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Exam Preview:

1. Under DOE requirements, permission of the Cognizant Secretarial Officer is required for all occupational doses in excess of 1 rem.
    a. True
    b. False
2. According to 10 CFR 100.11, the maximum calculated dose to an off-site individual from exposure that results from internal and external sources of radiation must not exceed ___-mSv, 50-yr CED to the whole body.
    a. 100
    b. 250
    c. 500
    d. 750
3. At frequencies below 1 Hz, the threshold limit value is 60 mT. For workers wearing cardiac pacemakers, the threshold limit value may not protect against electromagnetic interference with pacemaker function. The threshold limit for pace-maker wearers should be reduced by a safety factor of 10.
    a. True
    b. False
4. According to the reference material, plume rise can be calculated assuming either a momentum or buoyancy-driven plume. Assessments are done for a circular grid of distances and directions for a radius of __ miles around the facility.
    a. 15
    b. 30
    c. 50
    d. 75

5. A coordinated program of drills and exercises should be an integral part of the emergency management program. Off-site response organizations should be invited to participate in site-wide exercises at least every _ year(s).
    a. 7
    b. 5
    c. 3
    d. 1
6. Acute dose is defined for specific organs depending on what short-term exposure is the best predictor of acute health effects. For the same exposure time periods, the acute dose is always less than (or equal to for very short half-lives) the 50-yr CED.
    a. True
    b. False
7. ________ is the predominant nuclear material used at fusion facilities. It is of interest because of safety concerns, its monetary value, and possible unauthorized diversion for other applications.
    a. Beryllium
    b. Deuterium
    c. Uranium
    d. Tritium
8. 40 CFR 61 limits the amount of beryllium emitted to 25 g in a 24-h period or to an amount that would result in atmospheric levels of 0.01-μg beryllium/m3 of air, averaged over a 30-day period.
    a. True
    b. False
9. Using TABLE 2.1. Evaluation guidelines for public protection from radiation, what is the fusion radiological release requirement for Off-normal conditions (per event)?
    a. 10 mSv
    b. 250 mSv
    c. 100 μSv/yr
    d. 1 mSv/yr
10. Applications for a PTC and an Operating Permit for the proposed facility should be submitted to the state ________ months prior to commencement of construction.
    a. 6 to 10
    b. 8 to 12
    c. 15 to 18
    d. 18 to 24

FOREWORD (DOE-STD-6002-96)

1. INTRODUCTION

This Standard identifies safety requirements for magnetic fusion facilities. Safety functions are used to define outcomes that must be achieved to ensure that exposures to radiation, hazardous materials, or other hazards are maintained within acceptable limits. Requirements applicable to magnetic fusion facilities have been derived from Federal law, policy, and other documents. In addition to specific safety requirements, broad direction is given in the form of safety principles that are to be implemented and within which safety can be achieved.

2. SAFETY POLICY

Fusion facilities shall be designed, constructed, operated, and removed from service in a way that will ensure the protection of workers, the public, and the environment. Accordingly, the following points of safety policy shall be implemented at fusion facilities:

a. The public shall be protected such that no individual bears significant additional risk to health and safety from the operation of those facilities above the risks to which members of the general population are normally exposed.

b. Fusion facility workers shall be protected such that the risks to which they are exposed at a fusion facility are no greater than those to which they would be exposed at a comparable industrial facility.

c. Risks both to the public and to workers shall be maintained as low as reasonably achievable (ALARA).

d. The need for an off-site evacuation plan shall be avoided.

e. Wastes, especially high-level radioactive wastes, shall be minimized.

3. SAFETY REQUIREMENTS

To achieve safety in fusion facilities, it is important for safety to become an integral part of the design and operation of the facility. From the safety policy, two types of safety functions have been identified: public safety functions and worker safety functions. Fusion facilities shall be designed to ensure that public and worker safety functions are always achieved for conditions within the design basis. The public safety function for fusion facilities is the confinement of radioactive (e.g., tritium and activation products) and hazardous (e.g., beryllium or vanadium) materials. The worker safety function is the control of operating hazards including radioactivity and hazardous material.

Potential safety concerns that must be considered during the design process to minimize challenges to the public safety function of confinement of radioactive and/or hazardous materials include, but should not be limited to the following:

a. ensuring afterheat removal when required;

b. providing rapid controlled reduction in plasma energy when required;

c. controlling coolant energy (e.g., pressurized water, cryogens);

d. controlling chemical energy sources;

e. controlling magnetic energy (e.g., toroidal and poloidal field stored energy);

f. limiting airborne and liquid releases to the environment;

The specific design of any particular fusion facility must be considered in determining the importance of potential safety concerns in protecting the public and the environment. A risk-based prioritization scheme (graded approach) shall be used to determine the impact of these potential safety concerns for each specific fusion facility.

Application of these safety requirements will normally be an iterative process. Requirements shall be implemented in each phase of the facility life cycle, incorporating feedback from the results of the facility safety analysis and experience/lessons learned during the previous operating phases of the facility.

3.1 Public Safety Function—Confine Radioactive and Hazardous Material

Radioactive and hazardous material confinement barriers of sufficient number, strength, leak tightness, and reliability shall be incorporated in the design of fusion facilities to prevent releases of radioactive and/or hazardous materials from exceeding evaluation guidelines during normal operation or during off-normal conditions.

As shown in Table 1, two sets of radiological criteria shall be used for evaluating radioactive releases: regulatory limits (evaluation guidelines) that shall not be exceeded and fusion requirements. Regulatory limits (evaluation guidelines) are applicable to the maximum exposed individual off-site using conservative assumptions. Best-estimate techniques are used to evaluate against fusion requirements. In showing compliance with these guidelines, the ALARA principle shall be applied. Compliance with both sets of criteria shall be demonstrated for all

TABLE 1. Requirements for protection of the public from exposure to radiation[a]

	Fusion radiological release requirement	Regulatory limit (evaluation guideline)
Normal and anticipated operational occurrences	0.1 mSv/yr (10 mrem/yr)	1 mSv/yr (100 mrem/yr)
Off-normal conditions (per event)	10 mSv (1 rem) (No public evacuation)	250 mSv (25 rem)

[a]Basis for the exposure limits is provided in DOE-STD-6003-96, Chapter 2.

credible postulated events, noting the difference in analysis methodologies (conservative vs best estimate).

Routine releases of nonradiological effluents (including any hazardous materials) shall be controlled in accordance with Federal, State, and local regulations and permit requirements. The design shall also provide adequate means for sampling and monitoring of effluents to the environment.

In the design of confinement barriers, the principles of redundancy, diversity, and independence shall be considered. Specifically, in the case of multiple barriers, failure of one barrier shall not result in the failure of another barrier if evaluation guidelines could be exceeded thereby. Redundancy and diversity shall be considered in the total confinement strategy if new or untested components of a barrier are used.

The design basis for confinement barriers shall take into account identified postulated initiating events and extreme loadings and environmental conditions due to anticipated operational occurrences and off-normal conditions as identified in the safety analysis. In addition, consideration should be given to the provision of features for the mitigation of consequences of conditions outside of the design basis to meet the fusion requirement of no off-site evacuation for fusion facilities.

Consistent with the safety analysis, the design of confinement barriers shall specify an acceptable global leak rate under off-normal conditions, taking into account the vulnerable inventories of radioactive and hazardous materials and the potential energy sources available to liberate such inventories. Any confinement barrier, including equipment, penetrations, seals, etc. relevant to the establishment of an acceptable leak rate, shall be designed and constructed in such a way as to enable initial and periodic leak testing.

The following subsections establish the requirements related to the potential safety concerns that may affect the public safety function of confinement of radioactive and hazardous material.

3.1.1 Ensure Afterheat Removal

The design of fusion facilities shall provide a reliable means to remove any undesirable afterheat generated by activation products produced by neutron absorption in structures such that the public safety function of confinement is assured. The need for and reliability of afterheat removal systems shall be commensurate with the role of afterheat removal in complying with evaluation guidelines. Passive means are preferable to active means. For facilities with levels of afterheat that require active cooling, the concepts of redundancy, diversity, and independence shall be considered in the design of afterheat removal systems.

3.1.2 Provide Rapid Plasma Shutdown

A means of rapid plasma shutdown shall be provided for fusion facilities, if required to ensure that evaluation guidelines are met. The level of required reliability, redundancy, and diversity of such a system, its effectiveness, and speed of action shall be such that safety functions required to meet evaluation guidelines are assured. Consideration shall be given to heat, particle, magnetic, and mechanical loads on confinement barriers resulting from transient overpower events and plasma abnormalities (e.g., vertical displacement events or plasma disruptions in tokamaks) in assessing the need for rapid plasma shutdown.

3.1.3 Control of Coolant Internal Energy

For fusion facilities that use liquids for active cooling of components (e.g., water and cryogenic liquids), the design shall incorporate means to accommodate the accidental release of the liquid to ensure that confinement barriers are not breached in a manner that could result in exceeding evaluation guidelines. Special consideration shall be given to the effect of large spills of cryogenic liquids on the structural integrity of affected structures, systems, or components (SSCs) (e.g., embrittlement).

3.1.4 Control of Chemical Energy Sources

Fusion facilities shall be designed such that chemical energy sources are controlled during normal conditions, anticipated operational occurrences, and off-normal conditions so as to minimize energy and pressurization threats to radioactivity and hazardous material confinement barriers. Design measures shall assure that evaluation guidelines are met.

3.1.5 Control of Magnetic Energy

Magnet systems in fusion facilities shall be designed so that faults in the magnets and the associated ancillary systems (power supply and electrical systems) shall not threaten public or worker safety functions.

3.1.6 Limit Routine Airborne and Liquid Radiological Releases

Adequate systems or design features shall be provided to minimize airborne and liquid radioactive effluents from fusion facilities to meet the limits prescribed in 40 CFR 61, National Emission Standards for Hazardous Air Pollutants. That limit for members of the public is 0.1 mSv/yr (10 mrem/yr). Fusion facilities must provide a level of protection for persons consuming water from a public drinking water supply that is equivalent to public community drinking water standards as set forth in 40 CFR 141.16 from National Primary Drinking Water Regulations. This requirement translates into an effective dose equivalent of 40 μSv/yr (4 mrem/yr). In addition, exposure from all sources of radiation shall not exceed 1 mSv/yr (100 mrem/yr) per 10 CFR 20.1301 from Standards For Protection Against Radiation. The design shall also provide adequate means for sampling and monitoring of radioactive effluents to the environment.

3.2 Worker Safety Function—Control of Operating Hazards

Workers at the facility shall be protected from routine hazards to a level commensurate with that of comparable industrial facilities by a combination of administrative controls and design features. The level of protection required depends on the level of risk from the hazard present in the specific facility.

3.2.1 Limit Radiation Exposures to the Workers

Fusion facilities shall be designed to limit radiation exposures to the workers during normal operations below the limits prescribed in 10 CFR 20 or 10 CFR 835, Occupational Radiation Protection [50 mSv/yr (5 rem/yr)]. Fusion facilities shall have adequate shielding to limit radiation levels in operating areas. Special consideration shall be included in the design to limit worker doses due to the inhalation and absorption of tritium. The ALARA principle shall be used in developing worker radiological exposure limits for the facility.

3.2.2 Limit Electromagnetic Field Exposures

Fusion facilities shall be designed to limit electromagnetic field exposures to workers during routine operations. The limits for occupational exposures to steady-state and low-frequency magnetic fields shall be those established by the American Conference of Governmental Industrial Hygienists (ACGIH).[1]

3.2.3 Control of Other Industrial Hazards

Fusion facilities shall comply with the Occupational Safety and Health Administration (29 CFR 1910, 1926) to control the industrial hazards and hazardous materials present in the facility.

4. SAFETY AND ENVIRONMENTAL PRINCIPLES

The safety and environmental principles set forth in this section constitute a framework within which worker and public safety is assured and facility risks are limited. Application of these principles shall be commensurate with the magnitude of the hazards of the facility.

4.1 Defense-in-Depth

The design process for fusion facilities shall incorporate the defense-in-depth concept such that multiple levels of protection are provided against the release of radioactive and hazardous material. The level of protection needed is a function of the risk to the workers, the public, and the environment. Aspects of the defense-in-depth concept that may be applicable to fusion facilities include the following:

a. the selection of materials and other design processes to reduce radiological and hazardous materials inventories;

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[1] For further information, see “Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices,” published by the American Conference of Governmental Industrial Hygienists, 6500 Glenway Ave., Bldg. D-7, Cincinnati, Ohio 45211-4438, latest revision. See also “Documentation of the Threshold Limit Values and Biological Exposure Indices,” published by the ACGIH, latest revision.

b. the use of conservative design margins;

c. the use of a succession of physical barriers (passive preferred) for protection against release of radioactive and hazardous materials;

d. the provision of multiple means (inherent, passive, or active) for ensuring the public safety functions for fusion facilities;

e. the use of basic design features, equipment, and operating and administrative procedures to minimize anticipated operational occurrences and off-normal conditions and to control and mitigate their consequences should they occur;

f. the implementation of a rigorous and formalized quality assurance program, the organization of surveillance activities, and the establishment of a safety culture;

g. use of emergency plans as required to mitigate the effects of radiological and hazardous releases to workers and the public.

h. additional levels of defense may be needed to compensate for technological uncertainties.

4.2 Identification of Items Required to Implement Safety

Internal and external postulated initiating events (PIEs) that challenge the public safety functions shall be systematically identified. Event sequences that account for additional potential failures of items (structures, systems, components, and software, etc.) from PIEs shall be developed. Based on these event sequences, items that are required to function to prevent accidental releases of radioactive and/or hazardous materials in excess of evaluation guidelines or to maintain consequences to ALARA goals shall be identified.

4.3 Design Basis

The facility design basis shall define the necessary capabilities of the facility to cope with a specified range of operational states, maintenance and other shutdown activities, anticipated operational occurrences, and off-normal conditions to meet the evaluation guidelines presented in Section 3. The facility design shall recognize that both internal and external challenges to each level of defense may occur, and design measures shall be provided to assure that evaluation guidelines can be met.

The design basis shall include consideration of natural phenomena (e.g., earthquakes, floods, and high winds), environmental effects, and dynamic effects (e.g., pipe ruptures, pipe whip, and missiles) in order to establish a set of external challenges. The importance of these events in the design basis shall be evaluated based on the risk of event sequences developed for the facility.

Normal operation, anticipated operational occurrences, and off-normal conditions created by PIEs shall be classified for fusion facilities into two categories: (a) normal operation and anticipated operational occurrences; and (b) off-normal conditions that may be expected with lower but still credible probability. A bounding subset of these conditions shall be identified in the safety analysis.

4.4 Design for Reliability

Unavailability limits for items that perform public safety functions shall be specified to ensure the reliability needed to meet evaluation guidelines. Similar limits are recommended but optional for items that perform worker safety functions. The required reliability of items shall be developed in accordance with the importance of their safety function in protecting the workers, the public, and the environment.

4.4.1 Redundancy

The principle of redundancy shall be considered as an important design principle for improving the reliability of items and guarding against common-cause failures. Multiple sets of equipment that cannot be operated and tested independently do not meet the redundancy principle. The degree of redundancy shall reflect the potential for undetected failures that could degrade reliability.

4.4.2 Diversity

The principle of diversity s hall be considered as a means to enhance reliability and reduce the potential for common cause failures.

4.4.3 Independence

The principle of independence shall be considered to enhance the reliability of systems, in particular with respect to common-cause failures. Independence is accomplished in the design of items by using functional isolation and physical separation (e.g., separation by geometry or barriers).

4.4.4 Simplicity

The principle of design simplicity shall be considered to enhance the reliability of items. Less complex items are generally more reliable.

4.4.5 Testability/Surveillance Capability

Items performing public and worker safety functions shall be designed and arranged so that they can be adequately inspected, tested, and maintained as appropriate before being placed in service and at suitable and regular intervals thereafter.

4.5 Fail-Safe and Fault-Tolerant Design

The fail-safe principle shall be applied to items performing public and worker safety functions; that is, if an item were to fail, it would pass into a safe state without a requirement to initiate any actions. The design of systems shall also, to the extent feasible, be tolerant to faults.

4.6 Human Factors

Human factors and human-machine interfaces shall be considered in the design of items performing safety functions for fusion facilities.

4.7 Remote Maintenance

The design shall make provisions early in the design process, where necessary, for accessibility, adequate shielding, and remote handling of items performing safety functions to facilitate maintenance and repair, taking into account the need to keep worker exposures ALARA.

4.8 Quality Assurance

A quality assurance process shall be considered in the design, selection of materials, specifications, fabrication, construction, installation, operating procedures, maintenance, and testing of fusion facilities. The requirements of 10 CFR 830.120, Nuclear Safety Management, shall be used for development of the program.

4.9 Codes and Standards

Applicable codes and/or standards shall be identified for use on items performing safety functions when available. Justification for the applicability of the code for use on the components performing the safety functions shall be provided. For items performing safety functions in fusion facilities for which there are no appropriate established codes or standards, an approach for selecting the requirements that must be met to accomplish those safety functions shall be developed and justified.

4.10 Safety Analysis

The safety of fusion facilities shall be analyzed to demonstrate that the facility meets the evaluation guidelines presented in Section 3. The development of the safety analysis and the design of the facility are complementary processes that should be carried out interactively.

The evaluation of the safety of the facility shall include a hazard analysis and an analysis of the response of the facility to a range of PIEs under each mode of facility operation, including maintenance and shutdown. These PIEs shall include equipment failures and malfunctions, operator errors, and external events that could lead to either anticipated operational occurrences or off-normal conditions. These analyses shall be used as the basis for the selection of operational limits and conditions for the facility.

The safety analysis shall show that the set of PIEs bounds credible anticipated operational occurrences and off-normal conditions that influence the safety of the facility. The PIEs and their consequences shall be analyzed and categorized so that a subset of bounding or limiting events from each category (i.e., anticipated operational occurrences and off-normal conditions) can be selected for detailed quantitative analysis as part of the design basis. Off-normal conditions beyond the design basis should be analyzed for the purpose of emergency planning and to ensure that there are no events with probabilities near the limit of credibility with consequences that are much larger than those for the worst credible events.

A combination of probabilistic and deterministic approaches may be used in the safety analysis. Probabilistic approaches may be used to gain insight and to help establish events within the design basis as discussed in Section 4.3. When probabilistic approaches are used and data are scarce, conservative estimates shall be used and the rationale for their use shall be documented. These estimates may be based on inference from similar equipment, expert opinion, detailed analyses (such as probabilistic fracture mechanics), existing fusion experience, or other means. Deterministic analyses shall specify the assumptions used in the assessments (i.e., input parameters, initial conditions, boundary conditions, assumptions, models, and codes used) and the level of conservatism (i.e., safety margin) in the assessment. Results of these complementary approaches provide input into the design process of the facility.

4.11 Verification and Validation

The applicability of the design and safety analysis methods shall be verified and the methods validated. Furthermore, an equipment qualification procedure shall be established for items performing public safety functions to confirm that the equipment is capable of meeting the safety functions for the facility while subject to the environmental conditions (e.g., vibration, temperature, pressure, jet impingement, radiation, humidity, chemical attack, and magnetic fields) existing at the time of need. Experimental data used in the design process or in the safety analysis shall undergo formal validation.

4.12 Special Considerations for Experimental Use

Fusion facilities, especially those considered test facilities, may by their nature include experimental component modules or equipment. As a general rule, experimental systems should not be expected to perform safety functions. However, if such components are required to perform a safety function, the safety analysis must show that potential faults in experimental equipment shall not cause evaluation guidelines to be exceeded. The flexible nature and changing states of the system also require special precautions to be taken in the design and operation to minimize the effects of human error.

Experimental equipment shall be designed so that in each operational state it cannot cause unacceptable consequences to the facility, other experiments, workers, or the public. Specific considerations include but are not limited to the following:

a. factors in experiments that could cause a breach of any confinement barrier;
b. factors in experiments that could adversely affect items performing safety functions;

c. factors in experiments that could create additional radiological, hazardous, chemical, or other risks;

d. factors relating to interactions with other experiments or operational activities.

4.13 Waste Recovery and Recycling

Waste recovery and recycling shall be addressed in the design of the facility. The fusion waste shall be minimized. The goal for fusion facilities is that wastes be recoverable or disposable as low-level waste meeting the requirements of 10 CFR 61, Licensing Requirements for Land Disposal of Radioactive Waste.

4.14 Cleanup and Site Restoration

The design of fusion facilities shall consider aspects to facilitate cleanup and removal of the facility. Reduction of the amount of radioactive waste generated shall be considered in the design, selection of materials, and conduct of operations of a fusion facility. Adequate systems shall be provided, as necessary, for handling, collecting, processing, and storing on site any radioactive, hazardous, or mixed wastes generated in a fusion facility. Exposure to workers, the public, and the environment during cleanup and removal shall comply with 10 CFR 20 for the public and the environment and 10 CFR 835 for the workers and shall be maintained ALARA.

4.15 Emergency Planning

Emergency plans (on-site and off-site) for fusion facilities shall be developed in accordance with applicable requirements (e.g., the Environmental Protection Agency's 1-rem protective action guideline). Facilities meeting the fusion radiological release requirement of less than 1-rem off-site exposure do not require off-site evacuation plans for radiological emergencies.

4.16 Technical Safety Requirements

Requisite systems must be operational to stay within the limits identified in the safety analysis. The following paragraphs apply to a fusion facility during the operating period.

4.16.1 Authorization Basis

Each fusion facility shall have an authorization basis that is documented and approved by the regulatory authority. It shall specify the factual information that was used to determine that risks to persons and the environment from the operation of the facility were acceptable, and it shall specify an operating envelope within which the facility can be safely operated. The operating envelope shall include operational limits that protect and preserve the assumptions and safety margins specified in the safety analysis.

4.16.2 Configuration Management

Each fusion facility shall have a configuration management system. The configuration management program shall assure that the actual as-built configuration of the facility is known, that the configuration reflects and is accurate with respect to the design requirements, that the documentation is maintained as it relates to items performing safety functions, and that changes to this configuration are controlled.

4.16.3 Unreviewed Safety Questions

Each fusion facility shall have a system for performing evaluations of proposed actions against the facility's authorization basis. Evaluations shall be performed for changes to the facility described in the existing safety analysis, changes to procedures that affect items performing safety functions, and tests or experiments that are not bounded in the existing safety analysis. If a condition is discovered in the facility that is not covered by the existing authorization basis, then operations not enveloped by the existing authorization basis shall cease until an appropriate analysis has been completed and the facility's authorization basis has been changed to reflect the actual plant conditions.

4.16.4 Conduct of Operations

Each fusion facility shall have a conduct-of-operations program. The program shall address the operating organization and administration, shift routines and operating practices, control area activities, communications, control of on-shift training, investigation of abnormal events, notifications, control of equipment and system status, lockout and tagout, independent verification, log keeping, operations turnover, required reading, operator orders, operations procedures, operator aids, and equipment labeling. The extent of the conduct-of-operations program will be based upon a graded approach commensurate with the risks of the facility.

4.16.5 Operational Requirements

Each fusion facility shall prepare and maintain an operational requirements document . This document shall be based upon safety analysis and shall define the lowest functional operability or performance level of systems, components, and functions required for normal safe operation of the facility.

4.16.6 Training and Certification

Each fusion facility shall develop and implement a training, qualification, and certification program using a graded approach based upon the risk of the facility. The training program shall identify the required training, qualification, and certification program for each required operator position. The program shall include the theory and principles of operations, facility operating characteristics, facility instrumentation, items performing safety functions, normal and emergency procedures, radiation control and safety, authorization basis, and written evaluations and examinations. The training program shall also include operator proficiency requirements and medical examination requirements as applicable. Additional training programs shall include safety considerations for maintenance and support activities.

4.16.7 Maintenance Management

Each fusion facility shall develop and implement a maintenance program that addresses items performing safety functions . The program shall include as a minimum: planning, scheduling, and coordinating activities; maintenance history and trending; types of maintenance; listing of items performing safety functions; and indicators to measure the effectiveness of the maintenance program. A reliability-centered maintenance approach shall be considered.

TABLE OF CONTENTS

	Page
FOREWORD	ix
DEFINITIONS	xi
LIST OF ACRONYMS	xix
1. INTRODUCTION	1
1.1 Purpose	1
1.2 Background	1
1.3 Implementation	2
1.4 Overview	2
2. RADIATION AND HAZARDOUS MATERIAL	5
2.1 Dose Definitions	5
2.2 Public Exposures and Environmental Impacts	6
2.2.1 Evaluation Guidelines for Exposures to the Public	7
2.2.2 Additional Guidance	8
2.2.3 Environment	8
2.3 Routine Worker Exposure	9
2.3.1 Radiation	9
2.3.2 Hazardous Materials	9
2.3.3 Common Industrial Hazards	10
2.3.4 Magnetic Fields	10
2.4 Guidance for Meeting Regulatory Limits	11
2.4.1 Evaluation Guidelines	11
2.4.2 Exposure	12
2.4.3 Meteorological Dispersion	12
2.5 Consequence Thresholds for PAGs and Emergency Response Planning Guidelines	12
2.5.1 Radiological (No Ingestion)	13
2.5.2 Radiological (Ingestion)	13
2.6 Models Used in Relating Exposures to Estimated Consequences	13
3. ENVIRONMENTAL AND PERMITTING REQUIREMENTS	15
3.1 Federal Requirements	15
3.1.1 National Environmental Policy Act and Implementing Guidelines, Regulations, and Orders	15
3.1.2 Federal Statutes and DOE Orders Relating to Environmental Quality	16
3.2 Federal and State Consultation, Permits, and Approvals	21
3.2.1 Federal Permits and Approvals	21
3.2.2 State and Local Permits and Approvals	23
3.3 Environmental Compliance Procedures and Scheduling	24
3.3.1 Environmental Documentation Guidelines	24
3.3.2 Environmental Compliance Scheduling	26

4. PROGRAM MANAGEMENT FOR SAFETY 29
4.1 Design and Construction Management.. 29
4.2 Operations Management.. 30
4.3 Site Restoration Management 30
4.4 Tools for Program Management Safety 30
4.4.1 Configuration Management 30
4.4.2 Quality Assurance 32
4.4.3 Verification and Validation... 33
4.4.4 Conduct of Operations 34
4.4.5 Emergency Preparedness.. 35
4.4.6 Maintenance.. 37
4.4.7 Training and Qualifications.. 39
4.4.8 Tritium Control, Accountability, and Physical Protection.............................. 41

DEFINITIONS

Active—An adjective used to describe a feature or function of a component whose operation depends on an external input such as an actuation, mechanical movement, or supply of power.

Administrative Controls—Provisions relating to organization and management, procedures, recordkeeping, assessment, and reporting necessary to ensure the safe operation of a fusion facility.

ALARA—As low as is reasonably achievable.

Anticipated Operational Occurrences—Operational processes deviating from normal operation that are expected to occur once or more during the operating life of the fusion facility.

Authorization Basis—Those aspects of the facility design basis and operational requirements relied upon by the regulating authority to authorize operation. These aspects are considered to be important to the safety of facility operations.

Blanket—The region surrounding the D-T plasma that absorbs the fusion neutrons, transforming their energy into heat and breeding tritium to sustain the D-T fuel cycle.

Beyond-Design-Basis Event—An event of the same type as a design-basis event (e.g., fire, earthquake, spill, explosion, etc.), but defined by parameters that exceed in severity the parameters defined for the design basis event.

Certification—Process by which management provides written endorsement of the satisfactory achievement of qualification of an individual for a specialized operations position based upon its criticality or safety impact and generally in response to a DOE Order or national consensus code or standard.

Common Cause Failure—The failure of multiple devices or components to perform their functions as a result of a single specific event or cause.

Comparable Industrial Facility—A facility in the industrial sector where workers are exposed to hazards of a similar nature to those encountered in a fusion facility; for example, heavy lifting, vacuum, cryogenics, high electrical potentials and/or currents, and radioactivity.

Confinement—A barrier that surrounds radioactive or hazardous materials designed to prevent or mitigate the uncontrolled release of these materials to the environment.

Credible Events—Postulated events having estimated probabilities of occurrence $>10^{-6}$ per facility year. For natural phenomena, separate probability criteria based on site-specific information and facility characteristics should be used.

Cryostat—A chamber, normally metallic, which surrounds the superconducting magnets of a fusion facility to provide vacuum insulation from external heat loads.

Decommissioning—The process of closing and securing a fusion facility so as to provide adequate protection from radiation exposure and to isolate radioactive contamination from the human environment.

Decontamination—The act of removing a chemical, biological, or radiological contaminant from, or neutralizing its potential effect on, a person, object, or environment by washing, chemical action, mechanical cleaning, or other techniques.

Design Basis—The set of requirements that bound the design of systems, structures, and components within the facility.

Design Basis Events—Credible events considered in the facility safety analysis and in the design of systems, structures, and components within the facility.

Disruption—A rapid loss of the plasma-stored thermal energy to the plasma-facing components, introducing large thermal loads. Associated with this is a rapid decay of the plasma current that can introduce large mechanical loads to structural components. Disruptions can also generate high energy runaway electrons which impact the first wall.

Diversity—The existence of multiple components or systems to perform an identified function, where such components or systems incorporate one or more attributes that are different from each other.

Divertor—The component inside the vacuum vessel that diverts the plasma particles in the outer shell of the plasma into a region where they strike a barrier, become neutralized, and are pumped away.

Effluent—Material that is released into the environment.

Evaluation Guidelines—Dose/exposure values for radiation or hazardous materials that a safety analysis evaluates against.

Experimental Equipment—Equipment or components installed in or around the facility for the purpose of research and development, not including regular functioning parts of the fusion facility itself (i.e., even when such regular functioning parts may be less than fully developed).

First Wall—Systems and components inside the vacuum vessel directly exposed to the plasma ion and neutron fluxes; the first physical boundary that surrounds a plasma.

Fusion Facility—Any facility that utilizes or supports a magnetically confined plasma in which fusion reactions take place. It includes the associated facility plant and equipment and any experimental apparatus used at the facility.

Fusion Island—That part of the fusion facility on or inside the cryostat. Typically it includes the cryostat, the magnetic coils, the vacuum vessel and attached pumps, the breeding blanket, heating and fueling systems inside the cryostat, the divertor, and plasma diagnostics.

Hazard—A source of danger (i.e., material, energy source, or operation) with the potential to cause illness, injury, or death to personnel or damage to an operation or to the environment (without regard for the likelihood or credibility of off-normal conditions or consequence mitigation).

Hazard Analysis—The determination of material, system, process, and plant characteristics that can produce undesirable consequences, followed by the assessment of hazardous situations associated with a process or activity.

Hazard Classification—Evaluation of the consequences of unmitigated releases to classify facilities or operations into the following hazard categories:

- Hazard Category 1: The hazard analysis shows the potential for significant off-site consequences.
- Hazard Category 2: The hazard analysis shows the potential for significant on-site consequences.
- Hazard Category 3: The hazard analysis shows the potential for only significant localized consequences.

Hazardous Material—Any solid, liquid, or gaseous material that is toxic, explosive, flammable, corrosive, or otherwise physically or biologically threatening to health.

Inherent—An adjective to describe a design feature or function that operates without the application of a separate input such as an activation signal. An example of an inherent design feature is a fail-safe valve that closes automatically on loss of power.

ITER—International Thermonuclear Experimental Reactor.

Maintenance—The organized activity, both administrative and technical, directed toward keeping structures, systems, and components in good operating condition, including both preventive and corrective aspects.

Maintenance Personnel—Persons responsible for performing maintenance and repair of mechanical and electrical equipment.

Managers—Persons whose assigned responsibilities include ensuring that a fusion facility is safely and reliably operated and that supporting operating and administrative activities are properly controlled.

May—Permission; neither a requirement nor a recommendation.

Mitigative Feature—Any structure, system, or component that serves to mitigate the consequences of a release of hazardous materials in an off-normal event scenario.

Monitoring—Continuous or periodic measurement and/or observation of parameters or determination of the status of a system or component. Sampling may be involved as a preliminary step to measurement.

Normal Conditions—Conditions associated with the routine operation of the facility.

Normal Operations—Activities at a facility performed within specific normal operational limits and conditions, including startup, operation, shutdown, maintenance, and testing. Normal operations do not include anticipated operational occurrences.

Off-Normal Conditions—Conditions beyond anticipated operational occurrences that include all credible events.

Operations—Activities at a fusion facility performed within specific operational limits and conditions, including startup, operation, shutdown, maintenance, and testing.

Operations and Facility Support Personnel—Those individuals who perform technical functions (such as engineering evaluations, program reviews, technical problem resolution, or data analyses, within their area of expertise) or safety, quality assurance, radiation protection, emergency services, and training functions.

Operators—Persons responsible for manipulating fusion facility controls, monitoring facility parameters, and operating facility equipment.

Certified Operators—Operators who require certification as determined by facility management.

Qualified Operators—Operators who require qualification as determined by facility management.

Passive—An adjective that describes a function that requires no operation or movement of component parts.

Physical Separation—Isolation by geometry (distance, orientation, etc.), by appropriate barriers, or a combination thereof.

Plasma—The fourth state of matter; basically an ionized gaseous system composed of an electrically equivalent number of electrons and positive ions.

Plasma Beta—The ratio of plasma pressure (proportional to the product of density and temperature) to the confining magnetic field pressure (proportional to magnetic field strength squared). As the beta limit is approached, the plasma is more likely to experience a disruption.

Potential Safety Concern—A feature and/or process determined to be capable of challenging a public safety function and to which a risk-informed decision-making process is applied during design.

Poloidal Field Coils—Coils providing the magnetic field that encircles the plasma axis in toroidal devices.

Postulated Initiating Events (PIE)—Identified happenings or conditions that lead to anticipated operational occurrences, off-normal conditions, and their consequential failure effects.

Potential Safety Concern—A feature and/or process determined to be capable of challenging a public safety function and to which a risk-informed decision-making process is applied during design.

Preventive Feature—Any structure, system, or component that serves to prevent the release of hazardous material in an off-normal event scenario.

Public—All individuals outside the fusion facility site boundary.

Public Safety Function—Essential characteristics or performance needed to ensure the safety and the protection of the public and the environment during operations, anticipated operational occurrences, and off-normal conditions.

Qualification—Process by which factors, such as education, experience, and any special requirements (e.g., medical examination) are evaluated in addition to training to assure that an individual can competently perform a specialized job function to an anticipated level of proficiency.

Qualified—The ability to perform a specific job function based upon completion of a training, qualification, or certification program developed for the job function. Trained personnel are qualified to perform their job function based upon completion of training. Qualified and certified personnel are qualified to perform their job function based upon completion of a specific program. As used in this document, the term “qualified” personnel has two meanings, based upon context:

> Qualified personnel are those personnel who have successfully completed either training, qualification, or certification requirements appropriate to their job function.
>
> Qualified personnel are those personnel who have successfully completed a formal qualification program appropriate to their job function.

Quality Assurance—Those planned and systematic actions necessary to provide adequate confidence that an item or service will satisfy specified requirements for intended service.

Redundancy—Provision of more than the minimum number of similar elements or systems, so that loss of any one does not result in the loss of the required function.

Risk—The quantitative or qualitative expression of possible loss that considers both the probability that an event will occur and the consequence of that event.

Risk-Informed Prioritization Approach—A reasoned approach where the degree to which requirements or recommendations are applied and resources expended is commensurate with the risks involved and the facility programmatic importance. Minor hazards require implementation at a lower level than higher risk hazards to workers, the public, and the environment.

Runaway Electrons—Those electrons in a plasma that gain energy from an applied electric field faster than they lose energy from collisions; such high-energy electrons can damage plasma-facing components.

Safety Analysis—A documented process: (1) to provide systematic identification of hazards within a given facility; (2) to describe and analyze the adequacy of the measures taken to eliminate, control, or mitigate identified hazards; and (3) to analyze and evaluate potential off-normal events and their associated risks.

Safety Analysis Report (SAR)—A report that documents the adequacy of safety analysis to ensure that a fusion facility can be constructed, operated, maintained, shut down, and decommissioned safely and in compliance with applicable laws and regulations.

Safety Basis—The combination of information relating to the control of hazards at a fusion facility (including design, engineering analyses, and administrative controls) upon which is based the conclusion that activities at the facility can be conducted safely.

Safety-Class Structures, Systems, and Components (safety-class SSCs)—Systems, structures, or components whose failure could adversely affect the environment or safety and health of the public as identified by safety analyses. The phrase “adversely affect” means that Evaluation Guidelines are exceeded. Safety-class SSCs are systems, structures, or components whose preventive or mitigative function is necessary to keep radioactive and hazardous material exposure to the public below the off-site Evaluation Guidelines.

Safety Limits—Limits on process variables associated with those physical barriers, generally passive, that are necessary for the intended facility functions and that are found to be required to guard against the uncontrolled release of radioactivity and other hazardous materials.

Safety-Significant Structures, Systems, and Components (safety-significant SSCs)—Structures, systems, and components not designated as safety-class SSCs but whose preventive or mitigative function is a major contributor to defense-in-depth (i.e., prevention of uncontrolled releases to the public) and/or worker safety as determined from hazard analysis. Generally, safety-significant SSC designations based on worker safety are limited to those SSCs whose failure could result in an acute worker fatality or serious injury to workers.

Safety Structures, Systems, and Components (safety SSCs)—The set of safety-class structures, systems, and components, and safety-significant structures, systems, and components for a given fusion facility.

Shall—A firm requirement that must be met to be in compliance with this Standard.

Shall Consider—The need for and applicability of stated features or attributes must be evaluated and the results of the evaluation documented.

Should—A desirable option or recommendation, departure from which is permissible.

Site boundary—A well-marked boundary of the property over which the owner and operator can exercise strict control without the aid of outside authorities.

Standard Industrial Hazards—Hazards that are routinely encountered in general industry and construction and for which national consensus codes and/or standards (e.g., OSHA, transportation safety) exist to guide safe design and operation without the need for special analysis to define safe design and/or operational parameters.

Supervisors—Persons who are responsible for the quantity and quality of work and who direct the actions of the operators or other personnel.

Technicians—Persons responsible for performing specific maintenance or analytical laboratory work.

Technical Safety Requirement—Those requirements that define the bounding conditions for safe operation, the bases thereof, and the management or administrative controls required to ensure the safe operation of a facility.

Tokamak—The mainline magnetic fusion confinement configuration that employs discrete toroidal coils surrounding a torus-shaped vacuum vessel with poloidal field coils either captured by or external to the toroidal field coils. A large current induced in the plasma provides part of the magnetic field required for plasma confinement.

Toroidal Field Coils—The coils surrounding the vacuum vessel that provide the major confining magnetic field for the plasma.

Unreviewed Safety Question—A formalized uncertainty brought about by a proposed change, test, or experiment or the identification of analytic inadequacy when (a) the probability of occurrence or the consequences of an accident or malfunction of equipment important to safety previously evaluated by safety analyses could be increased; (b) the possibility for an accident or malfunction of a different type than any evaluated previously by safety analyses could be created; or (c) any margin of safety, as defined in the basis for any Technical Safety Requirement, could be reduced.

Vertical Displacement Event—A sudden loss of plasma position control. For highly shaped tokamak plasmas, active vertical position control is required to maintain the vertical position. Loss of the position control is known as a Vertical Displacement Event (VDE). If the main plasma contacts the plasma-facing components, the currents in the plasma can rapidly disappear, leading to a disruption.

Workers—Persons performing work at the facility or on the site of the facility.

Worker Safety Function—Essential characteristics or performance needed to assure the protection of workers during normal operations, anticipated operational occurrences, and off-normal conditions.

LIST OF ACRONYMS

AC	Administrative Control
ac	alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
AEA	Atomic Energy Act
AIRFA	American Indian Religious Freedom Act
ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BDBA	beyond-design-basis accident
CAA	Clean Air Act
CAP-88	Clean Air Act Assessment Package-1988
CCTV	closed-circuit television
CED	committed effective dose
CEQ	Council on Environmental Quality
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
D-D	deuterium-deuterium
D-T	deuterium-tritium
DBA	design-basis accident
dc	direct current
DOE	Department of Energy
DOT	Department of Transportation
EA	Environmental Assessment
EAL	Emergency Action Level
ED	effective dose
EG	Evaluation Guideline
EIS	Environmental Impact Statement
EIS/ROD	environmental impact statement/record of decision
EMM	electromechanical manipulator
EMS	Emergency Management System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FWS	Fish and Wildlife Service
HEPA	high-efficiency particulate air
HVAC	heating, ventilating, and air conditioning
I&C	instrumentation and control
ICRP	International Commission on Radiological Protection
IEEE	Institute of Electrical and Electronic Engineers
IPCEA	Insulated Power Cable Engineers Association
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LCE	loss-of-coolant event
LCOs	Limiting Conditions for Operations
LCS	Limiting Control Setting

LFE	loss-of-flow event
LLW	low-level waste
LVE	loss-of-vacuum event
MACCS	MELCOR Accident Consequence Code System
MAP	Mitigation Action Plan
MC&A	Materials Control and Accountability
MEI	most exposed individual
MG	motor generator
MSM	master slave manipulator
NAAQS	National Ambient Air Quality Standards
NCRP	National Council on Radiation Protection and Measurements
NDE	nondestructive examination
NEPA	National Environmental Policy Act
NESHAPS	National Emission Standards for Hazardous Air Pollutants
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
OSHA	Occupational Safety and Health Act
PAG	Protective Action Guideline
PF	poloidal field
PFC	plasma-facing component
PIE	postulated initiating event
PRA	probabilistic risk assessment
PSD	Prevention of Significant Deterioration
PTC	permit to construct
PVTC	pressure/volume/temperature/composition
QA	quality assurance
QAP	Quality Assurance Plan
QC	quality control
RCRA	Resource Conservation and Recovery Act
RF	radio frequency
SA	specific activity
SAR	safety analysis report
SARA	Superfund Amendments and Reauthorization Act
SHIPO	State Historic Preservation Office
SIP	State Implementation Plan
SL	safety limit
SR	Surveillance Requirement
SSCs	structures, systems, and components
TF	toroidal field
TFTR	Tokamak Fusion Test Reactor
TSCA	Toxic Substances Control Act
TSD	treatment, storage, and disposal
TSR	Technical Safety Requirement

UHMWPE	Ultra-high molecular weight polyethylene
UPS	uninterruptable power supply
USQ	Unreviewed Safety Question
V&V	verified and validated
VDE	vertical displacement event

1. INTRODUCTION

1.1 Purpose

This document provides guidance for the implementation of the requirements identified in DOE-STD-6002-96, Safety of Magnetic Fusion Facilities: Requirements. This guidance is intended for the managers, designers, operators, and other personnel with safety responsibilities for facilities designated as magnetic fusion facilities. While the requirements in DOE-STD-6002-96 are generally applicable to a wide range of fusion facilities, this Standard, DOE-STD-6003-96, is concerned mainly with the implementation of those requirements in large facilities such as the International Thermonuclear Experimental Reactor (ITER). Using a risk-based prioritization, the concepts presented here may also be applied to other magnetic fusion facilities. This Standard is oriented toward regulation in the Department of Energy (DOE) environment as opposed to regulation by other regulatory agencies. As the need for guidance involving other types of fusion facilities or other regulatory environments emerges, additional guidance volumes should be prepared. The concepts, processes, and recommendations set forth here are for guidance only. They will contribute to safety at magnetic fusion facilities.

1.2 Background

When the development of fusion facilities began changing from comparatively small-scale experiments in physics to large facilities with megawatt-power levels and significant activation concerns, a need to develop safety requirements and associated guidance for fusion became apparent. Fusion systems are sufficiently different from other nuclear facilities that the requirements and regulations governing existing nuclear facilities are not fully appropriate for the regulation of magnetic fusion facilities.

Efforts were begun to develop a group of documents that would be appropriate for safety regulation in magnetic fusion facilities. The documents that resulted from that process consist of a requirements document, DOE-STD-6002-96, Safety of Magnetic Fusion Facilities: Requirements, which attempts to assemble in one place those requirements needed for safety, and this guidance document, which sets forth information that will assist fusion developers in meeting those requirements.

The intent in this guidance document is to provide a fairly complete, though not exhaustive, set of instructions that if followed will contribute to the achievement of safety. There has been a conscious effort to include either directly or by reference those items that are germane to safety so that the manager, designer, or operator will be able to clearly identify actions that should be taken to meet the requirements using risk-based prioritization.

The guidance provided here represents the collective wisdom of a broad and diverse group with experience in nuclear facility safety as well as with fusion. The concepts presented are included not only because they have been applied successfully to other kinds of facilities, but because they were deemed to make sense for fusion.

A conscious attempt has been made to exclude from this document concepts and advice not directly related to safety. In this sense, this document is not intended to be exhaustive. Of the many sound design or management practices that make good sense for a project, the ones included here are those that are directly safety-related.

The intent here has been to identify concerns, practices, or procedures that will contribute to safety. Often, these are only summarized, not detailed here. Where appropriate guidance is available from other sources such as DOE Orders or other Standards, those sources are referenced here.

This Standard was written in the reference frame of the Orders, Standards, and other documents that were in force at the time of writing. It was recognized that the DOE directives system was under major revision and that some of the references included here may be out of date at the time this Standard is implemented. Therefore, the user is encouraged to use the most current version of documents referred to here or their replacements.

1.3 Implementation

The requirements in DOE-STD-6002-96 and the guidance in this Standard should be implemented using a risk-based prioritization approach. The degree to which they are applied should be commensurate with the risk involved. Fusion facilities that involve only minor hazards will require implementation at a lower level than will facilities such as ITER where activation and tritium inventories will be concerns.

1.4 Overview

The responsibility for safety at fusion facilities, as all other facilities, lies with those having charge of the program or project. Safety is a requirement during all phases of the facility life cycle. It must be incorporated into the design, implemented during operations, and integrated into facility removal and site restoration. Success in the latter two phases often hinges on the success with which safety foresight and planning have been included in the design. To assist managers, designers, operators, and removal staffs in achieving safety, there are a number of tools (i.e., considerations, practices, processes, or other vehicles) that if implemented will contribute substantially to the overall safety of the facility. Those deemed most appropriate for fusion facilities are described in subsequent sections of this Standard.

Chapter 2 of this volume provides guidance on radiation and hazardous materials management to ensure that safety objectives are met. A primary consideration in any nuclear facility, including fusion facilities, is the management of radioactivity and hazardous materials. Protection from radiation and hazardous materials at all times is a primary concern for worker safety. The design and operating protocols of the facility should incorporate features that will limit exposures to radioactivity or hazardous materials in off-normal events as well as under normal operating conditions. Guidance on how to provide that protection is presented in Chapter 2.

Environmental considerations are summarized in Chapter 3. References to requirements in the environmental area are listed here with annotations because such a listing is not readily available from other sources.

Program management considerations to achieve safety are addressed in Chapter 4. As indicated previously, the ultimate responsibility for safety lies with management. Integration of safety in the design, operation, and site restoration all involve the implementation of safety-related processes and a safety culture. In Chapter 4 the most significant of the tools available for achievement of safety are discussed: configuration management, quality assurance, conduct of operations, emergency planning, and tritium accountability.

A major area of involvement for safety professionals with management is in the preparation of safety analysis to evaluate the extent to which a given facility or design meets safety goals. Chapter 5 of this Standard includes guidance on how to establish the facility hazard classification; identify safety-related structures, systems, and components; develop technical safety requirements; and deal with unresolved safety questions. A key concept in safety analysis is the design basis and the associated requirements for approving facility operation. The analysis process described in Chapter 5 makes use of that concept and indicates how various off-normal event scenarios should be dealt with in the analysis.

Chapter 6 is the most comprehensive of the chapters. It addresses design requirements and considerations for safety in design of fusion facilities. It begins with general design guidance that applies to all systems; then systems performing safety functions are described with design considerations to achieve those functions. Guidance is also provided for systems with potential safety concerns. These systems are not required to operate to achieve safety, but their failure may influence the levels of defense-in-depth available to the facility. Safety design guidance for supporting systems (those systems that support those systems providing safety functions) is also presented. The chapter concludes with guidance on safety in experimental systems and facility support.

The final chapter in this Standard, Chapter 7, is concerned with facility removal and site restoration. It provides guidance for returning the site of the fusion facility to its original condition at the end of its useful life. Safety in this phase of the life cycle will be strongly influenced by planning and design features that have been incorporated from the outset of the project.

Appendices in this Standard provide additional supporting information. Appendix A is a list of isotopes for radiological considerations specific to fusion facilities. Appendix B is an overview of hazards typically associated with magnetic fusion facilities. Appendix C supplements this volume with a listing of available orders, standards, and other documents appropriate to management of projects within DOE and lists specific references cited in the text.

2. RADIATION AND HAZARDOUS MATERIAL

The neutron flux in a fusion facility will result in activation of the first wall and structure, resulting in the production of radioactive materials. The level of activation is a function of power level, fuel cycle [deuterium-deuterium (D-D) vs deuterium-tritium (D-T)], and materials choice. Fusion experiments and power plants presently envisioned will also use strong magnetic fields, radio-frequency heating, and some potentially hazardous materials such as beryllium and vanadium. This section summarizes general guidance regarding radiological, magnetic field, and hazardous material concerns expected to be present at fusion facilities.

Chemically hazardous materials are sometimes specified in the design of a fusion power core because of their mechanical or nuclear properties. The most prominent of these materials are beryllium, used as a first wall coating and as a neutron multiplier, and vanadium, used as a first wall and blanket structure material.

2.1 Dose Definitions

The effective dose E has associated with it the same probability of the occurrence of cancer and genetic effects whether received by the whole body via uniform irradiation or by partial or individual organ irradiation. Although an assumption of uniformity may be a sufficient approximation in many external irradiation cases, in others more precise evaluation of individual tissue doses will be necessary. With external irradiation, differences may arise with depth in the body and with orientation of the body in the generally nonuniform radiation field. *When irradiation is from radionuclides deposited in various tissues and organs, nonuniform or partial body exposures usually occur*. Tissues also vary in their sensitivity to radiation. The effective dose E is a concept similar to the effective dose equivalent H_E used by ICRP Publication 26 (ICRP 1977) and NCRP Report No. 91 (NCRP 1987). However, they are conceptually different. The effective dose E is intended to provide a means for handling nonuniform irradiation situations, as did the earlier dose equivalent.

The effective dose E is the sum of the weighted equivalent doses for all irradiated tissues or organs. The tissue weighting factor w_T takes into account the relative detriment to each organ and tissue including the different mortality and morbidity risks from cancer, the risk of severe hereditary effects for all generations, and the length of life lost due to these effects. The risks for all stochastic effects will be the same whether the whole body is irradiated uniformly or nonuniformly if

$$E = \sum_T w_T H_T \quad , \qquad (1)$$

where w_T is the tissue weighting factor representing the proportionate detriment (stochastic) tissue T when the whole body is irradiated uniformly, and H_T is the equivalent dose received by tissue T. For further explanation see NCRP Report No. 116 (NCRP 1993).

Doses mean the 50-yr committed effective dose (CED) unless otherwise stated. The exposure times and exposure pathways to be included in the calculation of CED should be appropriate for the fusion isotopes involved, the accident scenario, and the public mitigative actions (if any) being considered.

Acute dose is defined for specific organs depending on what short-term exposure is the best predictor of acute health effects. For example, the acute lung dose is typically the 1-yr CED, and the bone marrow acute dose is typically considered as the 7-day CED or 100% of the 7-day CED plus 50% of the 8–30th day CED. Thus, for the same exposure time periods, the acute dose is always less than (or equal to for very short half-lives) the 50-yr CED.

Early dose is the 50-yr CED from the first 7 days of exposure following the onset of an accident, specifically the inhalation and cloudshine doses during plume passage, inhalation from resuspended/re-emitted isotopes during the first 7 days, and the groundshine dose from the first 7 days. This dose measure is appropriate when contemplating the need for short-term public mitigative actions. The early dose is generally calculated for the most exposed individual (MEI) of the public, assumed to reside at the site boundary or (for release elevated above ground level) where the plume reaches the ground.

Two-hour (prompt) dose is the 50-yr CED resulting from the first 2 hours of exposure following the onset of an accident, as in DOE 6430.1A. This dose measure implicitly assumes evacuation within 2 hours.

Chronic dose is the 50-yr CED from 50-yr exposure after an event, specifically from inhalation of resuspended or re-emitted isotopes, groundshine, and ingestion of radionuclides. This dose measure is appropriate when contemplating whether long-term public mitigative actions are needed and, if so, when and for how long. When calculated for an individual, the chronic dose should include reasonable assumptions about the fraction of time an individual resides at the site boundary and the fraction of food produced at that location. Because of the long time scales, the chronic dose is more appropriately calculated for the “average” resident of the surrounding area.

The factor χ is the instantaneous concentration of a radioactive or hazardous material (in becquerels per cubic meter or grams per cubic meter) at a given location distant from the point where the material is released into the environment. The factor Q is the amount of material released, expressed in grams or becquerels; Q' is the rate of material release emission from a continuous point source. The ratios χ/Q and χ/Q' are determined by the atmospheric conditions, the distance between the source and distant location atmospheric transport, and the time since release. For further explanation, see Slade (AEC 1968).

2.2 Public Exposures and Environmental Impacts

A significant part of 10 CFR 20 is directed toward protecting the public, the environment, and workers from the risks of exposure to radiation. Part of 40 CFR 61 is also concerned with protecting the public from chronic exposure to radiation. In addition, exposures to workers, the public, and the environment must be kept “as low as reasonably achievable” (ALARA). “Reasonably achievable” levels are typically a fraction of those allowed by 10 CFR 20 and 40 CFR 61.

For comparison with the evaluation guidelines, only plume passage dose is evaluated. Plume passage dose includes the following pathways: (1) direct cloudshine and (2) 50-yr CED from inhalation for the duration of plume passage. These pathways are considered an immediate threat. Other slow-developing pathways are not included because they are a measure of the effectiveness of public health measures (e.g., interdiction) rather than the severity of the accident itself. If dose is evaluated on public access roads that are not controllable by the licensee, the time of exposure to the plume should be based on realistic vehicle passage time estimates.

2.2.1 Evaluation Guidelines for Exposures to the Public

The following goals and requirements have been established in DOE-STD-6002-96 for exposures to the general public during normal and anticipated operational occurrences and for off-normal conditions and accidents. The origin of each of the limits follows Table 2.1.

Evaluation guidelines for public exposures to nonradiological materials should be in accordance with federal, state, and local regulatory and permit requirements.

TABLE 2.1. Evaluation guidelines for public protection from radiation

	Fusion radiological release requirement	Regulatory limit (evaluation guidelines)
Normal and anticipated operational occurrences	100 µSv/yr [10 mrem/yr][a]	1 mSv/yr [100 mrem/yr][b]
Off-normal conditions (per event)	10 mSv [1 rem][c] (no public evacuation)	250 mSv [25 rem][d]

[a]This value, which is a limit for the MEI, is consistent with the limit on the emissions of radionuclides to the ambient air for DOE facilities as stated in 40 CFR 61.92. In meeting this limit, a facility would be well below the exposure limit mandated by the Nuclear Regulatory Commission (NRC) safety goals for nuclear facilities (51 FR 30028) and the DOE safety goals. Both of these goals, which consider the *average* exposure to the population within 10 miles of a facility, state that the risk to the population resulting from nuclear operations should not exceed 0.1% of the sum of all cancer fatality risks resulting from all other causes. The radiological cancer risk coefficient is about 0.4%/0.1 Sv for long-term exposures (BEIR-V, p. 6), and the annual cancer fatality risk due to all causes is about 200/100,000 people. If we conservatively assume that the site-boundary to average exposure ratio is 2, then the routine exposure limit should be

$$(0.1\%)\ (200 \text{ per year}/100{,}000 \text{ people})\ (0.1\ \text{Sv}/0.4\%)\ (2) = 0.1\ \text{mSv/yr} = 10\ \text{mrem/yr}.$$

[b]This value is based on the 10 CFR 20.1301 dose limits on individual members of the public.

[c]This requirement is based on the limit in the Protective Action Guideline (PAG) (EPA 1991) at which public sheltering and evacuation should be undertaken.

[d]This is the required limit for exposure due to an accident. This value is based on the design basis acceptance criteria for nuclear reactor siting in 10 CFR 100.

2.2.2 Additional Guidance

10 CFR 100 defines requirements for siting of nuclear reactor facilities. These guidelines have also been applied to nonreactor nuclear facilities (DOE 6430.1A). According to 10 CFR 100.11, the maximum calculated dose to an off-site individual from exposure that results from internal and external sources of radiation must not exceed 250-mSv (25-rem), 50-yr CED to the whole body. If multiple organs receive doses during the same exposure, the ED shall not exceed 250 mSv (25 rem). The exposure duration should be consistent with the requirement for no public evacuation. DOE 6430.1A recommends using meteorological conditions that result in unfavorable dispersion (e.g., the higher of the 0.5% χ/Q for each sector of the site and the 5% direction independent χ/Q for the site). In the absence of site-specific meteorology, conservative assumptions (Class F, 1.0-m/s wind speed) should be used for design assessments. Further guidance is contained in Sections 2.4.3 and 5.4.3.

DOE Order 6430.1A notes that these values are guidelines and do not constitute acceptable limits on the doses to the public in the event of an accident. These guidelines are used by DOE to evaluate the facility design in combination with the site characterization with respect to the risk to the public from low-probability accidents. Accidents to be evaluated for comparison to these dose guidelines include events with a probability of occurrence $>10^{-6}$/yr. When the doses are calculated, the degraded performance of engineered safety features and administrative controls should be assumed unless they can be shown to be capable of performing their safety function.

The radionuclides of concern in a fusion facility cover a wide range of characteristics. Tritium is generally the most mobile. Tritium is hazardous if it is taken into the body via ingestion, inhalation, or absorption through the skin. Because of the relatively low energy of the beta particle, 18-keV maximum energy, it does not present a significant hazard outside the body. Other radionuclides are the products of neutron activation. These radionuclides, usually imbedded in a metal, have much higher energies and undergo γ-decay. Typical radionuclides are Fe-55, Co-58, Co-60, Mn-54, Mn-56, Ni-59, and Ni-63. Alloying elements and impurities further increase the range of activation products.

2.2.3 Environment

Radiation protection standards have been developed expressly for the protection of humans. It has been generally accepted that by protecting humans we are protecting the environment. Recently, the ICRP stated (ICRP 1991):

The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species.

Additional guidance on other areas of environmental protection is provided in Chapter 3.

The Environmental Protection Agency (EPA) has set limits on the emissions of beryllium into the environment from industries that process beryllium ores, metal, oxide, alloys, or waste. 40 CFR 61 limits the amount of beryllium emitted to 10 g in a 24-h period or to an amount that would result in atmospheric levels of 0.01-µg beryllium/m^3 of air, averaged over a 30-day period. EPA's Office of Water Regulations and Standards limits the concentration of beryllium in water to between 0.68 and 68 ng beryllium/L for protection of human health.

2.3 Routine Worker Exposure

2.3.1 Radiation

In a fusion facility, occupational exposure to radiation can result from gamma radiation, neutron fluxes, tritium ingestion or inhalation, and the mobilization of activation products. The exposures from all these sources are combined into an effective dose (ED) that accounts for the energy, half-life, and biological mobility of each of the radionuclides.

Under 10 CFR 20 and 10 CFR 835, the radiological workers at commercial and DOE facilities are limited to an annual ED (internal and external) exposure of 50 mSv (5 rem). Exposures to organs, tissues, or extremities are limited to 500 mSv (50 rem). Lower limits apply to declared pregnant women, minors (less than 18 years old) and students, visitors, and the public. Under DOE requirements, permission of the Cognizant Secretarial Officer is required for all occupational doses in excess of 2 rem. Higher exposures are tolerated for emergency situations, such as saving a human life, recovering a deceased victim, and protecting health and property.

The goal for doses due to normal and anticipated operational occurrences is 10 mSv/yr (1 rem/yr). In all cases the dose to workers must be as low as reasonably achievable. This value is based on ICRP 26 and NCRP 116 recommendations.

Doses should be kept "as low as reasonably achievable" (ALARA). In the design of facilities the design objective for controlling personnel exposure from external sources of radiation in areas of continuous occupational occupancy (2000 hours per year) shall be to maintain exposure level below an average of 0.5 mrem (5 microsieverts) per hour and as far below this average as is reasonably achievable. The design objectives for exposure rates for potential exposure to a radiological worker where occupancy differs from the above shall be ALARA and shall not exceed 20 percent of the applicable standards of 10 CFR 835.202 (10 CFR 835).

2.3.2 Hazardous Materials

There may be a number of hazardous materials in a fusion facility such as metallic dust, diborane, inert gases, and organic compounds. Other regulations are concerned with exposures to these hazardous materials and other industrial hazards. In this guidance emphasis is given to beryllium and vanadium because these materials are more relevant to fusion facilities. Exposure limits should be taken from National Institute of Occupational Safety and Health (NIOSH) recommendations (NIOSH 1994), Occupational Safety and Health Act (OSHA) regulations (29 CFR 1910), and industrial standards.

2.3.2.1 Beryllium

Beryllium and beryllium compounds can pose potential health risks to humans. They may be used as plasma-facing components in ITER. This section summarizes the current U.S. regulations about allowable emission to the environment and permissible occupational exposure to workers.

OSHA regulations limit permissible exposures to a time-weighted average of 0.002 mg/m^3 for the beryllium concentration in workroom air. For short-term exposure (i.e., 30 min), the exposure limit is 0.025 mg/m^3. The NIOSH recommends an exposure guideline of 0.0005 mg/m^3 in workroom air during an 8-h shift. There are also limits on acceptable beryllium ambient air concentrations and drinking water quality standards for a number of states in the United States (DHHS 1993). This Standard recommends the adoption of the NIOSH exposure guidelines for beryllium in a fusion facility.

2.3.2.2 Vanadium Oxides

Since absorption of vanadium is chiefly by the respiratory tract, mechanical enclosure of many vanadium-using operations is required. If this is impractical, the worker must be provided with an air-fed unit to ensure complete respiratory protection from vanadium pentoxide (Finkel 1983). NIOSH 15-min time-weighted average exposure limits for vanadium compounds in air are 0.05 mg vanadium/m^3. For metallic vanadium, ferrovanadium dust, and vanadium carbide, the NIOSH exposure limits are 1.0 mg V/m^3 (3 mg V/m^3 for short-term exposures) (NIOSH 1994). OSHA exposure limits are 0.5 mg V_2O_5/m^3 for vanadium dust, 0.1 mg V_2O_5/m^3 for vanadium fume, and 1 mg/m^3 for ferrovanadium dust (29 CFR 1910). This Standard recommends the adoption of the NIOSH exposure guidelines for vanadium in a fusion facility.

2.3.3 Common Industrial Hazards

As with any large industrial facility, a fusion power plant facility will contain other hazards, such as flammable materials, rotating machinery, and nonbreathable gases. These hazards are not unique to fusion power and will therefore be regulated according to existing OSHA criteria (29 CFR 1910, 1926) or commonly accepted industrial safety practices.

2.3.4 Magnetic Fields

The magnetic confinement fusion facilities addressed in this Standard may have magnetic fields of considerable strength extending throughout areas of the facilities and possibly beyond interior rooms. These fields may be steady state, or they may vary in time and/or space. In general, the magnetic field at the site boundary will be very low, usually less than the earth’s magnetic field (~50 µT).

The recommended limits for occupational exposures to steady-state and low-frequency magnetic fields are those established by the American Conference of Governmental Industrial Hygienists (ACGIH). At present, the ACGIH states:

Routine occupational exposure should not exceed

$$B_{TLV} = \frac{C}{f} \quad , \tag{2}$$

where

B_{TLV} = the threshold limit value for the magnetic field in millitesla (mT)

C = a constant equal to 60 mT-Hz

f = the field frequency in Hertz (Hz).

At frequencies below 1 Hz, the threshold limit value is 60 mT. The magnetic field strengths in these limits are root-mean-square (rms) values.

For workers wearing cardiac pacemakers, the threshold limit value may not protect against electromagnetic interference with pacemaker function. The threshold limit for pacemaker wearers should be reduced by a safety factor of 10.

In the future, this Standard will adopt modifications of the ACGIH threshold limit value for magnetic fields.

2.4 Guidance for Meeting Regulatory Limits

This section provides guidance for calculational procedures to meet the regulatory limits given in DOE-STD-6002-96. Guidance on the types of off-normal analyses required to meet these regulatory limits is provided in Section 5.4 of this Standard.

2.4.1 Evaluation Guidelines

Evaluation Guidelines (EGs) are accident impact criteria established for the purpose of evaluating the acceptability of facility safety design. For radionuclide releases, criteria are given for ED and are termed “dose values.” It is important to note that these criteria do not necessarily constitute acceptable limits for human health impacts in the event of an accident. Rather, they are used to evaluate the level of safety associated with the design of the facility with respect to the risk from low-probability accidents. EGs are typically established using a risk-based framework. Higher dose values are associated with lower frequency to provide balance in the design with appropriate focus at both the high- and low-probability ends of the accident frequency scale. Dose values are given for normal operation and anticipated operational occurrences. A second set of dose values is given for off-normal conditions. Events with an estimated frequency of $<10^{-6}$/yr are considered hypothetical, and comparison to an EG is not required. The method is comparable to that established in DOE Standard 3009, Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports. EGs are provided for off-site (public) locations.

2.4.2 Exposure

Off-site doses are evaluated for the most exposed individual (MEI). This is a hypothetical individual located at the closest point on the site boundary (or at off-site distance of maximum air concentration for elevated releases).

2.4.3 Meteorological Dispersion

Site-specific 5% weather conditions (i.e., stability class and wind speed more unfavorable than 95% of the expected weather) without regard to wind direction, defined by at least 1 yr of weather data, should be used for diffusive transport to downwind receptors. Alternatively, site-specific climatological studies using actual measurements of diffusion/dilution characteristics under representative meteorological conditions can be used as a basis for determining site-specific dilution factors (χ/Qs) (see NOAA 1989 for example). These weather conditions should be determined using the anticipated release height of the accident cloud (e.g., ground level or elevated). For evaporating chemicals, a range of stability class/wind speed combinations should be examined due to the chemical-specific effects of these parameters on source emission rates and downwind dispersion. A dense gas model may need to be used for evaluation of impacts at near-field receptor distances if the chemical/air mixture density at the source exceeds the ambient air density by 50%. Dense gas effects are usually insignificant at far-field receptor distances.

2.5 Consequence Thresholds for PAGs and Emergency Response Planning Guidelines

As stated in DOE-STD-6002-96, the Fusion Radiological Release Requirement for off-normal events at fusion facilities is that no events result in a public exposure greater than 10 mSv (1 rem). If the projected early dose to the surrounding population can be shown to be less than 10 mSv, then no public protective action planning would be necessary.

In determining whether a given event at a fusion facility will require protective action, best estimate meteorology and system operation are assumed. All estimates of the site-specific transport coefficients (χ/Q) are based on at least 1 yr of meteorological data. Best-estimate meteorology can be used to determine public exposures in three ways:

a. Use the annual average windspeed and the highest-frequency stability conditions in determining the χ/Q at the site boundary.

b. Calculate the hourly χ/Q for meteorological conditions throughout the year. Select the 50 percentile χ/Q to determine off-site transport.

c. Using meteorological data for at least 1 yr, use a Monte Carlo technique to select random starting times for the off-normal event. Average the public exposure due to each of the transients to obtain the best-estimate off-site doses.

Because of differences among the mean, median, and mode of the χ/Q distributions through the year, the preferred method is “c” above. Further guidance in the application of best estimate off-site dose calculation can be found in NUREG-0654/FEMA-REP-1.

2.5.1 Radiological (No Ingestion)

Guidance for sheltering, evacuation, and food interdiction is given in the EPA “Manual of Protective Action Guides and Protective Actions for Nuclear Incidents” (EPA 1991). A nuclear incident is divided into three phases: early, intermediate, and late. During the early phases sheltering or evacuation is the appropriate measure to consider. The PAGs are criteria based upon the potentially avoided dose, which determine whether action must be taken.

a. Evacuation (or, for some situations, sheltering) should normally be initiated to avoid a 10-mSv (1-rem) dose to a standard man for ”early” pathways inhalation (CED) and external gamma ED (cloudshine/immersion and ground surface).

b. For radionuclides with long effective half-times in the body, use 50-mSv (5-rem) CED + ED as the action criterion. For committed effective dose equivalent to the skin, use 500 mSv (50 rem) for the action criterion.

2.5.2 Radiological (Ingestion)

During the intermediate and late phases of the incident, controls on the ingestion of contaminated food and water are appropriate (FDA 1982). The avoided doses at which such interdiction is appropriate are shown below:

a. “Preventative PAG”—5 mSv (0.5 rem) to “whole body, bone marrow, or any other organ.” This is the level at which protective actions having minimal impact should be taken.

b. “Emergency PAG”—50 mSv (5 rem) to “whole body, bone marrow, or any other organ.” This is the level at which food should be isolated for condemnation or other disposition.

2.6 Models Used in Relating Exposures to Estimated Consequences

The following code systems are examples of tools that have been accepted for use in a regulatory context for relating releases, exposures, and estimated consequences. This list is not all inclusive, and other codes of greater capability might be developed in the future.

GENII (Napier 1988) is a coupled system of computer codes used to estimate potential radiation doses to individuals or populations from both routine and accidental releases of radionuclides to air or water and residual contamination from spills or decontamination operations.

The MACCS (MELCOR Accident Consequence Code System) (Chanin 1990) code system calculates impacts of severe accidents at nuclear reactors on the surrounding environment. Principle phenomena considered include atmospheric transport dose mitigation actions, dose accumulation, and health effects. The MACCS code has been expanded to include isotopes of interest in fusion facilities.

The RSAC (Wenzel 1993) code calculates the consequences of the release of radionuclides to the atmosphere. A user can generate a radioactive inventory, decay and ingrow the inventory during transport through process facilities and the environment, model the downwind dispersion of the activity, and calculate doses to downwind individuals. Doses are calculated through the inhalation, immersion, ground surface, and ingestion pathways.

The CAP-88 (Clean Air Act Assessment Package-1988) (Parks 1992) computer model is a set of computer programs, data bases, and associated utility programs for estimation of dose and risk from routine radionuclide emissions to air. CAP-88 must be used to show compliance with 40 CFR 61.93(a) unless the EPA approves an alternate.

The CAP-88-PC software package allows users to perform full-featured dose and risk assessments in a personal computer environment for the purpose of demonstrating compliance with 40 CFR 61.93(a) for routine radionuclide releases to the air. CAP-88-PC provides the CAP-88 methodology for assessments of both collective populations and MEIs. The complete set of dose and risk factors used in CAP-88 is provided. CAP-88-PC used a modified Gaussian plume equation to estimate the average dispersion of radionuclides released from up to six sources. The sources may be either elevated stacks, such as a smokestack, or uniform area sources, such as a pile of uranium mill tailings. Plume rise can be calculated assuming either a momentum or buoyancy-driven plume. Assessments are done for a circular grid of distances and directions for a radius of 80 km (50 miles) around the facility.

3. ENVIRONMENTAL AND PERMITTING REQUIREMENTS

This chapter is a compilation of environmental and permitting requirements potentially applicable to magnetic fusion facilities. It is not intended nor should it be interpreted to be the definitive listing of all environmental laws and regulations to which a new fusion facility would be subject. The information is provided to facilitate planning for preparing the environmental and permitting documentation that may be required. Ongoing rulemaking may influence the applicability and completeness of the environmental and permitting requirements that must be satisfied for specific fusion facilities. In addition, state and local regulations may impose additional requirements and more stringent standards on those facilities. Requirements in this chapter are only repeated here from original sources for user convenience and do not constitute new requirements.

3.1 Federal Requirements

3.1.1 National Environmental Policy Act and Implementing Guidelines, Regulations, and Orders

National Environmental Policy Act (NEPA) of 1969 (42 USC 4321 et seq.; 40 CFR 1500–1508) establishes national policies and goals for the protection of the environment. Section 102 requires Federal agencies to incorporate environmental considerations into their planning and decision-making processes using a systematic interdisciplinary approach. The Council on Environmental Quality (CEQ) regulations implementing NEPA (40 CFR 1500–1508) contain action-forcing provisions to ensure that Federal agencies consider environmental information before making decisions on proposed actions. The NEPA process includes decision points at which the significance of environmental effects is considered, project alternatives are identified, and any appropriate mitigation measures are identified and adapted. Title 10 CFR 1021 establishes DOE's policy of complying fully with NEPA, and DOE Order 451.1 describes the roles of the various DOE offices in implementing the Act.

The NEPA review process consists of evaluating the potential environmental effects of a Federal undertaking, establishing possible alternatives to the proposed action, and determining the level of NEPA documentation required to proceed with the action. Three levels of NEPA documentation include determination of categorical exclusion, preparation of an environmental assessment/finding of no significant impact (EA/FONSI), and preparation of an environmental impact statement/record of decision (EIS/ROD). For major Federal actions with the potential for significant environmental impacts, an EIS is typically required.

The *National Environmental Policy Act Compliance Program* (10 CFR 1021, DOE Order 451.1) establishes procedures to implement NEPA, including the level of review necessary under NEPA. This Order promotes smooth generation, review, and release of documents pursuant to NEPA and provides for the cooperation between various elements of DOE. Further guidance on preparing EAs and EISs is provided in DOE's NEPA "Greenbook" (DOE, 1993b).

Executive Order 12114, "Environmental Effects Abroad of Major Federal Actions" (44 FR 1957), establishes procedural and other actions to be taken by Federal agencies to further the purposes of NEPA with respect to the environment outside the United States, its territories, and possessions. Final DOE guidelines for implementing the Order were published in the *Federal Register* in 1981 (46 FR 1009). Therein, the categories of actions and the mandatory environmental review requirements are identified. Major Federal actions that could potentially affect the global environment or resources require some level of environmental review and documentation, depending on the nature of the action and the environments potentially impacted.

3.1.2 Federal Statutes and DOE Orders Relating to Environmental Quality

3.1.2.1 Federal Statutes

The *Atomic Energy Act (AEA) of 1954, as amended* [42 USC 2011, et seq.; 10 CFR 20, 39, 60, 61, 71, 100, 762, 835, 960, 962 and 40 CFR 190–192], authorizes the conduct of atomic energy activities and governs the design, location, and operation of facilities (including Federal facilities) involved with nuclear materials. DOE facilities are not required by the AEA to be permitted or licensed but are required to comply with the act and its amendments.

The *Pollution Prevention Act of 1990* declares a national policy to prevent pollution at the source and to recycle pollution in an environmentally safe manner. The Act provides that the following hierarchical sequence of steps be taken in dealing with pollution: (1) pollution should be prevented or reduced at the source whenever possible; (2) polluting materials should be recycled in an environmentally safe manner whenever feasible; (3) polluting materials should be treated in an environmentally safe manner; (4) disposal or other release to the environment is to be employed only as a last resort and conducted in an environmentally safe manner.

The *Clean Air Act, as amended* [42 USC 7401 et seq. (40 CFR 50–80)], provides requirements to protect and enhance the quality of the nation’s air resources and to promote public health and welfare. The act establishes National Ambient Air Quality Standards (NAAQS), Prevention of Significant Deterioration (PSD) regulations, National Emission Standards for Hazardous Air Pollutants (NESHAPS), and New Source Performance Standards (NSPS). The EPA can delegate permitting and regulatory authority to a state. Delegation under the Clean Air Act can take forms other than a State Implementation Plan (SIP).

The *Water Pollution Control Act, amended by the Clean Water Act of 1977* (33 USC 1251 et seq.; 40 CFR 110, 116, 117, 121, 122, 124, 129, 230, 401, 403; 33 CFR 289, 320, 323, 327, and 330), pertains to restoration and maintenance of the chemical, physical, and biological integrity of the nation’s waters. Using minimum technology-based guidelines set by the Environmental Protection Agency (EPA), states will issue National Pollutant Discharge Elimination System (NPDES) permits to discharge wastes into U.S. waters; a NPDES permit is required for discharges to waters of the United States. Fusion facilities must comply with applicable U.S. Army Corps of Engineers dredge and fill regulations. Impacts to wetlands greater than 10 acres require a permit from the U.S. Army Corps of Engineers. In addition, some states have more stringent requirements pertaining to wetlands. It is recommended that an expert on water quality be consulted for establishing the water quality requirements for the site in question.

The *Safe Drinking Water Act, as amended* [42 USC 300(f–j) et seq.; 40 CFR 140–149], establishes uniform Federal standards for drinking water quality. The EPA has the authority to delegate enforcement of these standards to the states. This act sets two types of standards for drinking water, primary and secondary. Primary standards are mandatory and apply to substances that may have adverse affects on health. Secondary standards are advisory and affect color, smell, taste, or other physical characteristics of drinking water. This act also pertains to groundwater aquifers, banning underground injection of certain materials in or near groundwater recharge areas.

The *Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act* (RCRA) (42 USC 6901 et seq., 40 CFR 240–282 and 124), established a comprehensive program for regulating and managing solid waste (Subtitle D), hazardous waste, including radioactive mixed waste (Subtitle C), and underground storage tanks (Subtitle I), and for promoting the use of recycled and recovered materials (Subtitle F).

The *Toxic Substances Control Act (TSCA)* (15 USC 2601 et seq.; 40 CFR 700–799) provides the regulatory vehicle for controlling exposure and use of raw industrial chemicals that fall outside the jurisdiction of other environmental laws. TSCA assures that chemicals are evaluated before use to ensure they pose no unnecessary risk to health or the environment. Fusion facility personnel shall review proposed chemical use to assure that appropriate alternatives have been evaluated. The management of PCBs is also regulated under TSCA. There are specific requirements for facilities that maintain transformers and other equipment containing PCB dielectric fluid.

The *Federal Facility Compliance Act* waives sovereign immunity for fines and penalties for RCRA violations at Federal facilities. However, the effective date of the waiver has been delayed for mixed waste storage prohibition violations, as long as the Federal facility is in compliance with all other applicable requirements of RCRA. During this period, DOE is required to prepare plans for developing the required treatment capacity for mixed wastes stored or generated at each facility. Each plan must be approved by the host state or the EPA after consultation with other affected states, and a consent order must be issued by the regulator requiring compliance with the plan. The Federal Facility Compliance Act further provides that the DOE will not be subject to fines and penalties for land disposal restriction storage prohibition violations for mixed waste as long as it is in compliance with such an approved plan and consent order and meets all other applicable regulations.

The *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA), as amended (42 USC §9601 ET SEQ.), provides a statutory framework for the cleanup of waste sites containing hazardous substances and—as amended by the Superfund Amendments and Reauthorization Act—provides an emergency response program in the event of a release (or threat of a release) of a hazardous substance to the environment. Using the Hazard Ranking System, Federal and private sites are ranked and may be included on the National Priorities List. The Comprehensive Environmental Response, Compensation, and Liability Act, as amended, requires such Federal facilities having such sites to undertake investigations and remediation as necessary. The Act also includes requirements for reporting releases of certain hazardous substances in excess of specified amounts to State and Federal agencies.

The *Emergency Planning and Community Right-To-Know Act of 1986* (42 USC 10227; 40 CFR 350–372) was enacted as Title III of the Superfund Amendments and Reauthorization Act (SARA). This act establishes requirements for emergency planning, spill reporting, hazardous chemical inventory reporting, and toxic chemical release reporting. The act also provides for the establishment of state and local emergency planning committees to prepare plans to respond to potential chemical emergencies. A facility emergency coordinator must be designated, and a list or copies of Material Safety Data Sheets for hazardous substances at the site must be submitted to the Local Emergency Planning Committee, the State Emergency Response Commission, and the local fire department.

> *Reporting Requirements*. An annual hazardous chemical inventory report shall be submitted to the Local Emergency Planning Committee, the State Emergency Response Commission, and local fire department. A Toxic Chemical Release Form for specified toxic chemicals shall also be submitted annually. In the event of a hazardous substance release, appropriate notifications of Federal, state, and local authorities shall be made.

The *Hazardous Materials Transportation Act* (49 USC 180 et seq.; 49 CFR 171–178) establishes requirements for the transportation of hazardous materials by road, air, and rail. Packaging, labeling, marking, and shipping requirements are specified for quantities and forms of substances that are designated as hazardous. Hazardous materials, including radioactive materials and wastes, must be shipped from the fusion facility site in accordance with the applicable U.S. Department of Transportation packaging, labeling, marking, and placarding requirements.

Floodplain/Wetlands Executive Orders (EO 11988 & EO 11990; 10 CFR 1022) protect wetlands and minimize adverse effects of development in floodplains. The proposed site for the fusion facility must be evaluated to determine if it contains wetlands or floodplains. If floodplains/wetlands do occur at the proposed site, a notice must be published in the *Federal Register* and Federal, state, and local agencies notified of a proposed floodplain/wetlands assessment. This assessment shall identify alternate measures to minimize harmful impacts to floodplains or wetlands due to activities. A statement of finding must be published for public record.

The *Farmland Protection Policy Act* (7 USC 4201 et seq.; 7 CFR 658) seeks to minimize the extent to which Federal programs contribute to the unnecessary and irreversible conversion of farmland to nonagricultural uses and assure that Federal programs are administered in a manner that will be compatible with state and local government and private programs and policies to protect farmland. The Soil Conservation Service must be requested to determine whether the site or any part of the site is farmland by using site assessment criteria and the relative value of the site. If the evaluation results in a high score for the site, alternatives shall be considered that could lessen adverse effects on the site as farmland.

The *Archaeological Resources Protection Act of 1979* (16 USC 47000 et seq.; 43 CFR 7; 36 CFR 296) requires that a determination be made of the measures that shall be taken if archaeological resources present on Federal land may be damaged during project-related activities. Archaeological resources are defined as any material remains of past human life or activities of archaeological interest.

The *National Historic Preservation Act of 1966, as amended* (16 USC 470 et seq.; 36 CFR 60 and 800; Historic Sites, Buildings and Antiquities Act; 16 USC 461 et seq.), endeavors to preserve, maintain, and enrich irreplaceable cultural, educational, inspirational, and economic history. A determination must be made if the project area contains any site, structure, or object identified in, or eligible to be included, in the National Register of Historic Places and determine if the proposed project will affect the site, structure, or object adversely. If the effect would be adverse, the Advisory Council on Historic Preservation must be consulted to determine what actions should be taken.

The *American Antiquities Act* (16 USC 432 et seq.; 25 CFR 261; 36 CFR 296; and 43 CFR 3-7) protects historic and prehistoric ruins, monuments, and objects of antiquity on lands owned and/or controlled by the Federal government. Additionally, the act stipulates that the Federal government is to provide leadership in the preservation, restoration, and maintenance of the historical cultural environment of the nation.

The *American Indian Religious Freedom Act* (AIRFA) (42 USC 1996; 36 CFR 296 and 43 CFR 7) protects and preserves for Native Americans their inherent right of freedom to believe, express, and exercise their traditional religious rights guaranteed by the First Amendment of the U.S. Constitution. This includes access to sites; use and possession of sacred objects; and freedom to worship through ceremonial and traditional rites. A determination must be made whether the project site is in an area related to Native American religious rites or is a sacred site.

The *Migratory Bird Treaty Act* (16 USC 703 et seq.; 50 CFR 10) prohibits the killing, capturing, transporting, etc., of migratory birds, their nests, and eggs, and any part of such bird, nest, and egg.

The *Fish and Wildlife Coordination Act* (16 USC 661 et seq.) mandates that wildlife conservation receive equal consideration and coordination with other features of water resource programs through planning, development, maintenance, and coordination of wildlife conservation and rehabilitation.

The *Bald and Golden Eagles Protection Act* (16 USC 668–668d; 50 CFR Parts 13 and 22) prohibits the killing, capturing, and transporting of any bald and golden eagles, living or dead, their nests, and eggs, and any part of such a bird, nest, and egg.

The *National Wildlife Refuge Systems Administration Act of 1966* (16 USC 668OD–668EE; 50 CFR 25, 27, 28 and 29) establishes the National Wildlife Refuge System by consolidating fish and wildlife conservation under the Fish and Wildlife Service (FWS). This will include fish and wildlife in danger of extinction; wildlife ranges, game ranges, wildlife management areas; or waterfowl production areas.

The *Endangered Species Act of 1973* (16 USC 1531 et seq.; 50 CFR 17, 222, 226, 227, 402, 424, 450, 451, 452, and 453) prohibits Federal agencies from taking any action that would jeopardize the continued existence of any threatened or endangered species or result in the destruction or adverse modification of critical habitat unless an exemption has been obtained.

Objects Affecting Navigable Airspace (49 USC 1501; 14 CFR 77) requires that all persons give adequate public notice of the construction or alteration, or the proposed construction or alteration, of any structure that would be a hazard to air navigation, and regulates structures that could obstruct air navigation. The Federal Aviation Administration (FAA) has the following procedures that must be followed: Notice of Proposed Construction, Construction Permit, and a Notice of Progress of Construction or Alteration.

The *Rivers and Harbors Appropriations Act of 1899* (33 USC 401–413, 06; 33 USC 33 CFR 209, 320, 325, 326, 329, and 330), the *Bridge Act of 1949*, and *Construction and Operation of Bridges Act of 1946* (33 USC 525; 33 CFR 114–115) prevent alteration or modification of the course, location, current condition, or capacity of any navigable water in the United States without a permit. “U.S. navigable waters” have been defined in a loose manner by regulators. Dry lake beds, arroyos, and ditches have all been considered navigable waters. Bridge construction is also regulated under this act. The U.S. Army Corps of Engineers has established an integrated permitting process that allows a single permit application to be used for compliance with regulated activities. A permit must be obtained from the U.S. Army Corps of Engineers for any activity regulated under this act.

The *Noise Control Act of 1972, as amended* [42 USC 4901–4918 (EO 12088)] directs all Federal agencies to carry out programs within their jurisdictions in a manner that furthers a national policy of promoting an environment free from noise that jeopardizes health and welfare. If the noise levels and/or emissions from a fusion facility would jeopardize the health or welfare of the public in the area surrounding the site, a plan to minimize noise emissions must be prepared. The plan may require a change in design parameters.

3.1.2.2 DOE Orders and Guidance

DOE Orders are internal department documents that set policy and specify procedures for implementing that policy. They may apply to specific sites and facilities or to all areas of DOE operations. In some cases, DOE Orders may mandate compliance with existing Federal, state, and local regulations. Because specific DOE Orders may change or new Orders are issued, a review of the latest DOE Orders should be conducted.

The *General Environmental Protection Program* (DOE Order 5400.1) establishes environmental protection requirements, authorities, and responsibilities for DOE operations for ensuring compliance with applicable federal, state, and local environmental protection laws and regulations, executive orders, and internal DOE policies. This Order implements DOE policy, which mandates that all operations be conducted in an environmentally safe and sound manner, including protection of the public and the environment. DOE Order 5400.1 requires that DOE operations be conducted in compliance with the letter and spirit of applicable environmental statutes, regulations, and standards. This includes sound environmental management of current activities, the correction of existing problems, the minimization of risks to the environment or public health, and anticipating and addressing potential environmental problems before they threaten the quality of the environment or public welfare. DOE Order 5400.1 describes the environmental monitoring required to demonstrate compliance with environmental laws and regulations.

The *Waste Minimization Crosscut Plan* (SEN-37-92, March 13, 1992) was implemented by the DOE Secretary of Energy in accordance with the Pollution Prevention Act of 1990. This plan identifies key objectives and strategies for the Department's achievement of excellence in waste minimization.

The *Environmental, Safety, and Health Appraisal Program* (DOE Order 5482.1B) establishes the program to evaluate the protection of the environment and the health, and safety of the public. This Order also establishes criteria for a safe and healthful work place for employees of the DOE and the DOE contractors.

The *Environmental Protection, Safety, and Health Protection Information Reporting Requirements* (DOE Order 5484.1) establish the requirements and procedures for the reporting of information having environmental protection, safety, or health protection significance for DOE Operations. The Order identifies accidents and incidents and provides instruction in the areas of format and content of accident/incident investigation reports.

3.2 Federal and State Consultation, Permits, and Approvals

3.2.1 Federal Permits and Approvals

National Emission Standards for Hazardous Air Pollutants (NESHAPS) (40 CFR Part 61) regulate substances that potentially will be emitted by fusion facilities, such as beryllium and radionuclides. If the fusion facility will result in a predicted effective dose (ED) to a maximally exposed member of the public equal to or greater than 1% of the standard for radionuclides [i.e., 0.001 mSv/yr (0.1 mrem/yr)], a NESHAPS permit to construct (PTC) application must be submitted prior to the initiation of construction to obtain the approval of the Regional Administrator of the EPA. The EPA will provide notification of approval or intention to deny approval of construction within 60 days after receipt of a complete application. After construction of the fusion facility, the EPA must be notified of the anticipated date of initial start-up of the source at least 30 days prior to that date and the actual date of initial start-up of the source within 15 days after that date.

A Prevention of Significant Deterioration (PSD) of Air Quality review is required if the emission rate of any criteria air pollutant (carbon monoxide, hydrocarbons, nitrogen oxides, total suspended particulates, photochemical oxidants, sulfur oxides, and lead) from routine operations of a stationary source is greater than 250 tons/yr. If necessary, a new PSD permit application or a modification to an existing permit must be submitted to the appropriate state agency before construction of a fusion facility.

According to the *National Pollutant Discharge Elimination System* (NPDES), states will issue NPDES permits to discharge wastes into waters of the United States using minimum technology-based guidelines set by the EPA. An NPDES permit for all discharges to waters of the United States must be obtained. Fusion facilities shall comply with applicable U.S. Army Corps of Engineers dredge and fill regulations. Impacts to wetlands greater than 10 acres will require an additional permit from the U.S. Army Corps of Engineers.

Safe Drinking Water Act. If future fusion facilities affect existing or require new drinking water systems, a permit to conduct monitoring must be obtained as required.

The *Resource Conservation and Recovery Act* (RCRA) was established to regulate solid and hazardous wastes.

a. *Solid Waste*. Subtitle D requires each state to prepare a solid waste management plan to prohibit new open dumps and require upgrading or closing of all existing dumps. Federal guidelines for solid waste collection, transport, separation, recovery, and disposal practices have been promulgated.

b. *Hazardous Waste*. Under the land disposal restrictions (40 CFR 268) the generator of hazardous waste must assure a system of manifesting, reporting, standards, and permits to achieve control of hazardous waste from generation to final disposition. These requirements apply to generators and transporters of hazardous waste and owners and operators of hazardous waste treatment, storage, and disposal (TSD) facilities. Reuse, reclamation, and recycling of hazardous waste is also subject to the regulatory program.

Under the land disposal restrictions (40 CFR 268) waste generators must assure that the waste is treated prior to ultimate disposal to the land. Specific requirements have been established by the EPA, usually requiring treatment to a particular contaminant concentration, but occasionally requiring a specific treatment method.

There are also extensive regulations for the various processes or techniques by which hazardous wastes may be managed. These detailed standards include requirements for the proper management of containers, tank systems, surface impoundments, waste piles, land treatment, landfills, incinerators, and miscellaneous units (those not covered by the specifically identified techniques). State regulations may be more extensive than the Federal system and must be reviewed for applicability.

The operation of the fusion facilities may require preparation of a new RCRA Part A or Part B permit application, a change in existing interim status, or a modification to an existing permit, depending on site location.

1. *Underground storage tanks*. All new underground storage tanks must be permitted prior to installation. Any person proposing to install a tank must file a notification prior to installation and prior to operation. The underground tank rules in RCRA Subtitle I

cover any substance defined as hazardous under CERCLA (Superfund) and includes underground tanks containing petroleum products.

2. *Federal procurement guidelines*. The EPA has established and published Federal guidelines for several materials: building installation products containing recovered materials; cement and concrete containing fly ash; paper and paper products containing recovered material; lubricating oils containing re-refined oil; and retreaded tires. Particular attention should be paid to the cement and concrete guideline as it may apply to the construction phase of the program. Major procurement actions for services and materials for the fusion facilities should include specifications for the use of recycled and recovered materials.

The *Fish and Wildlife Coordination Act and National Wildlife Refuge Systems Administration Act Permit Requirements* include consultation with the FWS concerning project activities that (1) may conflict with the protection and conservation purposes set by the National Wildlife Refuge System (a permit may also be required); (2) may impact birds, especially migratory birds on the site; and (3) may modify, control, or impound, due to construction activities, a body of water greater than or equal to 10 acres. The State Administrator of wildlife resources must also be consulted for (2) and (3).

In the *Bald and Golden Eagles Protection Act*, a *Federal Fish and Wildlife License Permit* is required if upon investigation of the proposed site, a golden eagle's nest is found and must be disturbed. A Federal Fish and Wildlife License Permit Application shall be submitted to the Assistant Regional Director for Law Enforcement of the district in which the site is located. If a permit is granted, the Director of Law Enforcement of the district in which the site is located shall be notified in writing at least 10 days, but no more than 30 days, before any golden eagle nest is taken. Any mitigation measures determined by the Director shall be complied with and a report of activities conducted under the permit shall be submitted to the Director within 10 days following the permit's expiration.

The *Archaeological Resources Protection and National Historic Preservation Acts* require consultation with the Advisory Council on Historic Preservation if a proposed project will impact a site with historic/prehistoric ruins, monument, or object of antiquity, or a site on the National Register of Historic Places.

The *AIRFA* provides the following guidance. If a project site falls into the category of a Native American religious or sacred site, consultation is required with Native American leaders to determine if the proposed action would infringe on constitutional rights or impact Native American traditional religions.

3.2.2 State and Local Permits and Approvals

Specific state and local permitting and approval requirements may vary by location; however, general guidance is provided in the following sections.

3.2.2.1 Air

Most states have been granted the authority by EPA to implement some, if not all, of the requirements of the Clean Air Act.

a. *Permit to Construct (PTC)*. Applications for a PTC and an Operating Permit for the proposed facility should be submitted to the state 15 to 18 months prior to commencement of construction. Generally (although this may vary from state to state), the state will notify the applicant within 30 days whether the application for PTC or operating permit is complete and within 60 days will issue a proposed approval, proposed conditional approval, or proposed denial, with an opportunity for public comments to follow.

b. *NESHAP Analysis*. A NESHAP analysis is generally submitted to the state along with the PTC application. State review of the PTC application does not occur until the EPA approves the NESHAP document. Data collection (ambient air and engineering data) for the analysis typically takes 1 yr, and preparation of the analysis about 6 months.

3.2.2.2 Archaeological Finds

If archaeological resources are determined to be endangered by a project-related activity, application for a permit from the jurisdictional land manager to remove or excavate an archaeological site must be submitted. Activities are coordinated with the State Historic Preservation Office (SHIPO). The DOE must be qualified to do the permitted removal or excavation. Archaeological resources excavated or removed remain the property of the United States. The remains and the copies of records and data must be archived by a suitable institution.

3.2.2.3 Other State Requirements

Other state requirements will likely include water quality standards and wastewater treatment requirements, solid and hazardous waste requirements, and special provisions for wildlife. These vary by state and will have to be developed when specific fusion facility sites are selected.

3.3 Environmental Compliance Procedures and Scheduling

3.3.1 Environmental Documentation Guidelines

3.3.1.1 NEPA Compliance Plan

Specific environmental mitigation commitments identified in fusion facility NEPA documents are incorporated into the design and operation of the facility through an approved Mitigation Action Plan (MAP). The MAP describes how mitigation of adverse environmental consequences will be implemented and monitored to assure effectiveness. The implementation of the MAP will be the responsibility of the design, construction and operating organizations. The plan

a. details Program Manager quarterly reporting requirements,

b. documents progress in implementation of mitigation measures required by the MAP,

c. determines whether the measures are adequately reducing or eliminating adverse environmental impacts,

d. establishes procedures that prepare NEPA review and approval prior to implementation for unforeseen activities not addressed in the fusion facility EIS, and

e. is updated as required to accommodate changes to the MAP from unforeseen activities.

3.3.1.2 Environmental Compliance Plan

Each fusion facility will develop an Environmental Compliance Plan that describes the method by which a particular fusion facility complies with applicable environmental regulatory requirements. This includes addressing Federal, state, and local environmental statutes. While this guidance document provides a compilation of environmental requirements potentially applicable to fusion facilities, the Environmental Compliance Plan provides guidance on how the program managers can meet those requirements.

The Plan describes the program's understanding of environmental requirements for the preconstruction and construction phases of the fusion facility. The Plan is updated periodically to reflect results of periodic consultation with the appropriate Federal and state agencies and affected Indian tribes.

The Environmental Compliance Plan consists of five separate sections: Permits Requirements, Monitoring Requirements (Chapter IV of DOE Order 5400.1), Pollution Prevention Requirements, Training Requirements, and Site Unique Requirements.

3.3.1.3 OSHA Compliance Plan

The Occupational Safety and Health Administration (OSHA) has instituted a series of requirements that establish a level of safety and safety assurance. These requirements, those promulgated by state and local regulators, and internal DOE requirements published in DOE Orders must be followed. The OSHA program encompasses the protection of workers, the public, and property from the hazards associated with the construction, operation and maintenance, and decommissioning of a facility.

The program incorporates four separate disciplines: industrial safety, industrial hygiene, fire protection, and radiation protection. Additionally, the program requires that emergency procedures are in place to mitigate the impact of accidents that threaten the health and safety of the facility occupants, personnel in the immediate areas surrounding the facility, or the public.

3.3.2 Environmental Compliance Scheduling

Environmental review planning is an integral part of “phased compliance,” that is, a comprehensive, integrated environmental compliance strategy (DOE Order 4700.1); a sample schedule is shown in Fig. 3.1. The strategy is characterized by

a. conducting the environmental evaluations and consultative environmental reviews during the conceptual or preliminary design phase,

b. completing the NEPA documentation process prior to commencement of full detailed design, and

c. submitting permit applications and coordinating permit reviews with the detailed design phase.

Delayed compliance can result when inadequate attention is given to environmental requirements early in the design phase. In many instances, the permitting authority will not begin review of permit applications until at least a draft NEPA document has been circulated. Delay of the NEPA document, therefore, can delay start of construction and make the NEPA document and other environmental review processes critical path items.

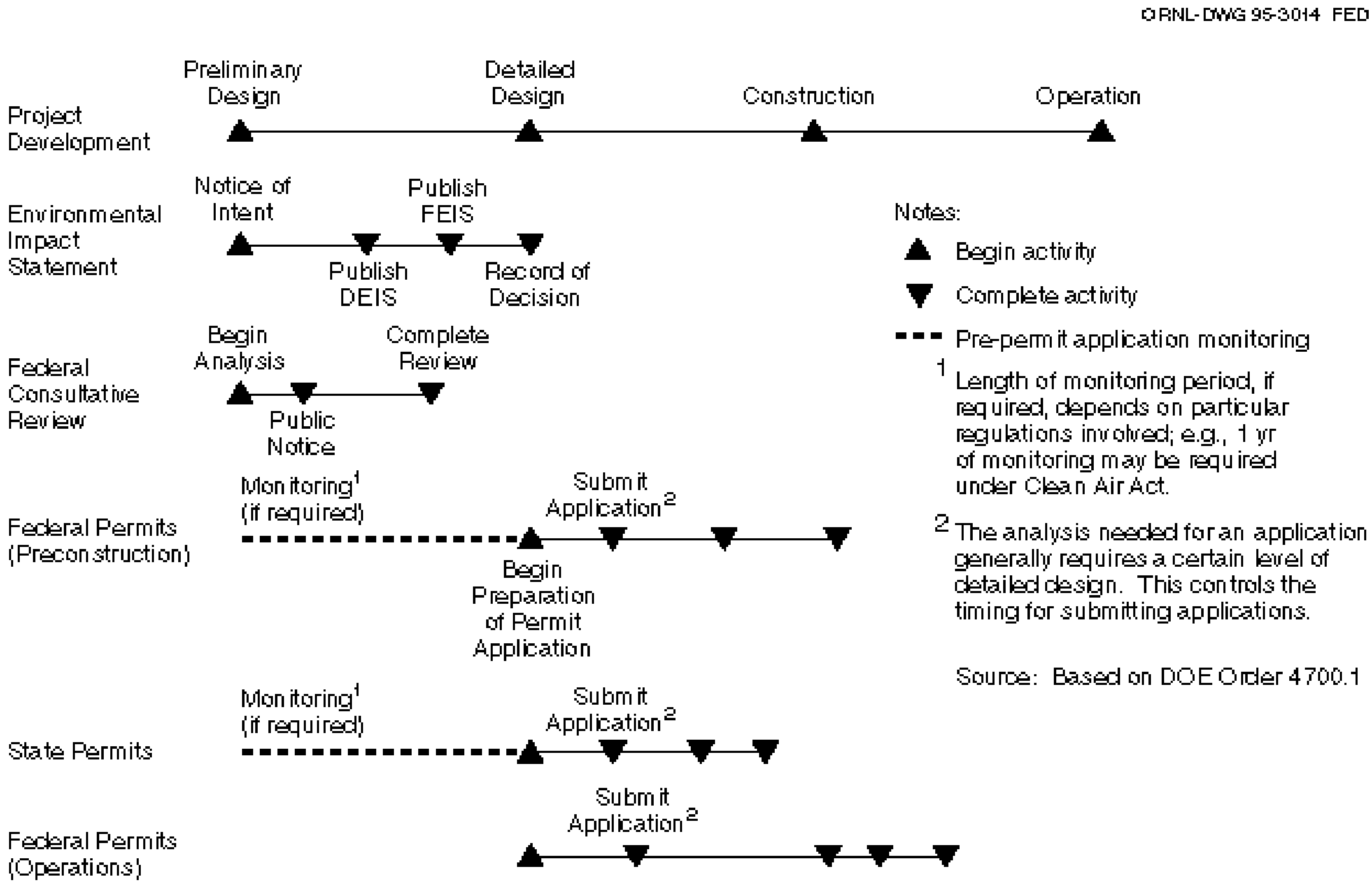

FIGURE 3.1. Phased schedule for environmental compliance activities.

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4. PROGRAM MANAGEMENT FOR SAFETY

Appropriate management practices and controls should be integrated into the fusion project life cycle to ensure safety. This integration function is key to ensuring that safety is “built-in” to the fusion facility life cycle process rather than an “add-on,” which is typically expensive and less effective. Related to this goal is the concept of making safety achievement a function of line management with criteria and hardware related to safety incorporated at the lowest practical level of the work breakdown structure. This section provides guidance on management-related areas needed to integrate safety into the fusion facility life cycle. Program management includes controlling the configuration of the facility and the documentation of that configuration so that operation within the authorized safety envelope can be demonstrated. In addition, this section presents tools (processes, systems, and controls) that can be used by program management to implement safety effectively. As used in this section, the facility life cycle includes design and construction, operations, and site restoration. Different organizations may be responsible for the various life cycle phases of the facility. Each organization must be aware of the need of the other organization and incorporate these needs in a safe and controlled manner.

4.1 Design and Construction Management

From project inception appropriate controls should be integrated into project execution to ensure that intended safety features are incorporated into the fusion facility. Safety should be integrated into project activities, including initial mission and performance criteria definition, design, and construction. A specific responsibility of project management is to ensure that this integration of safety with other project activities or disciplines takes place and to hold project line management accountable for each aspect of their assigned systems, including safety performance. The basic facility mission requirements, including protection of the facility workers and the public as well as minimization of the impact to the environment, should be established before design commences. For example, the no-public-evacuation requirement in DOE-STD-6002-96 should be a strong driver in fusion device size (power) and materials selection to ensure that the potentially releasable in-vessel tritium and hazardous material inventories are consistent with the no-evacuation requirement for the chosen site.

Safety assessment (Chapter 5) and design (Chapter 6) are complementary activities that should be performed iteratively throughout the design process to ensure that safety requirements are adequately incorporated into the design. Achievement of safety criteria and goals at an individual system level should be a documented part of conceptual, preliminary, and final design and should be evaluated as part of the formal design review process. Additionally, a systems integration approach should be used to evaluate interactions between individual systems including common-mode failures to ensure that safety goals are met globally.

The project manager’s responsibilities include developing systems, processes, and organizational structures that will facilitate safety during design and construction. The project manager should consider an organizational structure that will allow the safety and design professionals to work as a team and that will make line management responsible for both safety and performance requirements for each system. Furthermore, there will be cases where safety requirements will conflict with other design requirements for the facility. The project management system should have a process that will allow potential cost/safety/performance trade-offs to be made in a structured rational manner.

4.2 Operations Management

Operations management should ensure that the operations organization is knowledgeable of the safety envelope and authorization basis and the need to maintain the facility configuration and operation within these constraints. Proposed changes to facility configuration and operation should be reviewed against the safety envelope and authorization basis and approved prior to implementation. The operations manager may call upon safety professionals for analytical support, but the responsibility and authority for safe operations remains with the line management of the facility. The operations manager should establish a policy under which clear lines of responsibility for normal operations and off-normal conditions are established. Chapter 5 of this volume provides the details of the authorization basis and technical safety requirements.

4.3 Site Restoration Management

Site restoration involves the dismantling of the fusion facility and the packaging of radioactive hazardous materials prior to shipment to a repository or recycling center. Management of the fusion facility during the site restoration phase requires maintaining configuration control while the condition of the facility is rapidly evolving. The safety analyses may have to be updated as safety and confinement systems are removed from service. Documentation of the condition of components and their hazardous inventories as they are packaged is necessary. Removal of hazardous materials from the site may allow some relaxation of controls as the on-site inventory is reduced.

4.4 Tools for Program Management Safety

The following sections describe tools that can be used during the design, operations, and site restoration of a fusion facility. These tools include configuration management, quality assurance (QA), verification and validation, conduct of operations, emergency preparedness, maintenance, training and qualification, tritium control, accountability and physical protection. These tools, if used effectively, will help assure the safety of the fusion facility.

4.4.1 Configuration Management

Configuration management is a tool that is designed to determine and control baselines and ensure that each system/component properly interfaces physically and functionally. The role of safety in configuration management is to ensure that the original product and each approved change to the product do not jeopardize the safety of the product. Configuration management actions are called for in Department of Energy (DOE) Order 4700.1, Project Management Plan.

4.4.1.1 Configuration Management Process Application

Configuration management should be consistent with the quality, size, scope, and complexity of the project involved (graded approach). The configuration management process should be tailored to the specific project and to particular products. The selection of equipment and other items for formal configuration management is determined by the need to control its inherent characteristics or to control its interface with other systems. Configuration control applies to hardware, software, and documentation associated with the facility.

A permanent copy of the controlled identification documents should be maintained throughout the life cycle, beginning with the initial baseline documentation and including proposed and approved changes from those baselines.

Configuration control must be exercised on a basis appropriate to the level of importance and to the stage in the life cycle. Affected project activities, such as engineering, logistic support, QA, safety, maintenance, and procurement need to be involved in evaluating proposed changes in the configuration of an item throughout its life cycle. This would normally be accomplished through a Configuration Control Board.

4.4.1.2 Change Control

Changes affecting the configuration of an item are to be limited to those that are necessary or offer significant benefits. Changes are required to correct deficiencies; incorporate approved changes in experimental, operational or logistic support characteristics; or effect substantial life cycle cost savings.

Each change must be evaluated for Unreviewed Safety Questions (USQ). The process of reviewing for USQs is described in Chapter 5.

Data required for effective evaluation of changes must be made available to those individuals responsible for change decisions. Every proposed configuration change should be evaluated on the basis of change criteria, including not making the proposed change. The evaluation should take into consideration each aspect of the change on the products or systems with which it interfaces. Such aspects may include safety, design, performance, cost, schedule, operational effectiveness, logistics support, transportability, and training.

As changes are authorized, appropriate updates to safety envelopes, authorization basis and operating procedures must occur. This approach assures that operations personnel know the plant configuration and its operating limits.

4.4.1.3 Record Keeping and Reporting

Configuration records and reports include identification of the following:

a. technical documentation (drawings, calculations, specifications, etc.) comprising the approved configuration identification;

b. proposed changes to configuration, the status of such changes, and the individual responsible for change decisions;

c. approved changes to configuration, including the specific number or kind of items to which the changes apply, and the activity responsible for implementation.

Only the minimum information necessary to manage configuration effectively and economically will be recorded and reported.

4.4.2 Quality Assurance

A quality assurance (QA) process shall be considered in the design, selection of materials, specifications, fabrication, construction, installation, operating procedures, maintenance, and testing of fusion facilities. The requirements of 10 CFR 830.120 shall be used for development of this program.

A Quality Assurance Plan (QAP) is developed by applying the QA criteria specified in Sections 4.4.2.1–4.4.2.3 using a graded approach. The QAP discusses how these criteria are satisfied. Appropriate standards are used, wherever applicable, to develop and implement the QAP.

4.4.2.1 Management

A written QAP must be developed, implemented, and maintained. The QAP will describe the organizational structure, functional responsibilities, levels of authority, and interfaces for those managing, performing, and assessing the work, as well as management processes, including planning, scheduling, and resource considerations (cf. Sections 4.1–4.4).

Personnel must be trained and qualified to ensure that they are capable of performing their assigned work. Continuing training is provided to ensure that job proficiency is maintained (cf. Section 4.4.7).

Processes to detect and prevent quality problems must be established and implemented. Items, services, and processes that do not meet established requirements are identified, controlled, and corrected according to the importance of the problem and the work affected. Correction includes identifying the causes of problems and working to prevent recurrence. Item characteristics, process implementation, and other quality-related information are reviewed, and the data are analyzed to identify items, services, and processes needing improvement.

Documents must be prepared, reviewed, approved, issued, used, and revised to prescribe processes, specify requirements, or establish design. Records are specified, prepared, reviewed, approved, and maintained (cf. Section 4.4.1).

4.4.2.2 Performance

Work will be performed to established technical standards and administrative controls using approved instructions, procedures, or other appropriate means. Items are identified and controlled to ensure their proper use and maintained to prevent their damage, loss, or deterioration. Equipment used for process monitoring or data collection is calibrated and maintained (cf. Section 4.4.1).

Items and processes must be designed using sound engineering/scientific principles and appropriate standards. Design work, including changes, incorporates applicable requirements and design bases. Design interfaces are identified and controlled. The adequacy of design products is verified or validated by individuals or groups other than those who performed the work. Verification and validation work must be completed before approval and implementation of the design (cf. Chapter 6).

Procured items and services must meet established requirements and perform as specified. Prospective suppliers are evaluated and selected on the basis of specified criteria. Processes to ensure that approved suppliers continue to provide acceptable items and services must be established and implemented (cf. Section 4.4.1).

Inspection and testing of specified items, services, and processes must be conducted using established acceptance and performance criteria. Equipment used for inspections and tests must be calibrated and maintained (cf. Section 4.4.1).

4.4.2.3 Assessment

Managers must assess their management processes and identify and correct problems that hinder the organization from achieving its objectives.

Independent assessments are planned and conducted to measure item and service quality, to measure the adequacy of work performance, and to promote improvement. The group performing independent assessments must have sufficient authority and freedom from the line to carry out its responsibilities. Persons conducting independent assessments must be technically qualified and knowledgeable in the areas assessed.

4.4.3 Verification and Validation

Computer codes used to perform design and safety analysis for fusion facilities may be required to be verified and validated (V&V). Verification and validation will be performed using a graded approach that is based on the importance and complexity of the system/component. V&V actions are not specifically defined in DOE Orders.

The QA plan documents the functional requirements for each piece of software, the acceptance criteria to be used in the V&V process, the approach to be taken to verification and validation, and the software configuration control strategy that will be used. The results of the

V&V process should be documented. Documentation should be prepared to manage the configuration control of the software itself.

Many of the standards and requirements used to verify and validate computer codes were developed for commercial nuclear power plants. Guidance information is embodied in ASME NQA-1 and ASME NQA-2 standards, as well as several American National Standards Institute (ANSI)/Institute of Electrical and Electronic Engineers (IEEE) Standards (ANSI/IEEE STD 730, 828, 829, 830, 983, and 1012).

Verification is defined as the process of determining whether the software is coded correctly and conforms to the specified software requirements. Full verification would require a line-by-line check of the entire computer code to ensure correctness. However, other less stringent methods are considered applicable, such as developing a series of calculational cases or input decks that test much of the logic in the code to ensure that the code performs as stated in the users' manual. As a general rule, design and safety analysis should be verified because it is good engineering practice.

Validation is defined as the process of evaluating software to ensure compliance with software requirements and physical applicability to the process being modeled on the hardware being used. Validation is generally more involved than verification. Validation of a code consists of comparing its output with known analytical solutions for problems similar, yet perhaps simpler, than the problem at hand. Validation also includes benchmarking the code against relevant experimental data, thus ensuring that the analysis reasonably captures the correct physics and chemistry. Validation can also include comparison with an existing, already validated, computer code.

The number and type of benchmarking problems needed to validate a computer code are functions of the complexity of the phenomena being modeled, the codes range of applicability, and the data that are or could be available. For a complicated computer code, verification could require that individual models and submodels in the code be V&V using separate-effects data and that integral validation of the code also be performed. These issues are functions of the specific technical areas and need to be considered in the respective V&V processes.

Due to the current experimental nature of fusion devices, it may not be possible to completely verify and validate a code. In such cases, other options should be explored to assure safety of the facility. These options may include but are not limited to the use of test coupons to be evaluated after specific periods of operation and qualification of materials/equipment using deuterium-deuterium operations before using tritium as a fuel.

4.4.4 Conduct of Operations

Experience has shown that the better operating facilities have well-defined, effectively administered policies and programs to govern the activities of the operating organization, including the areas described by these guidelines. The guidance is based upon well-developed industrial operations practices. They are written to be flexible, so that they encompass the range of facilities and operations.

Each fusion facility should develop a conduct of operations program in accordance with DOE Order 5480.19, Conduct of Operations, using a graded approach. Specifics for each of the sections can be found in the references for this chapter.

Fusion facilities should have a policy that assures operations are managed, organized, and conducted in a manner to assure an acceptable level of safety and operators have procedures in place to control the conduct of their operations.

The following areas should be addressed by the conduct of operations program: Operations Organization and Administration; Shift Routines and Operating Practices; Control Area Activities; Communications; Control of On-Shift Training; Investigation of Abnormal Events; Notifications; Control of Equipment and System Status; Lockouts and Tagouts; Independent Verification; Logkeeping; Operations Turnover; Operations Aspects of Facility Chemistry and Unique Processes; Required Reading; Timely Orders to Operators; Operations Procedures; Operator Aid Postings; Equipment and Pipe Labeling.

4.4.5 Emergency Preparedness

Fusion facilities should develop an emergency management program, using a graded approach, consistent with the determined level of risk at the facility. The requirements for emergency preparedness at DOE facilities are specified in DOE Order 151.1, Comprehensive Emergency Management. Appendix C provides a listing of guidance documents that may be useful in developing the site-specific emergency management program.

The Emergency Management System (EMS) should include a graded approach to emergency management concepts such as planning, preparedness, and response. “Planning” includes the development and preparation of emergency plans and procedures and the identification of necessary personnel and resources to provide an effective response. “Preparedness” includes the training of personnel, acquisition and maintenance of resources, and exercising of the plans, procedures, personnel, and resources essential for emergency response. “Response” represents the implementation of planning and preparedness during an emergency and involves the effective decisions, actions, and application of resources that must be accomplished to mitigate consequences and recover from an emergency.

4.4.5.1 Operational Emergency Event Classes

Operational emergencies involving hazardous materials (radiological and nonradiological) should be classified as one of the operational emergency classes (e.g., Alert, Site Area Emergency, or General Emergency). Emergency Action Levels (EALs), the specific criteria used to recognize and categorize events, should be developed for the spectrum of potential operational emergencies consistent with the hazards assessment. The need for some emergency levels will be eliminated for radiological emergencies if the site boundary dose limit specified as a fusion radiological release requirement in DOE-STD-6002-96 is met.

4.4.5.2 Emergency Plans and Procedures

An emergency plan and procedures should be developed for the facility. The plan is a documented “concept of operation” that describes the essential elements that have been considered and the provisions that have been made to mitigate emergency situations. The plan should incorporate information about the emergency response roles of supporting organizations and agencies and should be consistent with a graded approach to managing an incident. Programs should contain emergency implementing procedures [e.g., EALs, event categorization, notification, and Emergency Operations Center (EOC) operation] as well as other procedures currently in use (e.g., equipment operation, radiological monitoring, and maintenance) that would be utilized in, or associated with, emergency response activities.

Procedures must maintain consistency with the general graded approach and nomenclature of emergency planning and preparedness elements within Federal and State agencies, private industry, tribal, and local authorities.

4.4.5.3 Hazards Assessment

Hazards assessments provide the technical basis for emergency management programs. The extent of emergency planning and preparedness required for a particular facility directly corresponds to the type and scope of hazards present and the potential consequences of off-normal events. A hazards assessment includes identification of any hazards and targets unique to a facility, analyses of potential events, and evaluation of potential event consequences. The Final Safety Analysis Report (see Chapter 5) provides for potential off-normal events at the facility.

Methodology, models, and evaluation techniques used in the hazards assessment should be documented. The assessment should include a determination of the size of the Emergency Planning Zones where applicable, that is, the area surrounding the facility for which special planning and preparedness efforts are required to ensure that prompt and effective protective actions can be taken to minimize the risk to workers, the general public, and the environment.

Other hazards assessments are documented in Material Safety Data Sheets; Safety Assessments; Spill Prevention, Control, and Countermeasure Plans; Pre-Fire Plans; Environmental Assessments and Impact Statements (EAs and EISs); Emergency Response Planning Guidelines; Severe Accident Analyses; and the Emergency and Hazardous Chemical Inventory Forms and Toxic Chemical Release Forms, prepared pursuant to the requirements of the Emergency Planning and Community Right-to-Know Act (SARA Title III).

4.4.5.4 Emergency Response Organization

An emergency response organization should have overall responsibility for the initial and ongoing response to, and mitigation of, an emergency, and must perform, but not be limited to, the following functions:

a. Provide for prompt initial notification of emergency response personnel and response organizations, including appropriate off-site elements and for continuing effective communication among the response organizations throughout an emergency.

b. Event categorization, determination of the emergency class, notification, provision of protective action recommendations, management and decision making, control of on-site emergency activities, consequence assessment, medical support, public information, activation and coordination of on-site response resources, security, communications, administrative support, recovery operations, and coordination and liaison with off-site support and response organizations.

4.4.5.5 Emergency Facilities Equipment and Personnel Preparedness

An EOC should be established. The staffing, operation, and response activities pertaining to the EOC should be predetermined and documented. Primary and backup means of communications should be available in the EOC.

Training must be provided to affected workers regarding operational emergencies and be available to off-site emergency response organizations. Training should be provided annually to workers who may have to take protective actions (e.g., assembly, evacuation) in the event of an emergency. Training should be in place for the instruction and qualification of personnel comprising the facility emergency response organization.

A coordinated program of drills and exercises should be an integral part of the emergency management program. Drills should be used to develop and maintain personnel skills, expertise, and response capability. Drills should be of sufficient scope and frequency to ensure adequate response capability. A full participation exercise should be conducted annually in accordance with established plans and implementing procedures. Off-site response organizations should be invited to participate in site-wide exercises at least every 3 years. A critique process should be conducted for each exercise to provide accomplishments and shortcomings discovered during the exercise.

4.4.6 Maintenance

Safe operation of a fusion facility is directly dependent on the scope, depth, and quality of the facilities maintenance program. Formal maintenance programs lead to increased effectiveness and safety benefits.

Maintenance at fusion facilities is the aggregate of those planned and systematic actions required to prevent the degradation or failure of, and to promptly restore the intended function of structures, systems, and components (SSCs). This applies to each part of the plant that could significantly impact safe operation. The basis for this is the fundamental principle of defense in-depth. Primary emphasis should be on the success of the maintenance program to prevent the degradation or failure of, and to promptly restore the intended function of, those SSCs.

Fusion facilities present unique situations for maintenance programs. As an example, a program to control magnetic tools and materials around the tokamak is necessary to prevent unexpected missiles during machine operations (due to magnetic fields). In addition, remote maintenance will be used on some components. These actions add a complexity to the program that must be controlled to assure safety.

Requirements for maintenance for DOE facilities are specified in DOE Order 430.1, Life Cycle Asset Management. The reference section for Chapter 4 provides a listing of guidance documents that may be helpful in developing the site specific maintenance program.

4.4.6.1 Maintenance Policy, Goals and Objectives, and Procedures

Effective implementation and control of maintenance should be achieved by establishing written standards for the scope, objectives, and conduct of maintenance; by defining responsibilities; and by periodically observing and assessing performance commensurate with importance to safety.

The policies, goals, and objectives should address planning to establish a proactive maintenance program as opposed to reactive maintenance and to ensure that the maintenance activities for SSCs are consistent with their importance and function.

Goals for maintenance should be established in those areas that have the potential for significant impact on plant safety. The goals should be directed toward improving or sustaining equipment reliability and performance by effective maintenance in areas key to plant safety and risk.

Procedures should be established and utilized as necessary for the conduct of maintenance activities commensurate with the activities importance to safety. The maintenance procedures should provide systematic guidance to the craftsman; should be technically correct, complete, and up-to date; and should be presented utilizing sound human factors principles.

Radiological exposure control during maintenance activities should be considered in developing procedures and work orders and in planning and scheduling maintenance. Health physics personnel should be involved in the planning and execution of appropriate maintenance work to ensure that personnel are not unnecessarily exposed and as-low-as-reasonably-achievable (ALARA) goals are met.

4.4.6.2 Plant Maintenance Organization

The management of maintenance should include a defined maintenance organization with specific lines of authority, responsibility, and accountability. The management of maintenance requires effective written and oral communication between the maintenance department and other supporting groups such as operations, health physics, and engineering. Criteria for selecting personnel with acceptable qualifications to perform their assignments are necessary for effective staffing. The personnel qualification and training requirements should be specified.

4.4.6.3 Types of Maintenance

The maintenance program should include surveillance to obtain in-service performance and operational data; predictive maintenance to analyze data collected from surveillance; preventive maintenance based on manufacturer's recommendations, operating experience, good engineering practice (including aging concerns), and predictive maintenance feedback; and corrective maintenance, as necessary. The maintenance program should ensure that recommendations and information from industry and individual vendors are reviewed and considered for incorporation into appropriate areas of the program.

4.4.6.4 Work Control Process

The work control process should be based on procedures that provide for the identification of deficiencies, planning and preparation for work, setting appropriate conditions for work, work procedures, supervisory authority, documentation of completed work, postmaintenance testing, return-to-service procedures, and review of completed work packages. The work control process begins with the identification of deficiencies or the need for planned or predictive maintenance and the generation of a maintenance request. Planning and scheduling activities should then be performed. The work package should specify the appropriate plant conditions for the work; define the required isolation or tagouts and component deenergization; incorporate appropriate QA, quality control (QC) functions, and ALARA considerations; and require appropriate supervisory authorization prior to starting work. The work package should contain postmaintenance testing requirements and clearances or return-to-service procedures, provide for documentation of completed work, and provide for a review of the completed package. The post-maintenance testing program should establish specific performance acceptance criteria that ensure a high level of confidence in the ability of the component to perform its design function when returned to service.

Process indicators, which provide information regarding the effectiveness of execution of the elements of the maintenance program, should be monitored to provide insight regarding potential problem areas in the conduct of maintenance activities. Examples are postmaintenance test results, periodic surveillance test results, ratio of preventive to corrective maintenance, maintenance work order backlog, time to restore component function after failure discover, and frequency of rework.

4.4.7 Training and Qualifications

The responsibilities and authority for training and certification must be specific, and appropriate plans and procedures must be developed and implemented. Each fusion facility should be responsible for the following:

a. Develop and implement a training and qualification program using a graded approach based upon the hazards of the facility.

b. Prepare, approve, and implement a training plan that sets forth the staffing, training, and qualification requirements.

c. Establish an organization that is responsible for the training and qualification of facility personnel. The duties, responsibilities, qualifications, and authority of training organization personnel should be documented and clearly defined.

d. Establish training and qualification criteria for contracted personnel used in facility organizations.

Training and qualification requirements for DOE nuclear facilities are specified in DOE Order 5480.20, Personnel Selection, Qualification, Training, and Staffing Requirements at DOE Reactor and Non-Reactor Nuclear Facilities. The reference section for Chapter 4 provides a listing of guidance documents that may be useful in developing the site-specific training and qualification programs.

4.4.7.1 Facility Training Plan

The facility training plan is the document that provides the overall description of facility staffing, training, qualification, and certification programs. This plan should be prepared to address the following:

a. initial and continuing training programs, including maintenance of training;

b. training and qualification programs for personnel who require formal qualification and certification; and

c. examination program requirements for qualification and certification.

The facility training plan should be supplemented, as needed, with written procedures that address, as a minimum: examination and operational evaluation development, approval, security, administration, and maintenance; administration of medical requirements; and record keeping requirements.

4.4.7.2 Personnel Selection and Staffing

Each facility should establish a process for the selection and assignment of personnel. The personnel selection process should include an evaluation of their education, experience, previous training, and existing job skills and capabilities. It is the responsibility of management to assure that personnel assigned to a specific job function have the requisite background and/or receive sufficient qualification training for the job.

The following categories of facility staff are identified as requiring training, qualification, or certification to perform job functions:

a. operators and their supervisors,

b. experimenters,

c. technicians—training,

d. maintenance personnel—training,

e. supervisors and managers—training,

f. operations and facility support functions.

Specific requirements for certifying, qualifying, and training personnel are specified in the Order and general guidance documentation.

4.4.7.3 Records

The program and procedures should specify the records used to document the training, qualification, and certification granted. Records should be documented and include the following types of information:

a. records of education and experience, including resumes;

b. results of medical examinations (when required);

c. records of training completed, such as attendance sheets or computer summaries;

d. results of examinations, including written examinations and operational evaluations (when required); and

e. approvals and effective dates, if applicable.

4.4.8 Tritium Control, Accountability, and Physical Protection

The purposes of requirements placed on tritium control, accountability, and physical protection at fusion facilities are to

a. meet legal requirements for environmental releases, waste disposal, and transportation of tritium;

b. prevent the diversion of the material for unauthorized use;

c. gain knowledge of the process efficiency, that is, how much tritium is produced and used in processes under investigation;

d. meet the requirements of the DOE Orders for DOE fusion facilities;

e. assure operational safety of the facilities by providing knowledge of the location and form of tritium;

f. prevent unwanted buildup of tritium within a facility; and

g. protect and control tritium commensurate with its monetary value.

It is difficult to determine the distribution and precise inventory of tritium in a fusion facility. Usually, measurement before injection into the plasma chamber and after removal from the plasma chamber is possible (referred to as inventory by difference). However, tritium production in the machine is also possible. Therefore, the actual amount of tritium remaining in the machine is difficult to determine (this can affect the safety analysis, because there is usually an upper bound on the amount of tritium allowed in the vessel). Sampling tiles or protective surfaces maybe a way of determining the tritium levels; however, those samples may or may not be representative of the tritium levels throughout the vacuum vessel.

It is therefore critical that the designers of the facility determine appropriate means to reliably measure tritium in the fusion facility. This should be done early in the design process to minimize tritium holdup, allow for pumping and purging systems to evacuate the tritium, and specify appropriate instrumentation for measurement. These actions will assure safety of the facility, reduce the risk of a release and improve worker safety. Methods for measurement of tritium are specified in later paragraphs.

Tritium is the predominant nuclear material used at fusion facilities. It is of interest because of safety concerns, its monetary value, and possible unauthorized diversion for other applications. Although public exposures and environmental releases are expected to be small and well below regulatory limits from a fusion facility, tritium is a radioactive material, and the public will need to be assured that safety has not been compromised.

Other nuclear material that must be controlled and accounted for at fusion facilities includes depleted uranium (U-238) and deuterium. Depleted uranium is used for storage of tritium, fission chambers, and various radioactive check- and calibration-sources. Deuterium in quantities greater than 100 g is also controlled at DOE facilities (DOE Order 5633.3B and 5660.1B). The control and accountability of these materials is relatively straightforward and does not present significant problems for operating facilities. The scope and extent of the accountability program for these materials should be based on the monetary value of the material and should include inventories and some measurements.

4.4.8.1 Requirements

The requirements placed on the control and accountability of tritium fall into three categories. Those required by the U.S. law, those required by DOE Orders, and those required by “good practices.” It is also important to note that requirements are not consistent throughout the international community.

a. *Legal requirements*. The legal requirements on tritium measurement are as follows:

   1. Environmental facility emissions, which include air emissions and releases to the ground water or at facilities outfalls, are regulated. These include federal and state

requirements in the following laws: Clean Water Act for water quality standards and effluent limitations, and Federal Clean Air Act, which set ambient air quality standards.

EPA regulates the type and quantity of facility emission. EPA specifies the measurement techniques for air emissions and must approve any requests for deviations. EPA sets the limits for exposure to the public and the notification required when certain quantities of radioactive materials are emitted. State laws usually regulate the facility outfalls. State requirements are not uniform across the country.

2. Department of Transportation (DOT) requirements specify packaging requirements that are dependent on the form and quantity of tritium. DOT must also approve packaging containers when the radioactive material is transported on public highways.

3. Waste storage requirements are in place when mixed hazardous waste may be involved. The EPA administers the Resource Conservation and Recovery Act (RCRA). In many cases this authority has been delegated to the state.

4. Waste disposal requirements are generally state specific.

5. 10 CFR 830 Nuclear Safety Rules and 10 CFR 835 Occupational Radiation Protection apply to the radiological activities in a fusion facility. Because these requirements are part of the U.S. law, they must be followed by each facility that handles tritium or radioactive materials as applicable.

   The details of the state requirements will not be discussed in this section because they vary widely.

b. *DOE Orders*. DOE Orders are requirements placed on DOE facilities that define operations and the methods of conducting business. DOE 5633.3B, “Control and Accountability of Nuclear Materials” specified the minimum requirements and procedures based on the amount of tritium and the form of the tritium in a facility. Important requirements from this order follow:

   1. Tritium is protected, controlled, and accounted for as Category III or IV Special Nuclear Material. The level of protection and control depends upon the form and quantity of the tritium. The reportable transaction quantity is 0.01 g (~100 Ci).

   2. Each facility must have a Materials Control and Accountability (MC&A) Plan. The scope and content requirements for the plan are determined by the manager of the DOE operations office.

   3. DOE Order 5633.3B requires that tritium be inventoried biennially. Where feasible, inventory values should be based on measured values.

4. Inventory requirements are placed on the shipper and receivers of controlled material and methods to control and resolve inventory differences.

5. Access controls, depending on the tritium form, must be established.

Each fusion facility must establish an independent organization to provide oversight of the nuclear materials control and accountability. The physical protection requirements are specified in DOE Order 5632.1C, “Protection and Control of Safeguards and Security Interests,” and DOE 5332.1C-1, “Manual for Protection and Control of Safeguards and Security Interests.” The current DOE requirements are dependent on the quantity and form. These include control of tritium by personnel with a U.S. DOE L clearance and controlled locks, alarms, and access during nonworking hours. A higher level may be required if there are sabotage risks or classified information interests at the facility.

Other Orders specify waste requirements, environmental monitoring, and personnel protection. These are not discussed in this section. The DOE Order requirements are in general not legal requirements. The facility can negotiate with DOE to determine the most cost-effective manner of implementing the requirements and still maintain facility safety and material accountability.

4.4.8.2 Nuclear Material Locations at a Fusion Facility

Typical locations, inputs, and outputs, and measurement points for tritium at a fusion facility are identified below.

a. Inputs to tritium are shipments into the facility and production of tritium at the facility.

b. Locations of tritium within a facility are “in-process,” in-system holdup, in-waste systems, and in-storage.

c. The exit streams of tritium from a facility include shipments of tritium from the facility and waste streams (tritium stack emissions, water releases, solid waste and accidental tritium releases).

d. Measurement locations include input tritium shipments to the facility, exit shipments from the facility, in-process measurements, in-storage measurements, waste stream measurements, personnel exposure measurements, workplace measurements, and stack emission measurements.

4.4.8.3 Tritium Measurements Method

Two primary categories of tritium measurements are made at fusion facilities. One category is for determining the quantity and location of tritium within the facility. These measurements are generally of large quantities of tritium in high concentrations. The second category is for environmental or safety determinations. These are generally lower concentrations and small quantities.

This section will discuss methods for both categories. The measurements techniques for tritium can be grouped in the three general areas: composition measurements, thermal measurements, and tritium concentration measurements.

Composition measurements determine the actual concentration determination for each atomic/molecular species. This method can be used for gases only. Thermal methods (calorimetry) rely on the radioactive heat of decay of tritium. For 1 g of tritium ~0.333 W is generated by decay. The temperature increase or heat generation is measured. Calorimetry can be used for tritium in any form: solid, liquid, or gas. The only radioactive material present must be tritium because other radioactive materials will contribute to the thermal properties of the sample. The final method determined the total tritium concentration by the measurement of the products or the effects of the products of the radioactive decay. The beta particle can cause scintillation effects or ionization effects. These effects can be measured and the concentration of tritium determined. The following methods are used or proposed to be used for measurement of tritium: Pressure/Volume/Temperature/Composition (PVTC), using either a mass spectrometer or laser RAMAN spectrometer for the composition measurement; Beta scintillation counter; Self-assaying tritium storage beds; Scintillation Counting; and Ion Chamber.

Most of the techniques discussed here are batch samples, however some techniques can be used for “on-line/real time” measurements.

a. *Composition Measurements*. PVTC measurement is used for measurement of gaseous samples only. A representative sample of the gas is taken. The gas that is to be measured must be mixed well. The volume, pressure, and temperature must be measured accurately. The temperature is difficult to measure accurately because of temperature gradients caused by the heat of decay of tritium. The composition of the gas in the sample is then measured using a mass spectrometer or a laser RAMAN spectrometer.

   The mass spectrometer will measure all gas species. A high-resolution mass spectrometer is required to distinguish between different molecules with the same mass number. For example HT and D_2 have the same mass number, but must be separated to determine the tritium concentration. All species that can contain tritium must be measured. This includes, water as HTO, methane as $C(H,D,T)_4$, ammonia as $N(H,D,T)_3$, etc. The sum of all the species containing tritium can then be determined. If the approximate gas composition is unknown, the use of the mass spectrometer may be difficult.

   The laser RAMAN spectrometer is a relatively new system that can be used to measure molecular concentrations in a gas mixture. The sample is placed in a cell with optical windows. The laser excites the rotational or vibrational atomic levels in the gas molecules. The light emitted as the excited levels decay back to the ground state is detected using a photodetector system. The measurement is absolute in that the frequency spectrum of each molecule is unique. The intensity is proportional to the amount of gas present. The disadvantages of the RAMAN method are that the amount of inert gases cannot be determined. Common inert gases at a fusion facility are the isotopes of helium. Both of these techniques can be used for real-time measurements. For the mass spectrometer system a sample is bled to a high vacuum system for measurement. The RAMAN system is easily adopted to real-time measurements. The gas stream at atmospheric pressure is passed through an optical cell. The spectrum for a mixture hydrogen isotopes can be determined in ~1 min. The total accuracy of these measurements is ~3 to 5%. The mass spectrometer technique has been the standard method that DOE facilities have used for the determination of the tritium inventory. It is a proven system although it requires an expensive spectrometer ($200K) and accurate determination of the temperature, pressure, and volume. The RAMAN system has not been accepted. Experiments are currently being performed to demonstrate that this will be an acceptable technique.

b. *Thermal Methods*. The primary method to inventory large quantities of tritium in the liquid or solid form is to use a calorimeter. The sample is placed in a thermally isolated container. The power required to maintain the temperature of the container is then a measure of the amount of tritium in the sample. Containers can accept samples that vary from several inches in diameter up to a 55-gal drum. The lower limit of accuracy can be as low as 100 Ci. Calorimeters are expensive ($200K+). They require high-tech electronics. They are the primary methods used to measure tritium in waste such as HTO on molecular sieve. They have not been used to measure process tritium except in a very specific application. For example, solid tritium storage beds that can be disconnected and moved have been placed in a calorimeter designed to accept the bed. New methods are being developed to allow for the determination of the amount of tritium stored on a solid storage bed, When tritium is stored on a uranium bed the temperature increase of the bed can be used to determine the amount of tritium stored on the bed. When tritium is stored on a material such as LaAlNi, usually gas is passed through the secondary containment to maintain the temperature. The temperature rise of the gas as it passes through the bed can then be used to determine the amount of tritium. Both of these methods are being proposed for tritium accountability. Their acceptance is now based on a case-by-case system, and they are not used widely. Development of these methods will be important for the operation of fusion facilities. They offer potential savings in time and effort to account for the tritium in a facility.

c. *Tritium Concentration Measurement*. A Beta scintillation counter has been used for tritium measurement if only the total tritium composition is required. In this instrument, the gas is passed over a crystal that will scintillate with the beta from the tritium decay. A photomultiplier tube is used to detect the light. The tritium concentration can then be determined from the signal from the photomultiplier tube. This method is commonly used for gas inventory requirements. Liquid scintillation is commonly used to determine small concentrations of tritium. The tritium liquid or compounds containing tritium are placed in a scintillation liquid. The liquid is then placed in a counter that determines the amount of tritium by the light emitted from the sample. Ion chambers are commonly used to determine environmental tritium releases and to monitor the atmosphere for personnel safety. Process ion chambers are used for determining tritium concentrations in secondary containment. Specially designed ion chambers can be used to determine high concentrations of tritium. Ion chambers will measure any radioactive material that can cause ion pairs. They are also susceptible to contamination from materials that adsorb on surfaces and can only be used for gas.

4.4.8.4 Facility Measurement Recommendations

a. *Measurement of tritium input/output to facility*. The primary method used historically for the measurements of the tritium shipment has been the PVTC measurement with the composition determined by either a mass spectrometer or beta scintillation counter. A calorimeter can be used for the measurement of tritium absorbed on solid storage beds that are designed to be used as primary shipping containers and also be placed in the calorimeter.

b. *In-process tritium measurements*. The measurement of tritium within a facility has usually been by PVTC. This requires a shutdown of the process and transferring of all the gas to a volume for sampling and measurement. This is usually a substantial disruption of the process and will take a significant time. Tritium that is "held up" in process cannot be directly measured. This includes tritium in walls of the system, tritium in process components such as a molecular sieve, and tritium contained within the waste disposal system. It must be estimated by difference measurements. Real-time measurements of tritium amounts are done when tritium is moved around the facility or process. These are usually done by PVTC measurements. The laser RAMAN system offered advantages for the measurement of composition as tritium flows from location to location. The use of self-assaying storage beds will greatly reduce the time required to determine the tritium in storage.

c. *Tritium in waste streams*. The characterization of tritium contained in waste streams is important, and one of the more difficult measurements to make. Ionization chamber measurements, calorimetry, and difference measurements are used to determine the tritium levels.

d. *Stack emission measurements*. Stack emissions are determined by ion chambers. The primary method used by facilities for the reporting to the EPA is based on a passive monitoring system. A small fraction of the air stream exhausted from a facility is passed through a system to remove the tritium. Both liquids such as glycol and solids such as molecular sieve are used to absorb HTO. These system can distinguish between HTO and HT by passing the sample through a catalyst that will convert HT to HTO. The second collection system then collects the HT as HTO.

APPENDIX A
CATEGORY 2 THRESHOLD QUANTITIES OF RADIONUCLIDES

Following is a list of radionuclides and their associated Category 2 threshold quantities as defined in DOE 1992. This list was taken from RSAC-5f, a modified version of the Radiological Safety Analysis Computer Program (Wenzel 1993). The RSAC-5 program was modified to calculate doses for airborne releases of International Thermonuclear Experimental Reactor (ITER) activation products (Abbott and Wenzel 1994). RSAC-5f used external dose conversion factors from DOE 1988a and internal dose conversion factors from DOE 1988b. Some internal dose conversion factors were taken from Fetter 1988 and 1991 for those radionuclides not covered in DOE 1988b.

These threshold quantities were calculated in accordance with guidance in Attachment 1 of DOE 1992. Specifically, the following equation, taken from page A-6 of DOE 1992, was used:

$$Q = (1\ \text{rem})/[RF*SA*\chi/Q*(CEDE*RR + CSDE)]\ ,$$

where

Q = quantity of material used as threshold (grams)

RF = Airborne release fraction of material averaged over an entire facility (unitless)

SA = Specific activity of radionuclide released (Ci/gm)

χ/Q = Expression accounting for dilution of release at a point under given meteorological conditions (Specific Concentration) (sec/m^3)

CEDE = Committed effective dose equivalent for a given radionuclide (inhalation)(rem/Ci). Note: The CEDE for tritium (H-3) includes a 50% addition for direct skin absorption in addition to the inhalation pathway.

RR = Respiration rate, which is assumed equal to the standard value used for an active man (3.5E-4 m^3/sec)

CSDE = Cloud shine (immersion) dose equivalent (rem*m^3/Ci*sec)

A χ/Q of E-4 was used as indicated in Attachment 1 to DOE 1992.

Release fractions (RFs) were also taken from Attachment 1 and are given in the table below.

Physical form	RF
Gases (tritium, krypton, etc.)	1.0
Highly volatile (phosphorus, halides, potassium, sodium, etc.)	0.5
Semivolatile (selenium, mercury, etc.)	10^{-2}
Solid/powder/liquid	10^{-3}

When a comparison was made between the quantities listed here and corresponding values in DOE 1992, some significant differences were noted. An investigation revealed that the calculations supporting DOE 1992 appear to have used the highest dose conversion factors to be found in DOE 1988b, whereas the calculations performed for this study used dose conversion factors (also from DOE 1988b) corresponding to the oxide forms of the radionuclides, the form expected to be found associated with fusion reactor materials. As a consequence of this difference in approach, the DOE 1992 threshold quantities are sometimes orders of magnitude less than those listed in this letter. Radionuclides showing significant differences for this reason were ^{32}P, ^{33}P, ^{35}S, ^{36}Cl, ^{44}Ti, ^{55}Fe, ^{59}Fe, ^{63}Ni, ^{89}Sr, ^{90}Sr, ^{93}Zr, ^{95}Zr, ^{109}Cd, ^{113}Cd, ^{114M}In, ^{153}Gd, ^{198}Au, ^{203}Hg, ^{227}Ac, ^{230}Th, ^{232}Th, ^{238}Pu, ^{239}Pu, and ^{241}Pu.

As a check, the dose conversion factors used in this study were compared with corresponding factors found in Fetter 1988 and 1991. Fetter's calculated dose conversion factors were intended to apply specifically to fusion reactor materials. The comparison showed general agreement with the dose conversion factors used here.

It should also be noted that the DOE 1992 calculations for ^{36}Cl used an RF of 1.0, while an RF of 0.5 was used for this study to be consistent with the other halides. An order of magnitude difference in the threshold quantity for ^{75}Se is due to the evident use in DOE 1992 of an RF of 0.001, while this study used an RF of 0.01 to be consistent with the instructions in Attachment 1 of DOE 1992.

There are also differences in some of the threshold quantities given in grams. These differences can be traced to the use in DOE 1992 of values for specific activity (SA) that are 2 and 3 orders of magnitude higher than the values used here. The use of these SA values when calculating threshold values in DOE 1992 appear to be due to error. The SA values used here were found to agree with values given in Shleien 1992.

The discrepancy in the values for ^{52}Mn is inexplicable. That was the only case in which the value in DOE 1992 was significantly higher than the corresponding value calculated here, and a reason could not be found for the difference.

In summary, the threshold quantities given in the Table A.1 are believed to apply accurately to radioactive materials generated in fusion facilities. Until Category 3 threshold limits are established for magnetic fusion facilities, the HC-3 threshold limits provided in DOE-STD 1027-92 should be used for HC-3 classification if the isotopes in question have threshold limit values in 1027. If the isotopes are not listed in 1027, calculate the threshold limits using the methodology contained in this Standard.

TABLE A.1. Thresholds for radionuclides Category 2

		Threshold quantities					
		Fusion values			DOE 1027		
Nuclide	Half-life T (days)	Q (grams)	Q (TBq)	Q (Ci)	Q (TBq)	Q (Ci)	Release fractions
H 3	4.49E+03	3.09E+01	1.12E+04	3.03E+05	1.11E+04	3.00E+05	1.00E+00
Be 7	5.34E+01	2.77E+02	3.61E+06	9.76E+07			1.00E–03
Be 10	5.84E+08	3.61E+06	3.02E+03	8.16E+04			1.00E–03
C 11	1.42E–02	7.28E–03	2.29E+05	6.19E+06			1.00E–02
C 14	2.09E+06	3.02E+05	5.03E+04	1.36E+06	5.18E+04	1.40E+06	1.00E–02
N 13	6.92E–03	4.21E–05	2.29E+03	6.19E+04			1.00E+00
N 16	8.25E–05	1.14E–07	4.21E+02	1.14E+04			1.00E+00
O 15	1.41E–03	9.94E–06	2.29E+03	6.19E+04			1.00E+00
F 18	7.63E–02	1.15E–03	4.08E+03	1.10E+05			5.00E–01
Na 22	9.50E+02	1.00E+00	2.35E+02	6.35E+03	2.33E+02	6.30E+03	5.00E–01
Na 24	6.25E–01	2.09E–03	6.80E+02	1.84E+04			5.00E–01
Mg 27	6.57E–03	8.53E–02	2.35E+06	6.35E+07			1.00E–03
Mg 28	8.75E–01	1.15E+00	2.29E+05	6.19E+06			1.00E–03
Al 26	2.61E+08	2.44E+07	1.75E+04	4.73E+05			1.00E–03
Al 28	1.56E–03	1.04E–02	1.17E+06	3.16E+07			1.00E–03
Si 31	1.09E–01	4.57E+00	6.59E+06	1.78E+08			1.00E–03
Si 32	6.28E+04	9.88E+03	2.40E+04	6.49E+05			1.00E–03
P 32	1.43E+01	3.60E–02	3.84E+02	1.04E+04	1.63E+00	4.41E+01	5.00E–01
P 33	2.54E+01	5.95E–01	3.47E+03	9.38E+04	1.11E+03	3.00E+04	5.00E–01
S 35	8.74E+01	4.57E+00	7.29E+03	1.97E+05	9.25E+02	2.50E+04	5.00E–01
S 37	3.51E–03	3.25E–03	1.22E+05	3.30E+06			5.00E–01
Cl 36	1.10E+08	8.16E+05	1.01E+03	2.73E+04	5.18E+01	1.40E+03	5.00E–01
Cl 38	2.58E–02	4.75E–04	2.36E+03	6.38E+04			5.00E–01
Cl 39	3.86E–02	6.72E–03	2.18E+04	5.89E+05			5.00E–01
Cl 40	9.38E–04	1.59E–03	2.07E+05	5.59E+06			5.00E–01
Ar 37	3.50E+01	4.57E+05	1.72E+09	4.65E+10			1.00E+00
Ar 41	7.61E–02	1.13E–03	1.77E+03	4.78E+04			1.00E+00
K 40	4.66E+11	6.69E+08	1.75E+02	4.73E+03	1.74E+02	4.70E+03	5.00E–01
K 42	5.15E–01	7.61E–03	1.72E+03	4.65E+04			5.00E–01
K 43	9.42E–01	1.75E–02	2.10E+03	5.68E+04			5.00E–01
Ca 41	3.76E+07	2.57E+08	8.13E+05	2.20E+07			1.00E–03
Ca 45	1.63E+02	2.60E+02	1.73E+05	4.68E+06	1.74E+05	4.70E+06	1.00E–03
Ca 47	4.54E+00	7.70E+00	1.76E+05	4.76E+06	1.78E+05	4.81E+06	1.00E–03

Ca 49	6.05E–03	3.67E–02	6.04E+05	1.63E+07			1.00E–03
Sc 44	1.64E–01	1.11E+00	7.50E+05	2.03E+07			1.00E–03
Sc 44m	2.44E+00	3.28E+00	1.49E+05	4.03E+06			1.00E–03
Sc 46	8.38E+01	3.98E+01	5.05E+04	1.36E+06	5.18E+04	1.40E+06	1.00E–03
Sc 47	3.42E+00	1.99E+01	6.04E+05	1.63E+07			1.00E–03
Sc 48	1.83E+00	3.66E+00	2.04E+05	5.51E+06			1.00E–03
Sc 49	3.99E–02	4.52E+00	1.13E+07	3.05E+08			1.00E–03
Sc 50	1.19E–03	9.88E–01	8.13E+07	2.20E+09			1.00E–03
Ti 44	1.73E+04	9.67E+02	6.22E+03	1.68E+05	1.18E+03	3.19E+04	1.00E–03
Ti 45	1.28E–01	2.29E+00	1.94E+06	5.24E+07			1.00E–03
Ti 51	4.00E–03	2.34E–01	5.61E+06	1.52E+08			1.00E–03
V 48	1.60E+01	1.77E+01	1.13E+05	3.05E+06	1.11E+05	3.00E+06	1.00E–03
V 49	3.37E+02	1.28E+04	3.78E+06	1.02E+08			1.00E–03
V 52	2.60E–03	4.23E–02	1.53E+06	4.14E+07			1.00E–03
V 53	1.12E–03	1.82E+00	1.50E+08	4.05E+09			1.00E–03
Cr 49	2.92E–02	5.87E–01	2.00E+06	5.41E+07			1.00E–03
Cr 51	2.77E+01	1.11E+03	3.85E+06	1.04E+08	3.70E+06	1.00E+08	1.00E–03
Mn 52	5.59E+00	8.71E+00	1.46E+05	3.95E+06	6.66E+05	1.80E+07	1.00E–03
Mn 52m	1.47E–02	1.42E–01	9.08E+05	2.45E+07			1.00E–03
Mn 53	1.35E+09	3.60E+10	2.46E+06	6.65E+07			1.00E–03
Mn 54	3.13E+02	5.38E+02	1.56E+05	4.22E+06			1.00E–03
Mn 56	1.08E–01	1.21E+00	9.78E+05	2.64E+07			1.00E–03
Mn 57	1.01E–03	3.12E–01	2.66E+07	7.19E+08			1.00E–03
Fe 52	3.45E–01	1.66E+00	4.52E+05	1.22E+07			1.00E–03
Fe 55	9.96E+02	9.88E+03	8.81E+05	2.38E+07	4.07E+05	1.10E+07	1.00E–03
Fe 59	4.46E+01	5.45E+01	1.01E+05	2.73E+06	6.66E+04	1.80E+06	1.00E–03
Fe 60	5.48E+08	2.64E+07	3.92E+03	1.06E+05			1.00E–03
Co 56	7.73E+01	3.37E+01	3.80E+04	1.03E+06			1.00E–03
Co 57	2.71E+02	4.42E+02	1.40E+05	3.78E+06			1.00E–03
Co 58	7.08E+01	1.18E+02	1.40E+05	3.78E+06			1.00E–03
Co 58m	3.81E–01	6.38E+01	1.41E+07	3.81E+08			1.00E–03
Co 60	1.92E+03	1.65E+02	6.99E+03	1.89E+05	7.03E+03	1.90E+05	1.00E–03
Co 60m	7.27E–03	2.42E+01	2.71E+08	7.32E+09			1.00E–03
Co 61	6.88E–02	7.06E+00	8.22E+06	2.22E+08			1.00E–03
Co 62m	9.66E–03	4.05E+00	3.30E+07	8.92E+08			1.00E–03
Ni 56	6.10E+00	1.61E+01	2.29E+05	6.19E+06			1.00E–03
Ni 57	1.48E+00	7.00E+00	4.05E+05	1.09E+07			1.00E–03
Ni 59	2.77E+07	5.05E+08	1.51E+06	4.08E+07			1.00E–03
Ni 63	3.65E+04	2.62E+05	5.56E+05	1.50E+07	1.67E+05	4.51E+06	1.00E–03
Ni 65	1.05E–01	3.45E+00	2.47E+06	6.68E+07			1.00E–03
Cu 61	1.40E–01	3.59E+00	2.05E+06	5.54E+07			1.00E–03
Cu 62	6.76E–03	1.77E–01	2.06E+06	5.57E+07			1.00E–03
Cu 64	5.29E–01	2.32E+01	3.35E+06	9.05E+07			1.00E–03
Cu 66	3.54E–03	2.38E+00	4.96E+07	1.34E+09			1.00E–03
Cu 67	2.58E+00	3.24E+01	9.17E+05	2.48E+07			1.00E–03
Zn 62	3.84E–01	2.57E+00	5.27E+05	1.42E+07			1.00E–03

Zn 63	2.67E–02	5.13E+00	1.49E+07	4.03E+08			1.00E–03
Zn 65	2.44E+02	1.88E+02	5.79E+04	1.56E+06	5.92E+04	1.60E+06	1.00E–03
Zn 69	3.89E–02	1.61E+01	2.94E+07	7.95E+08			1.00E–03
Zn 69m	5.73E–01	9.75E+00	1.20E+06	3.24E+07			1.00E–03
Zn 71m	1.65E–01	8.45E+00	3.52E+06	9.51E+07			1.00E–03
Zn 72	1.94E+00	7.19E+00	2.52E+05	6.81E+06			1.00E–03
Ga 66	3.96E–01	4.46E+00	8.32E+05	2.25E+07			1.00E–03
Ga 67	3.26E+00	8.65E+01	1.93E+06	5.22E+07			1.00E–03
Ga 68	4.71E–02	1.32E+00	2.01E+06	5.43E+07			1.00E–03
Ga 70	1.47E–02	8.90E+00	4.23E+07	1.14E+09			1.00E–03
Ga 72	5.88E–01	2.99E+00	3.45E+05	9.32E+06			1.00E–03
Ga 73	2.03E–01	9.73E+00	3.20E+06	8.65E+07			1.00E–03
Ge 68	2.71E+02	8.13E+01	2.16E+04	5.84E+05	2.15E+04	5.81E+05	1.00E–03
Ge 69	1.63E+00	3.92E+01	1.71E+06	4.62E+07			1.00E–03
Ge 71	1.14E+01	1.46E+03	8.81E+06	2.38E+08			1.00E–03
Ge 75	5.75E–02	1.51E+01	1.71E+07	4.62E+08			1.00E–03
Ge 77	4.71E–01	5.66E+00	7.63E+05	2.06E+07			1.00E–03
Ge 78	6.04E–02	4.25E+00	4.40E+06	1.19E+08			1.00E–03
As 72	1.08E+00	3.90E+00	2.44E+05	6.59E+06			1.00E–03
As 73	8.03E+01	4.09E+02	3.41E+05	9.22E+06			1.00E–03
As 74	1.78E+01	4.15E+01	1.54E+05	4.16E+06			1.00E–03
As 76	1.10E+00	5.01E+00	2.94E+05	7.95E+06			1.00E–03
As 77	1.62E+00	2.71E+01	1.06E+06	2.86E+07			1.00E–03
As 78	6.29E–02	4.62E+00	4.60E+06	1.24E+08			1.00E–03
Se 73	2.96E–01	5.75E–01	1.30E+05	3.51E+06			1.00E–02
Se 75	1.20E+02	2.32E+01	1.26E+04	3.41E+05	1.26E+05	3.41E+06	1.00E–02
Se 79	2.37E+07	4.56E+06	1.19E+04	3.22E+05			1.00E–02
Se 81	1.28E–02	1.07E+00	5.03E+06	1.36E+08			1.00E–02
Se 81m	3.98E–02	9.83E–01	1.49E+06	4.03E+07			1.00E–02
Se 83	1.55E–02	6.96E–01	2.64E+06	7.14E+07			1.00E–02
Br 77	2.38E+00	2.24E–01	5.97E+03	1.61E+05			5.00E–01
Br 80	1.23E–02	6.95E–03	3.45E+04	9.32E+05			5.00E–01
Br 80m	1.84E–01	2.25E–02	7.46E+03	2.02E+05			5.00E–01
Br 82	1.47E+00	2.15E–02	8.69E+02	2.35E+04			5.00E–01
Br 83	1.00E–01	4.53E–02	2.66E+04	7.19E+05			5.00E–01
Br 84	2.21E–02	7.93E–04	2.09E+03	5.65E+04			5.00E–01
Br 85	1.99E–03	2.33E–03	6.74E+04	1.82E+06			5.00E–01
Kr 79	1.46E+00	2.17E–01	9.18E+03	2.48E+05			1.00E+00
Kr 81	7.67E+07	2.91E+08	2.29E+05	6.19E+06			1.00E+00
Kr 83m	7.75E–02	3.27E+01	2.49E+07	6.73E+08			1.00E+00
Kr 85	3.92E+03	7.10E+04	1.04E+06	2.81E+07	1.04E+06	2.81E+07	1.00E+00
Kr 85m	1.87E–01	4.66E–02	1.44E+04	3.89E+05			1.00E+00
Kr 87	5.30E–02	2.47E–03	2.62E+03	7.08E+04			1.00E+00
Kr 88	1.18E–01	2.20E–03	1.03E+03	2.78E+04			1.00E+00
Kr 89	2.19E–03	4.61E–05	1.15E+03	3.11E+04			1.00E+00
Kr 90	3.77E–04	1.22E–05	1.76E+03	4.76E+04			1.00E+00

Rb 81	1.90E–01	8.84E+00	2.81E+06	7.59E+07			1.00E–03
Rb 82	8.74E–04	3.12E–02	2.12E+06	5.73E+07			1.00E–03
Rb 83	8.62E+01	3.02E+02	2.06E+05	5.57E+06			1.00E–03
Rb 84	3.29E+01	8.64E+01	1.53E+05	4.14E+06			1.00E–03
Rb 86	1.87E+01	5.23E+01	1.59E+05	4.30E+06			1.00E–03
Rb 87	1.75E+13	9.99E+13	3.20E+05	8.65E+06			1.00E–03
Rb 88	1.23E–02	5.80E–01	2.62E+06	7.08E+07			1.00E–03
Rb 89	1.07E–02	1.94E–01	9.95E+05	2.69E+07			1.00E–03
Rb 90	1.81E–03	3.04E–02	9.11E+05	2.46E+07			1.00E–03
Rb 90m	2.99E–03	3.47E–02	6.30E+05	1.70E+07			1.00E–03
Sr 82	2.54E+01	2.92E+06	6.86E+09	1.85E+11			1.00E–03
Sr 85	6.48E+01	5.60E+02	4.96E+05	1.34E+07			1.00E–03
Sr 85m	4.70E–02	8.08E+00	9.87E+06	2.67E+08			1.00E–03
Sr 87m	1.17E–01	1.21E+01	5.80E+06	1.57E+08			1.00E–03
Sr 89	5.05E+01	1.65E+02	1.79E+05	4.84E+06	2.85E+04	7.70E+05	1.00E–03
Sr 90	1.06E+04	9.00E+02	4.60E+03	1.24E+05	8.14E+02	2.20E+04	1.00E–03
Sr 91	3.96E–01	6.70E+00	9.08E+05	2.45E+07			1.00E–03
Sr 92	1.13E–01	1.93E+00	9.07E+05	2.45E+07			1.00E–03
Sr 93	5.14E–03	9.59E–02	9.79E+05	2.65E+07			1.00E–03
Y 86	6.14E–01	3.44E+00	3.18E+05	8.59E+06			1.00E–03
Y 87	3.35E+00	3.49E+01	5.85E+05	1.58E+07			1.00E–03
Y 88	1.07E+02	9.09E+01	4.73E+04	1.28E+06			1.00E–03
Y 90	2.67E+00	6.35E+00	1.29E+05	3.49E+06			1.00E–03
Y 90m	1.33E–01	3.55E+00	1.45E+06	3.92E+07			1.00E–03
Y 91	5.85E+01	2.62E+01	2.40E+04	6.49E+05	2.41E+04	6.51E+05	1.00E–03
Y 91m	3.45E–02	2.49E+00	3.87E+06	1.05E+08			1.00E–03
Y 92	1.48E–01	3.98E+00	1.43E+06	3.86E+07			1.00E–03
Y 93	4.25E–01	3.99E+00	4.93E+05	1.33E+07			1.00E–03
Y 94	1.30E–02	3.95E+00	1.58E+07	4.27E+08			1.00E–03
Y 95	7.15E–03	4.08E+00	2.94E+07	7.95E+08			1.00E–03
Zr 86	6.88E–01	6.32E+00	5.22E+05	1.41E+07			1.00E–03
Zr 88	8.34E+01	1.56E+02	1.04E+05	2.81E+06			1.00E–03
Zr 89	3.27E+00	2.48E+01	4.16E+05	1.12E+07			1.00E–03
Zr 93	5.48E+08	1.36E+08	1.31E+04	3.54E+05	3.29E+03	8.89E+04	1.00E–03
Zr 95	6.40E+01	9.86E+01	7.92E+04	2.14E+06	5.55E+04	1.50E+06	1.00E–03
Zr 97	7.00E–01	3.99E+00	2.87E+05	7.76E+06			1.00E–03
Nb 90	6.08E–01	2.81E+00	2.51E+05	6.78E+06			1.00E–03
Nb 92m	1.01E+01	7.62E+01	3.99E+05	1.08E+07			1.00E–03
Nb 93m	5.88E+03	4.23E+03	3.78E+04	1.02E+06			1.00E–03
Nb 94	7.30E+06	4.49E+05	3.20E+03	8.65E+04	3.18E+03	8.59E+04	1.00E–03
Nb 94m	4.35E–03	2.57E+01	3.07E+08	8.30E+09			1.00E–03
Nb 95	3.50E+01	1.48E+02	2.18E+05	5.89E+06			1.00E–03
Nb 95m	3.61E+00	3.33E+01	4.75E+05	1.28E+07			1.00E–03
Nb 96	9.75E–01	6.43E+00	3.35E+05	9.05E+06			1.00E–03
Nb 97	5.13E–02	2.84E+00	2.79E+06	7.54E+07			1.00E–03
Nb 97m	6.73E–04	4.11E–02	3.08E+06	8.32E+07			1.00E–03

Nb 98	3.36E–05	7.12E–03	1.06E+07	2.86E+08			1.00E–03
Mo 93	1.28E+06	9.19E+05	3.78E+04	1.02E+06			1.00E–03
Mo 93m	2.88E–01	1.61E+01	2.94E+06	7.95E+07			1.00E–03
Mo 99	2.75E+00	1.60E+01	2.88E+05	7.78E+06	2.89E+05	7.81E+06	1.00E–03
Mo101	1.01E–02	2.95E–01	1.41E+06	3.81E+07			1.00E–03
Tc 95	8.33E–01	2.59E+01	1.60E+06	4.32E+07			1.00E–03
Tc 95m	6.10E+01	4.06E+03	3.42E+06	9.24E+07			1.00E–03
Tc 96	4.28E+00	2.48E+01	2.95E+05	7.97E+06			1.00E–03
Tc 96m	3.61E–02	1.85E+01	2.60E+07	7.03E+08			1.00E–03
Tc 97	9.49E+08	2.24E+10	1.19E+06	3.22E+07			1.00E–03
Tc 97m	9.00E+01	4.50E+02	2.52E+05	6.81E+06			1.00E–03
Tc 98	1.53E+09	1.84E+09	5.99E+04	1.62E+06			1.00E–03
Tc 99	7.78E+07	2.22E+08	1.41E+05	3.81E+06	1.41E+05	3.81E+06	1.00E–03
Tc 99m	2.50E–01	6.65E+01	1.31E+07	3.54E+08			1.00E–03
Tc101	9.86E–03	1.28E+00	6.25E+06	1.69E+08			1.00E–03
Tc104	1.26E–02	4.91E+00	1.82E+07	4.92E+08			1.00E–03
Ru 97	2.89E+00	1.16E+01	2.01E+05	5.43E+06			1.00E–02
Ru103	3.93E+01	1.09E+01	1.32E+04	3.57E+05			1.00E–02
Ru105	1.85E–01	5.43E–01	1.37E+05	3.70E+06			1.00E–02
Ru106	3.72E+02	1.94E+00	2.40E+02	6.49E+03	2.41E+02	6.51E+03	1.00E–02
Rh101	1.21E+03	8.23E+02	3.30E+04	8.92E+05			1.00E–03
Rh101m	4.35E+00	1.42E+02	1.58E+06	4.27E+07			1.00E–03
Rh102	1.06E+03	2.69E+02	1.22E+04	3.30E+05			1.00E–03
Rh102m	2.07E+02	1.09E+02	2.52E+04	6.81E+05			1.00E–03
Rh103m	3.90E–02	2.02E+02	2.46E+08	6.65E+09			1.00E–03
Rh105	1.47E+00	3.62E+01	1.14E+06	3.08E+07			1.00E–03
Rh105m	4.63E–04	8.11E–01	8.15E+07	2.20E+09			1.00E–03
Rh106	3.46E–04	8.34E–02	1.11E+07	3.00E+08			1.00E–03
Rh106m	9.08E–02	1.39E+01	7.05E+06	1.91E+08			1.00E–03
Rh107	1.51E–02	1.75E+01	5.29E+07	1.43E+09			1.00E–03
Pd103	1.70E+01	2.70E+02	7.55E+05	2.04E+07			1.00E–03
Pd107	2.37E+09	4.23E+09	8.13E+04	2.20E+06			1.00E–03
Pd109	5.63E–01	1.21E+01	9.61E+05	2.60E+07			1.00E–03
Pd111	1.63E–02	4.42E+00	1.20E+07	3.24E+08			1.00E–03
Ag106	1.67E–02	1.47E+01	4.07E+07	1.10E+09			1.00E–03
Ag106m	8.41E+00	2.88E+01	1.58E+05	4.27E+06			1.00E–03
Ag108	1.66E–03	2.83E+00	7.72E+07	2.09E+09			1.00E–03
Ag108m	4.75E+04	5.53E+03	5.27E+03	1.42E+05			1.00E–03
Ag109m	4.61E–04	5.37E+00	5.23E+08	1.41E+10			1.00E–03
Ag110	2.85E–04	4.22E–01	6.59E+07	1.78E+09			1.00E–03
Ag110m	2.50E+02	1.10E+02	1.95E+04	5.27E+05	1.96E+04	5.30E+05	1.00E–03
Ag111	7.47E+00	3.04E+01	1.79E+05	4.84E+06			1.00E–03
Ag112	1.30E–01	5.75E+00	1.92E+06	5.19E+07			1.00E–03
Ag115	1.39E–02	5.67E+00	1.73E+07	4.68E+08			1.00E–03
Cd109	4.62E+02	2.60E+02	2.52E+04	6.81E+05	1.07E+04	2.89E+05	1.00E–03
Cd111m	3.37E–02	6.28E+00	8.21E+06	2.22E+08			1.00E–03

Cd113	3.29E+18	2.17E+17	2.86E+03	7.73E+04	6.66E+02	1.80E+04	1.00E–03
Cd113m	5.15E+03	3.31E+02	2.78E+03	7.51E+04			1.00E–03
Cd115	2.23E+00	1.42E+01	2.72E+05	7.35E+06			1.00E–03
Cd115m	4.46E+01	3.17E+01	3.02E+04	8.16E+05			1.00E–03
Cd117	1.04E–01	3.01E+00	1.21E+06	3.27E+07			1.00E–03
Cd117m	1.42E–01	2.65E+00	7.80E+05	2.11E+07			1.00E–03
In111	2.80E+00	7.17E+01	1.13E+06	3.05E+07			1.00E–03
In113m	6.91E–02	1.20E+01	7.49E+06	2.02E+08			1.00E–03
In114	8.32E–04	1.13E+00	5.80E+07	1.57E+09			1.00E–03
In114m	4.95E+01	2.49E+01	2.16E+04	5.84E+05	1.37E+04	3.70E+05	1.00E–03
In115	1.61E+17	4.31E+15	1.14E+03	3.08E+04			1.00E–03
In115m	1.87E–01	2.70E+01	6.14E+06	1.66E+08			1.00E–03
In116m	2.50E–05	5.18E–04	8.73E+05	2.36E+07			1.00E–03
In117	3.06E–02	2.28E+00	3.11E+06	8.41E+07			1.00E–03
In117m	8.08E–02	1.28E+01	6.59E+06	1.78E+08			1.00E–03
Sn113	1.15E+02	3.16E+02	1.19E+05	3.22E+06	1.18E+05	3.19E+06	1.00E–03
Sn117m	1.36E+01	9.93E+01	3.05E+05	8.24E+06			1.00E–03
Sn119m	2.93E+02	1.42E+03	1.99E+05	5.38E+06			1.00E–03
Sn121	1.13E+00	6.29E+01	2.25E+06	6.08E+07			1.00E–03
Sn121m	2.01E+04	5.91E+04	1.19E+05	3.22E+06			1.00E–03
Sn123	1.29E+02	1.15E+02	3.52E+04	9.51E+05	3.52E+04	9.51E+05	1.00E–03
Sn123m	2.79E–02	2.12E+01	3.02E+07	8.16E+08			1.00E–03
Sn125	9.63E+00	1.84E+01	7.47E+04	2.02E+06			1.00E–03
Sn126	3.65E+07	1.34E+07	1.43E+04	3.86E+05	1.22E+04	3.30E+05	1.00E–03
Sn127	8.83E–02	8.99E+00	3.92E+06	1.06E+08			1.00E–03
Sn128	4.10E–02	8.12E+00	7.55E+06	2.04E+08			1.00E–03
Sb117	1.17E–01	3.08E+01	1.10E+07	2.97E+08			1.00E–03
Sb120b	5.76E+00	4.27E+01	3.02E+05	8.16E+06			1.00E–03
Sb122	2.70E+00	1.45E+01	2.16E+05	5.84E+06			1.00E–03
Sb124	6.02E+01	7.38E+01	4.83E+04	1.31E+06	4.81E+04	1.30E+06	1.00E–03
Sb125	1.01E+03	2.73E+03	1.06E+05	2.86E+06			1.00E–03
Sb126	1.24E+01	3.00E+01	9.37E+04	2.53E+06	9.25E+04	2.50E+06	1.00E–03
Sb126m	1.27E–04	4.61E–03	1.40E+06	3.78E+07			1.00E–03
Sb127	3.84E+00	1.85E+01	1.85E+05	5.00E+06			1.00E–03
Sb128	3.79E–01	6.57E+00	6.61E+05	1.79E+07			1.00E–03
Sb128m	7.01E–03	1.62E+01	8.81E+07	2.38E+09			1.00E–03
Sb129	1.83E–01	4.10E+00	8.47E+05	2.29E+07			1.00E–03
Sb130	2.67E–02	1.21E+01	1.71E+07	4.62E+08			1.00E–03
Sb131	1.60E–02	3.77E+00	8.81E+06	2.38E+08			1.00E–03
Te121	1.68E+01	2.37E+01	5.69E+04	1.54E+06			1.00E–02
Te121m	1.54E+02	3.33E+01	8.74E+03	2.36E+05			1.00E–02
Te123	4.75E+15	2.75E+15	2.30E+04	6.22E+05			1.00E–02
Te123m	1.20E+02	3.33E+01	1.11E+04	3.00E+05			1.00E–02
Te125m	5.80E+01	2.34E+01	1.58E+04	4.27E+05			1.00E–02
Te127	3.92E–01	3.69E+00	3.62E+05	9.78E+06			1.00E–02
Te127m	1.09E+02	1.58E+01	5.56E+03	1.50E+05	5.55E+03	1.50E+05	1.00E–02

Te129	4.83E–02	1.47E+00	1.15E+06	3.11E+07			1.00E–02
Te129m	3.36E+01	4.69E+00	5.28E+03	1.43E+05	5.18E+03	1.40E+05	1.00E–02
Te131	1.74E–02	7.88E–02	1.69E+05	4.57E+06			1.00E–02
Te131m	1.35E+00	6.20E–01	1.71E+04	4.62E+05			1.00E–02
Te132	3.26E+00	1.19E+00	1.36E+04	3.68E+05			1.00E–02
Te133	8.61E–03	4.76E–02	2.03E+05	5.49E+06			1.00E–02
Te133m	3.85E–02	7.73E–02	7.38E+04	1.99E+06			1.00E–02
Te134	2.92E–02	1.70E–01	2.12E+05	5.73E+06			1.00E–02
I122	2.50E–03	2.98E–04	4.78E+03	1.29E+05			5.00E–01
I123	5.50E–01	8.55E–02	6.17E+03	1.67E+05			5.00E–01
I124	4.18E+00	1.15E–02	1.08E+02	2.92E+03			5.00E–01
I125	6.01E+01	1.36E–01	8.81E+01	2.38E+03	8.88E+01	2.40E+03	5.00E–01
I126	1.30E+01	1.64E–02	4.89E+01	1.32E+03			5.00E–01
I128	1.74E–02	1.22E–02	2.68E+04	7.24E+05			5.00E–01
I129	5.73E+09	1.78E+06	1.17E+01	3.16E+02			5.00E–01
I130	5.15E–01	8.31E–03	6.06E+02	1.64E+04			5.00E–01
I131	8.04E+00	1.42E–02	6.57E+01	1.78E+03	6.66E+01	1.80E+03	5.00E–01
I132	9.50E–02	3.88E–03	1.51E+03	4.08E+04			5.00E–01
I133	8.67E–01	8.79E–03	3.72E+02	1.01E+04			5.00E–01
I134	3.65E–02	1.57E–03	1.56E+03	4.22E+04			5.00E–01
I135	2.74E–01	8.64E–03	1.14E+03	3.08E+04			5.00E–01
I136	9.65E–04	4.51E–05	1.68E+03	4.54E+04			5.00E–01
Xe122	8.38E–01	8.10E–01	3.87E+04	1.05E+06			1.00E+00
Xe123	8.33E–02	7.69E–03	3.67E+03	9.92E+04			1.00E+00
Xe125	7.13E–01	1.70E–01	9.32E+03	2.52E+05			1.00E+00
Xe127	3.64E+01	8.36E+00	8.83E+03	2.39E+05			1.00E+00
Xe129m	8.89E+00	2.38E+01	1.01E+05	2.73E+06			1.00E+00
Xe131m	1.19E+01	8.75E+01	2.74E+05	7.41E+06			1.00E+00
Xe133	5.24E+00	9.56E+00	6.70E+04	1.81E+06	6.66E+04	1.80E+06	1.00E+00
Xe133m	2.19E+00	4.70E+00	7.88E+04	2.13E+06			1.00E+00
Xe135	3.79E–01	9.77E–02	9.32E+03	2.52E+05			1.00E+00
Xe135m	1.06E–02	1.60E–03	5.45E+03	1.47E+05			1.00E+00
Xe137	2.65E–03	9.11E–04	1.22E+04	3.30E+05			1.00E+00
Xe138	9.79E–03	5.17E–04	1.87E+03	5.05E+04			1.00E+00
Cs126	1.14E–03	6.07E–03	2.07E+05	5.59E+06			1.00E–02
Cs129	1.34E+00	1.39E+01	3.95E+05	1.07E+07			1.00E–02
Cs131	9.69E+00	1.68E+02	6.48E+05	1.75E+07			1.00E–02
Cs132	6.48E+00	1.21E+01	6.93E+04	1.87E+06			1.00E–02
Cs134	7.54E+02	4.58E+01	2.22E+03	6.00E+04	2.22E+03	6.00E+04	1.00E–02
Cs134m	1.21E–01	7.76E+00	2.33E+06	6.30E+07			1.00E–02
Cs135	8.40E+08	5.45E+08	2.35E+04	6.35E+05			1.00E–02
Cs135m	3.68E–02	4.14E+00	4.07E+06	1.10E+08			1.00E–02
Cs136	1.32E+01	4.55E+00	1.24E+04	3.35E+05			1.00E–02
Cs137	1.10E+03	1.02E+03	3.30E+03	8.92E+04	3.29E+03	8.89E+04	1.00E–02
Cs138	2.24E–02	5.39E–02	8.53E+04	2.31E+06			1.00E–02
Cs139	6.46E–03	1.29E–01	7.02E+05	1.90E+07			1.00E–02

Ba131	1.17E+01	3.78E+02	1.21E+06	3.27E+07			1.00E–03
Ba133	3.84E+03	1.57E+04	1.50E+05	4.05E+06	1.48E+05	4.00E+06	1.00E–03
Ba133m	1.62E+00	7.97E+01	1.81E+06	4.89E+07			1.00E–03
Ba135m	1.20E+00	7.56E+01	2.29E+06	6.19E+07			1.00E–03
Ba137m	1.77E–03	1.90E–01	3.82E+06	1.03E+08			1.00E–03
Ba139	5.82E–02	9.93E+00	6.00E+06	1.62E+08			1.00E–03
Ba140	1.28E+01	1.05E+02	2.87E+05	7.76E+06	2.89E+05	7.81E+06	1.00E–03
Ba141	1.27E–02	7.91E–01	2.16E+06	5.84E+07			1.00E–03
Ba142	7.43E–03	4.99E–01	2.31E+06	6.24E+07			1.00E–03
La137	2.19E+07	3.42E+07	5.56E+04	1.50E+06			1.00E–03
La138	3.83E+13	3.09E+12	2.86E+03	7.73E+04			1.00E–03
La140	1.68E+00	9.22E+00	1.92E+05	5.19E+06			1.00E–03
La141	1.63E–01	1.06E+01	2.25E+06	6.08E+07			1.00E–03
La142	6.42E–02	1.25E+00	6.71E+05	1.81E+07			1.00E–03
La143	9.79E–03	5.51E+00	1.92E+07	5.19E+08			1.00E–03
Ce139	1.38E+02	5.47E+02	1.40E+05	3.78E+06			1.00E–03
Ce141	3.25E+01	1.16E+02	1.24E+05	3.35E+06	1.22E+05	3.30E+06	1.00E–03
Ce143	1.38E+00	1.28E+01	3.19E+05	8.62E+06			1.00E–03
Ce144	2.85E+02	2.53E+01	3.02E+03	8.16E+04	3.03E+03	8.19E+04	1.00E–03
Pr142	7.97E–01	8.98E+00	3.88E+05	1.05E+07			1.00E–03
Pr143	1.36E+01	5.75E+01	1.45E+05	3.92E+06			1.00E–03
Pr144	1.20E–02	6.43E+00	1.82E+07	4.92E+08			1.00E–03
Pr144m	5.00E–03	6.56E+01	4.45E+08	1.20E+10			1.00E–03
Pr145	2.49E–01	1.22E+01	1.65E+06	4.46E+07			1.00E–03
Pr147	9.31E–03	1.10E+01	3.92E+07	1.06E+09			1.00E–03
Nd141	1.04E–01	3.86E+02	1.29E+08	3.49E+09			1.00E–03
Nd147	1.10E+01	5.58E+01	1.69E+05	4.57E+06			1.00E–03
Nd149	7.17E–02	6.21E+00	2.84E+06	7.68E+07			1.00E–03
Nd151	8.61E–03	1.08E+01	4.07E+07	1.10E+09			1.00E–03
Pm143	2.65E+02	1.13E+03	1.46E+05	3.95E+06			1.00E–03
Pm144	3.60E+02	2.69E+02	2.53E+04	6.84E+05			1.00E–03
Pm145	6.46E+03	7.51E+03	3.91E+04	1.06E+06	4.07E+04	1.10E+06	1.00E–03
Pm146	2.02E+03	5.79E+02	9.58E+03	2.59E+05			1.00E–03
Pm147	9.58E+02	8.96E+02	3.11E+04	8.41E+05	3.11E+04	8.41E+05	1.00E–03
Pm148	5.37E+00	1.68E+01	1.03E+05	2.78E+06			1.00E–03
Pm148m	4.13E+01	7.82E+01	6.25E+04	1.69E+06			1.00E–03
Pm149	2.21E+00	2.54E+01	3.77E+05	1.02E+07			1.00E–03
Pm150	1.12E–01	1.25E+01	3.65E+06	9.86E+07			1.00E–03
Pm151	1.18E+00	2.21E+01	6.04E+05	1.63E+07			1.00E–03
Sm146	3.76E+10	1.52E+07	1.36E+01	3.68E+02			1.00E–03
Sm147	3.87E+13	1.73E+10	1.49E+01	4.03E+02			1.00E–03
Sm151	3.29E+04	3.70E+04	3.65E+04	9.86E+05	3.66E+04	9.89E+05	1.00E–03
Sm153	1.93E+00	3.71E+01	6.14E+05	1.66E+07			1.00E–03
Sm155	1.54E–02	2.16E+01	4.40E+07	1.19E+09			1.00E–03
Sm156	3.92E–01	2.32E+01	1.85E+06	5.00E+07			1.00E–03
Eu150b	1.31E+04	1.58E+03	3.92E+03	1.06E+05			1.00E–03

Eu152	4.92E+03	7.34E+02	4.79E+03	1.29E+05	4.81E+03	1.30E+05	1.00E–03
Eu152m	6.67E–02	2.42E+00	1.17E+06	3.16E+07			1.00E–03
Eu154	3.14E+03	4.01E+02	4.06E+03	1.10E+05	4.07E+03	1.10E+05	1.00E–03
Eu155	1.72E+03	1.48E+03	2.71E+04	7.32E+05	2.70E+04	7.30E+05	1.00E–03
Eu156	1.52E+01	4.40E+01	9.06E+04	2.45E+06		0.00E+00	1.00E–03
Eu157	6.30E–01	2.14E+01	1.06E+06	2.86E+07			1.00E–03
Eu158	3.19E–02	1.30E+01	1.26E+07	3.41E+08			1.00E–03
Gd148	2.74E+04	1.04E+01	1.26E+01	3.41E+02			1.00E–03
Gd152	4.02E+16	2.17E+13	1.73E+01	4.68E+02			1.00E–03
Gd153	2.42E+02	9.48E+02	1.25E+05	3.38E+06	5.18E+04	1.40E+06	1.00E–03
Gd159	7.75E–01	2.94E+01	1.17E+06	3.16E+07			1.00E–03
Tb157	4.02E+04	1.52E+05	1.17E+05	3.16E+06			1.00E–03
Tb158	6.57E+04	8.99E+03	4.23E+03	1.14E+05			1.00E–03
Tb160	7.23E+01	1.11E+02	4.70E+04	1.27E+06	4.81E+04	1.30E+06	1.00E–03
Tb161	6.91E+00	7.77E+01	3.41E+05	9.22E+06		0.00E+00	1.00E–03
Dy157	3.38E–01	5.00E+01	4.61E+06	1.25E+08		0.00E+00	1.00E–03
Dy159	1.44E+02	2.37E+03	5.03E+05	1.36E+07		0.00E+00	1.00E–03
Dy165	9.71E–02	2.86E+01	8.73E+06	2.36E+08		0.00E+00	1.00E–03
Dy166	3.40E+00	1.77E+01	1.53E+05	4.14E+06		0.00E+00	1.00E–03
Ho164	2.01E–02	8.94E+01	1.32E+08	3.57E+09		0.00E+00	1.00E–03
Ho164m	2.64E–02	5.51E+01	6.22E+07	1.68E+09		0.00E+00	1.00E–03
Ho166	1.12E+00	1.43E+01	3.76E+05	1.02E+07		0.00E+00	1.00E–03
Ho166m	4.38E+05	2.18E+04	1.47E+03	3.97E+04	1.48E+03	4.00E+04	1.00E–03
Er169	9.40E+00	1.72E+02	5.29E+05	1.43E+07			1.00E–03
Er171	3.13E–01	1.74E+01	1.59E+06	4.30E+07			1.00E–03
Tm170	1.29E+02	2.06E+02	4.60E+04	1.24E+06	4.44E+04	1.20E+06	1.00E–03
Tm171	7.01E+02	3.02E+03	1.23E+05	3.32E+06			1.00E–03
Yb169	3.20E+01	1.64E+02	1.48E+05	4.00E+06			1.00E–03
Yb175	4.19E+00	1.05E+02	6.97E+05	1.88E+07			1.00E–03
Lu174	1.21E+03	1.42E+03	3.30E+04	8.92E+05			1.00E–03
Lu174m	1.42E+02	2.33E+02	4.60E+04	1.24E+06			1.00E–03
Lu176	1.31E+13	7.95E+11	1.68E+03	4.54E+04			1.00E–03
Lu176m	1.53E–01	2.65E+01	4.81E+06	1.30E+08			1.00E–03
Lu177	6.68E+00	1.11E+02	4.56E+05	1.23E+07			1.00E–03
Lu177m	1.61E+02	9.86E+01	1.69E+04	4.57E+05			1.00E–03
Lu178	1.98E–02	1.73E+01	2.40E+07	6.49E+08			1.00E–03
Lu178m	1.60E–02	2.13E+01	3.65E+07	9.86E+08			1.00E–03
Hf175	7.00E+01	5.89E+02	2.35E+05	6.35E+06			1.00E–03
Hf177m	3.57E–02	2.36E+01	1.82E+07	4.92E+08			1.00E–03
Hf178m	1.13E+04	7.79E+02	1.89E+03	5.11E+04			1.00E–03
Hf179m	2.51E+01	1.17E+02	1.27E+05	3.43E+06			1.00E–03
Hf181	4.24E+01	1.48E+02	9.40E+04	2.54E+06	8.14E+04	2.20E+06	1.00E–03
Hf182	3.29E+09	1.82E+08	1.49E+03	4.03E+04			1.00E–03
Hf183	4.46E–02	1.94E+01	1.16E+07	3.14E+08			1.00E–03
Ta179	6.57E+02	4.39E+03	1.82E+05	4.92E+06			1.00E–03
Ta180m	3.38E–01	1.55E+02	1.24E+07	3.35E+08			1.00E–03

Ta182	1.14E+02	1.20E+02	2.81E+04	7.59E+05			1.00E–03
Ta182m	1.10E–02	3.60E+01	8.81E+07	2.38E+09			1.00E–03
Ta183	5.10E+00	4.21E+01	2.20E+05	5.95E+06			1.00E–03
Ta184	3.63E–01	1.31E+01	9.61E+05	2.60E+07			1.00E–03
Ta185	3.40E–02	1.82E+01	1.41E+07	3.81E+08			1.00E–03
Ta186	7.29E–03	1.28E+01	4.60E+07	1.24E+09			1.00E–03
W179	2.64E–02	3.41E+02	3.52E+08	9.51E+09			1.00E–03
W181	1.21E+02	2.88E+04	6.42E+06	1.74E+08			1.00E–03
W185	7.51E+01	4.01E+03	1.41E+06	3.81E+07			1.00E–03
W187	9.96E–01	5.38E+01	1.41E+06	3.81E+07			1.00E–03
W188	6.94E+01	6.89E+02	2.58E+05	6.97E+06			1.00E–03
Re182a	5.29E–01	6.32E+01	3.20E+06	8.65E+07			1.00E–03
Re182b	2.67E+00	3.38E+01	3.40E+05	9.19E+06			1.00E–03
Re184	3.80E+01	3.77E+02	2.63E+05	7.11E+06			1.00E–03
Re184m	1.65E+02	5.40E+02	8.68E+04	2.35E+06			1.00E–03
Re186	3.78E+00	5.05E+01	3.51E+05	9.49E+06			1.00E–03
Re186m	7.30E+07	8.91E+07	3.20E+04	8.65E+05			1.00E–03
Re187	1.59E+13	1.31E+16	2.16E+07	5.84E+08			1.00E–03
Re188	7.08E–01	1.58E+01	5.79E+05	1.56E+07			1.00E–03
Re188m	1.29E–02	1.42E+01	2.86E+07	7.73E+08			1.00E–03
Re189	1.01E+00	3.77E+01	9.61E+05	2.60E+07			1.00E–03
Os185	9.36E+01	5.74E+02	1.62E+05	4.38E+06			1.00E–03
Os189m	2.42E–01	3.41E+02	3.65E+07	9.86E+08			1.00E–03
Os190m	6.88E–03	3.91E–01	1.46E+06	3.95E+07			1.00E–03
Os191	1.54E+01	1.71E+02	2.83E+05	7.65E+06			1.00E–03
Os191m	5.46E–01	8.01E+01	3.75E+06	1.01E+08			1.00E–03
Os193	1.27E+00	2.75E+01	5.48E+05	1.48E+07			1.00E–03
Os194	2.19E+03	1.37E+02	1.58E+03	4.27E+04			1.00E–03
Ir190	1.18E+01	8.02E+01	1.75E+05	4.73E+06			1.00E–03
Ir190m	5.00E–02	7.90E+01	4.06E+07	1.10E+09			1.00E–03
Ir190 N	1.33E–01	2.91E+02	5.60E+07	1.51E+09			1.00E–03
Ir192	7.38E+01	1.31E+02	4.52E+04	1.22E+06	4.44E+04	1.20E+06	1.00E–03
Ir192m	8.76E+04	1.10E+04	3.20E+03	8.65E+04			1.00E–03
Ir194	7.98E–01	1.22E+01	3.86E+05	1.04E+07			1.00E–03
Ir194m	1.71E+02	1.43E+02	2.11E+04	5.70E+05			1.00E–03
Pt191	2.90E+00	1.65E+02	1.45E+06	3.92E+07			1.00E–03
Pt193	1.83E+04	3.63E+06	5.03E+06	1.36E+08			1.00E–03
Pt193m	4.33E+00	2.17E+02	1.27E+06	3.43E+07			1.00E–03
Pt195m	4.02E+00	1.38E+02	8.60E+05	2.32E+07			1.00E–03
Pt197	7.63E–01	6.13E+01	1.99E+06	5.38E+07			1.00E–03
Pt197m	6.56E–02	1.81E+01	6.83E+06	1.85E+08			1.00E–03
Au194	1.65E+00	4.28E+01	6.55E+05	1.77E+07			1.00E–03
Au195	1.83E+02	6.42E+02	8.78E+04	2.37E+06			1.00E–03
Au195m	3.53E–04	1.67E–01	1.19E+07	3.22E+08			1.00E–03
Au198	2.70E+00	5.83E+01	5.33E+05	1.44E+07	3.44E+05	9.30E+06	1.00E–03
Au198m	2.30E+00	2.01E+01	2.16E+05	5.84E+06			1.00E–03

Au199	3.14E+00	8.78E+01	6.86E+05	1.85E+07			1.00E–03
Hg194	1.90E+05	1.90E+04	2.52E+03	6.81E+04			1.00E–02
Hg197	2.67E+00	1.84E+01	1.71E+05	4.62E+06			1.00E–02
Hg197m	9.92E–01	4.06E+00	1.02E+05	2.76E+06			1.00E–02
Hg199m	2.96E–02	4.55E+00	3.78E+06	1.02E+08			1.00E–02
Hg203	4.66E+01	4.45E+01	2.30E+04	6.22E+05	1.59E+04	4.30E+05	1.00E–02
Tl200	1.09E+00	4.40E+01	9.89E+05	2.67E+07			1.00E–03
Tl201	3.04E+00	4.92E+02	3.93E+06	1.06E+08			1.00E–03
Tl202	1.22E+01	4.50E+02	8.89E+05	2.40E+07			1.00E–03
Tl204	1.38E+03	2.65E+04	4.60E+05	1.24E+07			1.00E–03
Tl206	2.92E–03	1.55E+01	1.26E+08	3.41E+09			1.00E–03
Tl207	3.31E–03	1.45E+02	1.03E+09	2.78E+10			1.00E–03
Tl208	2.12E–03	5.34E–02	5.92E+05	1.60E+07			1.00E–03
Tl209	1.53E–03	6.93E–02	1.06E+06	2.86E+07			1.00E–03
Tl210	9.03E–04	3.08E–02	7.93E+05	2.14E+07			1.00E–03
Pb202	1.92E+07	8.46E+06	1.07E+04	2.89E+05			1.00E–03
Pb203	2.17E+00	1.45E+02	1.61E+06	4.35E+07			1.00E–03
Pb205	5.55E+09	6.65E+10	2.86E+05	7.73E+06			1.00E–03
Pb209	1.36E–01	6.81E+01	1.17E+07	3.16E+08			1.00E–03
Pb210	8.14E+03	2.85E+01	8.13E+01	2.20E+03	8.14E+01	2.20E+03	1.00E–03
Pb211	2.51E–02	1.43E–01	1.32E+05	3.57E+06			1.00E–03
Pb212	4.43E–01	1.27E–01	6.60E+03	1.78E+05			1.00E–03
Pb214	1.86E–02	1.27E–01	1.55E+05	4.19E+06			1.00E–03
Bi206	6.24E+00	3.74E+01	1.42E+05	3.84E+06			1.00E–03
Bi207	1.18E+04	3.58E+04	7.18E+04	1.94E+06	7.03E+04	1.90E+06	1.00E–03
Bi210	5.01E+00	1.20E+00	5.56E+03	1.50E+05	5.55E+03	1.50E+05	1.00E–03
Bi210m	1.10E+09	6.64E+06	1.41E+02	3.81E+03			1.00E–03
Bi211	1.48E–03	3.16E+00	4.94E+07	1.34E+09			1.00E–03
Bi212	4.21E–02	1.13E–01	6.19E+04	1.67E+06			1.00E–03
Bi213	3.17E–02	1.04E–01	7.52E+04	2.03E+06			1.00E–03
Bi214	1.38E–02	9.80E–02	1.62E+05	4.38E+06			1.00E–03
Po210	1.38E+02	7.77E–02	1.31E+01	3.54E+02	1.30E+01	3.51E+02	1.00E–02
Po211	5.97E–06	9.25E–03	3.59E+07	9.70E+08			1.00E–02
Po213	4.86E–11	1.55E–05	7.33E+09	1.98E+11			1.00E–02
Po214	1.90E–09	2.23E–04	2.69E+09	7.27E+10			1.00E–02
Po215	2.06E–08	1.42E–03	1.57E+09	4.24E+10			1.00E–02
Po216	1.69E–06	1.16E+00	1.55E+10	4.19E+11			1.00E–02
At211	3.01E–01	2.05E–01	1.58E+04	4.27E+05			1.00E–03
At217	3.74E–07	1.61E–01	9.71E+09	2.62E+11			1.00E–03
Rn218	4.05E–07	5.47E–05	3.03E+06	8.19E+07			1.00E+00
Rn219	4.58E–05	8.35E–05	4.06E+04	1.10E+06			1.00E+00
Rn220	6.44E–04	1.28E–01	4.43E+06	1.20E+08			1.00E+00
Rn222	3.82E+00	1.04E+03	5.98E+06	1.62E+08	5.92E+06	1.60E+08	1.00E+00
Fr221	3.33E–03	1.13E+01	7.52E+07	2.03E+09			1.00E–03
Fr223	1.51E–02	3.52E+01	5.09E+07	1.38E+09			1.00E–03
Ra222	4.40E–04	5.07E+00	2.53E+08	6.84E+09			1.00E–03

Ra223	1.14E+01	7.36E–02	1.41E+02	3.81E+03	1.41E+02	3.81E+03	1.00E–03
Ra224	3.62E+00	6.05E–02	3.65E+02	9.86E+03	3.66E+02	9.89E+03	1.00E–03
Ra225	1.48E+01	9.61E–02	1.41E+02	3.81E+03	1.41E+02	3.81E+03	1.00E–03
Ra226	5.84E+05	3.62E+03	1.34E+02	3.62E+03			1.00E–03
Ra228	2.10E+03	2.47E+01	2.52E+02	6.81E+03			1.00E–03
Ac225	1.00E+01	6.09E–02	1.32E+02	3.57E+03	1.07E+02	2.89E+03	1.00E–03
Ac227	7.95E+03	3.25E–01	8.81E–01	2.38E+01	1.59E–01	4.30E+00	1.00E–03
Ac228	2.55E–01	1.14E–01	9.57E+03	2.59E+05			1.00E–03
Th226	2.15E–02	3.00E–02	3.02E+04	8.16E+05			1.00E–03
Th227	1.87E+01	5.75E–02	6.61E+01	1.79E+03			1.00E–03
Th228	6.98E+02	1.11E–01	3.41E+00	9.22E+01	3.40E+00	9.19E+01	1.00E–03
Th229	2.68E+06	7.81E+01	6.22E–01	1.68E+01			1.00E–03
Th230	2.81E+07	5.38E+03	4.07E+00	1.10E+02	3.29E+00	8.89E+01	1.00E–03
Th231	1.06E+00	6.86E+01	1.36E+06	3.68E+07			1.00E–03
Th232	5.13E+12	2.34E+08	9.61E–01	2.60E+01	6.66E–01	1.80E+01	1.00E–03
Th234	2.41E+01	3.70E+01	3.20E+04	8.65E+05			1.00E–03
Pa230	1.74E+01	5.77E–01	7.05E+02	1.91E+04			1.00E–03
Pa231	1.20E+07	6.95E+02	1.23E+00	3.32E+01			1.00E–03
Pa232	1.31E+00	9.67E–01	1.55E+04	4.19E+05			1.00E–03
Pa233	2.70E+01	1.57E+02	1.22E+05	3.30E+06			1.00E–03
Pa234	2.79E–01	8.54E+00	6.38E+05	1.72E+07			1.00E–03
Pa234m	8.13E–04	7.64E+00	1.96E+08	5.30E+09			1.00E–03
U230	2.08E+01	5.18E–02	5.29E+01	1.43E+03			1.00E–03
U231	4.20E+00	1.86E+02	9.35E+05	2.53E+07			1.00E–03
U232	2.52E+04	1.88E+00	1.58E+00	4.27E+01			1.00E–03
U233	5.81E+07	2.25E+04	8.13E+00	2.20E+02	8.14E+00	2.20E+02	1.00E–03
U234	8.94E+07	3.48E+04	8.13E+00	2.20E+02	8.14E+00	2.20E+02	1.00E–03
U235	2.57E+11	1.09E+08	8.81E+00	2.38E+02	8.88E+00	2.40E+02	1.00E–03
U236	8.55E+09	3.64E+06	8.81E+00	2.38E+02			1.00E–03
U237	6.75E+00	1.03E+02	3.15E+05	8.51E+06			1.00E–03
U238	1.63E+12	7.01E+08	8.81E+00	2.38E+02	8.88E+00	2.40E+02	1.00E–03
U239	1.64E–02	1.57E+01	1.96E+07	5.30E+08			1.00E–03
U240	5.88E–01	1.45E+01	5.03E+05	1.36E+07			1.00E–03
Np235	3.96E+02	5.30E+03	2.78E+05	7.51E+06			1.00E–03
Np236a	4.20E+07	2.17E+04	1.07E+01	2.89E+02			1.00E–03
Np236b	9.38E–01	6.74E–01	1.49E+04	4.03E+05			1.00E–03
Np237	7.81E+08	8.18E+04	2.16E+00	5.84E+01	2.15E+00	5.81E+01	1.00E–03
Np238	2.12E+00	3.49E+00	3.38E+04	9.14E+05	3.37E+04	9.11E+05	1.00E–03
Np239	2.36E+00	5.35E+01	4.65E+05	1.26E+07			1.00E–03
Np240	4.30E–02	3.72E+00	1.76E+06	4.76E+07			1.00E–03
Np240m	5.01E–03	1.71E+00	6.94E+06	1.88E+08			1.00E–03
Pu236	1.04E+03	4.09E–01	8.13E+00	2.20E+02			1.00E–03
Pu237	4.53E+01	1.43E+03	6.52E+05	1.76E+07			1.00E–03
Pu238	3.20E+04	5.50E+00	3.52E+00	9.51E+01	2.29E+00	6.19E+01	1.00E–03
Pu239	8.81E+06	1.38E+03	3.20E+00	8.65E+01	2.07E+00	5.59E+01	1.00E–03
Pu240	2.40E+06	3.77E+02	3.20E+00	8.65E+01			1.00E–03

Pu241	5.24E+03	4.79E+01	1.85E+02	5.00E+03	1.07E+02	2.89E+03	1.00E–03
Pu242	1.36E+08	2.30E+04	3.41E+00	9.22E+01			1.00E–03
Pu243	2.07E–01	7.22E+01	7.03E+06	1.90E+08			1.00E–03
Pu244	2.95E+10	5.02E+06	3.41E+00	9.22E+01			1.00E–03
Pu245	4.38E–01	1.67E+01	7.59E+05	2.05E+07			1.00E–03
Pu246	1.09E+01	1.33E+04	2.44E+07	6.59E+08			1.00E–03
Am241	1.58E+05	1.58E+01	2.03E+00	5.49E+01	2.04E+00	5.51E+01	1.00E–03
Am242	6.68E–01	5.73E–01	1.73E+04	4.68E+05			1.00E–03
Am242m	5.15E+04	5.29E+00	2.07E+00	5.59E+01	2.07E+00	5.59E+01	1.00E–03
Am243	2.69E+06	2.72E+02	2.03E+00	5.49E+01	2.04E+00	5.51E+01	1.00E–03
Am244	4.21E–01	1.28E+00	6.08E+04	1.64E+06			1.00E–03
Am245	8.54E–02	5.65E+01	1.32E+07	3.57E+08			1.00E–03
Am246	2.71E–02	2.83E+00	2.07E+06	5.59E+07			1.00E–03
Cm242	1.63E+02	5.02E–01	6.22E+01	1.68E+03	6.29E+01	1.70E+03	1.00E–03
Cm243	1.06E+04	1.59E+00	3.02E+00	8.16E+01			1.00E–03
Cm244	6.64E+03	1.30E+00	3.92E+00	1.06E+02			1.00E–03
Cm245	3.10E+06	3.05E+02	1.96E+00	5.30E+01	1.96E+00	5.30E+01	1.00E–03
Cm246	1.73E+06	1.70E+02	1.96E+00	5.30E+01			1.00E–03
Cm247	5.69E+09	6.21E+05	2.16E+00	5.84E+01			1.00E–03
Cm248	1.24E+08	3.51E+03	5.56E–01	1.50E+01			1.00E–03
Cm249	4.46E–02	1.05E+01	4.62E+06	1.25E+08			1.00E–03
Cm250	3.54E+06	Unknown	Unknown	Unknown			1.00E–03
Bk249	3.20E+02	1.33E+01	8.13E+02	2.20E+04			1.00E–03
Bk250	1.34E–01	9.93E–01	1.44E+05	3.89E+06			1.00E–03
Cf248	3.34E+02	4.16E–01	2.46E+01	6.65E+02			1.00E–03
Cf249	1.28E+05	1.92E+01	2.94E+00	7.95E+01			1.00E–03
Cf250	4.77E+03	1.36E+00	5.56E+00	1.50E+02			1.00E–03
Cf251	3.28E+05	4.81E+01	2.86E+00	7.73E+01			1.00E–03
Cf252	9.65E+02	4.05E–01	8.13E+00	2.20E+02	1.11E+01	3.00E+02	1.00E–03
Cf253	1.78E+01	3.25E–01	3.52E+02	9.51E+03			1.00E–03
Cf254	6.05E+01	1.19E–02	3.78E+00	1.02E+02			1.00E–03
Es253	2.05E+01	3.40E–01	3.20E+02	8.65E+03			1.00E–03
Es254	2.76E+02	4.21E–01	2.94E+01	7.95E+02			1.00E–03
Es254m	1.64E+00	1.91E–01	2.25E+03	6.08E+04			1.00E–03
Fm254	1.35E–01	1.51E–01	2.16E+04	5.84E+05			1.00E–03
Fm255	8.36E–01	2.01E–01	4.60E+03	1.24E+05			1.00E–03

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APPENDIX B
IDENTIFICATION OF POTENTIAL HAZARDS, ENERGY SOURCES, AND GENERIC ACCIDENTS FOR FUSION FACILITIES

B.1 Introduction

This appendix presents a discussion of the potential hazards, energy sources, and generic accident scenarios associated with fusion facilities. A bibliography of the large amount of similar work that has been done in the worldwide fusion safety community in the past is included at the end of the document. Because of the generic nature of this list, a particular hazard, energy source, or accident scenario may or may not be relevant to every fusion system. The existence of a hazard and its magnitude are dictated by the specifics of a facility design including its mission, function, materials, size, and power level. The intent of the listing is to provide a starting point to implement the requirements in the main text related to hazard identification and development of event trees or accident scenarios for the specific fusion facility. A secondary but equally important use of this listing is to ensure that hazards that are not an integral part of a specific system but that can have an interfacing effect are also identified.

B.2 Hazards

The hazards associated with fusion consist of radiological, chemical, and industrial hazards. In addition, fusion has a number of energy sources that must be managed effectively to prevent accidents that would result in release of chemical and radiological hazards. The hazards are discussed below.

B.2.1 Radiological Hazards

The dominant radiological hazards are tritium, which is the fuel in the deuterium-tritium (D-T) fusion reaction, and activation products that are produced as a result of neutron interaction with materials and fluids surrounding the plasma. Hazards from direct exposure to fusion neutrons will normally be mitigated by design features and administrative controls.

Tritium inventories are a strong function of the fusion facility design. Tokamak Fusion Test Reactor (TFTR) is limited to contain less than 5 g of tritium, whereas the inventory of tritium in the International Thermonuclear Experimental Reactor (ITER) is expected to be between 1 and 10 kg. Tritium can be found in plasma-facing components (PFCs) in the fuel process system, the vacuum pumps and fuel injectors, in the blanket and associated processing system, and in storage. Tritium is also present in neutral beam injectors and associated cryopanels. The tritium inventory in each of these systems must be assessed to determine the associated hazard. The dispersion and oxidation characteristics in an off-normal event will influence the degree or severity of the hazard for tritium that may be released.

For machines such as ITER that will experience a high neutron fluence, activation products will constitute the largest source of radioactivity. For ITER, an inventory of 10^{20} Bq (3×10^9 Ci) is estimated for the stainless steel shield and vacuum vessel during the later phases of operation. The inventory in the structure and the potential hazard to the public are directly related to the structural material. The use of low activation materials for fusion structural components can influence the potential hazard. The majority of these activation products (~98 to 99%) will be bound in solid metal structures such as the first wall, blanket, and divertor and would only be mobilized during off-normal conditions. Mechanisms for mobilization include partial vaporization during a plasma disruption, oxidation-driven volatilization due to chemical reactions of the structure with air and/or steam, and magnet coil electrical arcing.

Smaller inventories of activation products include the following:

a. corrosion products that will be circulating in coolant streams from actively cooled structures like the blanket and divertor,

b. “tokamak dust” produced by erosion of material from the surfaces facing the plasma due to interaction with high-energy neutrals and ions from the plasma, and

c. activated air inside the building as a result of neutron leakage and streaming.

These activation product inventories are operational, maintenance, and accident concerns.

The hazard associated with activation products is a function of the structural, PFC, and coolant materials that are used in the design, the power level of the machine, and the expected neutron fluence.

B.2.2 Chemical Hazards

Many fusion devices may use materials that are chemical hazards. For example, beryllium is the current plasma facing material of choice for ITER. It is toxic, and special precautions need to be taken to work with it, as demonstrated at the Joint European Torus (JET), a large tokamak in the United Kingdom. Vanadium, a potential low-activation structural material, is chemically hazardous when in the oxide form. Because of the production of metallic dust in the tokamak, the hazard of PFC materials that are not normally considered toxic in solid form needs to be examined.

B.2.3 Industrial Hazards

Industrial hazards associated with fusion include asphyxiant gases, radio frequency (RF) fields, high voltage, magnetic fields, and heavy lifts. Many of the fusion machines will use superconducting magnets and/or cryopumps that are cooled with liquid nitrogen and helium. Accidental release of these gases would displace oxygen and could be an occupational hazard (e.g., suffocation). Some fusion machines will use RF heating as a means to supply power to the plasma to obtain ignition. Some may use neutral beam injectors. Both have high-voltage hazards. The magnets used to confine the plasma can cause high external magnetic fields. The RF fields and magnetic fields are hazards that needs to be managed at the facility during operation. None of these hazards are unique to fusion *per se* but are included for completeness.

Standards exist in other industries for dealing with these hazards to provide adequate protection for workers.

B.3 Energy Sources

In fusion a number of distributed energy sources could potentially induce accidents that can result in release of radioactivity or toxic materials. The amount of energy, the time scales for its release, and the potential consequences are a function of the specific fusion design. The various energy sources are discussed below.

B.3.1 Plasma Energy

The fusion plasma generally contains very little stored energy (e.g., on the order of 1 GJ for ITER). However, because the fusion reaction is a reaction that takes place in the plasma, a complex control system may be needed to provide for control of the plasma during the reaction. This is known as plasma burn control. The control system contains a fueling system, a magnetic confinement and plasma position control system, a current drive system, an auxiliary heating system, an impurity control system, and a vacuum system. Failure in any of these systems would result in extinguishing the plasma, which may be accompanied by a plasma disruption. The plasma can disrupt very quickly and the energy contained in the plasma can be imparted to the plasma-facing materials very quickly (~ms), which can cause significant PFC armor tile ablation and/or melting. In addition, the plasma current will rapidly quench (time scale is ~ms to 1 s) and produce magnetically induced forces in the structures that must be accounted for in the design.

B.3.2 Magnetic Energy

The energy stored in the superconducting magnets of a fusion device can be very large. For ITER, the magnets will contain on the order of 100 GJ that can be released on the order of seconds to minutes as the result of arcing, shorts, or a quench with magnet discharge (loss of cryogen). Fusion designs must contain provisions for control and potential dissipation of this stored energy source without causing propagating faults in other systems. The most important aspect of magnet design from a safety viewpoint is to ensure that the magnet structural integrity and geometry are maintained for credible accident conditions so that magnet structural failure cannot result in the release of radioactive or toxic materials.

B.3.3 Decay Heat

The activation products produced during operation of a fusion device will generate decay heat. The level of decay heat may be on the order of 2 to 3% of the steady state operating power but is a function of the structural materials used and the accumulated neutron fluence. For smaller fusion devices, decay heat may not be a significant energy source because of the low power level and fluence expected. For ITER, operating at 1500 MW, the decay heat would be about 30 to 40 MW. Removal of this energy is needed during normal operation between pulses, during maintenance and bakeout, and during decommissioning to prevent overheating of structures and volatilization of activation products. Because the decay heat is distributed throughout the entire structure, the overall power density is relatively low.

B.3.4 Chemical Energy

Large quantities of chemical energy can potentially be liberated by reaction of certain fusion materials with air or water under off-normal or accident conditions. Potential fusion materials include the following:

PFCs—W, Be, C, Cu, Nb
Structural Materials—stainless steel, ferritic steel, vanadium alloys
Coolants—water, Li, LiPb, NaK, Na, Ga, He

Most of the reactions between the PFCs and structural materials with water are exothermic (some are endothermic). Alkali liquid metals (Li, NaK, and Na) produce exothermic reactions with air, water, and concrete. In the event of an assumed in-vessel reaction, the heat generated by the reaction can cause the surrounding structures to heat up and volatilize activation products. Steam reactions can generate flammable or explosive concentrations of hydrogen. The magnitude of the chemical energy problem is a strong function of the materials that are used in the machine, the amount of material available for interaction, and the ability of the design to prevent the chemical interaction and to mitigate the consequences should it occur.

In addition to these chemical hazards, the production of explosive levels of ozone from external radiation in cryogenic systems such as the cryostat needs to be considered.

B.3.5 Coolant Internal Energy

Pressurized coolants will be used in some of the components of fusion machines. Water is a common coolant for PFCs. Liquid nitrogen and liquid helium are used in cryopumps and the cryoplant. Liquid helium is also used to cool the superconducting magnets. The energy released during a sudden loss of coolant for all of these coolants needs to be considered in the design because of the high pressures that could be developed as a result of the spill. The case of an in-vessel loss of coolant water is a particular concern because the blowdown of water will produce steam that could react with the hot PFCs and generate hydrogen, as discussed previously. Many design options are available to deal with the pressurization potential of these coolants including having expansion volumes available to collect the gas and making the component (e.g., cryostat, vacuum vessel, and building) robust enough to handle the peak coolant pressure during the event.

B.4 Potential Generic Accident Scenarios

Past conceptual design studies on fusion power plants and recent safety analyses performed for current machines have identified a number of generic accident scenarios that need to be considered in determining the potential for the energy sources mentioned earlier to mobilize the radioactive and/or toxic materials available in a fusion machine. This section contains a brief description of each class of accident that can be used as a starting point for a detailed machine-specific hazard analysis.

B.4.1 Loss-of-Coolant Event

Loss-of-coolant events (LCEs) refer to the actively cooled components that remove the fusion power (e.g., blanket, shield, vacuum vessel, or divertor cooling systems). The seriousness of the event depends on the coolant being used in the design (e.g., water, liquid metal, and helium) and details of the design (e.g., segmentation of cooling loops, material, and length of piping).

Two types of LCEs have generally been considered in fusion conceptual design studies: in-vessel LCE and ex-vessel LCE. The in-vessel LCE would spill coolant into the torus that could cause pressurization and potential chemical reaction with hot PFC surfaces. The magnitude of the pressurization is a function of the spill size, the coolant being used, the surface temperature of the PFC, the internal energy of the coolant, and for water the presence of condensation surfaces. The introduction of coolant into the plasma chamber would result in a plasma disruption and terminate the plasma.

Ex-vessel LCEs generally tend to be larger in terms of coolant loss than in-vessel LCEs because of the size of the ex-vessel piping that transports coolant to the heat removal systems (e.g., steam generator and heat exchanger). Rapid detection of ex-vessel LCE may be required so that the plasma shutdown system can terminate the plasma before damage would occur to the divertor and first wall. The time scale for such detection and shutdown is a strong function of the heat loads on the PFCs and could be on the order of seconds.

B.4.2 Loss-of-Flow Event

Both in-vessel and ex-vessel loss-of-flow events (LFEs) have been considered in past conceptual design studies for fusion machines. The consequences of such events are a strong function of the coolant material, the heat loads on the divertor and first wall, and the design of the heat transport systems. LFEs can lead to an in-vessel LCE because of the possibility of tube burnout if plasma shutdown is not accomplished quickly (in seconds).

Ex-vessel LFEs tend to be dominated by loss of off-site power, which results in pump coastdown. Loss of pumping power would need to trigger the plasma shutdown system to prevent propagation of the LFE into an in-vessel LCE. For an in-vessel LFE, the concern is tube plugging or coolant channel blockage. Because of the small tubing in most in-vessel components, an in-vessel LFE would result in burn-through of the tube or channel wall and a small in-vessel LCE. The subsequent injection of coolant into the plasma chamber would terminate the plasma probably due to a plasma disruption. The system would then have to be cooled down and the failed tube or channel isolated and plugged to recover from the event.

B.4.3 Loss-of-Vacuum Event

A loss-of-vacuum event (LVE) occurs when the vacuum inside the plasma chamber is lost. An LVE can occur as a result of a failure of a diagnostic window, port, or other seal due to either incipient flaws, wearout, radiation, embrittlement, or overpressurization of the plasma chamber due to an in-vessel LCE. The LVE can then provide a pathway for release of tokamak dust and any tritium gas from the vacuum vessel. The ingressed air can also react with hot PFC surfaces and generate additional chemical energy that could volatilize radioactivity from the PFC surface. The ultimate impact of such releases is a function of both in-vessel and ex-vessel features of the design.

B.4.4 Plasma Transients

The two classes of plasma transients that are potentially important to safety are transient overpower events and plasma disruptions. A fusion overpower event can occur in an ignited plasma when a balance is not maintained between fusion generation and loss. The result is an increase in plasma temperature (and thereby thermal energy) until either a power balance is reestablished or a beta limit is exceeded. Exceeding a beta limit would trigger a disruption and shutdown the plasma. Plasma disruptions cover a range of transient events in which confinement of the plasma is lost and the plasma energy is transferred to the surrounding structure very quickly. The rapid energy transfer can cause armor tile ablation and/or melting. In addition, the plasma current will rapidly quench (time scale is 1 ms to 1 s) and generate magnetically induced forces in the structures that must be accounted for in the design. There are numerous initiators for plasma disruptions including thermal plasma excursions, impurities injected into the plasma, loss of plasma position control, and vertical displacement events. Many of these disruptions are considered to be anticipated operational occurrences and hence would need to be covered by the design. In addition, certain plasma disruptions will generate high-energy electrons, termed "runaway" electrons. These electrons can damage PFCs and be an initiator for a common mode failure of blanket and divertor cooling systems.

B.4.5 Magnet Transients

The major concern about magnet transients is the potential for propagating faults to other components of the fusion machine. The magnet faults of concern from an accident propagation viewpoint are off-normal forces that would produce large coil displacements, break off magnet pieces, and pull in ferrous missiles from other areas or arcs that could produce melting and volatilization in other components. In ITER, these events could have the potential to damage the vacuum vessel, ducts and piping from the vacuum vessel, and the cryostat and could potentially result in radioactivity release. Off-normal forces could arise from shorts in coils, faults in the discharge system, or power supply faults. Arcs between coils, arcs to ground, and arcs at open leads could lead to melting and/or volatilization. Arcs could arise from insulation faults, gas ingress, overvoltage, or other causes.

B.4.6 Loss of Cryogen

Loss of cryogen (either helium or nitrogen) is a potential safety concern because the pressure that can be developed as a result of the leak can threaten radioactivity confinement barriers in the fusion machine, and the cryogen can displace oxygen and present a suffocation potential for personnel. For superconducting magnets, quenching of a superconductor without electrical discharge could lead to leakage or even local bursting of the superconductor and subsequent release of helium. Faults in the cryoplant can lead to flashing of liquid nitrogen. The amount of cryogen that can be released is a function of the design details of the cryoplant and of the superconducting magnets (if used).

B.4.7 Tritium Plant Events

The tritium processing and fueling/pumping systems contain inventories of tritium that can be released in the event of an accident that could breach the tritium confinement barrier system. Generally, tritium system design standards call for double or triple containment for components or systems that contain tritium that would tend to reduce the frequency of large releases. In addition, the potential for hydrogen explosions must be considered. Dispersion and oxidation characteristics will influence the severity of the hazard.

B.4.8 Auxiliary System Accidents

Fusion machines may use a number of auxiliary systems associated with plasma heating, current drive, machine bakeout, and fueling. In general, accidents with these systems may include toxic materials and gram-quantities of tritium that may reside on individual components.

B.4.8.1 Neutral Beams

Neutral beam injectors may be used as a means of providing heating to the plasma during startup and operation. Operation of the beam without a plasma or misalignment in the chamber can lead to ablation and/or melting of material from the surface where the beam lands and potential release of radioactivity. Circuitry control interlocks and protective armor in the torus are usually employed to preclude this scenario from being credible.

B.4.8.2 RF Heating

Some fusion designs call for the use of RF heating to assist in startup and operation. Safety concerns related to the high power levels are adequately addressed in traditional electrical safety standards.

B.4.8.3 Fuel System

Pellet injectors are one method of fueling the core of the plasma. These injectors drive solid pellets (T, D, Li, etc.) into the plasma at high velocity (several km/s). The kinetic energy imparted by the injector can be large enough to warrant preventive safety measures, such as backstops.

B.4.8.4 Vacuum Pumps

Fusion devices employ large vacuum pumps. Turbomolecular pumps generally have high-speed rotors that pose mechanical safety concerns. Vacuum reservoirs can be dangerous unless guarded to prevent personnel from being drawn against a leak location. Cryopumps have the additional concern of large gas inventories that may expand when the pumps are allowed to come to ambient temperature, causing pressurization and possible tritium contamination problems.

B.4.8.5 Wall Conditioning and Bakeout Systems

Wall conditioning of in-vessel components is performed by a variety of techniques (e.g., glow discharge cleaning, bakeout, and diborane deposition) to remove impurities from surfaces. In addition, external systems containing tritium may undergo bakeout and/or cleaning to reduce tritium inventories in the material. Accidents under these conditions need to be considered in addition to accidents during operation.

B.4.8.6 Energy Storage

Because of their pulsed operation, some fusion systems may use energy storage devices (e.g., alternating rotor and flywheel) in the power plant; the failure of these devices could pose a hazard not usually found in other power-conversion systems.

B.4.9 Maintenance Events

Activation of structures by fusion neutrons will require much of the maintenance of facilities such as ITER to be done remotely. While this may reduce direct exposure of personnel to radiation, the probability of accidentally breaking something is significantly increased. There will be hazards of fluid conduit rupture, activated dust dispersion, and similar kinds of events associated with remote maintenance. Also, for items removed to hot cells for maintenance or other activities, normal hazards associated with hot-cell facilities should be considered.

APPENDIX C
REFERENCES AND SUPPLEMENTAL GUIDANCE

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