0	0	571	420	0	18
Flibe	0		652				
Concrete		38 K	1250	2970	50 K		178 K
Structural Steel		12 K	2717	6.9 K	48		33 K
K		19					
B	1080						
Na							2000
Mg							909
U							55

quantities of superconductor materials (niobium, titanium, tin) are required in designs with superconducting magnets. For an order of magnitude indication of the amount of material needed and the variation between designs, see Table 3.

While magnets produce no effluent in the usual sense, they produce fields of magnetic force which close upon themselves. These fields contain energy and have electrical effects. Various types of fringing fields are anticipated in the vicinity of proposed CTRs. While the tokamak field will be relatively constant in time, the theta pinch field will be rapidly pulsed, and the mirror field will have high gradients. These magnetic fields thus have the potential for affecting the environment in the neighborhood of a CTR powerplant.

Pressure Vessels

Pressure pulses and blast effects generated in laser-pellet interactions require confinement and attenuation in pressure vessels made of structural materials such as stainless steel or refractory metal such as niobium. That significant amounts of structural materials are required may be seen in Table 3. Vibrations, including acoustical noise, which may be transmitted through the containment structure have a potential for affecting the environment. Tritium permeation through niobium at molten lithium temperatures may be expected, although leakage could be minimized by secondary containment at ambient temperatures. Escaping radioactive tritium, of course, is a source of environmental effect.

2.6.2 Fuel Injection Systems

The fuel injection systems include: neutral gas injectors, neutral atom beam injectors, and pellet injectors.

Neutral Gas Injectors

Tokamak and theta-pinch reactors begin their cycle with neutral D-T fuel gas in the reaction chamber. In addition, the theta-pinch reactor requires injection of neutral gas during the thermonuclear burn, between

the chamber wall and the plasma. Straightforward valving and metering systems are envisioned, with minor material requirements.

Tritium leakage from pipes, valves and connections represents a potential source of effluent from such systems, although releases will doubtless be minimized by plant secondary containment.

Neutral Atom Beam Injectors

Plasma heating and fueling by the injection of beams of neutral fuel atoms will require considerable extension of existing technology. Nevertheless, the process is conceptually straightforward. Neutral gas atoms are ionized and the positive ions electrostatically accelerated to low energies. The beam is passed through gas cells (perhaps cesium) where the ions are converted to negative ions by picking up electrons. (The charge conversion is inefficient, but energy losses at this stage are small.) The negative ions are accelerated to high energies and (efficiently) stripped of their extra electrons in another gas cell, then beamed into the confining magnetic field and the plasma.

No extensive material requirements are envisioned. Effluents could be gas cell leakage, used accelerator parts (possibly containing induced radioactivity) and tritium.

Pellet Injectors

The injection of solid pellets of D-T into a plasma is not well defined. Injection may be electrostatic, pneumatic or mechanical. Nevertheless, material requirements should not be extensive. Effluents could be activated mechanical parts, escaping pneumatic gas, and tritium.

2.6.3 Plasma Heating Systems

The plasma heating systems are the neutral atom beam injectors, compression magnet systems, and laser and beam systems.

Neutral Atom Beam Injectors

These have been discussed under Fuel Injection Systems.

Magnets

Compression and plasma current transformer magnets will require materials and produce fringing magnetic fields as discussed under confinement systems.

Laser and Beam Systems

Development of high power, short pulse lasers and beam transport systems is prerequisite to achieving inertial confinement fusion. Despite the need for major advances in this technology, indications are that materials requirements will be reasonable in type and quantity.

Laser emissions include acoustic noise, and electromagnetic noise radiated in the radio frequency range. Gas lasers require gas recirculation and cooling. Gas lenses and aerodynamic windows may be necessary for short wavelength lasers which are preferred. Thus, gas emissions are possible. Chemical lasers produce reaction products also. Although all of these potential effluents can be minimized by appropriate shielding and containment, they represent possible sources of environmental effect.

2.6.4 Plasma Recovery Systems

Plasma recovery is accomplished by direct convertor collection and vacuum systems.

Direct Convertor Collection System

Plasma leaking through the mirrors of a mirror CTR, including unburned D and T fuel, helium ash, and impurities, is channeled by magnetic fields to an electrode region in which charged ions are slowed down by electric fields. Structural and electrode material requirements will be significant due to the large size of the magnetic expander fans.

Following ion collection at the electrodes, the neutralized atoms are collected by a vacuum system. To enhance conversion efficiency, a thermal cycle is envisioned driven by particle energy deposited in the electrodes. A sodium heat pipe system cooled by helium has been proposed. Tritium

contamination of the coolant and subsequent release or disposal are potential sources of environmental effect.

Vacuum Systems

All magnetic confinement CTRs require evacuation of the plasma region, and evacuation may be necessary in inertial confinement CTRs to allow efficient transmission of laser beams. Neutral beam injectors and direct conversion expander fans will require evacuation, as will the particle collectors of magnetic divertors. Cold-trapped mercury diffusion pumps, cryopumps, and Roots blowers have been suggested for these functions.

The problem of pump oil hydrogenation and deterioration has been flagged for further study and, of course, tritium contamination of waste oil is a potential source of environmental effect.

Material requirements of vacuum systems should not be severe, and since vacuum pumps will probably be located outside the blanket, induced activation should not be a serious problem. Tritium, diffusing through plenum walls and venting from forepumps, is a potential effluent. Nevertheless, the necessity for recycling unburned fuel to the plasma requires collection and purification of exhaust gasses. It provides both an incentive and a means to limit releases.

2.6.5 Plasma Chamber Protection Systems

Plasma chamber protection systems include the magnetic divertor and protective coatings.

Magnetic Divertor

In a divertor, magnetic fields guide escaping plasma particles into special chambers for collection. Magnets have been discussed under Confinement Systems. The collection of neutralized plasma by the vacuum system is discussed under Plasma Recovery Systems.

Protective Coating

In the Wetted Wall, Blascon and Suppressed Ablation inertial confinement CTR concepts, a liquid lithium surface receives the fusion blast products, unburned fuel, reaction products, radiation, and any other pellet materials. In the first two concepts, the high rate of energy delivery to the surface causes vaporization and blowoff of surface material which must be contained, throttled and condensed. The Lithium Blowdown System is discussed in the next section.

2.6.6 Neutron Moderating/Absorbing Systems

The neutron moderating/absorbing systems include the fixed blanket structure, circulating lithium-bearing liquid, and lithium blowdown system.

Fixed Blanket Structure

The blanket surrounding the plasma must breed tritium and collect energy. In doing so it also functions as a neutron and energy absorbing shield. The fixed blanket structure may function as a neutron moderator (graphite) and/or multiplier (beryllium) in addition to providing support and containment. Blanket concepts including solid lithium compounds as part of the fixed blanket have also been proposed.⁽³⁵⁾ In any case, the non-lithium, fixed blanket structure must not be so absorptive of neutrons as to jeopardize the tritium breeding function of the blanket. Outer blanket regions, designed to absorb neutrons and gamma rays which penetrate the lithium-containing regions, are specified in some designs to enhance the shielding function of the blanket.

Due to the blanket thickness required to attenuate the flux of high energy neutrons produced, and due to the large size of the proposed reactor concepts, considerable material will be required in CTR blankets. Table 3 provides a comparison of materials requirements per 1000 MWe for the designs considered. While present material choices are based upon material properties (including physical properties, chemical compatibility, and activation properties), resource availability will doubtless influence material choices in powerplant design.

Neutron interactions in blanket structures produce various deleterious effects including: atomic displacements, gas production [through (n, α) and (n,p) reactions], transmutation to different chemical species [the gas production reactions do this directly - (n, γ) capture reactions can yield isotopes whose radioactive decay yields different chemical species], and post-shutdown release of "afterheat" through radioactive decay of activated materials.

Radioactivity induced in the fixed blanket structure should not affect the environment unless it is removed from the shielded confines of the reactor. However, various mechanisms exist which may cause such removal. Physical deterioration of the structure which is subject to high fluxes of energetic neutrons (sputtering, gas blistering, embrittlement, alloying by transmutation) requires periodic replacement of the blanket structure and wall material in some designs. Removed material must be either recycled or disposed of. If the material is not recycled, material supply problems will be compounded and a solid waste with potential impact upon the environment created. Recycle of removed material may create in-plant radiation problems, and will probably also create waste streams containing radioactivity.

Another mechanism by which induced radioactivity may leave the reactor confines is through neutron sputtering into, or corrosion by, a liquid coolant. Coolant replacement, leakage or purification will yield radioactive waste for disposal.

Much technology for radioactive waste management has been developed in the fission program. However, CTR blankets will use different materials and will have different neutron flux spectra than fission reactors. A partial list⁽³⁶⁾ of radioisotopes that may be produced and for which additional nuclear data and biological standards are needed is:

^{26}Al , ^{51}Ti , ^{49}V , ^{52}V , $^{92\text{m}}\text{Nb}$, ^{94}Nb , and $^{95\text{m}}\text{Nb}$.

Afterheat, generated following reactor shutdown by the decay of induced radioactivity, has a potential for causing problems in the event of an accidental loss of coolant. However, potential afterheat generation rates in activated structural material are expected to be much lower than in fission reactor fuels.⁽³⁷⁾ The ORNL Tokamak design document concludes that afterheat generation would not damage the reactor even if all blanket and shield cooling were cut off. Even should this not be the case, appropriate design of the reactor and containment should remove the potential for releases to the environment due to this cause.

Circulating Lithium-Bearing Liquid

Lithium plays a prominent role as a neutron moderator, as well as a neutron absorber, in proposed fusion reactor blankets. This is due to the necessity that the CTR breed tritium, which requires that a significant fraction of the fusion neutrons induce ${}^7\text{Li} (n,n'\alpha)\text{T}$ reactions while their energy exceeds the 2.5 MeV threshold for this reaction. As a consequence, large quantities of lithium incorporated in CTR blankets are projected (see Table 3).

The powerplant designs described herein specify a liquid form of lithium (molten metal for all but the PPPL Tokamak, which uses flibe). Circulation of the lithium-bearing liquid as the primary coolant is specified in all but the PPPL Tokamak. Even in that design, liquid flibe is circulated from the blanket for purposes of tritium removal.

Relative to most materials, molten lithium metal has a large capacity to dissolve hydrogen.⁽³⁸⁾ Due to this fact and to the extensive lithium-bearing regions needed in CTR blankets, blanket regions of CTR designs incorporating metallic lithium are expected to contain up to kilogram inventories of tritium.

Such predictions are based upon expectations that lithium processing systems can maintain tritium concentrations below several parts per million. That this is indeed possible remains to be demonstrated. Release

of a portion of such an inventory in an accident situation (a liquid metal fire, for instance) has been identified as the "... only accident resulting in any significant effect on the local population."⁽³⁹⁾

It is expected that the tritium concentration and inventory in the molten flibe lithium-bearing region of the PPPL Tokamak blanket can be maintained from one to two orders of magnitude lower than those of lithium-metal-bearing blankets. Furthermore, flibe is non-combustible. Consequently, such a blanket design might, "... achieve the most desirable aim of making possible a nuclear [fusion] reactor system with an extremely low probability of any accident resulting in hazardous radioactive doses to the general population."⁽³⁹⁾ However, it must be noted here for completeness that the PPPL design contains a half kilogram of tritium in the fuel loop and in the subsystem which chemically processes tritium compounds sparged from the flibe.

The necessity of maintaining excellent thermal contact between large quantities of liquid lithium and other coolant systems ensures a large, high temperature contact area through which tritium can permeate. Tritium migration down the chain of cooling systems to ultimate release from the steam system in blowdowns has been identified as the primary source of tritium releases in all systems studied. Minimization of tritium inventory and concentration in the blanket, and the inclusion of permeation barriers in heat exchangers by cladding or compound-metal construction will assist minimization of tritium releases to the environment.

Lithium Blowdown System

In both the Blascon and the Wetted Wall inertial confinement CTR concepts, gaseous lithium produced by vaporization and ablative blowoff of a liquid lithium surface must be contained, throttled and condensed. In the Blascon design, an inlet port with ramped walls is used to break up a normal shock wave into many oblique shocks for energy dissipation. The Wetted Wall design includes a diffuser, a condenser spray section, a deceleration spray section and an energy absorbing lithium pool.

The lithium pool which receives the condensed vapor and spray is connected with the primary coolant system of the lithium blanket and the condenser cavity communicates with the vacuum system. Thus, the possible environmental effects of blowdown are mainly those of tritium escape from lithium confinement or from vacuum systems.

2.6.7 Blanket Coolant Systems

Blanket coolant systems utilize liquid metal or gas coolants.

Liquid Metal Coolant

Molten lithium metal is proposed as the primary coolant in all systems described except the PPPL Tokamak. As has been noted in the previous section, large quantities are required and it will contain much tritium.

Tritium permeation through the intermediate heat exchanger and on through the heat transfer system is expected to be the major source of CTR radioactive effluent, and various ways are suggested to minimize it. Tritium removal from the lithium to minimum feasible concentrations is specified in the Wisconsin Tokamak, Theta Pinch, Mirror and Wetted Wall designs. An alumina diffusion barrier has been suggested for the primary heat exchanger in the Mirror CTR design. The ORNL Tokamak design allows tritium permeation into the intermediate coolant system from which it is removed.

In addition to tritium, liquid lithium coolant will contain products of corrosion, neutron sputtering and transmutation. Escape of any or all of these through leaks or deliberate system penetration for maintenance could yield an effluent with a potential for environmental impact.

Gas Coolant

A blanket tritium inventory of about 10g is expected in the PPPL Tokamak,⁽²⁹⁾ due to the fact that flibe has a lower capacity for dissolved tritium than lithium metal has. Considerable permeation of this bred tritium into the helium coolant system across the large surface areas necessary for heat exchange is expected. Tritium concentration in the

helium is controlled by addition of oxygen to the coolant and removal of HTO. Tritium permeation through the heat exchanger into the steam system will be impeded by use of a composite (sandwich) construction containing a layer of material of low tritium permeability (copper and aluminum have been suggested). Nevertheless, tritium permeation into the steam system and its subsequent release through steam blowdowns is expected to be the major source of tritium release for this design.

2.6.8 Tritium Extraction Systems

Tritium extraction methods include: metal wall diffusion, cold trapping, trapping by getter, molten salt contactor, and gas sparging/chemical recovery.

Metal Wall Diffusion

The simplest proposed system (for the mirror design) is to simply let tritium diffuse from the lithium coolant, through the stainless steel tubes which contain it, into the reactor vacuum system for collection.

Cold Trapping

The solubility of lithium tritide in metallic lithium is temperature dependent. Consequently, in the Wetted Wall, laser CTR system the concentration of tritium in the lithium primary coolant is to be controlled by crystallizing excess LiT in a sidestream cold trap. This operates off the low temperature stream from the heat exchanger. This method has been modified in other, more recent CTR designs by including a gettering agent in the cold traps.

Trapping by Getter

Tritium collection in traps containing material with an affinity for tritium is proposed in both the Wisconsin and ORNL Tokamak designs. However, the designs differ significantly. In the Wisconsin design the trap is in the lithium primary coolant stream; in the ORNL design the tritium is allowed to permeate into the potassium intermediate coolant circuit, which contains the trap.

The Wisconsin gettering system operates in a sidestream from the primary heat exchanger outlet at outlet temperature. Yttrium forms a hydride more stable than LiH; therefore, when the lithium coolant is passed through a yttrium bed, the tritium is bound. It is recovered by heating the bed after the lithium has been drained from it.

The ORNL system operates in a sidestream from the potassium system condensate tank. Lithium dissolved in the condensate binds the tritium as LiT which crystallizes in the cold trap and is filtered from the potassium. Tritium is later evolved by thermal decomposition of the tritide.

For reasons of economics such systems are likely to be designed to use reasonable amounts of obtainable materials. Leaked tritium and/or coolant are obvious effluents. Impurities in the coolant stream may be trapped in this system, and their removal represents another possible source of effluent. Getter material which has been contaminated or chemically altered by impurities may require replacement, yielding another effluent from such systems.

Molten Salt Contactor

This system, specified in the Theta Pinch design, is also a gettering system. It differs from the previous designs in that tritium is not trapped in a solid phase. Rather, a molten salt, in which LiT is more soluble than in molten lithium metal, is mixed with the lithium and then removed by centrifugation. Tritium recovery may be electrochemical or by sparging with DCl. As before, possible effluents are tritium, lithium, getter material, and captured impurities.

Gas Sparging/Chemical Recovery

Tritium bred in flibe in the PPPL design is entrained as TF, which is simply sparged with helium. Gas separation requires passage of the gas through potassium fluoride beds for formation of KTF_2 for subsequent decomposition. Almost 1/2 Kg of tritium is expected to be contained

in this processing system, in contrast to the 10g inventory of the flibe.

Materials requirements of this system should not be excessive. Tritium, in various chemical forms including TF, may escape.

2.6.9 Thermal Energy Systems Outside the Blanket

Thermal energy systems outside the blanket include the intermediate coolant system and the steam turbine system.

Intermediate Coolant System

An intermediate coolant system serves to isolate the steam system from the primary reactor coolant by more than just a heat exchanger wall. This reduces the escape of radioactive materials to the steam system. The systems using lithium metal in the blanket all circulate it as the primary coolant, and exchange heat to an intermediate system. Molten sodium (Wisconsin Tokamak, Theta Pinch), potassium liquid/vapor (ORNL Tokamak) and helium gas (Mirror) have been specified as coolants. (Helium gas is also specified as the primary coolant in the PPPL Tokamak design.) Significant amounts of coolant are required in these systems.

Tritium permeating down the chain of coolant systems has been identified as the principal effluent with potential environmental effect. Other effluents could be coolant and impurities which are leaked or ejected by a coolant cleanup system.

Steam Turbine System

The removal of tritium from the large quantities of water used in a powerplant steam system is expected to be economically unfeasible. Consequently, it is assumed that all tritium entering this system will eventually be released to the environment in a wastewater stream.

Control of tritium effluent is to be achieved by minimizing its concentration in the primary and intermediate coolant loops, and by inclusion of permeation barriers in heat exchangers. Tritium permeation

barriers considered in steam generators include alumina on stainless steel and copper or aluminum sandwiched in Incoly-800.

In addition to tritium effluent, various chemical compounds used in water treatment and in steam system cleaning will become effluent. Waste heat is an effluent of any thermodynamic cycle and will have to be dissipated.

2.6.10 Cryogenic Systems

The cryogenic systems are used for superconductor cooling, hydrogen isotope separation, and pellet fabrication.

Superconductor Cooling

Large liquid helium refrigerating systems will be required for the superconducting magnets. Magnet designs requiring "full stabilization" are specified. This means that the coils contain sufficient copper and have a liquid helium supply sufficient that, should the superconductor go normal and the current be carried entirely by the copper, superconducting temperature can still be maintained in the coil. Refrigerator and piping materials requirements will be large. The major effluent will be waste heat, along with leaked refrigerant. Helium ash from the fusion process is a potential source of refrigerant if economics permit.

Hydrogen Isotope Separation and Pellet Fabrication

It is necessary to collect and recycle unburned fuel and to remove impurities. To control levels of protium (^1H) in the fuel, cryogenic distillation will be required. A conceptual approach to pellet fabrication has been presented,^(40,27) based upon extrusion of solid D-T, with cutting and pellet shaping to be performed by laser beams. Materials requirements are not expected to be large, and effluents will be limited to leaked fuel, impurities, and refrigerant.

2.6.11 Lithium Impurity-Removal Systems

Lithium impurity-removal systems include tritium extraction systems and hot trapping.

Tritium Extraction Systems

As was noted previously, it is possible that gettering systems for removing tritium from lithium will also function to remove impurities, yielding possible effluents of tritium, lithium, getter material, and impurities.

Hot Trapping

Corrosion of stainless steel by lithium is affected by impurity levels in the lithium. In particular, nitrogen at one weight percent has an adverse effect. In the Wisconsin Tokamak design, high temperature gettering with zirconium or yttrium has been identified as the way to control impurity levels. This, coupled with operation of the tritium extraction bed at lower temperatures, minimizes tritium accumulation in the lithium cleanup system and helps to separate the functions of the two systems.

Materials requirements seem reasonable for such systems. Possible effluents are lithium, getter, impurities (possibly activated), and tritium.

2.6.12 Biological Shield Systems

The functions of radiation shielding and containment will likely be combined in a concrete structure encasing the CTR cell. Steel lining of the cell as a precaution against tritium permeation is to be expected. Inclusion of an inert atmosphere to guard against a possible hydrogen explosion in the event of tritium leakage within the containment has been suggested. Significant quantities of concrete will be required, presumably enough to reduce radiation outside the shield to acceptable levels. Tritium, escaping via permeation and via air lock operation for access and maintenance, has a potential for environmental effect.

2.6.13 Energy Systems

Energy systems include energy storage and transfer, and power line inputs.

Energy Storage (Magnetic) and Transfer

The pulsed operational mode of the Theta Pinch CTR requires a pulsed magnetic field which contains 1.8 times as much energy as the thermal energy released in the fusion pulses. A set of nested, spherical, superconducting coils and a transformer are proposed in the design document. As an alternative, mechanical energy storage in the rotation of a homopolar generator operated as a storage capacitor is suggested. While the equipment will not be small, material requirements appear reasonable, and effluents should be characteristic of non-radioactive electrical, cryogenic, and/or mechanical systems.

Power Line Inputs

The need for a large power input to transformer magnet coils which produce and control tokamak plasma current is discussed in the Wisconsin design document. To achieve a stable plasma discharge requires a rapid rise in plasma current, necessitating large power inputs to the magnets. The Wisconsin design calls for a plasma current rise-time of 100 sec, requiring a maximum power input somewhat less than 1000 MWe. Under the assumption that 500 MWe can be obtained "off the line", startup would require 10.4 MW-hr from the line and 4.6 MW-hr from an undefined energy storage unit.

Power line input will require poles, right-of-way, and a transformer and switching yard; these are standard equipment for a powerplant.

3.0 GENERAL INFORMATION NEEDED FOR CTR ENVIRONMENTAL STATEMENTS

An environmental statement examines the economic and environmental effects of an activity and its alternatives to determine the best course of action for mankind. This requires a comprehensive balancing of costs and benefits for any activity that has numerous interactions with the environment. For a new activity such as fusion powerplants, the environmental statement covers both the powerplants and the related activities necessary for providing for construction materials, operating materials, fuel, and wastes.

3.1 THE NATURE OF ENVIRONMENTAL STATEMENTS

There are three general types of environmental statements in accordance with the state of development of the related technology. These three types are:

1. The full technology statement.
2. The advanced technology statement.
3. The initial program statement.

The general characteristics of these three types of statements are presented in Table 4.

The full technology statement usually is written for a commercial facility, such as a nuclear powerplant. The estimates of environmental effects are based on actual experience at other similar operating facilities, and there is a relatively small uncertainty in the accuracy of the estimates.

Advanced technology statements generally are written for research facilities or for programs which have advanced far enough that the general design of facilities is known. The environmental effects usually can be estimated satisfactorily although with less certainty than for full technology statements because facilities of the same design have not been operated. Some extrapolation of technology is necessary during estimation of the effects.

TABLE 4. Characteristics of Environmental Statements

Type of Statement	Status of Technology	Status of Facility Design	Site Characteristics	Characteristics of Estimated Environmental Effects
Full Technology Statement	Advanced - sufficient technology available to permit adequate estimation of environmental effects. Similar facilities have been operated.	Final design available or obtainable. Minimum uncertainty concerning satisfactory design.	Specific site usually known.	Actual impacts estimated or measured at similar facilities.
Advanced Technology Statement	Advanced - most technology available for adequate estimation of magnitude of environmental effects. Data from prototype operation usually available.	General design available but may not have been shown satisfactory by operation of a similar facility.	Site may or may not be selected. Typical site description may be used to illustrate environmental effects.	Types of effects known. Magnitudes estimated with satisfactory accuracy.
Initial Program Statements	Limited Information available. Significant amounts of research and development necessary before a final design can be made.	Only concepts available. General design uncertain. Several designs may have potential with no basis for determining which designs will be satisfactory.	Site not selected. Typical site description used to illustrate environmental effects.	Order-of-magnitude estimates which illustrate the expected effects.

Initial program statements are written for development programs at a time when the final design of the facility is not known. The available technology is not sufficient to permit selection of a satisfactory design or estimation of the resultant environmental effects. Only conceptual designs are available, and there often is no basis for determining which designs (if any) will be satisfactory. As a result, initial program statements are written generically, considering the potential environmental effects of all concepts expected to be serious candidates for the final design.

At present, only an initial program statement can be written for the CTR development program. Because breakeven levels of fusion have not been demonstrated by an experimental device and because many design problems, such as determining an adequate vacuum-chamber wall design, have not been solved; it is not possible to state the design and operating characteristics of the first commercial fusion reactors. Advanced technology statements can be written at present for individual experimental facilities, but it is not expected that an advanced technology statement can be written for the program for several years.

An initial program statement has an important function in addition to describing the potential environmental effects of an action. It identifies significant deficiencies in capability for determining the quantities and the effects of releases. These deficiencies in knowledge are identified early enough in the development program that the necessary research to eliminate those deficiencies usually can be completed before the development program is completed. This should reduce substantially the uncertainties in the estimates of environmental effects in the final, full technology environmental statements.

Preparation of an environmental statement requires the general processes shown on Figure 27. An analysis of these processes shows that the primary information and techniques needed for writing an environmental statement are as follows:

FIGURE 27. Preparation of an Environmental Statement

1. A description of the purpose of the activity.
2. A description of the activity and its alternatives that identifies all releases to the environment. This includes both material releases such as chemicals and non-material releases such as noises, vibrations, and magnetic fields. Specifically in the case of powerplants, the description should also include estimates of the amount of time in years sufficient for the activity to produce its expected uses and benefits. This time factor may be crucial in determining whether development and adoption of the activity are justified. Levels of employment and the external appearance should be described as an aid in assessing social-economic effects.
3. Methods for determining the travel paths through the environment for each of the releases.
4. Methods for determining the effects of these releases on the components of the environment (land, water, air, flora, and fauna).
5. Methods for determining the effects on mankind of the changes in the environment.

In the first column, Table 5 contains a list of the environmental interaction factors that can exist at a powerplant or in the industries that provide the materials used during construction or operation of the plant. These are the factors that may affect the physical environment or mankind.

The second column lists the portions of the environment in which these factors may have an interaction. This column contains all interaction zones that normally may occur, whether inside or outside of the site boundaries. The environmental statement is concerned with all effects on the environment, regardless of the zone. However, it normally does not address effects on the plant employees, since it is assumed that effects

TABLE 5. Environmental Interaction Factors for Powerplants

<u>Interaction Factor</u>	<u>Interaction Zones</u>	<u>Unique Level of Significance Might Exist for Fusion Reactors</u>	<u>Causes of Unique Interactions</u>
Heat	Water	No	Material releases in accident situations
	Land	No	
	Air	No	
Chemicals	Water	Yes	
	Land	Yes	
	Air	Yes	
Sanitary Wastes	Water	No	
	Land	No	
Noise and Vibrations	Land	Yes	Laser-fusion devices
	Air	No	
Odors	Air	No	Magnetic confinement
Electromagnetic Waves	Air	Yes	
Non-Radioactive Liquids	Water	No	
	Land	No	Tritium
	Air	No	
Non-Radioactive Solids	Water	No	
	Land	No	Tritium
	Air	No	
Liquid Radio-active Wastes	Water	Yes	Tritium
	Land	No	
	Air	Yes	
Solid Radio-active Wastes	Land	No	Reactor wall storage
	Special Repositories*	Yes	
Gaseous Radio-active Wastes	Air	Yes	Tritium
	Special Repositories	No	
Visual Impacts	Local Viewscape	No	Lithium, Larger use of construction materials
Employment Effects	Local Economy	No	
Material Requirements	Land	Yes	
	Water	Yes	
	Air	Yes	
Land Use	Land	No	

* A special repository is a storage container designed to assure that the waste is not released to the water, land or air.

on employees are properly monitored and are in accordance with appropriate industrial safety regulations. Effects on plant employees generally are included only if a new unique effect or level of effect is expected.

The third and fourth columns in Table 5 show whether or not a unique environmental interaction in comparison to other powerplants might occur at fusion reactors and the causes of those unique interactions. The information in these columns was obtained by analysis of the descriptions of the fusion reactors presented in Chapter 2. The following section briefly discusses each of the interaction factors to show the basis for the information in columns 3 and 4 of Table 5.

3.2 IDENTIFICATION OF UNIQUE ENVIRONMENTAL INTERACTIONS

Each of the preliminary CTR designs described in Chapter 2 was analyzed to determine the potential for environmental interactions as described in Table 5. This analysis was made by visualizing the equipment and procedures needed to accomplish each of the activities necessary for construction and operation of the reactor and then estimating the resultant interactions with the environment. The primary basis for this analysis was the assumption that the necessary equipment and operations would be similar to those currently used in industry, particularly at fossil and fission powerplants. It was also assumed that the "as low as practicable" philosophy will be used for all environmental effects.

It was assumed in this evaluation that additional research to identify the nature and magnitude of environmental effects specifically for CTRs would not be necessary for any release to the environment that occurs at current powerplants - that ample research will have been completed by late in this century as part of the research for current powerplants.

Because the available plant designs are conceptual, it is possible that the final designs will be significantly different. Consequently, the conclusions presented below must be reviewed periodically, as the designs evolve.

3.2.1 Heat

All fusion powerplants are expected to produce waste heat because of the inherent inefficiency of known processes for converting energy to electricity. However, the problem of disposal of that waste heat is expected to be the same as the problem of disposal of waste heat from existing powerplants, and no additional development efforts appear needed solely for fusion reactors.

If the fusion powerplants have normal turbine-generator systems, the waste heat will occur primarily in the condenser coolant. This coolant is expected to be either water or air in the same manner as for current powerplants.

If a direct conversion system is used for generating the electricity, it is expected that large quantities of heat will be transferred to the coolants for the direct conversion equipment and other equipment such as shields, fueling equipment, etc. These coolants also probably will be water or air.

In either case this waste heat would be transferred to the environment by use of the same types of heat dissipation systems as will be used for fission and fossil powerplants. Transfer of heat to the land is not expected to occur in a unique manner for fusion plants since no method for such heat transfer is apparent other than the common methods of transfer from structures and cooling lakes.

Large size CTRs may present a larger heat dissipation problem than will fission or fossil powerplants. The CTRs may have to be much larger than current fission powerplants (5000 to 20,000 MWe for CTRs vs. 1300 MWe for current plants). However, construction of as many as four fission powerplants (5000 MWe) at one site currently is planned, and by the year 2000 as many as eight may be operating at one site. As a result, operation of large CTRs may represent no more than a factor of two increase in waste heat releases at one site.

3.2.2 Chemicals

Fusion plants are expected to use large quantities of chemicals that are not used at current powerplants or in other industries. An example is the proposed liquid salt coolants (e.g. flibe).

As a general rule, chemical releases do not have to cause a significant environmental effect. Ample technology currently is available to prevent releases. All liquid and gaseous waste streams can be treated to remove essentially all chemicals with the degree of removal being determined by a balance of costs and environmental effects.

However, chemical releases may occur during accidents because of breaches of containment systems by fires or explosions or because the waste treatment systems do not have enough capacity to handle the quantity of wastes generated during an accident.

The most severe accident expected is a massive liquid metal fire which would create enough pressure to breach the reactor building walls or which would burn through the walls. This could release large quantities of combustion products (e.g. lithium, sodium, potassium oxides or fluorides) which might dissolve in nearby water bodies or settle out on the ground.

Release of sodium or potassium compounds is not considered a unique situation since large quantities currently are expected to be used for such applications as liquid metal fast breeder reactors. Release of large quantities of lithium compounds on the other hand is unique and is discussed in Section 4.

Large releases of chemicals to the water and the air may occur during mining, refining and fabrication of materials used in construction and operation of fusion reactors. There, again, the chemical releases generally can be minimized by use of available technology, if incentive exists for applying that technology.

Ordinarily, the release of chemicals to the land does not result in a significant environmental impact if reasonable precautions are taken to prevent subsequent transfer to water or the air. This may require use of special repositories such as tanks or lined ponds.

3.2.3 Sanitary Wastes

There are no reasons apparent for a difference from other industrial plants in the composition or treatment methods for sanitary wastes generated at fusion powerplants.

3.2.4 Noise and Vibrations

The primary sources of noise at current powerplants are fuel handling equipment at fossil plants and transformers. The primary source at fusion plants is expected to be transformers. Since this source is not unique and adequate technology exists for reducing transformer noise to acceptable levels, no special development work is necessary.

A unique source of vibrations and possibly noise may exist for laser-fusion devices. The large instantaneous energy releases (e.g. the equivalent of 750 lb of TNT at 10 sec intervals or 110 lb TNT at 1 sec intervals) could result in ground shocks or establishment of resonant vibrations. This could have damaging effects on nearby structures and disturb nearby residents.

The magnitude and frequency of such vibrations will depend on the design of the fusion reactor, particularly the support mechanisms for the reaction chamber. No special development effort appears necessary at present. These vibrations probably can be reduced to an acceptable level by use of currently available construction techniques or selection of remote sites. Ample time should be available for developing satisfactory support mechanisms during the orderly progression from laboratory tests to prototype to commercial powerplant.

If ample technology is not available for eliminating vibrations for a plant supported on land, vibrations probably could be eliminated by use of hydraulic support. A plant on a barge in a large water body should cause insignificant land vibrations.

Although the final designs for laser-fusion plants are not known, it is expected that the vibrations will have to be reduced to a low level to prevent damage to plant components such as the lasers, instrumentation, and

turbine-generators. As a result, the vibrations probably will not have a significant effect outside of an exclusion area of about the same size as for current powerplants.

3.2.5 Odors

Significant odors generally result from releases of organic materials and sulfur compounds. In addition, such materials generally can be removed from air streams by charcoal filters and other air treatment equipment used for removing radioactive and chemical pollutants from air streams.

Analysis of the preliminary fusion reactor designs and comparison of those designs to fission reactors indicate that there will be no significant odors. However, each of the final fusion plant designs will have to be analyzed to determine if there are significant odor sources and if a satisfactory technology exists for eliminating that odor source. If such technology does not exist, a development effort is necessary. However, it is expected that all odors can be reduced to an insignificant level by use of available technology.

3.2.6 Electromagnetic Waves

Many of the proposed fusion reactor designs include magnets much larger than any currently in existence. In addition, some of these magnets will be pulsed frequently, creating rapidly changing large magnetic fields. This could create large voltages and forces on nearby metallic objects, and the effects of the magnetic fields on nearby wildlife and humans are not known. The effects on the plant operating personnel also may be significant, particularly during equipment test periods, when personnel may be close to the magnets.

Magnetic effects are considered a potential source of unique environmental effect and are discussed in Section 4.

Electromagnetic waves of radio frequencies may be generated by the large lasers or fuel injectors. These are not expected to create a significant environmental effect because they probably can be reduced to innocuous levels by shielding of the sources.

3.2.7 Non-Radioactive Liquids

Fusion powerplants are expected to use large quantities of condenser cooling water, service water, miscellaneous oils for equipment lubrication, and refrigerants such as Freon. All such uses exist for current powerplants, and adequate technology exists for identifying and preventing significant environmental effects. There is no apparent need for additional development work for fusion plants.

3.2.8 Non-Radioactive Solids

Fusion plants are expected to generate the normal solid nonradioactive wastes such as waste paper, obsolete or worn-out equipment, food wastes, etc. There is no reason to expect these wastes to be different from other industrial plants or to expect that unique disposal problems will exist.

3.2.9 Liquid Radioactive Wastes

Although large quantities of water are not expected to be used in the primary reactor systems where it would be irradiated or it could pick up radioactive materials, radioactive water will be created. The primary sources are expected to be wash waters used for building and equipment cleaning, laundry effluents and cooling water for reactor auxiliary equipment (e.g. fuel injectors). In addition, a unique liquid waste problem may exist for some fusion reactors because of the large quantities of tritium created and circulated throughout the plant systems. The tritium is expected to escape from the plant through the water systems because separation of tritium from water is very difficult. The quantity escaping may be several orders-of-magnitude higher than for a fission powerplant.

Methods for removal of radioactive materials other than tritium from water streams are well developed for fission reactors. It is not expected that special development efforts will be needed for fusion reactors.

Release of radioactive liquids to land does not need studying because such releases are not expected to occur. Standard nuclear powerplant practice is to solidify liquid radioactive wastes or release them to water bodies at predetermined levels.

Release of liquid radioactive wastes to the air normally does not occur. Evaporated liquid will be considered below under gaseous radioactive wastes.

Tritium will be discussed in Section 4 as a potential source of a unique environmental effects.

3.2.10 Solid Radioactive Wastes

No special analysis is needed for solid radioactive wastes released to the land. Ample technology exists as a result of fission reactor experience.

Disposition of solid radioactive wastes in special repositories may require a unique level of effort for some types of fusion reactors. This is because of the large quantities of reactor equipment which are expected to be replaced periodically as a result of degradation from exposure to 14 MEV neutrons. No unique environmental effects are expected to result from storing or transporting them in comparison to fission reactor experience.

3.2.11 Gaseous Radioactive Wastes

The primary radioactive gasses generated in fusion plants are expected to be tritium and argon-41. The argon-41 may occur because air may be present in blanket and shield materials and will gradually outgas after the equipment heats up to normal operating temperatures. (All other radioactive gasses generated in significant quantity are expected to decay rapidly because of half-lives shorter than one minute.)

The argon-41 is not expected to be a problem because it has only a 1.83 hour half-life. Since it will be generated inside of the reactor systems and will be released from the system primarily through the coolant purification processes, it can easily be stored with the other impurities removed from those systems for at least 20 half-lives (1-1/2 days). By such time it will have decayed by a factor of 10^6 to an insignificant level.

Part of the tritium in the reactor system is expected to escape into the surrounding gas spaces and possibly into the ventilation air. If the

surrounding gas spaces contain a controlled inert gas, much of the tritium probably could be removed by use of oxidizers and drying equipment. The tritium separated from the inert gas would then be recycled as reactor fuel.

The tritium escaping into the ventilation air may be diluted enough that removal may be too costly. In addition, large quantities of tritium may be released in accident situations, particularly if liquid metal fires breach the containment system. Because the quantity of tritium released annually to the environment may be many times the quantity released annually at fission powerplants, the availability of information about tritium will be analyzed in Section 4.

Although gaseous radionuclides other than tritium and argon-41 have not been identified as being a significant problem, any that might occur are not expected to require development of new technology. The techniques being developed for removal of krypton and xenon from fission reactor gaseous wastes should be adequate for any other radioactive gases created by fusion reactors. Use of evacuated buildings and special ventilation systems should assist isolation and separation of radioactive gasses by preventing dilution with large volumes of air.

3.2.12 Visual Impacts

The visual impacts for fusion reactors are not expected to be different from those for other powerplants and industrial complexes. No development effort appears necessary.

3.2.13 Employment Effects

The primary social-economic effect of fusion reactors on the local society probably will be the creation of additional employment. This effect is not expected to be different from that for any other large industrial activity. No development effort appears necessary.

3.2.14 Construction and Operating Materials

The plant descriptions in Chapter 2 show that construction and operation of CTRs will require large quantities of materials. Provision of

those materials will require large mining, extraction and fabrication facilities and their attendant environmental effects.

The order of magnitude of these material usages and environmental effects can be estimated by comparing the quantities that might be used for CTRs to 1) the quantities that might be used for liquid metal fast breeder reactors, and 2) the U.S. annual consumption of those materials. Table 6 presents such a comparison for the year 2000, assuming that Tokamaks are built in place of LMFBRs during that year. It is apparent that adoption of CTRs could result in a significant increase in use of certain materials and associated environmental effects.

TABLE 6. Effect of CTRs on U.S. Material Requirements

Material	Domestic U.S. Annual Consumption (34,41-43) (Thousands of Tons)		Year 2000 Consumption (Thousands of Tons)	
	1970	2000	LMFBRs	CTRs(a)
Aluminum	4,500	33,000	1	2 ^(b)
Carbon Steel	117,000	188,000	2,500	ne
Concrete	570,000	2,500,000	14,000	ne
Copper	3,000	12,000	54	250
Lead	1,400	3,000	4	9,500
Lithium	3	11	0	950
Magnesium	2,400	45,000	71	ne
Sodium	171	593	154	ne
Stainless Steel	1,300	4,400	166	690

a. Assumes that the University of Wisconsin Tokamaks are built in place of the LMFBRs.

b. Not estimated.

The information requirements for determining the environmental effect during procurement of materials will be discussed in Section 4.

3.2.15 Land Use

Construction and operation of fusion reactors will require land for the plant site and for the supporting industries providing materials and services. Because fusion reactors probably will not require larger exclusion areas than will fission reactors of the same size, it is not expected that plant siting will create a unique problem.

Determination of whether or not the supporting industries will create a unique land problem will have to await determination of the materials and the quantities of those materials that will be needed. However, it is not apparent how these supporting industries could create a unique problem since the land devastation resulting from current mining and extraction processes in some cases is total destruction (e.g. open pit copper mines and fossil plant strip mining).

Provision of large quantities of material may result in a significant increase in the quantity of land altered by the supporting industries. This may be a unique problem depending upon the location of the land that must be altered.

3.3 IDENTIFICATION OF UNIQUE ANALYSIS REQUIREMENTS

Special calculation techniques are required to convert raw data concerning individual powerplants and pollutant release rates into environmental effects. The primary calculations of interest for CTRs are those required for:

- Radiation Dose Calculations
- Forecasting the CTR Construction Schedule
- Forecasting Future Material Availability

These calculations may be unique for CTRs in comparison to current powerplants because of differences in the radionuclide releases, the time period of interest (after the year 2000), and the types of materials used. Each of these three types of calculations is analyzed below.

3.3.1 Radiation Dose Calculations

Radiation doses currently are calculated routinely for fission reactors for the entire range of radionuclides from tritium to the trans-uranics. These models use a description of the amount and location of a release, the surrounding physical environment, and the human use of that environment to determine the radiation dose to man. All significant pathways for travel of the radionuclides through the environment are considered.

The estimate of the dose to man and animals from tritium uptake may be calculated with existing models developed for calculating doses from light-water-cooled reactor effluents.^(44,45) Other models are available and may be used if applicable.⁽⁴⁶⁾ All these models assume that the tritium is in the form of HTO and behaves similarly to that of water. Although this may not always be true, it is felt that for the present, doses can be calculated to within a factor of two (given the source terms). No additional development work is necessary.

3.3.2 Forecasting the CTR Construction Schedule

Determination of the CTR environmental effects requires forecasting the electricity capacity of the fusion reactors that will be built after they become available commercially about the year 2000. Procedures are available for forecasting the construction schedule for any type of power-plant. Such procedures were used for predicting the construction schedule for LMFBRs through the year 2020 and could be used for CTRs.

No development work appears necessary.

3.3.3 Forecasting Future Material Availability

Determination of the availability of materials after the year 2000 requires estimating 1) the amount of material currently recoverable from ores at reasonable costs, and 2) the quantities of these ores that will be used through the time period of interest.

Numerous surveys have been made to determine the amounts of ores expected to be available throughout the world. These surveys generally show two classes of information:

1. Proven reserves, and
2. Probable reserves.

The proven reserves are known sources which have been measured and analyzed. The probable reserves are estimated quantities of materials based on the assumption that ores can be expected to be found in geologic formations similar to those in which they already have been found. The quality and thoroughness of the surveys to find new ore bodies have been dependent on the size of the market and the selling price for the materials. As a result, a large uncertainty can be expected for estimates of reserves for many materials because of the past lack of incentive for identifying additional reserves.

Obtaining additional information about availability of ores can be quite costly and time-consuming. As a general rule, additional information can be obtained only by geological exploration - a costly activity requiring surface exploration and exploratory drilling at promising locations. Such expenditures usually cannot be justified during a development program until the development has identified a substantial benefit from using a scarce material instead of an available substitute.

No additional research and development efforts appear justified until the CTR development has progressed far enough that the desirable construction and operating materials are known, and the justification for identifying additional sources for scarce materials can be determined. Until that time, it is expected that environmental statements will use available information concerning materials. The need for additional information will be discussed as a possibility that must be addressed at the proper time in the development effort.

Techniques also are available for estimating the use of ores in the future. An example is the EXPLOR⁽⁴⁷⁾ technique. No development of additional capability appears necessary other than modification of these techniques to consider materials unique to CTRs.

4.0 SPECIFIC ADDITIONAL INFORMATION REQUIREMENTS

The analysis in Chapter 3 identified four unique sources of environmental effects from fusion reactors. These require further investigation to assess whether sufficient information is available to permit determination of the effects. The unique sources are: effects due to releases of tritium, releases of lithium, magnetic forces, and procurement of the materials required for construction and operation of CTRs. Each of these four potential sources of environmental effects is discussed below. Although large vibrations from inertial confinement devices were identified as being unique, it is believed that ample technology exists for eliminating the environmental effects.

4.1 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.

4.1.1 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 (~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-yr 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 a 200 MWe pressurized water reactor (PWR) may exceed 1000 curies per year. Based on the projected nuclear power economy for the United States and the free world, the rate of production of fission-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 several 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 of 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 is 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.

4.1.2 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 Grounds 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 .

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 of 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, 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.

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

In profundal lake sediments, Gorham and Hoffstetter⁽⁶⁰⁾ found the influence of enriched precipitation from the early 1960's 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 a montane tropical rain forest in eastern Puerto Rico and determined that HTO moved downward through the soil in a wave-like pulse, maintaining 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 similar findings 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 an old-field ecosystem. They determined that a pulse of tritium moved downward through the soil as a function of the amount of rain water entering the soil above the pulse. Concomitant to 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 equalled 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 determined 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 annuus, 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 6 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 non-lactating 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 reinhardtii, 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 tshawytscha, 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 the 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 hr 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, Pacifastacus 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 $\mu\text{Ci/liter}$. 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 only 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 water-cress to crickets and determined that adult crickets reached tritium concentrations less than unity, ~ 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 (~11% by weight) as any compound of the biological organism (~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.

4.1.3 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 Vennart, 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 excluded. 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 for 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 suggests 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. Then, more sensitive parameters of radiation effects on individuals, populations, and communities need to be developed. Longer-term or chronic studies in which factors such as rates of growth, morphological abnormalities, onset of maturity and reproductive capacity are considered, need to be undertaken. Chromosomal 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.

4.1.4 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) 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, $(MPC)_a$, is $2 \times 10^{-3} \mu\text{Ci}/\text{cm}^3$ 400 times higher than the MPC for tritium oxide in air, $5 \times 10^{-6} \mu\text{Ci}/\text{cm}^3$.⁽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 microorganisms 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."⁽¹⁰⁴⁾ 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.

4.2 LITHIUM

Lithium is routinely used in industry and has a long history of mining, refining, and processing. As a result, there is considerable experience with handling lithium. Environmental quality standards have been defined and adequate technology is available to permit design of waste treatment systems that assure compliance with applicable air and water quality regulations.

However, a significant increase in the quantity of lithium at one location as could occur at some CTR powerplants could result in releases of large quantities during accidents. This may create a different impact than the routine small releases representative of past history.

In order to assess and predict with assurance the effect of lithium releases, it is necessary to know how readily the metal is metabolized by biological organisms, and at what levels toxicity may be expected. Entry of lithium into the food chain or food web with biomagnification could present a hazard to man. However, few studies to date relevant to this possibility have been undertaken. The existing information concerning lithium is summarized as follows:

4.2.1 Lithium and Its Compounds

Lithium is one of the alkali metals and is chemically related to sodium and potassium. It is not distributed widely in the environment, being found only in a few minerals and certain spring waters. Being

extremely reactive, the metal does not occur in the elemental state. When purified, it must be maintained free of interaction with oxygen and water. It is of use in metallurgy, for medicinal purposes, in some types of glass, and as lithium hydroxide in storage batteries.

Lithium forms many compounds. Of those of principal interest, it forms a nitride by direct combination with nitrogen at ordinary temperatures. Lithium chloride (LiCl) is produced directly from lithium metal and is very soluble in water, alcohol, and certain other nonaqueous solvents. Lithium carbonate (Li_2CO_3) is a light white alkaline compound that is readily solubilized in water. Lithium also forms the moderately soluble salts of lithium fluoride (LiF), lithium sulfate (Li_2SO_4), and the less soluble lithium oxide (Li_2O).

4.2.2 Qualitative and Quantitative Analysis

As with sodium and potassium, lithium is most readily determined in trace quantities by flame photometry (APHA 1971). The measurement is performed at a wave length of 671 mu. A Perkin-Elmer Model 52-C flame photometer or a Beckman Model DU spectrophotometer equipped with photo-multiplier tube and flame accessory is commonly used.

The minimum lithium concentration detectable by the flame photometric method is of the order of 0.1 mg/l. Barium, strontium, and calcium are known to interfere in the flame photometric determination of lithium, but can be removed by the addition of a sodium sulfate--sodium carbonate solution which precipitates BaSO_4 , SrCO_3 , and CaCO_3 . The quantity of either sodium or magnesium must not exceed 10 mg in the aliquot taken for analysis.

In general, the unknown lithium concentration is determined by direct intensity measurement at a wave length of 671 mu. Development of a standard curve relationship is necessary. The unknown, distilled water blank (mg/l Li) and the lithium standards are analyzed as nearly simultaneously as practical. In many cases, the calibration readings on the distilled water blank and a lithium standard will suffice.

The concentration of lithium in the unknown is determined from the calculation:

$$\text{mg/l Li} = \frac{\text{ug Li}}{\text{ml sample}}$$

The lithium concentration can be determined with an accuracy of ± 0.0 - 0.2 mg/l over a range of 0.7 - 1.2 mg/l.

4.2.3 Behavior and Effects of Lithium in the Environment

Terrestrial Considerations

In general, plants sensitive to sodium will show a sensitivity to lithium. Lithium toxicity in citrus has been identified in Santa Barbara County, California. In greenhouse experiments, 2 - 5 mg/l lithium sulfate caused the appearance of toxic symptoms in orange seedlings.⁽¹⁰⁷⁾ In the field, 1 , 2 and 4 mg/l of lithium chloride in the soil have caused lithium toxicity. Irrigation waters in the vicinity contained 0.045 - 0.080 mg/l lithium, and it was possible that lithium poisoning resulted from the accumulation in the soils of toxic concentrations over a relatively long period of time.⁽¹⁰⁷⁾

Hansen and Overstreet⁽¹⁰⁸⁾ studied the effects of alkaline earth salts on the growth of roots and hypocotyl of the radish. It was found that chlorides of the alkali group diminished elongation in the order $\text{LiCl} > \text{CsCl} > \text{RbCl} > \text{NaCl}$. It was concluded that the depressing effect of alkali-salts was not due primarily to increased osmotic pressure of the culture medium, but to a specific inhibitory effect by the alkaline ions. Hansen and Overstreet⁽¹⁰⁸⁾ also reported that Li as LiCl was toxic to citrus trees at 0.05 to 0.1 mg/l.

Bertrand⁽¹⁰⁹⁾ studied the distribution of lithium in seeds. Forty widely diverse species were examined. In general, it was demonstrated that the seeds contained a lower percentage of Li than the remainder of the plant.

The absorption of lithium in rye seedlings was investigated by Michael and Wilberg.⁽¹¹⁰⁾ The rye was grown in pure sand and the comparative absorption of Li and K determined. The quantity of Li was found to vary from 20 to 120% of that of K; the highest ratio occurred under conditions of poisoning with urethane. The ratio increased with age of the plants, with increase of CO₂ in the plant atmosphere, and with decrease in size of seeds. It had a maximum value at pH 5-6 in the medium and was not affected by either light or dark conditions.

Yamagata and Kurobe⁽¹¹¹⁾ studied the absorption of Li, Cs and Rb in plants. They found that the rate of absorption of Li by rice decreased as the concentration in the water of cultivation increased. While that of Cs was found to increase as the concentration in the water increased, the rate of absorption of Rb had no relation to the concentration in the water.

Fewer studies are available on the influence of Li on animal forms. The tolerance of Drosophila melanogaster to LiCl, NaH₂PO₄, KH₂PO₄, KCl, and NaCl was studied by King.⁽¹¹²⁾ It was concluded that Li⁺ (0.02M) was by far most toxic, while K⁺ was slightly more toxic than Na⁺ at higher concentrations (0.4M). King also concluded that inhibition was specific rather than due to osmotic or hydration phenomena. The time required for the completion of development of Drosophila reared on a culture medium containing 0.02M LiCl was increased 2- to 3-fold. Characteristic abnormalities were produced in male terminalia and wing venation.

The effect of lithium carbonate on egg shell formation and serum calcium level of the hen was studied by Creek, et al.⁽¹¹³⁾ The inclusion of lithium carbonate in the diet of hens at levels of 282-685 mg of Li per kg of diet produced diarrhea, excess salivation, regurgitation, and production of shell-less eggs as early as 24 hours after being placed on the experimental diet. Li also was found to decrease serum Ca levels; however, soft shelled eggs were produced before any reduction in serum Ca was detectable. It appeared that Li inhibited shell deposition in some other manner.

The oral LD₅₀ for lithium fluoride in guinea pigs was reported by Simonin et al.⁽¹¹⁴⁾ to be approximately 200 mg/kg of body weight.

Aquatic Considerations

Lithium is a minor constituent of minerals and usually is present in fresh waters at concentrations below 10 mg/l. Brines and thermal waters are known to contain higher lithium levels.

In the protozoan Microregma, food intake was inhibited at a concentration of LiCl of 66 mg/l.⁽¹¹⁵⁾ Employing Escherichia coli and Scenedesmus spp. as test organisms, no toxic effects were observable at concentrations of <100 mg/l.⁽¹¹⁵⁾

Karlander and Krauss⁽¹¹⁶⁾ demonstrated that under optimal growth conditions of light, CO₂ and temperature, concentrations up to 100 mg/l of lithium were not inhibitory to growth of Chlorella vannielli. At 1000 mg/l lithium, the autotrophic growth rate was reduced to 52% of the control.

Anderson⁽¹¹⁷⁾ found the threshold concentration for immobilization of Daphnia magna in Lake Erie water to be <7.2 mg/l. In River Havel water at 23°C, the threshold of toxic effect was observed at 16 mg/l for 48 hours' exposure.⁽¹¹⁸⁾

To evoke stimulation and movement of the water beetle, Laccophilus maculosis, a concentration of LiCl at 19,000 mg/l was required.⁽¹¹⁹⁾

It has been reported that low concentrations of LiCl are deleterious to the eggs of various aquatic organisms, retarding development and producing abnormalities. King⁽¹¹²⁾ demonstrated that concentrations of 848 mg/l were highly toxic to fly larvae, inhibiting emergence of offspring and retarding development of both larvae and pupae.

Cyclopic embryos of the pond snail, Limnaea stagnalis, produced by the action of Li as LiCl, were studied by Raven.⁽¹²⁰⁾ It was found that Li caused the formation of a cyclopic eye, shortening of the cerebral commissure, other changes in the cerebral ganglion, and suppression of differentiation of most cell lines of the embryo of this species of snail. In related studies, Geilenkirchen⁽¹²¹⁾ studied the effects of Li treatment of whole egg-masses and isolated egg capsules in Limnaea stagnalis. Three

series of egg masses of Limnaea were treated with 0.01% of LiCl for 1 hour during second cleavage. Group I contained egg capsules treated within the jelly; Group II, egg capsules isolated from the jelly; Group III, egg capsules isolated from the jelly, then treated and washed. All eggs were subsequently cultured until hatching. Group I produced many more exogastrulae than either Group II or III. The number of head malformations was the same in all groups; however, the number of dead after 6 days was significantly greater in Group I than in Groups II or III. The authors concluded that the presence of the jelly during treatment did not influence the results; but its presence during rinsing resulted in the greater number of exogastrulae due to a delay in removal of LiCl from the eggs still in jelly during rinsing. The most susceptible period for production of exogastrulae was observed during the four-cell stage.

Emanuelsson⁽¹²²⁾ studied the effects of lithium chloride on embryos of the polychaete, Ophryotrocha labronica. High concentrations strongly inhibited development in cleavage embryos and led to endodermal protrusion; whereas moderate concentrations permitted development of larvae, although with characteristic disturbance as a consequence. Ultrastructure analyses of embryos revealed changes manifest in 24 hours, i.e., of lipid droplets and yolk granules, the latter being ruptured and the contents dispersed to an extent far surpassing that at normal development.

Farinella-Ferruzza⁽¹²³⁾ produced similar results in exposures of eggs of Ascidia malaca to LiCl at a concentration of 0.8% and eggs of Phallusia mamillata at concentrations of 1.0, 0.8, and 0.5%. In both species, eggs fertilized in LiCl developed with abnormalities, and development beyond gastrulation was generally arrested. However, eggs exposed to LiCl, washed, and then fertilized in normal sea water developed without gross abnormality. Sensitivity to LiCl was found to diminish with development, as determined for the unfertilized egg, the 2-blastomere stage, and the 64-blastomere stage. With strong concentrations (18%), and in stages of precocious development (undivided egg, 2-blastomere stage) exogastrulas were obtained; while with weaker concentrations (0.8 and 0.5%) and in later stages,

defective larvae were obtained. Abnormalities observed in surviving larvae included deleted palps, sense organs, cerebral vesicles, and reduced or deleted tails. The author concluded that the mechanism of action of LiCl was not due to its affect on sperm; rather, in the physico-chemical modification of the ovular plasma that always follows fertilization. The Li ions are incorporated in the plasma molecular structure such that their influence is exercised throughout development.

At a concentration of 3750 mg/l, lithium chloride in distilled water was lethal to goldfish in 22 to 27 hours.⁽¹²⁴⁾ For adult small freshwater fish, the 24-hour lethal concentration was found to be 2600 mg/l.⁽¹²⁵⁾ In other studies, lithium chloride at concentrarions between 1950 and 3770 mg/l killed freshwater fish in 24 hours or sooner at warmer temperatures. In contrast, Meinck et al.⁽¹²⁶⁾ reported that 100 mg/l of LiCl is toxic, but 33 mg/l is harmless to fish. The lethal dose in 48 hours in fish, Tinca vulgaris, for the compound lithium fluoride is considered to be ~20,000 mg/l.⁽¹¹⁴⁾

Human Considerations

Hibbard⁽¹²⁷⁾ recommended that lithium in water for drinking and cooking purposes should not exceed 5 mg/l. In man, the kidneys seem to be the site of toxic action of lithium.⁽¹²⁸⁾

Conclusions and Research Needs

Lithium released to the environment either during the mining cycle, from reactor operation, or accident may be in the form of a number of compound types varying widely in their solubility and their affinity for biological organisms. From available data, toxicity would appear to vary according to solubility and possibly pH shift.

When comparative data are presented, as in the case of lithium chloride, animal forms are generally more susceptible than plant forms to lithium poisoning; the embryonic or juvenile life states demonstrate greater sensitivity than the adult animal.

From the above compiled literature review, it is evident that the existing data base is incomplete and oftentimes contradictory; and, in general, is of questionable value for the prediction and assessment of impacts resulting from release of lithium and the related compounds to the environment.

For both acute and chronic type exposures, concentration factors and turnover rates in the various compartments of both terrestrial and aquatic ecosystems must be determined. The potential for biomagnification must also be defined.

Longer-term or chronic tests extending over the entire life cycle of selected test organisms should be used to determine the highest "safe" concentration of lithium at which no adverse biological effects are observed. Data derived from these studies should be used to develop "application" factors that facilitate estimation of "safe" concentrations of lithium from short-term acute tests.

Assessment of sublethal stress, i.e., development, growth, feeding, and salient biochemical processes, should be conducted to permit rapid detection of responses to lithium at stressing levels as low as those found by chronic tests to be biologically "safe."

4.3 MAGNETIC FIELDS

Magnetic fields are used in some fusion reactor concepts to confine the high temperature plasmas. The strength and geometry of these fields will depend on the reactor concept ultimately employed. Extensive calculations and plotting of the magnetic field patterns have been performed for at least one reactor concept, the UWMAK-I.⁽¹²⁹⁾ Two types of magnetic fields will be encountered in 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 will be generated in the plane of the torus and the strength will 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, on the other hand, will radiate both vertically and horizontally relative to the torus and will require a distance of 500 meters to reach <1 gauss. However, certain manipulations such as use of 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. Also, 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. The above calculations are based on a 5000 Mwt plant.

Magnetic field exposures could be classified in two categories, those occurring within the reactor facility and those extending beyond. In the example of UWMAK-I, the fields produced by the toroidal magnets are confined to the reactor building while the poloidal field may extend for a considerable distance beyond. Radiation levels will limit access to parts of the reactor building; thus, there may be little likelihood of exposure to the toroidal field. However, sizeable poloidal fields may be encountered outside of the main reactor area 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, it is expected that the field strength will have decreased to background so populational 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.

Less detailed information is available concerning the magnetic field patterns for other fusion reactor concepts. However, differences between them and the UWMAK-I will be primarily quantitative.

4.3.1 Information Requirements

The information that is needed in order to determine the environmental effects of magnetic fields include:

1. The magnetic field patterns for the several reactor concepts.
2. Behavioral, physiological and morphological consequences of exposure of mammals to above normal magnetic fields, particularly prolonged exposures.
3. Behavioral, physiological and morphological consequences of exposure of avian species to above normal magnetic fields.
4. Consequences of exposure of people with implanted electronic medical devices to magnetic fields.
5. Sensitivity of people with extant medical problems, recognized or subclinical, to exposure to magnetic fields, alone or in combination with radionuclides or other stresses.
6. Effects on plant operating systems.
7. Effects of magnetic field gradients vs. constant field.
8. Effects of magnetic fields on differentiation and on the development of embryos and fetuses.
9. Development of acceptable and testable hypotheses for interaction of magnetic energy with biological material.

4.3.2 Information Currently Available on Effects of Magnetic Fields

Biological Effects

A number of studies have been performed to examine the response of biological systems to magnetic fields.^(130,131,132) 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 parameters have been studied in animals exposed under many experimental conditions to 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 of mammalian and plant structures, genetic defects, tumor growth and function of enzymes. In

addition, several attempts have been made to correlate human behavioral patterns with natural 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 pre-existing 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 exposure.⁽¹³³⁾

Evidence for an influence of magnetic fields on growth and development has been presented from studies on plant seedlings, sea urchin eggs and mice. Of the various studies reported, most have been performed at field strengths above 2500 gauss and the most consistent effects appeared to be found with the plant seedlings. The results of the animal studies 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.

Non-Biological Effects

Magnetic fields may disrupt plant operations by creating magnetic forces or electrical voltages on metallic equipment in the reactor plant. This could cause equipment malfunctions and create electrical hazards for plant personnel.

The technology of magnetism is far enough advanced that these magnetic effects can be estimated at present. In addition, enough is known about magnetic shielding to permit design of shield structures for plant components.

Ample information appears to be available to permit adequate estimation for an initial program statement of the non-biological effects of magnetism.

4.3.3 Reduction of Magnetic Fields

Magnetic fields can be distorted and reduced by magnetic materials such as iron. Consequently, it is possible to reduce the magnetic fields around a CTR by including shielding materials in the building structure. Ample information is available for making calculations to determine shielding material needs and possibilities.

The optimum amount of shielding would be determined by a balance of the costs of the shielding vs. the costs due to the effects of magnetic fields. Such calculations must await better definition of the biological effects.

4.3.4 Conclusions and Research Needs

Insufficient experimental data is available to permit accurate calculation of the biological effects of magnetic fields. The primary experimental deficiency seems to be in the area of large scale, multigeneration demonstration experiments. These should be designed to study the full range of both

stable and changing magnetic fields. Properly-designed experiments should identify the reasons for the highly variable and nonreproducible results reported for past experiments. The experiments should also investigate the possible synergistic effects of the low-level radiation typical of that expected in the vicinity of CTRs.

4.4 CONSTRUCTION AND OPERATING MATERIALS

Because of the current uncertainties in the quantities and types of materials that might be needed for the CTRs, no attempt has been made to identify the additional information that may be needed to determine the environmental effects due to providing specific materials. It appears more appropriate to determine that information later after the quantities and types of materials are better known.

As a general rule, ample information probably is available at present for determining the environmental effects associated with the materials. Because most of the materials that might be used in large quantities already are used extensively in the U.S., there are established industries which can be used as a basis for estimating effects. In addition, estimates of the availability of adequate resources for CTR supplies can be made.

When the types and quantities of materials are better known, the following information should be obtained by use of available literature and by obtaining descriptions of existing mining and extraction activities and their environmental effects:

1. Estimate of quantity of each material needed for constructing and operating CTRs.
2. Estimate of U.S. and world use of those materials.
3. Estimate of ore reserves for those materials.
4. Description of processes for mining the ores and extracting the desired materials.
5. Estimate of environmental effects due to mining the ores and extracting the materials.

The depth of the analysis made for steps 4 and 5 would depend on the percent increase in material consumption and associated environmental effects if CTRs are built. If the increase in environmental effect for a material is small (e.g. less than 10%), a detailed analysis probably would not be necessary. If the increase is large, a detailed analysis may be necessary to identify the severity of the effect.

5.0 ADEQUACY OF AVAILABLE INFORMATION

As described in Section 3.1, the information needed for writing an environmental statement is as follows:

1. A description of the purpose of the activity.
2. A description of the activity that identifies the releases to and direct effects on the environment.
3. Methods for determining the travel paths through the environment for the releases.
4. Methods for determining the effects on the environment and on mankind.

In addition, it is apparent that only an initial program environmental statement can be written at this time for the controlled thermonuclear reactor program. The development of CTR's has not progressed far enough that the designs of the first commercial CTR's are known.

Sufficient information is available to permit preparation of an adequate initial program environmental statement for the CTR program. The concepts of CTR's and the related technology have been developed far enough that it is apparent that the initial commercial CTR's probably will have a D-T reaction, lithium in the blanket region for breeding tritium, liquid metal coolants, large quantities of solid radioactive waste, large tritium inventories, and standard electricity generation systems. It is also probable that they will have large magnetic fields. As a result the initial CTR's can be expected to have potential for significant environmental effects due to releases of caustic chemicals (lithium, sodium, potassium, etc.), magnetic fields, solid and liquid radioactive wastes, and heat. They also would have the normal environmental effects for industrial plants due to sanitary wastes, chemical releases, aesthetic impacts, socio-economic changes, land use, and material procurement.

The unique environmental effects in comparison to current industrial plants appear to be the potentials for large releases of tritium and

magnetic fields. Ample information appears to be available to permit estimation of the effects of tritium releases because of experience with tritium releases at current nuclear powerplants. Both the travel paths and the biological effects are well known.

Magnetic fields and their effects can be easily restricted to the CTR site. This may require site areas similar to those of fission powerplants (e.g., up to 500 acres) to assure that the general public is not exposed to magnetic fields significantly stronger than normal. The biological effects of magnetic fields are not well enough known to permit adequate estimation of such effects and, consequently, additional research appears necessary. However, the persons exposed to above normal magnetic fields can easily be limited to plant personnel, and it is possible that the exposure can be essentially limited by design of the CTR's and associated facilities such that the magnetic fields outside of the reactor halls or in areas normally occupied by personnel are essentially at normal levels.

The quantities of tritium released and the magnetic field strengths for the several CTR concepts can be estimated well enough to permit preparation of an initial program statement. There have been many years of experience with storing and processing tritium in USAEC laboratories and production facilities. This experience has created ample knowledge concerning leakage rates and solubilities of tritium.

Similarly, experience with magnetic fields is ample to permit estimation of the field strengths around CTR's. Ample information concerning the effects of releases of chemicals, solid and liquid radioactive wastes, heat, and sanitary wastes should be available from current industrial experience. Similarly, aesthetic, socio-economic, land use, and material procurement effects can be estimated.

Because only an initial program statement can be written at this time for the controlled thermonuclear reactor program, only order-of-magnitude estimates may be possible for some of the environmental effects. Such estimates are adequate for an initial program statement.

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