TOKAMAK BUILDING—DESIGN CONSIDERATIONS FOR A LARGE TOKAMAK DEVICE*

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Summary

The characteristics and functions of the building to house a large tokamak device [Fusion Engineering Device (FED)] have been discussed and investigated. The most important functions which need to be performed by the tokamak building have been categorized for discussion as operational, maintenance, and public safety functions. The safety functions require establishing guidelines, assessment of consequences, and development of design techniques. Possible ranges of consequences have been identified for FED tritium releases; and a number of design techniques to reduce the probability and consequences of tritium releases have been discussed.

Design and construction of a satisfactory tokamak building to support FED appears feasible. Further, a pressure vessel building does not appear necessary to meet the plant safety requirements. Some of the building functions will require safety class systems to assure reliable and safe operation. A rectangular tokamak building has been selected for FED preconceptual design which will be part of the confinement system relying on ventilation and other design features to reduce the consequences and probability of radioactivity release.

Operating Functions

A basic function of the tokamak building is to protect the device and supporting equipment from natural elements such as rain, snow, dust, and sun. The building will also have to provide a satisfactory environment for machine operation and maintenance. Temperature, dust, and humidity need to be controlled to assure satisfactory operation of the machine and an adequate working environment for personnel. Temperature control could be important to the operation of instrumentation, safety systems, structural alignment and support, and preservation of structural concrete. The tokamak building also serves as a major part of the shielding system to protect the rest of the plant and workers from excessive radiation during machine operation which may require wall thicknesses of about two meters of concrete.

Maintenance Functions

Most of the building functions needed to support operation will also be needed to support maintenance. Temperature and building environment still need to be controlled to allow maintenance operations. Building design will require careful consideration of the space requirements for maintenance activities and maintenance equipment. The current FED maintenance approach requires some or all of the major components to be maintained in a separate area, away from tokamak device so that the device can be operated while component maintenance is being performed. Thus, provisions must be made for the transport of major components from the device to the hot cell facility. This transport may be either by overhead crane, or by surface transport such as wheels, roller, tracks, or airfloat. Clearance and surface conditions must be provided to move major components and shield sectors out of the toroidal field (TF) coil windows and away from the machine.

The FED preconceptual design studies[1] have shown that most of the required building volume will be needed to allow adequate space for device maintenance. The height of the building will be determined by the machine height plus the necessary crane operating space to lift major components out of the center of the device. The radial dimensions of the building will be determined by the device size, space to move components out of the TF coil windows, access requirements for vacuum pumps, the requirements for transportation right of ways, major component laydown areas for device disassembly, and allowance for clearance during component movements. Additional space may be required for maneuvering of remote maintenance equipment.

Contact maintenance (hands-on) is also a part of the FED maintenance approach. The machine shielding is not sufficient to allow personnel entry into the tokamak area during operation. However, personnel entry is being planned twenty-four hours after tokamak shutdown. This requires sufficient shielding of the irradiated components, the ability to decontaminate the tokamak area, and control of tritium levels.

The major components will be highly radioactive after device operation with tritium. Device disassembly operations and component transport are expected to produce high level radiation in the tokamak area. Thus, personnel entry and movements will be restricted, and disassembly operations of the major components are expected to require remote operations. Initial estimates show that approximately two meters of concrete will be required for adequate shielding during shield sector transit within the tokamak building and hot cell facility.

Safety Functions

The safety functions of the tokamak building will be highly influential in determining the building characteristics. Public safety will have a major impact while most of the important plant worker safety and machine protection issues are dealt with as operating and maintenance functions. The primary public safety issue for FED is the potential release of radioactivity and more specifically the release of tritium. Thus the main safety function of the tokamak building will be to provide a part of the confinement system to prevent or reduce the effects of an accidental release of radioactive material.[2] The definition and design for safety functions of the tokamak building involve establishing acceptable guidelines and standards, determining the consequences of radioactivity releases, and providing design techniques to reduce consequences.

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Safety Standards and Criteria

Safety standards and criteria for the FED are expected to be similar to other large projects which have the possibility for radioactivity release. For DOE projects, the DOE manual[3] and DOE Order[4] 5480.1 provide the basis for establishing safety criteria and gives several applicable guidelines. The policy stated in these references is that DOE and DOE contractor operations be conducted in a manner to assure that radiation exposure to individuals and population groups is limited to as low as reasonably achievable (ALARA). For DOE projects, most of the burden of interpreting the ALARA policy falls under the DOE safety analysis and review system as described by DOE order.[5] This review system will determine when the proposed design meets the intent of the ALARA policy.

Radiological Guidelines. Nevertheless, it is important to establish some appropriate safety criteria guidelines so that preconceptual design activities may proceed before complete safety review is undertaken. Those guidelines which may affect design and construction of the tokamak building need to be identified and their applicability determined. Various guidelines[1,2,4,5,6] are available for different operating conditions, but the events most likely to influence building design are limiting faults which are not expected to occur during the life of the facility. These events are postulated because their consequences would include the potential for the release of significant amounts of radioactive material and because they represent upper bounds on failures or accidents with a probability of occurrence sufficiently high to require consideration in design. Generally, the event would have a probability of occurrence of between 10^{-3} and 10^{-7} per year. The occurrence of these events may cause facility damage which would preclude returning to operation. The consequences of these limiting events can be characterized in a number of ways but are often characterized by the resulting dose rate of the site boundary. A guideline for such limiting events as applied to FED preconceptual design studies is suggested as a maximum of 25 rem at the site boundary.

Confinement System Criteria. The confinement of radioactive release normally involves the development of a confinement system which provides the desired level of protection. Reference 1 contains a discussion of confinement systems which has been reviewed and adapted to the FED situation. Confinement systems should prevent or mitigate the effects of an uncontrolled release of radioactive material such that on-site and off-site doses and effluent concentrations are maintained within recommended guidelines during all facility operating conditions. Current estimates of tritium release consequences confirm that a confinement system is likely to be necessary to maintain on-site and off-site doses and effluent concentrations within the suggested guidelines for the FED design. The design should consider the use of primary, secondary, and tertiary confinement boundaries to provide a defense-in-depth against a release of radioactive material to the environment. When warranted by lesser potential hazards, portions of the facility should be designed with fewer confinement boundaries (e.g., primary and secondary confinement or, in some cases, primary confinement alone).

Typical characteristics of confinement barriers include safety classification recommendations.[2] Even though the safety importance of potential FED confinement systems has not yet been established, the following definitions from Reference 1 are suggested for establishing the safety importance of various FED systems and components.

1. Safety class applies to those components, systems, and structures that are required to prevent or mitigate the consequences of a postulated release of radioactive material that has the potential for causing off-site doses in excess of 0.5 rem to the whole body, or the equivalent to any part of the body.

2. Nonsafety Class components, systems, and structures, are those which are not defined as safety class. The maximum off-site dose resulting from the failure of a nonsafety class system should not exceed 0.5 rem to the whole body, or the equivalent to any part of the body.

The designation of safety class carries with it the adoption of special quality and reliability to establish a high level of assurance that safety class systems will perform their safety related functions. These special attributes will include, among other characteristics, the ability to withstand severe natural phenomena. The implications of safety class designation on design of systems are considerable and will need to be worked out specifically for FED. The determination of safety class requires certain accident and consequence analysis. Since these types of analysis are just beginning for most FED components and systems, no firm determinations of safety class can be made at this time.

Radiological Consequences. The major potential radioactive material which poses a threat to the general public from the FED is tritium. The radiological aspects of released tritium are discussed in Ref. 8. Since the impact of released tritium on the general public is a basic concern, the potential concentration and dose rate at the site boundary due to accidental tritium release are parameters most likely to be established by guidelines. These tritium concentrations and dose rates depend on a wide variety of variables, many of which are site dependent. The distance to the site exclusion boundary, potential wind, atmospheric, and topographical conditions all play major roles in the necessary analysis as well as building and ventilation designs.

Tritium Dose Calculations. The potential environmental effects of tritium are discussed by Rohwer and Wilcox.[8] Several methods for calculating the dose from tritium release are available (e.g., McKone and Kastenberg.[9]). However, all of the methods require information about the plant design and site which is not currently available for FED. Since no site has been selected, no reliable estimates of expected consequences of tritium release can be made for FED. An effort has been made to try to bracket the possible consequences by reviewing published tritium release dose rate calculations[6,7,9] and by making some rough calculations for two different sets of possible FED configurations. The literature review and rough calculations suggest that FED dose rate consequences may lie somewhere between 0.10 and 4.4 rem at the site boundary for each gram of tritium in the oxide form released at ground level. Design features and site selection should be able to assure that potential consequences are below 1 rem at the boundary per gram released. Assuming for this discussion that consequences can be held to 1 rem/g or less, a maximum ground level release of 25 grams of tritium could be tolerated before exceeding the suggested guideline of 25 rem at the site boundary for limiting faults. The FED plant is expected to contain considerably more than 25 grams of tritium (i.e., greater than 1 kilogram). The tokamak building should contain between 10 and 300 grams of tritium during operation depending on design options. Any system which is necessary to prevent the ground level release of 0.5 gram or more of tritium will be a safety class system in keeping with the suggested definition of safety class systems. It appears from the total amount of tritium needed for FED operation that several safety class systems may be required. Favorable conditions could greatly reduce the need for safety class functions and special building features. Unfavorable conditions would require more safety class systems and special building functions to protect against releases of tritium. In between these two extremes is a wide range of possible FED conditions for which varying degrees of protection might be required. In spite of the wide range of uncertainty, the possible uncontrolled tritium releases from FED indicate that confinement techniques will need to be applied to limit the possible consequences of a tritium release.

Design Techniques

The primary safety function of the tokamak building is to prevent or mitigate the consequences of release of radioactive material. In addition to building design features, other system design techniques can be used to reduce consequences of radioactive releases. All the various possibilities must be reviewed in order to assess the building design options.

Since the main radioactive material to be considered for FED is tritium, a general level of effectiveness of any particular design feature can be discussed in terms of the reduction of the consequences of a tritium release. For example, if an unrestrained groundlevel release of 100 grams of tritium had the estimated consequences of 100 rem at the site boundary, then the reduction of the potential release from 100 g to 10 g would have the estimated effect of reducing the dose rate from 100 rem to 10 rem or a reduction factor of 10.

If tritium and cryogenic fluids are released at the same time, they may mix and the volume of gas from the cryogenic fluid vaporization will increase the difficulty of processing or containing the radioactive tritium. Thus the various cryogenic fluid release scenarios will play a major role in establishing the building and confinement system design criteria.

Pressure Vessel Building. One technique that is sometimes used to reduce the consequences of radioactive release is to design the building as a pressure vessel capable of withstanding the limiting accidental release situation. The pressure vessel will then contain all the radioactivity from an unexpected release until slower acting systems can be used to reduce the building pressure and remove the radioactivity. This method has the advantage of being demonstrated and having a very high reduction factor (on the order of 1000 or greater). Reduction factors in this range would reduce potential consequences below the suggested guidelines. However, these advantages can be expensive. A cylindrical or spherical shape is more desirable for pressure vessels than rectangular shapes; and a cylindrical building may cost on the order of 30 to 40 percent more than a rectangular building with the same volume. In addition, a steel liner may be necessary to withstand the overpressure and could more than double the cost of a cylindrical building. Arrangement flexibility and space usage are also somewhat reduced for a cylindrical building.

Confinement Building. If the consequences of possible cryogen vaporization can be reduced without a pressure vessel building, than the simpler and potentially less expensive rectangular building can be used to help control the potential release of tritium. A confinement building would prevent unrestrained ground-level tritium release with ventilation systems and other design techniques used to reduce the consequences of tritium release. A rectangular building could be relatively inexpensively designed to withstand some low amount of overpressure (3 to 5 psi) while maintaining a low leakage rate (on the order of one building volume per day). Such a building could provide a reduction factor of 1.5 to 2 without any other design features depending on the maximum amount of cryogen that could potentially be released. For several types of potential releases which would not involve cryogen release or where the cryogen release is small, a confinement building of this suggested type would contain most of the released tritium, thus yielding a high reduction factor (e.g., 100 to 1000 depending on leakage rates).

Reduce Vulnerable Tritium. One objective of the system design is to reduce the amount of tritium which could be released in an accident. The amount of vulnerable tritium should be made as low as possible. This might be accomplished by reducing the process inventories in the processing equipment, e.g., recycling cryovacuum pumps more often. One possible design alternative that can have a significant impact on the vulnerable tritium within the tokamak building is the choice of vacuum pumping system. The use of compound cryopumps to attain the desired plasma chamber vacuum will result in accumulation of as much as 300 g of tritium on the cryopanels between pump regenerations. On the other hand, the use of turbomolecular vacuum pumps would essentially add no vulnerable tritium. The other major inventory of tritium is in the fueling machine and has been estimated between 10 and 20 g. Thus, the use of turbomolecular pumps instead of cryopumps provides a reduction factor between 15 and 30.

Partitioning the vulnerable tritium within the tokamak building so that postulated accidents will not cause the release of a large fraction of tritium is another design objective. This might be accomplished by using secondary confinement structures capable of withstanding and protecting the enclosed tritium from postulated accidents and capable of preventing further release if the enclosed primary containment system should be breached. The fueling machine and individual vacuum pumps are likely candidates for a secondary confinement structure. A possible feature of these suggested secondary confinement systems might be isolation valves between the equipment and the plasma chamber to reduce the release of the tritium from the equipment if plasma chamber integrity were lost. The reduction factor for these design techniques is expected to be high and could contribute significantly to the overall reduction of consequences.

Partition Cryogens. Since the potential impact of cryogen evaporation is quite significant, another design object should be to reduce the amount of cryogen that could possibly be released by a single accident. This might be accomplished with piping arrangements and valving so that a major cryogen leak in one part of the system does not cause the blowdown of the whole system. For example, each TF coil might be piped separately. The cryostat could be vented separately from the building so that gas from cryogen leakage and evaporation inside the cryostat would not be mixed with any tritium in the building. The reduction factor for these design features could be substantial with the limit being a reduction in cryogen release to the level where it could be handled with no tritium mixing. The separation of cryogen release from tritium releases should be attempted for all important limiting accident scenarios.

Vent Stack. The use of a vent stack is an existing technology which can significantly reduce the consequences of tritium release. By releasing the tritium or other radioactive effluents well above ground level better mixing and greater dispersion is achieved which results in significantly less dose at the boundary. The consequences from the stack effluent can be further reduced by processing or diluting the effluent stream before release. Releasing tritium through a vent stack with no other processing could reduce the consequences by a factor of between five and 100 depending on a number of variables. A factor of five reduction substantially improves the possibilities of meeting the suggested guidelines.

Processing Building Effluent. Processing of the vent system effluent can potentially provide great reductions in tritium release. Emergency tritium removal system may be capable of reducing the tritium concentration by a factor of 10^6. The big problem is processing capacity. For FED the processing rate would have to be on the order of the cryogen evaporation rate to have a significant impact on the limiting events. No accident anlaysis has been performed to estimate the potential cryogen evaporation rates for FED, but these rates may be fairly substantial. However, it appears that processing systems can be developed which would provide significant reduction in the tritium released for many FED cases.

Form of Released Tritium. One very important aspect of the potential consequences of tritium release is the form of the tritium. Tritium in the gaseous form, HT or T_2, has a very small biological effect because it is not taken up rapidly by the body. On the other hand, tritium in the form of water, HTO or T_2O, has a large biological effect because it is readily absorbed into the body. The dose consequences are roughly estimated to be on the order of 10,000 times less for the gaseous form than for the water form. Thus, design efforts should be directed toward assuring that as high a fraction of gas as possible is maintained for any tritium release. One way to help achieve this objective is to try to avoid fires in conjunction with tritium release. Review[10] of past tritium gas releases suggests that no more than one percent of the releases were converted from gaseous to oxide form. This effect by itself would result in a potential reduction factor of 100.

Site Characteristics. Since site characteristics can have a major influence on the consequences of radioactive releases, it follows that site selection criteria can influence the radiological consequences. Such characteristics as site exclusion boundary and population density of the surrounding areas directly affect the dose rate at the boundary and postulated average population dose resulting from tritium releases. Large distances from the plant to the site boundary can significantly reduce the consequences of tritium release.

Discussion. A number of design techniques are available to help reduce the consequences of tritium release. The feasibility of designing a combination of systems to provide adequate protection from tritium release appears to be likely. Design alternatives will probably be decided based on potential impact on cost and schedule. It does not appear necessary to use a pressure vessel building to meet FED safety requirement, A rectangular building should allow the use of less expensive and quicker construction techniques and should provide more flexible and efficient site arrangements.

Conclusions

The principle conclusion of the initial review of tokamak design considerations is that the necessary building characteristics can be provided using current design and construction techniques. The main questions are those of cost and schedular impacts and not feasibility. This discussion supports the position of not providing a pressure vessel tokamak building for tritium confinement which allows selection of a potentially less expensive rectangular building. A variety of design techniques are available to significantly reduce the probability and consequences of tritium release and appear to be applicable to FED. The size of the building will be dictated by the operating and maintenance requirements, while the construction quality and other building characteristics will likely be determined by safety considerations. At least some of the building functions will probably require a safety class designation which implies greater operating reliability than normal construction techniques.

References

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