Review Article

Health Physics Aspects of an Inertial Confinement Fusion Power Facility

Joseph Bevelacqua[1]

1. Bevelacqua Resources, United States

Recent advances at the National Ignition Facility resulted in the achievement of fusion ignition using inertial confinement. This milestone event provided positive evidence for the potential viability of an inertial confinement power facility. Although these achievements are important advances, numerous challenges remain for the construction and sustained operation of a fusion power facility based on inertial confinement. These open issues significantly impact the associated radiological hazards. Definitive radiological consequences cannot be assessed until a final design is forthcoming, and operational experience is gained.

Corresponding author: J. J. Bevelacqua, bevelresou@aol.com

1. Introduction

Concepts for the development of a fusion power facility involve two major approaches. The first utilizes magnetic confinement to contain the fusion reaction. Magnetic confinement fusion utilizes magnetic fields to contain the plasma inside a toroidal vacuum vessel, and provides a stable environment for the reaction to occur and be sustained. This approach and its health physics consequences were addressed in previous publications [1][2][3][4][5][6].

The second method, inertial confinement fusion (ICF), utilizes an energy source (typically a laser) to heat and compress fuel material composed of deuterium and tritium. Laser power creates the high temperatures, pressures, and densities to initiate fusion. These laser induced conditions compress the fuel, and plasma confinement is achieved by inertia. The ICF approach creates the necessary conditions for the fusion reaction to occur. Numerous publications address the ICF approach [7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28].

In the ICF process, the fuel maintains a compressed state until it naturally relaxes after the fusion event. ICF must sustain this confinement and fusion reaction through multiple fusion events. During this fusion process, energy must be extracted to form a driving force for electricity production. Typically, the energy is used to boil a working fluid (usually light water) to produce steam that drives a turbine/generator to produce electricity. There are significant engineering challenges to sustaining the fusion reaction, extracting energy, and maintaining these processes in a stable and sustained manner.

In ICF, the laser creates an energy wave in the target that occurs in a time frame on the order of a fraction of a nanosecond. ICF events are pulsed and must be cyclically repeated. Energy extracted from the target should be achieved in a manner that does not interfere with subsequent fusion events. A necessary condition for a successful ICF facility is that the total energy output must exceed the energy input. To date this has yet to be achieved.

In 2002, the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory demonstrated that a controlled fusion reaction could produce more energy output than the energy input into the fuel target [23][24][25]. In particular, the ICF reaction yielded 3.2 MJ from an energy input of 2.1 MJ. However, significantly more energy was required to produce the 2.1 MJ of input laser energy. This NIF achievement has motivated numerous commercial organizations to pursue the ICF approach to develop a fusion power facility.

Additional descriptions of the ICF process and its progress are provided in Refs. [7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26]. These papers focus on basic principles and not the health physics aspects of this emerging power generating technology. This paper will review the current challenges to the development of an ICF power facility, and will focus on their health physics considerations.

This review is challenging because there is no definitive ICF design for a power facility, and no fusion prototype power reactor exists. The descriptions and design summaries assume that the radiological hazards will be qualitatively consistent with fission power reactor and ITER design criteria.

2. Basic ICF Fusion Reaction

Although there are numerous candidate fusion reactions, the baseline ICF process utilizes a deuterium (D or ^{2}H) plus tritium (T or ^{3}H) reaction. This reaction produces a ^{4}He nucleus and a high energy neutron

$^{2}H + ^{3}H \rightarrow ^{4}He$ (3.5 MeV) + n (14.1 MeV) (1)

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where the energy values in parenthesis are threshold values. There are significant health physics and fusion design consequences that result from this reaction.

The alpha particles can impact subsequent ICF reactions. This is particularly important because the ICF process is cyclic and reaction energy and fusion products must be extracted in a manner that does not perturb subsequent fusion events. The alpha particle interactions, energy transfer effectiveness, and impact of subsequent reactions are open issues that must be resolved before a production scale ICF power facility becomes a reality.

The 14.1 MeV neutrons are a health physics concern. These high linear energy transfer particles will be a significant contributor to occupational radiation doses. Radiation shielding can minimize these radiological effects.

These neutrons also produce activation products in the materials comprising the ICF reaction chamber and the hohlraum enclosing the fuel. In view of uncertainties in the materials utilized in the chamber, specific reaction products produced in a production scale facility can not be identified. A listing of candidate activation products in a magnetic confinement fusion device is provided in Refs. [1][2][6].

The fusion reaction products and their subsequent interactions present both an internal as well as external source of radiation exposure. Airborne activation products must be carefully controlled and monitored.

In addition to creating activation products, the 14.1 MeV neutrons will produce radiation damage to systems, structures, and components that are in the vicinity of the ICF reaction chamber. This radiation damage could require periodic maintenance activities that will increase worker doses due to component replacement and repair activities in elevated radiation fields. Depending on the dose rates, remote maintenance may be required for component repair and replacement.

3. Comparison of ICF and Fission Reactors

The ICF plant design is not well established. This is in contrast with the magnetic confinement facility that has the ITER and DEMO designs that are significantly more advanced [1][2][3][4][5][6]. ITER is currently under construction.

Table 1 compares ICF and fission reactor radiological source terms. A number of health physics considerations including radioiodine, noble gases, particulates, tritium, activation products, ^{16}N, laser radiation, and fission products are summarized. Given limited ICF design specificity, Table 1 provides a

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generic description of the health physics hazards. Extrapolations of these hazards to a generic ICF design are provided in subsequent discussion. However, given the DT fuel material, it is likely that the dominant fusion reaction products are the neutrons and alpha particles noted in Eq. 1. There is the possibility that fusion products could be produced in the materials comprising the hohlraum. Given these uncertainties, no further discussion of fusion reaction products is provided. In addition, there are other options to the use of a hohlraum. The direct drive approach will be addressed in subsequent discussion.

Radiation Component	**ICF**	**Fission**
Radioiodine	None	• Internal hazard • Significant offsite dose consideration during a severe accident
Noble gasses	None	• Submersion hazard • Significant offsite dose consideration during a severe accident
Particulates	• Internal hazard • High energy fusion neutrons create a wealth of activation products • Activation products contribute to offsite and worker doses	• Internal hazard • Fission neutron spectrum creates activation products • Activation and fission products contribute to offsite and worker
Tritium	• The unfused tritium fuel is an internal radiation hazard	• Copiously produced in pressurized water reactors • Internal radiation hazard
Activation Products	• Specific radionuclides depend on the fusion reaction chamber materials	• Produced copiously and contribute to worker and severe accident doses
^{16}N	• 14.1 MeV neutrons create a ^{16}N hazard near primary coolant piping	• Fission neutron spectrum creates a ^{16}N hazard near primary coolant piping.
Laser Radiation	• Class 4 laser support systems can produce x-rays • Requires controls to limit worker exposure	• None
Fission Products	• None	• Noble gases, particulates, and radioiodine

Radiation Component	ICF	Fission
Fusion Products	• Neutrons and alpha particles • Other radionuclides depend on the fuel material constituents including the hohlraum materials and impurities	• None
Spent Fuel	• None	• Contains copious quantities of long-lived actinides and fission products. • No permanent disposal option is available.
High Level Waste	• None	• Spent fuel contains plutonium and minor actinides
Actinides	• None	• Pu, Am, Np, and Cm present an obstacle to licensing a permanent disposal facility

Table 1. Comparison of Inertial Confinement Fusion and Fission Reactor Radiological Source Terms

4. Inertial Confinement

A generalized ICF process description includes the fuel material that could be encased in a hohlraum, and the fusion reaction occurs within this structure. The fuel is irradiated by laser radiation from multiple devices [10][14][19]. The outer layers of the fuel are heated and form a plasma. The pressure from the laser induced plasma forces the interior of the fuel capsule to implode. Qualitatively, implosion results in the formation of a hot zone that is encompassed by denser, cooler fuel material. The formation of this hot zone drives ignition of the plasma reaction of Eq. 1. Once ignition is achieved, the fusing fuel expands outward. The released fusion energy can be captured and used to produce electricity.

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This generic ICF description can be more specifically defined if the direct drive or indirect drive fusion approach is specified. In the direct drive approach, nanosecond pulse duration laser energy impinges upon a capsule of DT fuel. The fuel is heated and compressed, and the inertia of the fuel material confines it for a sufficient duration to become a burning plasma. Given these conditions, the fuel has obtained sufficient pressure, temperature, and density to sustain the fusion reaction.

In an indirect drive model, the laser radiation irradiates the DT fuel that is encased in a cylindrical container or hohlraum. The laser energy produces x-rays in the hohlraum. These x-rays provide the energy to heat the DT fuel to create and sustain the fusion reaction.

Given the success at the NIF, it is likely that the indirect drive approach creates a relatively uniform compression wave that generates sufficient pressure, temperature, and density to facilitate the fusion reaction. If this correct, the uniformity will minimize any plasma instabilities in the initial phase of the fusion process.

Indirect drive is likely less efficient than direct drive. The conversion of laser energy into x-rays in the hohlraum is less than 100% efficient. This loss of energy efficiency, that must be determined, needs to be minimized for a commercial scale ICF facility using indirect drive to become a viable production approach.

Although this paper only outlines the current DT approach, there are numerous other possible approaches to producing an ICF facility. For example, the $^{11}B + {}^{1}H$ approach has a number of potential positive aspects [29].

Following the DT fusion, most of the 14.1 MeV neutrons escape the fuel, but the alpha particles are attenuated and deposit a portion of their energy. For ignition to occur a number of conditions must be met. First, the fuel temperature should be about $50 - 60 \times 10^6$ K (about 5 keV). Second, a significant part of the alpha particle energy must be absorbed in the fuel. In addition, pressures must exceed those in the Solar interior by approximately a factor of two[10][14].

Heating of the fuel by the deposition of alpha energy remains an open issue. Alpha heating of the fuel has yet to be verified in a fusion reactor environment.

The deposition of ICF energy, requires that the laser pulse be shaped to ensure a smooth, uniform compression of the fuel. A spherical, compression requires precise impingement of the laser beams. Any instability, perturbation, or imperfection in the fuel material or the hohlraum could impact the fusion

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reaction and sustainability of the ICF process. In addition, any fuel or hohlraum impurities could cause foreign material to contaminate the plasma and affect the stability of the ICF process.

5. National Ignition Facility Results

Although the NIF was not designed to produce power, it is an important test bed to demonstrate the efficacy of the ICF approach. At NIF, the indirect drive model is utilized. This approach was selected because Lawrence Livermore National Laboratory believed that this model provides better control of the stability and symmetry of the fusion reaction occurring within the hohlraum enclosed fuel[19][22].

The NIF fuel target is a 1 cm length cylindrical hohlraum that encloses a hollow spherical DT fuel capsule. The hohlraum is irradiated by 192 laser beams that deliver 15 – 25 ns pulses of 350 nm laser light. The total energy delivered by the lasers is about 2 MJ with a peak power of about 500 TW[19][22]. A summary of recent NIF test results is shown in Table 2.

In Table 2, the energy delivered to the target E_{in}, energy output from the target E_{out}, and target gain (G) defined as the ratio of $E_{ou}t/E_{in}$ are provided. The trend in results is encouraging and supports the potential viability of the ICF approach.

Date	E_{in} (MJ)	E_{out} (MJ)	G
December 5, 2022	2.05	3.15	1.54
July 30, 2023	2.05	3.88	1.89
October 8, 2023	1.9	2.4	1.26
October 30, 2023	2.2	3.4	1.55
February 12, 2024	2.22	5.2	2.34

Table 2. NIF Performance 2022 – 2024[a]

[a] Derived from Ref.[22].

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6. Selected Open Issues

The results of Table 2 are encouraging, but a number of issues must be recognized. The following open issues require resolution for achieving a viable ICF design. These issues are representative of the ICF challenges, but the listing is not complete. Other issues associated with the Table 2 items may require resolution, and new challenges will likely emerge as the ICF design evolves.

First, the energy required to power lasers and the balance of plant systems supporting laser operation have not been included in Table 2. Accordingly, significant improvements in laser efficiency must be achieved. Improvements in laser efficiency and power level are possible. However, additional progress and laser development are required for a production scale ICF facility to become a viable enterprise.

Second, there is no proven method to extract the fusion energy efficiently and produce electricity. Heat transfer is well established in a fission reactor, but the temperature gradients are less severe. An effective heat transfer approach has yet to be demonstrated in a fusion reactor.

Third, the required fusion repetition rate has yet to be demonstrated. Sequentially loading fuel, and creating sustaining fusion events without interfering with a previous event has yet to be demonstrated.

Fourth, cost effective construction of fuel / hohlraum components is required, but this has yet to be achieved. Mass production of fuel must minimize contaminants and achieve the design material specifications. Both fuel and hohlraum production must ensure the required quality and desired quality.

Fifth, a successful method for fuel injection and reaction product removal has yet to be developed. The fueling and extraction of heat and fusion products must be achieved in a manner that minimizes plasma perturbations and sustains the fusion reaction.

Sixth, materials utilized in the various system components must meet the temperature and pressure extremes of the ICF reaction chamber. These materials must also withstand the neutron, gamma, and alpha impacts and associated radiation damage on the ICF reaction chamber and support systems. Significant development will be required to produce materials that meet the ICF operating requirements.

Finally, sufficient tritium inventories do not currently exist. The method to produce tritium in blanket assemblies is a possible solution, but has yet to be demonstrated. Other production approaches using fission reactors have yet to be successful on a scale that is required to sustain a fleet of ICF power facilities.

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6.1. Engineering Considerations

As noted previously, numerous engineering issues must be overcome for an ICF power facility to reach production scale maturity. A portion of these is provided in subsequent discussion.

6.2. Lasers

Ref.[19] suggests that 0.25 is the maximum fraction of energy used to power the laser systems in order to ensure a viable design. In addition, the product of the target gain and laser efficiency should be on the order of 10 for a viable ICF design. Ref.[19] indicates these goals can be achieved if the fuel injection repetition rate achieves at least several fuel target fusion events/s. Refs.[7][9][26][27] suggest that there are significant avenues for improvement in the ICF process beyond the current NIF baseline. However, these improvements must be achieved and associated assumptions verified for an economical plant design.

The NIF currently uses flash lamp pumped glass lasers that have a relatively low efficiency[19]. These devices are limited to single-shot operations, but a production scale ICF facility requires multiply-pulsed lasers to support continuous operations.

The NIF lasers could be replaced with higher efficiency diode pumped lasers, but these systems would need to be developed to reach MJ power levels. Other options for an ICF facility could include excimer lasers (noble gas plus halogen lasing medium). Once developed to the requisite pulse repetition rate and power levels, these lasers could provide an improved performance level over the current NIF devices[19].

Laser development is one of the technical upgrades that needs to be achieved. Development programs and proposed enhancements at US National Laboratories and private industry have a reasonable probability of achieving the ICF laser requirements. However, success is dependent on technical advances.

6.3. Energy Extraction

The ICF facility must effectively interface with conventional steam/turbine generator systems to extract the fusion energy and produce electricity, or a new heat transfer approach must be developed. Conventional heat transfer systems are used in fission power facilities and have an efficiency of about 40%. The economics of an ICF power facility must account for this efficiency, as well as the power requirements for laser systems and balance of plant equipment (e.g., fueling systems, pumps, valves, ventilation systems, and safety systems).

6.4. Fuel Targets

Currently NIF fuel targets are made in limited quantities by National laboratory personnel. This is a labor intensive process that would not support the volume of targets required in an ICF production scale facility. For a commercial power facility, approximately 10^6 fuel targets per day would need to be produced for sustained power operations[19]. This level of production requires an automated production process that would reduce costs, and increase the efficiency and quality of the fuel targets.

These production advances have yet to be achieved and remain an open ICF issue. In addition, quality requires that a minimum of contaminants be part of the hohlraum and fuel materials. Any contaminants could affect sustained plasma operations and must be rigorously controlled.

6.5. ICF System Considerations

In a production scale ICF power facility, the plasma chamber would be supported by a number of systems. These include laser support systems and components, tritium breeding-blanket assemblies, fuel injection system, plasma waste contaminant extraction systems, and instrumentation and control systems. These systems provide critical support functions for a production scale ICF facility. An ICF power facility will not be possible without the development of these systems at the requisite scale. There is currently no proven production scale design for these support systems.

6.5.1. Laser Support Systems and Components

The ICF laser support systems are expected to be located in a separate structure that is physically separated from the plasma reaction chamber. This separation minimizes the health physics hazards associated with system maintenance. These components are physically removed from locations directly exposed to fusion neutrons and photons, and should not contain radioactive materials and activated structures.

6.5.2. Tritium Breeding-Blanket Assemblies

The limited availability of tritium necessitates the need to evaluate a mechanism to produce the fuel material for an ICF power facility. A decision regarding the need to incorporate a breeding-blanket depends upon the availability of tritium fuel, production cost, efficiency of the proposed design, and actual operating experience. There is currently no viable tritium breeding-blanket design capable of supporting sustained ICF power operations.

6.5.3. Fuel Injection System

The fuel injection system must be developed to insert hohlraum capsules (indirect drive) or fuel pellets (direct drive) in a manner that sustains plasma operations. System performance must be reliable and synchronized with the waste extraction system to ensure that an ICF production facility is economically viable. A proven fuel injection system, capable of supporting sustained plasma operations, has yet to be developed.

6.5.4. Plasma Waste Contaminant Extraction Systems

Any impurities generated or remaining after the generation of the fusion plasma, should be removed for subsequent events to be sustainable. Impurities could perturb or alter the plasma, and reduce the power generated by subsequent fusion events. Removal of unwanted waste products as they are generated enhances ICF efficiency and maintains the system in a state that permits subsequent fusion events to occur. To date, no production scale waste extraction system has been demonstrated,

6.5.5. Instrumentation and Control Systems

Instrumentation and control (I&C) systems would include radiation monitoring systems and detectors to monitor the fusion reaction and devices to measure output power, plasma parameters, contaminants, and fusion reaction products. Additional instrumentation will need to be developed to monitor cooling water flows, fusion chamber pressure and temperature, primary and secondary system flow parameters, and system leak rates. The final I&C system configuration will depend on the plant design and the facility integration and control concept.

7. Fusion Licensing Basis

In July 2024, Congressional Action directed that fusion energy systems to be deployed through the 2030s be governed using the regulatory requirements designed to control particle accelerators. This decision reduces the licensing requirements that would have subjected fusion reactor systems to the more rigorous regulations used for fission reactors[30][31]. This action is consistent with the Nuclear Regulatory Commission's (NRC) decision to classify the radioactive materials produced by the fusion process to be byproduct material[28].

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The byproduct material classification is less restrictive than the licensing requirements associated with nuclear fission. This classification presents fewer regulatory requirements than the special nuclear material classification (e.g., enriched uranium and plutonium) utilized in fission reactor licensing. An initial rule governing low power fusion power system licensing is expected in 2025. The NRC Commissioners also directed the NRC staff to review this initial licensing basis if fusion power systems present additional hazards (e.g., a commercial scale plant).

In view of the uncertainties in licensing a one GW-scale electric fusion power facility, and the increase in hazards over prototype reactors, this paper assumes additional hazards will be present and require a revised licensing basis. This philosophy is included in subsequent discussion involving the description of the health physics hazards associated with a full scale fusion power facility. These health physics requirements are specified in the Code of Federal Regulations 10CFR20[30] and 10CFR835[31]. The applicable regulatory requirements will depend on the appropriate government agency's licensing basis requirements (i.e., NRC or Department of Energy (DOE)), and will likely be an analogue of 10CFR50 .

8. ICF Energy Sources

Various energy sources inherent to an ICF facility could release tritium, fusion products, activation products, and other materials following an accident or off-normal event. There are a variety of ICF energy sources that could provide a means to mobilize radioactive and toxic materials. These energy sources, possible consequences of their discharge, and control measures are summarized in Table 3. All of these energy sources have the potential to mobilize radioactive material and lead to elevated onsite and offsite doses.

The reader is cautioned that the extrapolation of the ITER power and energy design conditions[8] to ICF is speculative. However, it will suffice until a detailed ICF design emerges. Accordingly, the content summarized in Table 3 should be considered an initial first-order estimate.

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Energy Source	Power or Energy	Potential Consequences of Energy Discharge	Design Control Measures
Fusion Power	~ GW	• Melting of plasma chamber components • In-vessel loss of coolant accidents • Mobilization and release of ICF reaction chamber materials, activation products, and tritium.	• Coolant systems design and control systems • Fusion power shutdown systems design • Passive shutdown systems for major transients
Plasma	~ GJ	• Energy releases following a plasma transient damage the ICF reaction chamber and associated systems • Damage to reaction chamber components leads to a release of radioactive material	• Plasma control systems • ICF design and energy dissipation systems
Activation Product Decay Heat	~ 0.1 1 GJ	• Heating near plasma chamber components and materials • Waste management concerns due to replacement of activated components • Decay heat is a driving force to mobilize radioactive materials	• Process control of decay heat production • Defense in depth design features • Design cooling system operations • Active decay heat removal systems • Passive heat removal using radiative heat transfer and natural circulation cooling

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Energy Source	Power or Energy	Potential Consequences of Energy Discharge	Design Control Measures
Chemical (following a fusion chamber reaction)	~ GJ	• Overheating of reaction chamber components • Hydrogen fires or explosions • Overpressurization or damage to the ICF reaction chamber • Driving force to mobilize radioactive materials	• Limit temperature increases on the reaction chamber walls • Design measures to minimize the accumulation of fusion generated materials
Coolant leakage	~100 GJ	• Pressurization of ICF reaction chamber and heat transport system • Pressurization creates a driving force for radioactive material mobilization	• Overpressure suppression systems

Table 3. Estimated ICF Energy and Power Inventories

9. Health Physics Issues

In an ICF power facility, normal, abnormal, and emergency conditions impact the health physics response and subsequent radiation exposure of workers. These occupationally exposed workers include all groups (e.g., operations, maintenance, engineering, and health physics). Tables 4, 5, and 6 provide a summary of projected activities during normal, abnormal, and emergency plant conditions, respectively. For each activity, health physics concerns and mitigating controls are provided. In these tables, the term fusion products allow for other nuclear reactions following the fusion event.

In general, radiological hazards arise from neutron radiation and tritium that was not consumed in fusion reactions. Any unfused tritium at an ICF facility will present similar radiological hazards that occur at D_2O cooled/moderated Canadian deuterium (CANDU) reactors[1][2][3][4][5]. ICF neutron hazards are expected to be similar to those that occur at a fission reactor or low-energy accelerator facility.

An ICF fusion power facility will contain a number of unique plant systems. Their configuration and operational characteristics will depend on the final design basis. These systems could include:

tritium/hohlraum injection, plasma cleanup, tritium breeding-blankets, tritium recovery, vacuum control, and plasma control. The occupational dose associated with the maintenance, repair, and operation of these systems will depend on the specific ICF design, performance, and operating characteristics. For an ICF facility, this information is not yet available.

9.1. Normal Operations

Routine operations and maintenance activities involve the use of radioactive materials and workers are protected from these hazards by engineered safety features, strict procedural compliance, and work controlled by radiological work permits. In addition, as low as reasonably achievable (ALARA) reviews are performed for high dose operations. These essential documents and health physics job coverage ensure that activities incur limited worker exposures, and maintain a level of radiological control consistent with regulatory requirements[30][31]. Table 4 summarizes a set of routine ICF operations, and notes their associated health physics concerns. Controls utilized to mitigate the associated hazards are also provided.

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Activity	Health Physics Concern	Controls
ICF reaction chamber maintenance and component replacement during facility outages	• Direct dose from activated components • Internal doses from airborne activation products • Tritium intakes from reaction chamber contamination	• Radiation work permit restrictions (e.g., protective clothing, respiratory protection, and eye protection) based on survey data of the radiological conditions minimize worker doses. • Engineering controls (e.g., local ventilation) minimizes the release of airborne radioactive material.
Neutron activation of the cooling medium (e.g., water)	• The $^{16}O(n, p)^{16}N$ reaction is facilitated by the 14.1 MeV fusion neutrons	• Delay lines permit the ^{16}N to decay before reaching occupies areas • Shielding to attenuate the capture gamma and neutron radiation
Routine maintenance and calibration activities (e.g., pumps, valves, and instrumentation)	• Mobilization of activation products and tritium	• Radiation work permit restrictions • Engineering controls
DT fueling operations	• Tritium intakes	• Remote insertion of DT hohlraums or fuel capsuled minimizes worker exposures • Fueling system control measures
Heat exchanger/steam generator maintenance (e.g., tube plugging and eddy current testing)	• Tube leakage transports radioactive materials to clean areas of the facility	• Radiation work permit restrictions • Engineering controls
Radioactive waste processing	• I nternal and external doses are incurred from waste materials processing (e.g., activated	• Radiation work permit restrictions • Engineering controls

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Activity	Health Physics Concern	Controls
	components, protective clothing, and damaged equipment)	

Table 4. Normal ICF Operational Activities

9.2. Abnormal Operations

In spite of rigorous procedural controls, radiological work permits, and health physics oversight, off normal events occur as a results of component failures, fires, inclement weather, personnel errors, and loss of control of radioactive material. Abnormal operations produce a more significant radiological hazard, and a dedicated set of Abnormal Operating Procedures are developed to govern the plant response. Examples of ICF abnormal conditions are summarized in Table 5 that includes the associated radiological hazards, and mitigation measures.

Activity	Health Physics Concern	Controls
Reduction in component and reaction chamber cooling flow	• Overheating of reactor components could lead to a localized release of tritium and activation products.	• -Termination of the fusion process via reactor trip • -Supplemental systems reestablish cooling
Elevated direct radiation levels in localized plant areas	• -Increased worker doses	• -Interlocks terminate the fusion reaction • -Local radiation monitors alarm that signals workers to evacuate the effected areas
Elevated airborne activity levels in localized plant areas	• Increased worker internal doses	• Interlocks isolate breached systems to mitigate the release • Local airborne radiation monitors
Loss of power to localized plant areas	• Loss of plant and radiological assessment capability • Failure of engineering systems designed to control radioactive material	• Emergency power systems restore effected systems
Security events affecting equipment and facility areas	• Intruder affects systems that impact the control of radioactive material • Damage to systems that could impact safety related equipment.	• Security response plans • Health physics response
Fire in localized plant areas	• Mobilizes radioactive material	• Fire brigade response • Health physics response
Abnormal weather	• Unusual weather (e.g., high winds, flooding, and snowfall) damages power supplies and safety	• Emergency power systems restore effected systems • Local radiation monitors

Activity	Health Physics Concern	Controls
	systems leading to releases of radioactive materials to localized plant areas	• Operator actions isolate damaged systems
Limited seismic event	• The event damages power supplies and safety systems	• Emergency power systems restore effected systems • Local radiation monitors • Operator actions isolate damaged systems

Table 5. Abnormal ICF Abnormal Operating Conditions

9.3. Emergency Operations

Conditions more severe than the abnormal operating conditions require additional control and plant support. An emergency condition presents a significant potential for the release of radioactive material to the environment. In view of this possibility, a dedicated emergency response organization exists to minimize the effects of these emergency conditions. The facility design includes barriers and engineered safety features to minimize the effects of the emergency condition. These emergency conditions, their health physics consequences, and mitigating measures are summarized in Table 6.

Table 6 provides a listing of potential ICF emergency conditions. Each of these events has the potential to mobilize radioactive material that could be released to the environment. The fusion design basis accidents are not readily defined without a specific ICF concept. Their specific form and content will likely differ significantly from fission accidents [2][3][4][15].

The ICF fusion power facility will not produce actinides, noble gases, and radioiodine that are typical of a fission facility source term (See Table 1). However, activation products and tritium could be released. The specific release source term will depend on a number of considerations including the design fuel and hohlraum materials, the materials of construction of the ICF vacuum chamber, and composition of balance of plant equipment subjected to the fusion neutron spectrum.

Tritium will also be part of the fusion facility source term [2][3][4][15]. The ICF chamber exhaust system that vents unfused tritium will be an important consideration in any offsite release scenario. In addition, the inclusion of a containment structure and tritium retention systems in the design basis will also impact the release consequences.

In Table 6, the listed controls are similar to those utilized in fission reactors. These features would be part of the design basis engineering controls that are part of an integrated plant protection approach. The assumed controls could include a containment structure that may be required to mitigate offsite releases of radioactive materials. The addition of a containment will depend on the final design and associated accident analysis.

Failure of safety systems, power supplies, radioactive materials barriers, and containment structures would lead to a loss of control of radioactive materials. These failures could lead to a release of radioactive materials to plant areas and the environment.

Event/Activity	Health Physics Concern	Controls
Loss of offsite power	• Loss of power to safety systems and radioactive materials barriers	• Emergency AC diesel generators • DC battery systems • Emergency response procedures
Loss or degradation of coolant flow	• Failure of reaction chamber cooling system components	• Emergency cooling systems • Emergency response procedures • Engineered safety systems
Hydrogen/tritium detonation	• Accumulation of hydrogen gas leads to an explosion that damages safety systems	• Safety features designed to withstand the explosion (i.e., fuel design, ICF reaction chamber, and containment building) mitigate the release
Loss of radioactive materials barriers	• Breaching of barriers facilitates the release of radioactive material	• Emergency response procedures • Engineered safety systems
Fueling system damage	• Significant damage to the DT fueling system releases tritium	• Emergency safety system features • Emergency response procedures
Major security event	• Unauthorized individuals enter the facility and damage safety systems and power supplies	• Emergency response procedures facilitate the return of safety system functions and power supplies • Security response procedures mitigate the threat • Surviving safety systems and design features mitigate the event
Extreme weather	• Extreme weather (e.g., tornados, hurricanes, tsunami, 100 year floods, and 100 year snowfall) damages power supplies and safety systems	• Emergency response procedures • Engineered safety systems

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Event/Activity	Health Physics Concern	Controls
Major seismic event	• Damage to radioactive materials barriers, safety systems and power supplies	• Emergency response procedures • Engineered safety systems
Aircraft crash	• Damage to radioactive materials barriers, safety systems and power supplies	• Emergency response procedures • Engineered safety systems
Major fire	• Mobilizes radioactive material	• Fire brigade response • Emergency response procedures • Engineered safety systems

Table 6. ICF Emergency Conditions

The release of fusion generated radioactive materials and tritium following an emergency event will be mitigated by a set of barriers specified by the ICF design basis. These barriers are summarized in Table 7. The candidate barriers include the fuel and it hohlraum/capsule, the ICF reaction chamber and its included components, and if required a containment building.

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Barrier	Function
Fuel and Enclosing Hohlraum or Fuel Capsule	• Contains ^{3}H and minimizes its release to plant areas and the environment
Fusion Reaction Chamber and Included Components	• Contains activation products and tritium within its boundary
Containment Structure	• If deemed to be warranted by the ICF facility design, this structure provides an additional barrier to the release of activation products and tritium to the environment

Table 7. ICF Radioactive Material Barriers

10. Unique Hazards Affecting Worker Doses

The ICF power facility is unique because fusion is utilized to generate heat. This is analogous to existing nuclear power facilities that utilize the fission of uranium, plutonium, and thorium as the heat production mechanism. Therefore, the balance of plant equipment (i.e., components outside a fusion reaction chamber and associated containment structure) should be similar in function and purpose to existing fission reactor systems, and present analogous worker hazards. However, the systems, structures, and components utilized to control the reaction and extract heat from the fusion process may be unique due to the differences in the fission and fusion reactions. These differences include plasma temperature, density, and pressure, reaction chamber pressure and temperature, and heat extraction chamber pressure and temperature.

The associated fusion systems will encounter temperature extremes beyond those encountered in a fission facility. Unique materials may be required to facilitate the transfer of heat in a fusion power plant. After the initial fusion heat is transferred to the cooling medium, subsequent transfers to conventional steam generators could introduce additional hazards beyond those encountered in a fission reactor.

Many of the health physics issues associated with fission reactor steam generators should bound fusion reactor events. Given the absence of fission gases and iodine, the associated fusion related steam generator events should be less severe. In a fission reactor, the coolant is in direct contact with the fuel, and this contact leads to the deposition of radioactive material on the surfaces of the steam generator tubes in contact with the primary (contaminated) coolant. The contaminated coolant in a fission reactor is also a significant contributor to releases of radioactive material to the environment following on off-normal event (e.g., steam generator tube ruptures[2][3][4][15]).

The ICF cooling water should not be in direct contact with the DT fuel. Worker doses from the radioactive material in the coolant and maintenance and repair work on steam generator and support systems should be less significant than in fission reactors.

ICF laser radiation presents a nonionizing hazard. Since the lasers are physically removed from the fusion reaction chamber, there should be limited radiological impact on work in the vicinity of the laser systems. However, any misalignment of the laser systems could result in reaction chamber impacts. The consequences of these impacts on sustained plasma operations, damage to the reaction chamber, creation of debris that could impact plasma operations, and mobilization of activated debris on worker doses have yet to be evaluated.

High power laser support equipment can have an associated x-ray hazard.[1][2][3][4][5]. The x-ray hazard is managed with a variety of controls including shielding, access restrictions, and remote maintenance and repair operations.

The reaction chamber will be subjected to damage caused by the 14.1 MeV fusion neutrons. Materials comprising the reaction chamber will also suffer neutron activation. The activated chamber structure presents an external radiation hazard to personnel during maintenance, repair, and refurbishment operations. Any particulate material generated from the chamber wall materials presents an internal radiation hazard as well as a possible source to be released to the environment during an off normal event. Appropriate radiological controls are needed to minimize worker doses. The extent of these controls depends on the doses and quantity of material generated in the reaction chamber.

Neutron damage to the reaction chamber may require periodic replacement of the chamber and support equipment. These activities are likely to be dose intensive and require remote operations to minimize worker exposures. If these conditions occur, their impact will depend on the specific ICF design and its operational characteristics. The reaction chamber design and lifetime are significant open issues.

11. Accident Scenarios/Design Basis Events

The previous discussion of possible normal, abnormal, and emergency operations provides a basis for developing a set of accident scenarios and design basis events that an ICF facility will be required to meet. These projected accident scenarios include events based on fission reactor designs and the ITER fusion prototype (e.g., loss of coolant accidents (LOCAs), loss of flow accidents (LOFAs), loss of vacuum accidents (LOVAs), and plasma transients)[6][8].

11.1. Loss of Coolant Accidents

In a conventional light water fission reactor, a LOCAs is a serious event because the water coolant transfers heat from the fuel[1][2][3][4][5][15]. Any reduction in heat transfer from fuel to coolant can result in fuel damage or melting. From a health physics perspective, a LOCA at an ICF facility would limit cooling of safety related systems that could release radioactive material (e.g., activation products and tritium) into facility areas and potentially to the environment.

At an ICF power facility, LOCAs could impact reaction chamber components and the integrity of the chamber itself. Coolant loss would increase reaction chamber temperature and pressure with a subsequent impact on structural integrity. Line breaks inject coolant into the reaction chamber that could cause an overpressurization event as well as chemical reactions with the chamber components and materials.

During plasma operations, any coolant entering the reaction chamber would disrupt and terminate the fusion reaction. A thermal or chemically induced reaction would facilitate the dispersal of radioactive material. Tritium and activation products would be expected to dominate the LOCA accident source term. The severity of a LOCA would depend on ICF design characteristics, its operating history, and sequence of events producing the accident. If fusion reaction chamber temperature and pressure set point limits were exceeded, the I&C system would terminate plasma operations.

LOCAs could also include damage to piping in systems external to the reaction chamber. These ex-vessel LOCAs would involve damage to piping connected to heat removal systems such as steam generators or damage to steam generator tubes. The effects of an ex-vessel LOCA are expected to be less severe than events involving damage to cooling systems directly in contact with the ICF reaction chamber.

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11.2. Loss of Flow Accidents

Loss of flow events are less severe than LOCAs. In a fission reactor, these events limit the flow of cooling water to the core[1][2][3][4][5][15]. Similar event types will occur in an ICF facility, and result from transient conditions that interrupt of cooling water to the fusion reaction chamber. Mechanical failures of valves, pumps, and instrumentation; human errors including valve mispositioning and procedure violations; and off-site power failures could initiate these events. The duration of the off normal event and recovery from system failures determine the severity of a LOFA and subsequent recovery from the reactor coolant system piping and component damage.

If recovery is not timely, a LOFA can escalate to a LOCA. This occurs when a loss of coolant flow leads to overheating and subsequent coolant piping failure. The time to terminate fusion production is a key parameter in the severity of a LOFA. I&C systems would terminate fusion operations if design basis flow rates were not achieved.

11.3. Loss of Vacuum Accidents

In an ICF reactor, the plasma chamber will be designed to operate under vacuum conditions. A loss of vacuum event occurs when the reaction chamber pressure increases. Pressure increases could be induced by a gas or air leaking into the reaction chamber, misdirected lasers vaporizing wall material, failure to vent unfused fuel material, component failures, and pressurization of the reaction chamber following an in-vessel LOCA. The severity of a LOVA depends on the operating cycle of the ICF facility and is most severe during plasma operations. In general, a LOVA should be less significant than a LOCA. In an analogous manner with fission reactors, I&C systems would be expected to terminate reactor operations if vacuum conditions were lost.

11.4. Plasma Transients

Plasma transients disrupt steady state operations. These transients include overpower, overpressure, overtemperature, and plasma perturbation events. When the balance between fusion energy generation and energy loss via heat transfer to the steam system is eliminated, a perturbation condition can occur. Plasma perturbations also occur when contaminants increase in the plasma density or ICF lasers are misdirected and strike the reaction chamber wall. These events can lead to plasma instabilities and the release of localized energy that has the potential to mobilize radioactive material. In a severe event, the ICF reaction chamber and associated support systems could be damaged. Damage to these confinement structures could facilitate the release of radioactive material to plant areas and the environment. The I&C design of an ICF facility would monitor plasma conditions, and terminate the fusion reaction during a severe transient.

12. Radioactive Source Term

As noted in Table 1, the ICF source term will be dominated by activation products and tritium. Limited quantities of fusion products could also be released if the plasma exhaust system is not functioning properly.

Postulated ICF design basis accidents have sufficient energy to increase the possibility that radioactive material would be released into plant areas as well as the environment. The release magnitude depends on the available radioactive material and the specific accident conditions. More specific characterization of these events will depend on details of the ICF facility design and operating characteristics.

13. Beyond Design Basis Events

Following fission reactor design approaches, events having consequential, but a low probability of occurrence are specified. These beyond design basis events are specified to ensure the consideration of bounding events that could occur for a specific reactor design.

Following usual nomenclature, ICF beyond design basis events (BDBEs) would have frequencies of $<10^{-6}$/y. BDBEs could include, but not be limited to (1) rupture of the vacuum vessel/reaction chamber, complete loss of onsite and offsite power, multiple steam generator faults and ruptures, and building structural failure. Analysis of these and other possible events requires a detailed ICF facility design. Until a specific design is forthcoming, a more specific discussion of BDBEs must be deferred.

14. Assumptions for Evaluating the Consequences of Postulated ICF Events

If the ICF facility follows the proposed ITER design approach, the established set of assumptions can be utilized in its accident analysis[8]. Although the ICF assumptions may differ from those of the ITER facility, these assumptions provide an initial basis for evaluating the consequences of the ICF design basis events[8]. These assumptions are outlined in subsequent discussion.

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14.1. Accident Model Parameters

Calculations of offsite doses require a specification of a number of calculational parameters. These include the release duration, release height, distance from the release point, and dispersion factors.

ITER dose calculations to the nearest member of the public are based on a release duration of 1 hour, and a 1 km distance from the release point. The dispersion factors for accident releases with worst-case meteorology and a ground-level release are $2 - 4x10^{-4}$ s/m^3 Accident releases that assume worst-case meteorology and an elevated release are based on a dispersion factor of $1.4 - 2.7x10^{-5}$ s/m^3. Events that assume average annual meteorology utilize a dispersion factor of $1.0x10^{-6}$ s/m^3. These dispersion factors do not include ground deposition and washout effects, and are consistent with parameters used in the ITER design report[8].

If the ITER dose criteria are utilized to evaluate the ICF candidate accidents, the probability of these events would be categorized as operational events, likely events, unlikely events, extremely unlikely events, and hypothetical events. These events are described in subsequent discussion.

As the ICF design matures, these candidate accidents may reveal hazards that eventually become design basis accidents. In the interim, the categorized events provide a formalization for subsequent accident assessment and analysis.

14.2. Operational Events

Operational events are expected to occur during routine facility activities. Radiological consequences are managed by the facility's radiation protection program that is governed by the as low as reasonably achievable (ALARA) principle. A public dose limit of 0.1 mSv/y chronic dose is assumed for all release pathways. Federal regulators would govern worker dose limits[30][31].

14.3. Likely Events

Likely events are not operational events, and only a few occurrences are expected to occur during the lifetime of the facility. Likely events are events that have a probability of occurrence of >0.01/y. A dose limit of 0.1 mSv/y is imposed for all inhalation pathways[8]. This recommended limit does not include the ingestion pathway. Ingestion doses would depend on long-term emergency planning requirements that have yet to be specified for fusion power facilities.

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14.4. Unlikely Events

Unlikely events should not occur during ac ICF's operational lifetime, and have an expected frequency (f) of 0.01/y $\geq$ f $>10^{-4}$/y. The design basis requires that facility events avoid the need for any public countermeasures (e.g., evacuation and sheltering). A dose limit of 5 mSv/event chronic dose (without ingestion) is specified in the ITER design criteria[8].

14.5. Extremely Unlikely Events

Extremely unlikely events have an occurrence frequency of 10^{-4}/y $\geq$ f $>10^{-6}$/y. For these events a 100 m elevated release is assumed. In addition, extremely unlikely events utilize conservative meteorology. Avoiding the potential for public evacuation is an integral design assumption for these events. A dose limit of 5 – 50 mSv/event is specified in the ITER design criteria[8]. Specific events will depend on a complete ICF power reactor design.

14.6. Hypothetical Events

Hypothetical events that have a projected frequency of $\leq 10^{-6}$/y. A hypothetical event incorporates a ground level release with building wake effects. For these events, average meteorology conditions are utilized. The hypothetical event category is included in the design approach as a method to limit the radiological risk. This event category also assumes that no evacuation will be required if doses to the local population are limited to ~50 mSv/event during the assumed release period plus 7 days [8]. Specification of hypothetical ICF power facility events are dependent on a final design and associated technical basis.

15. Economic Viability Issues

The D-T fusion reaction of Eq. 1 provides 17.6 MeV that is transferred to alpha particles (3.5 MeV) and neutrons (14.1 MeV). Fusion reaction products include the neutrons and alpha particles that can initiate other nuclear reaction including activation. If not removed, these reaction products could contaminate the plasma, perturb the sustainability of the reaction, and complicate energy transfer to the cooling medium that is used to produce steam. These events as well as any unfused tritium could affect plasma stability and the economic viability of an ICF facility. Any event impacting the economic production of electricity must be mitigated for the ICF facility to become viable.

In addition, the open issues summarized in Section 6.0 must be resolved to achieve a viable ICF power facility design. The resolution of the aforementioned issues requires overcoming numerous technological challenges and achieving significant engineering advances.

16. Maintenance

ICF maintenance activities involve internal as well as external radiation hazards. Typical power facility maintenance involves cutting, welding, and grinding work that generates respirable particulate material. The ICF health physics controls to mitigate the hazards of maintenance work should be similar to those adopted by commercial fission reactors [1][2][3][4][5][15].

An overview of likely maintenance and repair activities and their associated health physics issues are summarized in Table 8. These maintenance activities include the following systems: (1) ICF reaction chamber support components during outages and power operations, (2) ICF reaction chamber during outages, (3) routine repair and surveillance activities, (4) waste processing, (5) defueling and plasma cleanup operations, and (6) DT addition to the ICF reaction chamber.

The health physics hazards associated with these maintenance activities lead to external radiation exposure resulting from the plasma process or activation products. Internal deposition of radioactive material can occur from inhalation and ingestion.

Limited worker exposures should be encountered during waste processing. Waste processing is assumed to be performed at locations well separated from the ICF reaction chamber.

Table 8 notes the term hot particles. Hot particles are small particulate matter that is produced by maintenance activities, the operation of valves and pumps, and the mechanical wear of components. These particles become activated when subjected to the fusion neutron flux, and present an external radiation hazard that can lead to highly localized doses [1][2][3][4][5]. Skin doses as high as 5 Sv have been encountered in fission power reactors. Hot particles can reside on the skin, ear, and eye. These particles can also be inhaled and ingested. Hot particles require careful health physics monitoring and control measures [3][4].

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Maintenance and Repair Activity	Health Physics Hazards
ICF reaction chamber support component maintenance during an outage	Activation products Hot particles Tritium
ICF reaction chamber support component maintenance during power operations	Activation products Hot particles Tritium Neutrons Gammas
ICF reaction chamber maintenance during outages	Activation products Hot particles Tritium
Routine maintenance and surveillance activities during power operations	Activation products Hot particles Tritium Neutrons Gammas
Waste processing	Activation products Hot particles Tritium
Defueling and plasma cleanup operations	Activation products Hot particles Tritium Neutrons Gammas
DT addition to the ICF reaction chamber	Tritium

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Maintenance and Repair Activity	Health Physics Hazards
	Activation products Hot particles Neutrons Gammas

Table 8. Health Physics Hazards Associated with Anticipated Maintenance and Repair Activities at an ICF Power Reactor

The Table 8 health physics hazards are mitigated by sound radiological controls measures. These practices include comprehensive radiation surveys to characterize the hazards, radiation work permits to specify protective clothing and task parameters, ALARA reviews to minimize worker doses, and dose tracking to ensure that the controls were effective.

Without a detailed ICF design, only a qualitative description of the health physics implications of maintenance operations is possible. However, more specific health physics considerations for reaction chamber maintenance, reaction chamber cooling water system maintenance, and routine maintenance are presented in subsequent discussion.

16.1. Reaction Chamber Maintenance

Neutron and heavy ion interactions have the potential to induce radiation and subsequent physical damage to the ICF reaction chamber. As a result of this damage, replacement of reaction chamber components as well as the reaction chamber may be required. The frequency of these activities will depend on the ICF design, expected fusion reaction rates, and neutron flux values. ITER design studies suggest that maintenance activities that occur in radiation fields on the order of $3x10^4$ Sv/h will require remote handling equipment [8]. This is a reasonable criterion to apply to a first-order ICF design approach.

Any ICF reaction chamber surface repair/replacement operations have the potential to produce respirable particulates that are an internal deposition hazard. Mechanical repair operations would also create airborne particulates from activated components. Any residual tritium contamination within the reaction chamber also represents an internal radiation hazard.

The ICF reaction chamber structure and the support components will be exposed to neutron radiation that will activate these structures. Activation reactions create an external radiation hazard that can be mitigated using shielding to attenuate these radiation fields. The magnitude of the radiation fields will depend on the design neutron fluence, component and reaction chamber materials of construction, and design power levels. These parameters are not yet established.

16.2. Reaction Chamber Cooling Water System Maintenance

Effective dose values associated with the reaction chamber cooling water system are uncertain and will depend on the final design. Neutron radiation will activate the reaction chamber coolant and coolant piping. Depending on the chemistry controls, piping surfaces could also be contaminated. The $^{16}O(n, p)^{16}N$ reaction will provide a significant gamma source term.

External radiation fields from the cooling system and piping will be governed by internal piping contamination and subsequent deposition of activated material in piping, valves, pumps, and heat transfer systems. The magnitude of these radiation levels will have a significant impact on maintenance activities and govern if they require remote operations.

16.3. Routine Maintenance

Cutting, grinding, and welding activities during routine maintenance produce respirable aerosols. These airborne particulates are internal radiation concerns that can be inhaled and ingested.

Additional activated particulate material result from the operation of systems exposed to neutron radiation. These include the fuel system, coolant system, and waste extraction system. This source term has not been developed and will be significantly affected by the ICF operating characteristics, maintenance requirements, and the operational neutron spectrum of the facility.

At ITER, 25 μSv/h is the limit for hands-on maintenance. This value is based on maintenance staff working in this radiation field for 40 hours a week and 50 weeks a year. These assumptions lead to 50 mSv/yr that is consistent with US regulations[30][31].

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17. Conclusions

In many respects, an ICF power facility will have comparable radiation hazards and worker doses as an equivalently sized fission facility. This conclusion assumes that a viable fusion power facility design is achieved with an appropriate design basis and set of radioactive materials barriers.

The technological challenges of an ICF power facility are significant. These issues are magnified by the fact that there is no current power facility design, and the ICF concept is significantly less mature than the magnetic confinement design based on ITER that is under construction.

ICF issues include, but are not limited to the availability of a reliable and sustainable source of tritium fuel, high temperatures materials development, component reliability, development of sufficiently reliable high powered lasers, economical production of fuel enclosed in a hohlraum or bare fuel capsule, and establishing sustained power operations with a sufficient fusion repetition rate.

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