CONF-9610240--3
INEL-96/00285
INEL--96/00285

OVERVIEW OF SAFETY AND ENVIRONMENTAL ISSUES FOR INERTIAL FUSION ENERGY

S. J. Piet[1], S. J. Brereton[2], J. M. Perlado[3], Y. Seki[4], S. Tanaka[5], and M. T. Tobin[2]

(1) Idaho National Engineering Laboratory, U.S.; (2) Lawrence Livermore National Laboratory, U.S.; (3) Instituto de Fusión Nuclear, Spain; (4) Japanese Atomic Energy Research Institute, Japan; (5) University of Tokyo, Japan

This paper summarizes safety and environmental issues of Inertial Fusion Energy (IFE): inventories, effluents, maintenance, accident safety, waste management, and recycling. The fusion confinement approach among inertial and magnetic options affects how the fusion reaction is maintained and which materials surround the reaction chamber. The target fill technology has a major impact on the target factory tritium inventory. IFE fusion reaction chambers usually employ some means to protect the first structural wall from fusion pulses. This protective fluid or granular bed also moderates and absorbs most neutrons before they reach the first structural wall. Although the protective fluid activates, most candidate fluids have low activation hazard. Hands-on maintenance seems practical for the driver, target factory, and secondary coolant systems; remote maintenance is likely required for the reaction chamber, primary coolant, and vacuum exhaust cleanup systems. The driver and fuel target facility are well separated from the main reaction chamber.

KEY WORDS: Inertial fusion; tritium; activation products; safety; environment

1. INTRODUCTION

Research and development in IFE is partly motivated by analyses suggesting that it could have lower environmental impact and greater safety than competing energy sources. Rather than focus on a single conceptual design, our approach is to consider the range of IFE concepts and put matters into context by comparisons with Magnetic Fusion Energy (MFE). An older and longer version of this information appears as a chapter in the IAEA book on IFE.(1) Fig. 1 lays out the primary parts of an IFE power plant. Most important is the separation of the driver energy and the fuel target facility from the main reaction chamber, thereby decoupling accidents in these systems from the fusion reaction chamber.

2. INVENTORIES OF RADIOACTIVE MATERIALS

2.1. Tritium Inventories

The estimated tritium inventories in IFE power plants are up to a few kilograms of tritium, similar to MFE. The accuracy of the estimates is limited by the depth of design studies and degree of understanding of tritium behavior in fusion systems.

Consider the IFE tritium flows in Fig. 2. There is a **target** processing loop. Unburned tritium is exhausted from the reaction chamber, purified of target debris, sent to the target factory, adjusted for proper D-T isotope mix, filled into new targets, and then re-used as new targets. There is also a **breeding** loop where tritium is bred, extracted, sent to the target factory, and adjusted for D-T isotope mix. For example, a 3-GW fusion power (1 GWe) plant must burn (and breed) about 460 g-T/day. A burn fraction of 30% means that 1500 g-T/day must be processed, filled into targets, and injected as new targets.

The total tritium processing rate for either IFE or MFE roughly scales as $1-f_b$, with f_b being the tritium burn fraction. The higher the burn fraction, the lower the processing rate and the tritium

DISCLAIMER

inventory. The IFE burn fraction is given by $f_b = \rho R / (k + \rho R)$, where ρR describes compression and k is a constant. For required ρR values of 2–3 g/cm^2 and k = 5 or 6,[2] the burn fraction is ~30%. All unburned tritium must go through all the target loop steps, including filling into new targets. One cannot directly re-inject tritium into the reaction chamber as DT gas. In contrast, the MFE burn fraction is typically only a few percent, but some direct re-injection of D-T is possible as gas without complex target filling or isotope mix adjustment.

In some indirect drive targets, roughly 99% of the mass is the shell (including protium) and high atomic number (high-Z) materials.[3] After target burn, this debris must be separated from unburned fuel. In direct drive targets, there is no high-Z material, but still significant low-Z materials like protium and carbon in plastic shells. There could be more protium than D-T fuel. The type of target thus determines impurity and protium sources. Two cases illustrate the range of exhaust flows in moles/hour:[4]

Laser: 12.8 (DT) + 5.5 (He) + 0.4 (impurity) + 15.3 (protium) = 34
Heavy ion: 12.8 (DT) + 5.5 (He) + 1.5 (impurity) + 130.2 (protium) = 150

In contrast, MFE pellets are simpler and are essentially pure frozen D-T ice.

Helium and debris must be removed from the exhaust. Conventional separation technologies lead to significant tritium inventories, a few hundred grams. Advanced technologies may reduce the inventory associated with this step, to ~100 g-T or less for the exhaust cleanup system.[4]

Protium in the exhaust (from hydrocarbon target shells, water somewhere in the system, etc.) must be removed via an Isotope Separation System (ISS). More protium increases the difficulty and the resultant tritium inventory in that system. Likely ISS tritium inventories are of order 100 g-T. For example, one study estimated 50-70 g-T, respectively, for laser and heavy ion target isotope separation systems.[4]

A key factor influencing the tritium inventory in the target factory is the time to fill targets, which is related to the target type and fill technology. The inventory associated with filling will be roughly the processing rate times one-half the fill time. For example, if the average processing holdup time (half the time for complete filling) for filling targets is 1 day and the burn fraction is 30% (as above), there is 1.5 kg-T in the target factory. One can consider three types of target shells and fill technologies with decreasing fill times and tritium inventories.

1. Glass targets, most likely with permeation filling (kilograms of T)
2. Plastic or polymer targets, possibly with injection filling (100's of grams of T)
3. Pure D-T targets, no separate filling or shell required (< 100 g-T)

With permeation filling, the time to fill targets has been estimated as 40 to 48 hours.[5,6] The Cascade study estimated 1-8 kg-T inventory,[7] depending on how many tritium targets are kept in storage as backup for system unavailability, fill time, and other details. The HYLIFE-II study estimated 4 kg-T in the target factory, half in the filling steps and half in associated piping and systems.[5]

Newer studies make use of advanced (and less studied) technologies. One study using polymer targets with injection filling estimated 300 g-T in the target factory.[8] The time to fill is only minutes. Pure D-T targets would have even lower net inventory in the target factory. The practicality of either injection filling or even pure D-T targets must be established, including having highly uniform surfaces (>99% uniform).

In either IFE or MFE, the breeding loop inventories are controlled by material and design selections, not so much by the fusion confinement approach.

In summary, the IFE fuel cycle (exhaust cleanup, ISS, target factory) inventories range from several hundreds of grams to several kilograms primarily depending on target type and filling method. Fortunately, the target factory is likely to be well separated from the main reaction chamber so that there should be little accident coupling between the target factory and the rest of the facility. MFE fuel cycle work, e.g., ITER, the Tritium Systems Test Assembly (TSTA), and the Joint European Torus (JET) should help decrease the inventory uncertainty for both MFE and IFE. However, pellet filling technology and related tritium inventories are unique to IFE.

2.2. Activation product inventories

IFE/MFE activation differences influence whether MFE "low activation" materials are also "low activation" in IFE. This, in turn, is important because there is no IFE materials program due to inadequate resources. The intent is to take advantage of MFE development; this requires understanding IFE/MFE differences and developing appropriate IFE protective fluids/beds.

IFE indirect drive targets contain materials that will activate, typically 0.4 g/target.[3,7] Target debris that is exhausted should be recycled as new targets (Fig. 2), adding activation each time through the cycle. For a 1-week turn-around cycle for high-Z material,[5] repetition rate of 5 Hz, and 0.4 g/target, the re-circulating inventory of activated target material is 1200 kg.

IFE reaction chambers usually employ some means to protect the first structural wall from fusion pulses. This protective fluid or granular bed also moderates and absorbs most neutrons before the first structural wall. Although the protective fluid itself activates, most candidate fluids (lithium, 17Li83Pb, FLiBe) and moving beds (Li_2O, C) are low activation hazard.

There are neutron spectra differences between IFE and MFE. There is significant neutron moderation in the compressed burning target for $\rho\mathbf{R}$ of 3-5, so that roughly 70% of the energy leaving the burning target is in the form of neutrons whereas 80% of the initial D-T energy is in the form of neutrons. The protective fluid further moderates neutrons. Thus, the neutrons activating the first structural wall are significantly attenuated in number and moderated in energy (more so than in MFE). This means that it is possible to retain the first structural wall for the entire plant lifetime because of reduced radiation damage. This also means that the wall receives comparable neutron fluence as does an MFE first wall, which is removed every few years. On balance, the IFE neutron spectrum seen by structures is softer. Thus, isotopes produced by (n,γ) reactions are relatively more important; isotopes produced by high-energy-neutron threshold reactions are relatively less important.

These differences mean that activation studies for MFE do not apply to IFE. Materials that are "low activation" in MFE may or may not be as attractive in IFE. Basically, Fe, Ni, Mo, and W are undesirable structural elements from an activation standpoint. This reduces the desirability of austenitic steels (Fe-Ni-Mo) and ferritic/martensitic steels (Fe-W). Elements like C, Si, Ti, V, and Cr are desirable so that V-Cr-Ti alloys and SiC composite structures are quite low activation. These latter conclusions are the same as in MFE, but the details differ.

3. OPERATIONAL SAFETY

3.1. Operational Effluents

IFE plants will emit airborne or liquid effluents of both tritium and activation products. Regulations impose limits on the maximum exposure to individual members of the public from these routine radioactive releases. National and international effluent limits range from 100 μSv/a to 1000 μSv/a.[9,10] A survey of IFE estimates gives a range of 120-1200 TBq-tritium/year, producing doses to the maximum offsite individual of 4.5-45 μSv/a.[1] This range meets the regulatory requirement and is lower than the dose from natural background radioactivity, typically 1-3 mSv/a.

Major contributors to tritium effluents for IFE are expected to be steam generator losses and releases from fuel processing systems. IFE target factory tritium releases appear significant, but not dominating. Overall, routine tritium releases from IFE and MFE plants appear to be similar as they are likely dominated by cooling systems not confinement approach.

Although tritium likely dominates routine fusion effluents, other effluents may arise. Activated corrosion/erosion products in the coolant may be significant but are unlikely to be dominating, similar to the situation in MFE.[9,11] Activated target material is unique to IFE, but

perhaps is analogous to tokamak dust. Small amounts of condensed activated target material would routinely be carried out of the chamber with the exhaust gases. Target debris is likely recycled to make new targets. Activated target debris may also be circulated with the coolant and/or breeder. Thus, activated target materials may become a source for release from fuel-processing or target-preparation equipment.

IFE plants will not emit toxic chemicals having potential global impact. Some IFE chemical effluents may be possible for concepts that use chemically toxic materials like beryllium, lead, or fluorine. However, they should be only a minor effluent, partly because these elements are used in non-volatile form.

Any power plant with a thermal conversion cycle (fission, fusion, coal, natural gas, oil) will reject heat to the environment. The higher the net thermal efficiency of the system, the lower the heat rejection. The reject heat from IFE plants should be generally less than other options because the candidate materials give rise to higher thermal efficiencies. Also, the larger land area required for IFE (versus MFE or fission) because of the driver may allow (depending on the site) that the thermal effluent may be spread more diffusely, lowering local environmental impacts. If, however, IFE requires high power recycling for the drivers, the net thermal efficiency suffers, increasing net heat rejection. IFE or MFE may ultimately go beyond thermal conversion cycles to more direct and efficient conversion schemes that make use of the high energy quality of fusion neutrons and charged particles. If so, reject heat would be lower than fission or chemical fuels.

3.2. Maintenance

The ICRP recommends limiting average annual occupational exposure below 20 mSv/a.[10] Some countries set slightly lower national limits. An average work year of 2000 hours implies an average tolerable dose rate of 10 μSv/h. Because IFE studies lack sufficient detail for thorough assessments, discussion is limited to predicting which components will require remote versus hands-on maintenance. Hands-on maintenance is faster; it may be less expensive.

The driver is physically separate from the reaction chamber. The driver interface is shielded from neutrons generated in the chamber and is expected to be a minimal source of decay radiation due to activation.[5,12,13] Most driver maintenance should be hands-on even immediately after shutdown of the reactor, since backward migration of reaction chamber radioactivity or neutron streaming is anticipated and can be mitigated. For heavy ion drivers, however, there will also be radiation fields typical of particle accelerators; these may require remote maintenance during shutdowns because of residual dose rate levels.

Any reaction chamber concept results in a dose rate during operation that will allow only remote maintenance. Thus, the reaction chamber will require remote maintenance, except perhaps for final decontamination and decommissioning, when it may be best to wait years before such procedures. Because the IFE first wall is possibly not changed out during its lifetime, one avoids the major maintenance personnel exposure facing MFE systems.

The reaction chamber exhaust will have activation products from some vaporized materials and activated target materials from high-Z indirect drive targets. Thus, the exhaust cleanup system may require remote maintenance.

After these gamma-emitting materials are removed, the subsequent ISS step will only involve tritium. Existing tritium technology maintenance will be adequate and no special problems are foreseen.

The target factory gamma-emitter inventory depends on whether high-Z targets are used, whether the target debris is recycled for new targets, and the holdup time before making new targets. Direct drive targets without high-Z materials only have hydrocarbons, which give no gamma emitters that could complicate maintenance if the target debris is recycled. If high-Z materials are used and are recycled as new targets, hands-on maintenance in the target factory may still be possible if low activation materials are used or sufficient holdup time allows decay. In this sense, lower activation target materials like lead are more desirable; higher activation Ta is less desirable.

The thermal-to-electrical conversion system and support systems will be accessible for hands-on maintenance during operation and all outages, as long as leakage of activated blanket material from the primary to the secondary loop remains acceptably small. The primary coolant system will require remote maintenance.

4. ACCIDENT SAFETY

This section looks at potential energy sources to drive accidents, the safety features that mitigate them, and lastly some very preliminary offsite dose estimates from IFE design studies.

4.1. Nuclear Energy Sources

There are two nuclear energy sources: (a) the operational fusion energy per pulse and (b) decay heat from induced radioactivity, which is only an issue during loss of coolant or loss of flow accidents.

The fusion energy per pulse is the driver energy (typically 5 MJ) times the repetition rate (typically 5 Hz) times the target energy gain (typically 100), for a total of about 2.5-GW fusion power. That is, a blast of 500 MJ occurs five times a second. The reaction chamber must withstand these blasts for 5 billion pulses for typically 40-year life and 75% availability. This motivates protective schemes like thick (~1 m) fluids or moving beds separating the blast from structural walls.

All candidate drivers (laser, light ion, heavy ion) require a vacuum (<1 kPa) for the driver energy to propagate to the target. Reaction chamber failure means loss of vacuum, hence fusion reactions will stop. A major chamber failure would prevent even the next target burn (<200 ms at 5 Hz) from occurring because the driver energy could not propagate or the target would not arrive at the right location at the right time. Then the only available energy is the incoming driver beam, which is less than 1% of the fusion energy per pulse (for target gain over 100).

If adequate cooling is lost, one must consider the short-term issue of removal of continued fusion reactions and the long-term issue of decay heat removal. Even if fusions were initially maintained, the blast heat on surrounding walls (if not cooled) would quickly vaporize sufficient material to overcome the vacuum system, thus spoiling the vacuum, hence blocking subsequent fusions. Nothing could be released from the chamber until it came up to atmospheric pressure, by which time fusion reactions certainly would have stopped and some vaporized material would have condensed. Little material could be released from the chamber in this manner.

The quantity of decay heat varies by multiple orders of magnitude depending on what material absorbs neutrons. Virtually all IFE designs use low activation materials so that they have sufficiently low decay heat to make its removal an insignificant concern even with total loss of all cooling to the reaction chamber. For example, HYLIFE-I absorbs most neutrons with low activation lithium, resulting in decay heat at shutdown under 0.1% of operating power.(14) Cascade uses a higher activation absorber, lithium aluminate, resulting in 1.4% at shutdown but only 0.16% after 1 day.(7) This amount of decay heat will not be a major concern even without any emergency cooling systems. MFE decay heat is typically somewhat higher.

4.2. Chemical Energy Sources

The main potential chemical energy source is reaction chamber material reacting with air or water. The most obvious example is liquid lithium, which burns in air and even in carbon dioxide.(15) MFE safety analyses still find good safety performance, mainly because of the reduced activation inventory in liquid lithium designs, which typically use low activation V-alloys.(16) Still, IFE designers generally avoid liquid lithium, preferring liquid 17Li83Pb, molten salts like FLiBe, or moving beds using lithium oxide (Li_2O) granules. 17Li83Pb is mildly reactive and can be handled safely.(15) Fluoride salts like FLiBe and ceramics like Li_2O are not chemically

reactive in any accident sense (slow corrosion of certain structural materials is a different issue). Carbon (potential granule or even structure) and beryllium (potential neutron multiplier) are also reactive; beryllium has more stored energy density than lithium.

4.3. Thermal-hydraulic Energy Sources

Fluids can store energy via enthalpy (internal energy and pressure), translational kinetic energy (momentum), and gravitational potential energy. Hot liquid metals or molten salts can damage equipment that they spill on, but short of chemical reactions (or accidents induced by damaged equipment), this does not pose public safety concerns. Release of pressurized water into ambient conditions will result in flash to steam and subsequent pressurization of the volume. Yet, very few IFE designs have used pressurized water (or pressurized helium) since they cannot be used as the fluid first wall because of their high vapor pressure.

Some moving granular bed concepts may have significant kinetic energy in the moving particles. The available energy is unlikely to damage the reaction chamber because it must be designed to withstand such moving particles on a operational basis. Possible damage to equipment outside the reaction chamber would be assessed and designed against in a detailed design and safety study.

Targets also have kinetic energy, but several-gram targets moving at typically 100 m/s are unlikely to damage reaction chambers built to routinely survive 500-MJ blasts.

4.4. Electromagnetic and Electrostatic Energy Sources

The driver is a source of energy in two regards: (a) the stored energy in the driver systems and (b) driver energy delivered into the reaction chamber.

The stored energy in lasers and light ion beam drivers is probably small, roughly the delivered energy (5 MJ) divided by the driver efficiency (10-25%), or only 20 MJ. The electrical supply system may have somewhat more, but still small. Heavy ion beam drivers include many magnets, would might store significant energy. However, the energy is both diffuse (spread over a large area) and separated from the radioactivity in the reaction chamber. At most, such an event would trigger a coolant disturbance in the reaction chamber, which must be mitigated anyway.

If the driver energy is not properly delivered to the target, such as the target failing to be in place to absorb the incoming driver energy, little damage is expected. The driver energy is only about 1% of the operational fusion energy, and could not significantly damage the inside of the reaction chamber.

If the driver beam/laser fails to remain centered down the delivery duct into the reaction chamber, it would strike the duct walls (or beam focusing magnets) likely damaging them. Although this would damage the plant, the major issue would be the ingress of air or duct coolant into the beam/laser line, hence into the reaction chamber. (This opens a release pathway.) Were chemically reactive materials in the reaction chamber, chemical energy release might result.

4.5. Preliminary Offsite Dose Estimates

The consequences of releasing radioactivity to the environment and public depends on the amount of material and the specific dose (mSv/kg). Detailed designs and accident sequence and consequence analyses would be required to calculate definitive consequence numbers. Still, it is instructive to look at possible worst-case values, while recognizing that many inherent, passive, and active safety features will be provided to decrease the chance of such releases and doses.

Very few integrated accident dose calculations have been done for IFE designs that properly reflect all dose pathways (inhalation, groundshine, cloudshine, and ingestion for longer time periods). The MFE International Thermonuclear Experimental Reactor (ITER) Conceptual Design Activities (CDA) found a general value for tritium release of 0.5 mSv/g-T released to the environment for worst-case accident conditions and 1-km site boundary.[9] (Doses here are

generally "early" dose, including 50-year dose commitment from inhalation, groundshine, and cloudshine within a week of the accident.) It is difficult to know how much tritium would be released under accident conditions. But, as an upper bound, even total release of all the tritium in the reaction chamber could not trigger acute radiation fatalities among the public. More realistic consequences would be far lower. IFE design studies have typically claimed upper-bound tritium releases within the radioactivity confinement of order 100 g-T (or less),[1] implying worst-case doses of 50 mSv. If so, public evacuation would not be required in most countries or recommended internationally.[17] A good, detailed design assessment would likely show lower worst-case doses as well as limiting overall probabilistic risk.

This would also be true of accidents in the tritium target factory and processing systems, if the tritium inventories there are of the same order, as would be the case with injection filling of targets.

Activation product doses are a strong function of the selected material. Fluids like FLiBe and lithium and moving beds like lithium oxide are low activation materials; of these the FLiBe dose is the highest at typically 1 mSv/kg-FLiBe.[5,18] Estimates indicate a plausible upper-bound release of 10 kg,[1] implying upper-bound early doses of 10 mSv, comparable to the tritium doses above. Extending the dose calculation to 50 years and adding the ingestion pathway increases this dose by as much as a factor of 5.[18] So, these low activation materials are quite beneficial in limiting hypothetical doses.

Higher activation materials like steels imply higher potential doses. Depending on neutron flux and fluence, steels have specific doses of 10-80 mSv/kg exposed at the first wall.[9,18] Fortunately, such materials are not used next to the burning targets in IFE designs and are highly unlikely to be released. Some designs avoid steel and use only lower activation V-Cr-Ti or SiC composite, with yet lower potential doses.

For indirect drive targets, the high-Z material is another source of activation. Lead is low activation with regard to early dose, 1-5 mSv/kg depending on neutron energy spectrum, flux (5 MW/m^2), fluence (4 yr), etc.[18] The longer-term dose is 10,000 times higher if ^{210}Po is not routinely removed. Tantalum is a high activation material, 60-1800 mSv/kg early dose, depending on neutron energy spectrum, flux, etc.[18]

5. WASTE MANAGEMENT AND RECYCLING

The nature of IFE, specifically the need to withstand billions of 500-MJ blasts, tends to determine the amount of material required in the reaction chamber. However, most of the neutrons are absorbed in protective fluids or moving beds. The chemistry (purity, tritium level, ^{6}Li enrichment, etc.) of these will be continuously controlled. Thus, it should be practical to directly re-use these in subsequent IFE power plants, or in refurbishment of existing plants.

Recycle of activated structures is a different matter, and it is not clear what recycling will be practical. There are no regulatory limits for recycle of material within a fusion economy. The desirability and practicality of recycling increases as the raw material cost increases and contact dose rates decrease, as is true of vanadium and beryllium. Typical fusion criteria are about 10 μSv/h for hands-on or 10 mSv/h for remote recycling and refabrication.[19] The limit on remote recycling is mainly one of cost and practicality for shielding and remote visual inspection during the various operations involved.

Depending on impurity level, assuming 30-year total irradiation, and accepting the 10-mSv/h criterion, steels may need to cool for over a hundred years,[1] which seems impractical. V-Cr-Ti alloys may require only tens of years, and the relatively high cost of vanadium makes it a logical recycle candidate. High purity SiC may require only about 10 years cooling, but the low raw material cost may make it less desirable to recycle. The impurity levels of certain elements must be controlled, including Ag (6 ppm), Nb (16 ppm), and W (480 ppm). Since these elements are neither alloying constituents nor normally associated with alloying constituents for V-Cr-Ti or SiC,

it is possible to consider meeting these goals. The exact values for allowed impurity concentrations depend on design details (fluence and neutron spectrum) and the remote recycle criterion. Far more work is needed to establish the economic, safety, and environmental aspects of recycling IFE materials.

IFE waste has been compared against one country's criteria, namely the near-surface burial criteria in the U.S., which serves as an illustrative example. Steels do not appear to qualify for near-surface burial because the potential exposure to inadvertent intruders 100-500 years after disposal would be too high. Thus, a more protective disposal technology would be required, such as shallow geological or even deep geological burial. The situation for V-Cr-Ti alloys and SiC is more promising, depending on impurity levels for key elements. Note that the limits on impurities for near-surface burial for key elements like Nb (0.7 ppm), Ag (2 ppm), and W (57 ppm) are lower than for remote recycling.(1) Again, the exact values will depend on the design and future near-surface burial criteria.

6. CONCLUSIONS

Table I summarizes the desirable attributes for fusion power plants, and compares the features of IFE and MFE. Routine impacts from IFE are low. IFE appears to have the potential to avoid **any** catastrophic or severe accident. Inherent and passive safety features should be capable of preventing any catastrophic public impact. Runaway fusion reactions are physically impossible. However, several technologies contributing to low hazards (like injection target filling and low activation fluid walls) require development and demonstration. IFE should be environmentally benign, relative to competing energy sources. There is no evidence of significant environmental impact from IFE power plants.

ACKNOWLEDGMENT

This work is supported by the U.S. Department of Energy, Office of Energy Research, under DOE Idaho Operations Office Contract DE-AC07-94ID13223.

REFERENCES

1. S. J. Piet, et al, "Safety and Environmental Impact," Chapter 6, Energy from Inertial Fusion, International Atomic Energy Agency, Vienna, 1995.
2. J. M. Martinez-Val, G. Velarde, and Y. Ronen, An Introduction to Nuclear Fusion by Inertial Confinement, Nuclear Fusion by Inertial Confinement: A Comprehensive Treatise, CRC Press, 1993, p. 24.
3. B. Badger, et al, "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," University of Wisconsin report UWFDM-450 or KfK-3202, June 1981.
4. O. K. Kveton, et al, "Fuel Processing Design for Inertial Confinement Reactors," Fusion Technology, 21 (3), May 1992, pp. 1541-1546.
5. R. W. Moir, et al, "HYLIFE-II Progress Report," Lawrence Livermore National Laboratory report UCRL-ID-21816, December 1991.
6. R. S. Matsugu, et al, "Tritium Fill Station to Charge Microballoons for Fusion Experiments," Fusion Technology, 19 (3), May 1991, pp. 1634-1639.
7. J. H. Pitts, et al., "The Cascade Inertial Confinement Fusion Reactor Concept," Lawrence Livermore National Laboratory report UCRL-LR-104546, December 1990.
8. W. R. Meier, et al, "Osiris and Sombrero Inertial Fusion Power Plant Designs," W. J. Schafer Associates report WJSA-92-01, March 1992.
9. J. Raeder and S. J. Piet, ed., ITER Safety Analyses, IAEA ITER Documentation Series No. 36, Vienna, 1991.

10. "1990 Recommendations of the International Commission on Radiological Protection," ICRP-60, Annals of the ICRP, 21 (1-3), November,1990.
11. D. L. Smith, et al, "Blanket Comparison and Selection Study," Argonne National Laboratory report ANL/FPP-84-1, September 1984.
12. H. Y. Khater, et al, "Environmental and Safety Aspects of "Osiris": A Heavy ion Beam Driven IFE Reactor, Fusion Technology, 21 (3), May 1992, pp. 2138-2144.
13. H. Y. Khater, et al, "Safety Analysis for 'Sombrero': A KrF Laser Driven IFE Reactor," Fusion Technology, 21 (3), May 1992, pp. 2023-2028.
14. J. A. Blink, et al, "The High-Yield Lithium-Injection Fusion-Energy, (HYLIFE) Reactor," Lawrence Livermore National Laboratory report UCRL-53559, December 1985.
15. S. J. Piet, et al, "Liquid Metal Chemical Reaction Safety in Fusion Facilities," Fusion Engineering and Design, 5, 1987, pp. 273-298.
16. J. P. Holdren, et al, "Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics with Safety and Environmental Characteristics," Fusion Technology, 13 (1), January 1988, pp. 7-56.
17. International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115-I, Interim Edition, Vienna, 1994.
18. S. J. Piet, et al, "Accident Safety Comparison of Elements to Define Low-Activation Materials," Fusion Technology, 17, July 1990, pp. 636-657.
19. G. J. Butterworth, "Can We Recycle Fusion Materials?," Fusion Technology, 21, May 1992, pp. 1994-2000.

Table I. Desirable Attributes of Fusion Power Plants

Desirable attribute	IFE	MFE
Low mobile radioactivity in reaction chamber	Desire low activation fluid walls and good target debris cleanup	Limit co-deposited tritium and dust; desire low activation armor
Low re-circulating tritium inventory	Has relatively high (good) burn fraction, but target fill technology is unknown	Has low burn fraction, effect of which could be mitigated by direct recycle of fuel
Low long-lived structural (solid) radioactivity	Typically protect structure by low activation fluid walls	Desire low activation structural materials
Isolate tritium plant from fusion reaction chamber	Has target factory well separated	Has tritium plant integrated with reaction chamber
Confine penetrations into reaction chamber	Needs isolation on many types of penetrations to the reaction chamber	
Low coolant/fluid pressurization potential	Has fluid walls at low pressure	Desire either low pressure coolants or use pressure suppression systems
Low chemical reactivity in reaction chamber	Desire low chemical reactivity fluid walls	Desire either low reactivity dust/walls or low reactivity coolant
Isolate energy responsible for fusion confinement from radioactivity sources	Has drivers typically well separated	Has magnets near-by radioactivity

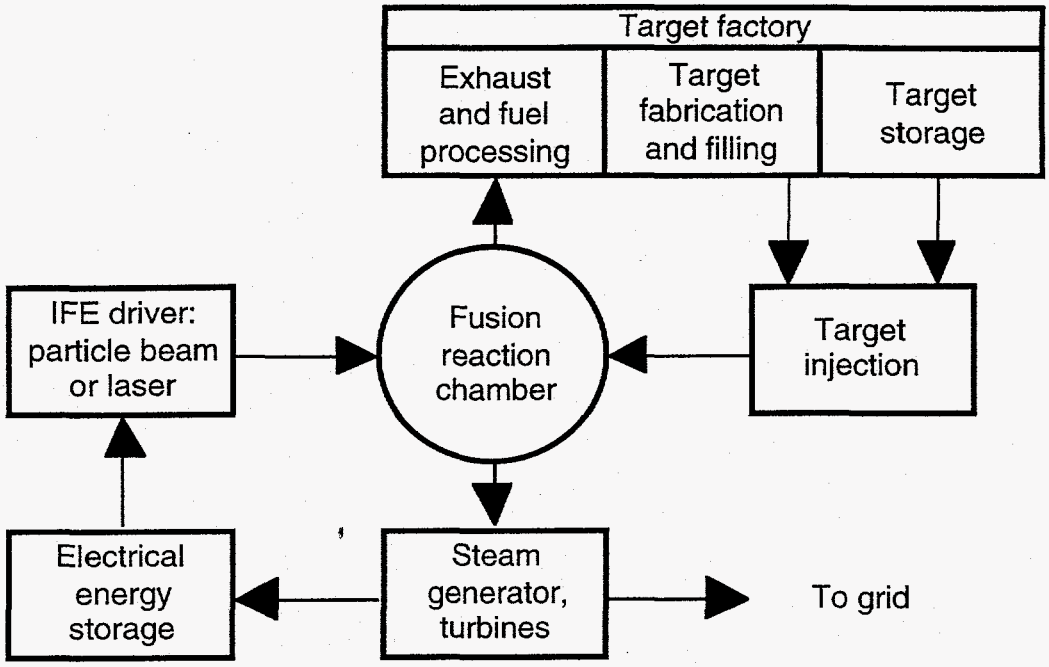

Fig. 1. General schematic of IFE power plant systems

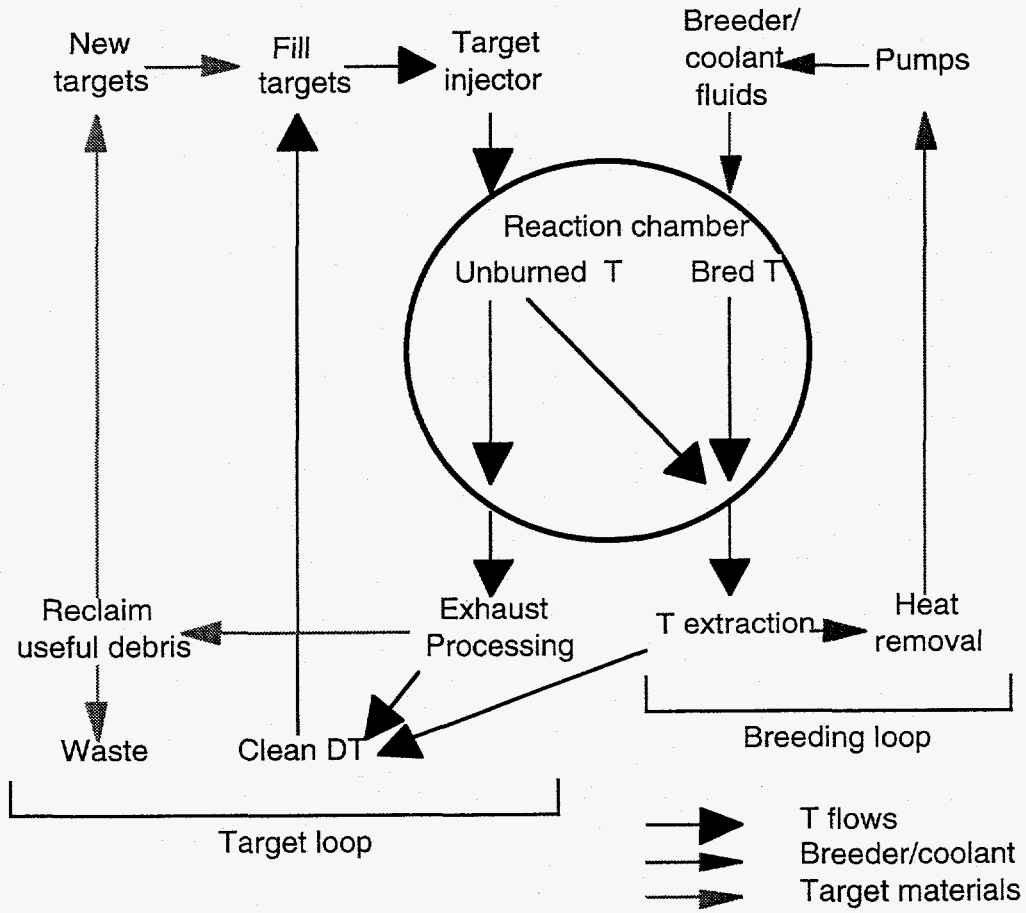

Fig. 2. IFE tritium processing loops and components