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Exam Preview:

1. Confinement/HVAC systems include structures, systems, and components designed to serve as barriers against the spread or uncontrolled release of radioactive or other hazardous materials throughout the facility or to the environs.
   a. True
   b. False
2. According to the Recommended Design Practice section of the reference material, factors of safety lose meaning for glass, because subsurface imperfections can cause failure below the expected tensile strength. Therefore, a factor of safety of __ on the modulus of rupture is recommended.
   a. 15
   b. 8
   c. 12
   d. 10
3. Tritium systems design should provide for confinement barriers to reduce tritium releases to an acceptable level.
   a. True
   b. False
4. Tritium systems design should implement requirements and provide for corresponding safety functions to make the accident consequences acceptable. A typical frequency for design basis accidents is ______.
   a. $P>10^{-2}$/year
   b. $P>10^{-4}$/year
   c. $P>10^{-6}$/year
   d. $P>10^{-8}$/year

5. Thermal methods (calorimetry) rely on the radioactive heat of decay of tritium. For one gram of tritium approximately 0.333 watts is generated by decay.
    a. True
    b. False
6. Hydrogen and air mixtures can ignite and sustain a flame over a very wide range of composition, from 4% to 74% by volume of hydrogen, at room temperature and pressure. A minimum limit of __% is needed to sustain a coherent flame.
    a. 23
    b. 18
    c. 15
    d. 9
7. According to the reference material, Carbon steel is significantly less susceptible to hydrogen embrittlement than Type 300-series stainless steel and is recommended material for primary confinement.
    a. True
    b. False
8. Which of the following materials was NOT listed as options for instruments, gaskets and seals of the primary confinement system can contact tritium without detriment in the pressure and temperature ranges of most tritium system?
    a. Copper
    b. Stellite
    c. Delrin
    d. Nickel
9. According to the reference material, the vacuum vessel chamber should be pneumatically tested in accordance with ______ or comparable safety-related code.
    a. 10CFR50
    b. RG 1.140
    c. Caldwell 89
    d. ASME 93
10. According to the reference material, Deuterium, in quantities greater than ___ grams, is also controlled at DOE facilities. The requirements are primarily records management. There are not requirements to perform measurement.
    a. 10
    b. 50
    c. 100
    d. 250

CONTENTS

ACRONYMS

ACI	American Concrete Institute
AFOSH	Air Force Occupational Safety and Health
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
BIL	Basic Impulse Level
BSR	Bureau of Standards Review
CFR	Code of Federal Regulations
CMMA	Crane Manufacturers Association of America
EIA	Electronic Industries Association
EJMA	Expansion Joint Manufacturers Association
ESF	Engineered Safety Features
H&V	heating and ventilating
HEI	Heat Exchanger Institute
HIS	Hydraulic Institute Standards
HMI	Hoist Manufacturers Institute
HVAC	heating, ventilating, and air conditioning
I&C	instrumentation and controls
IEC	Institute of Electrical Contractors

IEEE	Institute of Electrical and Electronics Engineers
IPCEA	Insulated Power Cable Engineers Association
ISA	Instrument Society of America
ITER	International Thermonuclear Experimental Reactor
JIC	Joint Industrial Council
MCC	motor control center
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
NPH	Natural Phenomena Hazards, (DOE 5480.11)
NUREG	Nuclear Regulatory Commission document
OSHA	Occupational Safety and Health Administration
PIE	postulated initiating events
PPE	personal protective equipment
PVTC	pressure-volume-temperature-composition
RG	Regulatory Guide
RIA	Robotics Industrial Association
SAR	Safety Analysis Report, (DOE 5480.28)
SSC	Structures, subsystems, and components
TEMA	Tubular Exchanger Manufacturers Association
UHMWPE	Ultra high molecular weight polyethylene

SECTION I

VACUUM VESSEL

Many of the components within and part of the vacuum vessel vacuum are unique to fusion systems. Thus, there is little precedence in the established codes and standards and little experience in the design of those components. Much of the design experience is taken from the design of plasma experiments where the power levels and radiation fluxes are much lower.

The vacuum vessel is assumed to be a torus-shaped container usually made of a metal or metallic alloy, and its volume can be several times the plasma volume. It can be thin-walled or thick-walled. It may be double-walled with coolant passages between the walls. The perimeter of the vacuum vessel is outfitted with a number of ports for mounting hardware for plasma fueling and heating, plasma conditioning and for vacuum pumping. These ports can vary in size and shape and are usually located above, below, and on the horizontal plane as well as on top and bottom of the vacuum vessel. It may be of all-welded, continuous construction or use bolts between toroidal segments with vacuum seal welds at the joint.

GENERAL SAFETY DESIGN CRITERION

If required by the facility safety analysis, the vacuum vessel will be a confinement or containment barrier for tritium and tritiated compounds, radioactive impurities and activated dust. The requirement for robustness of the barrier will be defined in the safety analysis and implemented in the design. In performing this function, the vacuum vessel will be classified as a safety-class system. If the vacuum vessel is not considered a confinement or containment barrier in the safety analysis, those vacuum vessel components whose single failure results in loss of capability of another safety-class system to perform its safety function should be designated as safety-class components. The vacuum vessel may also be a physical barrier between different fluid streams (such as liquid metal and water) whose interconnection could potentially produce large energy release events which could compromise nearby safety-class systems.

POTENTIAL SYSTEM SAFETY FUNCTIONS

If the safety analysis requires that the vacuum vessel be a confinement or containment barrier, the following safety functions are specified:

1. <u>Normal operation including anticipated operational likely and unlikely events</u> - to act as the first barrier for tritium and tritiated compounds, radioactive impurities and activated dust.

2. <u>Maintenance</u>

   a) To act as the first barrier for tritium and tritiated compounds, radioactive impurities and activated dust during maintenance external to vacuum vessel.

   b) To act as a partial confinement barrier as defined in the safety analysis for tritium and tritiated compounds, radioactive impurities and activated dust during maintenance inside the vacuum vessel.

3. Design Basis Accidents - To act as the first barrier for tritium and tritiated compounds, radioactive impurities, activated dust, or any other coolant or material located in the vacuum vessel during design basis accidents.

Design basis accidents will be specified in the safety analysis and mitigated in the system design requirements. A accident probability, P, for defining a design basis accident is typically 10^{-4}/year>P>10^{-6}/year; the actual probability will be specified in the facility safety analysis. The following are potential design basis accidents for fusion DT facilities: burn excursion, loss of vacuum pumping, loss of vacuum, loss of flow or coolant pressure to actively-cooled components inside the vacuum vessel, chemical reactions including hydrogen detonation, site-generated missile impact, and design basis natural phenomenon: earthquake, flooding, and severe winds. However, any of these may be categorized as likely or unlikely events depending on the probability as assessed in the safety analysis.

4. Beyond Design Basis Accidents - There are no system safety functions required for beyond design basis accidents.

DESIGN CONSIDERATIONS

General

The primary confinement or containment should normally be provided by the pressure boundary of the fusion machine, its associated vacuum system, and the various tritium systems (DOE 6430.1A (c)). If this barrier is deemed a safety-class system, then other hardware with pressure containing surfaces on the vacuum boundary are safety-class components and must be designed to function as confinement or containment as appropriate in the same operational and accident modes for which the vacuum vessel is designed.

Structural Design Codes

DOE Order 6430.1A, General Design Criteria, required that safety-class components be designed, fabricated, inspected, and tested in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Class 3 or to a comparable safety-related code. The following discussion modifies this requirement for fusion safety-class items to provide more flexibility in design and manufacturing without compromising the safety function of the item. The complex nature of many fusion components may require specific analysis under the alternate design rules of Section III, Class 1 or 2 or the comparable elements of Section VIII, Division 2 for pressure vessels. In defining a comparable code to ASME Section III, the use of ASME Section VIII is acceptable if additional standards are provided in areas such as attached valves, pumps, piping and supports, enhanced quality assurance and radiation effects which are comparable to relevant parts of Section III. In general, a detailed comparison should be made between ASME, Section III and the comparable code to be used to design safety-class items to demonstrate actual comparability. This code comparison should be performed early in the design phase and should be endorsed by the licensing or regulatory authority to ensure the design product will be acceptable for construction. Finally, the actual stamping of a vessel designed, fabricated, inspected, and tested to Section III or VIII is not addressed by this document nor in the Fusion Safety Standards and is considered to be a decision between the owner, fabricator, and the cognizant regulatory agency.

Hydrogen Detonation

A hydrogen detonation is a potential hazard which may occur as part of a design basis accident (typical probability > 10^{-6} per year). If it does occur and the vacuum vessel is a confinement or containment barrier, then the required integrity of the barrier must be maintained during and after this event, although the non-safety-related functions of the vacuum vessel (such as ability to maintain high vacuum) can be compromised. If the vacuum vessel is not a confinement or containment barrier and a hydrogen detonation is credible, it must be shown that no failure of a vacuum vessel component due to this event can degrade the function of an adjacent safety-class system or item.

To determine if a potential hydrogen detonation can occur in a design basis accident, it is necessary to evaluate the likelihood of having the three ingredients for detonation at the same time: hydrogen and oxygen in the appropriate mixtures and an ignition source (NUREG/CR-4961). Generally, direct initiation of hydrogen-air mixtures is possible with about 1 gram of high explosive (NUREG/CR-4961) (this is equivalent to about 4 kJ of energy). Since the plasma typically contains much higher levels of stored energy, it should be assumed that a point ignition source is always present during normal operations and wall conditioning. The factors determining the likelihood of a detonation are then the availability of hydrogen isotopes and air. Hydrogen isotopes are present in the solid matrix of the plasma facing components at substantial levels. This is not ordinarily available for combustion or detonation although a portion (including tritium) may be released if a detonation occurs. If hot plasma facing components or the vacuum vessel are cooled with water, a leak could result in the generation of hydrogen from water (steam)-Be (or C or W) reactions (Smolik 92, Smolik 91). The precise amount of hydrogen generated depends on the first wall material and temperature and the size and duration of the water leak but typical conditions in a D-T fusion plasma can generate sufficient quantities of hydrogen for a detonation. Air (oxygen) also has to be present for a detonation. If air is adjacent to the vacuum vessel, the in-leakage of air is possible due to the same event which generated the hydrogen. For example, Be-steam reactions from a water leak during wall conditioning can result in internal pressures of several bar or more (NET 93), which may be beyond the design value of the vacuum vessel. This air source can be eliminated in the device design by incorporating an inert gas volume in the region between the vacuum vessel and its ducts, and the next confinement barrier. To determine the probability of a hydrogen detonation, a conservative analysis of the above factors must be performed for a particular design. The likelihood of an in-vessel loss-of-coolant accident cannot be generally excluded given performance of such actively-cooled systems to date and the anticipated service conditions in a D-T fusion vacuum vessel.

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

1. Material selection in the plasma facing components or the fluids used for active in-vessel component cooling, or

2. Use of an inert gas boundary as discussed above.

SAFETY-RELATED DESIGN STANDARDS AND CRITERIA

If the vacuum vessel system or individual components are designated safety-class the following design standards should apply to the system or components:

Structural

The vacuum vessel system boundary should be defined as the vacuum vessel proper including attached windows, flanges, and ports and all penetrations up to and including the first isolation valve in system piping which penetrates the vacuum vessel.

Loads

Individual Loads

The vacuum vessel should be designed to withstand the static load, normal operating pressure, normal operating thermal load, electromagnetic loads (normal operating and fault), disruption/vertical displacement (VDE) loads, interaction loads from adjacent systems, and transient loads due to design basis accidents such as natural phenomena, loss-of-coolant into the vessel and subsequent chemical reactions, site-generated missile impacts, and hydrogen detonation. (These design basis accidents are for example only, since some of them may not be credible for a particular facility.)

Static Load

The static load should include the weight of the vacuum vessel and all supported hardware.

Normal Operating Pressure

The normal operating pressure of the vacuum vessel may be one of the following:

1. 1 atmosphere internal pressure,
2. 1 atmosphere external pressure,
3. No net pressure.

If the vacuum vessel is double-walled with a coolant in the annulus, the maximum coolant pressure should be the normal operating pressure in the annulus.

Normal Operating Thermal Load

The normal operating thermal load should include transient thermal loads during pulsed operation as well as the temperature distribution during bakeout and wall conditioning.

Electromagnetic Loads

Electromagnetic loads induced during normal pulsed operation of the device are experienced as a result of eddy currents in the vessel interacting with the magnetic fields crossing them. Loads should include the electromagnetic effects of discharge cleaning.

1. Electromagnetic Loads During Faults - Electromagnetic loads induced during abnormal operating events such as control failures, power supply failures, bus opens or shorts, or magnet faults should be included in the design.

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

Interaction Loads

Interaction loads are loads imposed on the vacuum vessel by other components during normal or fault conditions.

Natural Phenomena Hazard Loads

Natural phenomena hazard loads are site-specific loads due to earthquakes, wind, and floods. Guidelines for methods of establishing load levels on facilities from natural phenomena hazards and for methods of evaluating the behavior of structures and equipment to these load levels are contained in DOE 1020.

Loss-of-coolant Loads

The confinement or containment should be designed to remain functional after a potential loss-of-coolant to the interior of the vessel including subsequent chemical reactions if this is evaluated as a design basis accident.

Hydrogen Detonation Loads

The confinement or containment should be designed to remain functional after a potential hydrogen detonation if this is evaluated as a design basis accident. For guidance on determining if this is a design basis accident, see Section IV "Design Considerations" within this Vacuum Vessel section.

Site-generated Missile Impact Load

The confinement or containment should be designed to remain functional after a potential missile impact if this is evaluated as a design basis accident.

Combined Loads

Considerations for combined loads are indicated in Table I-1.

Table I-1 Combined Loads

		Hydraulic		Thermal		Electro-magnetic				
Plant Condition	**Static**	**Norm.**	**Trans.**	**Norm.**	**Trans.**	**Norm.**	**Fault**	**Nat. Phen.**	**Miss. Imp.**	**Cyc**
Normal Operation	X	X		X		X				X
Maintenance	X	X[1]		X[1]						
Design Basis Accidents										
Internal Initiators										
1. Coolant Leak in Vacuum Vessel.	X		X		X	X				
2. In-cryostat Leak	X		X		X	X				
3. Out-of-cryostat Leak	X		X		X	X				
4. Loss of Pumping	X		X		X	X				
5. Loss of Flow	X		X		X	X				
6. Loss of Heat Sink	X				X	X				
7. Missile or Pipe Whip	X	X	X	X	X	X	X		X	
8. Increase in Fusion Power	X				X	X				
9. Human Error or Control Fault	X		X		X	X	X		X	
External Initiators										
1. Natural Phenomena	X	X	X	X	X	X	X	X	X	
2. Fires	X	X	X	X	X	X	X			
3. Aircraft or Missile Impact	X	X	X	X	X	X	X		X	
Beyond Design Basis Accidents[2]										

1. Pressure and thermal loads are applicable for portions of system which remain pressurized during maintenance.

2. There are no load combinations for beyond-design-basis accidents.

Cyclic Loading

The vacuum vessel and its supports are subject to cyclic loading during normal operations. Thermal cycling and unavoidable plasma disruption loads are expected. The necessity of a fatigue analysis should be evaluated based on the criteria of ASME 93 or comparable safety-related code using conservative values for variables such as number of pulses, percentage of pulses that have disruptions, and service life including expected changes in material properties with time. Cyclic loading must be defined on load/time diagrams so that a fatigue analysis, if necessary, can be performed.

Structural Acceptance Criteria

Vacuum vessel

The vacuum vessel and its appendages should be designed, fabricated, inspected, and tested in accordance with a recognized safety-related code such as the ASME Boiler and Pressure Vessel Code. The design of the fusion facility components which is outside the scope of conventional codes or standards due to design temperature, materials selection and/or any other design feature, should meet the safety design criteria of this Fusion Safety Standard and should employ a design and analysis methodology which is consistent with requirements of a recognized safety-related code.

Piping, Pumps and Valves

Piping, pumps and valves should be designed in accordance with relevant criteria in ASME 93 or a comparable safety-related code.

Other

Hardware internal or adjacent to the vacuum vessel whose credible failure could impact the safety function of the vacuum vessel should be classified as safety-class components or items.

Deflection Analysis

Vacuum vessel deflections should be calculated and analyzed to determine potential interferences and to verify seal integrity.

Testing

Weld Inspection

Non-destructive examination should be performed in accordance with Section V of the ASME Boiler and Pressure Vessel Code as modified by Section III, Article NC-5111 or approved equal. Non-destructive test personnel qualification and weld acceptance criteria are found in Article NC-5000 of the ASME Boiler and Pressure Vessel Code or approved equal.

Pressure Test

1. Vacuum Vessel - All vacuum vessels that provide a containment barrier should be leak checked before initial operations and periodically thereafter and meet the requirements specified in the

safety analysis (guidance on leak testing is provided in 10CFR50(J). All vacuum vessels that provide a confinement barrier should be leak checked before initial operations and periodically thereafter against the leakage criteria in the facility safety analysis. The vacuum vessel chamber should be pneumatically tested in accordance with ASME 93 or comparable safety-related code. A double-walled vacuum vessel should be hydrostatically tested in accordance with ASME 93 or comparable safety-related code.

2. Valves - System isolation valves should be hydrostatically tested in accordance with the ASME 93 or a comparable safety-related code.

Computer Code Verification

Computer codes used for design analysis of the vacuum vessel for normal operating and design basis accident conditions should have validation and/or verification as described in DOE Standard 6003-96. This validation and verification should support the use of the code in each intended application.

Materials

Material properties used in the structural analysis of safety-class structures, systems, and components must be appropriate for the operating environment and compensated for the degradation of the material with time due to radiation, fatigue, corrosion, or any other harsh treatment.

1. Radiation - Materials selected should be qualified for the anticipated lifetime in the radiation environment. With irradiation, yield strength usually increases as ductility decreases. Conservative end-of-life properties should be used in the structural design analysis.

2. Thermal - Material properties used in analysis should always be those appropriate at the given temperature. If no published property data for a particular temperature exists, then materials should be tested for properties at the operating temperature. For those items to be designed in accordance with the ASME Boiler and Pressure Vessel Code, temperature limits are imposed within the Code. If the item will be subjected to temperatures higher or lower than the limit, material properties, such as allowable stress and creep, used in the analysis should be justified by testing the material at the anticipated temperature.

3. Swelling - The energetic neutron flux on the first wall, diverter and other plasma facing components results in displacement cascades and helium-producing nuclear reactions. During long-term irradiations vacancies coalesce to form helium-filled voids within the material. Dimensional changes are most severe at about half the melting point of the material. Allowance must be made for irradiation-induced swelling in the design of any components exposed to the high-energy neutron flux.

4. Hydrogen Embrittlement - Hydrogen reacts to some degree with almost all metals. When a metal comes in contact with hydrogen, its surface adsorbs the gas. Surface or physical adsorption is followed by activated adsorption, a preliminary stage of the diffusion of hydrogen into metals. With continued exposure, materials can become embrittled. The material properties based on end-of-life hydrogen embrittlement should be used in the structural design analysis. The actual

embrittlement of the vacuum vessel in the hydrogen environment should be determined by placing coupons in the vessel to be periodically removed and inspected for embrittlement. An inspection schedule should be developed and implemented.

Instrumentation and Controls

Instrumentation and controls, where appropriate, should be provided to monitor system parameters important to the safety function of the vacuum vessel over their anticipated ranges for normal operation and design basis accidents to ensure continuity of the required safety function. The design should incorporate sufficient instrument independence, redundancy and/or diversity to ensure that a single failure will not result in a loss of monitoring capability for safety-class systems. The different designs and operating characteristics of fusion facilities limit the amount of specific guidance that can be provided. However, helpful general guidance for implementing this criteria at a particular fusion facility may be obtained by reviewing the existing DOE and NRC design requirements and guidance documents (IEEE 603, DOE 6430.1A (a), NUREG-0800, 10CFR50(A), RG 1.47). The power to operate safety-class instrumentation should meet the requirements of Class 1E Electric Power Systems (IEEE 308).

Vacuum Vessel Penetrations

For vacuum vessel containment penetrations, each line that is part of the vacuum vessel pressure boundary and that penetrates the vacuum vessel should be provided with isolation valves, unless it can be demonstrated that the containment isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis. A simple check valve should not be used as the automatic isolation valve outside containment. Isolation valves outside containment should be located as close to containment as practical and upon loss of actuating power, automatic isolation valves should be designed to take the position that provides greater safety. The power to operate isolation valves should meet the requirements of Class 1E Electric Power Systems (IEEE 308).

Ventilation and Exhaust System Criteria

Confinement Systems

The design of a vacuum vessel confinement ventilation system should ensure the ability to maintain desired airflow characteristics when personnel access ports or hatches are open. When necessary, air locks or enclosed vestibules should be used to minimize the impact of this air flow on the ventilation system and to prevent the spread of airborne contamination within the facility. The ventilation system design should provide the required confinement capability under all normal operations and design basis accidents with the assumption of a single failure in the system. If the maintenance of a controlled continuous confinement airflow is required, electrical equipment and components required to provide this airflow should be supplied with safety-class electrical power and provided with a backup power source. Air cleanup systems should be provided in confinement ventilation exhaust systems to limit the release of radioactive or other hazardous material to the environment and to minimize the spread of contamination within the facility as determined by the safety analysis. Guidance for confinement systems is included in DOE 6430.1A (b).

Containment Systems

For containment systems, RG 1.140 presents guidance for design testing and maintenance for exhaust systems air filtration that is acceptable to the DOE. As with the confinement systems the basic criteria are based on the As Low As Reasonably Achievable (ALARA)As Low As Reasonably Achievable (ALARA) concept given the present state of technology. 10CFR50(I) presents specific methods and evaluation criteria that are acceptable to DOE in implementing ALARA with respect to exhaust systems from a containment system.

Inspection

Components should be designed to permit periodic inspection and testing of important areas related to the intended safety function to assess their structural and leak tight integrity. There should be an appropriate material surveillance program.

RECOMMENDED DESIGN PRACTICE

Windows

In the analysis of the windows, the condition of the edge restraint is important. It is recommended that it be assumed that the window is simply supported at the edges, since this is a more conservative approach (Robinson). However, the weak point in the window may be the edge glass-to-metal braze. The braze must be analyzed for stress with the fixed-edge assumption. All calculations should be based on the modulus of rupture which is equal to the ultimate tensile strength/1.75. Factors of safety lose meaning for glass, because subsurface imperfections can cause failure below the expected tensile strength. Therefore, a factor of safety of 10 on the modulus of rupture is recommended. Windows should be designed to minimize the risk of cracking due to a water leak onto the hot disc. This can be accomplished by providing an inner sacrificial disc with the main sealed disc on the outside. The connecting inner space is vented to the vacuum by a small hole. This hole would allow vacuum pump down but would prevent a water leak from reaching the outer window. (Caldwell 89)

Bellows

Double bellows with a vacuum-tight inner space are recommended. See the Standards of the Expansion Joint Manufacturers Association, 6th Edition, 1885.

Ceramic Breaks

Ceramic breaks are used to insulate electrical lines that penetrate the vacuum boundary or to insulate attached piping that is connected to external equipment at a different potential or ground. Where possible, ceramic breaks should be designed to be shielded from direct line-of-sight with the plasma or potential spray from rupture of coolant lines.

Ceramic breaks are used on radio frequency (RF) antennas to isolate inner and outer coaxial conductors at the vacuum boundary. The volume outside of the vacuum boundary contains a pressurized gas. These RF ceramic breaks are subject to voltage breakdown which could cause local melting of the coax and could lead to a breach of confinement or even a water leak. Ceramic breaks should be located away from where the coax is cooled. A breach in the ceramic break would allow pressurized gas into the vacuum vessel and tritium into the coax and through the transmission lines all the way back to the power supply. If the vacuum boundary is defined as a confinement system, then the use of redundant ceramic breaks is recommended which reduces the possible leak rate to what is determined acceptable by the facility safety analysis. If a vacuum vessel functions as a containment, which is a more stringent requirement, then containment of the RF/vacuum vessel interface could extend along the transmission line back to the power supply.

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SECTION I REFERENCES

10CFR50 (A)	10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," specifically: GDC 1, 13, 19, 20, 22, 23, 24, and 64.
10CFR50 (I)	10 CFR Part 50, Appendix I.
10CFR50 (J)	10 CFR Part 50, Appendix J, "Primary Reactor Containment Leakage Testing for Water-cooled Reactors."
ASME 93	ASME Boiler and Pressure Vessel Code, 1992 Edition with 1993 Addenda.
Caldwell 89	Design Features of the JET Vacuum Enclosure for Safe Operation with Tritium, C. J. Caldwell-Nichols, E. Usselmann; IEEE Thirteenth Symposium on Fusion Engineering, October 1989, Knoxville, TN, p.716.
DOE-STD-1020-94	DOE-STD-1020-94 DOE Standard, "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities," April, 1994.
DOE 6430.1A (a)	Division 13 of DOE Order 6430.1A, "General Design Criteria," 1989.
DOE 6430.1A (b)	DOE 6430.1A, Section 1550.99, "Special Facilities," 1989.
DOE 6430.1A (c)	DOE Order 6430.1A Section 1328-7.1, "Fusion Test Facilities," 1989.
IEEE 308	IEEE Std 308 "Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Equipment," 1991.
IEEE 603	IEEE-603, " Criteria for Safety Systems for Nuclear Power Generating Stations," 1991.
NET 93	Next European Torus Predesign Report, Fusion Engr. and Design 21, pp. 335-338 (1993).
NUREG-0800	Chapter 7.1 of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," July 1981.
NUREG/CR-4961	Summary of Hydrogen-Air Detonation Experiments, NUREG/CR-4961, May 1989.
RG 1.140	USNRC Regulatory Guide (Reg. Guide): 1.140.
RG 1.47	USNRC Regulatory Guides (Reg. Guides): 1.47, "Bypassed and Inoperable Status Indication for Nuclear Power Plant Safety Systems," May 1973 .

RG 1.75	USNRC Regulatory Guides (Reg. Guides): 1.75 Rev. 2, “Physical Independence of Electric Systems,” September 1978.
RG 1.97	USNRC Regulatory Guides (Reg. Guides): 1.97, Rev. 3 Instrumentation for Light Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident,” May 1983.
Robinson 80	James Robinson, “Design of Viewing Windows for Controlled-atmosphere Chambers,” ORNL/TM-6864, 1980.
Smolik 91	G. R. Smolik, B. J. Merrill, S. J. Piet and D. F. Holland, “Evaluation of Graphite/Steam Interactions for ITER Accident Scenarios,” Fusion Technol. 19, pp. 1342-1348 (1991).
Smolik 92	G. R. Smolik, B. J. Merrill and R. S. Wallace, “Implications of Beryllium: Steam Interactions in Fusion Reactors,” J. Nuclear Material 191-194, pp. 153-157 (1992).

SECTION II

EX-VESSEL SYSTEMS

MAGNET SYSTEMS

Description

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

Recommended Design Practice

The dielectric strength of the insulation should be provided either by materials with an intrinsic dielectric strength, or by materials tested before assembly onto the magnet.

The mechanical integrity of the magnets should not depend on the shear strength of the insulating materials or the shear bond between insulation and structural materials.

Since leaks at coolant connections are a common cause of magnet faults, such connections should be kept away from mechanical load paths, placed outside the winding pack and, as far as possible, in regions where some access is, in principle, possible for inspection or repair.

Manufacturing can allow many faults to occur. Machining chips left in the coil slowly abrade insulation and then cause a failure after some years of machine operation. Very strict tests to determine the cleanliness of finished units should be performed.

CRYOSTAT

Description

The cryostat is a metal chamber surrounding the fusion device which provides a thermal barrier to conduction and thermal radiation between the superconducting coils and other cold structures and the rest of the facility. It may also serve as the biological shield for radiation from the tokamak. The chamber is usually cylindrical with a top and bottom. There are usually large penetrations in the top, bottom, and sides of the cryostat, primarily for access to the vacuum vessel and magnets for maintenance and inspection. The cryostat may be double-walled with an evacuated or filled annulus. The cryostat itself is usually evacuated and it may be lined with cryogenic panels or insulating material to reduce radiant heat transfer.

General Recommendations

For large DT fusion facilities the cryostat volume may be of order 10,000-30,000 m^3. This volume is a significant fraction of the internal volume of a fission reactor containment vessel and it may be appropriate to design the fusion cryostat under the rules for metal containment structures rather than designing it as a pressure vessel. Double bellows with a vacuum tight interspace are recommended.

CONFINEMENT

General

Confinement/HVAC systems include structures, systems, and components designed to serve as barriers against the spread or uncontrolled release of radioactive or other hazardous materials throughout the facility or to the environs.

The facility confinement strategy may consist of successive confinement barriers based on the hazards present. The successive barriers are generally referred to as primary, secondary, tertiary, etc. and are defined by the facility safety analysis. Primary confinement is often the function of the vacuum vessel, cryostat, or system piping, but may be the function of ex-vessel structural barriers and process enclosures such as gloveboxes, piping, tanks, and ductwork.

Secondary confinement consists of building structural elements and associated ventilation systems that confine any potential release of hazardous materials from the primary confinement system. This system includes the operating area boundary and the ventilation system and associated air cleaning systems serving the operating area. Penetrations of the secondary confinement barrier are generally provided with positive seals to prevent migration of contamination out of the secondary confinement area.

Tertiary confinement consists of building elements and associated exhaust system of the process facility. This is often the final barrier to release of hazardous material to the environment. Tertiary confinement surrounds the secondary confinement with space which is controlled but not expected to become contaminated.

Ventilation/HVAC

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

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

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

Safety-class systems and components should be designed per ASME AG-1 (ASME 93c) or a comparable code or standard which considers the safety function(s) of the particular system or component (ASME 89a, ASME 89b). Non-safety-class systems and components should be designed per codes and standards used for industrial and commercial grade applications.

Design Considerations

Ventilation systems

1. The ventilation systems should be designed so that air flows from the cleaner areas with less potential for contamination to the potentially more contaminated areas.

2. The ventilation system should be designed so that the system parameters which are important to operational and nuclear safety can be monitored and if necessary tested. This includes but is not limited to pressure, temperature, air flow, filtering efficiency, environmental releases, etc.

3. The design of the ventilation system should ensure that each of the following design parameters can be met:

   a) Required differential pressures between confinement barriers

   b) Required air change rate to maintain concentrations of airborne radioactivity and other hazardous substances at or below acceptable levels.

   c) Required temperature and humidity conditions

4. The ventilation system should be capable of isolating released tritium gas (or other radiologically hazardous gas) in the event of a breach of the confinement system. In addition the system should be designed to limit potential releases during normal and accident conditions. The ventilation system should be designed to control the concentrations of other radiological, toxic and explosive substances below unacceptable levels.

5. The ventilation system should be capable of monitoring routine as well as accident releases to the environment through all possible discharge paths.

6. The resultant leak-tightness of the confinement zone pressure boundary should be considered in the design. Utilization of air locks to achieve the required leak-tightness between confinement/containment zone boundary interfaces should be considered. The pressure boundary of any confinement zone should have sufficient leak-tightness so that contamination control is achieved without excessive in-leakage.

Structural Design Codes

General design criteria for all DOE facilities is given in the DOE Order 1020. Requirements for the environmental, safety and health protection are given in the DOE Order 5480.4. Requirements for natural phenomena hazards (NPH) mitigation are given in the DOE Order 5480.28 with the accompanying DOE Standards 1020 and 1021. Although DOE 5480.28, DOE 1020 and DOE 1021 are for NPH they provide a baseline to be extended to fusion related SSCs.

General Safety Design Guidance

The confinement system design should establish the features which minimize the spread of both gaseous and particulate contamination throughout the facility. The confinement systems discussed here are those that are beyond the boundary of the vacuum vessel and its ancillary systems.

In order to establish the confinement areas for the facility outside the vacuum vessel, a safety analysis considering normal and accident conditions should be performed. The resultant safety classification of confinement zones from the safety analysis should be the basis for determining the ventilation system design requirements as well as the architectural/structural requirements for the respective confinement areas. (Burchsted 76)

The confinement systems should be divided into the following confinement systems as necessary to support the safety analysis:

1. The ex-vessel primary confinement system should consist of structural barriers and process enclosures such as gloveboxes, piping, tanks and any associated ductwork and their associated ventilation and air cleaning systems that are required to prevent the release of hazardous material to areas beyond the confinement boundary. In addition, credible breaches in the primary confinement barrier should be compensated for by provision of adequate inflow of air or safe collection of hazardous material that escapes the confinement. This is accomplished by multistage HEPA filtration of the exhaust or by an equivalent filtering capability. The exhaust ventilation system must be sized to ensure adequate inflow of air in the event of the largest credible breach of confinement.

2. The secondary confinement system should consist of the walls, roofs and associated ventilation systems that confine any potential release of hazardous materials from the primary confinement system. This system includes the operating area boundary and the ventilation system and any associated air cleaning systems serving the operating area. The ventilation system should be designed to ensure proper airflow direction and velocity to counteract the largest credible breach in secondary confinement barrier. Penetrations of the secondary confinement barrier should be provided with positive seals to prevent migration of contamination out of the secondary confinement area.

3. The tertiary confinement system should consist of the walls, floor, roof and associated exhaust system of the process facility. It is the final barrier to release of hazardous material to the environment. This level of confinement should be provided for the space bounding the secondary confinement which is not expected to become contaminated.

Potential System Safety Functions

The confinement systems along with their associated HVAC systems should be designed to provide the following functions for the facility:

1. Normal Operation:

    a) Prevent and control the spread of gaseous and particulate contamination. This is accomplished by controlling confinement zone differential pressures as well as providing sufficient air exchange rate within the confinement zones. (ASHRAE, ASHRAE 91, DOE 6430.1A)

b) Monitor the contamination levels in the zones to ensure personnel radiological safety is maintained. (ASHRAE 91, DOE 5480.11, DOE 6430.1A) In addition, any potential for airborne toxic and corrosive products in the atmosphere that may compromise personnel safety or equipment operability should be monitored and controlled.

c) Monitor the radiological releases to the environment to ensure the continued effectiveness of the confinement system to capture and retain radioactive contaminants before they are exhausted to the environment. (ASHRAE 91, DOE 5480.11, DOE 6430.1A)

d) Maintain the required temperature and humidity conditions in the zone. (ASHRAE 91)

2. Maintenance:

   Provide the necessary ventilation system functional capabilities to allow for any intentional breaches of the confinement system that are required to perform maintenance on any portion of the system. (ASHRAE 91)

3. Design Basis Accidents:

   a) Prevent and control the spread of gaseous and radioactive contamination during and following all credible design basis accidents. (ASHRAE, ASHRAE 91, DOE 6430.1A)

   b) Monitor the radiological releases to the environment during and following any credible design basis accident. (ASHRAE 91, DOE 5480.11, DOE 6430.1A)

   c) Maintain temperature, pressure and humidity conditions for the equipment required to operate during and following a DBA. This includes the ability to rapidly remove heat in worst case loss of coolant accident condition.

Safety-Class Design Standards and Criteria

The safety analysis to determine the safety system classification of the confinement systems and their associated HVAC systems should be based on the requirements given in DOE-STD-1027-92 or equivalent. Ventilation systems that are classified as “safety class” should be designed to operate in conjunction with their associated physical barriers to limit the release of radioactive or other hazardous material to the environment. In addition they should be subject to appropriately higher quality design, fabrication and test standards and codes to increase the reliability of the system and allow credit to be taken for their functional capability in a safety analysis. In addition the safety analysis should determine the appropriate level of redundancy, diversity, independence and the need for emergency power to ensure safety system function capability during and following all credible postulated design basis accidents.

Structural

1. Design Approach

The structural design philosophy should be similar to that given for the design and evaluation of DOE facilities for NPH in DOE Order 6430.1A, (DOE 6430.1A), with its supplemental Standards, (DOE 1020, DOE 1021). The design procedure combines probabilistic and deterministic approaches and is summarized below:

a) Establish performance category based on the desired target probabilistic performance goal, expressed as mean annual probability of exceeding the acceptable behavior limits.

b) Develop loads from hazards assessment by specifying mean annual probabilities of exceeding the acceptable limits.

c) Use deterministic design and evaluation procedures for the resulting load combinations, to achieve performance goals and to provide a consistent and appropriate level of conservatism. The design procedures conform closely to industry practices using national consensus codes and standards. The procedures extend to methods of analyses and to criteria to assess whether or not the computed response is within acceptable behavior limits.

d) Implement design detailing provisions

e) Maintain appropriate quality assurance and peer review.

Detailing, quality control and peer review are emphasized because:

a) Inelastic energy absorption capacity depends explicitly upon ductility in the structural behavior.

b) New technology may involve judgments beyond routine engineering.

The structural design should be based on a graded approach. A graded approach is one in which various levels of design, evaluation and construction requirements of varying conservatism and rigor are established ranging from common practice for conventional facilities to very rigorous practices used for more hazardous facilities. The motivation for the graded approach is that it enables design or evaluation to be performed in a manner consistent with their importance to safety, importance to mission, and cost.

2. Design Basis Loads

Design basis loads are derived from the internal and external events identified as the PIE (Postulated Initiating Events) in the safety analysis. Loads and the combinations thereof should envelop loads considered in structures per ANSI 83.

Design basis loads arise from different categories: normal operations, unlikely events, and extremely unlikely events. The performance classification incorporates the probabilities of these events. Loading combinations should be generated from the bounding sets of these events identified in the safety analysis.

3. Methods of Analysis

The method of analysis should depend on the performance category and loads being considered. Some of the methods are described in (ASCE 80). Elastic system analysis methods may be adequate for lower performance categories whereas for higher performance categories inelastic analysis methods nay be required. Guidelines to seismic analysis are available in (DOD 86). Dynamic seismic structural analysis may be performed for predicted ground motions based on geotechnical site specific information including variability using response spectra or time history. For large embedded structures, soil structure analysis may be considered.

4. Acceptance Criteria

For lower performance categories, and for normal operations damage should be limited so that hazardous materials can be controlled and confined, occupants are protected, and functions are not interrupted. Thus damage should typically be limited in confinement barriers, ventilation systems and filtering, and monitoring and control equipment.

For the higher performance categories, and for unlikely events, structures should be permitted to undergo limited inelastic deformations without unacceptable damage when subjected to transient loads. Energy absorption factors may be used to achieve appropriate conservatism in the design or evaluation process. Stability and other post yield behavior criteria should be met.

For extremely unlikely events risk analysis should be performed to determine the extent of permissible damage.

In design approaches where ductility and inelastic energy absorption are taken benefit of, attention should be paid to the design details and quality assurance.

For all performance categories deformations expected from design load combinations should be able to be withstood. If concrete is used as a pressure boundary, inelastic energy absorption should not be considered.

5. System Interaction Effects

Any SSC whose structural failure could impact the function of SSC of a higher performance category SSC are evaluated for interactions. To account for adverse interactions, a determination of failure probability of an SSC given a postulated failure in the lower performance category is required.

HVAC

The application of design criteria from codes and standards for systems and components should be applied in a graded approach relative to the significance of the safety function. For safety-class systems and components, the design requirements of ASME AG-1 (ASME 93b) or a comparable code or standard which considers the safety function(s) of the particular system or component should be applied (ASME 89a and ASME 89b). For non safety-class systems and components, codes and standards for industrial and commercial grade application should be applied. Some of the major HVAC components that should have a graded approach application of codes and standards are fans, dampers, ductwork, filters and filter housings and instrumentation and controls.

Potential Safety Functions

The potential safety functions for confinement systems and their associated HVAC systems are:

1. Provide barriers against the release or spread of gaseous and particulate contamination during normal and off-normal conditions (ASHRAE , ASHRAE 91 and DOE 6430.1A)

2. Provide the necessary ventilation system functional capabilities to control differential pressures such that air flows from cleaner areas to potentially more contaminated areas during normal and off-normal conditions. (ASHRAE 91)

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

4. Maintain the required ambient conditions within confinement, e.g. temperature, pressure, humidity, and concentrations of radiological, toxic, corrosive or explosive substances, to protect personnel and ensure the capability of personnel or equipment to perform safety functions. (ASHRAE 91)

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

6. Provide instrumentation and/or testing and surveillance to monitor the condition and capabilities of the confinement system, the ambient conditions within confinement, and the effluents from confinement to the environs. Applicable items should be monitored during normal and off-normal conditions as required to ensure and verify safety function. In addition potential airborne contaminants or corrosive agents that may compromise the ability of personnel or equipment to perform safety functions should be monitored and controlled. (ASHRAE 91, DOE 5480.11 and DOE 6430.1A)

Safety-Related Design Guidance

System Boundary

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

Structural Design

Design basis loads are derived from the internal and external events identified as the PIE (Postulated Initiating Events) in the safety analysis. Loads and the combinations thereof should envelope loads considered in structures per ASCE 93.

The methods of analysis depend on the performance category and loads being considered. Some of the methods are described in ASCE 80. Elastic system analysis methods may be adequate for lower performance categories whereas for higher performance categories inelastic analysis methods may be required. Guidelines to seismic analysis are available in DOD 86. Dynamic seismic structural analysis may be performed for predicted ground motions based on geotechnical site specific information including variability using response spectra or time history. For large embedded structures, soil structure analysis may be considered.

Capacity calculations, DOE 1994a, depend primarily on the national consensus code, UBC 94. For reinforced concrete structures DOE 1984 and ACI 318 provide the criteria for safety-class and other building structures, respectively. For steel structures AISC Codes, ANSI 84 and AISC 86a provide the criteria for safety-class and other building structures. AISC 86b is an alternate for AISC 86a if load and resistance factor design procedure is used. ASME Code (ASME 93a) should be used for equipment and components, and ASME Code (ASME 93b) for piping.

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

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

For the higher performance categories, and for unlikely events, structures should be permitted to undergo limited inelastic deformations. Energy absorption factors may be used to achieve appropriate conservatism in the design or evaluation process. Stability and other post yield behavior criteria should be met.

For extremely unlikely events risk analysis should be performed to determine the extent of permissible damage.

INSTRUMENTATION AND CONTROL SYSTEMS

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

General Safety Design Guidance

The purpose of this section is to present the principal design criteria for the Instrumentation and Control (I&C)Instrumentation and Control systems and components. The I&C system design should be separated into the basic control system and the safety system. The separation of these I&C system functions is necessary to ensure that once a safety system is called upon the control function will not stop or impede the proper safety system function execution. Conversely, the safety system must not interfere with the operation of the control function, when the facility or system is operating within the normal design envelope. The basic control and the safety systems analysis and design should ensure independence of system functions and displays with sufficient analytical margin, physical separation, and electrical isolation to enable each system to support the others function without interference under failure, accident, or normal operating conditions. To ensure that these basic principles are properly addressed, the I&C analysis and design efforts must be properly integrated between control and safety system design and with the design and analysis of the facility systems (FS) they are intended to service.

I&C System Analysis and Design

The design of the I&C systems should be integrated with the design of the facility systems (FS) to account for both normal and off normal operation and to prevent or mitigate postulated accidents. The integration of the facility systems and I&C system design functions should address:

1. the capability of I&C system to provide the proper measuring, detection, and control functions, including adequate control and safety margins,

2. the necessary taps, ports, and penetrations to obtain the most desirable measurement parameters for control and safety function actions,

3. a central control room with sufficient displays and command features to allow monitoring and response to all accident Postulated Initiating Events (PIE), except those that are highly unlikely,

4. automatic initiation of all safety function actuations which are not assigned to the operator,

5. feedback from control function actions to determine the effect on the process,

6. a system of interlocks and permissives to reduce the likelihood of erroneous operator action,

7. a system of controlled by-passes to permit deliberate operator action in abnormal unanticipated situations,

8. manual initiation and control for safety function actions not appropriate for automatic initiation or for chosen automatic action interruption or adjustment capabilities.

Control System

Basic Control systems should be designed with sufficient margin to ensure that the design conditions are not exceeded, during any condition of normal operation including anticipated operational occurrences and transients.

The Basic Control System should be capable of maintaining the normal operating parameters and should provide all operator interface (indication, alarm, and data collection), during normal operation and anticipated operational occurrences and transients that may be created by postulated initiating events. A Task Analysis should be conducted to determine which control functions are to be assigned to the operator and which functions are to be machine (automatic action) assigned.

The control system design should provide for operator control and monitoring of essential facility systems in a central control room. The control room, as well as supporting I&C system local control and monitoring panels, should be designed for man/machine interface and local area or room habitability considerations. This design should consider control and monitoring functions for conduct of operations under both normal operation and postulated accident scenarios.

Safety System

The Safety System should be capable of maintaining the facility within the design basis safety analysis limits and provide operator interface (indication, alarm, data collection, and any necessary manual interaction), during accident or off normal conditions that may be created by any PIE.

A safety system task analysis should be conducted to determine which safety functions are to be assigned to the operator and which safety functions are to be machine (automatic action) assigned. The operator should be provided with manual safety action initiating capability for all safety functions and with feedback information to confirm the occurrence of the proper actuation and completion of the selected safety function.

Safety Systems should be designed to fail safe on loss of motive force or power. In addition, safety systems should be designed to meet single failure criteria. The system should be designed to preclude failure of a component or subsystem from preventing completion of the required safety function. Diversity in the monitoring of the parameters and actuation of the control systems should be a basic principle of the safety system design.

To prevent a failure in the basic control system from degrading the operation of the safety system, isolation should be provided between any interface of the basic control and safety systems and separation should be provided and maintained between these systems.

Instrumentation

The process variables (parameters) that are selected to provide inputs to the I&C system should be those which characterize the relevant safety and operational status of the monitored systems and barriers. This selected set of variables must be analyzed to determine their adequacy to measure and provide for the necessary control and safety functions. The analysis should include the measurability, variability, and response action time capability of the process parameter variables and the operational demands and limitations placed upon the control or safety system design by these parameter variable properties.

The instrumentation selected to measure a process variable should directly measure the variable, instead of some secondary parameter. Instrumentation should be analyzed to determine if its reliability, accuracy, and response time characteristics satisfy the control or safety system needs for all required operating conditions.

Instrumentation should be provided to monitor variables of the facility systems over their anticipated ranges for normal operation, anticipated operational transients and occurrences, and for postulated accident conditions to ensure adequate safety and design margins are maintained.

Potential System Safety Function

The potential safety functions for the I&C Systems are:

1. Monitor and indicate by alarm off normal facility systems operating parameters or transient conditions.

2. Display parameter values necessary for operator response to off normal systems operating parameters or transient conditions.

3. Operate permissive or interlock functions designed to prevent facility systems from:

   a) entering into off normal operating parameter or transient conditions, or

   b) allowing an existing transient condition to continue its off normal excursion.

4. Operate automatically to:

   a) respond to off normal or accident conditions,

   b) move the facility toward or attain a safe operational state, or

   c) mitigate the consequences of the off normal or accident conditions.

5. Enable operator manual initiation of safety related control actions or bypasses.

6. Detect and indicate parameters necessary to ensure the integrity of designated defense in depth barriers. These parameters may include but are not limited to:

   a) indicators of radioactive, toxic, or other material leakage or migration to detect breach of a barrier,

   b) temperature conditions indicative of trends toward undesired material conditions (e.g., nil ductility considerations or high-temperature loss of strength),

   c) over or under pressurization detection for facility systems, or

   d) chemical or gas mixture potential flammability or deflagration detection.

7. Monitor safety barriers and provide for response or mitigation action designed to prevent the breach of a barrier or to control the effect of barrier breach.

8. Post accident monitoring or control functions necessary for indication, data logging or required continued systems operations.

9. Measure, display, and alarm conditions approaching or exceeding parameter limits defined by Technical Specification Requirements or Technical Standards.

Safety Related Design Standards and Criteria

The following listed standards and criteria provide a cohesive philosophy and set of principles appropriate for application to the analysis and design of I&C Systems and components for fusion devices. The concepts and principles contained in these documents, including referenced standards, should be applied, using the necessary adjustments required to account for any specific fusion technology special considerations.

These standards and criteria cover both component level and system level design feature considerations for safety systems. Component design features necessary for safety systems include attributes such as equipment qualification, maintainability, failure criteria and testability. In addition to these attributes, the system level design features should include but not be limited to reliability, independence, redundancy, human factors and separation.

Each of the standards listed below form a portion of the overall design philosophy for I&C safety systems. As such, the design intent of all of these standards should be taken as a whole for the analysis and design of I&C systems.

IEC 964 (1989-03)

Design for control rooms of nuclear power plants.

IEEE 603 Standard Criteria for Safety Systems for Nuclear Power Generating Stations

IEEE 323 Qualifying Class IE Equipment for Nuclear Power Generating Stations

IEEE 352 IEEE Guide for General Principles for Reliability Analysis for Nuclear Power Generating Station Safety Systems

IEEE 577 IEEE Standard Requirements for Reliability Analysis in the Design and Operation of Safety Systems

IEEE 420 IEEE Standard for the Design and Qualification of Class IE Control Boards, Panels, and Racks used in Nuclear Power Generating Stations.

IEEE 379 IEEE Standard Application of the Single Failure Criterion to Nuclear Power Generating Station Safety Systems

IEEE 384 IEEE Standard Criteria for Independence of Class 1E Equipment and Circuits

IEEE 338 IEEE Standard Criteria for Periodic Surveillance Testing of Nuclear Power Generating Station Safety Systems

ISA 67.02 S67.02.01: Nuclear Safety-Related Instrument Sensing Line Piping and Tubing Standard for Use in Nuclear Power Plants

ISA 67.04 S67.04--Part I: Setpoints for Nuclear Safety-Related Instrumentation-- ANSI/ISA-1994

RP67.04--Part II: Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation-1994

ISA 67.06 S67.06: Response Time Testing of Nuclear Safety-Related Instrument Channels in Nuclear Power Plants-- ANSI/ISA-1984

ANSI/ANS 3.8.5-1992

Criteria for Emergency Radiological Field Monitoring, Sampling, and Analysis

ANSI/ANS 3.8.6-1995

Criteria for Conduct of Offsite Radiological Assessment for Emergency Response for Nuclear Power Plants

IEEE 730 Software Quality Assurance Plans

IEEE 829 Standard for Software Test Documentation

IEEE 830 Guide for Software Requirements Specifications

IEEE1012 Standard Software Verification and Validation Plans

IEEE 1016 Recommended Practice for Software Design Descriptions

IEEE 1042 Guide to Software Configuration Management

IEEE 1063 Standard for Software User Documentation

Design Considerations

Diversity

In the selection of the sensors and measuring systems for the in-vessel and near vessel parameters, multiple diverse technologies should be implemented since these instrument components will be exposed to harsh environments (potential radiation exposure, magnetic fields, temperature gradients, ion pulses, etc.) Unexpected failure mechanisms within a single measurement technology could lead to erroneous control or safety actions. Provision for the use of diverse measurement technologies in the design would provide alternative sensing capabilities and reduce the possibility of failure to detect and initiate a safety function due to common mode or common cause failures.

Graded Approach to Defense In Depth

The failure consequence and frequency of the PIE should be considered in the determining the degree of the redundancy and diversity required in the I&C system. Anticipated operational events of high consequence should require an analyzed probability of successful action. This analysis should include the presence of an undetected failure in the safety related I&C system equipment necessary to accomplish the required safety function. Events of lower frequency and/or consequence may be shown to be mitigated by less rigorous analysis and subsequently less rigorous I&C equipment requirements.

Response Time Requirements and Margins

Facility system designs should be sufficiently robust, to withstand a process perturbation, without damage or degradation, until the I&C system can detect the change in the monitored parameter, command a change in the controlled variable and have that system return to the safe or process normal state. The margin (allowed variation of the process parameter for the allowed time) should be sufficient for the I&C system to detect the change in the process and respond within some defined degree of internal delay or failure.

The Basic Control System should be reliable and exhibit adequate response time to maintain normal fusion operations without unnecessary challenges to or actuation of the safety system. These necessary attributes should be addressed by performance of sufficient setpoint and instrumentation uncertainty and response time analysis to ensure adequate margins exist between normal control and safety system setpoints and limits.

Qualification

Safety related I&C components should be qualified to perform their intended safety function for the life of the component. Qualification should address operational requirements and environmental requirements. Qualification for operational conditions should consider maintenance, testing, and operation during all operational modes, such as, normal, off normal shutdown, and postulated accidents. Qualification for environmental conditions should be limited to normal operational environments, except for those components and systems that must remain operable during and/or after an accident. Those I&C systems and components required to remain operable during and/or after an accident should be environmentally qualified for the conditions they are subjected to during the time it takes to complete their safety functions.

Seismic qualification of I&C systems and components should be considered for those items that are required to maintain their structural integrity and operability during and after a design basis earthquake.

Qualification requirements (if any) for systems credited in Design Basis Events should be explicitly stated in the overall functional requirements. Additional Graded Approach guidance should be provided to ensure consistency across Facility System Boundaries. This is important to I&C since the I&C System crosses these boundaries.

Human Factors

A human factors analysis of the control room or local I&C panel operator interfaces with console or panel controls, displays, indications and alarms should be performed. This includes the interface of control room functions with local panel operations capability and the interface with digital system displays and control and response capabilities.

Testability and Maintainability

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

The I&C system should include maintainability considerations in the design process. These considerations should include ease of replacement of components, modules, or subsystems, the access availability of the equipment with consideration for personnel hazard conditions (radiation, magnetic fields, temperature, proximity to steam piping or other stored energy conditions, etc.), and the provision for sufficient bypass or disable capability and test point access to allow for the valid performance of necessary and adequate testing.

Power

The I&C power system design should provide for the necessary redundant power sources to ensure that the system will be capable of performing its required function under all normal and postulated accident scenarios. Power sources that should be considered for the I&C system include uninterruptible power sources, critical instrument busses capable of being powered from diesel generator back up power, and battery back up systems.

Control Room Design

The design of the control room should be implemented in accordance with IEC 964 standard guidelines, with the appropriate modifications for fusion versus fission technologies and hazards. The underlying principles of the man/machine interface and functional analysis presented in IEC 964 are appropriate to the design of fusion control facilities.

Adequate radiation and environmental protection should be provided to permit access and occupancy of the control room under accident conditions where the operator monitoring, mitigative or response actions are required during or following an accident.

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

Safety Actuation

Safety function actuation should be sealed in, so that the safety function actuation is maintained even if the logic that initiates the actuation is lost.

Monitoring

Monitoring of after-heat removal after-heat removal (and normal operating heat removal) should include sufficient information processing and displays to present the heat balance and energy transport and verify parameters are within the expected ranges. Higher order logical processing and display may be required to present operators with an integrated picture of the fusion heat removal system. The input sensors, algorithms, software and hardware required for this safety-significant activity should meet appropriate reliability standards.

The inherent robustness of the facility confinement systems should be analyzed (and demonstrated) to show survivability during PIE with the worst case performance of the I&C System. The design basis (or Graded Approach) should specifically describe the requirements for coupling PIE and internal transients; the influence of PIE on parameter measurements, uncertainties and response times should be evaluated for those scenarios requiring coupling of events.

Monitoring of the inventory levels and barrier integrity should address the Postulated Initiating Event of concern. Active detection and venting to expansion volumes must meet the response times assumed in the analysis criteria. Passive designs for channeling coolant to the expansion volume should be considered.

TRITIUM SYSTEMS

General Safety Design Criteria

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

1. Segmentation of the tritium inventory such that release of all tritium from the single largest segmented volume has acceptable consequences,

2. Confinement barriers[1] to reduce tritium environmental release to an acceptable level,

3. Materials and equipment which are tritium compatible and minimize exposure of tritium to oxygen, and

4. Cleanup systems to recover gaseous tritium released within any confinement barrier or to process streams exhausting to atmosphere.

Tritium system functions should be designated safety functions if they are credited in the facility safety analysis in order to meet prescribed safety criteria. Systems or components needed to perform safety functions should be designated safety-class systems or components. Components which do not perform safety functions but whose single failure causes the failure of a safety function should be designated safety-class components.

Generic System Description

The following sketch illustrates the tritium system consisting of five major functional areas within multiple confinement barriers:

Primary confinement, a sealed system rated for design maximum pressure and low leak rate, is the

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[1] This document considers the tritium containment system to be a type of confinement. Sealed high-integrity process equipment and piping provide the containment system, for vacuum and pressure conditions, and constitute the primary confinement barrier. The secondary confinement barrier consists of gloveboxes and cabinets which house the primary confinement (containment) system. To complete the secondary confinement, process piping between glove boxes or cabinets are within a jacket enclosure which seals to the glovebox or cabinet. Additional sealed cabinets or rooms may extend the concept to tertiary, quaternary or higher orders of confinement in accordance with the facility's safety analysis.

primary barrier for tritium. Although primary confinement is sealed and leak tight, tritium is an elusive molecule and small tritium leaks will occur inevitably. Secondary confinement, a system with controlled outflow, collects the leaked tritium in a recirculating nitrogen (or inert) gas stream for subsequent recovery of the tritium. Secondary confinement operates at a subatmospheric pressure, by virtue of a small purge stream to the exhaust stack, and thus is unlikely to leak tritium to the tertiary or higher order confinements.

Personnel may not enter primary confinement or secondary confinement zones during normal operation. They may enter for maintenance activities, and only after tritium removal is complete for the affected systems.

Personnel may routinely occupy the tertiary or higher order confinement zones without wearing protective clothing and respiratory equipment. But personal protective equipment (PPE) is available for rapid donning if the safety analysis reveals a credible event wherein tritium enters tertiary or a higher order confinement zone.

The tritium facility's heating and ventilation system (H&V) promotes the confinement concept by maintaining pressure differentials such that air flow is always towards zones with greater contamination potential. In the above sketch, fresh air enters the quaternary zone then flows to the tertiary zone from which it discharges to a stack.

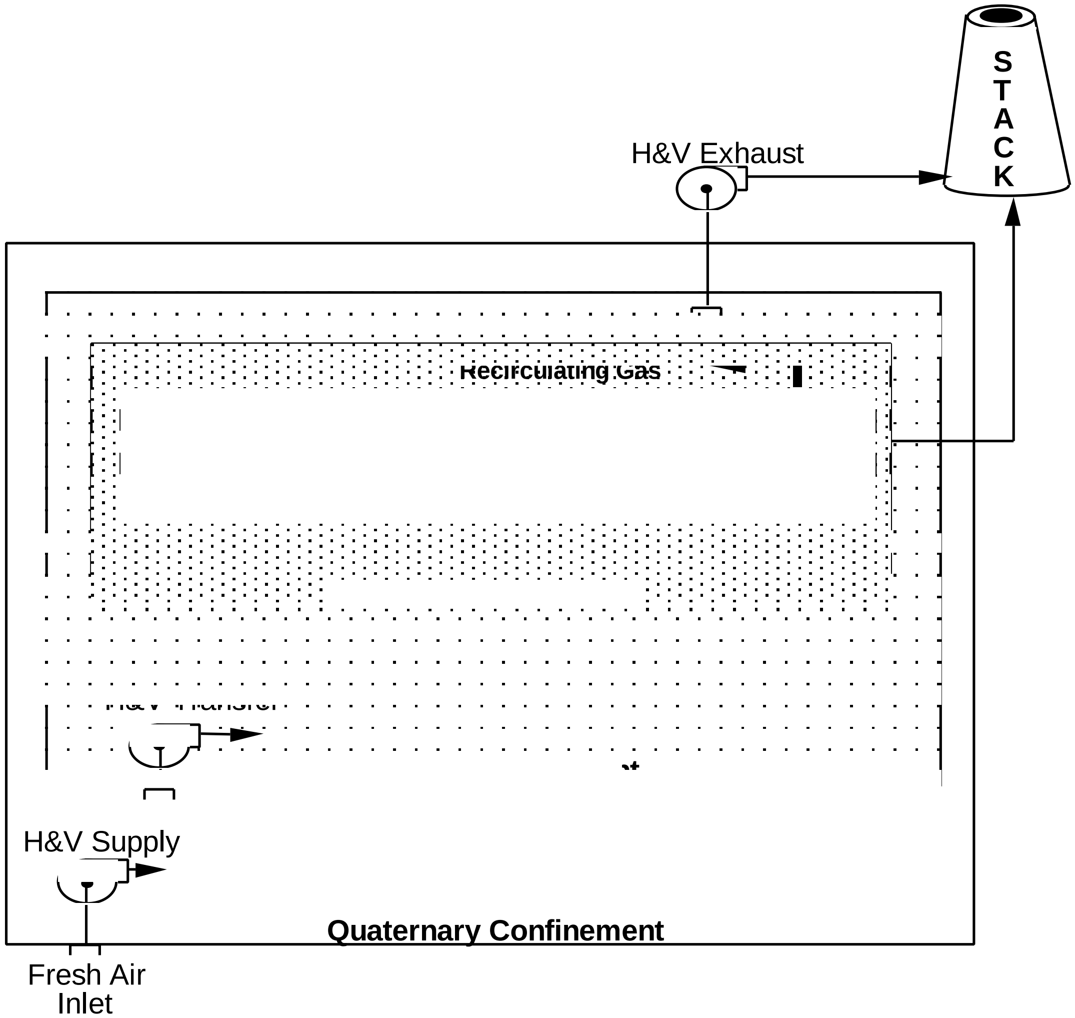

Figure II-1. Tritium confinement scheme.

The function of each major tritium area within primary confinement is as follows:

Tritium Storage

The tritium inventory resides in the storage medium unless it is undergoing transfer, recovery, purification or burning in the fusion machine. The storage medium can be tankage or hydride beds.

Tritium Transfer

The transfer function moves tritium from one part of the primary confinement to another or to the fusion machine vacuum vessel or a pellet process. The transfer motive force can be either residual differential pressure, or active pumping, or thermal cycling of a hydride bed, or all three.

Tritium Recovery

The recovery function recovers the small amounts of tritium that invariably escape from the primary confinement during operations and maintenance. Recovery involves removing tritium and any deuterium or protium isotopes from the secondary confinement volume and holding the isotopes for subsequent processing in the purification function. The recovery process can use zeolite beds or metal hydride beds.

- A primary recovery system operates continuously, and recovers tritium from small leaks occurring during normal operation.
- A secondary recovery operates on demand and provides a greater tritium recovery capacity necessary for large leaks or maintenance operations.
- A purge recovery system maintains the secondary confinement at a subatmospheric pressure by exhausting continuously some of the secondary confinement atmosphere to the environment. The purge system recovers tritium from these exhaust flows.

Tritium Purification

The purification function removes the hydrogen isotopes protium, deuterium and tritium from other gases and then separates the tritium isotopes from protium and deuterium. The purification process can use thermal diffusion columns or cryogenic distillation or a chromatographic process or (preferred) a thermal cycling absorption process. The thermal cycling absorption process uses a palladium-coated kieselguhr[2] hydride bed which, upon temperature cycling, separates tritium from protium and deuterium.

System Cleaning

The cleaning function operates on demand and cleans impurities (suspended solids, oils, moisture, halides, etc.) from the tritium systems. Cleaning uses various detergents, chlorinated fluorocarbons, solvents and water, followed by vacuum drying to $<10^{-2}$ torr. Removal of impurities is important to prevent stress corrosion cracking of stainless steel and contamination of the fusion machine's vacuum vessel.

Potential System Safety Functions

The potential safety functions for the tritium systems are:

Normal Operation:

1. Provide for primary and secondary confinement barriers that separate tritium from onsite and offsite personnel and the environment. If the safety analysis requires tertiary or higher levels of confinement, the tritium systems should provide the additional barriers. This safety function includes the structures, systems and components necessary to establish the barriers and the power sources necessary to maintain the barrier operation within prescribed safety limits.

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[2] loose or porous diatomite

2. Provide for monitors and signals or alarms dictating a need to isolate or otherwise control a tritium system to prevent monitored system variables exceeding a safety limit. The safety analysis should identify the system variables requiring monitoring, which will normally include system pressure, oxygen inleakage and tritium out leakage from a confinement barrier.

3. Provide for recovery from anticipated off-normal events by providing systems that remove tritium from secondary and greater confinements and from any air stream exhausting a confinement to the environment.

Maintenance:

1. Provide for primary confinement of tritium during maintenance within secondary, tertiary or any greater levels of confinement barriers.

2. Provide for tritium removal, evacuation and cleansing of primary confinement systems prior to breaking the primary confinement barrier for maintenance. This preparation for maintenance will minimize the resultant tritium losses.

Design Basis Accidents:

The safety analysis should specify design basis accidents. Tritium systems design should implement requirements and provide for corresponding safety functions to make the accident consequences acceptable.

A typical frequency for design basis accidents is $P>10^{-6}$/year. The safety analysis will specify the actual frequency. The quantity and form of tritium released during a design basis accident will determine the consequences of the accident. Probability and consequence are the parameters determining risk. The following are potential design basis accidents for tritium systems:

Internal Initiators

1. Tritium fire or detonation

2. Missile or pipe whip resulting from sudden failure of high energy system. This accident has potential for causing a release of tritium and simultaneously disrupting multiple confinement barriers.

3. Human errors

External Initiators

1. Natural phenomena, including earthquakes, hurricanes, tornadoes, floods, tsunami, etc.

2. Aircraft and other missile impact (excluding sabotage).

Beyond Design Basis Accidents:

There are no system safety functions required for beyond design basis accidents.

Beyond design basis accidents include internal and external initiators whose frequency is lower than the design basis frequency limit specified in the safety analysis.

Safety-Class Design Standards and Criteria

For safety-class tritium systems, the following design standards and criteria should apply to the system, structures or components:

Structural

General

The tritium systems boundary is the pressure (or vacuum) confinement barrier afforded by the piping, fittings, vessels, valves, and instrumentation that are wetted on their interior surfaces by tritium. The boundary extends to the first or second isolation valve in system piping to the fusion device's vacuum vessel.

Loads

1. Individual Loads

Tritium systems should withstand the static load, vacuum, normal operating pressure, normal operating thermal load, electromagnetic loads (normal operating and fault), interaction loads from adjacent systems, natural phenomena hazard loads and loads due to missile impact and hydrogen detonation (if these are design basis accidents, see Section IV).

a) Static Load - The static load should include the weight of the equipment identified as constituting the system (or component), and any supported hardware.

b) Vacuum Load - The vacuum load should include forces arising from complete vacuum within the primary confinement barrier. A vacuum of $<10^{-2}$ torr within the primary confinement system is customary for cleansing prior to and following maintenance, inspections, etc.

c) Normal Operating Pressure - Normal operating pressure loads should range up to and include the design pressure of the system or components.

d) Normal Operating Thermal Load - The normal operating thermal load should include temperatures associated with routine processing operations, both cryogenic and elevated, and elevated bakeout conditions required for cleansing prior to equipment removal.

e) Electromagnetic Loads - Electromagnetic loads should include the forces induced as a result of power, instrument and control and eddy currents in the tritium system interacting with magnetic fields of the fusion machine's normal operation.

f) Electromagnetic Loads During Faults - Electromagnetic loads should include the loads induced during abnormal operating events such as control failures, power supply failures, bus opens or shorts, or magnet faults.

g) Interaction Loads - Interaction loads should include the loads imposed on the tritium systems by adjacent systems during normal or fault conditions.

h) Natural Phenomena Loads - Natural phenomena hazard loads should include loads resulting from earthquake, wind, flood, tsunami and seiche. UCRL-15910 provides guideline methods for establishing load levels and for evaluating the response of structures, systems and components to the load levels.

i) Hydrogen Detonation Loads - Hydrogen detonation loads should include the mechanical and thermal effects of tritium, deuterium and protium ignition or detonation, if the safety analysis includes such failure as a design basis accident.

j) Missile Impact Loads - Missile impact loads should include missiles and pipe whip resulting from failure of high energy systems, if the safety analysis includes such failure as a design basis accident.

2. Combined Loads

Table I-1 lists the load combination which the design should consider for normal and anticipated off-normal operations.

Because maintenance involves isolating, depressurizing and evacuating a system, the load during maintenance is the static load only.

3. Cyclic Loads

Tritium systems are subject to thermal and pressure cyclic loadings during normal and anticipated off-normal operation and maintenance. An evaluation should determine if a formal fatigue analysis is necessary. ASME 93a or comparable computational methods provide criteria for the evaluation which should use a conservative analysis for the number of cycles and service life including the expected changes in material properties with time.

Structural Acceptance Criteria

Tritium systems that are safety-class should have design, fabrication, inspection and testing in accordance with a recognized safety-class code such as the ASME Boiler and Pressure Vessel Code. The specific codes and criteria selected should be commensurate with the level of safety required and should have a technical justification.

Tritium systems that are NOT safety-class should have design, fabrication, inspection and testing in accordance with a recognized national consensus code such as the ANSI/ASME Standard B31.3 "Chemical Plant and Petroleum Refinery Piping" (ANSI 93).

Structures, systems and components near a tritium system should be safety-class if their credible failure could impact the safety function of a tritium system.

Deflection Analysis

An analysis of tritium system deflections over the full range of temperatures, vacuums and pressures should confirm no interferences or loss of confinement integrity.

Testing and Inspection

Non-destructive testing and inspection of safety-class welds, vessels, piping and valves should be in accordance with the ASME Boiler and Pressure Vessel Code (ASME 93a). Personnel qualification and weld acceptance criteria should also be in accordance with ASME 93a.

Testing and inspection should occur before initial operations. The hazards associated with testing of contaminated systems, processing of the contaminated test medium, and increased potential for environmental losses of tritium, may impede subsequent periodic testing and inspection. Any system, subsystem, or component, that is determined to require periodic testing and inspection should be identified during the design of that system so that the test requirements are incorporated into the design.

Computational Methods Validation

Computer codes or other computational methods supporting the design of tritium systems should have validation and verification for the range of normal and off-normal operations including design basis accidents. This validation and verification should support the use of the computational method in each intended application.

Materials

Radiation

Materials of construction should be qualified for the lifetime radiation environment. The structural design analyses should use conservative end-of-life properties. If a component's expected lifetime is less than the system's lifetime, design should provide for component replacement.

Radiation environment refers principally to external sources of radioactive energy, but it includes the beta energy of tritium decay also.

Thermal

The structural design analyses should use material properties appropriate for the operating conditions. If no published materials property data exist for a particular operating temperature, tests should establish the material properties at the temperature.

The ASME Boiler and Pressure Vessel Code (ASME 93a) imposes temperature limits for structural designs. For items whose design complies with the Code and whose temperature could exceed the Code's limit, the design analyses should reduce allowable stress to an acceptable value determined by testing the material at the elevated temperature.

Tritium Embrittlement

The structural design analysis should use material properties based on tritium and helium embrittlement for the projected end-of-life.

Penetrations of Confinement Systems

Penetrations should meet the same materials requirements as the penetrated confinement system.

Instrumentation and Controls

Tritium systems design should provide for instrumentation and control to monitor parameters important to the safety function for normal operation and design basis accidents. The safety analysis should identify and the design should implement:

1. Instruments to monitor safety-related variables. Primary confinement will typically provide monitoring for pressure, vacuum, temperature, and the ability to provide batch-based qualitative gas analysis. Secondary confinement will typically provide for tritium detection, pressure (relative to ambient or tertiary confinement), and oxygen level (if secondary has a reduced oxygen atmosphere). Subsequent levels of confinement will provide monitoring abilities commensurate with the hazard anticipated and the operating conditions of the barrier.

2. Controls to maintain measured variables within prescribed limits and to isolate tritium subsystems when necessary for safety reasons.

3. The design for safety-class systems, including their ventilation systems, should incorporate sufficient redundancy and/or diversity to ensure that a single failure will not result in total loss of instrumentation or control for a safety function.

The power supply for safety-class instrumentation and controls should meet the requirements for Class 1E electric power systems (IEEE 308).

The different designs and operating characteristics of fusion facilities limit the amount of specific guidance that these criteria can provide. Existing DOE and NRC design requirements and guidance documents (IEEE 603, DOE 6430.1A, NUREG-0800, 10CFR50(A), USNRC Regulatory Guides (RG 1.100 - RG 1.89)) provide helpful general guidance for implementing these criteria at a particular fusion facility.

Confinement Systems

Tritium systems design should provide for confinement barriers to reduce tritium releases to an acceptable level. The safety analysis should define and the design should implement appropriate robustness and leak tightness for the barriers. The confinement system should include as a minimum primary confinement system and a secondary confinement system. Design should also provide for tertiary, quaternary or higher orders of confinement if the safety analysis indicates these higher orders are necessary. The assumption of a single failure within the system does not compromise the confinement function.

The safety analysis should identify the confinement safety functions and the process conditions for which the functions are required. The confinement systems should provide the required confinement safety functions for normal operation, anticipated off-normal events and design basis accidents with the assumption of a single failure in the system.

Primary Confinement Systems

All tritium systems should enclose tritium within a primary confinement that provides a low leak rate, pressure-rated static barrier. Normally, primary confinement systems are sealed systems and are opened only for maintenance, testing and inspection of confinement subsystems.

Electrical equipment necessary to provide the required confinement safety function should be safety-class and should have a safety-class electrical power supply including a backup electrical power supply (DOE 3003).

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

10CFR50(I) provides specific methods and evaluation criteria that are acceptable in implementing ALARA with respect to exhaust systems from a confinement system. DOE 6430.1A provides additional guidance for design of confinement systems. RG 1.140 provides guidance for design, testing and maintenance for exhaust system cleanup systems.

Secondary and Higher Order Confinement Barriers

A secondary confinement barrier should enclose the primary confinement system. Tritium systems should also have tertiary or higher orders of confinement in accordance with requirements of the safety analysis. Secondary and higher order confinement barriers should comply with the criteria of this section.

Secondary confinement barriers should have a recirculating nitrogen or inert gas atmosphere. For the purposes of this document, when the term “inert” is used in reference to the confinement atmosphere, any combination of reduced oxygen environments is intended. Tertiary and higher orders of confinement should have atmospheres as directed by the safety analysis.

Secondary and higher order confinement barriers should operate at subatmospheric pressure by exhausting some of the atmosphere to the environment. The atmospheric exhaust should be through an tritium removal system to limit the environmental release of tritium consistent with release limits and ALARA principles. The safety analysis should prescribe limits for tritium releases to the environment.

10CFR50(I) provides specific methods and evaluation criteria that are acceptable in implementing ALARA with respect to exhaust systems from a confinement barrier. DOE 6430.1A provides additional guidance for design of confinement barriers. RG 1.140 provides guidance for design, testing and maintenance for tritium removal systems.

Segmented Tritium Systems

Tritium systems design should provide for segmentation of the tritium inventory to make acceptable the amount of tritium releasable in a single event. Design should provide for isolation of each segmented volume using valves or piping blanks. Check valves and other one-way valves are not acceptable as isolation devices.

Release of tritium from the single largest segmented volume should not result in exceeding prescribed dose limits or other unacceptable consequences.

Segmentation may be accomplished by either

1. Utilization of processes or devices with small inventory, or

2. Separation of the tritium inventory into isolable volumes, or

3. Storage of tritium in an immobile condition relative to the single event (e.g., metal hydride beds).

Protection For Natural Phenomena

For the tritium systems that are safety class, including structures and components, design should provide robustness to withstand the effects of design basis natural phenomena such as earthquake, tornado, hurricane, flood tsunami, seiche, etc., without loss of safety function. The design should also provide for protection of safety-class equipment and systems from potential failure of non-safety-class hardware during natural phenomena events. If protection includes isolation of safety-class systems, the equipment, instruments and electrical systems that provide for the isolation should be capable of withstanding the effects of design basis natural phenomena without failure of function and should be fail-safe in the event of power loss or failure within electrical systems.

Protection from Environmental Conditions and Missiles

For the tritium systems, including structures and components, that are safety class, design should provide robustness to accommodate the effects of environmental conditions of normal operations, maintenance, testing and postulated accidents without loss of safety function. Safety-class tritium systems should have robustness or protection to withstand dynamic effects of a missile, pipe whip, or runaway plasma that may result from equipment failures and from events outside the tritium systems if the safety analysis evaluates these as design basis accidents.

Fire Protection

The design should minimize the probability and consequences of tritium fires or explosions. Because fire oxidizes elemental tritium to tritium oxide, a form with a much greater biological hazard, design should place high priority on preventing fires. The design should use noncombustible or fire resistant materials to the greatest practical extent throughout the tritium systems.

Where the safety analysis evaluates fires as design basis accidents, design should provide for fire detection and suppression systems having appropriate capacity and capability to minimize adverse effects of fires on safety-class systems, structures and components. Rupture or inadvertent operation of fire suppression systems should not significantly impair the safety function of tritium systems, structures and components.

Fire suppression systems should emphasize use of dry chemical or gas suppressants. Because of the natural affinity of tritium for water and the increased biological hazard of tritiated water, the use of water as a tritium fire extinguishing agent should require a technical or economic justification. Facilities that have the potential for introducing fire suppression water into a tritium contaminated environment should provide a tritiated water collection system with the capacity to store the total volume of fire suppression run-off. Design should provide for facilities to dispose of any tritiated water in an environmentally acceptable manner.

Conversion of Elemental Tritium to Tritium Oxide

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

Heat Removal

The design should provide for reliable removal of total heat loading from all confinement barriers. Total heat loading consists of tritium decay heat and equipment energy dissipation within a barrier and heat transfer into the barrier from external energy sources.

System Cleaning

The design should provide for cleaning of tritium systems before and after installation. Tritium systems should be able to withstand vacuum conditions necessary for cleaning purposes. Once tritium has contaminated the primary confinement, only limited cleaning is permissible for tritium-wetted surfaces.

Tests and Inspections

The design should provide for periodic tests and inspections of structures, systems and components related to the intended safety function. The tests and inspections should assess structural integrity, hydrogen embrittlement, leaktightness and other parameters related to the safety function.

The design should provide for and operations should have an appropriate materials surveillance program.

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

Design Considerations

General

The tritium primary confinement is the pressure (or vacuum) boundary, wetted routinely by tritium, outside the fusion machine's vacuum vessel and associated vacuum system. Gages, stubs or other pressure-containing hardware attached to a safety-class primary confinement subsystem are safety-class components and design should have them serve as confinement barriers for all operational and accident modes of the tritium primary confinement.

Radiation Shielding

Radiation shielding is not a design consideration for tritium systems. Tritium decays to a stable element, helium (^3He) by emission of low energy beta radiation, maximum 0.0185 MeV and average 0.0057 MeV. The maximum range (i.e., density thickness) of beta particles, about 0.6 mg/cm^2, is less than the generally accepted 7 mg/cm^2 thickness of the epidermis of the skin. The beta radiation is easily and completely shielded by a relatively thin layer of almost any material, including the materials of the tritium confinement system. Thus, if the primary confinement system is leak tight, tritium poses no radiological hazard to operating personnel.

Confinement Barriers

Tritium primary confinement is a major design consideration because tritium is difficult to contain. As noted above, tritium is not an external radiation hazard. However, when tritium is oxidized and ingested it produces a significant internal dose. Regardless of the care taken to assure physical integrity and leak tightness of the confinement, small quantities of tritium will escape at the various process connections during normal operations. Additionally, an increased level of loss will occur during maintenance operations which usually breach the primary barrier. By escaping to unwanted areas and reacting with normally present materials, tritium can create significant biological hazards. For example, tritiated water (tritium oxide) is a water molecule in which one or both of the hydrogen atoms is a tritium atom rather than the normal protium, e.g., T_2O, HTO, DTO. Tritiated water is on the order of 10^4 times more hazardous to humans than elemental tritium. The human radiation dose hazard is through inhalation, ingestion or absorption through the skin.

Because tritium is very mobile and can create a biological hazard, tritium systems must have barriers to protect personnel and the environment from tritium and its compounds.

As a minimum, a tritium system should have primary and secondary confinements. If the safety analysis determines that tritium systems, or certain components, require tertiary or higher order confinements, the design should provide for these confinements in a similar manner as secondary confinement as discussed below.

The primary confinement system should consist of piping, tubing, valves, fittings, equipment and instrumentation components that define the pressure boundary of the tritium systems. The primary confinement system is normally a closed system in direct contact with tritium and containing it for conditions ranging from vacuum to full system pressure. Physical integrity is assured by compliance with the applicable ASME Code for boiler and pressure vessels, or equivalent Codes. If the safety analysis determines a portion or all of tritium primary confinement to be a safety-class system, the associated individual components are safety-class and the design should consider them as the primary confinement barrier for all operational and design basis modes.

Secondary confinement includes the 1) barriers that enclose the primary confinement and 2) systems that ventilate the secondary confinement volumes. If the safety analysis deems a portion or all of secondary confinement to be a safety-class system, the associated individual barrier components are safety-class and the design should consider them as confinement barriers for all operational and design basis modes. Examples of secondary confinement systems are glove boxes, sealed enclosures, bell jars, double jacketed vessels/duct work/piping, and stripper/scrubber systems. Ventilation systems for secondary and higher order confinement volumes will operate at a negative pressure relative to the ventilation systems of zones occupied by personnel. The negative pressure will assure that any air flow between zones will flow from personnel zones and into the zones that could be confining a tritium release.

Structural Design Codes

The design, fabrication, testing and inspection of safety-class tritium structures, systems or components should be in accord with the ASME Boiler and Pressure Vessel Code (ASME 93a), or to a comparable safety-related code.

Either ASME Code Section III, Class 1 or 2 or the comparable elements of ASME Code Section VIII, Division 2 may apply for pressure vessels. For tritium systems, ASME Code Section III is acceptable. ASME Code Section VIII is acceptable if the design uses additional standards in areas such as attached valves, pumps, piping and supports, enhanced quality assurance and tritium/helium embrittlement effects which are comparable to relevant parts of ASME Code Section III.

In general, the designer should prepare a detailed comparison between ASME Code Section III and the comparable code, for safety-class systems, and demonstrate comparability. The designer should prepare this comparison early in the design phase and the safety regulatory or licensing authority should endorse the comparability to ensure acceptability for construction. Finally, this document does not address the actual stamping of a vessel or component complying with Section III or VIII; this is a decision among the owner, fabricator and the cognizant regulatory agency.

Hydrogen Fire and Detonation

Hydrogen fire and detonation are potential hazards which the safety analysis may declare design basis accidents (typical frequency > 10^{-6}/year). If tritium primary confinement is a safety-class system, it must retain a required integrity during and after a fire or detonation event, although the non-safety-related functions of the confinement can be compromised. If it is not a safety class, the tritium primary confinement may fail in a fire or detonation event, but the failure should not degrade the function of an adjacent safety-class system, structure or component.

Hydrogen Fires

The hydrogen isotopes tritium, deuterium and protium leak easily and can form a highly flammable mixture with air. Hydrogen and air mixtures can ignite and sustain a flame over a very wide range of composition, from 4% to 74% by volume of hydrogen, at room temperature and pressure (Hord 78). A minimum limit of 9% is needed to sustain a coherent flame. At room temperature and pressure, a spark energy of 0.02 millijoule can ignite a stoichiometric mixture (29.5% tritium by volume). The potential for hydrogen fires can be minimized through leak prevention, elimination of ignition sources, reduction of available oxygen, and/or increased ventilation.

Hydrogen Detonations

The mode of burning in which the flame travels at supersonic speeds is called detonation. Heated to a high temperature, a mixture of hydrogen and air can spontaneously ignite and detonate. This temperature is the spontaneous ignition temperature which is a function of composition, pressure and container size. At one atmosphere of pressure, this temperature is about 540°C. Favorable conditions for detonation are stoichiometric mixture (29.5% hydrogen by volume), high energy ignition sources and confining surroundings. Unconfined hydrogen-air mixtures do not detonate unless the ignition source delivers considerable energy in the form of a shock wave.

For a potential hydrogen fire or detonation to be a design basis accident, the safety analysis should evaluate the frequencies of the required conditions occurring at the same time:

1. Hydrogen isotopes in sufficient concentration,

2. Oxygen in sufficient concentration, and

3. High temperature or ignition source.

To preclude a tritium fire or detonation as a design basis accident, the safety analysis must demonstrate a low event frequency, typically $<10^{-6}$/year.

Design features that promote a low event frequency include:

1. Leak tight primary confinement to prevent out leakage of tritium to the secondary confinement,

2. Inert gas in the space between primary confinement and secondary confinement barrier walls, to prevent oxygen contacting tritium,

3. Monitors to detect tritium out leakage or oxygen inleakage,

4. Minimize ignition sources or high temperatures near the primary or secondary confinement barriers, and

5. Utilize NFPA rated enclosures (NFPA 70) for electrical equipment in a location potential for contact with flammable mixtures exist.

Metal Embrittlement

Almost all metals will absorb hydrogen gas in a thin surface layer from which hydrogen will diffuse deeper into the metal. Additionally, some of the hydrogen isotope tritium will decay to helium-3. With time and continued exposure, both the diffused hydrogen isotopes and the tritium decay product helium will embrittle the metal.

Embrittlement alters the material properties of some metals significantly, by reducing ductility which leads to failure by crack growth at ambient temperature. In addition, some metals containing helium can crack at elevated temperatures, including welding temperatures, by bubble agglomeration and creep crack growth.

Design should eliminate embrittlement as a design issue by considering in the choice of materials a lifetime projection of pressures and temperatures and exposure to hydrogen isotopes.

Exchange with Hydrogen, Hydrogenated Compounds, and Hazardous Wastes

Tritium will readily exchange with a hydrogen atom in water, oils and almost all other hydrogenated compounds. Tritiated water and some tritium hydrocarbon compounds are absorbed quickly into the human body where the beta energy of tritium decay can cause biological damage. When tritiated, mercury, oils and other hazardous wastes become mixed waste with a significant disposal cost.

The design should avoid use of water, moisture, mercury, hydrocarbons (oils), plastics, asbestos or elastomeric gaskets and other hydrogenated compounds that could contact tritium. Gaskets and O-rings in contact with tritium should not use elastomers or plastics or asbestos; tritium will degrade them and cause premature failure. Ultra-high molecular weight polyethylene (UHMWPE) is an exception to this rule; see "Recommended Design Practices" below.

Components of Primary Confinement System

Piping, pumps, valves and pressure relief devices should meet all pressure requirements and vacuum requirements for the primary confinement, and should comply with applicable ANSI/ASME standards (ASME 89d, ASME 93a, ASME 93b).

Welded joints are preferable to compression fittings which are preferable to threaded fittings. Welded joints or mechanical joints are acceptable for piping enclosed in a secondary confinement glove box or cabinet. But outside glove boxes or cabinets, piping should have all welded joints. Pumps should comply with National Electrical Code requirements for explosion proof installation (NFPA 70), and should not use organics, hydrocarbons or other volatiles for surfaces that will contact the tritium process gas. Valves should meet prescribed leak requirements across the valve seat and from the valve bonnet and body.

Recommended Design Practices

Materials of Construction for Primary Confinement

Recommended Materials

For the primary confinement system for tritium, the recommended materials of construction are austenitic stainless steels:

Type 304-L,

Type 316, or

Type 316L.

In addition, the following materials for instruments, gaskets and seals of the primary confinement system can contact tritium without detriment in the pressure and temperature ranges of most tritium systems:

Copper,

Aluminum,

Nickel,

Silver,

Type 304 stainless steel,

Stellite, or Nitronic 60® (Titanium Corporation of America)

Vespel®, and

Indium.

For cryogenic processes, Type 316L austenitic stainless steel is the recommended material of construction.

The design should give particular attention to avoid conditions that could cause stress corrosion cracking of austenitic stainless steels.

If the performance of a particular material in a hydrogen environment is not well known, the designer should perform bench tests to establish performance in simulated operating and accident conditions.

Materials Not Recommended

The design should avoid use of the following materials of construction and materials of operation for tritium primary confinement:

Metals that are susceptible to embrittlement and cracking upon exposure to hydrogen,[3]

Water

Hydrocarbons (oils)

Mercury,

Iron oxide contamination on either the tritium wetted surface or an outside surface as a contaminant,

[3] Precipitation hardened steels (e.g., 17-4 PH, 15-5 PH) are especially subject to embrittlement by tritium and helium. Some metals including some type 300 stainless steels containing helium alone can crack at elevated temperatures, including welding temperatures, by bubble agglomeration and creep crack growth.

Materials capable of forming methane,

Elastomers, plastics or asbestos. An exception is the use of ultra-high molecular weight polyethylene (UHMWPE) as a step tip in automatic valves. Valves will remain leak-tight longer with an UHMWPE step tip than with a metal tip (e.g., stellite).

Carbon steel is significantly more susceptible to hydrogen embrittlement than Type 300-series stainless steel and is not a recommended material for primary confinement. Additionally, at elevated temperatures, carbon steel is vulnerable to hydrogen combining chemically with carbon, decarbonizing the metal, forming methane and causing cracking and blistering.

Piping

The recommended piping construction method is welding in accordance with the applicable ANSI/ASME standard (ASME 89d). Design should minimize the use of mechanical joints but, where use is necessary, the recommended mechanical joint is a high vacuum connector. Mechanical joints or welded joints are acceptable for piping enclosed within a secondary confinement glove box or cabinet. Outside a glove box or cabinet, only welded joints are acceptable.

Metal-to-metal seals are preferable to elastomer seals. Where conditions necessitate the use of elastomer sealing, design should provide a dual O-ring configuration with ease of replacement.

Pumps

Process requirements will dictate the selection of pumps. In addition to providing for maximum design pressure, pumps should also have the capability of withstanding vacuum for cleaning purposes. Therefore, the selection of pumps for normal operations should include compliance with the vacuum specification. Pumps should not use organics, hydrocarbons or other volatiles on surfaces that can contact the tritium process gases. Metal-to-metal pumping surfaces are satisfactory, and other technologies may be also.

If the safety analysis indicates a pump is safety-class, it should meet the requirements of the applicable ANSI/ASME standard (ASME 89c, ASME 93a). Pump motors should meet National Electrical Code requirements for explosion-proof installation (NFPA 70).

Valves

Valves are components of the primary confinement, and as such, should be designed and tested to the same standards of confinement/vacuum/leak tightness. When specifying leak rate for valves it is necessary to understand that there are two modes of leakage; 1) across the seat, where the tritium is still contained within primary confinement, and 2) bonnet/body leakage, where the tritium exits the primary confinement.

Bonnet/body leakage creates a confinement problem and poses a personnel hazard potential. In addition, recovery from the primary confinement breach requires processes to be shut down to repair the leak. Welded, double metal bellows valve bonnets have proven to meet current leak tightness criteria.

Metal-to-metal valve seats are preferred. An exception is the use of ultra-high molecular weight polyethylene (UHMWPE) as a step tip in automatic valves that are not subject to high temperature environments. Valves will remain leak tight longer with an UHMWPE step tip than with a metal tip (e.g., stellite). During normal operation, seat leakage does not present a personnel or confinement hazard, but it does have a major impact on process operations, accountability, operability and volumetric segmentation. Consideration should be given to the use of double valve isolation to mitigate the potential for valve seat leakage consequences during maintenance breaching of primary confinement and to increase the confidence level for product purity.

Pressure Relief

Where the potential exists for the over, or under, pressurization of primary or secondary confinement barriers, pressure relief should be provided. Pressure protection may serve as process equipment protection without providing a safety function. For the primary confinement system, stringent leak tightness specifications necessitate that pressure protection be through the use of rupture disks instead of pressure relief valves, seal pots, etc. For the secondary confinement system, pressure differentials and leak tightness requirements are not as stringent, therefore pressure protection may use seal pots, bubblers, surge volumes, etc.

Relief valves should not be used for tritium service. Their performance is inadequate for leak tight resealing after relief and reliable relief at low differential pressures.

Heating and Ventilation - Personnel Zones

Heating and ventilation systems should promote tritium confinement for zones occupied continuously or intermittently by operations or maintenance personnel.

The design should provide heating and ventilation systems with pressure differentials to cause air flow from least contaminated areas to most contaminated in tritium process areas. Ventilation pressure in personnel zones should be greater than pressure in secondary confinement.

Primary System Cleaning

The design should include provisions to accommodate the cleaning of all tritium systems for initial installation, particularly vacuum cleaning of the primary confinement system. After tritium has contaminated the primary confinement's interior, limited cleaning is permissible and this limited cleaning must avoid use of waters or organics that could oxidize tritium.

Past Design Practice

Tritium Confinement

Some tritium facilities have used primary confinement, secondary confinement and tertiary confinement. The minimum essential design, however, uses a primary confinement with a secondary confinement as a cost effective and safe design for tritium operations. The following sketch illustrates this minimum essential design.

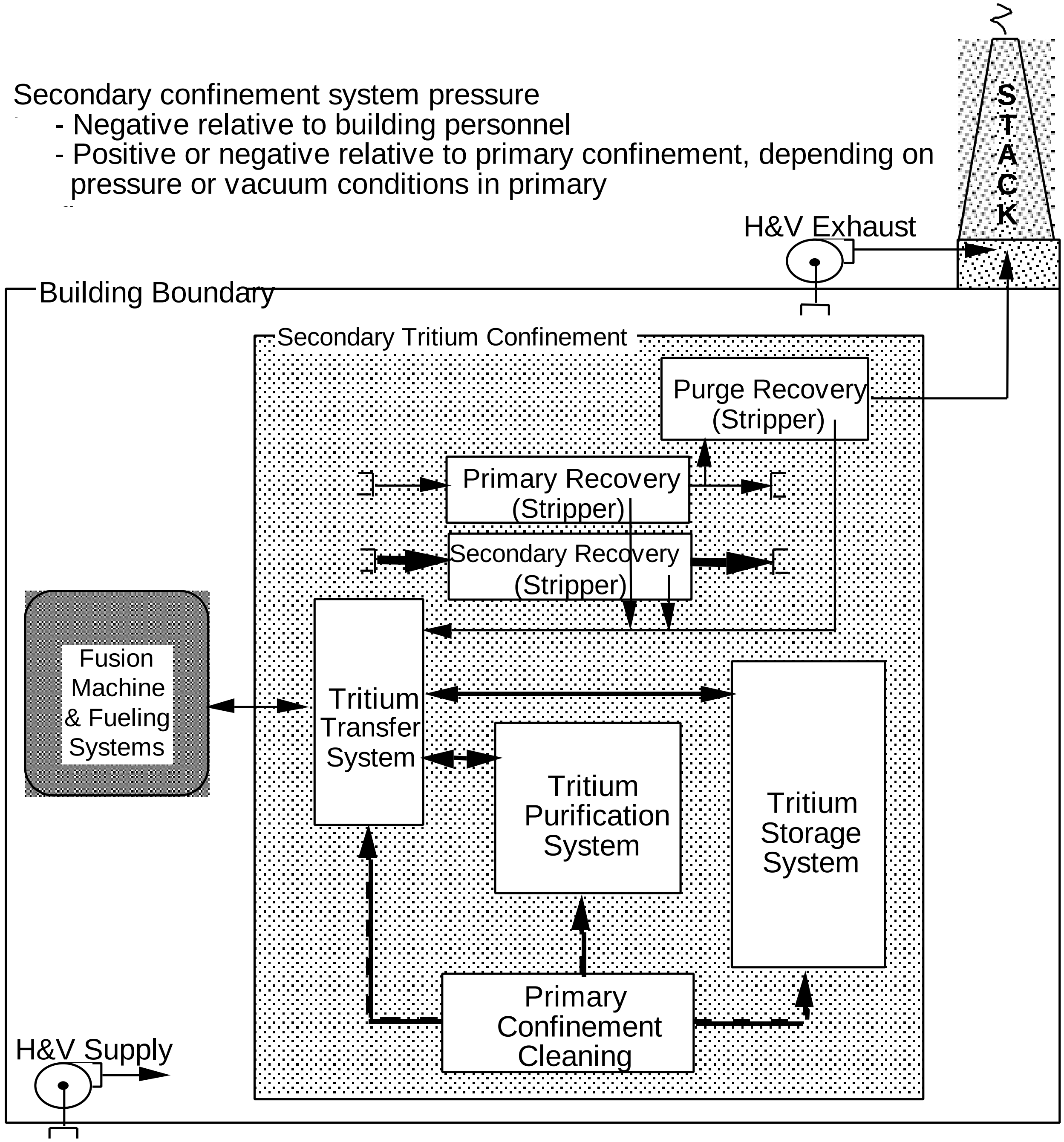

Figure II-2. Tritium processing schematic.

The primary confinement system encloses tritium in a sealed, low leak system rated for all operating pressures and vacuum. Primary confinement is essentially a static, high integrity system of process equipment and piping. There is no intent that tritium will leave primary confinement except under controlled transfers.

But tritium is difficult to contain, even in the highest integrity systems, and some small leakage is likely to occur. To ensure that tritium loss to the environment or exposure of personnel is minimal, the primary confinement system is within a secondary confinement barrier. The secondary confinement system is dynamic, depending on differential pressures or gas flows to confine and channel tritium within certain volumes or pathways. The secondary (or higher order) confinement system may not be sealed or leak tight.

Metal Hydride Technology

Metal hydridemetal hydride beds technology is multipurpose and has replaced several older technologies for tritium storage, pumping and hydrogen isotope separation. Hydride beds require less process space than does conventional equipment.

Hydride beds are metal containers filled with other granular alloys or metals that can absorb hydrogen isotopes when the beds are cold and desorb the isotopes when the beds are heated. Electrical, gas or other heating and cooling systems are satisfactory. The following sketch shows nitrogen gas to heat and cool the hydride beds via shell and tube heat exchangers.

Several types of hydride metals have been successfully used in past applications:

- *LANA* (lanthanum, nickel, aluminum) for pumping and storage,

- *Mischmetal* (calcium, mixed rare earth metals, and nickel) for compression,

- *Pd/K* (palladium-coated kieselguhr) for purification and separation, and

- *Uranium* for storage.

Tritium Storage Process

Past practices have stored tritium in conventional tankage and on metal hydride beds. Metal hydride beds provide significant safety advantages because they are low pressure devices and, if maintained below desorption temperature, will not release tritium should the bed wall rupture. Also, hydride beds require less process space with no significant sacrifice of storage capacity and are the preferred storage option for most modern applications.

Purification Process

The purification process removes hydrogen isotopes from other waste gases and then separates the hydrogen isotopes. A palladium diffuser bed removes hydrogen isotopes from helium and other waste gases. To separate the hydrogen isotopes from each other, past practices have used four processes:

1. Thermal Diffusion Columns,

2. Chromatograph Columns,

3. Cryogenic Distillation Stills, and

4. Thermal Cycling Absorption Process (TCAP).

The TCAP offers improved operating efficiency and a more compact process package with no sacrifice in separative capacity. It has replaced thermal diffusion and cryogenic distillation in modern applications. TCAP is a metal hydride bed using Pd/K (palladium-coated kieselguhr) that is thermally-cycled to separate tritium from H_2 and D_2 isotopes.

The isotopes removed from the TCAP process may be stored separately on LANA storage beds for later use.

Tritium Purification, Stripping and Recovery Processes

Purification Process

The fusion machine will transfer some of its burned and unburned fuel gas to the tritium systems for purification and storage. The tritium purification process will recover tritium and deuterium isotopes by processing fuel gas through a Pd diffuser to separate tritium and deuterium from other gases. The tritium and deuterium mixture then proceeds through a separation process such as TCAP which separates tritium from deuterium. Separated tritium and deuterium gases go to separate storage facilities such as LANA metal hydride storage beds.

Stripping and Recovery Processes

The tritium system will also recover the small amounts of tritium that inevitably leak from the primary or secondary confinement. The recovery of leaked tritium involves use of a “stripper” system and a recovery process. The stripper consists of a oxidizer-reactor , a pumping system, and zeolite beds (Z-beds). The oxidizer-reactor incinerates elemental hydrogen isotopes to form oxides of these isotopes (water vapors: H_2O, D_2O, etc.).

The recovery system will regenerate the zeolite beds and store the hydrogen isotopes prior to transfer to the purification process. A typical system consists of magnesium or uranium beds, a pumping system, and tanks. The magnesium or uranium beds break the hydrogen isotope oxides into O_2 and H_2, D_2 and T_2.

The nitrogen (or inert gas) atmosphere of secondary confinement flows through the oxidizer-reactor and any hydrogen isotopes convert to oxides (water vapors). The gases then flow through the zeolite beds which absorb the water vapors. As a zeolite bed approaches water saturation, it goes off-line and another (regenerated) zeolite bed comes on-line. The zeolite bed saturated with water vapors undergoes regeneration which involves heating to drive off the water vapors. The water vapors pump to the uranium bed which breaks the water into elemental gases. Hydrogen elemental isotopes go to a separation process which recovers tritium for storage.

Past practices used a system of three strippers (primary, secondary, and purge systems) and one recovery process to augment confinement and recovery of tritium.

The secondary confinement’s nitrogen or inert gas atmosphere cycles to and from the primary stripper systems which remove any tritium that might leak from primary confinement. The secondary stripper is available should secondary confinement accumulate a significant tritium concentration from leaks or maintenance work.

The purge stripper maintains secondary confinement at subatmospheric pressure by exhausting a small portion of secondary atmosphere to the environment. Secondary confinement is an enclosed, but not sealed, system. Ventilation differential pressures will cause some building air to flow into the secondary atmospheric, causing a gradual pressure build up. To maintain secondary confinement at slightly below atmospheric pressure, some of the secondary atmosphere must discharge to atmosphere through the primary and purge strippers. The purge stripper system can safely handle all planned exhausts to the environment from tritium secondary confinement. The system includes redundant components to assure continuous stripping capability.

Tritium Control, Accountability and Physical Protection

The purpose of requirements placed on tritium control, accountability, and physical protection at DOE fusion facilities are:

1. Meet legal requirements for environmental releases, waste disposal, and transportation of tritium,

2. Meet the requirements of the 10 CFR 830,

3. Prevent the diversion of the material for unauthorized use,

4. Knowledge of the process efficiency, i.e. how much tritium is produced and used in processes under investigation,

5. Meet the requirements of the DOE Orders,

6. Increase operational safety of the facilities by providing knowledge of the location and form of tritium,

7. Prevent unwanted buildup of tritium within a facility.

Scope

This section will primarily cover methods for the control and accountability of tritium. Tritium is the predominate nuclear material used at fusion facilities. It is of interest because of safety concerns and possible unauthorized diversion for military applications. Tritium will be an issue for operation of fusion facilities since it will be a radioactive material released to the environment for operating facilities during normal operations. Although public exposures and environmental releases are expected to be small and well below regulatory limits, it is a radioactive material and the public will need to be assured that safety has not been compromised.

Other radioactive materials that must be controlled at fusion facilities include depleted uranium (U238) for storage of tritium and various radioactive sources used for checks and calibration of radiation monitoring devices. The control and accountability of these materials is relatively straight forward and does not present significant problems for operating facilities.

Deuterium, in quantities greater than 100 grams, is also controlled at DOE facilities. The requirements are primarily records management. There are not requirements to perform measurement. The accountability requirements are also straight forward and do not present concerns.

It is important to distinguish between a DOE nuclear facility and a DOE general radiological facility. The requirements on DOE nuclear facilities are substantially greater because of the possible greater risk to the public, the environment and the worker for accidents. The current categorization of nuclear facility is by inventory of radioactive materials. For this document, tritium is of concern. The current categorization is based on DOE-STD-1027-92:

Less than 1,000 Curies	General Radiological Facility	
1,000 to 30,000 Curies	Category IV Nuclear Facility	Low Hazard
30,000 Curies and up	Category II Nuclear Facility	Moderate Hazard

Category I is a High Hazard facility and are currently only category A reactors and other facilities as designated by the DOE Program Secretary Office.

There are no tritium facilities in the US that are designated as Category I. It has not been determined if a demonstration fusion power plant would be a Category I facility. The Nuclear Safety Rules and Nuclear Safety Orders discussed in section 3 apply to all nuclear facilities.

The requirements for control and accountability in other countries is not discussed in this section.

Requirements

The requirements placed on the control and accountability of tritium fall into three categories. Those required by the US Law, those required by DOE Orders and those required by "good practices." It is also important to note that requirements are not consistent throughout the international community. There is considerable variation across the international community.

Shipping requirements are defined for international shipments.

Legal Requirements

The legal requirements on tritium measurement are of the following types:

Environment facility emissions which included air emissions and releases to the ground water or at facilities outfalls. These include federal and state requirements. Some of the requirements for fusion facility that handles tritium are defined in the following laws:

1. Clean Water Act for water quality standards and effluent limitations,

2. National Environmental Policy Act for impacts of proposed activities,

3. Federal Clean Air Act which sets ambient air quality standards,

4. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

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

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

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

Waste disposal requirements. These are generally state-specific. The details of the state requirements will not be discussed in this section since they vary widely.

Nuclear Safety Rules

10CFR834 (Radiation Protection of the Public and the Environment) (proposed), and 10CFR835 (Occupational Radiation Protection): Current DOE orders that are nuclear safety related are being reissued as “rules” that are law. Rule requirements were placed on DOE funded nuclear facilities by the US Congress in the amendments to the Price Anderson Act.

The requirements and implications of the DOE Rules as defined in the 10CFR laws listed above are still to be determined for tritium control and accountability. Currently, the DOE orders dealing with nuclear materials control and physical protection will not be released as Rules. Rules specify requirements that will result in fines and criminal prosecution (as defined in 10CFR820) if they are not followed. The only rules that have been released are the Occupation Radiation Protection Rule and Quality Assurance Rule. These will have implication on the procedures and techniques that are used to determine personnel exposure to tritium and environmental releases of tritium.

Since these requirements are part of the US law, they must be followed by all facilities that handle tritium or radioactive materials as applicable.

DOE Orders

DOE Orders are requirements placed on DOE facilities that define operations and the methods of conducting business.

DOE 5633.3B, “Control and Accountability of Nuclear Materials” specified the minimum requirements and procedures based on the amount of tritium and the form of the tritium in a facility.

Important requirements from this order are:

1. Tritium is treated as a Special Nuclear Material and the reportable transaction quantity is one hundredth of a gram (approximately 100 Curies).

2. Each facility requires a Materials control and accountability (MC&A) plan the specifies the following type of information:

    a) Material location,

    b) Measure techniques, calibration methods and frequencies, DOE interlaboratory measurement program, and accuracy requirements,

    c) Personnel responsibilities,

    d) Category type, Category III Greater than 50 grams or IV, and

    e) Holdup analysis.

    f) Inventory requirements for category III materials are semi annual with a complete measured inventory at least annual.

    g) Inventory requirements on the shipper and receivers of controlled material and methods to control and resolve inventory differences.

Access controls, depended on the tritium form and “attractiveness” must be established.

Each facility DOE laboratory must establish an independent organization to provide oversight of the nuclear materials control and accountability.

The physical protection requirements are specified in DOE order 5632.1C, “Protection and Control of Safeguards and Security Interests.” The current DOE requirements are dependent on the quantity and form. These include:

1. Control of tritium by personnel with a US DOE “Q” clearance.

2. Controlled locks, alarms and access during non working hours.

3. Other Orders specify waste requirements, environmental monitoring, and personnel protection.

These physical protection requirements will not be discussed in this section.

The DOE order requirements are in general not legal requirements. The facility can negotiate with DOE to determine the most cost effective manner of implementing the requirements and still maintain facility safety and material accountability.

Good Practices - Nuclear Material Locations at a Fusion Facility

Figure II-1, at the beginning of this section, is a block diagram of the primary locations, inputs and outputs, and measurement points for tritium at a nuclear facility.

Inputs to the tritium inventory at a nuclear facility are:

1. Shipments into the facility,
2. Production of tritium at the facility,
3. Locations of tritium within a facility,
4. “In Process,”
5. In system holdup,
6. In waste systems, and
7. In storage.

The exit streams of tritium from a facility include:

1. Shipments of tritium from the facility.
2. Waste streams that include:
    a. Facility routine tritium stack emissions,
    b. Waste water releases, and
    c. Solid waste including trash and “high concentration” tritium.
3. Accidental tritium releases.

Measurement locations:

1. Input tritium shipments to the facility,
2. Exit shipments from the facility,
3. In process measurements,
4. In storage measurements,
5. Waste stream measurements,
6. Personnel exposure measurements,
7. Work place measurements, and
8. Stack emission measurements.

Tritium Measurement Methods

There are two primary categories of tritium measurements that are made at fusion facilitates. The first category of measurements determine the quantity and the location of tritium within the facility. These measurements are generally of large quantities of tritium in high concentrations. The second category is for environmental or safety determinations. These are generally lower concentrations and small quantities.

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

1. Composition measurements,

2. Thermal measurements, and

3. Tritium concentration measurement.

Composition measurements determine the actual concentration determination for each atomic / molecular species. This method can be used for gases only.

Thermal methods (calorimetry) rely on the radioactive heat of decay of tritium. For one gram of tritium approximately 0.333 watts is generated by decay. The temperature increase or heat generation is measured. Calorimetry can be used for tritium in any form; either solid, liquid or gas. The only radioactive material present must be tritium since other radioactive materials will contribute to the thermal properties of the sample.

The final method determined the total tritium concentration by the measurement of the products or the effects of the products of the radioactive decay. The beta particle can cause scintillation effects or ionization effects. These effects can be measured and the concentration of tritium determined. The following is a listing of methods that are used or proposed to be used for measurement of tritium:

1. Pressure/Volume/Temperature/Composition, using either Mass Spectrometer or laser Raman spectrometer for the composition measurement,

2. Beta scintillation counter,

3. Self assaying tritium storage beds,

4. Scintillation counting, and

5. Ion Chamber.

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

Composition Measurements

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

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

The laser Raman spectrometer is a relatively new system that can be used to measure molecular concentrations in a gas mixture. The sample is placed in a cell with optical windows. The laser excites the rotational or vibrational atomic levels in the gas molecules. The light emitted as the excited levels decay back to the ground state are detected using a photodetector system. The measurement is absolute in that the frequency spectrum of each molecule is unique. The intensity is proportional to the amount of gas present. The disadvantages of the Raman method is that the amount of inert gases can not be determined. Common inert gases at fusion facility are the isotopes of helium.

Both of these techniques can be used for real time measurements. For the mass spectrometer system a sample is bled to a high vacuum system for measurement. The Raman system is easily adopted to real time measurements. The gas stream at atmospheric pressure is passed through an optical cell. The spectrum for a mixture hydrogen isotopes can be determined in approximately one minute. The total accuracy of these measurements is approximately 3 to 5 %.

The mass spectrometer technique has been the standard method that DOE facilities have used for the determination of the tritium inventory. It is a proven system although it requires a expensive spectrometer ($200k) and accurate determination of the temperature, pressure and volume.

The Raman system has not been accepted. Experiments are currently being performed to demonstrate that this will be an acceptable technique.

Thermal Methods of Inventory Measurement

The primary method to inventory large quantities of tritium in the liquid or solid form is to use a calorimeter. The sample is placed in a thermally isolated contained. The power required to maintain the temperature of the container is then a measure of the amount of tritium in the sample. Containers that can accept samples that vary from several inches in diameter up to a 55 gallon drum.

The lower limit of accuracy can be as low as 100 Curies. Calorimeters are expensive (>$200k). There require high tech electronics. They are the primary methods used to measure tritium in waste such as HTO on molecular sieve. They have not been used to measure process tritium except in very specific application. For example solid tritium storage beds that can be disconnected and moved have been placed in a calorimeter designed to accept the bed.

New methods are being developed to allow for the determination of the amount of tritium stored on a solid storage bed. When tritium is stored on uranium bed the temperature increase of the bed can be used to determine the amount of tritium stored on the bed. When tritium is stored on a material such as LaAlNi, usually gas is passed through the secondary containment to maintain the temperature. The temperature rise of the gas as it passes through the bed can then be used to determine the amount of tritium. Both of these methods are being proposed for tritium accountability. Their acceptance is now based on a case by case system and they are not used widely.

Development of these methods will be important for the operation of fusion facilities. They offer potential savings in time and effort to account for the tritium in a facility.

Tritium Concentration Measurement.

A beta scintillation counter has been used for tritium measurement if only the total tritium composition is required. In this instrument, the gas is passed over a crystal that will scintillate with the beta from the tritium decay. A photomultipier tube is used to detect the light. The tritium concentration can then be determined from the signal from the photomultipier tube. This method is commonly used for gas inventory requirements.

Liquid scintillation is commonly used to determine small concentrations of tritium. The tritium liquid or compounds containing tritium are placed in a scintillation liquid. The liquid is then placed in a counter which determines the amount of tritium by the light emitted from the sample.

Ion chambers are commonly used to determine environmental tritium releases and to monitor the atmosphere for personnel safety. Process ion chambers are used for determining tritium concentrations in secondary containment. Specially designed ion chambers can be used to determine high concentrations of tritium.

Ion chambers will measure any radioactive material which can cause ion pairs. They are also susceptible to contamination from materials which adsorb on surfaces and can only be used for gas.

Facility Measurement Recommendations.

Measurement of tritium input / output to facility

The primary method used historically for the measurements of tritium shipments has been pressure / volume / temperature/ composition (PVTC) measurement with the composition determined by either a mass spectrometer or beta scintillation counter.

Calorimeter can be used for the measurement of tritium absorbed on solid storage beds that are designed to be used as primary shipping containers and also be placed in the calorimeter.

In Process tritium measurements

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

Tritium in Waste Streams

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

Stack emission measurements.

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

COOLING SYSTEMS

The cooling systems include all systems, structures and components that remove heat from the facility and transfer it to a heat sink such that:

1. Thermal, hydraulic and mechanical parameters are within design limits for the cooling system, fusion device, confinement barriers and other safety-class equipment.

2. A leaktight barrier is maintained against uncontrolled release of fusion ash and radioactivity to the environment.

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

Fusion devices requiring cooling systems usually radiate heat to the first wall of the plasma chamber. The first wall re-radiates the heat to the shield wall. Cooling pipes in the shield wall remove the majority of the heat. The divertor is a secondary but significant source of heat. Components such as the cryostat, vacuum pumps, magnetic coils may also require component cooling.

General Safety Design Criterion

The cooling systems should remove heat from safety-class structures, systems and components and transfer it to a heat sink such that:

1. Thermal, hydraulic and mechanical parameters are within design limits for the cooling system, fusion device, confinement barriers and other safety-class equipment.

2. The cooling system provides and maintains a leaktight barrier against uncontrolled release of fusion ash and radioactivity to the environment.

The cooling systems should comply with these criteria for normal operations, anticipated off-normal events, and design basis accidents, assuming a worst-case single failure.

Potential System Safety Functions

Cooling system functions credited in the facility safety analysis in order to meet prescribed safety criteria should be designated safety functions. Potential safety functions for cooling systems include:

Normal Operation, Shutdowns and Anticipated Off-normal Events

1. Remove heat from safety-class structures, systems and components to maintain temperatures within design limits. For shutdown conditions, to the extent practical, heat removal should be passive and require no human intervention.

2. Transfer the combined heat load to a safety-class heat sink. For shutdown conditions, to the extent practical, transfer of heat to a heat sink should be passive and require no human intervention.

3. Confine radioactivity entrained or deposited in the coolant system, and provide for suitable releases to environment or transfer to a waste facility.

4. Detect, measure and isolate leaks or breaks in the coolant system pressure boundary.

5. Provide makeup coolant for small breaks or leaks in the cooling system pressure boundary.

Maintenance

Maintenance of the cooling system maintenance will normally occur during shutdown of the fusion device. Portions of the cooling system may, however, receive maintenance during normal operations. Whether maintenance occurs in normal operation or in a shutdown condition, the cooling system will have the following safety functions.

1. Remove heat from safety-class structures, systems and components to maintain temperatures within design limits. For shutdown conditions, to the extent practical, heat removal should be passive and require no human intervention.

2. Transfer the combined heat load to a safety-class heat sink. For shutdown conditions, to the extent practical, transfer of heat to a heat sink should be passive and require no human intervention.

3. Partially confine radioactivity entrained or deposited in the coolant system, and provide for suitable releases to environment or transfer to a waste facility.

4. Collect coolant drained from the coolant system in preparation for maintenance.

5. Provide makeup coolant for small breaks, leaks or draining required for maintenance activities in the cooling system pressure boundary.

Design Basis Accidents

The safety analysis should specify design basis accidents. Cooling systems design should implement the applicable safety functions credited in the safety analysis for design basis accidents. A typical frequency for design basis accidents is greater than 10^{-6}/year. The safety analysis should specify the actual frequency. The following are potential design basis accidents for the cooling systems of fusion devices:

Internal Initiators

1. Cooling leak within vacuum vessel

2. In-Cryostat tube leak

3. Out-of-Cryostat leak

4. Loss of coolant pumping

5. Low of coolant flow

6. Loss of heat sink

7. Missile or pipe whip

8. Increase in fusion power

9. Human Error

External Initiators

1. Natural phenomena, including earthquake, tornado, hurricane, seiche, tsunami, etc.

2. Fires

3. Aircraft or other missile impact (excluding sabotage).

Potential Safety Functions

The cooling system potential safety functions for design basis accidents are:

1. Remove heat from safety-class structures, systems and components.

2. Transfer the combined heat load to a safety-class heat sink.

3. Partially confine radioactivity entrained or deposited in the coolant system, and provide for suitable releases to environment or transfer to a waste facility.

4. For a large break in the cooling system pressure boundary:

    a) Provide makeup coolant at a sufficient rate that the system's heat removal and rejection capacity will prevent damage of safety-class structures, systems or components while allowing only negligible materials reactions with the coolant.

    b) Collect coolant spilled from a large break to prevent damage to safety-class structures, systems or components.

Beyond Design Basis Accidents

Beyond design basis accidents include internal and external initiators whose frequencies are lower than the design basis frequency limit specified in the safety analysis. There are no cooling system safety functions for beyond design basis accidents.

Safety Design Standards and Criteria

Structures, systems and components needed to perform safety functions should be designated safety class. Components which do not perform safety functions but whose single failure causes loss of a safety function should also be designated safety class. Included in the safety-class are:

1. Gauges, instrument tubing, sensing lines, stubs and other pressure containing hardware on the pressure boundary of the safety-class coolant system,

2. Membrane interfaces and isolation devices between safety-class and non-safety-class coolant systems.

The different designs and operating characteristics of fusion facilities limit the amount of specific guidance that these criteria can provide. Existing DOE and NRC design requirements and guidance documents provide helpful general guidance for implementing these criteria at a particular fusion facility.

For safety-class cooling systems, the following design standards and criteria should apply to the structures, systems and components.

Structural

General

The cooling system boundary includes:

1. Heat removal, transfer and sink systems wetted on the interior by the coolant. The boundary includes piping, fittings, vessels, valves, pumps, heat exchangers, storage tanks and instruments.

2. Coolant makeup systems

3. Spilled or drained coolant collection systems.

The cooling system design should reflect consideration of service temperatures and other conditions of the boundary materials, the uncertainties in determining material properties, effects of irradiation on those properties, residual, steady state and transient stresses, and size of flaws.

Loads

1. Individual Loads

Cooling systemscooling system loads should withstand the static load, normal operating pressure and temperature, anticipated operating transients, electromagnetic loads (normal operating and fault), interaction loads from adjacent systems, natural phenomena hazard loads and loads due to missile impacts.

a) Static Loads - The static load should include the weight of the equipment and coolant identified as constituting the system (or component) and any supported hardware.

b) Normal Operating Pressure Load - The normal operating pressure load should range from the minimum to the maximum capability of the cooling system, including the capabilities of all pressure or vacuum sources. Additionally, the pressure load range should include temperature induced pressures, hydrostatic test pressures and any credible pressure augmentation resulting from small leaks between two coupled cooling systems.

c) Normal Operating Thermal Load - The normal operating thermal load should include temperatures associated with normal processing operations, both cryogenic and elevated, and elevated bake out conditions required for cleansing prior to equipment removal.

d) Anticipated Operating Transients - The anticipated operating transient load should include the pressure, flow and temperature fluctuations resulting from anticipated off-normal events in addition to normal system start up, operations, and shut down.

e) Normal Electromagnetic Loads - Electromagnetic loads should include the forces induced as a result of plasma operation, fusion operation, eddy currents and control changes. Such forces will result in the cooling systems interacting with magnetic fields of the fusion machine's normal operation.

f) Electromagnetic Loads During Faults - Electromagnetic loads induced during abnormal operating events such as control failures, power supply failures, bus opens or shorts, or magnet faults.

g) Natural Phenomena Loads - Natural phenomena hazard loads should include loads resulting from earthquakes, winds, and floods. UCRL-15910 provides guideline methods for establishing load levels and for evaluating the response of structures, systems and components.

h) Missile Impact Loads - Missile impact loads should include missiles and pipe whip resulting from failure of high energy systems, if the safety analysis includes such failures as a design basis accident.

2. Combined Loads

The system structural design evaluations will be based on predicted responses for concurrent event load combinations that are compared against the corresponding allowable stresses. In applications involving the ASME Code for example, the evaluation of load combinations would be performed as shown in Table II-1.

3. Cyclic Loads

Cooling systems are subject to thermal and pressure cyclic loadings during normal and anticipated off-normal operation and maintenance. Also, systems and components are subject to vibration loading from motors, cavitation, water/steam hammer, etc. The ASME/ANSI design codes or comparable computational methods provide criteria for the evaluation which should use conservative analysis for the number of cycles and service life including the expected changes in materials properties with time.

Table II-1. Design Codes For Equipment[1]

	CODES			
EQUIPMENT	Design and Fabrication	Materials	Welder Qualification and Procedures	Inspection and Testing
Pressure Vessels	ASME Code Section VIII	ASME Code Section II	ASME Code Section IX	ASME Code Section VIII
Atmospheric Tanks	API 650, or AWWA D-100[2]	ASME Code[2] Section II	ASME Code Section IX	API 650, or AWWA D-100[2]
0-15 PSIG Tanks	API 620[2]	ASME Code[2] Section II	ASME Code Section IX	API 620[2]
Heat Exchangers	ASME Code Section VIII, and TEMA	ASME Code Section II	ASME Code Section IX	ASME Code Section VIII
Piping and Valves	ANSI/ASME B31.3	ASTM and ASME Code Section II	ASME Code Section IX	ANSI/ASME B31.3
Pumps	Manufacturers' Standards[3]	ASME Code Section II or Manufacturers' Standards	ASME Code Section IX (as required)	Hydraulic Institute

[1]The preferred design code for safety-class pressure retaining components is ASME Code.

[2]Fiberglass-reinforced plastic tanks may be used in accordance with appropriate articles of Section X of the ASME Boiler and Pressure Vessel Code for applications at ambient temperature.

[3]Manufacturers' standard for the intended service. Hydrotesting should be 1.5 times the design pressure.

Structural Acceptance Criteria

Cooling systems that are safety-class should have design, fabrication, inspection and testing in accordance with a recognized safety-class code such as the ASME Boiler and Pressure Vessel Code (ASME 93a). The specific codes and criteria selected should be commensurate with the level of safety required and should have a technical justification. Where ASME design is not feasible, such as in the case of unique materials or designs, the alternate codes may be used. Piping and equipment supports should be designed to AISC N690 and ASME 95.

Cooling system components that are not safety-class should have design, fabrication, inspection and testing in accordance with a recognized national consensus code such as the ANSI/ASME Standard B31.3 "Chemical Plant and Petroleum Refinery Piping."

Deflection Analysis

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

Testing and Inspection

The design of structures, systems and components of the safety-class cooling system should permit initial and periodic testing and inspection of important areas and components to assure integrity and capability to perform the safety function. The design should also permit a materials surveillance program.

Non-destructive testing and inspection of safety-class welds, vessels, piping and valves should be in accordance with the ASME Boiler and Pressure Vessel Code (ASME 93a). Where ASME design is not feasible, such as in the case of unique materials or designs, alternate codes such as those listed in Table II-1 may be used with justification. Weld acceptance criteria should be in accordance with the requirements of codes listed in Table II-1.

Computational Methods Validation

Computer codes or other computational methods supporting the design of cooling systems should have validation and verification for the range of normal and off-normal operations including design basis accidents. This validation and verification should support the use of the computational method in each intended application.

IEEE standard 730-1984, "IEEE Standard for Software Quality Assurance Plans" describes the validation and verification process.

Materials

The cooling system boundary materials and design should provide sufficient margin to assure that, when stressed, the boundary behaves in a non-brittle manner with a very low probability of rapidly propagating fracture.

Coolant should be compatible with structural materials which it may contact during normal operation, off-normal events and design basis accidents throughout the range of anticipated physical parameters.

Table II-2 lists the materials requirements. Alternative codes and standards may be used with appropriate justification.

Table II-2 Applicable DOE Orders and Design Standards

DOE 6430.1A	General Design Criteria
IEEE-308	Power Systems Criteria
IEEE-323	Equipment Qualification
IEEE-338	Periodic Testing
IEEE-344	Seismic Qualification
IEEE-379	Single Failure Criterion
IEEE-383	Electrical Cable Qualification
IEEE-384	Electrical Separation Criteria
IEEE-603	Criteria for Power and I&C

Instruments and Controls

The cooling system design should provide for instrumentation to monitor safety related variables and controls to maintain the variables within design limits.

The cooling system design should provide for instruments that detect and measure abnormal leakage and controls to isolate or mitigate the leak.

To the extent practical, the primary mode of actuation of safety functions should be automatic and should be initiated by detection and control channels of suitable diversity and redundancy.

Provisions should be made for manual monitoring and actuation of safety functions.

Instrumentation and controls should be able to perform their intended safety function assuming a single failure.

The power supply for safety grade instrumentation and controls should meet the IEEE Standard requirements for Class 1E power systems.

Passive Systems

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

Design Considerations

Cooling system structures, systems and components should be designed, fabricated, constructed and tested to the highest quality standards practical.

Cooling system design should provide defense in depth through multiple confinement barriers and redundant or diverse critical components or systems.

Unavailability of the onsite electrical power supply or the offsite power supply should be a consideration in assuring cooling system functions, assuming a single failure within the cooling system. Coincident failure of offsite and onsite power systems should not be a design consideration.

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

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

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

Coolant system pumping should provide for coolant flow coastdown to prevent exceeding design limits for safety-class structures, systems and components.

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

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

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

The coolant system design should minimize the number of interfaces between safety-class systems and non-safety-class systems.

Coolant system design should include provisions for maintenance and radiation protection.

Cooling system design should include features to facilitate decontamination and decommissioning at the end of service life.

Recommended Design Practices

Use of a primary cooling system and a secondary cooling system is the recommended design to comply with the general design criterion for containment of radioactivity assuming a single failure. Closed heat exchangers are the recommended coupling between primary and secondary cooling systems.

Use of multiple cooling loops in the primary and secondary systems is recommended as a design feature to reduce the operational thermal-hydraulic transient associated with single (loop) failure.

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

The use of leak before break (LBB) is recommended in the analysis of pipe break accidents. The methodology described in section 3.6 of the Standard Review Plan, NUREG-0800 is recommended.

Generic System Descriptions

Fusion devices requiring cooling systems will usually radiate heat to the first wall of the plasma chamber. The first wall will re-radiate heat to the shield wall. Cooling pipes in the shield wall will remove the majority of the heat. The divertor provides a secondary but significant source of heat which must be removed. Components such as the cryostat, vacuum pumps, magnetic coils will also require some component cooling.

For further information on the latest new design, the International Thermonuclear Experimental Reactor (ITERITER) has issued "ITER Outline Design Report," "ITER Outline Design Summary," and "Safety and Environment" (ITER). These documents provide generic descriptions of the cooling systems.

Past Design Practices

Past design practice has been to provide defense in depth, redundancy of critical components or systems and diversity. Some of these past practices may be applied to fusion machines. However, the essential need for rigorous quality levels, impeccable safety standards and stringent regulations will not be as applicable with the fusion machine. The needs of the fusion machine will be investigated further before past design practices will be recommended for the fusion machine.

However, one may refer to International Thermonuclear Experimental Reactor (ITER) documentation "ITER Outline Design Report," "ITER Outline Design Summary," and "Safety and Environment" (ITER) for current information on current tokamak design practice.

APPENDIX A

CONDUCT OF OPERATIONS SUPPLEMENTAL GUIDANCE

DOE-STD-1030-96	Guide to Good Practices for Lockouts and Tagouts
DOE-STD-1031-92	Guide to Good Practices for Communications *(includes Change Notice No. 1, December 1998)*
DOE-STD-1032-92	Guide to Good Practices for Operations Organization and Administration *(includes Change Notice No. 1, December 1998)*
DOE-STD-1033-92	Guide to Good Practices for Operations and Administration Updates through Required Reading *(includes Change Notice No. 1, December 1998)*
DOE-STD-1034-93	Guide to Good Practices for Timely Orders to Operators *(includes Change Notice No. 1, December 1998)*
DOE-STD-1035-93	Guide to Good Practices for Logkeeping *(includes Change Notice No. 1, December 1998)*
DOE-STD-1036-93	Guide to Good Practices for Independent Verification *(includes Change Notice No. 1, December 1998)*
DOE-STD-1037-93	Guide to Good Practices for Operations Aspects of Unique Processes *(includes Change Notice No. 1, December 1998)*
DOE-STD-1038-93	Guide to Good Practices for Operations Turnover *(includes Change Notice No. 1, December 1998)*
DOE-STD-1039-93	Guide to Good Practices for Control of Equipment and System Status *(includes Change Notice No. 1, December 1998)*
DOE-STD-1040-93	Guide to Good Practices for Control of On-shift Training *(includes Change Notice No. 1, December 1998)*
DOE-STD-1041-93	Guide to Good Practices for Shift Routines and Operating Practices *(includes Change Notice No. 1, December 1998)*
DOE-STD-1042-93	Guide to Good Practices for Control Area Activities *(includes Change Notice No. 1, December 1998)*
DOE-STD-1043-93	Guide to Good Practices for Operator Aid Postings *(includes Change Notice No. 1, December 1998)*
DOE-STD-1044-93	Guide to Good Practices for Equipment and Piping Labeling *(includes Change Notice No. 1, December 1998)*
DOE-STD-1045-93	Guide to Good Practices for Notifications and Investigation of Abnormal Events *(includes Change Notice No. 1, December 1998)*
DOE-STD-1050-93	Guideline to Good Practices for Planning, Scheduling and Coordination of Maintenance at DOE Nuclear Facilities

APPENDIX B

EMERGENCY PREPAREDNESS SUPPLEMENTAL GUIDANCE

DOE 5500.1A	Emergency Management System
DOE 5500.2	Emergency Planning, Preparedness and Response for Operations
DOE 5500.2A	Emergency Notification, Reporting and Response Levels
DOE 5500.3A	Emergency Planning and Preparedness for Operational Emergencies
DOE 5500.4A	Public Affairs Planning Requirements for Emergencies
DOE 5500.8	Emergency Planning and Management
ANS 15.16	Emergency Planning for Research Reactors
NFPA 1561	Standard on Fire Department Incident Management System

APPENDIX C

EMERGENCY PREPAREDNESS DEFINITIONS

Affected Persons	Individuals who have been exposed or physically injured as a result of an accident to a degree requiring special attention, e.g., decontamination, first aid, or medical services.
Assessment Actions	Those actions taken prior to, during or after an accident which are collectively necessary to make decisions to implement specific emergency measures.
Corrective Actions	Those emergency measures taken to ameliorate or terminate an emergency situation at or near the source of the problem.
Emergency Action Levels	Radiological dose rates; specific contamination levels of airborne, water-borne, or surface-deposited concentrations of radioactivity; or specific instrument readings that may be used as thresholds for initiating specific emergency measures.
Facility	Equipment, structure, system, process, or activity that fulfills a specific purpose. Examples include accelerators, storage areas, fusion research devices, and research laboratories.
Operational Emergencies	Are those radiological and non-radiological accidents and events associated with the serious degradation of safety or security at a DOE owned or leased Research & Development facility, operation, or activity.
Protective Actions	Those emergency measures taken after an uncontrolled release of radioactive material has occurred for the purpose of preventing or minimizing radiological exposures to persons that would be likely to occur if the actions were not taken.
Population at Risk	Those persons for whom protective actions are or would be taken.
Recovery Actions	Those actions taken after the emergency to restore the plant as nearly as possible to its pre-emergency condition.

APPENDIX D

TRAINING AND QUALIFICATION REQUIREMENTS

TERMS AND DEFINITIONS

Certificate of Qualification - document signed by the certifying authority attesting to an individual's certification.

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

Certifying Authority - that individual who certifies operators and operator supervisors, in accordance with a certification procedure.

Maintenance Personnel - persons responsible for performing maintenance and repair of mechanical and electrical equipment.

Managers - persons whose assigned responsibilities include ensuring that a facility is safely and reliably operated, and that supporting operating and administrative activities are properly controlled. Each facility should determine which level personnel and higher are considered Managers.

On-Shift Training - that portion of qualification training where the student receives training within the job environment and with as much hands-on experience as possible.

Operators - persons responsible for manipulating facility controls, monitoring facility parameters, and operating facility equipment.

Certified Operators - operators who require certification as determined by facility management.

Qualified Operators - operators who require qualification as determined by facility management.

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

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

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

Qualified personnel are those personnel who have successfully completed a formal qualification program appropriate to their job function.

Statement of Qualification - document signed by an appropriate individual (supervisory or higher) indicating that an individual is qualified to perform a specialized job function to an anticipated level of proficiency.

Supervisors - persons who are responsible for the quantity and quality of work, and who direct the actions of the operators or other personnel.

Certified Supervisors - supervisors who are responsible for the operational activities of certified operators who require certification as determined by facility management.

Qualified Supervisors - supervisors who are responsible for the operational activities of qualified operators who require qualification as determined by facility management.

Technicians - persons responsible for performing specific maintenance or analytical laboratory work.

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

Training Matrix - A listing of the courses and other appropriate requirements to be completed by an individual in order to satisfy training requirements for a specified job function. Training requirements and recommendations are matrixed by position.

GUIDANCE DOCUMENTS

10 CFR 830	Nuclear Safety Management
29 CFR 1910	OSHA Regulations
29 CFR 1926	OSHA Construction Regulations
DOE Order 4330.4A	Maintenance Management Program *(canceled, replaced by DOE Order 4330.4B)*
DOE Order 5480.20A	Personnel Selection, Qualification, and Training Requirements for DOE Nuclear Facilities
DOE Order 5480.9A	Construction Project Safety and Health Management
DOE-HDBK-1001-96	Guide to Good Practices For Training and Qualification of Instructors
DOE-HDBK-1002-96	Guide to Good Practices for Training and Qualification of Chemical Operators
DOE-HDBK-1003-96	Guide to Good Practices for Training and Qualification of Maintenance Personnel
DOE-HDBK-1074-95	Alternative Systematic Approaches to Training
DOE-HDBK-1080-97	Guide to Good Practices For Oral Examinations
DOE-HDBK-1114-98	Guide to Good Practices For Line and Training Manager Activities
DOE-HDBK-1116-98	Guide to Good Practices for Developing and Conducting Case Studies
DOE-HDBK-1200-97	Guide to Good Practices For Developing Learning Objectives
DOE-HDBK-1201-97	Guide to Good Practices Evaluation Instrument Examples
DOE-HDBK-1202-97	Guide to Good Practices For Teamwork Training and Diagnostic Skills Development
DOE-HDBK-1203-97	Guide to Good Practices For Training of Technical Staff and Managers
DOE-HDBK-1204-97	Guide to Good Practices For the Development of Test Items
DOE-HDBK-1205-97	Guide to Good Practices for the Design, Development, and Implementation of Examinations
DOE-HDBK-1206-98	Guide to Good Practices For On-the-Job Training
DOE-STD-1029-92	Writer's Guide for Technical Procedures *(includes Change Notice No. 1, December 1998)*
DOE-STD-1059-93	Guide to Good Practices for Maintenance Supervisor Selection and Development

DOE-STD-1060-93	Guide to Good Practices For Continuing Training
DOE-STD-1061-93	Guide to Good Practices For the Selection, Training , and Qualification of Shift Supervisors
DOE/EH-0256T Rev 1	DOE Radiological Control Manual
DOE/EH-0353P	Occupational Safety and Health Technical Reference Manual
DOE/NE-0102T	TAP 2 - Performance-Based Training Manual
DOE/NE-0103T	TAP 3 - Training Program Support Manual
SG 830.120	Safety Guide for Quality Assurance
SG 830.310	Guidelines for the Conduct of Operations at DOE Facilities
SG 830.330	Guidelines for the Selection, Training, Qualification and Certification of Personnel at DOE Nuclear Facilities
TTR89-009	TRADE Document TTR89-009,"Job Task Analysis - Guide to Good Practices: Volumes I & II"
TTR92-010	TRADE Document TTR92-010, "The Occasional Trainer's Handbook," 1992

EDUCATION AND EXPERIENCE

Minimums

Position	Education	Experience
Operators	High School	2 Years
Technicians	High School	1 Year
Maintenance Personnel	High School	1 Year
Supervisors	High School	3 Years
Operations and Facility Support Functions (Note 1)	Baccalaureate in Engineering or Related Science	2 Years
Operations and Facility Support Functions (Note 2)	High School	Work experience as appropriate to the specific job-function
Managers	Baccalaureate in Engineering or Related Science	4 Years
Training Manager	Baccalaureate with course work in education and technical subjects	4 Years

Note 1 Operations and Facility Support personnel who perform engineering or analytical support functions.

Note 2 Operations and Facility Support personnel who perform specialized support functions (such as quality control, radiation control, or emergency response).

Alternatives Guidelines

The education and experience guidelines written below may be considered when making an evaluation of alternatives, recognizing that other factors (such as job incumbency and the ability to competently perform the assigned job function) and may also be appropriate in lieu of the education and experience minimums specified.

Education Alternatives

The education requirements identified in this section are high school diploma and baccalaureate degree. Persons who do not possess the formal educational requirements specified should not be automatically eliminated where other factors provide sufficient assurance of their abilities to fulfill the duties of a specific position. These factors should be evaluated on a case-by-case basis, and approved and documented.

High School Alternatives:

General Educational Development (GED) diploma or completed test.

Certificate of Completion from a post-secondary technical institution.

Completion of technical training provided by the US Armed Forces.

College Alternatives:

Professional engineer license.

Completion of technical portions of a baccalaureate program, with the overall completion of 80 semester credit hours, as determined by a written transcript.

Related experience substituted for education at the rate of six semester credit hours for each year of experience up to a maximum of 80 credits.

Experience Alternatives

Persons who do not possess the experience requirements specified should not be automatically eliminated where other factors provide sufficient assurance of their abilities to fulfill the duties of a specific position. These factors should be evaluated on a case-by-case basis, and approved and documented in accordance with this procedure.

General:

In those cases where an individual does not meet the literal experience required for a position, <u>and no other basis for an experience alternative is available</u>, consideration may be given to the collective experience of the operating organization in lieu of the individual meeting the required experience. Individuals may be assigned to positions providing the overall operating organization is considered balanced and strong. In such cases, management approval of this approach (documented in a memorandum) is required.

Substitution of Course Work and Training:

Where course work is related to job assignments, post-secondary education may be substituted. Formal education may not be substituted for more than 50% of the experience requirements unless otherwise specified herein.

Job-related training in the position sought may qualify as equivalent to nuclear experience on a one-to-one basis for up to a maximum of two years.

Completion of technical training provided by the United States Armed Forces.

Training And Qualification Requirements - Basis and Rationale

The Training and Qualification section of the Fusion Safety Standard is based upon the referenced documents shown in Appendix 1. The program is a compilation of expected requirements [10CFR830] as well as existing programs in place due to DOE orders. It also includes information from other standards and documents. If a facility develops a comprehensive program for training and qualification of its staff using this document on a graded approach, the intent of the requirements and reference documents will be achieved. The overall effectiveness of such a program can only be determined by evaluating the effectiveness of the facility during operations.