SAFETY OF MAGNETIC FUSION FACILITIES - VOL 3 OF 3

Main Category:	Nuclear Engineering
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Exam Preview:

1. According to the reference material, a hydrogen detonation is a potential hazard that may be a design-basis event (typical probability $>10^{-8}$/yr).
   a. True
   b. False
2. Using TABLE 6.1. Suggested design codes for equipment, which of the following codes dictates the design and fabrication of tanks with operating pressures between 0 to 15 psig?
   a. ANSI/ASME B31.3
   b. AWWA D-100
   c. API 620
   d. API 650
3. It is likely that several (_______) confinement barriers will be needed to confine in-vessel radioactive and toxic materials. The design of successive confinement barriers must therefore ensure that each separate barrier be independent.
   a. 1 to 2
   b. 2 to 3
   c. 3 to 4
   d. 4 to 5
4. According to the reference material, the lower flammability limit for H2 is about 4% volume in air; the lower explosive limit for H2 in air depends on geometry and is about 25% by volume
   a. True
   b. False

5. A radiation seal or shield should be considered for a penetration or void in the case where the centerline is <_ ft above the floor and the penetration is >2 in. (except for high-dose-rate cubicles).
    a. 4
    b. 6
    c. 8
    d. 10
6. According to the requirements for land disposal of radioactive waste, Class C waste is assumed to be stable for 200 yr.
    a. True
    b. False
7. The safe removal of afterheat (decay heat) is an issue to be evaluated in D-T fusion facilities. Typically, the afterheat amounts to several percent of the normal operating fusion power. One day following shutdown, it decreases by a factor of 3 to __ depending on the materials and the operating scenario (pulsed vs continuous operation).
    a. 10
    b. 12
    c. 6
    d. 9
8. According to the reference material, sealed, quick-disconnect-type connectors should be avoided, and individual wiring methods should be used wherever possible.
    a. True
    b. False
9. According to the reference material, the _______°C range is critical with respect to beryllium reactions. Since the beryllium–water and beryllium–air reactions are exothermic (377 kJ/gmole beryllium), the major concern for short-term hydrogen production comes from reactions that are self-sustained.
    a. 450-500
    b. 500-550
    c. 550-600
    d. 600-650
10. Which of the following codes and standards should be considered for the design, fabrication, inspection and testing of overhead and gantry cranes?
    a. NFPA 70, Art 610
    b. CMAA 70 and /or ASME NOG-1
    c. ANSI B30.2
    d. ANSI B30.10

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.

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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

6. FACILITY DESIGN GUIDANCE

6.1 Introduction and General Guidance

This section describes an acceptable but not necessarily unique way to implement DOE-STD-6002-96, “Safety of Magnetic Fusion Facilities: Safety Requirements,” in the design and construction of near-term deuterium-tritium (D-T) fusion facilities that will satisfy the intent of Department of Energy (DOE) nonreactor nuclear safety requirements. To achieve adequate safety, it is important to take safety into account as an inherent element in the design process, beginning with conceptual design. Basic early design decisions, such as materials selection and performance specifications, can have a significant impact on safety. A graded approach should be used in the application of these safety design criteria to ensure that the level of detail required and the magnitude of resources expended for the design are commensurate with the facility’s programmatic importance and the potential environmental, safety, and/or health impact of normal operations and off-normal events, including design-basis events.

6.1.1 Design Basis

The facility design basis should specify the necessary capabilities of the facility to cope with a specified range of operational states, maintenance, and other shutdown activities, as well as off-normal conditions to meet the radiological and toxic material acceptance criteria in DOE-STD-6002-96. The facility design should recognize that both internal (down to a probability of 10^{-6}/yr per event) and external challenges to all levels of defense may occur, and design measures should be provided to ensure that key safety functions are accomplished and that safety objectives can be met.

In establishing a set of external challenges, the design basis should include consideration of natural phenomena (e.g., earthquakes, floods, high winds); environmental effects; and dynamic effects (e.g., pipe ruptures, pipe whip, and missiles). The importance of these off-normal events in the design basis should be evaluated based on the risk (both probability and consequences) of these types of scenarios as identified by the event trees developed for the facility safety analysis (see Chapter 5). Design-basis events should be specified in the safety analysis and mitigated in the system design. The following are potential design-basis events for fusion D-T facilities:

a. fusion overpower transient;

b. loss of flow or coolant pressure to actively cooled components;

c. loss of vacuum or vacuum pumping;

d. chemical reactions including hydrogen detonation;

e. site-generated missile impact from, for example, a catastrophic motor generator (MG) set failure;

f. design-basis natural phenomenon: earthquake, flooding, severe winds, and so on.

However, any of these may be categorized as beyond-design-basis events depending on the probability per event as assessed in the safety analysis. There are no specific design requirements for beyond-design-basis events although such events may be considered in the safety analysis process to quantify a range of hazards for site or public evacuation analysis.

The detailed design process should establish a set of requirements and limitations for safe operation of the facility including consideration of

a. constraints on process variables and other important system parameters;

b. safety-class structures, systems and components (SSCs) settings;

c. requirements for maintenance, testing, and in-service inspection of the facility to ensure the SSCs required to implement safety functions are within the design envelope;

d. training requirements for facility personnel.

6.1.2 Safety Functions and Structures, Systems, and Components

Public safety functions as defined in DOE-STD-6002-96 are those essential characteristics needed to ensure the safety of the facility and protection of the public and the environment. DOE-STD-6002-96 defines the public safety function for fusion facilities as

> confinement of radioactive (e.g., tritium, activated dust, activation and corrosion products) and toxic (e.g., Be and V dust) materials.

SSCs required for the performance of a public safety function necessary to meet DOE-STD-6002-96 evaluation guidelines should be designated as safety-class. This includes supporting systems such as power, instrumentation and control (I&C), and cooling that directly support a system performing such a public safety function (see Section 6.4). Safety-class items should be subject to more formal and rigorous design, fabrication, and industrial test standards and codes as well as an enhanced quality assurance (QA) program to increase the reliability of the item and allow credit to be taken for its capabilities in the safety analysis process. These SSCs should be designed to function in operational states and during and following off-normal conditions, including design-basis events if credited to function in the safety analysis.

Associated with the public safety function are potential safety concerns that must be addressed during the design process to minimize challenges to the public safety function. Potential safety concerns associated with confinement of radioactive and/or toxic materials should be considered:

a. ensuring afterheat removal when required;
b. providing rapid plasma shutdown 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.

These safety concerns are normally addressed by SSCs, preferably passive, with *a design goal to eliminate the potential concern as a safety issue.* If degradation or failure of such SSCs could threaten the continued ability to perform a public safety function or significantly reduce defense-in-depth relative to public safety, the SSCs should be designated as safety-significant. If degradation or failure of such SSCs results in the exceeding of the public evaluation guideline, the SSCs should be designated as safety-class.

Worker safety functions as defined in DOE-STD-6002-96 are those essential characteristics needed to ensure the safety of the facility and protection of workers. DOE-STD-6002-96 defines the worker safety function for fusion facilities as

> control of operating hazards such as worker exposure to: ionizing radiation, hazardous materials, high magnetic fields, high power lasers, high voltage sources, cryogenic fluids, etc.

SSCs required for the performance of a worker safety function should be designated as safety-significant if acute worker fatality or serious injury could result from SSC failure. These SSCs should be designed to function in operational states and during and following off-normal events as specified in the safety analysis.

The concept of safety-significant SSCs is discussed in DOE 1994a. Incremental design and QA standards (over and above conventional industrial practice) as well as functionality testing, enhanced surveillance, etc. for safety-significant SSCs should be evaluated and applied for each safety-significant SSC in a given facility considering

a. the degree to which failure can threaten a public or worker safety function (i.e., consequence of failure),

b. the potential degradation of defense-in-depth protection,

c. the probability of degradation or failure, and

d. the ability to restore or repair the SSC in a timely manner to resume operations.

The design of SSCs that are not safety-class items should, as a minimum, be subject to conventional industrial design standards, codes, and quality standards. Failure of these items should not adversely affect the environment or the safety and health of the public. In addition, their failure should not prevent safety-class items from performing their required safety functions.

6.1.3 General Design Guidance

Before providing system-specific design guidance, some general principles of design are given below. These principles will assist in achieving facility safety requirements and goals and also have broader value in meeting device performance specifications and providing a measure of investment protection, which is a requirement for eventual electric utility acceptance of fusion power plants. These principles apply specifically to safety-class SSCs but should be considered using a graded approach for safety-significant SSCs.

6.1.3.1 Design for Reliability

Unavailability limits for safety-class SSCs should be established to ensure the required reliability for the performance of the key safety functions. The measures below should be used, if necessary in combination, to achieve and maintain the required SSC reliability. The required reliability should be developed in accordance with the importance of the safety function performed by the SSC to protect on-site personnel and the public.

a. *Simplicity.* The principle of design simplicity should be applied, as appropriate, to enhance the reliability of systems. Less complex systems are generally more reliable. An example of simplicity may be choosing a burst disk over a relief valve for overpressure protection or designing the system for a greater pressure than all credible design-basis events.

b. *Diversity.* The principle of diversity can enhance reliability and reduce the potential for common cause failures. It should be adopted wherever feasible. Note that there is an operational cost for diversity in terms of spare parts, operator training, and device complexity. An example of diversity involves a relief valve and burst disk on a mechanical system, each of which can relieve overpressure at the required rate.

c. *Independence*. The principle of independence should be applied, as appropriate, to enhance the reliability of systems, in particular with respect to common cause failures. Independence is accomplished in the design of systems by using functional isolation and physical separation (e.g., separation by geometry and barriers). An example of independence is a situation in which two relief valves on a mechanical system are at opposite ends of the piping runs.

d. *Redundancy*. The principle of redundancy should be applied as an important design principle for improving the reliability of safety-class SSCs and guarding against common cause failures. Multiple sets of equipment that cannot be tested individually should not be considered redundant. The degree of redundancy should reflect the potential for undetected failures that could degrade reliability of the safety function. An example of redundancy is a situation in which each of two relief valves on a mechanical system can relieve overpressure at the required rate.

e. *Fail-safe and Fault-tolerant Design.* The fail-safe principle should be applied to safety-class and safety-significant SSCs; that is, if a system or component failed, the device should pass into a safe state without a requirement to initiate any actions. The system design should be fault-tolerant to the maximum extent feasible. An example of a fail-safe feature would be a safety-related isolation valve that automatically fails closed on loss of power or actuating air. Additionally, the design should ensure that a single failure does not result in the loss of capability of a safety-class SSC to accomplish its required public safety function. Fluid and electrical systems are considered to be designed against an assumed single failure if neither

1. a single failure of any active component (assuming passive components function properly) nor

2. a single failure of a passive component (assuming active components function properly)

results in a loss of the capability of the system to perform its safety function. Note that for some passive mechanical components such as piping or pressure vessels, there may not be a credible failure mode. For other passive mechanical components such as burst disks, vacuum windows, or bellows, the credibility of a single failure should be determined on a case-by-case basis.

f. *Testability.* All safety-class and safety-significant SSCs should be designed and arranged so that they can be adequately inspected, tested, and serviced as appropriate before commissioning and at suitable and regular intervals thereafter. If it is not feasible to provide adequate testability of a component, then the safety analysis should take into account the possibility of undetected failures of such equipment. For example, an installed burst disk cannot be tested, but there may be no credible failure modes that prevent it from performing the intended safety function.

6.1.3.2 Defense-In-Depth

Fusion facilities should apply the "defense-in-depth" concept in design. The design process should incorporate defense in depth such that multiple levels of protection are provided against the release of radioactive and toxic material if required. The necessary level of protection is a function of the risk to the public and workers. Aspects of the defense-in-depth concept that are applicable to fusion facilities include the following:

a. the selection of materials (especially fusion island materials) and other design inputs to reduce radiological and toxic materials inventories;

b. the use of conservative system design margins, taking into account uncertainties in material performance and the operating environment;

c. the use of a succession of *independent* physical barriers (passive is preferred) for protection against release of radioactive and/or toxic materials;

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

e. the use of basic design features, equipment, operating and administrative procedures to prevent off-normal events and to control and mitigate off-normal events should they occur;

f. the implementation of a rigorous and formalized QA program during the design, construction, and operation phases on safety-class SSCs; it may be of benefit to apply the QA program consistently to the entire fusion island or facility for investment protection and assurance of completing the programmatic mission;

g. use of emergency plans as required to mitigate the effects of radioactive and/or toxic releases to the workers and the public;

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

A graded approach should be used in the implementation of the defense-in-depth concept for fusion facilities depending on the level of hazard in the facility and the risk to on-site personnel and the public.

6.1.3.3 Design Verification

As stated in DOE-STD-6002-96, the applicability of the design methods shall be verified and the methods validated. Computer codes or other computational methods supporting the design of safety-class SSCs should have validation and verification (IEEE 1984) for the range of normal operations and off-normal events, including design-basis events. This validation and verification should support the use of the computational method in each intended application. Furthermore, an equipment qualification procedure should be established for safety-class items to confirm that the equipment is capable of meeting the public safety function for the facility while subject to the environmental conditions (e.g., vibration, temperature, pressure, jet impingement, radiation, humidity, chemical attack, magnetic fields) existing at the time of need. Experimental data used in the design process or in the safety analysis should undergo formal certification. This general area is also discussed in Chapter 4 of this document.

6.1.3.4 Codes and Design Standards

Where appropriate, safety-class SSCs should be designed in accordance with recognized industry standards such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME 1992) for mechanical or structural systems. The applicable code and/or design standard should be identified for each safety-class SSC and its use justified by the fusion facility project manager prior to initiating the detailed design phase of a project. If different codes and standards are used for different aspects of the same part of a safety-class SSC, the consistency among them, insofar as safety is affected, should be demonstrated. Areas addressable by codes and standards may include but are not limited to the following:

a. mechanical design;
b. structural design;
c. earthquake resistant design;
d. selection of materials;
e. fabrication of equipment and components;
f. inspection of fabrication and installed safety-class items;
g. thermohydraulic and neutronic design;
h. electrical design;
i. design of instrumentation and control systems;
j. shielding and radiological protection;
k. fire protection;
l. inspection, testing, and maintenance as related to design;
m. cryogenic design;
n. magnetic system design;
o. vacuum system design;
p. safety.

For safety-class SSCs in fusion facilities for which there are no appropriate established codes or design standards, an approach derived from existing codes and design standards for similar equipment may be applied, or, in the absence of such codes and design standards, the results of experience, tests, analysis, or a combination thereof may be applied. Either approach should be justified. The approach should be shown to meet the intent of a recognized safety-related code or design standard.

Where codes are available and applicable, SSCs that are not safety-class should be designed, fabricated, inspected, and tested in accordance with a recognized national consensus code for general construction such as (as an example for mechanical systems) ANSI 1993a.

a. Structural Design Considerations

DOE 1989 states that safety-class SSCs shall be designed to the ASME Boiler and Pressure Vessel Code (ASME 1992), Section III or other comparable safety-related codes. For structural design of safety-class SSCs using ASME 1992, the complex nature of many fusion components may require specific analysis under the alternate design rules of Section III, Class 1 or 2 or the comparable elements of Section VIII, Division 1 or Division 2 for pressure vessels. In defining a comparable code to ASME Section III, the use of ASME Section VIII is acceptable if additional standards are provided in areas such as attached valves, pumps, piping and supports, enhanced QA, and radiation effects that are comparable to relevant parts of Section III. In general, a detailed comparison should be made between ASME, Section III and the comparable code to be used to design safety-class SSCs to demonstrate actual comparability. This code comparison should be performed early in the design phase and should be endorsed by the controlling authority to ensure the design product will be acceptable for construction. Finally, the actual stamping of a vessel designed, fabricated, inspected, and tested to ASME Section III or VIII is not addressed by this Standard and is considered to be a decision between the owner, fabricator, and the controlling authority. Table 6.1 provides general recommendations for use of design codes for various mechanical components.

TABLE 6.1. Suggested design codes for equipment[a]

Equipment	Design and fabrication	Materials	Welder qualification and procedures	Inspection and testing
Pressure vessels	ASME Code Sect. VIII or III	ASME Code Sect. II	ASME Code Sect. IX	ASME Code Sect. VIII or III
Atmospheric tanks	API 650, or AWWA D-100[b]	ASME Code Sect. II[b]	ASME Code Sect. IX	API 650, or AWWA D-100[b]
0- to 15-psig tanks	API 620[b]	ASME Code[b] Sect. II	ASME Code Sect. IX	API 620[b]
Heat exchangers	ASME Code Sect. VIII, and TEMA	ASME Code Sect. II	ASME Code Sect. IX	ASME Code Sect. VIII
Piping and valves	ANSI/ASME B31.3	ASTM and ASME Code Sect. II	ASME Code Sect. IX	ANSI/ASME B31.3
Pumps	Manufacturers' Standards[c]	ASME Code Sect. II or Manufacturers' Standards	ASME Code Sect. IX (as required)	Hydraulic Institute

[a]The preferred design code for safety-class pressure retaining components is the ASME Code.
[b]Fiberglass-reinforced plastic tanks may be used in accordance with appropriate articles of Section X of the *ASME Boiler and Pressure Vessel Code* for applications at ambient temperature.
[c]Manufacturers' standard for the intended service. Hydro or pneumatic pressure testing should be 1.5 times the design pressure.

b. Loads

The following are typical loads to consider in the structural design process. The example given is for an in-vessel component; for ex-vessel components, loads due to plasma disruptions, for example, may not be a design factor. This list is provided as a starting point for the delineation of loads for specific SSCs and may be incomplete for a particular design. The structural designer must consider all normal and off-normal events identified in the safety analysis process in defining load combinations for particular safety-class SSCs.

The SSC under consideration should be designed to withstand the static load, pressure load, thermal load, electromagnetic loads (normal operating and fault), disruption/vertical displacement event (VDE) loads, interaction loads from adjacent systems, and transient loads due to normal operations and off-normal events, including design-basis events.

1. Static loads—The static load should include the weight of the equipment identified as constituting the system (or component), any supported hardware, and process media such as liquid inventory.

2. Pressure load—The pressure load should include the full range of credible internal and external pressures during normal operations and off-normal events including design-basis events. Additionally, the pressure load range should include temperature-induced pressures, hydrostatic or pneumatic test pressures, and any credible pressure augmentation resulting from small leaks between two coupled systems.

3. Thermal load—The thermal load should include transient thermal loads as well as the temperature distribution during bakeout and wall conditioning.

4. Electromagnetic loads—Electromagnetic loads induced during operation of the device are experienced as a result of currents in the component under evaluation interacting with external magnetic fields. Loads should include the electromagnetic effects of discharge cleaning where appropriate.

5. Electromagnetic loads during faults—Electromagnetic loads should include those induced during off-normal operating events such as control failures, power supply failures, bus opens or shorts, or magnet faults.

6. Disruption/VDE loads—Disruption/VDE loads are any thermal or electromagnetic loads induced in the component due to loss of control of the plasma. A range of plasma motions and current behaviors should be considered to determine the worst case events. Analysis should include conservative assumptions for event amplitude, time scale, and event frequency.

7. Interaction loads—Interaction loads are loads imposed on the component by other adjacent systems or components during normal or off-normal conditions. For example, a magnet failure may result in a nonsymmetrical load distribution in the magnet support structure that could cause deflections resulting in an additional load transmitted to adjacent vacuum vessel structure.

8. Natural phenomena hazard loads—Natural phenomena hazard loads are site-specific loads due to earthquakes, wind, floods, and so on. Guidelines for methods of establishing load levels on facilities from natural phenomena hazards and for methods of evaluating the behavior of structures and equipment to these load levels are contained in DOE 1993b, DOE 1993c, DOE 1994b, DOE 1995a, and DOE 1995b.

9. Off-normal event loads—Component internal and external loading from credible off normal events, including design-basis events, should be considered as appropriate.

The SSC structural design evaluations will be based on predicted responses for concurrent event load combinations that are compared against the corresponding allowable stresses. In applications involving the ASME Code, for example, the evaluation load combinations would be performed in a conservative manner using design-basis event propagation assumptions in the facility safety analysis. Service levels defined in ASME 1992 to be used in the structural design process should also be assigned using information derived from the safety analysis process.

SSCs are subject to thermal and pressure cyclic loadings during normal operation and anticipated off-normal events such as disruptions/VDEs. Also, systems and components are subject to vibration loading from motors, cavitation, water/steam hammer, and so on. The ASME/ANSI design codes or comparable computational methods provide criteria for the evaluation that should use conservative analysis for the number of cycles and service life including the expected changes in material properties with time.

6.1.3.5 Materials

Material properties used in the analysis of safety-class SSCs must be appropriate for the operating environment, including off-normal events, and compensated for the degradation of the material properties with time due to radiation, fatigue, embrittlement, corrosion, or any other environmental factor. This applies to the relevant properties of safety-class SSCs that perform specific safety functions. For safety-class SSCs that provide confinement or structural support, the degradation of yield strength would be an important property to consider in the anticipated operating environment. For safety-class SSCs that provide a control or monitoring function, the degradation of insulation or changes in the dielectric behavior would be an important property to consider in the anticipated operating environment.

a. Radiation—Materials selected should be qualified for the anticipated lifetime in the anticipated radiation environment. This includes external radiation from the fusion reaction and component activation and internal radiation due to tritium beta decay. Conservative end-of-life properties should be used in the design analysis.

b. Thermal—Material properties used in analysis should always be those appropriate for the given temperature range. If no published property data for a particular temperature range exist, then materials should be tested for properties at the operating temperatures, or the design analysis should be based on estimated (conservative) material properties and the actual component performance should be monitored by formal in-service testing. For those items to be designed in accordance with ASME 1992, temperature limits are imposed within the code. If the item will be subjected to temperatures higher or lower than the limit, material properties, such as allowable stress and creep, used in the analysis should be justified by testing the material at the anticipated temperature.

c. Hydrogenic and helium embrittlement—The structural design analysis should base the material properties on end-of-life hydrogen and helium embrittlement (note He^3 is a product of tritium beta decay). The actual embrittlement of the SSC in the hydrogenic and helium environment should be determined by a monitoring and testing program. Where feasible, designers should eliminate embrittlement as a design issue by considering in the choice of materials a lifetime projection of pressures and temperatures and exposure to hydrogen isotopes and helium.

d. Material compatibility—An SSC may use a variety of materials in close proximity. In addition to changes in material properties due to external factors, the design should evaluate and resolve any material compatibility problems within an SSC such as accelerated corrosion due to galvanic effects of dissimilar metals or erosion due to long-term fluid motion.

6.1.3.6 Testing and Inspection

a. General requirements—Safety-class SSCs should be designed to permit initial and periodic inspection and testing of areas related to the intended safety function to assess their continued ability to perform the function. The tests and inspections should assess parameters related to the safety function (e.g., structural integrity, hydrogen embrittlement, leak tightness, effectiveness of electric or thermal insulation, brittleness of windows, etc. as appropriate). The design should provide for and operations should have an appropriate materials surveillance program.

   If the configuration does not permit periodic inspections and tests in accordance with applicable codes, particularly for systems contaminated with tritium, the safety analysis process should develop and prescribe an acceptable testing program. The facility authorization basis should include the test and inspection program.

b. Nondestructive examination (NDE) of safety-class SSCs—Nondestructive testing and inspection of safety-class welds, vessels, piping and valves, including test personnel qualification, should be in accordance with ASME 1992 or equivalent. Where design to ASME 1992 is not feasible, such as in the case of unique materials or designs, alternate codes such as those listed in Table 6.1 may be used with justification. Weld acceptance criteria should be in accordance with the requirements of codes listed in Table 6.1.

c. Leak testing—All safety-class SSCs that provide a containment barrier should be leak checked before initial operations and periodically thereafter and should meet the requirements specified in the safety analysis

d. Pressure testing—All safety-class SSCs that provide a safety function at a specified design pressure should be pneumatically or hydrostatically tested in accordance with ASME 1992 or comparable safety-related code for initial acceptance. The need for periodic retesting should be evaluated in the safety analysis process; if this is required, the design should provide appropriate fittings for this function.

e. Equipment Qualification Testing—Safety-class SSCs that perform safety functions should be qualified to operate under the limiting environmental conditions associated with normal operating and off-normal events for the facility, including the designated off-normal natural phenomena. The qualification of passive structures could be satisfied by analysis, testing, or experience associated with similar components. The qualification of active components could be satisfied by either tests performed on the components or experience with similar components. Justification shall be provided to demonstrate the applicability or experience from testing of similar components for the components requiring equipment validation.

The above areas have emphasized SSCs performing a structural safety function derived from the confinement evaluation guidelines. The testing and inspection program also applies to safety-class SSCs performing a control, monitoring, or power function. The tests and inspections that assess parameters related to the safety function should be identified. For safety-class I&C components, this could include periodic or continuous testing of circuit continuity, presence of grounds, or determination of circuit noise levels.

6.1.3.7 Remote Maintenance

The design should make provisions for appropriate accessibility, adequate shielding, and reliable remote handling equipment to facilitate planned maintenance and conceivable repairs. Remote maintenance requirements should be developed *early* in the design process taking into account the need to keep worker exposures as low as reasonably achievable (ALARA). It is strongly recommended that mockups or models be constructed during the detailed design phase to confirm the feasibility of human and remote maintenance system design. More detailed guidance is provided in Section 6.4.4.

6.1.3.8 Human Factors

Fusion facilities should consider human factors and operator-machine interfaces in the early design and throughout the entire design process. The final design should eliminate, to the extent practicable, the need for human interaction in the detection and mitigation of off-normal events, including design-basis events. To the extent that human interactions are required, these interactions should be specifically identified and justified by appropriate analysis, such as human reliability analysis, to ensure the human interaction can be performed under the anticipated environmental conditions and within required time constraints at an acceptable level of reliability.

6.1.3.9 Fire Protection

The probability and effect of fires and explosions at fusion facilities should be minimized. Safety-class SSCs should be designed and located to minimize, consistent with their intended safety function, the probability and effect of fires and explosions. Noncombustible and heat-resistant materials should be used whenever practical throughout the facility, particularly in areas vital to the control of hazardous materials and maintenance of safety functions. Fire detection and mitigation systems should be designed and provided with sufficient capacity and capability to minimize the adverse effects of fires and explosions on safety-class SSCs. Fire fighting systems should be designed to ensure that their rupture or operation does not significantly impair the safety function provided by safety-class SSCs. The effect of fire suppression systems on the facility should be considered. Current requirements for fire protection programs are provided in DOE 1995a.

6.1.3.10 Hydrogen Explosions

For a potential hydrogen explosion in a safety-class SSC, DOE 1989 specifies design requirements that require clarification. This is provided in some detail below.

A hydrogen detonation is a potential hazard that may be a design-basis event (typical probability $>10^{-6}$/yr). If it is within the design basis and the SSC under evaluation is a confinement barrier, then the required integrity of the barrier must be maintained during and after this event, although the non-safety-related functions of the SSC (such as ability to maintain high vacuum) can be compromised. If the SSC is not safety-class and a hydrogen detonation is credible, it must be shown that no failure due to this event can degrade the function of an adjacent safety-class SSC.

To determine if a potential hydrogen detonation is a design-basis event, it is important to evaluate the likelihood of having the three ingredients for detonation at the same time: hydrogen and oxygen in the appropriate mixtures and an ignition source (NRC 1989). Generally, the energy required to ignite hydrogen-air mixtures is modest (NRC 1989). Since the plasma typically contains much higher levels of stored energy, for analysis of the vacuum vessel it should be assumed that a point ignition source is always present during normal operations and wall conditioning. The factors determining the likelihood of a detonation are then the availability of hydrogen isotopes and air. Hydrogen isotopes are present in the solid matrix of the plasma-facing components at substantial levels. This is not ordinarily available for combustion or detonation although a portion (including tritium) may be released if a detonation occurs. If hot plasma-facing components or the vacuum vessel are cooled with water, a leak could result in the generation of hydrogen from water (steam) and beryllium (or carbon or tungsten) reactions (Smolik 1991, 1992). The precise amount of hydrogen generated depends on the first wall material and temperature and the size and duration of the water leak, but typical conditions in a D-T fusion plasma could generate sufficient quantities of hydrogen for a detonation. Air also has to be present for a detonation. If air is adjacent to the SSC under evaluation, the in-leakage of air is possible due to the same event that generated the hydrogen. For example, beryllium-steam reactions from a water leak during wall conditioning can result in internal pressures of several bar or more (NET 1993), which may be beyond the design value of the SSC under evaluation. This air source can be eliminated in the device design by incorporating an inert gas volume in the region between the SSC under evaluation and the next confinement barrier. To determine the probability of a hydrogen detonation, an analysis of the above factors must be performed for a particular design. The likelihood of a loss-of-coolant event cannot be generally excluded given performance of actively cooled systems to date and the anticipated in-vessel service conditions in a D-T fusion facility.

To preclude a hydrogen detonation for consideration as a design-basis event, it will typically be necessary to demonstrate a low event probability by

a. minimizing hydrogen generation by careful design, including material selection of the plasma-facing components or the fluids used for active in-vessel component cooling, or

b. using an inert gas boundary as discussed above.

6.2 Systems Performing Safety Functions

As stated above, SSCs required for the performance of a public safety function necessary to meet the evaluation guidelines of DOE-STD-6002-96 should be designated as safety-class. Section 6.2.1 provides design guidance for systems providing the radioactive and hazardous materials confinement public safety function. Section 6.2.2 provides design guidance for systems providing the worker safety function involving control of operating hazards.

6.2.1 Public Safety Function: Confinement Systems

The major public safety function is the confinement of radioactive (e.g., tritium, activated dust, activation, and corrosion products) and hazardous (e.g., beryllium and vanadium dust) materials (see Section 6.1.2). The systems that *typically* provide the first barrier of the confinement boundary (sometimes called primary confinement or containment) are the vacuum vessel (and associated penetrations) and ex-vessel systems (such as the isotope separation and fuel storage systems), which provide tritium confinement. Design guidance for these systems is provided in Section 6.2.1.1, Vacuum Vessel, and Section 6.2.1.2, Tritium Systems, respectively. The major systems that (typically but not always) provide the second or (if required) the third barriers of confinement (sometimes called secondary or tertiary confinement) are the cryostat, ex-vessel gloveboxes/rooms, double-walled piping systems, and/or the fusion building. Design guidance for these systems is provided in Section 6.2.1.3, Cryostat, and Section 6.2.1.4, Secondary Confinement Systems. It is emphasized that the number of confinement barriers is design specific and depends on the anticipated radioactive and hazardous material inventories, the distance of these sources from the public or workers, the proximity of major energy sources to these inventories, and the quality and independence of each confinement barrier. For example, segmentation of radioactive and hazardous material inventories where feasible is a potential design tool to reduce the number of independent barriers around each individual inventory location. Care must be taken to define the system boundaries carefully and ensure that adjacent systems are independent and have no common failure modes.

Primary and secondary (or greater) confinement systems are properly viewed as an integrated barrier to provide confidence that net leakage rates specified in the facility safety analysis are not exceeded. The safety analysis process will estimate radioactive and toxic source terms and specify barrier integrity in terms of net leak rates to meet DOE-STD-6002-96 requirements for exposure to on-site workers and the public during normal and off-normal events, including design-basis events. Releases of hazardous materials postulated to occur as a result of design-basis events that would exceed DOE-STD-6002-96 release guidelines should be limited by designing facilities such that at least one confinement barrier remains fully functional following any credible event. (i.e., unfiltered/unmitigated releases of hazardous levels of such materials should not be allowed following such events).

Fusion vacuum vessels are typically subject to complex and transient stresses and have many penetrations, some of which are of large cross-sectional area. It is, therefore, unlikely that the net leakage from such a complex vessel could approach that of a simple pressure vessel or pipe. It is likely that several (2 to 3) confinement barriers will be needed to confine in-vessel radioactive and toxic materials. The design of successive confinement barriers must therefore ensure that each separate barrier be independent. This independence should be preserved during normal and off-normal events. For example, the design-basis earthquake will cause off-normal loading to all fusion island components, and it should be verified that concentric penetrations from multiple confinement barriers do not have mutual interactions that result in exceeding specified leak rates.

6.2.1.1 Vacuum Vessel

The vacuum vessel is normally the primary confinement system for in-vessel radioactive and toxic materials. It is, for the tokamak configuration, a torus-shaped container usually made of a metal or metallic alloy, and its volume is up to several times the plasma volume. It can be thin-walled or thick-walled. It may be double-walled with coolant passages in the annulus. The perimeter of the vacuum vessel is outfitted with a number of ports (extensions) for mounting hardware for plasma fueling, plasma heating, plasma conditioning, plasma diagnostics, vacuum pumping, and blanket/divertor maintenance. These ports can vary in size and shape and are usually located above, below, and on the horizontal plane as well as on top and bottom of the vacuum vessel. It may be of all-welded, continuous construction or use bolts between segments with vacuum seals at the joints.

If the safety analysis indicates that vacuum vessel is a primary confinement barrier to meet the evaluation guidelines, the robustness of the barrier will be defined in the safety analysis and implemented in the design. In performing this public safety function, the vacuum vessel should be classified as a safety-class system. Hardware internal or adjacent to the vacuum vessel whose credible failure could result in evaluation guidelines being exceeded should be classified as safety-class. If the vacuum vessel is not considered a confinement barrier in the safety analysis, those vacuum vessel components whose single failure results in loss of capability of another safety-class system to perform its safety function should be designated as safety-class components.

If the safety analysis requires that the vacuum vessel be a confinement barrier, the following safety features should be considered:

The vacuum vessel serves as the first barrier for tritium and tritiated compounds, radioactive impurities, and activated dust during normal operation, anticipated operational occurrences, maintenance external to the vessel, and off-normal events.

In addition to the general design guidance in Section 6.1, the following system-specific design guidance is provided:

a. Confinement Boundary

The vacuum vessel confinement boundary should be defined as the vacuum vessel proper including attached windows, flanges, and ports and all penetrations up to and including the first or second isolation valve as appropriate (depending on system pressure and as defined in the facility authorization basis) in system piping that penetrates the vacuum vessel. For vacuum vessel penetrations, each line that is part of the vacuum vessel pressure boundary and that penetrates the vacuum vessel should be provided with isolation valves, unless it can be demonstrated that the confinement isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis. A simple check valve should not be used as the automatic isolation valve. Isolation valves outside the vacuum vessel should be located as close to the vessel as practical and upon loss of actuating power, automatic isolation valves should be designed to take the position on failure that provides greater safety. The power to operate isolation valves whose function is required to meet the evaluation guidelines should meet the requirements of Class 1E Electric Power Systems (IEEE 1980).

b. Structural Design

See Section 6.1.3.4 for general guidance. The vacuum vessel and its appendages should be designed, fabricated, inspected, and tested in accordance with a recognized safety-related code such as ASME 1992. Vacuum vessel deflections should be calculated and analyzed to determine potential interferences and to verify seal integrity.

Loads on the vacuum vessel should be carefully determined using input from the safety analysis process. Pressure loadings are typically inward for normal service and outward for off-normal events. Off-normal events could include large disruptions or VDEs, release of plasma energy (e.g., runaway electrons) or coolant energy inside the vacuum vessel. Loadings from the response of adjacent systems to off-normal events should be evaluated. For example, a plasma disruption or VDE may result in some loading of the vacuum vessel from attached penetrations and supports. Load combinations should be developed conservatively based on event sequences postulated in the safety analysis.

The vacuum vessel is subject to cyclic loading during normal operations. Thermal cycling and unavoidable disruption loads are to be expected. The necessity of a fatigue analysis should be evaluated based on the criteria of ASME 1992 or comparable safety-related code using conservative values for variables such as number of pulses, percentage of pulses that have disruptions, and service life including expected changes in material properties with time.

Windows—The use of windows should be minimized to a level consistent with the need to evaluate plasma properties with optical diagnostics. Where windows are used the area should be minimized, and the windows should be qualified by analysis or testing in the anticipated operating and design-basis event environment to demonstrate required confinement integrity.

Bellows—The use of bellows should be minimized to a level consistent with needs to accommodate differential movement and alignment between fusion island components. Where bellows are used the area experiencing differential pressure should be minimized, and the bellows should be qualified by analysis or testing in the anticipated operating and design-basis off-normal event environment to demonstrate required confinement integrity. As a minimum, bellows should conform to relevant criteria in ASME 1992 or a comparable safety-related code. The use of double-walled bellows should be considered as a design approach to minimize component leakage.

Ceramic Breaks—The use of ceramic breaks should be minimized. When ceramic breaks are used, they should be qualified by analysis or testing in the anticipated operating and design-basis off-normal event environment to demonstrate required confinement integrity.

c. Testing

See Section 6.1.3.6 for general guidance. All vacuum vessels and attached components that provide a confinement barrier should be leak checked at design pressures before initial operation to demonstrate that leakage requirements specified in the safety analysis are met by the as-built design. Potential hazards of in-service leak testing at the design vessel pressure after D-T operations have commenced may not justify such periodic leak testing. In its place, a program of periodic vacuum leak testing and a formal configuration control program to ensure vacuum vessel repairs or modifications do not compromise the design pressure rating should be implemented. Replacement structural components should be pressure tested before assembly in the vacuum vessel. Local repairs in the vessel should be subject to rigorous NDE.

d. Instrument and Control Systems

Instrument and control systems (I&C), where appropriate, should be provided to monitor system parameters important to the safety function of the vacuum vessel over their anticipated ranges for normal operation and off-normal conditions to ensure continuity of the required safety function. The design should incorporate sufficient redundancy and/or diversity to ensure that a single failure will not result in a loss of monitoring capability for safety-class systems. The electric power to operate safety class instrumentation should meet the requirements of IEEE 1980. More information is provided in Section 6.4.1, Instrument and Control Systems, and Section 6.4.2, Electrical Power Systems.

e. Ventilation and Exhaust Systems

The design of a vacuum vessel confinement ventilation system should ensure the ability to maintain desired airflow characteristics when personnel access ports or hatches are open. When necessary, air locks or enclosed vestibules should be used to minimize the impact of this on the ventilation system and to prevent the spread of airborne contamination within the facility. Ventilation system components required to be safety-class should provide the required confinement capability under all normal operations and off-normal conditions with the assumption of a single failure in the system. If the maintenance of a controlled continuous confinement airflow is required to meet evaluation guidelines in DOE-STD-6002-96, electrical equipment and components required to provide this airflow should be supplied with safety-class electrical power and provided with a backup power source. Air cleanup systems should be provided in confinement ventilation exhaust systems to limit the release of radioactive or other hazardous material to the environment and to minimize the spread of contamination within the facility as determined by the safety analysis. Guidance for confinement systems is included in DOE 1989.

f. System Maintenance

Opening a confinement system such as the vacuum vessel requires prior removal of tritium, radioactive dust, and loose toxic materials (if any) to the maximum extent feasible. If required by the safety analysis, cleansing steps that exhaust to atmosphere should exhaust through a tritium and particulate removal system to limit the release of tritium and other radioactive and toxic materials to the environment consistent with release limits and ALARA principles. The safety analysis should prescribe limits for tritium and other radioactive and toxic material releases to the environment during vacuum vessel maintenance openings. The exhaust from the vacuum vessel may be through a dedicated tritium removal system or through a secondary confinement subsystem that has a tritium removal system. The tritium removal systems should have capacity to recover from a design basis tritium release from the vacuum vessel.

6.2.1.2 Tritium Systems

Tritium systems include all process equipment outside the vacuum vessel with surfaces routinely in contact with tritium and other hydrogen isotopes. Examples include tritium processing and transfer systems, plasma fueling systems, blanket tritium transport and recovery systems, and the vacuum vessel pumping systems. Useful design guidance for tritium systems is provided in IAEA 1981, IAEA 1991, and DOE 1994c.

Tritium system confinement strategies generally include primary and secondary confinement. Sealed high-integrity piping and process equipment normally constitute the primary confinement for vacuum and pressure conditions. The secondary confinement includes gloveboxes and/or dedicated enclosures or rooms housing the primary confinement. Process piping between gloveboxes or other secondary enclosures is generally surrounded by another pipe or jacket sealing to the gloveboxes or secondary enclosures. Additional sealed cabinets or rooms may extend the confinement in accordance with the facility safety analysis.

Tritium system design should include features that limit the quantities of tritium available for release during off-normal events, limit the environmental release of tritium and exposure of personnel during normal and off-normal conditions, and limit the unintended conversion of elemental tritium to an oxide form. Consistent with facility safety analysis, design features may include the following:

a. Segmentation

Tritium system design may provide for segmentation of the facility tritium inventory as necessary to make acceptable the amount of tritium releasable in a single event. Design should provide for isolation of each segment using valves or piping blanks. Where isolation valves are employed, the failed position should be as specified in the facility safety analysis. Check valves and other one-way valves are not acceptable as isolation devices.

Segmentation may be accomplished by utilization of processes or devices with small inventory, separation of the tritium inventory into isolatable volumes, or storage of tritium in an immobile condition relative to the single event (e.g., metal hydride beds).

b. Confinement

Tritium confinement generally includes a primary confinement subsystem and a secondary confinement subsystem. Design may also provide higher orders of confinement if the safety analysis indicates these are necessary to reduce tritium exposure and environmental release to acceptable levels. The confinement subsystems include the SSCs necessary to establish the confinement barriers and the power sources necessary to maintain the barrier operation within prescribed safety limits.

The primary confinement should provide a low leak rate, pressure-rated static barrier. Normally, primary confinement systems are sealed and are opened only for maintenance, testing, and inspection. Welded joints are preferable to compression fittings, which are preferable to threaded fittings. Welded joints or mechanical joints are acceptable for piping enclosed in secondary confinement gloveboxes or enclosures. However, only welded joints should be used for piping outside gloveboxes or enclosures. Pumps should comply with National Electric Code requirements for explosion-proof installation if required by safety analysis and should generally not use organics, hydrocarbons, or other volatiles for surfaces that will contact the tritium process gas. Valves should meet prescribed leak requirements across the valve seat and from the valve bonnet and body.

Secondary confinement barriers should have a recirculating nitrogen or inert gas atmosphere. The term “inert” represents any reduced oxygen environment. Tertiary and higher orders of confinement should have atmospheres as specified by the safety analysis. Secondary and higher order confinement barriers should operate at subatmospheric pressure maintained by a pressure control system. If required by safety analysis, the confinement exhaust should be through a tritium removal system to limit the environmental release of tritium consistent with release limits and ALARA principles. The safety analysis will prescribe limits for tritium releases to the environment.

Opening a confinement subsystem requires prior removal of tritium and cleansing. If required by safety analysis, cleansing steps that exhaust to atmosphere should exhaust through a tritium removal system to limit the release of tritium to the environment consistent with release limits and ALARA principles. The exhaust from a confinement subsystem may be through a dedicated tritium removal system or through a secondary confinement subsystem that has a tritium removal system. The tritium removal systems should have capacity to recover from a design-basis tritium release from primary confinement.

c. Instrument and Control Systems

Design should provide for I&C to monitor parameters important to safety and to indicate a need to isolate or otherwise control a tritium system or tritium confinement subsystem to prevent monitored variables exceeding a safety limit. The safety analysis should identify and the design should implement monitoring of the safety-related variables. Primary confinement typically includes instrumentation for pressure, vacuum, and temperature monitoring, and for qualitative gas analysis. Secondary confinement typically provides instrumentation for relative pressure monitoring, tritium detection, and oxygen concentration analysis (if the secondary has an inert gas or reduced oxygen atmosphere). Subsequent levels of confinement will provide monitoring capabilities commensurate with the hazard anticipated and the operating requirements of the barrier.

d. Structural Design

See Section 6.1.3.4 for general guidance. Tritium systems that are safety-class should have design, fabrication, inspection, and testing in accordance with a recognized safety-related code. The specific codes and criteria selected should be commensurate with the level of safety required and should have a documented technical justification.

Tritium systems that are not safety-class should have design, fabrication, inspection, and testing in accordance with a recognized national consensus code.

e. Tritium Embrittlement

The structural design analysis should use material properties that account for tritium and helium embrittlement at the projected end-of-life. Tritium embrittlement adds a physical mechanism to the generally understood hydrogen embrittlement. Tritium permeates the metal structure, like other hydrogen isotopes, but tritium decays to produce interstitial helium-3. The helium damage is additive to the damage caused by the tritium.

f. Conversion of Elemental Tritium to Tritium Oxide

The design should include engineered features as necessary to minimize the potential for tritium contact with ignition sources, water, moisture, hydrocarbons, and other oxidizing sources. Because oxidized tritium presents a significantly higher biological hazard than elemental tritium, the design must reduce to a practical minimum the unintended conversion of tritium to any oxidized form. It is recognized that some tritium cleanup systems convert elemental tritium to an oxide form with deliberate intent to facilitate removal from flowing gas streams.

g. Exchange with Hydrogen, Hydrogenated Compounds, and Hazardous Wastes

Designers should avoid use of water, moisture, mercury, hydrocarbons (oils), plastics, asbestos or elastomeric gaskets, and other hydrogenated compounds that could contact tritium. Gaskets and o-rings in contact with tritium should not use elastomers, plastics, or asbestos; tritium will degrade them, cause premature failure, and may create a source of mixed waste. Ultra-high molecular weight polyethylene (UHMWPE) and certain polyimides such as VESPEL are exceptions to this rule. Valves with UHMWPE stem tips will remain leak tight longer than valves with metal (e.g., stellite) tips.

h. Hydrogen Fires and Detonations

Hydrogen fire or detonation requires the following concurrent conditions: hydrogen isotopes in sufficient concentration, oxygen in sufficient concentration, and high temperature or ignition source.

Design features that discourage or prevent hydrogen fires and detonations include (1) leak tight primary confinement to prevent out-leakage of tritium to the secondary confinement, (2) inert gas in the space between primary confinement and secondary confinement barrier walls, (3) monitors to detect tritium out-leakage or oxygen in-leakage, (4) minimization of ignition sources or high temperatures near the primary or secondary confinement barriers, (5) utilization of National Fire Protection Association (NFPA) rated enclosures for electrical equipment with potential for contact with flammable mixtures. Additional guidance is provided in Section 6.1.3.10.

i. Fire Protection

Because fire oxidizes elemental tritium to tritium oxide, a form with a much greater biological hazard, design should place high priority on preventing fires. The effect of fire suppression systems on the facility and the environment should be considered. Chemicals may have a deleterious effect on tritium cleanup systems, while water may present waste disposal difficulties. Because of the natural affinity of tritium for water and the increased biological hazard of tritiated water, the use of water as a tritium fire extinguisher should require a technical or economic justification. Facilities that have the potential for introducing fire suppression water into a tritium-contaminated environment should provide a tritiated water collection system with the capacity to store the total volume of fire suppression run-off. Design should provide for facilities to dispose of any tritiated water in an environmentally acceptable manner. Additional guidance is provided in Section 6.1.3.9.

j. System Cleaning

Design should provide for cleaning of tritium systems before and after installation. Tritium systems should be able to withstand vacuum conditions necessary for cleaning purposes and elevated temperatures during bakeout if required prior to equipment removal. Once tritium has contaminated the primary confinement, only limited cleaning is permissible for tritium-wetted surfaces.

6.2.1.3 Cryostat

The main function of the cryostat is to provide a vacuum region for thermally insulating the superconducting coils surrounding the vacuum vessel from the normal building environment. Based on the safety analysis process, it may be necessary to assign the public safety function of confinement to the cryostat since it naturally encloses the vacuum vessel. Thus, the cryostat can be a confinement system for in-vessel radioactive and toxic materials. It could be a primary confinement if no credit is taken for the vacuum vessel confinement ability, or it could be a secondary confinement if the cryostat barrier is needed to meet evaluation guidelines. It can also be a secondary confinement barrier for piping and tubing containing tritium or other radionuclides that penetrate and are inside the cryostat boundary. It could be a primary confinement boundary for in-vessel radioactive and toxic materials if the vacuum vessel is opened for maintenance or inspection. The cryostat is normally a metal chamber surrounding the fusion device which provides a thermal barrier to conduction and thermal radiation between the superconducting coils and other cold structures and the fusion building. It may also serve as part of the biological shield. The chamber is usually cylindrical with a top and bottom. There are usually large penetrations in the top, bottom, and sides of the cryostat, primarily for access to the vacuum vessel and magnets for maintenance and inspection. The cryostat may be double-walled with an evacuated or filled annulus. It may be lined with cryogenic panels or superinsulating material.

If the safety analysis indicates that the cryostat is a confinement barrier to meet the evaluation guidelines, the required robustness of the barrier will be defined in the safety analysis and implemented in the design. In performing this public safety function, the cryostat should be classified as a safety-class system. Hardware internal or adjacent to the cryostat whose credible failure could result in evaluation guidelines being exceeded should be classified as safety-class. If the cryostat is not considered a confinement barrier in the safety analysis, those cryostat components whose single failure results in loss of capability of another safety-class system to perform its safety function should be designated as safety-class components.

If the safety analysis requires that the cryostat be a confinement barrier, the following safety functions should be considered:

The cryostat may serve as a barrier (normally a secondary barrier but this is design specific) for tritium and tritiated compounds, radioactive impurities and activated dust during normal operation, anticipated operational occurrences, maintenance external to the cryostat, and off-normal events including design-basis events. The cryostat may serve as part of the structure of the biological shielding; if this is the case see Section 6.2.2.2 for shielding guidance.

During maintenance inside the vacuum vessel, the cryostat may serve as a partial confinement barrier as defined in the safety analysis. That is, the vacuum vessel may be breached for specific repairs, but the confinement function should be provided by the cryostat, to ensure evaluation guidelines are not exceeded from residual in-vessel radioactive and toxic materials; this confinement barrier may include temporary features to allow maintenance access.

In addition to the general design guidance in Section 6.1, the following system-specific design guidance is provided:

a. Confinement Boundary

The cryostat system confinement boundary should be defined as the cryostat proper, including all penetrations up to and including the first or second isolation valve as appropriate (depending on system pressure and as defined in the facility authorization basis) in system piping that penetrates the cryostat. For cryostat penetrations, each line that is part of the cryostat system boundary and that penetrates the cryostat should be provided with isolation valves, unless it can be demonstrated that the confinement isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis. A simple check valve should not be used as the automatic isolation valve. Isolation valves outside the cryostat should be located as close to the cryostat as practical and upon loss of actuating power, automatic isolation valves should be designed to take the position on failure that provides greater safety. The power to operate isolation valves whose function is required to meet the evaluation guidelines should meet the requirements of Class 1E Electric Power Systems (IEEE 1980).

b. Structural Design

See Section 6.1.3.4 for general guidance. The cryostat and its appendages should be designed, fabricated, inspected, and tested in accordance with a recognized safety-related code such as ASME 1992. Cryostat deflections should be calculated and analyzed to determine potential interferences and to verify seal integrity.

Loads on the cryostat should be carefully determined using input from the safety analysis process. Pressure loadings are typically inward for normal service and outward for off-normal events. Off-normal events could include release of magnet energy inside the cryostat as well as energy from release of cryogenic fluid (liquid helium or nitrogen) to the interior of the cryostat. Loadings from the response of adjacent systems to off-normal events should be evaluated. For example, a plasma disruption or vertical displacement event may result in some loading of the cryostat and attached supports. Load combinations should be developed conservatively based on event sequences postulated in the safety analysis.

The cryostat is subject to cyclic loading during normal operations. Thermal cycling and disruption loads (for tokamak devices) are to be expected. The necessity of a fatigue analysis should be evaluated based on the criteria of ASME 1992 or comparable safety-related code using conservative values for variables such as number of pulses, percentage of pulses that have disruptions, and service life including expected changes in material properties with time.

The use of bellows should be minimized to a level consistent with needs to accommodate differential movement and alignment between fusion island components. Where bellows are used the area experiencing differential pressure should be minimized, and the bellows should be qualified by analysis or testing in the anticipated operating and design-basis event environment to demonstrate required confinement integrity. As a minimum, bellows should conform to relevant criteria in ASME 1992 or a comparable safety-related code. The use of double-walled bellows should be considered as a design approach to minimize component leakage.

c. Testing

See Section 6.1.3.6 for general guidance. The cryostat vessel and attached components that provide a confinement barrier should be leak checked at design pressures before initial operation to demonstrate that leakage requirements specified in the safety analysis are met by the as-built design. Potential hazards of in-service leak testing at the design vessel pressure after D-T operations have commenced may not justify such periodic leak testing. In its place, a program of periodic vacuum leak testing and a formal configuration control program to ensure cryostat repairs or modifications do not compromise the design pressure rating should be implemented. Replacement structural components should be pressure tested before assembly in the cryostat. Local repairs should be subject to rigorous NDE.

d. Instrument and Control Systems

I&C, where appropriate, should be provided to monitor system parameters important to the safety function of the cryostat over their anticipated ranges for normal operation and off-normal conditions to ensure continuity of the required safety function. The design should incorporate sufficient redundancy and/or capability for safety-class systems. The electric power to operate safety class instrumentation should meet the requirements of IEEE 1980. More information is provided in Section 6.4.1, Instrument and Control Systems, and Section 6.4.2, Electrical Power Systems.

e. Ventilation and Exhaust Systems

The design of cryostat confinement ventilation systems should ensure the ability to maintain desired airflow characteristics when personnel access ports or hatches are open. When necessary, air locks or enclosed vestibules should be used to minimize the impact of this on the ventilation system and to prevent the spread of airborne contamination within the facility. The ventilation system design should provide the required confinement capability under all normal operations and off-normal conditions with the assumption of a single failure in the system. If the maintenance of a controlled continuous confinement airflow is required, electrical equipment and components required to provide this airflow should be supplied with safety-class electrical power and provided with a backup power source. Air cleanup systems should be provided in confinement ventilation exhaust systems to limit the release of radioactive or other hazardous material to the environment and to minimize the spread of contamination within the facility as determined by the safety analysis. Guidance for confinement systems is included in DOE 1989.

f. System Maintenance

Opening a confinement system such as the cryostat requires prior removal of tritium, radioactive dust, and loose toxic materials (if any) to the maximum extent feasible. If required by the safety analysis, cleansing steps that exhaust to atmosphere should exhaust through a tritium removal system to limit the release of tritium and other radioactive and toxic materials to the environment consistent with release limits and ALARA principles. The safety analysis should prescribe limits for tritium and other radioactive and toxic material releases to the environment during cryostat maintenance openings. The exhaust from the cryostat may be through a dedicated tritium removal system or through a confinement subsystem that has a tritium removal system. The tritium removal systems should have capacity to recover from a design-basis tritium release from the cryostat. If the cryostat is part of the biological shield, maintenance planning should consider the effect of planned tasks on the shielding integrity.

6.2.1.4 Confinement/Heating, Ventilating, and Air Conditioning (HVAC) Systems

Confinement/HVAC systems include SSCs designed to serve as barriers against the spread or uncontrolled release of radioactive or other hazardous materials throughout the facility or to the environs. The facility confinement strategy may consist of successive confinement barriers based on the hazards present. The successive barriers are defined by the facility safety analysis.

The confinement/HVAC system boundary is generally defined for each confinement barrier and includes the contiguous structural barrier and its associated ventilation and filtration equipment.

Design features for confinement systems and their associated HVAC systems include the following:

a. Provide barriers against the release or spread of gaseous and particulate contamination during normal and off-normal conditions. (DOE 1989, ASHRAE 1988, ASHRAE 1991)

b. Provide the necessary ventilation system functional capabilities to control differential pressures such that air flows from cleaner areas to potentially more contaminated areas during normal and off-normal conditions. (ASHRAE 1991)

c. Provide filters or other means to remove contaminants before exhausting the environs.

d. Maintain the required ambient conditions within confinement (e.g., temperature, pressure, humidity, and concentrations of radiological, toxic, corrosive, or explosive substances), to protect personnel and ensure the capability of personnel or equipment to perform safety functions. (ASHRAE 1991)

e. Provide the capability to isolate and control tritium or any other contaminant released within confinement.

f. Provide instrumentation and/or testing and surveillance to monitor the condition and capabilities of the confinement system, the ambient conditions within confinement, and the effluents from confinement to the environs. Applicable items should be monitored during normal and off-normal conditions as required to ensure and verify safety function. In addition potential airborne contaminants or corrosive agents that may compromise the ability of personnel or equipment to perform safety functions should be monitored and controlled. (DOE 1989, ASHRAE 1991, and DOE 1990)

Design-basis loads are derived from the internal and external events identified in the safety analysis. Loads and the combinations thereof used in the design should envelop loads considered in structures per ANSI 1993b.

Methods of analysis depend on the performance category and loads being considered (e.g., ASCE 1980). Elastic system analysis methods may be adequate for lower performance categories, whereas for higher performance categories inelastic analysis methods may be required. Guidelines to seismic analysis are available in DOE 1994b. Dynamic seismic structural analysis may be performed for predicted ground motions based on geotechnical site-specific information including variability using response spectra or time history. For large embedded structures, soil structure analysis may be considered.

Capacity calculations, DOE 1994b, depend primarily on the national consensus code, UBC 1991. For reinforced concrete structures, DOE 1984 and ACI 1989 provide the criteria for safety-class and other building structures, respectively. For steel structures, ANSI 1984 and AISC 1986a provide the criteria for safety-class and other building structures. AISC 1986b is an alternate for AISC 1986a if load and resistance factor design procedure is used.

ASME 1992 should be used for equipment and components and ANSI 1993a for piping.

Deformation may be allowed and inelastic energy absorption credited for ductile structural materials, especially for lower performance categories. Inelastic absorption capacity should not be credited if concrete or other nonductile materials are used as a pressure boundary.

For lower performance categories and for normal operations, damage may be permitted but should be limited so that hazardous materials can be controlled and confined, occupants are protected, and safety functions are maintained.

For the higher performance categories and for off-normal conditions, structures should be permitted to undergo limited inelastic deformations. Risk analysis may be performed to determine the extent of permissible damage. Energy absorption factors may be used to achieve appropriate conservatism in the design or evaluation process. Stability and other postyield behavior criteria should be met.

Ventilation systems should be designed to operate in conjunction with their associated physical barriers to limit the release of radioactive or other hazardous material to the environment. The ventilation system capabilities should be sufficient to allow for any intentional breaches of the confinement system that are required during maintenance on any portion of the facility.

Leak-tightness of the confinement pressure boundary should be considered in the design. Air locks to achieve the required leak-tightness between confinement/containment zone boundary interfaces should be considered.

Appropriate filtration may be accomplished by multistage high-efficiency particulate air (HEPA) filtration of the exhaust or by an equivalent filtering capability. The exhaust ventilation system must be sized to ensure adequate inflow of air in the event of the largest credible breach of confinement.

Safety-class systems and components should be designed per ASME 1993 or a comparable code or standard which considers the safety function(s) of the particular system or component (ASME 1989a and ASME 1989b). Non-safety-class systems and components should be designed per codes and standards used for industrial and commercial grade applications.

6.2.2 Worker Safety Function: Systems Controlling Operating Hazards

The worker safety function is control of operating hazards. This function is somewhat more subtle than the other confinement of radioactive and toxic materials due to the spectrum of potential radioactive and industrial hazards to which the facility worker may be exposed.

6.2.2.1 ALARA Design Considerations

It is DOE's policy that exposure to radiation resulting from operations be maintained ALARA. The application of ALARA to fusion facilities has two principal divisions: occupational exposure and public exposure. For occupational exposure, specific evaluation criteria for radiation protection of the worker from ionizing radiation are provided in DOE-STD-6002-96, which references 10 CFR 20 and 10 CFR 835. The DOE Radiological Control Manual also provides guidance on implementing ALARA with regard to occupational exposure to radiation. For public exposure, DOE-STD-6002-96 (Table 1) provides specific guidelines consistent with the overall goal of ALARA.

The design of the fusion facility should have the following features to minimize worker exposure during maintenance (routine and corrective) and decommissioning activities as well as release to the environment:

a. choice of materials and design that minimize the activation of components and structures and eliminates the need for deep geologic burial;

b. designs that ease cut-up, dismantlement, removal, and packaging of contaminated equipment;

c. equipment design that minimizes the accumulation of radioactive or hazardous materials;

d. use of modular separable confinements;

e. use of localized liquid transfer systems;

f. location of exhaust air cleanup components at or near individual enclosures; and

g. fully drainable piping systems, including tanks.

The following techniques should be considered in the design, as applicable, in order to facilitate decommissioning at the end of operating life. These techniques are grouped by primary objective.

Waste volume reduction is the objective for these six techniques:

a. Use sealed nonporous insulation—Use of such insulation materials prevents the absorption of contaminated liquids by the insulation.

b. Enclose cable trays—Totally enclosing the trays with solid sheet metal (to the extent that such enclosures do not interfere with plant maintainability) will prevent the contamination of large quantities of cabling, but heat buildup should be considered in this closed geometry.

c. Minimize cable trays in contaminated areas—Locating the trays in clean areas to the extent possible minimizes contamination.

d. Relocate motor control centers—The amount of contaminated equipment will be reduced by locating motor control centers in areas that are not susceptible to contamination.

e. Use bolted steel construction—This construction technique reduces radioactive waste by using an easily decontaminated construction material. This technique will also reduce exposure by decreasing disassembly time.

f. Smooth and coat concrete surfaces —These are preventive and protective measures against the radioactive contamination of concrete surfaces and thus decrease the quantity of radwaste associated with the decontamination of such surfaces.

Exposure reduction is the objective for these 19 techniques:

a. Material selection—Apply design techniques and selection of materials to minimize activation or to ensure that activated material can readily be removed and disposed.

b. Substitution and purification of materials—For example, use of low-cobalt steels will result in lower Co-60 activation products and thus in lower occupational exposures during decommissioning.

c. Scale models—Exposure savings can be realized during and after the operational life of the facility by using models as planning aids.

d. Flanged construction—This construction technique (to the extent it does not compromise technical specifications on leakage, especially tritium) will reduce exposure by decreasing the time required to disconnect components and by reducing the use of dismantling methods that spread contamination (e.g., power hacksaws and circular cutters).

e. Quick disconnect components—This construction technique (to the extent it does not compromise technical specifications on leakage, especially tritium) will reduce exposure by decreasing the time required to disconnect components.

f. Remote sampling—This capability reduces exposure associated with environmental sampling activities by allowing the data to be collected remotely.

g. Waste storage capacity—Provision should be made in the site layout for a waste storage facility (which may not be constructed until just prior to decommissioning if it is intended only for decommissioning wastes) to provide temporary storage space so that accumulated waste will neither slow down decommissioning nor be stored in areas that may pose exposure hazards.

h. Nonembedment of pipes, ducts, and equipment in concrete—This design feature (to the extent it does not compromise release of fluids from the pipes) reduces the effort and exposure time required to remove items at the time of decommissioning.

i. Removable roof, wall panels, and plugs—This design feature provides improved access for removal of radioactive components and thus reduces exposure time.

j. Access to and into all tanks—Such access will shorten setup time and thus reduce exposure.

k. Facility breathing air supply system—Breathing air supplies for decommissioning work should be considered in the facility design and, if incorporated, should be installed at the time of construction to avoid the problems with portable units at the time of decommissioning.

l. Preinstalled manipulator supports—This design feature is intended to reduce exposure during segmentation of the fusion island components by performing the preliminary work in a low-radiation environment during construction rather than in a high-radiation environment after shutdown.

m. Lifting fixtures on large components—Installation of the lifting fixtures prior to facility startup rather than in a radioactive environment after shutdown will prevent significant radiation exposures.

n. Anchor points for lifts—Incorporation of anchor devices for lifting large components prior to facility startup rather than in a radioactive environment after shutdown will prevent significant radiation exposures.

o. Tracks for remote cutting devices—Installation of guide tracks for segmentation cutting devices prior to facility startup rather than in a radioactive environment after shutdown will prevent significant radiation exposures.

p. Preplaced concrete core samples—To obtain activated concrete profiles for radiological characterization of the concrete, core samples should be drilled or cast in place prior to facility startup rather than in a radioactive environment after shutdown.

q. Complete drainage capacity—Exposure due to pockets and traps containing contaminated liquids is minimized. Complete flushing and drying of the system is possible prior to dismantling.

r. Containment and isolation of liquid spills—Containment features instituted during the design phase (e.g., curbing, dikes, reserve tankage, increased sump capacity) will reduce contamination during the operational life of the facility and thus reduce the contaminated surface area to be removed during decommissioning.

s. Preplaced blast holes—By incorporating blasting holes into monolithic concrete structures during the construction of the facility before they have become radioactive, the occupational exposure associated with their demolition is reduced.

6.2.2.2 Access Controls and Shielding from Radioactive Hazards

10 CFR 835 specifies that radiation exposure in controlled areas shall be kept below regulatory limits and also ALARA through facility and equipment design and administrative controls. The primary (preferred) methods to be used are physical design features such as confinement, ventilation, shielding, and remote operation. Administrative controls, including procedural requirements, are to be used as secondary methods. Confinement and ventilation are addressed in Section 6.2.1.4., access controls and radiation shielding are addressed below.

a. Access Controls

10 CFR 835 specifies that personnel access control shall be maintained for each radiological area, with the degree of control to be commensurate with the potential or actual hazard. One or more of the following methods is to be used.

1. Signs and barricades,

2. Control devices on entrances,

3. Conspicuous visual or audible alarms or both,

4. Locks on entrances, and

5. Administrative controls.

Items 1 and 5 are not a part of facility design and are not addressed below. For a High or a Very High Radiation Area, one or more of the following seven features should be used for each entrance or access point where radiation levels exist such that an individual could receive an external dose to the whole body of 1 rem or more in any 1 h at 30 cm from the source or from any surface through which the source radiation penetrates:

1. a control device that prevents entry to the area when high radiation levels exist or that upon entry of a person causes the radiation level to be reduced to below the lower limit for a High Radiation Area;

2. a device that functions automatically to prevent use or operation of the radiation source or field while personnel are in the area;

3. a control device that energizes a conspicuous visual or audible alarm signal so that the individual entering the High or Very High Radiation Area and the supervisor of the activity (e.g., in a control room) are made aware of the entry;

4. entryways that are locked when not accessed and over which positive control can be maintained when accessed;

5. continuous direct or electronic surveillance that is capable of preventing unauthorized entry;

6. a control device that automatically generates audible and visual alarm signals to alert personnel in the area before use or operation of the radiation source in sufficient time to permit evacuation of the area or activation of a secondary control device that prevents use or operation of the source;

7. for Very High Radiation Areas, additional measures as necessary to prevent access to the area when dose rates are above the lower limit for a Very High Radiation Area.

Consideration should be given, in the selection of controls, to the allowance of space for the controls, the necessity for administrative oversight of the controls, the need for periodic inspection of the controls, and the ease with which a control may be bypassed. No control should be installed such that it would prevent rapid evacuation of personnel.

b. Shielding

Shielding design should be based on the appropriate design objectives given in 10 CFR 835. The choice of design, arrangement, and material for shielding should be optimized considering the following factors at a minimum: efficacy of dose rate reduction, potential corrosive or galvanic effects, the advantages of homogeneity vs the advantages of layers, weight, the need for mobility of the shield, radiation heating potential, temperature resistance, and activation potential. Occupancy considerations should be considered, including purpose of access(es), required frequency of access, stay times, and number of workers requiring access.

The design of concrete radiation shields should be in accordance with the requirements of ANS 6.4. The quality factors given in 10 CFR 835 should be used for determining the dose equivalent of the various types of radiation for dose rate calculations in conjunction with the appropriate methodology of ANSI/ANS-6.1.1-1977; alternatively, ANSI/ANS-6.1.1-1991 may be used, where justified, with quality factors corresponding to its methodology (e.g., as given in NCRP 116).

The shielding design for fusion facilities should consider the anticipated high-energy neutron spectrum; appropriate high-density shielding should be provided as necessary for these neutrons and made compatible with shielding for neutrons of lower energies and for gammas.

The design of shielding and work spaces should permit the later installation of additional temporary or permanent shielding to accommodate anticipated increases in workload or production of hot spots by activation or the accumulation of radioactivity. This includes consideration of size and weight of shielding and of such provisions as rigging fixtures, racks, portable shielding carts, and the like. The design of shielding should also include consideration of eventual decommissioning of the facility.

The need to protect equipment and materials from radiation that may damage them or cause them to become unduly activated should be considered in shielding design. The provision of shielding should be balanced against the alternate choices of moving the equipment or materials, selecting other types of equipment or materials, and replacing the equipment or materials more frequently.

Local shielding or portable (temporary) shielding should be considered, where appropriate, such as for the removal of hot equipment, the protection of personnel doing contact maintenance, and the protection of sensitive equipment. Modular construction and mobility of shielding should also be considered. Fortuitous shielding by structural materials and equipment (i.e., shielding by items not designed for that purpose) should be employed where appropriate; however, such shielding should be fixed, in general.

Removable shielding should be provided for large, infrequently moved pieces of equipment. In general, removable block may be used if access is required less than once a year. If access is required at more frequent intervals, steel doors, removable concrete panels, or the like should be considered. Blocks in removable block walls should be staggered both horizontally and vertically. Grout used for block walls should be of a type, density, and application thickness appropriate for the radiation type and strength of the source to be shielded.

Shielding should be provided for appropriate areas to allow personnel entry after off-normal events. Shielding should be provided as needed to reduce doses to equipment required to function following off-normal events.

In general, piping should not be embedded in shielding (e.g., concrete floors, walls, columns, or earthen foundations); however, embedment of pipe sleeves in concrete, from which the piping could be removed, may be acceptable.

The use of labyrinths should be considered for entryways to areas or cubicles containing a source producing a potentially high dose rate. Labyrinths should generally be double where there may be a high scatter fraction of the incident radiation and single where there is not; however, the choice also depends on the magnitude of the potential dose rate. If the labyrinth top is lower than the height of the ceiling in the room served, the labyrinth should generally be supplied with its own roof. Entrances with shield doors generally do not require a labyrinth.

An access hole for inserting a telescoping detector through a shield plug should generally be provided in the plug; it should have a shielding subplug or cap to cover it when not in use. Similarly, such an access hole should be considered for the roofs or labyrinth walls of cubicles containing equipment producing high dose rates.

Penetrations should generally be located as high up on a wall as possible. Penetrations should not line up directly with the source or with any area or space that may be potentially occupied (e.g., stairways and platforms). In particular, doors should be located or shielded so that personnel standing in front of a closed door are not exposed to direct radiation from the equipment within.

The number of penetrations should be minimized, particularly in shields serving as primary or secondary confinements; however, several smaller and dispersed penetrations are preferred to one large one. Penetrations should have the minimum diameter necessary. The radiological effects of voids (partially penetrating openings or areas of lesser density) should be considered.

The selection and design of penetrations should include consideration of the need for the penetration to be sealed for radiation reduction, air flow or airborne radioactivity control, fire protection, or flooding. A radiation seal or shield should generally be provided for a penetration or void under these conditions:

1. There is otherwise a direct shine from the source to a general access area through the penetration.

2. It creates a hot spot in a frequently or continuously occupied area.

3. The dose rate exceeds an assumed hot spot criterion in an infrequently but regularly occupied area (e.g., stairways, platforms, etc.).

4. It is into an area of varying but possibly high dose rate.

5. It is in a floor or roof slab.

6. It would create an area of unacceptably high dose rate after off-normal events in an area where people or equipment must perform a mitigation or recovery function.

A radiation seal or shield should be considered for a penetration or void in these situations:

1. Radioactivity buildup in a pipe passing through it might cause it to exceed an assumed hot spot criterion.

2. The centerline is <8 ft above the floor and the penetration is >2 in. (except for high-dose-rate cubicles).

3. The void is a glove port in a glovebox potentially containing, even when not in use, radioactivity producing a high dose rate outside the box.

4. It is a gap between the top of a wall and the soffit of the floor above the wall, if offsetting is not adequate to satisfy applicable shielding requirements.

6.2.2.3 Nonradioactive Worker Hazards

Nonradioactive worker hazards at large fusion facilities typically include the following:

a. a large number of high-voltage electrical systems, some of which are custom designs;

b. cryogenic materials such as liquid helium and nitrogen in significant quantities for magnet operation and plasma diagnostics;

c. class III and IV laser systems for plasma diagnostics;

d. large electromagnetic fields for plasma magnetic confinement and heating;

e. high power radio frequency and microwaves for plasma heating;

f. rotating devices including centrifuges for vacuum pumping and plasma fueling; and

g. large vacuum chambers and extensive vacuum piping.

As stated in DOE-STD-6002-96, existing Federal regulations (e.g., OSHA standards in 29 CFR 1910 and 1926) provide requirements on control of industrial hazards to workers in such areas as asphyxiation, electrocution, exposure to cryogenic materials, vacuum, and rotating machinery as well as hazardous substances.

One area where there are not specific regulations is exposure to electromagnetic fields. Fusion facilities should be designed to limit static electromagnetic field exposures to personnel during routine operations. More information in this area is provided in Section 2.3.4. The major concern for the fusion designer is to minimize large fringing electromagnetic fields because they could create difficulties for access near the fusion island during troubleshooting and maintenance activities. Measurements of real-time worker exposure to electromagnetic fields should be provided to ensure the limits given in Chapter 2 are not exceeded.

6.3 Systems Involved with Potential Safety Concerns

Because of the large impact facility design options have on potential hazards affecting public and worker safety and the developmental nature of fusion, only two safety functions could be identified at this time as applying to all fusion facilities: confinement of radioactive and hazardous material (Section 6.2.1), a public safety function, and control of operating hazards (Section 6.2.2), a worker safety function. Additionally, potential design-specific safety concerns that should be considered *during the design process* to minimize challenges to the public safety function of confinement of radioactive and/or hazardous materials have been identified:

a. ensuring afterheat removal when required;

b. providing rapid plasma shutdown 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); and

f. limiting airborne and liquid releases to the environment.

The above functions have been identified as “potential safety concerns” if their failure could *threaten* the public safety function of confinement of radioactive and hazardous material. However, the ultimate impact of these safety concerns on the public safety function can only be judged in the context of a specific design of the fusion facility. Evaluation of these safety concerns will normally be an iterative process. Fusion facilities contain a number of systems that may interact in a complex way to sustain the fusion reaction. Identification of safety requirements for such systems requires a systematic methodology to ensure that, for a given facility, each hazard is properly identified, that its impact on safety is assessed, and that the requirements to protect the worker, public, and environment from those hazards are balanced and integrated into the facility design. Because of the range of potential hazards in fusion facilities and the design options available, functional analysis combined with results from recent safety studies of conceptual fusion power plants were used to identify the potential safety concerns noted above for fusion plants. Because the hazards and their impact on public and worker safety are facility design-specific, development of detailed prescriptive system-level safety requirements is felt to be inappropriate. Instead, an approach has been used to develop broad functional safety requirements that can be used by fusion facility designers to integrate safety into the design up front in a cost-effective way. Design measures (as opposed to administrative measures) are the primary means to deal with these potential safety concerns, and such measures are discussed in the following paragraphs.

6.3.1 Afterheat Removal Systems

The safe removal of afterheat (decay heat) is an issue to be evaluated in D-T fusion facilities. Typically the afterheat amounts to several percent of the normal operating fusion power. One day following shutdown, it decreases by a factor of 3 to 10 depending on the materials and the operating scenario (pulsed vs continuous operation). Unlike fission cores, the decay heat relative to thermal power level is smaller and distributed over large surfaces, and large heat sinks are available in the fusion island structures. The design of fusion facilities should provide a reliable means to remove any undesirable afterheat generated by activation products produced by neutron absorption in structures such that the confinement public safety function is ensured. The need for and reliability of afterheat removal systems should be commensurate with the role of afterheat removal in complying with evaluation guidelines. Passive afterheat removal (i.e., no major hazard or component melting can be expected even when all active cooling capacity is lost, and removal is accomplished by only heat conduction and thermal radiation) is preferable to active systems. For fusion facilities with high levels of afterheat (i.e., levels where active cooling is required), the concepts of redundancy, diversity, and independence should be considered in the design of afterheat removal systems.

In addition to the general design guidance in Section 6.1, the following system-specific design guidance is provided.

A complete loss of all in-vessel cooling is an off-normal event and should be evaluated to provide an upper bound on the importance of this safety concern. In most off-normal event scenarios, there will be at least some active cooling. The vacuum vessel may have a safety function in afterheat removal. Cooling system diversity (i.e., multiple, independent cooling loops) for in-vessel components may provide a measure of defense-in-depth for this safety concern even though active cooling of individual in-vessel components may not be reliable because of the severe plasma-facing operational environment and their experimental nature.

If an active afterheat removal system is required, there should be specific reliability requirements for a given duration after shutdown. For example, up to one day after shutdown is important because the afterheat may decrease by up to an order of magnitude. Another 2 months is required for an additional order of magnitude in austinetic stainless steel components. Lower activation materials will decay more quickly. The required heat removal capacity should be evaluated based on actual materials specified in the design and the rated thermal operating power.

6.3.2 Rapid Plasma Shutdown System

A means of rapid plasma shutdown should be provided for fusion facilities, if required to ensure that evaluation guidelines are met. An example of a rapid plasma shutdown system would be a system that reliably injects a fast high-Z impurity pellet into a plasma for rapid termination in response to a precursor signal for a large plasma disruption. The level of required reliability, redundancy, and diversity of such a system, its effectiveness, and speed of action should be such that safety functions required to meet evaluation guidelines are ensured. Consideration should be given to heat, particle, magnetic, and mechanical loads on confinement barriers resulting from worst-case credible transient overpower events, VDEs, or disruptions in assessing the need for a rapid plasma shutdown.

An off-normal fusion power rampdown system will act on a time scale of the order of a few tens of seconds and might be sufficient to cover loss-of-flow events in the plasma-facing components if sufficient pump inertia is installed. In case of the unlikely event of coolant flow channel blockage, an off-normal fusion power shutdown system acting on the few seconds time scale is needed. Possible mechanisms are impurity injection by gas puffing/pellets or controlled equilibrium disturbance. A design constraint is fast termination without otherwise undesirable consequences. If all above mentioned active fusion power shutdown actions fail during an off-normal event, the plasma would always be shutdown by passive means due to overheating of plasma-facing components and consequent impurity influx.

6.3.3 Control of Potential Energy Sources

Five energy sources could drive fusion facility off-normal events including design-basis events: coolant energy (6.3.3.1), chemical reactions (6.3.3.2), magnets (6.3.3.3) and plasma (6.3.3.4) as well as afterheat (6.3.1), discussed previously.

6.3.3.1 Coolant Energy

For fusion facilities that use fluids for active cooling of in-vessel components (e.g., high-pressure water or steam, liquid metals) or cryogenic liquids inside the cryostat, the design should incorporate a means to accommodate the accidental release of the fluids to ensure that confinement barriers such as the vacuum vessel or cryostat are not breached in a manner that could result in exceeding evaluation guidelines. Consideration should be given to the effect of large spills of cryogenic liquids inside the cryostat on the structural integrity of affected SSCs due to loss of ductility at lower temperatures.

a. Discussion of Sources of Coolant Energy

For water coolant systems, the overpressure depends on mass and energy. Energy sources include the stored energy in the water, energy from plasma operation if the water is not being adequately cooled (overpower transient, loss of flow, loss of heat sink), energy from chemical reactions, decay heat, and heat transferred from surrounding surfaces. Heat transfer to energy sinks takes place via vaporization of water, conduction, and condensation on surfaces.

For typical water-cooled designs, the potential sources for overpressure of the confinement barriers (vacuum vessel and cryostat) are

1. release of cryogenic fluid in the cryostat;

2. steam production from leakage of coolant in the vacuum vessel, or, if applicable in the cryostat; and

3. hydrogen production, with ingress of air and explosion in the vacuum vessel (see Section 6.1.3.9).

The dynamics of the scenarios involving overpressure are different and lead to consideration of two time scales. Short-term scenarios lead to overpressure in a time span of minutes following the release of coolant or cryogenic fluid in the vacuum vessel or in the cryostat. Medium-term scenarios are driven by decay heat and chemical reactions and lead to overpressure in a time span of days if no sufficient decay heat removal can be provided.

The short-term scenarios include the release of cryogenic fluid in the cryostat and the short-term pressurization of the vacuum vessel due to ingress of coolant with and without hydrogen production.

The release of the cryogenic fluid from the magnet systems in the cryostat leads to typical pressures in the cryostat of the order of several atmospheres. Note that in the absence of blowdown volumes or venting, this pressure has to be supported by the cryostat as an internal load and by the vacuum vessel as an external load.

The ingress of coolant in the vacuum vessel would lead to rapid pressurization of the vacuum vessel to pressures that, for large quantities of water released, come close to saturation pressure (about 1.6 MPa at 200°C). Venting to the cryostat or a blowdown volume (suppression pool) would lead to significantly lower maximum pressures.

Another possible source is hydrogen production (see Section 6.1.3.9) and energy release from chemical reaction between the water coolant or air and the plasma-facing components (e.g., beryllium tiles and coatings on the first wall). Although the reaction rates between water or air and beryllium are uncertain and need further analysis, it is known that the form of beryllium (porous or dense) has a big impact on these rates.

The 600–650°C range is critical with respect to beryllium reactions. Since the beryllium–water and beryllium–air reactions are exothermic (377 kJ/gmole beryllium), the major concern for short-term hydrogen production comes from reactions that are self-sustained. Self-sustained reactions require that the heat production (from the reaction) exceeds the heat loss (from cooling). Scenarios including short-term hydrogen production start with overheating of the beryllium in the first wall or divertor to the 650°C range. The following scenarios are examples.

Loss-of-Flow Events (LFEs) in shield lead to Loss-of-Cooling Events (LCEs) by local penetration of the overheated first wall and subsequent self-sustained beryllium–water reaction. Preliminary calculations show that this scenario (without mitigation) gives rapid production of a few kilograms of hydrogen (in the solid beryllium case) to tens of kilograms of hydrogen (if the beryllium is in porous form).

Another possibility is an LFE with ingress of air in the vacuum vessel (LVE). Worst-case scenarios of this type (without mitigation) with a porous beryllium–air reaction could lead to production of hundreds of kilograms of hydrogen in time scale of minutes.

The medium-term scenarios involve extensive steam production from the coolant inventory by energy sources like decay heat, stored heat, and heat produced by chemical reactions as well as hydrogen production due to chemical reactions. Examples of such scenarios are in-vessel LCEs in the vacuum vessel or shield, combined with reduced or no decay heat removal.

b. Pressure Suppression Strategies

The strategies with respect to pressure limitation and suppression can be divided into preventive and mitigative strategies. In both preventive and mitigative strategies, use can be made of passive or active means to implement the strategies. Whenever possible, the priority should be given to preventive strategies and to passive means.

Preventive strategies have the goal to reduce the amounts of steam and hydrogen produced. Prevention of pressure buildup can be achieved by acting upon the phenomena that lead to hydrogen production (see Section 6.1.3.9) and by limiting the amounts involved in chemical reactions or in steam formation.

1. Limit temperature of first wall—As pointed out above, 650°C is a critical temperature with respect to hydrogen-producing reactions. Therefore, the operating temperature and the rapid plasma shutdown (if required, see Section 6.3.2) should be designed to prevent the first wall from reaching this critical temperature in the reference off-normal event sequences defined in the safety analysis. In low-frequency severe accidents where plasma-facing component (e.g., beryllium) reactions can not be excluded, a backup strategy is to provide sufficient passive heat transfer between the reacting material and the structures to avoid self-sustained reaction. Segmentation of the shield coolant loops and of the vacuum vessel coolant loops should be performed in such a way to optimize the likelihood of heat transfer from the shield.

2. Prevent ingress of air (see Section 6.1.3.9)—The ingress of air is a necessary condition for the forming of an explosive mixture with hydrogen (the detonation limits of hydrogen-air mixtures range from about 14% to 70% H_2). Therefore, prevention of air ingress by maintaining the cryostat vacuum boundary and by providing inert atmosphere around the cryostat are possible strategies to avoid hydrogen explosion.

3. Limit inventory—For the steam generation scenarios, the total amount of steam produced can be limited by limiting the amount of water spilled in the vacuum vessel in case of a LCE. One way of limiting this amount is to segment the coolant loops for the shield and for the vacuum vessel.

4. Limit chemical reactivity—The chemical reactivity of beryllium is dependent on its form: porous or dense. Characterization of beryllium coating should be performed and if possible the existence of porous beryllium in the vacuum vessel should be limited.

5. Provide adequate afterheat removal in all scenarios—The afterheat is the driving force for the medium-term overpressurization scenarios. The strategies to provide adequate afterheat removal are covered in Section 6.3.1.

The mitigative strategies have the goal to limit the pressures that are caused by steam production and hydrogen explosion.

1. Blowdown volumes—The expansion volume provided by the vacuum vessel itself may be insufficient to limit the pressure to reasonable design values from the blowdown of the coolant circuit in case of an in-vessel LCE. If the vacuum vessel vents to a suppression pool or an adjacent larger volume such as the cryostat, peak pressures can be reduced.

2. Vacuum vessel draining—Another process to mitigate peak pressures is one in which the water from a LCE in the vacuum vessel is drained and led over cold surfaces to reduce the pressure. The same cold surfaces are used as condensation surfaces for the steam formed in the LCE.

6.3.3.2 Chemical Energy

Fusion facilities should be designed such that chemical energy sources are controlled during normal and off-normal conditions to minimize energy and pressurization threats to radioactivity and toxic material confinement barriers. Design measures should ensure that evaluation guidelines are met. Chemical reactions should be prevented from releasing energy that threatens a confinement boundary, either by preventing the reaction or by accommodating the additional energy and pressure.

Additional design guidance for chemical energy sources is provided.

a. Chemical Reactions

Much of the chemical energy source term in a typical fusion device is from plasma-facing components made of beryllium or carbon. Examples of chemical reactions include beryllium–steam (or carbon–steam), H_2-air, and beryllium–air. The lower flammability limit for H_2 is about 4% volume in air. Beryllium–steam reactions are exothermic, and the energy release will tend to increase overpressures, cause higher accident structural temperatures, and volatilize some chemically toxic beryllium. Unlike beryllium–steam, carbon–steam cannot become chemically ignited because it is an endothermic reaction. Both beryllium–steam and carbon–steam reactions will mobilize the tritium in these materials.

Several scenarios could lead to beryllium–steam (or carbon–steam) reactions, such as the following:

In-vessel LCE (water ingress) triggers a plasma disruption; the disruption heats the first wall or divertor surface above operating temperature; a thermal gradient starts to relax but beryllium–steam reactions may be sufficient to either ignite the beryllium or generate an undesirable amount of H_2 (plus mobilize tritium and beryllium)—depending on operating temperature and temperature rise from the disruption. Even if short-term temperatures are too low for significant beryllium–steam reactions, afterheat (without adequate decay heat removal) could raise temperatures sufficiently for beryllium–steam reactions to start later. Similar scenarios start from in-vessel LCE (flow blockage), overpower transient, or ex-vessel LFE or LCE.

At present, it appears difficult to argue that much of the beryllium on the first wall and divertor surface will not be porous (85–90% of theoretical density) because of possible effects from neutron irradiation, ion irradiation, and redeposited and accumulated beryllium dust. Additional research on this is needed, as well as further testing of beryllium–steam and beryllium–air reaction rates as a function of porosity, temperature, and gas pressure. Another potential chemical reaction is liquid metal-water reactions; for example, this reaction should be evaluated if a liquid metal such as lithium is used in the blanket with pressurized water used for in-vessel cooling.

b. Explosions

Another related chemical energy source term is from explosions. Examples include H_2, metal/carbon dust, and cryogenic ozone. The lower flammability limit for H_2 is about 4% volume in air; the lower explosive limit for H_2 in air depends on geometry and is about 15% by volume (deflagrations are possible with lower concentrations of H_2). The lowest H_2 concentration shown experimentally to detonate in air is 13.5%.

Where explosion hazards theoretically exist, the design must do one or more of the following:

1. keep oxidizers (e.g., air) out preventing an explosive mixture (only applicable if oxidizer is required);

2. contain the explosion;

3. show consequences are acceptable in terms of public and plant personnel safety.

An explosion hazard exists related to the use of liquid nitrogen in the thermal shield, specifically irradiation-induced ozone production (Brereton 1989). Explosions in liquid nitrogen systems in a radiation environment have been reported over the years. These explosions are thought to be caused by the production of ozone (O_3) by the action of radiation on the intrinsic oxygen impurity. Ozone can spontaneously decompose back into oxygen releasing 144 kJ/mole. Production rates for large thermal shields could be of order several moles of O_3/day. Ozone is even less volatile than oxygen and may accumulate in the shield. Seven moles of O_3 represents an explosion hazard with a potential energy release of 1 MJ (250 g TNT). This much energy represents a significant hazard and seems to indicate the necessity of operating with very pure nitrogen or replacing liquid nitrogen with cold helium gas or a passively cooled structure.

6.3.3.3 Magnetic Energy

The magnet system (for a tokamak device) consists of the toroidal field (TF) coils, the poloidal field (PF) coils, and the central solenoid. TF coils are normally superconducting cables cooled with liquid helium and are wound into D shapes. The PF coils are also typically superconducting cables cooled with liquid helium and wound into horizontal rings, which are located above and below the vacuum vessel with typically some coil sets inside and outside the TF coils. The TF and PF coils provide the basic magnetic field geometry for plasma confinement and position control. The central solenoid cables are typically superconducting cables wound horizontally and situated at the center of the vacuum vessel torus supported by, for example, a bucking cylinder. The central solenoid set provides the transient field to induce all or part of the plasma current.

Fusion magnets contain significant stored energy that can cause materials, either in the magnet itself or in adjacent structures, to become volatile. Such faults could release missiles which could then cause damage that would release cryogenic liquids whose overpressure could threaten confinement. Excessive motion of magnets or associated supports could break tritium lines or diagnostic penetrations into the vacuum vessel. In general, due to the developmental nature of this system, it is desirable that the fusion magnets not be classified as a safety-class or safety-significant system in the performance of their primary design function of plasma ion and electron confinement. Therefore, magnet systems in fusion facilities should be designed such that faults in the magnets and the associated ancillary systems (power supply, electrical systems) should not threaten safety functions. Where feasible, a design goal should be to design for symmetrical fault conditions to minimize loads.

The mechanical integrity of the magnets should not depend on the shear strength of the insulating materials or the shear bond between insulation and structural materials. The dielectric strength of the insulation should be provided either by materials with an intrinsic dielectric strength, or by materials tested before assembly into the magnet. Since leaks at coolant connections are a common cause of magnet faults, such connections should be kept away from mechanical load paths, placed outside the winding pack and, as far as possible, in regions where some access is possible for inspection or repair. Manufacturing can allow many faults to occur. Machining chips left in the coil slowly abrade insulation and then cause a failure after some years of machine operation. Very strict tests to determine the cleanliness of finished units should be performed.

6.3.3.4 Plasma Energy

For the next several generations of magnetic confinement devices, the plasma will be part of the experimental program, and there will be a need to decouple plasma physics issues, where possible, from facility safety issues, especially public safety. Where there is overlap between facility safety and the plasma system, such as during VDEs or strong disruptions, it is recommended that plasma-related consequences be confined to the interior of the vacuum vessel or cryostat to minimize potential public safety concerns. Several considerations regarding how the plasma is operated may affect the overall device safety. In particular, the issue of plasma stability is the primary concern. In the domain of stability, there are two primary categories: (1) thermal stability of the plasma and (2) plasma disruptions.

The disruption area concerns the sudden loss of thermal and /or magnetic energy from the plasma. This category of events can produce undesirable transient heat and/or mechanical loads on fusion island components.

a. Thermal Stability

The thermal stability area concerns a prevention of a plasma transient to higher fusion powers than provided by the facility design. In the event of uncontrolled thermal runaway, plasma-facing components could be subjected to higher heat loads than during normal operations. The plasma can be operated in either a thermally stable or unstable regime. There are several options to ensure a stable level of fusion power. One option is to operate at the high-temperature, thermally stable operational point. Another option is to operate in a driven mode. This is the case when auxiliary power must be injected into the plasma to drive currents in the plasma or to simply maintain the plasma power balance. With a driven plasma the only possibility of an increase in the plasma temperature would be if the auxiliary power is increased. Finally, it is possible to operate at or near the thermally unstable point, if active feedback mechanisms are employed. This issue is primarily an operational one; the main task for the in-vessel component designer is to design for a conservative, but credible, value of fusion power taking into account all credible plasma transients.

b. Disruptions

Any magnetic confinement geometry has the consequence of both thermal and magnetic stored energy in the plasma. If the confinement scheme is known to have the possibility of suddenly losing this stored energy, the in-vessel device hardware that receives these loads should be designed to accommodate these events. For example, the tokamak configuration is known to “disrupt” due to magnetohydrodynamic instabilities. In this event, the stored thermal energy in the plasma is rapidly lost to the plasma-facing components, introducing large thermal loads. Loss of the magnetic energy associated with fields generated by current flowing in the plasma can induce large currents in the surrounding first wall, breeding blanket, and vacuum vessel, which results in large mechanical loads. Disruptions can also generate high-energy runaway electrons that impact the first wall (with currents of the order of the plasma current). All of these disruption-related issues impose special design requirements on the affected fusion island hardware components.

The fusion island hardware should be designed to withstand credible disruptions. Care has to be taken during the safety analysis process to conservatively identify credible disruptions/ VDEs and resultant loadings to components; some insight can be gained from the disruption data base of contemporary large tokamaks. It is also prudent to operate in a parameter regime where these events can be minimized. For instance, in tokamaks, disruptions can be initiated by (1) exceeding a plasma density limit, (2) operating at too low an edge safety factor, or (3) operating at too high a plasma beta. It is especially important to avoid this latter type disruption during plasma startup and shutdown. In practice, these disruption causes can be identified and avoided, greatly reducing the probability of a disruption. Also, it may be possible to identify the onset of disruption and use active means to subsequently control it.

Another known concern for sudden loss of plasma control is related to position control. For highly shaped tokamak plasmas, active vertical position control is required to maintain the vertical position. Loss of the position control due to noise in the feedback system or power supply saturation is known as a VDE. If the main plasma contacts the plasma-facing components, the currents in the plasma can rapidly disappear, leading to a disruption.

6.3.4 Limiting Airborne and Liquid Releases to the Environment

The facility design should include means to control the release of radioactive materials in gaseous and liquid effluent and to handle radioactive solid wastes produced during normal operation. Furthermore, the design should aim at minimizing the generation of radioactive and hazardous wastes in all forms. Suggested means to accomplish this and also minimize worker exposures are discussed in Section 6.2.2. A specific long-term goal for fusion facilities is the elimination of all materials in the fusion island whose activation would require disposal by deep geologic burial. Sufficient holdup capacity should be provided for retention of gaseous and liquid effluent containing radioactive materials, particularly where unfavorable site environmental conditions can be expected to impose unusual operational limitations upon the release of such effluent to the environment. The design should limit the release of radioactive materials in effluents and emissions to ALARA levels during normal operation. There should be no interconnections between liquid effluent streams such as streams containing radioactive and/or hazardous waste, potable water streams, other incoming non-potable streams, and other outgoing streams.

Means for measuring the amount of radionuclides in effluents and emissions during normal operation and off-normal conditions should be provided. Means should be provided for monitoring the fusion island components, fusion island building, and the site areas for radioactivity that may be released from normal operations and off-normal events including design-basis events. Alarms should be provided that will annunciate if radioactivity levels above specified limits are detected in exhaust streams. Appropriate manual or automatic protective features that prevent the uncontrolled release of radioactive material to the environment or workplace should be provided. Systems designed to monitor the release of radioactive materials should have means for calibration and testing their operability. Sampling and monitoring should ensure adequate and accurate measurements under normal operations and off-normal events including design-basis events. Monitoring systems should be calibrated annually at a minimum with appropriate national standards to ensure validity of reported values. Radiation monitoring, alarm, and warning systems that are required to function during a loss of normal power should be provided with an emergency uninterruptable power supply (UPS) unless it is demonstrated that they can tolerate a temporary loss of function without losing needed data, and they are provided with standby or emergency (switched) power. Determination of the power supply type and quality should be based on the safety classification of the monitoring system or device. In addition to a local station alarm, radiation monitoring systems should have central (i.e., control room or radiation monitoring office) readout and alarm panels that are accessible after design off-normal event conditions to evaluate internal conditions.

6.4 Systems That Support Safety Functions

As noted in Section 6.1.2, SSCs required for the performance of a public safety function should be designated as safety-class. This includes supporting systems such as power, I&C, and cooling that directly support the system in the performance of the public safety function. In a similar manner, systems directly supporting a safety-significant SSC should be classified as safety-significant. Guidance for these support systems is given in Sections 6.4.1–6.4.4.

6.4.1 Instrument and Control Systems

I&C systems include equipment and components that monitor and display facility parameters, indicate parameter value changes, actuate equipment to maintain the parameters within specified limits, return the facility to operation within these limits, and mitigate conditions resulting from operation outside limits. Specific equipment includes sensors, signal transfer media, signal processors, control circuits, and actuation devices.

In addition to the general design guidance in Section 6.1, the following system-specific design guidance is provided:

a. I&C system functions may generally be considered either control or safety functions. Physical separation, electrical isolation, and independence of these functions is essential in I&C system design to ensure that safety functions, once initiated, will not be stopped or impeded by control functions. Conversely, safety functions must not interfere with the operation of the control function when the facility is operating within the normal design envelope.

b. The design of the I&C systems should be integrated with the design of other facility systems to ensure an integrated response to process demands.

c. The process variables that are selected as inputs to the I&C system should be a complete set that permits automatic or manual detection and response to off-normal conditions that challenge the integrity of designated confinement barriers. The selection process should consider the measurability, variability, and time response of the variables, and the operational demands and limitations. Postevent monitoring and control should be provided where the safety analysis has assumed their continued function in the postevent environmental conditions.

d. The instrumentation selected to measure a process variable should be analyzed to determine if its reliability, accuracy, and response time characteristics satisfy the control or safety needs for all required operating conditions. Taps, ports, and penetrations should be positioned to obtain the most desirable measurement parameters.

e. Enabling or interlock functions should be designed to prevent facility systems from entering into off-normal conditions or allowing a transient condition to continue its off-normal excursion.

f. Setpoint, instrumentation uncertainty, and response time analysis should ensure adequate margins between normal control and safety setpoints and limits. Control functions should maintain normal operations without unnecessary challenges to or actuation of a safety function. Safety margins and system response times should be sufficient to ensure that conditions do not exceed the robustness of facility systems or do not exceed consequences documented in the facility authorization basis.

g. Instrumentation should monitor variables over their full anticipated ranges for normal and off-normal conditions to ensure adequate safety and design margins are maintained. The instrumentation should measure, display, and alarm conditions approaching or exceeding limits defined by the safety analysis.

h. Multiple, diverse technologies should be considered in the selection of the sensors and measuring systems for the in-vessel and near-vessel parameters because these instrument components will be exposed to harsh environments (potential radiation exposure, magnetic fields, temperature gradients, ion pulses, etc.). Unexpected failure mechanisms within a single measurement technology could lead to erroneous actions.

i. A task analysis should be conducted to determine functions that may be assigned to the operator and those that are to be machine assigned. The operator should be provided with manual action-initiating capability for all safety functions, including automatic functions. Manual initiation should be provided for actions not appropriate for automatic initiation or for chosen automatic action interruption or adjustment. The operator should also be provided with feedback information to confirm the occurrence of the proper actuation and completion of the selected safety function.

j. The control room and supporting local control and monitoring panels should be designed for man/machine interface and local area or room habitability. Sufficient central control room displays and command features should be provided to allow monitoring and response to off-normal events, Adequate radiation and environmental protection should be provided to permit access and occupancy of the control room under accident conditions where the operator monitoring, mitigative, or response actions are required during or following an off-normal event. A human factors analysis of the control room and local operator interfaces should be performed consistent with the safety analysis. The design of the control room should be implemented in accordance with *IEC 1989* with appropriate modifications for fusion technologies and hazards.

k. Equipment at locations outside the control room should be provided if required to achieve and/or maintain the facility systems in a safe or shutdown condition in the absence of the control room functions designated for that purpose.

l. The I&C system and components should be designed to provide the capability for performance of periodic testing of all instruments, logic, interlocks, permissive features, bypasses, and other facility systems. The safety system portion of the I&C system should be capable of confirming the required calibration, setpoint, and time responses with test frequencies that meet the uncertainty analysis requirements. Test features of the safety-class system I&C should be able to detect failures of the system that could degrade or prevent a safety function from occurring in the presence of a single failure. The I&C system design should include the provision for sufficient bypass or disable capability and test point access to allow for the valid performance of necessary and adequate testing.

m. The I&C power system design should provide for the necessary redundant power sources to ensure that the system will be capable of performing its required function under all normal and off-normal conditions. Power sources that should be considered for the I&C system include UPSs, critical instrument busses capable of being powered from diesel generator backup power, and battery backup systems. The power supply for safety-class instrumentation and controls should meet the IEEE Standard requirements for Class 1E power systems (IEEE 1980).

n. Safety-class and safety-significant equipment should be designed to fail safe on loss of motive force or power. In addition, safety-class equipment should be designed to meet single failure criteria.

o. If required by the safety analysis, safety function actuation should be sealed in so that the safety function actuation is maintained even if the logic that initiates the actuation is lost. Controlled bypasses may be provided for operator interruption or adjustment of automatic actions.

6.4.2 Electrical Power Systems

The electrical power system includes on-site alternating current (ac)/direct current (dc) sources and distribution networks and feeders(s) from the off-site grid. The switchyard is the interface between the off-site grid and the fusion facility. From the switchyard, the electrical power distribution system divides into two main parts: the fusion facility system and the balance-of-plant system.

The fusion facility distribution system supplies the heavy (and often pulsed) loads for fusion facility operation, including the magnet power supplies and various plasma-fueling and heating power supplies. The system may provide for safety-class loads in addition to non-safety-class loads, in accordance with the facility safety analysis. An emergency generator or UPS or both should provide power for safety-class loads in the event of loss of off-site supply.

Additional design guidance specific to the electrical system is provided.

a. Safety-class electrical systems

If the facility safety analysis concludes that safety-class electrical systems are necessary, design of these electrical systems should comply with IEEE Standards 308 (IEEE 1980), 379 (IEEE 1988), 384 (IEEE 1992) and 603 (IEEE 1991).

The safety-class systems should be testable in compliance with the following standards:

1. ac systems and components—IEEE Standards 308 (IEEE 1980) and 338 (IEEE 1993),

2. dc systems and components—IEEE Standards 308 (IEEE 1980) and 338 (IEEE 1993).

b. Radiation/contamination and equipment life

Safety-class electrical equipment required to be in areas of radiation and contamination should comply with IEEE Standard 323 (IEEE 1983).

c. Instrument and Control Systems

The safety-class electrical systems should have I&C elements to monitor and ensure the necessary parameters for normal operation and for off-normal conditions, in accordance with IEEE Standard 603 (IEEE 1991).

d. Backup power generation

Safety-class backup power supplies should comply with the requirements of U.S. Nuclear Regulatory Commission (USNRC) Regulatory Guide 1.9 and IEEE Standard 387. Provisions should be made for auto/manual synchronizing each emergency/backup power source to its respective bus for periodic testing during normal facility operation.

The manufacture and testing of safety-class diesel generators should comply with nationally recognized ANSI Standards C50.10 and C50.12, NEMA Standard Publication MG-1, and IEEE Standards 115 and 386.

e. Switch gear and load centers

Safety-class electrical equipment with 480 V or higher should comply with IEEE Standards 323 (IEEE 1983) and 344 (IEEE 1987). Fault calculations should be in accordance with the latest issue of ANSI Standards C37.010 and C37.13.

All switch gear and load centers should be located indoors if possible.

f. Direct Current Systems

The safety-class dc power systems should be of adequate size to provide control and switching power to safety-class systems and components in addition to safety-class dc loads. The dc systems should operate ungrounded.

All batteries and chargers should have sufficient capacity to comply with IEEE Standard 308 (IEEE 1980). Battery capacity determinations should be in accordance with the method of IEEE Standard 485. Restoration of the battery from the design-minimum charge state to the fully charged state should be within the time period stated in fusion safety analysis.

g. Vital instrumentation and control power supply

If the fusion facility safety analysis requires systems of vital instrumentation and controls, emergency or backup power supply to these systems should be by independent and ungrounded power supplies. Each vital ac power supply should consist of an invertor, distribution panel, and manual transfer switch.

h. Motors

All safety-class motors should comply with NEMA Standard MG-1 and other applicable USA and ISC standards for sizing, manufacturing and testing. The sizing of all motors should ensure operation within the temperature limits given in NEMA Standard MG-1.

Enclosed motor windings should have moisture-resistant Class B insulation systems, suitable for power plant service, in compliance with NEMA Standard MG-1.

Motors installed indoors should be open, drip-proof, and fully guarded or should be totally enclosed and fan cooled. Motors installed outdoors should be NEMA weather-protected Type I or should be totally enclosed and fan cooled.

i. Power, control, and instrumentation cables

Except for thermocouples, metal conductors should be Class B stranded, tin-coated or lead-alloy-coated, soft or annealed copper. Safety-class cables should be capable of passing the cable tray vertical flame test set forth in IEEE Standard 383 (IEEE 1974). Individual conductor in cables should be capable of passing the vertical flame test of Subsection 6.19.6 of IPCEA S-19-81 and/or S-66-524.

Safety-class cables should be qualified for intended service in compliance with IEEE Standard 383 (IEEE 1974). Insulation and jacket thickness for power cables should be in accordance with Insulated Power Cable Engineers Association (IPCEA) standards. Control cable insulation and jacket thicknesses should also comply with IPCEA standards.

The overcurrent capacity of cables and individual conductors should comply with the NFPA 70 standard. Cable current carrying capacity (ampacity) information contained in IPCEA Publications P-46-426 and P-54-440 should be used to select cable size.

j. Raceways and trays

Safety-class cables and conductors inside the facility should be in trays or in rigid steel conduit and should route only through safety-class raceways and should comply with IEEE Standard 344 (IEEE 1987). No other circuits should route through safety-class raceways.

Trough-type cable trays should be utilized where practicable. Tray strength should be verified by tests in accordance with the latest revisions of NEMA Standards Publication VEI-1976. The dead weight-carry capacity of the cable trays should comply with NEMA 3-14-1079 and VE-1-1991.

k. Electrical penetrations

Safety-related and other electrical penetrations of the fusion confinement barriers should comply with IEEE Standards 317 and USNRC Regulatory Guide 1.63. Penetrations should meet the same requirements of robustness and leak tightness as the confinement system. Physical separation of penetrations should comply with USNRC Regulatory Guide 1.75.

l. Separation of facility safety systems/components

Physical separation and independence of electrical systems should comply with IEEE Standards 384 (IEEE 1992) and 603 (IEEE 1991).

m. Facility and building grounding

The facility grounding grid should comply with the procedures and recommendations of IEEE Standard 80. Grounding within buildings should be in accordance with the NFPA 70.

n. System and equipment grounding

System and equipment grounding should comply with IEEE Standard 142.

o. Cathodic protection

Cathodic protection should be in accordance with the results of soils analysis and resistivity readings. Cathodic protection may be necessary for metal underground pipes and storage tanks, surface-mounted storage tank bottoms, sheet piling, and the fusion facility confinement barriers.

p. Lightning protection

The lightning protection system should comply with ANSI Standard C-62 series and NFPA Standard 780.

6.4.3 Cooling Systems

The cooling systems include all SSCs that remove heat from the facility and transfer it to a heat sink such that

- thermal, hydraulic, and mechanical parameters are within design limits for the cooling system, fusion device, confinement barriers, and other safety-class equipment;
- a leaktight barrier is maintained against uncontrolled release of radioactive and other hazardous materials to the environment.

The cooling system includes coolant makeup systems and collection and disposal systems for spilled or drained coolant.

A number of fusion facility components may require cooling during normal operation and off-normal events. These include the first wall, divertor, shield wall, cryostat, vacuum pumps, magnet coils, and so on.

In addition to the general design guidance in Section 6.1, the following system-specific design guidance is provided.

a. Structural design should consider service temperatures and other conditions of the boundary materials; the uncertainties in determining material properties; effects of irradiation on those properties; residual, steady-state, and transient stresses; and size of flaws.

Additionally, the pressure load range should include temperature-induced pressures, hydrostatic test pressures, and any credible pressure augmentation resulting from small leaks between two coupled cooling systems.

Cooling systems that are safety-class should have design, fabrication, inspection, and testing in accordance with a recognized safety-class code such as ASME 1992. The specific codes and criteria selected should be commensurate with the level of safety required and should have a technical justification. Table 6.1 gives suggested design codes for the cooling system. Where ASME design is not feasible, such as in the case of unique materials or designs, the alternate codes listed in Table 6.1 may be used. Piping and equipment supports should be designed to ANSI/AISC N690 (ANSI 1984) or equivalent. Cooling system components that are safety-significant should have design, fabrication, inspection, and testing in accordance with a recognized national consensus code such as ANSI/ASME B31.3 (ANSI 1993a).

b. An analysis of cooling system deflections over the full range of temperatures, vacuums, and pressures should confirm no interferences or loss of pressure boundary integrity.

c. The cooling system boundary materials and design should provide sufficient margin to ensure that, when stressed, the boundary behaves in a nonbrittle manner with a very low probability of rapidly propagating fracture. Coolant should be compatible with structural materials that it may contact during normal operation and off-normal events throughout the range of anticipated physical parameters. Table 6.1 lists the materials requirements. Alternative codes and standards may be used with appropriate justification.

d. Cooling system design should provide for instrumentation to monitor safety-related variables and controls to maintain the variables within design limits (see also Section 6.4.1). The cooling system design should provide for instruments to detect and measure abnormal leakage and controls to isolate and mitigate the leak. To the extent practical, the primary mode of actuation of safety functions should be automatic and should be initiated by detection and control channels of suitable diversity and redundancy.

e. Design should provide means to collect spilled coolant to prevent damage to safety-class SSCs and to limit contamination and environmental releases.

f. Design should provide makeup coolant for breaks, leaks, or draining required for maintenance activities. The coolant makeup rate should be sufficient to maintain the heat removal and rejection capacity to prevent or limit damage of safety-class SSCs while allowing only negligible materials reactions with the coolant.

g. For shutdown conditions, the cooling system design should incorporate passive features to the extent practical for heat removal, transfer, and rejection functions. The design objective should be to provide adequate cooling of all safety-class SSCs without human intervention for the period specified in the safety analysis and for as long a period as practical following shutdown of the fusion device.

h. Unavailability of the on-site electrical power supply or the off-site power supply should be a consideration in ensuring safety-class cooling system functions, assuming a single failure within the cooling system. Coincident failure of off-site and on-site power systems should not be a design consideration.

i. Cooling system design should consider the thermal, hydraulic, and mechanical effects of unintended operation of active components, such as valves and pump motors.

j. Cooling system design should consider the thermal, hydraulic, and contamination effects of cross leaks between adjacent systems, such as the primary and secondary sides of a heat exchanger.

k. Materials properties for cooling systems should include the effects of radiation embrittlement at all levels of service temperatures.

l. Coolant system pumping should provide for coolant flow coastdown to prevent exceeding design limits.

m. Discharge of coolant for pressure relief should be to a confinement tank that maintains the confinement function of the coolant system.

n. The coolant system should include protection for overpressure to prevent degradation of safety function.

o. The coolant system should include provisions for sampling to analyze coolant properties and to identify entrained radioactivity or other contaminants.

p. Use of a primary cooling system and a secondary cooling system is the recommended design for containment of radioactivity where required by the safety analysis. Closed heat exchangers are the recommended coupling between primary and secondary cooling systems.

q. Multiple cooling loops are recommended for consideration as a design feature to reduce the operational thermal-hydraulic transient associated with single-loop failure.

r. Components and headers of systems should be designed to provide individual isolation capabilities to ensure system function, control system leakage, and allow system maintenance.

s. The use of leak-before-break may be considered in the analysis of pipe break and pipe whip events. The methodology described in Section 3.6 of the Standard Review Plan, NUREG-0800 is recommended.

6.4.4 Remote-Handling Systems

Remote-handling systems may perform a number of functions to minimize personnel exposure to radiation and other hazards during normal and off-normal conditions. In addition, remote operations functions may be required to prevent or mitigate the consequences of off-normal events. Potential remote operations include the following:

- Erect portable radiation shielding panels.
- Place or relocate experimental devices or other equipment in high radiation fields.
- Test or inspect SSCs as necessary to ensure performance of safety functions.
- Replace equipment or components in high radiation fields.
- Decontaminate SSCs in preparation for maintenance.
- Install/place diagnostic instruments.
- Install consequence mitigation devices in high radiation fields or otherwise unsafe conditions.

Remote-handling systems should be considered where it is anticipated that personnel exposures may otherwise exceed dose or contamination guidelines.

Design guidance for remote-handling systems includes the following items:

a. General

Remote-handling systems may be operated and stored near the fusion device in an area subject to intense magnetic, thermal, neutron, and gamma radiation environments. Persistent low levels of hydrogen, deuterium, and tritium gases, as well as potential high levels of these gases during off-normal events, may be present and should be considered in design. Activated dust from plasma-facing components may be present during maintenance or off-normal conditions and should be considered. The design should accommodate the following general guidance:

1. The remote-handling system should be designed such that the operator will not be exposed to a radiation dose rate greater than the facility ALARA exposure limits.

2. Remote-handling systems and components should not cause a collision with safety systems or components while performing normal or abnormal plant maintenance. Wiring through sections and/or modules of remote handling equipment should be provided within the equipment.

3. Allowances should be made for equipment movement so that, in performing intended operations, safe distances can be maintained from personnel in normally accessible work areas.

4. Equipment should be operated and stored in areas accessible, or that may be made accessible, for testing, inspection, and maintenance. Where this is not possible, a means of safely retrieving the equipment to a safe area should be provided. This must include backup methods of safely disconnecting from radioactive or other hazardous materials, for which the remote equipment is intended.

5. The operator should be provided a full view of the remote operation.

6. Equipment should fail safe upon the loss of motive power.

7. Features should be incorporated such that failure of one of the drive mechanisms or any component of the equipment will not result in exposure of personnel to excessive radiation while recovering from such failure.

8. Redundancy of critical controls should be provided to prevent single-mode control failure of remote or robotic equipment causing unplanned or unanticipated equipment motion.

9. The expected high levels of RF and magnetic interference potentially present should not interfere with control systems or the normal operation of systems.

10. The presence of large quantities of cryogenic materials during both normal and off-normal conditions must be considered in the design of remote equipment.

11. Design should consider radiation shields between the fusion device and the remote-handling system components as necessary to reduce exposure to and neutron activation of the system components.

b. Structural design

The design, fabrication, testing, and inspection of safety-class and safety-significant remote-handling equipment should be in accordance with commercial codes and standards applicable to that particular type of equipment. The majority of the systems and components should be considered as non-safety-class and should be designed and fabricated to industrial standard requirements.

Allowable design stresses in mechanical components should provide a safety factor of at least 5 when under rated load. Brittle fracture and fatigue during all operation and testing conditions should be design considerations.

Joint and weld details should be designed to prevent lamellar tearing.

c. Materials

Materials of construction should be resistant to the chemical, high-temperature, low-temperature, and other anticipated hazards. The specific hazards to be addressed are relative to the equipment's expected location within the fusion facility. Major concerns are the activation of materials by the intense neutron bombardment, the degradation of materials by all forms of radiation, the contamination of surfaces from the transfer of radiological materials, and the embrittlement of materials from exposure to hydrogen isotopes.

Activation and degradation issues should be addressed by careful choice of materials. Materials should be radiation tolerant to the cumulative exposure expected during their service life with an acceptable margin for safety. Design values that have proven acceptable in practice are 1×10^8 rads for replaceable materials and 1×10^9 rads for inaccessible materials. Structural materials should be chosen for their nonoxidizing surface characteristics and resistance to neutron activation, to the extent possible. Stainless steels should be used unless other materials are acceptable. Nonmetallic materials should be chosen for their resistance to neutron activation and to radiological degradation. The failure mode of the materials should not directly cause failures of other systems (e.g., elastomers that become liquids upon radiological exposure). Nonmetallic materials that cause degradation of adjoining metallic materials, such as materials that release chlorine, should not be used.

The contamination issue should be addressed by careful surface selection and preparation to prevent the entrapment of radioactive materials and facilitate the removal of material. Metal surface characteristics should be smooth and free of paints or coatings, with the exception of strippable coatings used for decontamination. High-polish or electropolished surfaces are preferred, due to their ease of decontamination.

Materials should be resistant to degradation by decontamination processes to be used prior to maintenance. These methods include cleaning with high-pressure water, cryogenic materials, and mild acids. Special care must be used to prevent gaps and crevices from entrapping and retaining radiological materials.

General guidelines for the selection of materials include the following:

1. The effects of galvanic or chemical corrosion should be evaluated as part of the material selection process.

2. Lubricants, sealants, and protective coatings should be compatible with their intended service and environment.

3. Materials selection, including lubricants, sealants, and electrical insulation for equipment, should consider the design-life radiation exposure (during normal operation and, where applicable, off-normal event conditions) to ensure no loss in function for the design life of the equipment. Materials that will preclude or minimize generation of mixed wastes should also be considered.

4. The surface finish of all external materials should allow for ease of decontamination. Highly polished, nonoxidizing, and nonpainted surfaces should be used so as to not entrap radiological material.

5. The potential for hydrogen embrittlement and weakening of structural members should be considered in all locations where exposure to hydrogen, deuterium, or tritium is anticipated. High-stress components that see a significant tritium environment should be monitored for hydrogen embrittlement.

6. The radiological activation of materials in areas of high gamma and neutron fluxes should be considered in the choice of materials. This includes metals, greases, fluids, and elastomers.

d. Instrument and Control Systems

The following I&C features should be provided in the design of the remote-handling equipment as necessary to prevent damage to the handling equipment, to nearby safety-class or safety-significant SSCs, and to the handled components; to provide for personnel safety; and to remotely recover equipment (to prevent the necessity of personnel recovery of equipment):

1. Underload—An interlock actuated upon a reduction in load, while lowering with grapple attached, at other than full down position, to prevent any further downward travel.

2. Overload—An interlock actuated upon an unacceptable increase in hoisting force to prevent upward travel.

3. Up-position—An interlock set at a predetermined operational limit to prevent any further upward travel.

4. Down-position—An interlock set at the predetermined operational limit to prevent any further down travel.

5. End-travel (hardstop)—Physical limit to translation.

6. Up-limit (hardstop)—Physical limitation to hoisting.

7. Slow zone—Region of travel where a reduction in hoist speed is mandatory and automatic.

8. Nonsimultaneous motion—Automatic restriction against simultaneous hoisting and translating motions.

9. Grapple release—An interlock to prevent opening a grapple under load.

10. Bridge travel—An interlock at a predetermined operational bridge travel limit.

11. Trolley travel—An interlock at a predetermined operational trolley travel limit.

12. Slack cable—An interlock actuated at a loss of cable load to prevent further downward travel.

13. Translation Inhibit—An interlock to prevent bridge or trolley movement unless its associated hoist is at or above a predetermined operational up position.

14. Robotic systems—Provide with intelligent systems to avoid known structures and obstacles. This may include direct sensing of obstacles or knowledge-based systems that have been preloaded with the location of obstacles.

15. Remotely controlled systems—Provide with a backup means of safe release of attached radiological hazardous materials, to facilitate remote recovery of failed remote-handling equipment for repair.

16. Redundancy of critical controls—Prevent single-mode control failure of remote or robotic equipment, causing unplanned or unanticipated equipment motion.

17. Equipment maintenance—Provide maintenance of anticipated large-capacity remote or robotic equipment in the presence of personnel, without creating impact hazard to the personnel. It is anticipated that most equipment will require a minimum of maintenance functions while energized, typical of robotic systems. This must be provided for in a personnel-safe manner.

18. RF control—The expected high presence of RF and magnetic fields during both normal and off-normal operation should not create hazards to personnel through unplanned movements or other means.

Remote-handling system controls that, on failure, can cause either (1) a system to perform unintended motions or (2) a system to fail in a nonrecoverable mode should be redundant. Manual bypasses for interlocks may be supplied at the discretion of the designer.

e. Electrical

The remote systems should be designed to the equivalent of the NFPA Class 1, Division 1 requirements. It is assumed, but not required, that this would be met with the pressurized, interlocked systems approach.

Wiring should be resistant to radiation damage. Cabling should be protected from physical hazards.

Cabling should be adequately shielded from any high magnetic and RF fields it is expected to encounter. The shielding should be such that the equipment serviced by that cabling is adequately protected from cabling-induced interference.

Electrical connectors and wiring methods (per National Electric Code definitions, or equivalent) should be used to minimize repair or replacement time. Sealed, quick-disconnect-type connectors should be used wherever possible, and individual wiring methods (e.g., terminal strips) should be avoided. These requirements are intended to minimize the exposure of personnel related to maintenance.

The wiring count from remote equipment to personnel areas should be minimized. The failure probability for remote-handling equipment is directly related to the amount of vulnerable wiring and connectors required from the work area.

f. Tests and inspections

Provisions should be made to allow testing on a scheduled basis in accordance with applicable codes and standards to verify the following:

1. Limit switches are operable and functioning as required.
2. Controlling signals from sensing devices are within specifications.
3. Control switches are operable.
4. Indicating instrumentation is operable and within specified accuracy.
5. Annunciators are operable as specified.
6. Electrical interlocks are operable and functioning as required.
7. Load cells are performing properly.
8. Motors are operable and functioning as required.
9. Hoists and brakes are functioning correctly.
10. Any special function is performing properly.

g. Hydrogen fires and detonation

Remote-handling systems should not initiate a fire or detonation in normal or off-normal conditions in the presence of hydrogen gases. Safety-significant remote-handling systems and components may fail in a fire or detonation event, but the failure should not degrade the function of an adjacent safety-class SSC. Safety-class remote-handling equipment should withstand the effects of design-basis fire or detonation and retain its basic safety functions.

h. Equipment maintenance considerations

Remote-handling equipment will potentially require maintenance while radiologically activated or contaminated (tritium or other) and should be designed accordingly. Maintenance requirements should allow for personnel using rubber gloves, plastic suits, or similar personal protective means. Additionally, the time required to perform maintenance may be directly related to the resultant exposure of personnel to radiological hazards.

Maintenance methods should allow for rapid replacement of components or modules utilizing quick disconnects for all services. Fasteners should be designed for gloved handling and be of the captive type if possible.

i. Assembly and disassembly techniques

Systems should be of modular construction, if possible, to facilitate maintenance. Modules can be replaced or relocated to other maintenance facilities with less potential for personnel exposure. Systems for use in highly congested areas must also allow for modular construction to a sufficient degree to allow for access and recovery of components.

Systems or modules of systems should provide for handling by fully protected personnel (e.g., plastic suits) with a minimum of special requirements. Permanent lifting points are desired, and lifting slings (ropes, cables, straps) should be avoided.

Gloved or double-gloved, hand-compatible electrical and service connectors should be used to facilitate connections. Sharp edges or rough surfaces are to be particularly avoided, to prevent compromising protective clothing.

j. Special handling requirements

The handling of typically large and powerful remote equipment in confined spaces and the subsequent maintenance of that equipment should be a design factor. System designs should allow for required personnel work without hazard to personnel.

k. Mode of operation

Remote-handling systems should be operable in the operational modes of less sophistication than their normal mode to facilitate recovery from off-normal events without personnel entry.

Programmed assistance should be provided in the form of graphics-based workcell modeling, or similar analysis, coupled to the movements of any automated system. This should display the location of all known obstacles or objects within a work cell and the present location of the remote system. The control systems should display all programmed motions in the modeled environment, in real time, with display-before-movement capabilities. This will allow all actions to be tested before started.

l. Collision avoidance

The most desirable mode of operation is with active system control to prevent operation in areas of exclusion. In this type of operation, the control system will intervene when commands direct a system into a predetermined exclusion area. The environment can be either statically modeled, when unchanging, or actively modeled, when dynamic. The active modeling can be vision-based, structured-light-sensed, or similar.

The control system should be the primary means of obstacle avoidance. Active sensors on systems should also be provided where needed to avoid high-damage-potential collisions.

m. Multiple remote device coordination

Multiple remote-handling systems in the same or overlapping workspace(s) should have coordinated motions to prevent their direct interaction. When two systems have an interaction potential, one system will be designated as the lead and the other the follower.

n. Closed-circuit television (CCTV)

CCTV is generally used to monitor the remotely performed handling and operations activities. The CCTV equipment should meet the electrical performance standards for monochrome television studio facilities EIA Standard RS-170-57 (Revision TR-135), 1957. CCTV electrical wiring should be in accordance with NFPA 70, National Electric Code.

The radiation hardness of the required CCTV system is a function of the particular application, with significant cost and complexity advantages to the nonradiation-hardened systems, when they are applicable. Each application should define its realistic radiation-hardness needs.

o. Electromechanical manipulator (EMM)

Design, fabrication, inspection, and testing of EMM should comply with the requirements of following codes and standards:

Controls	NEMA ICS-6
Electrical	NFPA 70

For additional guidance, see ANS 1985 and NASA 1991.

p. Cranes

The following codes and standards should be considered in the design, fabrication, inspection, and testing of cranes:

Cranes and Hoists	CMAA 70 and /or ASME NOG-1
Seismic Analysis	CMAA 70 and /or ASME NOG-1
Overhead and Gantry Cranes	ANSI B30.2
Hooks	ANSI B30.10
Electrical	NFPA 70, Art 610
	IPCEA S-61-402
	NEMA MG1, NEMA ICS-1, NEMA WC-3
	ANSI C2
Fire Protection	NFPA 12A
	NFPA 72E
	FM-Approval Guide
	UL-Fire Protection Equipment

The cranes should be provided with all components and appurtenances required for safe operation and handling, in accordance with the Occupational Safety and Health Administration (OSHA) Regulations Section 1910.179 and ANSI B30.2, ANSI B30.1, B30.16 Safety Codes as applicable.

q. Master slave manipulators (MSMs)

Design, fabrication, inspection, and testing of MSMs should be in conformance with applicable requirements of the following codes and standards:

Hooks	ANSI 30.1
Hydraulic Power	JIC-H-1

r. Hoists

Auxiliary hoists should be designed and manufactured to comply with the Hoist Manufacturers Institute Specification HMI 100 for Electric Wire Rope Hoists.

s. Remote connector systems

Remote connector systems (sometimes referred to as “Hanford” type) can be used in the process piping as mechanical jumpers. This type of jumper system allows remote assembly and disassembly of mechanical components such as pumps, valves, and pressure vessels. These mechanical jumpers and/or connectors can be remotely operated. The design, fabrication, inspection, and testing of these connector/jumpers and associated equipment should be per manufacturer standards.

The electrical type connector systems must protect the connecting pins or sockets from damage during the coupling operations. The entire assembly must meet the electrical classification requirements of the particular service.

t. Robots

Standards and Codes recommended for robot design, fabrication, and safety requirements include the following:

Group[a]	Standard	Subject
ANSI/RIA	RI506-1986	American national standards for industrial robots and robot systems
BSR/RIA	R15-06-19XX	Proposed standard for industrial robots and robot systems
ANSI/RIA	R15.02-1990	American national standard human engineering design criteria for hand-held robot control pendants
OSHA	Pub. 2254 (rev.)	Training Requirements in standards and training guidelines
NIOSH	Pub. 88-108	Safe maintenance guidelines for robotics workstations
OSHA	Pub. 8-1.3, 1987	Guidelines for robotics safety
OSHA	29 CFR 1910.147	Control of hazardous energy source (lockout/tagout final rule)
AFOSH	127-12,1991	Occupational safety machinery
OSHA	DOE/EH-0353P	OSH Technical Reference Manual

[a]ANSI/RIA = American National Standards Institutes/Robotics Industrial Association.
BSR/RIA = Bureau of Standards Review/Robotics Industrial Association.
NIOSH = National Institute for Occupational Safety and Health.
OSHA = Occupational Safety and Health Administration.
AFOSH = Department of the Air Force.

6.5 Impact of Facility Support and Experimental Systems on Safety Functions

Several fusion facility support and experimental systems that are not discussed explicitly above will be covered below. They are generally in one of two groupings. The first group (Group 1) are systems that have a specific function in support of the fusion facility mission but also perform a potential (depending on inventory of radioactive and hazardous materials) public safety function or worker safety function (see Table 6.2).

The second group (Group 2) are systems that may not perform a specific safety function but have either a large energy content and/or are physically adjacent to safety-class systems such that care has to be taken in their potential influence on facility safety (see Table 6.3).

TABLE 6.2. Group 1 systems

System	Facility specific function	Potential safety function
Plasma fueling	Provide H/D/T	Primary confinement of tritium
Pumping systems	Maintain specified vacuum and torus exhaust	Primary confinement of tritium
Plasma heating	Heat plasma to ignition and main-tain driven plasma current	Primary confinement of tritium
Tritium plant	Separate H/D/T from plasma exhaust; remove tritium from process streams	Primary confinement of tritium
Breeding blanket	Breed tritium for fusion reaction; transfer heat to balance of plant	Primary confinement of tritium; (depending on design)
Magnet shielding	Shield cryogenic magnets from nuclear heat loads	Part of biological shield for plant staff

TABLE 6.3. Group 2 systems

System	Stored energy	Proximity to safety-class SSCs
Plasma	Less than a few GJ	Can focus energy on plasma-facing com-ponents (e.g., runaway electrons)
Magnets	100s of GJ	Close to cryostat and tritium piping
Vessel cooling	100s of GJ	Close to vacuum vessel
Divertor	10s of GJ	Close to vacuum vessel
Breeding blanket	10s–100s of GJ	Close to vacuum vessel and interface to tritium processing systems

6.5.1 Group 1 Systems

The important design consideration for these systems is that they should be subject to the *same* design criteria in performing their public safety function as more visible safety-class systems, such as the vacuum vessel, while providing primary confinement. Thus plasma-fueling and vacuum-pumping systems should be designed as safety-class SSCs while performing the public safety function of tritium confinement if this is shown as required in the safety analysis process. Parts of these systems not performing public safety functions (e.g., control subsystems used for the plasma-fueling or vacuum-pumping functions) would not be designated safety-class. Additional factors to be considered are the presence of new energy sources (e.g., high-pressure propellant gases, rotating energy of centrifuges, kinetic energy of pellets in plasma-fueling systems) in these systems and the vulnerable tritium inventory in determining how many confinement barriers are needed. Designers should try to minimize the portion of these Group 1 systems that supports a public safety function and have clearly defined boundaries between safety-class and non-safety-class components in such systems. Group 1 systems could potentially be safety-significant relative to the worker safety function if the inventory level and proximity of workers result in this designation.

6.5.2 Group 2 Systems

The important design consideration for these systems is that they are typically experimental in nature (magnets, plasma, divertor, breeding blanket) and their performance in a future fusion reactor environment is not known a priori. Environmental conditions that these systems potentially experience include high heat fluxes, high neutron and gamma irradiation, high-energy particle flux including very high energy runaway electrons, cyclic loading, and significant thermal gradients. Typically these conditions result in design decisions to use materials for plasma-facing components such as carbon and beryllium that do not have an extensive nuclear industry data base. Thus, it is strongly recommended that decisions be made early in the design phase to preclude these systems from being designated as safety-class. Some of these systems have significant stored energy as shown in Table 6.3, and innovative strategies should be developed to ensure that this energy is locally contained within these systems and their support structure during off-normal events. An example of design guidance for a typical Group 2 system, the divertor, follows.

a. Divertor system

The divertor (more specifically referred to as a poloidal divertor in the case of interest here) for a tokamak device consists of a set of structures that, taken together, form a toroidally continuous element(s). The plasma-facing surfaces of the divertor are configured to intercept or enclose the magnetic flux surfaces that lie outside the last closed flux surface that contains the confined plasma. This surface, referred to as a separatrix, is formed by one or two nulls in the poloidal magnetic field and separates the confined plasma from that diverted toward the exhaust region. A configuration with a single null in the poloidal field is referred to as a single-null divertor configuration, whereas a double-null arrangement is referred to as a double-null divertor configuration. Poloidal divertors are usually located on the top and/or bottom regions of the plasma chamber. Since the plasma exhausts most of its heat and particles to the divertor, active cooling and vacuum pumping are required in the divertor region for long-pulse operation.

The divertor system consists of targets (plasma-facing structures), coolant piping, support structure, and nuclear shielding. The surfaces of the divertor target are directly exposed to the particle and energy fluxes resulting from the plasma exhaust processes. These surfaces are usually constructed from two separate materials, each with different functions. The plasma-facing or armor tile material is selected for its plasma interface characteristics, such as sputtering erosion and thermal shock capability. Plasma-facing material candidates include metals such as beryllium or tungsten, carbon-containing materials such as graphite or carbon-carbon composites, or ceramic materials such as silicon carbide. The plasma-facing material is attached to a structural metal, whose primary functions are to contain the coolant and to act as a heat-conducting element between the coolant and the plasma-facing material.

The primary function of the divertor system is to protect the vacuum vessel from direct interaction with the plasma while providing a means for plasma particle and energy exhaust.

Due to the challenging nature of its loading conditions and developmental status, it is desirable that the divertor system not be classified as a safety-class system. However, since the divertor structure will become radioactive and its plasma-facing surfaces will become contaminated with absorbed tritium, the impact of the divertor system on other safety-class systems must be considered.

The goal of the divertor design should be that a single failure of the divertor system does not threaten any in-vessel or ex-vessel safety-class system. The divertor system design should prevent damage to safety-class components, which might include the vacuum vessel, fueling and vacuum pumping system piping, and in-vessel coolant system pipes. If this goal cannot be met and individual components within the divertor system are designated as safety-class, the design guidance listed in Section 6.1 should apply to these components. Divertor components designated as safety-class should be designed, fabricated, inspected, and tested in accordance with an approved structural acceptance criteria. Because the divertor environment and material candidates differ significantly from more conventional applications with regard to (1) handling the high, steady-state heat and energetic particle fluxes on the surface of the divertor target, (2) withstanding the intense thermal and electromagnetic loads during plasma disruptions, and (3) experiencing fluences of high-energy neutrons leading to property changes, embrittlement, and irradiation-induced creep, existing safety-related codes are largely inapplicable. The design of the divertor should meet the safety design criteria of this Standard and should employ a design and analysis methodology that is consistent with a recognized safety-related code. Design standards and practices for non-safety-class divertor components are not addressed in this document.

b. Special considerations for divertors

In addition to conventional materials and effects, special consideration of the following items, which are unique to the fusion divertor environment, must be included in the design and analysis of the divertor and in defining appropriate design practices and criteria:

1. Armor Tile Materials—Many of the armor tile material candidates considered for use in protecting the divertor target structure are brittle metals or nonmetals. The behavior of these materials and their influence on the structures to which they are attached must be considered in evaluating the integrity of the coolant confinement structure.

2. Erosion and Redeposition—Reduced or increased armor tile thickness due to erosion or redeposition of previously eroded material could have a significant effect on the thermal stresses in the coolant containment structure to which the armor tiles are attached.

3. Plasma Disruptions/VDEs—The transient dynamic mechanical and thermal effects during plasma disruptions/VDEs, which are extremely intense but of very short duration, must be considered in evaluating the integrity of the divertor structure and in defining appropriate structural design criteria.

4. Irradiation Effects—The effects of irradiation-induced hardening, loss of ductility, swelling, creep, and changes to other material properties must be considered in design and analysis of the divertor as well as in the formulation of structural design practices and criteria.

c. Recommended design practice for divertors

To minimize the potential for and/or consequences of off-normal events, the following practices are recommended for divertor design:

1. minimization of coolant temperatures and pressures,
2. use of double-contained coolant wherever reasonable,
3. minimization of chemically reactive materials,
4. minimization of radioactive dust and tritium inventories through appropriate,
5. selection of plasma-facing materials.

The items listed above serve only as guidance in the design process. Divertor designs which result from compromises between the above practices and overall performance of the fusion device are acceptable as long as they do not lead to a conflict of any of the safety design guidance presented in this document.

Because of the effects of neutron irradiation, welding of structural materials in the divertor region should be avoided. If unavoidable, welds should be located in regions of low stress. Stress limits for irradiated weld material should receive special consideration in the structural design criteria.

7. SITE RESTORATION

7.1 General

This section provides guidance for returning the site of a fusion facility to its original condition at the end of its useful life. The guidance includes recommendations for the initial design of the facility, the degree to which both radioactive and chemically hazardous materials must be removed from the facility before returning the facility or land to unrestricted public use, the limitations on the concentrations of radionuclides in the waste going to a low-level waste (LLW) repository, and the requirements for acceptance by the repository. In this section we assume that the fusion facility and the LLW repository are separate facilities and that the fusion facility will not serve as a long-term storage location for radioactive or hazardous wastes. However, if a repository does not yet exist at the time of fusion facility operation, we assume that the facility will provide short-term storage for wastes.

7.2 Decommissioning, Decontamination, and Site Restoration in the Initial Design

The designers of a facility can greatly reduce the difficulty of site restoration by providing for the ultimate decommissioning of the facility in the initial design. The Department of Energy (DOE) General Design Criteria (DOE 1993) provides guidance for the demolition, decontamination, and decommissioning of DOE facilities. Note particularly Sections 1300-11.1 Decontamination, 1300-11.2 Decommissioning, 1326-9 Tritium Facilities, and 1328-9 Fusion Test Facilities. 10 CFR 50.75 (10 CFR 50) contains requirements for design, financial data, and recordkeeping in anticipation of the decommissioning of U.S. Nuclear Regulatory Commission (NRC) licensed facilities.

A dedicated area furnished with appropriate equipment and utilities for decontamination of tools and as much equipment as practical should be considered for inclusion in the design of the facility. Tritium adsorbed on metal surfaces can be rapidly liberated when the metal is heated; water, detergents, and certain solvents are only moderately effective in removing tritium contamination. This property should be considered in the design of decontamination facilities.

7.3 Site Restoration

The requirements for the condition of the fusion facility site after restoration can be divided into two categories: the requirements for the removal of radioactive materials and the requirements for the removal of chemically hazardous materials. Both sets of requirements identify the maximum amounts of hazardous materials that can remain in the facility if it is to be released for public use.

Decontamination of DOE facilities is addressed in DOE Order 5400.5, “Radiation Protection of the Public and the Environment.” (DOE 1990) Table 7.1 shows the maximum contamination levels of beta-gamma activity allowable if the facility is to be released for public use. Order 5400.5 also specifies allowable levels of thorium, uranium, and transuranic activities, which would not ordinarily be found in fusion facilities. The DOE Radiation Control Manual allows ten times the above values for tritium surface contamination (DOE/EH-0256T Rev. 1).

TABLE 7.1. Surface contamination guidelines

Radionuclides[a]	Allowable total residual surface contamination[b] (dpm/100 cm^2)		
	Average[c,d]	Maximum[d,e]	Removable[d,f]
Beta-gamma emitters (radionuclides with decay modes other than alpha emission)	5,000	15,000	1,000

[a]Where surface contamination by both alpha- and beta-gamma-emitting radionuclides exists, the limits established for alpha- and beta-gamma-emitting radionuclides should apply independently.

[b]As used in this table, disintegrations per minute (dpm) means the rate of emission by radioactive material as determined by correcting the counts per minute measured by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[c]Measurements of average contamination should not be averaged over an area of more than 1 m^2. For objects of less surface area, the average should be derived for each such object.

[d]The average and maximum dose rates associated with surface contamination resulting from beta-gamma emitters should not exceed 0.002 mGy/h and 0.01 mGy/h, respectively, at 1 cm.

[e]The maximum contamination applied to an area of not more than 100 cm^2.

[f] The amount of removable material per 100 cm^2 of surface area should be determined by wiping an area of that size with dry filter or soft absorbent paper, applying moderate pressure, and measuring the amount of radioactive material on the wiping with an appropriate instrument of known efficiency. When removable contamination on objects of surface area less than 100 cm^2 is determined, the activity per unit area should be based on the actual area and the entire surface should be wiped. It is not necessary to use wiping techniques to measure removable contamination levels if direct scan surveys indicate that the total residual surface contamination levels are within the limits for removable contamination.

7.4 Waste Sent to a Low-Level Waste Repository

Waste considered for present low-level waste (LLW) repositories has been generated primarily in fission reactors, through nuclear medicine, or through the use of accelerators. The isotopes considered to date are not typical of those expected in fusion facilities. Therefore, it is important that the basic methods and limits used for present LLW be extended to the broader spectrum of isotopes expected in fusion-generated waste.

7.4.1 Requirements for Land Disposal of Radioactive Waste

10 CFR 61 was issued in final form in 1982 primarily to deal with the burial within 30 m of the surface of LLW produced in fission power plants, medical diagnosis and treatment, and tracers used in research [10 CFR 61.7(a)(1)]. The regulation explicitly does not deal with high-level radioactive waste, transuranic waste, or spent nuclear fuel. LLW is divided into three classes, for which packaging requirements and radioisotope concentration limits are specified.

The guiding philosophy behind 10 CFR 61 is that no member of the public, including an inadvertent intruder, should be exposed to an unacceptable risk due to accidental exposure to radioactive waste. Annual dose limits of 0.25 mSv (25 mrem) to the whole body, 0.75 mSv

(75 mrem) to the thyroid, and 0.25 mSv (25 mrem) to any other organ of the body (10 CFR 61.41) were used to establish radionuclide concentration limits based on several exposure scenarios (NRC 1981 and NRC 1982). The intruder construction scenario produced the highest dose to individuals. This scenario begins with the construction of a house on the waste disposal site after the period of institutional control, assumed to be 100 yr. Construction workers are exposed to direct gamma radiation from the waste and inhale waste particles while digging the foundation. If the waste is still recognizable as being radioactive, construction is assumed to stop after 6 h. Class C waste is assumed to be stable for 500 yr.

If the waste is not recognizable as being radioactive, construction is assumed to continue for 500 h. The completed house is occupied, and the inhabitants inhale suspended waste particles and are exposed to direct gamma radiation from the waste. In addition, they are assumed to grow one-half of all their food on the waste site. The inhabitants there ingest radionuclides deposited on the leaves of plants and absorbed through their roots, either directly in the case of vegetables or indirectly through the meat and milk of cows in the case of grass. 10 CFR 61 limits the specific activity of radionuclides so that the 50-yr whole-body dose commitment ("intruder dose") to workers from construction or the 50-yr dose commitment to inhabitants from exposure during the first year does not exceed 5 mSv (0.5 rem), which is currently the maximum permissible annual dose for members of the public.

7.4.1.1 Classification of LLW for Near-Surface Disposal

Determination of the classification of radioactive waste involves two considerations. First, consideration must be given to the concentration of long-lived radionuclides (and their shorter-lived precursors) whose potential hazard will persist long after such precautions as institutional controls, improved waste form, and deeper disposal have ceased to be effective.

These precautions delay the time when long-lived radionuclides could cause exposures. In addition, the magnitude of the potential dose is limited by the concentration and availability of the radionuclide at the time of exposure. Second, consideration must be given to the concentration of shorter-lived radionuclides for which requirements on institutional controls, waste form, and disposal methods are effective.

7.4.1.2 Classes of Waste

Class A waste is waste that is usually segregated from other waste classes at the disposal site. The physical form and characteristics of Class A waste must meet the minimum requirements set forth in 10 CFR 61.56(a). If Class A waste also meets the stability requirements set forth in 10 CFR 61.56(b), it is not necessary to segregate the waste for disposal.

Class B waste is waste that must meet more rigorous requirements on waste form to ensure stability after disposal. The physical form and characteristics of Class B waste must meet both the minimum and stability requirements set forth in 10 CFR 61.56.

Class C waste is waste that not only must meet more rigorous requirements on waste form to ensure stability but also requires additional measures at the disposal facility to protect against inadvertent intrusion. The physical form and characteristics of Class C waste must meet both the minimum and stability requirements set forth in 10 CFR 61.56.

Waste that is not generally acceptable for near-surface disposal is waste for which form and disposal methods must be different, and in general more stringent, than those specified for Class C waste. In the absence of specific requirements in 10 CFR 61, such "greater than Class C" waste must be disposed of in a geologic repository as defined in 10 CFR 60 unless proposals for disposal of "greater than Class C" waste in a near-surface disposal site are licensed by the NRC. Licensing criteria for disposal of "greater than Class C" waste are currently under development.

a. Classification determined by long-lived radionuclides—If radioactive waste contains only radionuclides listed in Table 7.2, classification shall be determined as follows:

TABLE 7.2. Classification boundaries as given in 10 CFR 61

Radionuclide	Concentration (Ci/m^3, unless stated otherwise)
C-14	8
C-14 in activated metal	80
Ni-59 in activated metal	220
Nb-94 in activated metal	0.2
Tc-99	3
I-129	0.08
Alpha-emitting transuranic nuclides with half-life >5 yr	100 nCi/g
Pu-241	3,500 nCi/g
Cm-242	20,000 nCi/g

If the concentration does not exceed 0.1 times the value in Table 7.2, the waste is Class A. If the concentration exceeds 0.1 times the value in Table 7.2 but does not exceed the value in Table 7.2, the waste is Class C. If the concentration exceeds the value in Table 7.2, the waste is not generally acceptable for near-surface disposal. For wastes containing mixtures of radionuclides listed in Table 7.2, the total concentration shall be determined by the sum-of-fractions rule.

b. Classification determined by short-lived radionuclides.

If radioactive waste does not contain any of the radionuclides listed in Table 7.2, classification shall be determined based on the concentrations shown in Table 7.3. However, if radioactive waste does not contain any nuclides listed in either Table 7.2 or 7.3, it is Class A.

TABLE 7.3. Classification based on long-lived radionuclides

Radionuclide	Concentration (Ci/m^3) Column 1	Column 2	Column 3
Total of all nuclides with <5 yr half-life	700	[a]	[a]
H-3	40	[a]	[a]
Co-60	700	[a]	[a]
Ni-63	3.5	70	700
Ni-63 in activated metal	35	700	7000
Sr-90	0.04	150	7000
Cs-137	1	44	4600

[a]There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentration for these wastes. These wastes will be Class B unless the concentrations of other nuclides in Table 7.3 determine the waste to be Class C independent of these nuclides.

If the concentration does not exceed the value in Column 1, the waste is Class A. If the concentration exceeds the value in Column 1, but does not exceed the value in Column 2, the waste is Class B. If the concentration exceeds the value in Column 2, but does not exceed the value in Column 3, the waste is Class C. If the concentration exceeds the value in Column 3, the waste is not generally acceptable for near-surface disposal.

Again, the limits for mixtures of nuclides are listed in Table 7.3; the total concentration shall be determined by the sum-of-fractions rule.

No limits are specifically given for heat generation with a waste package, aside from the requirement that the package must be shown to be capable of removing the decay heat.

7.4.2 Methodology of 10 CFR 61 Extended to Fusion-Specific Isotopes

10 CFR 61 gives specific activity limits for only a dozen radionuclides, many of which are fission products or transuranics and thus of little relevance in fusion materials selection. Fetter et al. have used the NRC's intruder scenario to calculate Class C limits for other long-lived radionuclides (Fetter 1988). The specific activity limits in Table 7.4 are those for Class C waste that is activated metal. The limits in Table 7.4 should be compared with those in column 3 of Table 7.3. Differences between Tables 7.3 and 7.4 result from (a) the fact that the waste is assumed to be an activated metal and (b) corrections made to the dose conversion factors made by Fetter et al. Footnotes to the table indicate specific activity limits derived by other authors.

TABLE 7.4. Specific activity limits for shallow land burial of all radionuclides with Z < 88 and half-lives >5 yr and <10^{12} yr[a,b]

Radionuclide	Half-life	Specific activity limit (Ci/m^3)	Other values
H-3	12.3 yr	TMSA[c]	TMSA[d]
Be-10	1.6 My[c]	3,000	7,000[e], 3[f]
C-14	5.7 ky[c]	700–7,000	80[d]
Al-26	720 ky	0.09	0.1[g]
Si-32	104 yr	900–4,000	600[e], 30[f]
Cl-36	301 ky	10–100	3[f]
Ar-39	269 yr	10,000	2,000[f]
Ar-42	33 yr	20,000	0.8[g], 7,000[f]
K-40	1.3 Gy[c]	1.5	
Ca-41	103 ky	8,000–20,000	3[f]
Ti-44	47 yr	200	0.60[g], 300[f]
Mn-53	3.7 My	TMSA	600[e], 30[f]
Fe-60	100 ky	0.1	0.01[g], 0.1[f]
Co-60	5.3 yr	3×10^8	TMSA[d]
Ni-59	75 ky	900	220[d]
Ni-63	100 yr	1×10^6 to 1×10^7	7,000[d]
Se-79	65 ky	100–1,000	3[f]
Kr-81	210 ky	30	300[f]
Kr-85	10.7 yr	TMSA	
Rb-87	48 Gy	TMSA	
Sr-90	28.5 yr	1×10^6 to 9×10^6	70,000[b,d]
Zr-93	1.5 My	2,000	200[e], 10[f]
Nb-91	680 yr	200	
Nb-92	36 My	0.2	0.3[e]
Nb-93m	13.6 yr	TMSA	
Nb-94	20 ky	0.2	0.2[d]
Mo-93	3.5 ky	300	30[e], 30[f]
Tc-97	2.6 My	1–10	
Tc-98	4.2 My	0.03–0.1	0.02[g]
Tc-99	213 ky	0.2–2	30[b,d]
Pd-107	6.5 My	TMSA	
Ag-108m	127 yr	3	3[g], 3[f]
Cd-113m	13.7 yr	TMSA	
Sn-121m	55 yr	100,000	3,000[f]
Sb-126	100 ky	0.1	0.01[g]
I-129	15.7 My	30	0.8[b,d]
Cs-135	3.0 My	TMSA	3[f]
Cs-137	30.0 yr	50,000	46,000[b,d]

TABLE 7.4. Specific activity limits for shallow land burial of all radionuclides with Z < 88 and half-lives >5 yr and <10^{12} yr[a,b] (Continued)

Ba-133	10.5 yr	2×10^8	55[g]
La-137	60 ky	30	
La-138	106 Gy	TMSA	
Pm-145	17.7 yr	TMSA	
Pm-146	5.5 yr	TMSA	
Sm-146	103 My	TMSA	
Sm-147	106 Gy	TMSA	
Sm-151	90 yr	TMSA	3,000[f]
Eu-150m	36 yr	3,000	3,000[f]
Eu-152	13.3 yr	300,000	
Eu-154	8.8 yr	5×10^6	
Gd-148	98 yr	7×10^5 to 7×10^6	
Gd-150	1.8 My	TMSA	
Tb-157	150 yr	1,000	
Tb-158	150 yr	4	5[f]
Dy-154	10 My	TMSA	
Ho-166m	1.2 ky	0.2	0.2[f]
Lu-176	35.9 Gy	TMSA	
Hf-178m_2	31 yr	9,000	0.25[g], 3,000[f]
Hf-182	9 My	0.2	0.02[g]
Re-186m	200 ky	9.0	10[f]
Re-187	40 Gy	TMSA	
Os-194	6.0 yr	TMSA	
Ir-192m_2	241 yr	2	1[f]
Pt-190	600 Gy	TMSA	
Pt-193	50 yr	9.E+6	
Hg-194	520 yr	0.5	
Pb-202	53 ky	0.6	0.07[g]
Pb-205	19 My	TMSA	5[e], 3[f]
Pb-210	22.3 yr	9×10^6 to 8×10^7	
Bi-207	32.2 yr	8,000	17,000[g]
Bi-208	368 ky	0.09	0.1[g], 0.1[f]
Bi-210m	3.0 My	1	2[g], 0.5[f]
Po-209	102 yr	3,000	

[a]Specific activity limit depends on waste form indices; values shown are for nonfuel reactor components and high-activity industrial waste.
[b]The 10 CFR 61 specific activity limits for Sr-90, Tc-99, I-129, and Cs-137 are multiplied by a factor of ten because they are assumed to be contained in activated metal.
[c]TMSA = Theoretical Maximum Specific Activity: ky = 1000 years; My = 1,000,000 years; Gy = 10^9 years.
Other values: [d]10 CFR 61.55, 61.56; [e]Ponti 1986; [f]Maninger 1985; [g]Kennedy 1983.

7.4.3 Chemically Hazardous Materials Sent to a Hazardous Waste Site

The ultimate disposal of components from the fusion facility will be in accordance with state and federal permits. State and local laws will naturally depend on location of the facility. Among the federal laws governing the disposal of hazardous materials are those listed in Sections 7.4.3.1–7.4.3.6.

7.4.3.1 Clean Air Act

The Clean Air Act (CAA) established national goals for air quality to protect public health and welfare, and it required the use of quality standards and criteria for the control of pollutants in the environment. The approach of the CAA is to determine the relationships between public health and welfare and air quality, while restoring, maintaining, and improving the quality of the environment. The Clean Air Regulations are listed in 40 CFR Parts 50, 53. 56, 58, 60–62, 65–67, 69, and 81.

7.4.3.2 Clean Water Act

The goal of the Clean Water Act is to restore, maintain, and enhance the chemical, physical, and biological integrity of the nation's water. To accomplish this goal, regulations were set forth establishing stream water quality and effluent limitations.

Particular importance is placed on the control of effluents containing hazardous pollutants. Regulations concerning the discharge of radioactive and hazardous materials are set forth in 40 CFR Parts 116 and 141–143.

7.4.3.3 Safe Drinking Water Act

The Safe Drinking Water Act regulates the quality of drinking water with provisions aimed at protecting the quality of groundwater. 40 CFR 141 and 142 establish the National Primary Drinking Water Regulations and the enforcement responsibilities for these regulations. 40 CFR 143 establishes the National Secondary Drinking Water Regulations, and Part 144 sets forth the requirements for an Underground Injection Control Program.

7.4.3.4 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. RCRA defines all hazardous wastes as *solid waste*; this includes all types of hazardous wastes, whether they are solid, semisolid, liquid or even gaseous (so long as they are in containers).

40 CFR 262 details standards for generators of hazardous waste. These requirements include obtaining an Environmental Protection Agency identification number, meeting waste accumulation standards, labeling wastes, and keeping appropriate records. 40 CFR 262.34a allows generators to store wastes for up to 90 days without a permit and without gaining interim status as a treatment, storage, and disposal facility, provided specific conditions are met.

40 CFR 262.34(b)–(f) provides specific allowances for a generator to store waste on-site for greater than 90 days without a permit under certain limited circumstances. Otherwise, if treatment residues are stored on site for 90 days or more, 40 CFR 265 requirements apply. Any facility (on-site or off-site) designated for permanent disposal of hazardous wastes must be in compliance with RCRA. Disposal facilities must fulfill permitting, storage, maintenance, and closure requirements contained in 40 CFR Parts 264–270. 40 CFR 264 Subparts F and S, include requirements for corrective action for RCRA-regulated facilities. If treatment residues are disposed of off-site, 40 CFR 263 transportation standards apply.

7.4.3.5 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) was enacted in response to the concern for the dangers of negligent hazardous waste disposal practices in the past. This Act could apply to new facilities at the time of facility shutdown if other regulations were violated which caused environmental damage or a threat to public health.

7.4.3.6 Superfund Amendment and Reauthorization Act of 1986

The Superfund Amendment and Reauthorization Act (SARA) deals primarily with the reporting requirements for organizations handling hazardous materials.

7.4.4 Mixed Waste Requirements

Various mixed (i.e., both chemically hazardous and radioactive) waste streams will be produced by fusion facilities. These could include beryllium contaminated with tritium, activated tungsten-rhenium mixtures, and dust produced on the first wall of the vacuum chamber. The requirements for the disposal are now being formulated and will be included in this Standard when developed.

7.5 Requirements on Low-Level Waste Repository

The requirements for the LLW Repository itself are given in 10 CFR 61. The design of the repository is outside the scope of this Standard.

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

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.

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