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Exam Preview:

1. The safety-class SSCs should be designed such that a minimum number of active or passive mitigative systems identified from and credited within the safety analysis are available to ensure that the evaluation guidelines are not exceeded.
   a. True
   b. False
2. Which of the following hazard category matches the description: Hazard analysis shows the potential for significant off-site consequences. Fusion facilities in this category would be designated by the cognizant DOE official.
   a. Hazard Category 4
   b. Hazard Category 3
   c. Hazard Category 2
   d. Hazard Category 1
3. According to the reference material, the safety analysis report (SAR) process is a four-step approach to identifying the safety concerns associated with a facility.
   a. True
   b. False
4. There is varying information that can be used to develop an appropriate criterion to be used in the SAR. DOE Order 420.1 (DOE 1995a) and DOE-STD-3009 (DOE 1994) indicate that events down to ~____/yr should be considered.
   a. 10^{-2}
   b. 10^{-4}
   c. 10^{-6}
   d. 10^{-8}

5. According to the reference material, the criterion used to determine whether emergency planning is required for a given facility is if the results of the off-normal event analysis exceed __ mSv.
    a. 10
    b. 25
    c. 50
    d. 100
6. 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.
    a. True
    b. False
7. According to the reference material, the schedule for the SAR updates should be at least annually for facilities having a Hazard Category 1, 2, or 3, and every _ yr for Below Category 3 facilities.
    a. 5
    b. 3
    c. 2
    d. 4
8. According to the reference material, from the safety policy, two types of safety functions have been identified: public safety functions and facility safety functions.
    a. True
    b. False
9. According to the reference material, Hazard Category 3 facilities should normally require only ____ to achieve an accept-able level of safety assurance.
    a. Limiting Control Settings
    b. Safety Limits
    c. Surveillance Requirements
    d. Administrative Controls
10. Using TABLE A.1. Thresholds for radionuclides Category 2, which of the options blow is the appropriate half-life for Kr 85m?
    a. 5.75E–02 days
    b. 1.99E–03 days
    c. 1.87E–01 days
    d. 3.98E–02 days

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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5. SAFETY ANALYSIS

This chapter of the Standard describes the safety analysis requirements applicable to fusion facilities and provides guidance for the implementation of these requirements and criteria for determining that the requirements have been met.

Safety analyses are performed to show that the risks associated with operation of a facility have been identified, quantified, and managed. Management of risk can be accomplished (1) by demonstrating that the risk is within the bounds of an approved safety envelope, (2) by showing that the risk consequences are mitigated to meet the established evaluation guidelines, and (3) by having the risks themselves eliminated or reduced by demonstrable controls.

The completion of a safety analysis requires information on the facility, the site characteristics important for evaluating facility safety, and the principal equipment and processes required to fulfill the facility mission. From this baseline descriptive information, hazards can be identified. Facility risk descriptions are then developed from the hazard inventories, system functional process descriptions, and a listing of off-normal conditions postulated to result from both internal and external causes. The entire analysis process is documented in a Safety Analysis Report (SAR) and in Technical Safety Requirements (TSRs); the guidance for these is addressed in later subsections.

The safety analysis has many purposes. In addition to establishing the safety of the facility, the safety analysis is used to develop TSRs and to determine readiness for construction and operational authorization. The graphical illustration of the functional relationship of the major items included in the safety analysis process is shown in Fig. 5.1.

As discussed in Section 1.3, a risk-based prioritization approach is to be taken in the implementation of safety analysis requirements as well as in the implementation of the other elements of this Standard. Actions taken to ensure compliance with requirements are a function of the several factors cited in the definition of risk-based prioritization. The factors most relevant to fusion safety analysis considerations are risk and magnitude of hazard. The other factors included in the risk-based approach are mission and facility life cycle. As such, the importance of these factors is discussed where appropriate in the applicable sections of this chapter.

The project has the responsibility for the development of specific criteria for the application of a risk-based prioritization approach to the system specific criteria. Concurrence with the specifics of the risk-based approach taken by a facility should be obtained from the regulator prior to its implementation. The identification of relevant criteria will flow from the nature and purpose of the system itself.

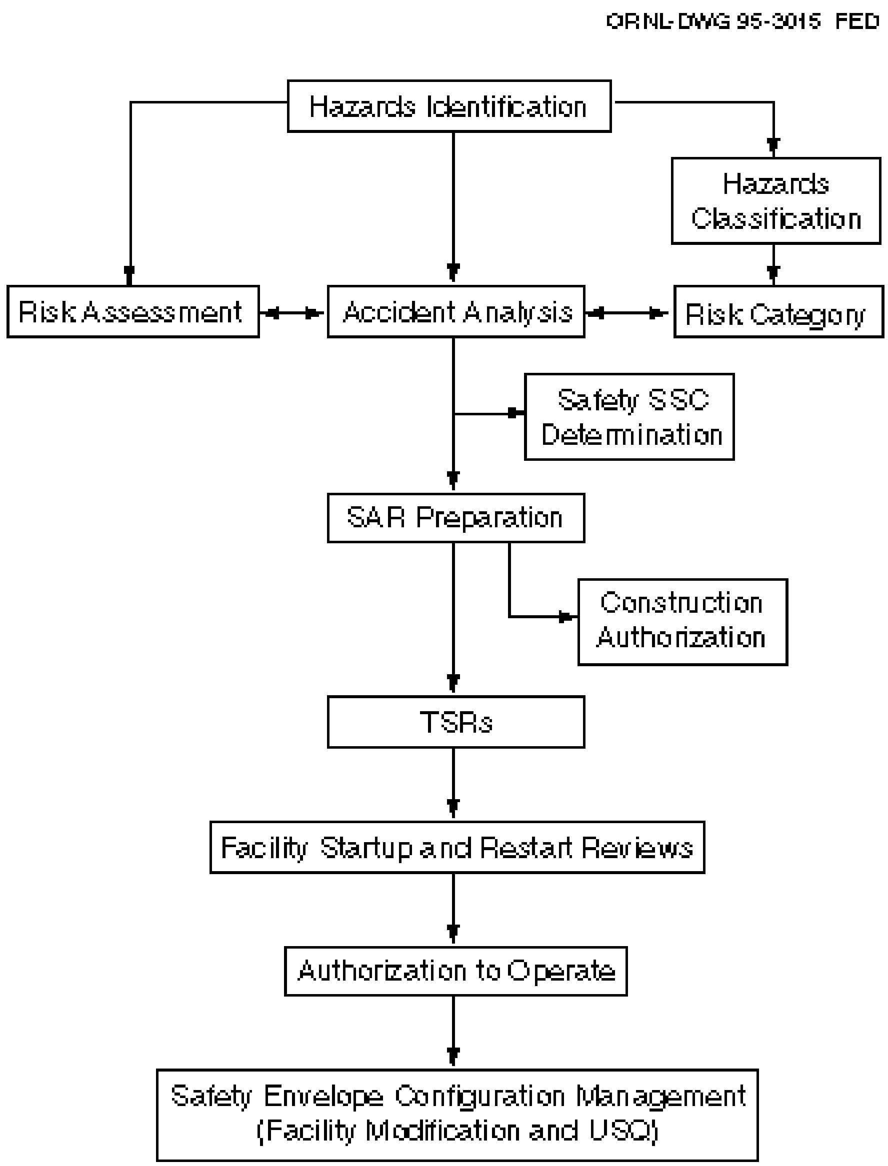

FIGURE 5.1. Flow logic of the safety analysis process.

5.1 Facility Description

5.1.1 General

Safety analyses inherently contain a description of the facility being analyzed that is sufficient to convey an understanding of the nature and magnitude of the physical plant and systems involved in the implementation of the facility mission. The description should be sufficient to allow the reader to understand how the hazardous materials, systems, components, and processes that are discussed later relate to the system as a whole and to understand the role and relevance of the safety systems in the facility. The facility description should also include those site characteristics that constitute or contribute to facility hazards. The site information should be sufficient to provide a basis of understanding of the hazards and the mechanisms by which radiological or hazardous material could have consequences to the public, environment, or workers.

Useful guidance on the content of a facility description portion of a safety analyses is available in Department of Energy (DOE) Order 5480.23, attachment 1, page 24 (DOE 1992b):

> *Safety analyses should contain descriptions of the facility and the principal equipment and processes provided to fulfill the mission of the facility and should delineate the plans, provisions, and requirements for their operation, maintenance, and surveillance. Information on the design of principal structures, components, and systems should be furnished in sufficient detail to support the identification of hazards, principal safety criteria, selection of engineered safety features, and the analysis of off-normal conditions. This information should include the following, using drawings as necessary:*
>
> *a. A listing of the safety structures, systems, components, equipment, and processes discussed in this section of the report;*
>
> *b. Detailed descriptions of structures or containers used to confine radioactive materials or hazardous chemicals;*
>
> *c. Detailed descriptions of safety-significant mechanical, electrical, and fluid systems (i.e. decay heat removal methods...) including functions, design bases, and relevant design features;*
>
> *d. Detailed descriptions of chemical process systems, including information on design configuration, dimensions, materials of construction, pressure and temperature limits, corrosion allowances, and any other operating limits, and;*
>
> *e. A functional description of process and operational support systems, including instrumentation and control systems...*

The facility description information must be an integral part of the safety analysis, but it is possible to accomplish this by providing the information in nonsafety analysis sections of facility documentation or even in totally separate documents, either of which would then be referenced in the specific safety analysis discussions. The configuration control requirements applicable to SARs would also apply to information referenced in the SARs but contained in other documents. (See configuration control requirements of Chapter 4.)

5.1.2 Safety Structures, Systems, and Components

Safety structures, systems, and components (SSCs) implement the safety functions associated with a facility. The two categories of safety functions associated with fusion facilities are (1) public safety functions or essential characteristics needed to ensure the safety of the facility and protection of the public and environment during operations and during and following off-normal conditions; and (2) worker safety functions that ensure the health and safety of the workers.

The public safety function for fusion is the confinement of radioactive and hazardous material under normal and off-normal conditions. Potential public safety concerns related to confinement include (1) ensuring afterheat removal, (2) providing rapid plasma shutdown, (3) controlling of coolant internal energy, (4) controlling of chemical energy sources, (5) controlling of magnetic energy, and (6) limiting air and water discharges from the facility.

Worker safety functions are related to worker hazards and routine releases. The issues associated with the worker safety function that should be evaluated are (1) limiting occupational exposure to radiation, (2) limiting the exposure to electromagnetic fields, and (3) controlling other industrial hazards and hazardous materials.

It is recommended that the SSCs required to implement the public safety function should employ the requirements imposed on systems defined as being safety-class SSCs in DOE 1994 (DOE STD-3009-94). The specific definition of a safety-class system is as follows:

> *Systems, structures, or components including primary environmental monitors and portions of process systems, whose failure could adversely affect the environment, or safety and health of the public as identified in the safety analysis.*

The safety-class SSCs are associated with the public safety function of confinement that protects the public and the environment from exceeding the radiological evaluation guidelines in DOE-STD-6002.

It is recommended that the SSCs that address potential safety concerns or are required to protect the worker safety functions should employ the requirements imposed on systems defined as being designated as safety-significant SSCs in DOE 1994 (DOE STD-3009-94). The specific definition of a safety-significant system is as follows:

> *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 material releases) and/or worker safety as determined from hazard analysis.

The safety-significant SSCs have the goals of (1) ensuring the availability of the public safety functions via defense-in-depth and (2) supporting the health and safety of workers during routine operations. The safety-significant SSCs would not be required to mitigate the consequences of off-normal events to meet the evaluation guidelines for the public or the environment. This function is the responsibility of the safety-class SSCs. However, because the SSCs that address the potential safety concern related to confinement will reduce potential threats to confinement through either accident prevention or mitigation, they are considered to contribute to defense-in-depth and thus are designated as safety-significant.

The categorization of a safety-class SSC is a two-step process. The first step is to identify early in the design the SSCs whose failure would result in exceeding evaluation guidelines. This should be by a “top down” functional hazards analysis. The second step is to verify in the final stages of design that the safety-class SSCs are actually needed to be functional, as indicated by the safety analysis process. If the SSCs are verified as being needed in the safety analysis process, then the equipment would be designated as safety-class SSCs. These components also must perform the required safety functions. This design approach would be as follows:

a. identify all potential hazards associated with the facility,

b. identify all SSCs needed to control those hazards,

c. identify the safety-class SSCs necessary to ensure that evaluation guidelines are not exceeded, and

d. verify, through detailed safety analysis, the need for the systems in item (c) to meet the evaluation guidelines provided in DOE-STD-6002.

The safety-class SSCs should be designed such that a minimum number of active or passive mitigative systems identified from and credited within the safety analysis are available to ensure that the evaluation guidelines are not exceeded. Reliable SSCs are required to be employed to satisfy the requirements of safety-class items. Use of defense-in-depth principles such as redundancy, simplicity in design, independence, fail safe, fault tolerant, and multiple (diverse) methods for increasing the reliability and reducing the consequence to acceptable levels is permitted and encouraged. In most cases, the use of passive methods of accomplishing the safety function is preferred over using active systems.

The next step in the process would be to perform the required system safety analysis. The safety analysis results would verify the adequacy of the safety-class SSCs to mitigate the release of hazardous material to meet the evaluation guidelines specified in DOE-STD-6002. Thus, the results of this evaluation determine which of the SSCs would be required to satisfy the public safety function. It may result in multiple SSCs being required to satisfy the safety system requirements for a particular off-normal condition scenario. In most cases, the SSCs identified in the hazards assessment review would be the same as those verified by the safety analysis as being SSCs required to implement safety. In addition, the safety analysis would verify the adequacy of safety-significant SSCs in addressing the potential safety concerns. Worker protection and potential safety concerns associated with the public safety function are identified in DOE-STD-6002.

Descriptions of each SSC that is providing safety functions are required in the SAR. A basic descriptive model of the facility and its equipment must be provided in which the required SSCs are addressed in detail commensurate with their preventive or mitigative role in meeting off-normal condition evaluation guidelines. For example, consider a facility that cannot meet evaluation guidelines, as discussed in DOE-STD-6002, unless credit is taken for system A. Besides being noted in the general facility description, system A together with associated codes and standards would be described in the section on safety-class SSCs. This system would typically be associated with a specific TSR (discussed in Section 5.7) and would be described in detail commensurate with its importance to the safety basis. However, only the characteristics of the SSC that are necessary to perform the safety function are classified as part of the safety system. For example, if a valve in a system is only required to provide an external pressure boundary, then only the pressure boundary function would be classified as a safety system characteristic and all other functions, such as the valve operability, response time, etc. would not be included in the safety system definition.

Conversely, if the consequences of all hazardous releases or off-normal conditions examined meet the evaluation guidelines without relying on the safety-class function of process system B, then system B would not be considered to be a safety system performing a safety function. Detailed identification of its functional basis and construction is not necessary because it is not a significant contributor to the overall facility safety basis. There would also be no need to discuss administrative provisions (e.g., initial testing, maintenance) required to ensure the operability of system B, nor would there be a need for a specific TSR (e.g., Safety Limit, Limiting Condition For Operation, etc.) covering system B. If a system is designated as safety-significant, industry recognized codes and standards are to be applied and minimal, if any, TSRs are to be specified for the operation of the system components (see Section 5.7).

A risk-based prioritization approach can be used to develop requirements for the safety-class and safety-significant SSCs. One of the dominant factors governing risk-based prioritization is the severity of the off-normal condition consequences associated with the facility and the number and type of the SSCs needed to prevent evaluation guidelines from being exceeded. If, for example, the defense-in-depth principles are satisfied by providing other SSCs to mitigate the consequences, then added inspections and other quality pedigree requirements of the first system would not be as important as if the original SSCs were the only means of accomplishing the safety function. If the consequences of the off-normal condition exceed the evaluation guidelines by a large margin and there is no other system that will mitigate or prevent the release for the off-normal condition, then special precautions should be taken in the design and in developing the inspection program to ensure that the system will be available to function when called upon. This may involve special inspections, alternate design approaches, or other actions that would significantly enhance system reliability. The rigor of compliance with the design and inspection requirements could be relaxed for systems that have multiple backups for preventing off-normal conditions or mitigating the off-normal condition consequences.

The design of the SSCs that perform the safety-class and safety-significant safety functions should meet the appropriate requirements established in Table 5.1.

TABLE 5.1. Safety system functional requirements

Requirement	Safety-Class Safety Function	Safety-Significant Safety Function
System design	Reliable methods of accomplishing the required safety function should be provided. Some of the design techniques that would ensure system reliability would include redundancy, diversity, simplicity in design, independence, fail safe, fault tolerant. Each method should be analyzed to identify potential failure mechanisms from performing the safety function in the system and to minimize those failures in the design. For further guidance on providing reliable system designs, see Section 6.7.3.1.	Nonredundant systems are normally used to perform the worker safety function. The safety system should be analyzed to preclude failures mechanisms that could disrupt the system function. Multiple systems may be employed, at the discretion of the facility developer, to ensure that the system functions are performed.
Codes and Standards	Nationally accepted design codes should be used in the design (see Chapter 6). The applicability, adequacy, and sufficiency of the codes and standards used should be evaluated. These codes and standards should be supplemented or modified as necessary to ensure system performance in keeping with the importance of the safety functions to be performed.	The codes and standards used for these systems should be those which have been validated through satisfactory performance in commercial application.
Reliability	Safety system should be demonstrated to have a high reliability. One of the ways to demonstrate this is by providing multiple, redundant, diverse systems/barriers to accomplish the safety function.	The safety system should be equivalent to that associated with commercial industrial safety practices.
Quality	The SSCs should require an appropriate level of quality for the design and construction to ensure the system function is performed. Quality assurance in accordance with the requirements of 10 CFR 830.120 should be implemented.	The systems required should be designed in accordance with industrial quality requirements.
Testability/ surveillance	The SSCs should be tested/surveyed periodically to determine that the function can be provided. Acceptance criteria should be established to evaluate the test results that demonstrate when the system is performing its intended function. The test frequency should be established to ensure that the system demand and reliability requirements are achieved.	The SSCs should be tested/surveyed periodically to determine that the function can be provided.
Natural phenomena	The SSCs should be designed to withstand appropriate natural phenomena and continue to provide the required safety function. Design for natural phenomena should be in accordance with facility performance goals per DOE Order 420.1 (DOE 1995a).	Design for natural phenomena should be in accordance with facility performance goals per DOE Order 420.1 (DOE 1995a).

5.2 Facility Mission/Processes

Descriptive information on the overall mission is required as part of the SAR. It is also a major factor in the development of the risk-based prioritization approach being implemented throughout each aspect of facility safety design.

Information on the facility processes is used primarily in the hazards analysis phase of the safety analysis. Facility process information and facility description information are used to develop the inventory of facility hazards. Facility risks can then be established by identifying the accessibility of each hazard.

The first criterion for determining the sufficiency of mission and process information in the safety documentation is whether there is enough to support closure of the safety analysis. That is, are there undocumented aspects of the facility mission or its processes that would in any way affect the conclusions of the safety analysis with respect to the particular component, system, and so on. The conclusion should be that there are not; should there be any situation that produces an answer to the contrary, then the mission/process descriptive information is deficient.

A second criterion for the sufficiency of mission information is whether there is enough to implement a risk-based prioritization approach throughout the safety design activity. The previously described design and analysis activities would normally provide the necessary information to satisfy the requirement.

5.3 Hazards Analysis

The hazards analysis performed for a given facility provides a measure of the risk potential for operation of that facility. The results of the hazards analysis will dictate the level of detail required for the safety analysis that must be performed for approval to operate. The following steps must be performed in the development of the hazards analysis:

a. Identify the potential energy sources, the initiating events, and inventories of radioactive and hazardous material that could be present in the facility both during routine operations and shutdown conditions, based on the classification methodology developed in such documents as DOE-STD-1027-92 (DOE 1992d).

b. Classify the facility into categories according to the its hazard potential using an approach that does not account for safety system mitigation.

The categories with the higher hazard potential for a facility require a more detailed safety analysis to demonstrate that the facility can be operated safely.

5.3.1 Inventory

The inventory of the radioactive and hazardous material is one of the determining factors in the hazards analysis classification of a facility. A set of radioactive inventory limits has been developed for use in the classification of fusion facilities into various hazard categories described in the following section. Because the radionuclide inventory limits contained in DOE-STD-1027 are primarily associated with the fission process, the radionuclide list has been expanded to include additional isotopes that could be present in fusion facilities. The expanded limits for Category 2 fusion facilities are provided in Appendix A to this Standard.

The radioactive and hazardous material inventories can be segmented provided it can be shown that the potential consequences associated with the hazardous material are limited to the segmented amount rather than the inventory present in the more than one segment or the entire facility. Based on the guidance presented in DOE 1992d, inventory segmentation is allowed if the hazardous material in one segment could not interact with the inventory in other segments to result in larger potential consequences than from any of the individual segments. For example, independence of the heating, ventilating, and air conditioning (HVAC) and piping must exist to demonstrate independence for facility segmentation purposes. This independence must be demonstrated and places the “burden of proof” on the analyst.

5.3.2 Classification

The classification of fusion facilities should follow the guidance provided in DOE-STD-1027-92 (DOE 1992d). This guide provides for three facilities hazard categories summarized as follows:

a. Hazard Category 1—Hazard analysis shows the potential for significant off-site consequences. Fusion facilities in this category would be designated by the cognizant DOE official.

b. Hazard Category 2—Hazard analysis shows the potential for significant on-site consequences. Examples include facilities with the sufficient quantities of hazardous radioactive materials that meet or exceed the inventory values contained in the guidance document used for classifying facilities (DOE 1992d).

c. Hazard Category 3—Hazard analysis shows the potential for significant localized consequences at a facility. Examples include facilities with quantities of hazardous radioactive materials that meet or exceed the inventory values contained in the guidance document used for classifying facilities.

In addition to these three categories, there is an additional category for all of the facilities that have less hazard potential than the least of the previous three categories. This category is defined as follows:

d. Below Hazard Category 3—Hazard analysis shows the potential consequences to be below the guidelines of the requirements described in DOE-STD-1027-92, as modified by this Standard. An example of this is those facilities that have inventories of radioactive material less than those specified for Category 3 facilities for hazard categorization. Thus, these facilities would be classified as non-nuclear facilities. It should be noted that many of the smaller fusion facilities could fall into this category.

5.4 Analysis of Off-Normal Conditions

The requirements of this Standard indicate that the safety of fusion facilities should be analyzed to demonstrate that the facility meets the evaluation guidelines discussed in DOE-STD-6002. This section provides guidance on the type of analysis of off-normal conditions required for use in meeting the evaluation guidelines and the fusion requirements related to no off-site evacuation. The types of analyses used to demonstrate compliance with these requirements are different and need discussion in this section.

The level of analysis of off-normal conditions for fusion facilities should be based on the risk to the public, the environment, and the worker. Facilities with minimal risk will only require that a scoping conservative analysis be performed to satisfy the safety analysis requirements. However, a facility with a large potential safety risk to the public, the workers, or the environment (Category 1 and 2 facilities) will require a more detailed analysis of off-normal conditions to satisfy the safety analysis requirements for such facilities as given in this section.

It is important that the safety analysis address the institutional and human factors safety issues. Experience has confirmed that the risk associated with operating nuclear facilities is a combination of the institutional approach to safety, human factors safety, and safety in design.

As used here, the institutional approach to safety includes

a. management and organization of facility operations;

b. the safety culture sustained by management;

c. performance objectives and the measurement of operational performance;

d. management oversight and assessment;

e. feedback of operational experience;

f. management controls of operations, surveillance, and maintenance;

g. related management efforts to achieve and sustain safe operations.

Human factors safety, as used here, refers to

a. the allocation of control functions to personnel vs automatic devices;

b. staffing and qualification of operating crews;

c. personnel training;

d. the preparation, validation, and use of written procedures to guide operations, surveillance, and maintenance;

e. the design of human-machine interface to build on strengths and protect against the susceptibility of human error in operating crews.

Safety in design includes

a. identifying the potential off-normal conditions and incorporating systems performing safety functions in the facility design to reduce the overall risk from those conditions;

b. designing reliable safety features using appropriate codes and standards that will ensure the availability of the safety when required;

c. categorizing the facilities to their appropriate risk potential because the level of safety features that are required for a given facility will be a direct function of the significant risks present in a facility;

d. using defense-in-depth concepts in the design to ensure the safety of the public, worker, and the environment;

e. incorporating the as-low-as-reasonably-achievable (ALARA) principles in the facility design to reduce the risk potential to the workers during normal and off-normal conditions.

The specific features associated with the design of a facility are discussed in detail in Chapter 6.

5.4.1 Event Scenario Identification and Classification

Figure 5.2 is a flow chart that can be used to understand the steps required in the analysis process. First, a list of postulated initiating events should be developed. Based on the generic hazard and accident scenario identification (presented in Appendix B), these initiating events could include the following:

a. loss of coolant (e.g., water and cryogen);

b. loss of flow;

c. magnet transients (arcing, quench, coil displacement, and magnet missile);

d. transient overpower;

e. plasma disruptions [including vertical displacement events (VDEs) and runaway electrons];

f. loss of vacuum;

g. initiating events in the tritium plant;

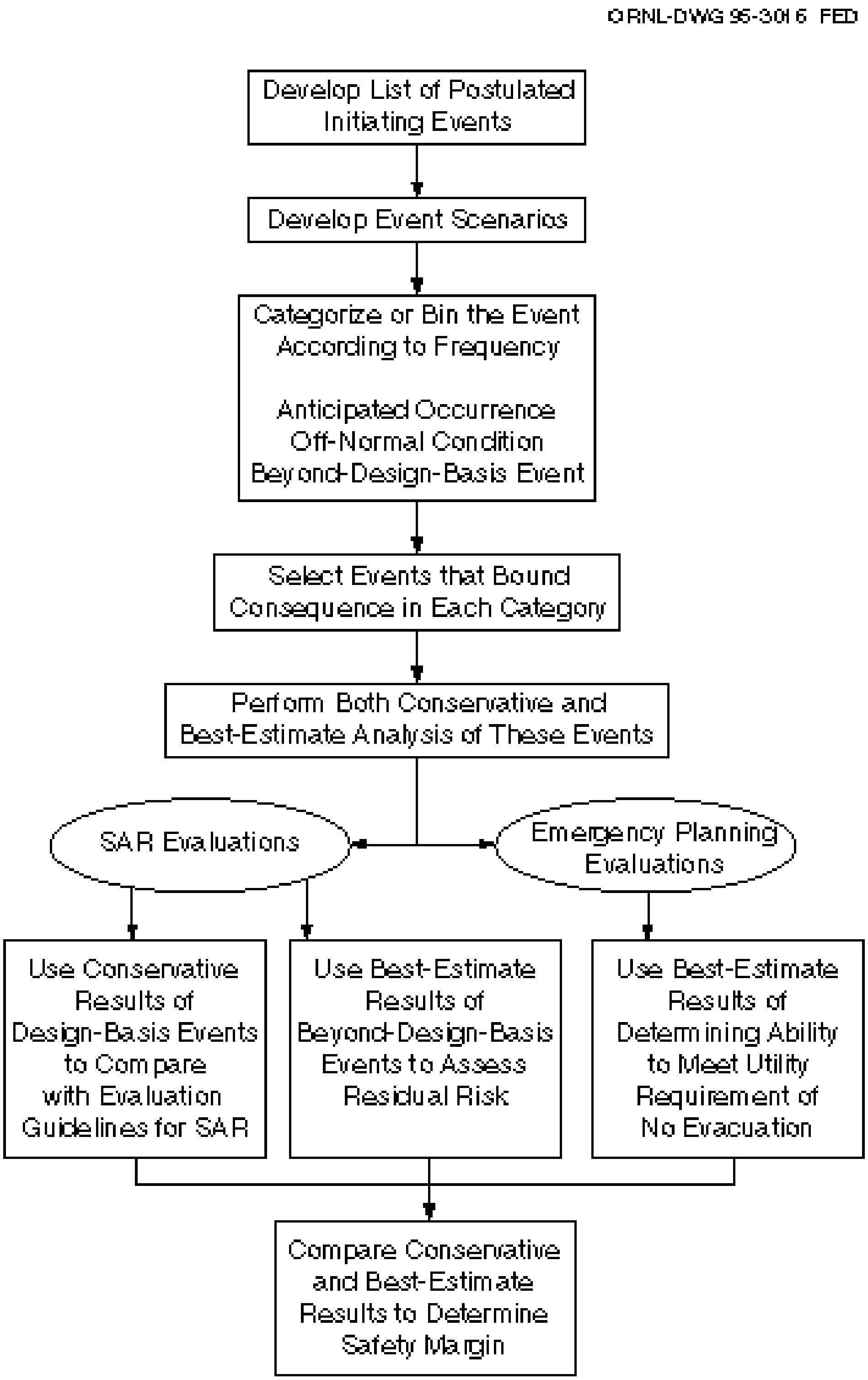

FIGURE 5.2. Event scenario/safety analysis process.

h. initiating events in auxiliary systems [e.g., neutral beams, radio frequency (RF), pumping, and fueling];

i. initiating events in balance of plant systems (e.g., loss of off-site power);

j. operator errors; and

k. external events.

The initiating events should consider all aspects of fusion facility operation, including plasma operation, bakeout and conditioning, and maintenance. Because fusion facilities operate in modes that are different from other facilities (e.g., bakeout and conditioning, in pulsed mode for some machines), these potential plant states should be examined carefully. In the development of these postulated initiating events, completeness is somewhat problematic. Practical completeness can then best be achieved by collective review of the results by safety analysts and designers who understand the facility.

From these postulated initiating events, event scenarios should be developed that examine the response of the fusion facility to these initiating events, accounting for potential failure of other systems (e.g., confinement). The use of event trees or event sequence diagrams may be useful here. The event scenarios should span a wide range of expected frequencies, including those events expected to occur once or more during the operating life of the facility [i.e., an anticipated operational occurrence ($f > \sim 10^{-2}$/yr); those events not expected to occur, but may occur, during the life of the plant (10^{-2}/yr $> f > 10^{-4}$/yr); those events that would not be expected to occur during the life of the plant but which form the limiting events needed in the design basis (10^{-4}/yr $> f > 10^{-6}$/yr); and events beyond the design basis ($f < \sim 10^{-6}$/yr)].

Once the events have been developed, they should be categorized into three types based on their estimated frequency: anticipated operational occurrence, off-normal conditions, and beyond-design-basis events. The off-normal conditions type includes both the anticipated operational occurrences and events expected to occur once or more during the lifetime of the facility. Based on these events, bounding or limiting events of each kind (e.g., loss of flow, loss of coolant, and loss of vacuum) should then be selected for detailed quantitative analysis.

Two types of analysis methodologies should be used for the safety assessment for the fusion facilities: a deterministic, conservative approach and a best-estimate, realistic approach. Each type of analysis methodology is required for a different portion of the required safety assessment. The deterministic, conservative approach is to be used in the design-basis assessment for the SAR to ensure that a bounding estimate of the facility safety is determined. The best-estimate, realistic approach is to be used for analysis of beyond-design-basis events for the SAR and in the determination of the emergency planning assessment. However, a conservative risk-based approach can be used in place of the deterministic conservative approach since either approach would satisfy the intent of performing a conservative safety assessment. These are discussed in the next two sections.

5.4.2 Analysis Approach for the Safety Analysis Report

Because there is no previously identified design basis for large fusion facilities like the International Thermonuclear Experimental Reactor (ITER), a subset of the event scenarios identified in Section 5.4.1 needs be selected to form the design basis and to undergo detailed quantitative analysis as part of the SAR. There is varying information that can be used to develop an appropriate criteria to be used in this selection. DOE Order 420.1 (DOE 1995a) and DOE-STD-3009 (DOE 1994) indicate that events down to $\sim10^{-6}$/yr should be considered. Many advanced fission plants are also considering similar criteria. It is recommended that for fusion facilities, internally initiated event sequences down to $\sim10^{-6}$/yr be used. For external events, guidance given in DOE Order 420.1 (DOE 1995a) should be consulted.

Two different types of calculations should be performed: best estimate and conservative. Conservative calculations should be performed for those events identified as part of the design basis. As part of the calculation, all key assumptions need to be stated and the level of conservatism noted (e.g., 110% nominal power). The results of these conservative calculations are then compared to the evaluation guidelines (discussed in DOE-STD-6002) to determine classification of safety systems (see Section 5.1). The best-estimate calculations are then performed so that the degree of conservatism or the safety margin in the facility can be established.

The deterministic approach used for evaluating the safety of the facility design basis provides a conservative approach for assessing the safety of the facility by using bounding estimates of the releases from the postulated off-normal conditions, bounding estimates for the release fractions, and bounding estimates for the transport through the environment. This approach is designed to result in a bounding estimate of the safety consequences from the postulated events.

Guidance on the conservative release assumptions to be used in the design-basis accident (DBA) analysis is available from several safety analysis reference sources. One of these sources is a report published in the late 1980s, Elder 1986. This report was published to provide guidance for assessing the radiological consideration for siting and the design of DOE nonreactor nuclear facilities. Some of the information may be dated, but in general it provides useful guidance for the assumptions and release fractions that are appropriate for deterministic analysis methodology. Guidance for the selection of conservative assumptions to be used in assessing the transport of the release to the receptor can be found in Nuclear Regulatory Commission (NRC) 1974 or NRC 1983. Guidance for documenting the analysis methodology used in assessing the consequences is provided in DOE 1994.

To assess the residual risk associated with the operation of a facility and to provide perspective on possible facility vulnerabilities, an evaluation of beyond-design-basis accidents (BDBAs) should be performed per DOE 1992c. Such BDBAs evaluations are not required to provide assurance of the public health and safety. These results are to serve as basis for evaluating the completeness of the events identified in the DBAs and to ensure that there is no significant threshold increase in the facility risk. For a well-designed facility, there should be no sharp increase in consequences when moving from DBA to BDBA scenarios. It is expected that the BDBAs would not be analyzed to the same level of detail as the DBAs. The insight into the magnitude of consequences of BDBAs has the potential for identifying additional facility features that could prevent or reduce severe BDBA consequences.

A key issue relates to the severity and associated probability of the accidents that need to be analyzed. There is no lower limit to a BDBA frequency specified in current DOE documents. However, it is understood that as frequencies become very low, little or no meaningful insight can be gained (DOE 1994). In terms of accident severity, the following guidance is applicable. 40 CFR 1502.22 gives some limited guidance on identifying BDBAs. These events have highly catastrophic consequences, although there is a low frequency of occurrence. BDBAs must be possible from a scientific viewpoint, not based on conjecture. DOE guidance in DOE Order 5500.3 (DOE 1992c) indicates that scenarios somewhat more severe than that considered in the design basis should be used. DOE 1994 states that BDBAs can simply be DBA events with more severe conditions or equipment failures than were in the DBA. For fusion facilities, this is interpreted as design-basis scenarios in which the loss of active safety systems is assumed. Another criterion, expressed in terms of the frequency is that internally initiated scenarios with estimated frequencies of occurrence greater than 10^{-7}/yr should be considered. Another option of evaluating BDBAs is to evaluate maximum credible events determined by assuming one additional system failure beyond the maximum design-basis events. BDBAs are not evaluated for external events, as stated in DOE 1994. The BDBA analysis is to be performed using realistic best-estimate assumptions.

After the completion of the safety analysis for the postulated events, the results of the DBA assessment should be compared to the evaluation guidelines established in DOE-STD-6002. The guidelines should include those associated with the protection of the public and the environment. As a result of the comparison of the safety analysis results to the guidelines, the events should be divided into the following groups: those that exceed the public safety evaluation guidelines, those that result in a significant fraction of the public safety function evaluation guidelines, and those that could affect the worker safety.

For the events that would exceed the public or environmental evaluation guidelines, any SSC that is required to mitigate the consequences to meet the evaluation guidelines would be classified as being safety-class. For those events that have a significant contribution but do not exceed the public or environmental guidelines, any SSCs installed to minimize the consequences or installed to provide defense-in-depth for the public safety functions would be classified as being safety-significant. For those items that could affect the worker safety, any SSCs needed to prevent acute worker fatalities and serious injuries from other than standard industrial hazards (see DOE-STD-3009-94) would also be classified as safety-significant.

5.4.3 Emergency Planning Basis Analysis

The Environmental Protection Agency (EPA) has developed requirements for protection of the public during events involving a release of significant hazardous material. The requirements establish the Protective Action Guide limits under which protective action should be initiated to protect the public. These requirements, established in EPA 1991, the event scenario severity and assumptions, the method of performing the analysis, and the evaluation guidelines to be used in determining when public protection is required are discussed in the following paragraphs.

DOE, EPA, and NRC guidance on emergency planning indicates that a spectrum of accident scenarios should be considered to determine the emergency planning basis. To ensure that emergency response would encompass breadth, versatility, and flexibility, events should include both design-basis (those events specifically designed for) and beyond-design-basis events. The discussion of the types of BDBA events to be selected for analysis is also applicable here.

Best-estimate calculations should be performed for emergency planning basis events, similar to that used for BDBA analysis. Because the conservatisms associated with the traditional deterministic design-basis type of analyses can mask the actual behavior of the plant, such calculations are not appropriate for emergency planning. For example, two key inputs into such emergency planning decisions are (a) the timing, quantity, and duration of the release of radioactive material and (b) the meteorological conditions at the time of the release. Differences in the conservative calculations of these inputs and the expected values could cause emergency planners to execute the wrong public countermeasure (e.g., evacuation vs sheltering). Thus, EPA requirements and NRC guidance on the issue indicate that for the purposes of emergency planning, it is important to know the *expected* response of the facility so that prudent emergency plans can be developed. Thus, the need exists for best-estimate analysis of facility response under a range of off-normal conditions using realistic models for evaluating the off-normal scenario and resulting consequences to the potential receptors (NRC 1978). The results should include the unavoidable dose received during the evacuation, if evacuation is dictated over other mitigative measures (e.g., sheltering). In practical applications, dose projections will usually begin at the time of the anticipated (or actual) initiation of the release.

The criterion used to determine whether emergency planning is required for a given facility is if the results of the off-normal event analysis exceed 10 mSv (1 rem). This criterion would eliminate the necessity for performing emergency planning for either personnel evacuation or sheltering. If the consequence results exceed this criterion, then an emergency plan must be developed to protect those off-site personnel. Thus, if the analysis of off-normal events for a fusion facility does not result in exceeding 10 mSv (1 rem), the fusion requirement of no off-site evacuation/sheltering is satisfied.

5.5 Safety Analysis Report Process

The safety analysis report (SAR) process is a two-step approach to identifying the safety concerns associated with a facility. The first is an identification of the potential safety risks associated with a facility and classification into the proper hazard categorization. The second step is to perform the required safety analysis to demonstrate that the safety concerns associated with a facility design and operations are adequately addressed. The amount and type of safety analysis required is dictated by the facility hazard categorization. The content and format for documenting the safety analysis in the SAR is provided based on the applicable DOE requirements. As discussed earlier, the type of safety analysis required for the SAR is primarily deterministic in nature, although probabilistic approaches may have been used but are not mandatory for establishing the design basis. Each of these topics associated with the SAR process is discussed in the following subsections.

5.5.1 Risk Assessment

The level of detail of the risk assessment performed for a fusion facility is dependent on the potential risk that is associated with the facility. For facilities with large-consequence off-normal conditions, a more detailed quantitative risk assessment [e.g., a probabilistic risk assessment (PRA)] should be required. However, a complete and accurate risk assessment, for example, a PRA, in which the true risk is very close to the analysis may be difficult to perform because of the lack of failure data for some unique components and because relatively few PRAs have been performed to date for these types of facilities. When failure rate data are not available, conservative estimates of failure rates should be assumed and used in the evaluation. Also, conservative estimates should be made regarding the operability of safety systems. Risk assessment performed on the facilities with low hazards should include, as a minimum, the probability of occurrence and predicted consequences of hazards expressed in qualitative terms. Quantitative results should be used unless no data or information are readily available. For a facility categorization, the minimum requirement is to provide a general qualitative approach to categorize facility risk. An example of the minimum approach that could be used is presented in DOE-STD-3009-94 (DOE 1994).

The required quantification of risk is determined from a knowledge of the probability of the event and of its potential consequences. If potential consequences could have a significant effect on the public or the environment, a quantitative evaluation of the risk would be required. For lesser consequences, the risk could be evaluated on a qualitative basis. The level of quantification of the risk is directly proportional to the potential magnitude of the consequences. The risk quantification will assist in identifying the critical components in the design and the SSCs that would be the most beneficial in mitigating off-normal condition consequences. The worker risk should be evaluated in a qualitative manner in accordance with guidelines of DOE-STD-3009 (DOE 1994).

The following guidelines are provided for the risk assessment required for fusion facilities having the indicated hazard categories:

a. Hazard Category 1—Perform a detailed risk analysis (e.g., PRA type analysis) using available data and conservative extrapolations of similar data sources. The results should be quantitative in nature and identify the significant contributions to the overall risks. They may also include sensitivity studies to show uncertainties in data and other parameters in the analysis if the required data are available. The risk analysis should be quantitative in nature and identify the significant contributions to the overall risks.

b. Hazard Category 2—Ensure that the risks associated with the on-site workers are adequately identified. The risk could be established, as a minimum, in a qualitative manner.

c. Hazard Category 3—Ensure that the risks associated with the localized consequences are adequately identified. A qualitative risk evaluation would be adequate to satisfy the risk evaluation requirements.

d. Below Hazard Category 3—Ensure that the risks associated with this category of facilities are below the threshold consequence limits values for the categories 1, 2, and 3. Thus, the associated risks associated with below category 3 facilities are low and as a result, the safety requirements that must be imposed on these facilities are substantially less than for the facilities in the hazard categories 1, 2, or 3. Only a qualitative risk evaluation would be required, at most, to satisfy the risk evaluation requirement for this hazard category. Satisfying the risk requirements for a Below Hazard Category 3 facility should employ the graded approach as defined in DOE 1992d and DOE 1994.

5.5.2 Safety Analysis Report

SARs for fusion facilities should address the vulnerabilities in the design, management, and human factors to ensure that the areas that could affect plant safety are evaluated. Historically, the main emphasis has been on the evaluation of just the safety design considerations. The safety analysis documentation associated with a fusion facility should be updated on a periodic basis so that a current evaluation of the safety vulnerabilities and mitigative measures is maintained. The schedule for the updates should be at least annually for facilities having a Hazard Category 1, 2, or 3, and every 2 yr for Below Category 3 facilities. The specific requirements are provided in the following sections.

SARs should include the results of the safety analysis that identifies dominant contributors to the risk of the facility so these vulnerabilities can be better managed. The SAR for Hazard Category 1, 2, and 3 facilities should address the following based on DOE 1992b using a deterministic analysis approach:

1. *Executive Summary;*

2. *Applicable statutes, rules, and regulations;*

3. *Site characteristics;*

4. *Facility description and operation, including design of principal structures, components, all systems, engineered safety features, and processes;*

5. *Hazards analysis and classification of the facility;*

6. *Principal health and safety criteria;*

7. *Radioactive and hazardous material waste management;*

8. *Radiation protection;*

9. *Hazardous material protection;*

10. *Analysis of normal, abnormal, and accident conditions, including design basis accidents; assessment of risks; consideration of natural and man-made external events; assessment of contributory and causal events, mechanisms, and phenomena; and evaluation of the need for an analysis of beyond design basis accidents, however, the SAR is to exclude acts of sabotage and other malevolent acts since these actions are covered under security protection of the facility;*

11. *Management, organization, and institutional safety provisions;*

12. *Procedures and training;*

13. *Human factors;*

14. *Initial testing, in-service surveillance, and maintenance;*

15. *Derivation of the TSRs;*

16. *Operational safety;*

17. *Quality assurance;*

18. *Emergency preparedness;*

19. *Provisions for decontamination and decommissioning;*

20. *Applicable facility design codes and standards.*

A recommended guide for the format and content for the SAR is contained in DOE-STD-3009 (DOE 1994). This Standard was specifically generated to provide guidance on the format for Hazard Category 2 and 3 facilities. Due to the lack of SAR format guidance for Category 1 facilities, it is recommended that the format guidance for Hazard Category 1 facilities use the same format guidance as provided in DOE 1994. This Standard also provides a "risk-based prioritization approach" application for facilities with varying degrees of hazards and potential consequences.

For Below Hazard Category 3 facilities, the following items should be addressed in the safety analysis in appropriate detail to the extent practical:

a. facility mission or purpose;

b. a description and evaluation of the site;

c. design criteria for SSCs;

d. normal and emergency operation procedures to be used;

e. identification of hazards;

f. probability of occurrence and predicted consequences of hazards expressed in qualitative or quantitative terms;

g. physical design features and administrative controls provided to prevent or mitigate potential off-normal conditions;

h. potential off-normal conditions, including those resulting from natural phenomena; and

i. operational limitations.

Based on the required content of the safety analysis that must be performed for a Below Hazard Category 3 facility, the format and content for the SAR could be significantly simplified. Usually, the risks associated with these facilities are rather small, and scoping off-normal condition assessments would adequately cover the analysis requirements.

5.6 Safety Envelope Configuration Control

Configuration control of the safety envelope, which provides the basis of operational authorization, is important for fusion just as it should be for any technological activity involving hazards. The concept adopted in the United States for addressing this issue for nuclear activities is the Unreviewed Safety Question (USQ). The fusion facility needs in this area of configuration control can be adequately addressed by compliance with the following guidance.

> The operative requirement for fusion is to ensure that activities are performed within the bounds of an operational safety envelope that adequately reflects a disciplined hazards identification, risk quantification and risk acceptance. The process for accomplishing this is termed safety analysis and the results of it are documented in a Safety Analysis Report with the operational limits that characterize the bounds of the safety analysis being labeled Technical Safety Requirements.

For every activity in a fusion facility a system must be established to ensure that operations, experiments, and any other work are encompassed by the explicit documented safety envelope that has been submitted to the activity-approving authority and thereby has become an inherent part of the facility operating approval and risk acceptance. This process is the authorization basis as described in Section 5.9.

If at any time it is determined that either (a) a proposed change in physical or operational configuration in the safety analysis or (b) existing physical or operational conditions (including previous analytical work) would create or has created conditions that are not encompassed in the safety analysis that is the basis of the facility Authorization Basis, then the activity associated with the discovered condition will be ceased (or will not be initiated). The activity will not be resumed until the Authorization Basis has been modified to address the concern, and has been documented, reviewed, and approved in the same manner as the original Authorization Basis. These actions, which constitute elements of configuration management of the activity, should be guided by procedures that provide for ensuring that (1) the probability of hazardous events associated with the activity, (2) the potential consequences of hazardous events associated with the event, and (3) the scope of events that could constitute a hazardous challenge to the activity are encompassed in the documented safety analysis of the activity. Because the basis of risk acceptance of an activity can involve information sources external to the activity itself, it is also imperative that the management system for ensuring configuration management of the safety of an activity contain the elements that will guarantee professional awareness of the lessons learned throughout the technology of the activity, particularly those that would affect analytical bases for risk acceptance decisions. Specifically, the activity risk managers must be aware of the ongoing history of everything used in establishing the activity risk acceptance basis so that changes in such things as the professional codes, materials properties, analytical models can be factored into the periodic revisitation and reaffirmation of the safety envelope.

The following are some useful guidelines to be considered when assessing the adequacy of the configuration management of the fusion activity safety envelope. These guidelines have been extracted from experiences with the fission USQ process. An activity (ongoing or contemplated) is or will be outside of the configuration bounds of the activity safety envelope under any of the following circumstances:

a. if the risk resulting from the product of the event occurrence frequency or the consequences of an off-normal condition assessed and documented in the approved safety analysis is increased;

b. if the possibility is identified for an off-normal condition of a different type or for a different cause than those assessed and documented in the approved safety analysis and the off-normal condition type or cause is not clearly encompassed by those off-normal conditions and causes that are addressed in the approved safety analysis;

c. if the margin of safety, as defined in the basis for any TSRs, is reduced.

In addition the guidance explicitly acknowledges the reality and acceptability of encompassed but not explicitly stated issues. While not explicitly stated in this guidance, the basis for acceptability of encompassed issues is the professional judgment inherent in the generation and various reviews and approvals that are an integral part of the safety analysis and operational approval process. The implementation guidance for the USQ process is contained in DOE 1991, “Unreviewed Safety Questions.”

5.7 Technical Safety Requirements

Whenever significant safety hazards associated with the fusion facilities are present, the requirements that define the conditions, safe boundaries, and management or administrative controls necessary should be identified and agreed upon with the controlling authority to ensure that the facility is operated safely and to reduce the risk to the public and workers from off-normal conditions. The implementation of the TSRs would satisfy this objective for fusion facilities. The TSRs will be applicable to Hazard Category 1, 2, and 3 facilities to ensure the safe operation of a facility without exceeding the evaluation guidelines. Below Hazard Category 3 facilities, by definition, will not exceed the evaluation guidelines and as such will not require TSRs to impose operational restrictions and equipment operability safety requirements. However, economic considerations or other facility protection concerns may warrant including some administrative controls in a TSR document.

TSRs are those requirements that define the conditions, safe boundaries, and the management or administrative controls necessary to ensure the safe operation of a fusion facility and to reduce the potential risk to the public and facility workers from uncontrolled release of radioactive or hazardous materials. A TSR consists of safety limits, operation limits, surveillance requirements, administrative controls, use and application instructions, and the basis thereof.

5.7.1 Implementation of Technical Safety Requirements

The complexity of the TSRs should be commensurate with the hazards associated with the facility. For example, the facilities with potentially more severe risks will require more detailed and specific requirements in the TSRs, and the facilities with less severe risks should require simpler and less complicated TSRs. The requirements contained in the TSRs should be derived from the safety analysis performed for the facility. If the basis for the surveillance intervals is not contained in the safety analysis, then engineering judgment or other bases (e.g., industrial experience or manufacturer's recommendations) should be used.

Guidance for the development and implementation of TSRs is contained in DOE 5480.22, "Technical Safety Requirements" (DOE 1992a).

5.7.2 Risk-Based Prioritization in Technical Safety Requirements

The facility characteristics that determine the level of detail and sophistication needed in the safety assessment, under the risk-based approach concept, are the same as those that determine the makeup of the TSR. The characteristics are (1) the magnitude of the potential hazard, (2) the complexity of the facility and the systems relied on to provide safety assurance, and (3) the stage in the life cycle of the facility.

The overall guiding concept is that an acceptable and uniform level of safety assurance should be provided for each type of facility, all hazards categories, and all fusion sites. Facilities with small potential hazards and little complexity do not need sophistication or detailed information in their TSR (or their safety analysis) to achieve the uniform level of safety assurance.

Only Hazard Category 1 facilities should normally need the full complement of TSR elements; that is, Safety Limits (SLs), Limiting Control Settings (LCSs), Limiting Conditions for Operations (LCOs), Surveillance Requirements (SRs), and Administrative Controls (ACs). Although some Hazard Category 2 facilities may require SLs or LCSs, the majority of these facilities should be able to achieve the required level of safety assurance with only LCOs, SRs, and ACs. Hazard Category 3 facilities should normally require only ACs to achieve an acceptable level of safety assurance. Normally Below Hazard Category 3 facilities would not require TSRs for the safe operation of the facility. However, some ACs may be desirable for the protection of the facility from an economic point of view.

5.8 Startup and Restart of Fusion Facilities

It is a recommended policy that new fusion facilities should be started up and existing fusion facilities that have been shutdown should be restarted only after documented reviews of readiness have been conducted and approvals have been received. The readiness review should, in each case, demonstrate that it is safe to startup (or restart) the applicable facility. The readiness reviews are not intended to be tools of line management to confirm readiness. Rather, the readiness reviews provide an independent verification of readiness to start or restart operations.

The startup and restart of complex fusion facilities warrant an independent operational review of the facility readiness to ensure that operational safety can be achieved. The startup and restart of fusion facilities will require a documented independent review of the readiness of the facility for operation prior to startup. This can be in the form of either an operational readiness review or a readiness assessment, depending on the hazard class of the facility and the requirements established by the controlling authority.

5.8.1 Implementation of Startup and Restart Reviews

The startup and restart reviews required for Hazard Category 1, 2, and 3 fusion facilities should generally follow the requirements of DOE Order 425.1 (DOE 1995b). These reviews are generally required whenever the following conditions exist:

a. initial startups of new hazard category 1, 2, and 3 fusion facilities;

b. restart after an unplanned shutdown directed by a regulatory official for safety or other appropriate reasons;

c. restart after an extended shutdown for Hazard Category 1 (6 months) and Category 2 (12 months) facilities;

d. restart of Hazard Category 1 and 2 nuclear facilities after substantial plant or facility modifications required for future program work and/or for enhanced safety which require changes in the safety basis previously approved by the controlling authority;

e. restart after a fusion facility shutdown because of operations outside the safety basis; or

f. when deemed appropriate by regulatory officials, including facilities with a Hazard Category less than 1 or 2.

Startups and restarts of fusion facilities not requiring an Operational Readiness Review should be evaluated as to the need for performing a Readiness Assessment prior to startup or restart. Guidance for the development and implementation of Startup and Restart Requirements is contained in DOE 1995b, and guidance for the planning and development of the Operational Readiness Review is contained in DOE 1993.

5.8.2 Risk-Based Prioritization Implications for Startup and Restart Reviews

Implementation of risk-based prioritization principles in formulating startup and restart review criteria is based on the hazard classification for the facility and described in Section 5.6. Those facilities that have been assessed as having high levels of hazards require reviews before initial startup, when significant modifications have been made to the plant, when the facilities have been shutdown for extended periods of time, and when the facility has been shutdown because of safety concern. Facilities with low hazards (at least a Hazard Category 3 facility) should, as a minimum, receive an initial startup review and another review when the facility has been shutdown due to safety concerns or an unplanned shutdown. Facilities designated as Below Hazard Category 3 are not required to undergo the startup review process.

5.9 Authorization Basis

"Authorization Basis" is the term given to the total body of information used as the basis for approving operation of a facility. All aspects of the design basis and operational requirements, safety analysis, and any other item relied upon by the authorizing agency to authorize operation constitute the Authorization Basis. These are considered to be important to protecting the environment and/or the health and safety of workers and the public. The Authorization Basis is described in documents such as the SARs, the TSRs, the authorization agency's issued evaluation reports, and other specific commitments made in order to comply with the authorization requirements. Guidance for the development and implementation of Authorization Basis Requirements is contained in DOE 1986, 1992a, 1992b, and 1995b.

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;

APPENDIX A
CATEGORY 2 THRESHOLD QUANTITIES OF RADIONUCLIDES

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

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

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

where

Q = quantity of material used as threshold (grams)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

TABLE A.1. Thresholds for radionuclides Category 2

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

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

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

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

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

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

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

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

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

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

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

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

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

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

B.1 Introduction

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

B.2 Hazards

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

B.2.1 Radiological Hazards

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

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

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

Smaller inventories of activation products include the following:

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

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

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

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

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

B.2.2 Chemical Hazards

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

B.2.3 Industrial Hazards

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

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

B.3 Energy Sources

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

B.3.1 Plasma Energy

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

B.3.2 Magnetic Energy

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

B.3.3 Decay Heat

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

B.3.4 Chemical Energy

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

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

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

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

B.3.5 Coolant Internal Energy

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

B.4 Potential Generic Accident Scenarios

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

B.4.1 Loss-of-Coolant Event

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

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

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

B.4.2 Loss-of-Flow Event

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

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

B.4.3 Loss-of-Vacuum Event

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

B.4.4 Plasma Transients

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

B.4.5 Magnet Transients

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

B.4.6 Loss of Cryogen

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

B.4.7 Tritium Plant Events

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

B.4.8 Auxiliary System Accidents

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

B.4.8.1 Neutral Beams

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

B.4.8.2 RF Heating

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

B.4.8.3 Fuel System

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

B.4.8.4 Vacuum Pumps

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

B.4.8.5 Wall Conditioning and Bakeout Systems

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

B.4.8.6 Energy Storage

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

B.4.9 Maintenance Events

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

CHAPTER 5 REFERENCES

10 CFR 830.120	Code of Federal Regulations, "Nuclear Safety Management," Title 10, Part 830, Subpart 120, "Quality Assurance Requirements," May 5, 1994.
40 CFR 1502.22	Code of Federal Regulations, "Environmental Impact Statement," Title 40, Part 1502, Subpart 22, "Incomplete or Unavailable Information," Nov. 29, 1978.
DOE 1986	United States Department of Energy Order, "Safety Analysis and Review System," DOE 5481.1B, September 23, 1986.
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