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SAFETY CONSIDERATIONS IN NEXT STEP FUSION DESIGN AND BEYOND

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SAFETY CONSIDERATIONS IN NEXT STEP FUSION DESIGN AND BEYOND[a]

ABSTRACT

Recent US and international design studies provide insights into the potential safety and environmental advantages of fusion as well as the development needed to realize this potential. We in the Fusion Safety Program at EG&G Idaho have analyzed the Compact Ignition Tokamak (CIT), the International Thermonuclear Engineering Reactor (ITER), and the Advanced Reactor Innovative Engineering Study (ARIES). I have reviewed these three designs to determine issues related to meeting the safety and the environmental goals that guide fusion development in the U.S. The paper lists safety and environmental issues that are generic to fusion and approaches to favorably resolve each issue. The technical developments that have the highest potential of contributing to improving the safety and environmental attractiveness of fusion are identified and discussed. These developments are in the areas of low-activation materials, plasma-facing components, and plasma physics relating to off-normal plasma events and tritium burn-up.

1. INTRODUCTION

Safety and environmental considerations are strongly impacting next step designs and long-term fusion development. This impact results from the greater emphasis now given to nuclear issues in siting facilities as well as the need by funding sources for assurances that fusion energy has sufficient advantages to justify the large costs for development. Fusion energy clearly has the potential for safe and environmentally benign operation, but attaining this potential requires overcoming difficult challenges. Recent design studies have illuminated these challenges and provide a clearer picture of the road ahead.

1.1 Safety and Environmental Advantages of Fusion Energy

Increased use of fossil fuels, renewable energy sources, and fission reactors is severely constrained by economic, safety, or environmental concerns. The fusion process has inherent advantages that could overcome these concerns:

- No emissions are produced to degrade visibility, increase greenhouse gases, cause acid rain, or reduce the ozone layer.
- The fuel supply and processing are contained at the facility.
- Overpower transients are not a serious public safety concern.

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- o Low power density operation reduces severity of coolant disturbances and decay heat.
- o Materials and design can limit hazards from accidental release of radioactive material.
- o Recycle and near-surface burial are potential options for radioactive waste management.

The first step in realizing these advantages of fusion energy is to set goals for fusion development.

1.2 Safety and Environmental Goals for Fusion Energy

Fusion energy can go beyond the regulatory requirements currently in effect throughout the world. I believe that the goals given in Table I are responsive to public concerns and are attainable.[1] The approach required is to place an early emphasis on development of low activation materials that reduce releasable inventories and waste management concerns. These early investments will be repaid by reduced cost for reactor confinement, nuclear-grade components, and waste disposal.

2. SAFETY AND ENVIRONMENTAL FEATURES OF RECENT DESIGNS

Safety and environmental considerations become more important as fusion progresses from physics to technology test reactors and then to demonstration and commercial reactors. The Fusion Safety Program at EG&G Idaho has performed safety studies on three recent design efforts, the Compact Ignition Tokamak (CIT), the International Thermonuclear Experimental Reactor (ITER), and the Advanced Reactor Innovative Engineering Study (ARIES-I). Table II shows the trend towards higher neutron fluence and tritium inventories. All three designs could meet current safety and environmental standards and satisfy national regulatory requirements. In the process of the analyses, insights have been gained that would enhance the safety and environmental attractiveness of fusion. In the following sections, I discuss the safety features and accident and environmental concerns for each of these designs as well as the insights into enhancing fusion's attractiveness.

2.1 CIT Design

The CIT is designed to study burning plasmas close to the ignited mode. It will be located at the Princeton Plasma Physics Laboratory (PPPL) next to the Tokamak Fusion Test Reactor (TFTR). Because of the small site (site boundary of approximately 140 m) and proximity to populated areas, a high priority was given to reducing safety and environmental concerns.

The compact plasma, major radius of 2.6 m, is contained in a high magnet field of 10 T. Copper-Inconel laminated conductors employed in the field coils will be cooled by liquid nitrogen. The CIT will be operated in the pulsed mode, 7 s pulses and a 1 hour cool-down time between pulses, for approximately 1000 full-power pulses per year. The first wall and divertor will be covered with graphite tiles. The vacuum vessel, composed of Inconel 625, will be cooled by helium gas. The vacuum vessel and magnets are enclosed in a cryostat which will be located in a test cell.

Safety features have been incorporated into the design to reduce radioactive effluents and mitigate accidents. The liquid nitrogen cooling system for the magnets is fully enclosed to prevent losses of N-13 produced by neutron activation, as well as losses of any activated particulates that may be present. The test cell is inerted with nitrogen to reduce air activation and the prospects of air entering the vacuum vessel and reacting with the hot graphite. The nitrogen is slowly vented through a delay line to allow for decay of N-13 produced by neutron activation. A triple containment philosophy has been adopted for tritium inventories.

Because of the low neutron fluence, tritium is the primary radioactive material of concern. Approximately 0.5 g of tritium is required for each pulse. For 1000 pulses/year, the throughput is about 0.5 kg/yr. About 90 percent of the throughput is recycled which results in about 50 g shipped off-site for processing and an equal amount shipped to the site for resupply. Tritium and activation inventories are given in Table III.

2.1.1 CIT Safety and Environmental Issues

Safety and environmental analyses have been completed based on the conceptual design.[2],[3] Because of the limited radioactive inventories and energy sources, CIT is inherently safe; acute fatalities are not possible. Most of the safety analysis focused on determining the maximum credible accident and minimizing the risk from small but more frequent accidents. Accident probabilities were estimated by developing event trees and using failure rates estimated from data collected from related industries. The following accident scenarios received the most study:

- Release of activated nitrogen resulting from pressurization of the center cell by an accidental release of cryogenic nitrogen or by pressurization of the cryostat by liquid nitrogen inadvertently left in the cryostat during a pulse.

- Release of tritium resulting from a failure of a storage bed or holding tank.

- Release of activated copper or Inconel resulting from a magnet arc.

- Release of co-deposited tritium and activated dust resulting from an air inlet into the vacuum vessel and reaction with hot graphite.

The risks determined for these accident scenarios were well within goals established for nuclear systems.[4]

2.1.2 Implications for Fusion Power

Although these scenarios are specific to the CIT design, they provide insights into safety issues that are generic to fusion power.

Large amounts of cryogenic liquids are expected to be present in superconducting magnet systems. Common mode failures or propagating accidents such as structural failure of the magnets could release radioactive material from adjacent structures. A cryogen release could then pressurize the building, releasing the radioactivity to the environment.

Tritium releases are not a significant risk for CIT because the individual inventories are small, and the total inventory consists of isolated inventories that, even when combined, will not pose the threat of acute fatalities. For a commercial reactor, the tritium throughput and inventories are expected to be much larger. A fusion reactor producing 1 GW of electrical power would have a tritium throughput several thousand times that for CIT. Tritium inventories would be correspondingly higher and would become a significant safety concern.

The low integrated burn time and resulting low fluence mitigates several safety concerns for CIT. Activated and tritiated graphite dust, co-deposited tritium buildup on graphite, tritium resulting from permeation into bulk graphite and coolants, and activated materials are problems that await more advanced machines.

2.2 ITER Design

The ITER project[5] has both a physics and technology mission. The physics mission of this reactor is to demonstrate controlled ignition and extended burn as well as explore steady-state operation using various means of current drive. The technology mission is to operate with sufficient plasma parameters, heat and particle flux, and neutron fluence to perform testing of components in an integrated fusion environment. Since the site has not been selected, a generic site with a boundary of 1000 m is used for dose calculations.

The ITER project selected materials that would be available for near-term construction. Carbon was selected for the first wall and divertor for the physics phase. A conventional 316 stainless steel was selected for the vacuum vessel and structure. The tritium breeding blanket will use beryllium as a neutron multiplier with lithium oxide as the leading candidate as the breeder material. All structures are cooled by low temperature water.

For the ITER design to demonstrate the safety attractiveness of fusion, safety experts realized the value of passive safety features. The approach used was to reduce radioactive inventories as much as possible. Where inventories remain significant, reduce the possible mobilization without depending on active systems. Where mobilizable inventory remains significant, reduce releases by passive confinement systems. Important passive features that have been incorporated into the design include low-temperature coolants, limitations on operating temperature of graphite, natural coolant circulation, auxiliary passive heat exchanger, and inert gas zones. The passive safety accomplishments are not adequate to reduce accident doses below the 100 mSv (10 rem) regulatory limit for credible accidents. The ITER design can meet regulatory requirements for ITER host countries by use of confinement systems. Several additional passive safety ideas are being actively pursued which could improve ITER attractiveness.

Because of the need for higher fluence and the use of conventional (not low activation) materials, this device will contain sizable inventories of both tritium and activation products. Tables IV and V show inventories for the technology phase. Energy and pressure sources available to release these inventories include heat content of the carbon (physics phase), decay heat of activated materials, plasma disruptions and runaway electrons, and pressurized water for first wall conditioning and bakeout.

2.2.1 ITER Safety and Environmental Issues

The dominant hazard for the physics phase is the tritium in the reactor which includes the tritium co-deposited on the graphite and in bulk graphite, tritiated graphite erosion dust, and tritium in the cryopumps. The major accidents of concern are coolant disruptions that result in breaks into the torus followed by graphite reactions with the steam producing explosive hydrogen. Other tritium related accidents are releases from the inventories contained in the processing and storage systems.

The dominant hazard for the technology phase is the activated tungsten in the first wall and divertor. Selection of the divertor material for the technology phase is severely constrained and tungsten may be the only practical choice. With a total loss of coolant, the first wall, divertor and surroundings will heat up from the decay heat. Temperatures may remain high enough to volatilize the activated tungsten in an oxidizing environment with air or steam present. Activated dust and tritium could also be released.

Radioactive waste management approaches have not been developed yet for ITER because of the differing requirements in the participating countries. Only in the U.S. does it appear that regulations would permit a significant amount of the waste to qualify for shallow land disposal.

2.2.2 Implications for Fusion Power

The ITER design confirmed the concern about high tritium flows and inventories identified by the CIT safety studies and provided additional insights relevant to a long pulse, power producing, high fluence machine. Plasma physics was seen to have a major impact on safety. Examples are low tritium burn fraction increasing inventories, rapid time scale and energy deposition from plasma disruptions, potential for runaway electrons that could damage coolant systems, potential for overpower transients, need to shutdown in seconds in the event of a divertor coolant failure, and need for vertical position control to avoid damage to the machine.

The divertor and other plasma facing components have a major impact on safety and practical solutions are difficult because of the severe operating environment. Materials that have good erosion and thermal properties have concerns due to activation, decay heat, and volatility in an oxidizing environment. Advance divertor designs are needed as well as advanced low activation materials.

2.3 ARIES-I Design

The purpose of the ARIES design study[6] is to determine the potential economics, safety, and environmental features of a range of possible tokamak reactors and to identify critical development areas in physics and technology. The ARIES-I design assumes a minimum extrapolation in physics and incorporates technologies that would be available over the next 20 to 30 years.

The first wall and blanket structure is composed of SiC/SiC composite material. The divertor is coated with tungsten. The reference tritium breeding material is lithium zirconate and beryllium was used as a neutron multiplier. The design uses advanced, high-field superconducting coils. Current drive is employed to sustain continuous operation. The primary coolant is helium gas.

The safety approach followed in the design was to reduce radioactive inventories and energy sources so that accidental releases would be small even without mitigation by active safety systems or confinement systems. Low activation materials were emphasized, isotopic tailoring was employed for the tungsten in the divertor and zirconium in the breeder, and tritium inventories were minimized. Energy and pressure sources were minimized by using helium gas rather than water for the primary coolant and by using structural materials with low decay heat.

Several approaches were used to reduce tritium inventories. A high tritium burn fraction (0.13), reduced the size required for the processing system. The tritium processing system used a Pd diffuser to remove helium ash and directly recycle part of the stream to the reactor. Since high tritium to deuterium mixtures were not required for fueling, the cryogenic distillation system was not required to enrich tritium which eliminated the largest processing inventory. The inventory in the vacuum pumps was essentially eliminated by replacing cryopumps with turbomolecular pumps. The largest uncertainty in tritium inventories is in the SiC composite first wall. The designers assumed that the implanted tritium would be eroded away before it diffused into the SiC structure. If this assumption is not correct, inventories could be several kilograms. Tritium produced in the beryllium multiplier is reduced by operating the majority of the blanket at sufficiently high temperature (over 610 C) that the tritium would be removed from the beryllium. In addition, the blanket would be baked at high temperature once a year to remove tritium from the beryllium. Table VI gives the tritium inventories remaining after applying these techniques.

Isotopic tailoring was employed to reduce the safety and environmental concerns resulting from activation. Activation of naturally occurring zirconium produces Zr-89 which is an accident concern and Zr-93 which has a long half-life and is therefore a waste management concern. By enriching the stable isotope Zr-92 in natural zirconium and reducing all heavier and lighter isotopes, the accident concern can be significantly reduced and the materials can qualify as low level waste for disposal. The Laser Isotope Separation (LIS) method would be ideal for this application and costs have been estimated at about $2000/kg of product.

Activation of the tungsten used to coat the divertor produces radioactive isotopes of tungsten and rhenium. By enriching the tungsten to 90% W-183 and reducing all other naturally occurring isotopes, the accident concern is significantly reduced and the material will qualify for disposal as low level waste.

The energy sources available to mobilize radioactive material consists of the energy stored in the magnet and the decay heat of the activation products. Decay heat is low since the dominate material is SiC which is a low activation material. Use of helium as the coolant rather than water eliminates steam pressurization as a concern.

2.3.1 ARIES-I Safety and Environmental Issues

The safety analysis focused primarily on ARIES-I potential to meet the inherent or passive safety goal. Since one unique feature of the design was the use of low activation materials, analysis focused on these materials. Consequently, tritium accidents were not analyzed in detail. To determine if inherent or passive safety goals could be achieved, the fraction of activated material that could be mobilized by the energy sources available was estimated and the resulting dose calculated for a generic site. Table VII summarizes the results of these calculations which are discussed in the following sections. Although there are large uncertainties, these results show that the ARIES-I design has the potential to be passively safe; passive features prevent acute fatalities (doses over 2 Sv).

Since the zirconate has a very low vapor pressure at temperatures attainable from decay heat, the only mechanism available for release is mechanical generation of dust during operation and during accidents such as missile impact. A bounding value of 2% converted into dust was assumed for the accident analysis.

The tungsten coating on the divertor could be exposed to air at high temperatures during an accident. In experiments at the Idaho National Engineering Laboratory (INEL) [7], volatilization rates were measured for tungsten alloyed with rhenium exposed to air. These rates were applied to ARIES-I assuming a temperature of 1000 C for 10 hours would result from decay heat in a loss of cooling accident. The calculated release fractions were 0.0003 for the tungsten and 0.29 for the rhenium.

The only significant activation resulting from the SiC results from the impurities. Based on the impurities assumed in the ESECOM study[8], an accident dose was determined by assuming complete release. Even with the impurities, the SiC would qualify as low level waste.

Because of the high-field magnets, analysis was done on off-normal magnet transients. The magnets are protected by dump resistors to absorb the energy during off-normal transients. Failure of circuit components, shorts, and arcs were considered. The most severe transient in terms of energy deposited are the arcs within one winding. For the most severe accident analyzed, the maximum arc power was 1.2 MW, and the total energy deposited in the arc was 17 MJ. The maximum heating rate of the stabilizer was 90 MW with a total deposited quench energy of 2 GJ. Although the arc would do considerable damage to the magnet, the energy deposited in the stabilizer would only increase the temperature to near room temperature.

2.3.2 Implications for Fusion Power

The ARIES-I design provides a good picture of what fusion can accomplish, but it also points out development tasks that lie ahead.

Magnet safety is an important issue both because of the high cost of the magnet systems, and the potential for a structural failure that could release adjacent radioactive materials.

The approaches used to reduce tritium inventories demonstrated their value; although there were important uncertainties in the analysis. Two of the largest uncertainties are the tritium burn fraction and the behavior of tritium implanted into the SiC.

The use of low activation material both eliminated the risk of catastrophic accidents and the generation of high level waste, achievements I believe are necessary for the acceptance of fusion reactors. This task should be pressed still further by developing materials to replace the zirconate breeding material and the tungsten divertor material. Fortunately, there are several good candidates for breeder material, lithium oxide and lithium aluminate are examples, but the divertor material is a more challenging problem.

3.0 DEVELOPMENTS TO IMPROVE SAFETY AND ENVIRONMENTAL ATTRACTIVENESS

The design studies reviewed in this paper have identified safety concerns and designers have suggested the following approaches to resolving these concerns. In the physics area, work has been proposed on fueling schemes to establish D/T plasma profiles that would enhance tritium burnup, emergency plasma shutdown that could be accomplished without causing a density limit disruption, and control of runaway electrons produced during disruptions by injecting neutral gas. In the technology area, work has been proposed on methods to reduce tritium inventories near the reactor by developing a continuous regeneration cryopump and substituting beryllium for carbon in plasma facing components. Use of beryllium rather than tungsten would also reduce activation. Development is needed on passive protection of magnets to avoid accidents that propagate to initiation of radioactive releases, recycle of radioactive waste to reduce waste management concerns, and passive confinement to remove both elemental tritium and tritiated water released in the building. R&D tasks, being proposed in these areas, could bring significant improvements.

4. CONCLUSIONS

It has been instructive to look over the recent design activities in which we in the U.S. have participated. I can see four points that need to be strongly emphasized that would influence future design efforts and fusion development programs:

- Consider safety and environmental concerns early in the design. Selection of materials, coolants, plasma parameters, tritium systems, and siting should all have early safety input. Cost savings will result for confinement buildings and in reduction of the need for nuclear grade systems. Siting of fusion reactors will be much easier.

- Establish a strong materials development program (including a high flux neutron source) that meets the wide variety of needs in fusion and maintain a strong emphasis on environmental and safety attractiveness.

- Maintain R&D programs in all areas of fusion technology and plasma physics that specifically address safety and environmental issues.

- Combine international resources as a means to address the wide spectrum of development tasks that are needed.

The design efforts have been successful in showing the attractiveness of fusion designs. They have also been successful in showing the fusion community areas where improvements can be made. With an improved image of the development path ahead, it is now possible to make progress in many of these areas.

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TABLE I. SAFETY AND ENVIRONMENTAL GOALS FOR FUSION POWER

Issue	Goal	Comment
Accidents-high consequence	Achieve inherent or passive safety	Prevent prompt fatalities and thus avoid catastrophic risk label
Accidents-low consequence but high frequency	Meet risk-based limit	Avoid prescriptive approach, reduce cost
Waste management	Maximize recycle and generate only low-level waste for disposal	No high-level waste

TABLE II. PARAMETERS FOR CIT, ITER, AND ARIES-I USED IN THIS ANALYSIS

Parameter	CIT	ITER	ARIES-I
Site boundary (m)	140	1000	1000
Major radius (m)	2.6	6.0	6.75
Thermal Power during pulse (MW)	500	1000	1991
Tritium inventory (g)	12	6000 Phys. 4300 Tech.	700
Tritium throughput (kg/yr)	0.5	500[a]	820[b]
Neutron fluence (MW-yr/m^2)	0.0016[c]	1	11[d]
Activation product inventory (Sv)[e]	0.00001	4.4[f]	1.2[f]
Decay energy from 1 day (GJ)	small	264	<80
Magnet energy (GJ)	18	55	105
Protection against high consequence accidents	inherently safe	confinement based	passively safe
Radioactive waste-Type/Quantity(MT)[g]	SLD 1400	SLD 20000 DGD 1400	SLD 17000

[a] Based on 25% peak year availability and tritium burn fraction of 0.025
[b] Based on 70% availability and a tritium burn fraction of 0.13
[c] Assumes 5 TJ lifetime neutron energy over 100 m^2
[d] Assumes lifetime of 4 years at 2.8 MW/m^2
[e] All mobilizable activation products using site specific dispersion
[f] No credit is taken for confinement building
[g] SLD-Shallow Land Disposal in U.S., DGD-Deep Geological Disposal in U.S. Lifetime quantities except the DGD for ITER is one divertor replacement.

TABLE III. MAJOR RADIOACTIVE INVENTORIES IN CIT

Source	Inventory TBq (kCi)
Co-deposited in torus	tritium 370 (10)
Pellet injector	tritium 185 (5)
Plasma exhaust tank or storage beds	tritium 925 (25)
Molecular sieves or loadout	tritium 925 (25)
Recycle tanks	tritium 370 (10)
Recycle beds	tritium 185 (5)
Activated nitrogen in center cell	N-13 70 (1.9)
Activated liquid nitrogen	N-13 52 (1.4)
Activated Inconel from magnet arc to vacuum vessel	Co-58 1 (0.027) Cr-51 0.5 (0.014) Co-57 0.4 (0.011)

TABLE IV. MAJOR TRITIUM INVENTORIES IN ITER TECHNOLOGY PHASE (NO GRAPHITE)

Source	Inventory PBq (kCi)
Backing pumps	30 (800)
Fuel cleanup system	160 (4300)
Isotope separation system	74 (2000)
Short-term storage	110 (3000)
Atmosphere cleanup system	80 (2200)
Vacuum pump	56 (1500)
Pellet injector	74 (2000)
Surface on plasma facing components	74 (2000)
Errosion dust in torus	37 (1000)
Solid breeder plus processing	118 (3200)
Beryllium multiplier	440 (12000)
Water processing	44 (1200)
Solid waste system	56 (1500)
Long-term storage	220 (6000)

TABLE V. MAJOR ACTIVATION HAZARDS FOR ITER TECHNOLOGY PHASE

Source	Mobile percent [a]	Mobile dose (mSv) [a]
Tungsten dust on first wall	100.0	893
Tungsten dust from divertor	100.0	241
Tungsten first wall- air reaction -steam reaction	0.36 0.06	2441 444
Tungsten divertor-air reaction -steam reaction	0.34 0.18	2305 1256
Copper side wall -air reactions blanket module -steam reactions	0.24 0.25	263 265

[a] Since no credit is taken here for confinement, values are not for regulatory purposes. Dose based on site specific dispersion.

TABLE VI. MAJOR TRITIUM INVENTORIES IN ARIES

Source	Inventory PBq (kCi)
Cryogenic distillation	18.5 (500)
Implanted in first wall	2.2 (60) [a]
Implanted in divertor wall	3.7 (100) [a]
Breeder material	0.4 (10)
Beryllium in breeder blanket	240 (6400) [a]

[a] Inventory is highly uncertain

TABLE VII. MAJOR ACTIVATION HAZARDS FOR ARIES-I

Source	Mobile percent [a]	Mobile dose (mSv) [a]
Tungsten divertor	0.03 for tungsten 29 for rhenium	112
Zirconium in breeder	2	910
Impurities in SiC	100 [b]	210

[a] Since no credit is taken here for confinement, values are not for regulatory purposes.
[b] Actual mobility is unknown but very small.