FUSION REACTOR ECONOMIC, SAFETY, AND ENVIRONMENTAL PROSPECTS

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ABSTRACT

Controlled fusion energy is one of only a few energy sources available to mankind in the future. Progress in fusion reactor technology and design is described for both magnetic and inertial confinement fusion energy. The projected economic prospects show fusion will be capital intensive and the historical trend is towards greater mass utilization efficiency and more competitive costs. Recent studies emphasizing safety and environmental advantages show that fusion's competitive potential can be further enhanced by specific material and design choices. Fusion's safety and environmental prospects appear to substantially exceed those of advanced fission and coal but will not be achieved automatically. A significant and directed technology effort is necessary. Typical parameters have been established for fusion reactors, and a tokamak at moderately high magnetic field (about 7 T on axis) in the first regime of MHD stability ($\beta \leq 3.5$ I/aB) is closest to present experimental achievement. Directions to further improve economic and technological performance include the development of higher magnetic fields to lower the required plasma current and reactor size, improvement in the beta value in the second stable MHD regime to lower requirements of field and plasma current, and improvement in techniques for plasma current drive to efficiently achieve steady-state plasma operation. For inertial confinement, reactor studies are at an earlier stage but two essential requirements are a high-efficiency (\geq 10\%) repetitively pulsed pellet driver capable of delivering up to 10 MJ of energy on target, and targets capable of yielding an energy gain (ratio of energy produced to energy on target) of 100.
INTRODUCTION

Fusion energy is one of only a few future energy sources available to mankind. The quest to achieve practical fusion energy continues around the world in programs aimed largely at establishing the plasma physics conditions needed for a burning fusion system. Our understanding of the potential of fusion as an energy source is derived primarily from reactor design and systems studies. These in turn are used to assess the safety, environmental, and economic characteristics of fusion power. Fusion is found to have the characteristics for a desirable energy source including significant potential advantages with respect to accident consequences, waste disposal, and air pollution. This outcome is not guaranteed, however, it requires that fusion research and development achieve the characteristics and performance goals identified through design, safety, and environmental studies. We address here the potential of fusion energy in terms of reactor design, economics, safety, licensing, and environmental issues.

"Fusion energy" in this paper will encompass both magnetic fusion energy (MFE) and inertial confinement fusion (ICF) energy. Section 2 provides a summary of fusion reactor studies. The economic potential of fusion energy is examined in Section 3. Safety, environment, and licensing issues are considered in Section 4. Section 5 presents some concluding remarks concerning the potential of fusion energy.

FUSION REACTOR TECHNOLOGY AND DESIGN

The key features of fusion reactor design and technology are described here to set the stage for a discussion of fusion's economic, safety, and environmental characteristics. Reactor design influences, and is influenced by, economic, safety, and environmental requirements. Because of the technological differences between MFE and ICF reactors, each is addressed separately.

Magnetic Fusion Reactor Technology And Design

Magnetic fusion energy (MFE) power plants will consist of a plasma reaction chamber, magnet coils, a blanket for energy recovery, plasma heating and fueling systems, a technique for controlling plasma purity, and a balance of plant for converting the fusion energy to electricity. The schematic elements of such a plant are shown in Figure 1. In the context of deuterium-tritium (DT) fueled reactors, the blanket provides tritium breeding since tritium is radioactive and has a half-life of 12.6 years. Deuterium occurs naturally in large abundance in water and both deuterium and tritium, isotopes of hydrogen, are the key components of the fuel. Even with alternative fuel cycles that are more difficult to achieve in terms of required plasma parameters [i.e., deuterium-deuterium (DD) or deuterium - helium - 3 (D-3He)], there will remain requirements for operation in a radiation environment and tritium handling. As such, both the MFE and ICF fusion reactors will incorporate radiation shielding, radioactive material handling systems, and remote maintenance equipment.

Conceptual design studies of MFE reactors have been carried out for over two decades. Progress through about 1980 is reviewed in References [1-6]. Several important studies [7-10] have been performed in this decade, but no single review of these has been published.

Many concepts for magnetic confinement of plasma have been studied [e.g., tokamak, reversed field pinch (RFP), and helical systems such as the stellarator] [7-14]. The effort devoted to reactor design for a particular concept is generally related to the relative maturity of that concept, the tokamak (having received the largest and most sustained effort) is the most mature of the magnetic confinement designs. Work on the tokamak has included studies of both commercial reactors and more near-term devices. International studies of near-term devices are the INTOR [2] and, more recently, the International Thermonuclear Experimental Reactor (ITER) activity [16]. Although the focus of this paper is on commercial fusion power, the benefit of the
Figure 1. Schematic elements of a magnetic fusion energy (MFE) power plant.
interplay between near-term and long-term studies is crucial. The most thorough and well-documented tokamak reactor study is STARFIRE [7].

Next to the tokamak, the mirror approach has received great attention with the MARS work [8] being the most thorough and well-documented tandem mirror reactor study. During this decade the reversed field pinch (RFP) has been examined in several reactor design studies, the most comprehensive of which is the recently completed TITAN study [9]. Conceptual design studies based on a variety of alternative confinement schemes have also been performed [10-14] at a modest level of effort.

Early reactor studies identified engineering problems, technology requirements, and physics implications. Second generation studies developed solutions to issues raised in the early studies. During the past decade, reactor studies have focused upon improving fusion's economic and safety features and achieving design simplicity in order to maximize the potential of fusion as an energy source. The evolution of MFE reactor design is seen in the changes of certain key, generic features: mass power density, magnetic field requirements, pulsed or steady-state operating mode, auxiliary plasma heating techniques, blanket design and energy conversion, plasma purity control, and fuel exhaust. Since the tokamak concept is the most developed, we emphasize here the physics and technology requirements for attractive tokamak reactors.

Mass power density (MPD) is a useful figure-of-merit to assess the economic potential of MFE power reactors. MPD is the ratio of the net electrical power output of a plant to the mass of the fusion power core (the blanket, shield, and magnets). This figure-of-merit places emphasis on the physics and technology of the reactor. Therefore, it is sensitive to fusion-specific cost factors and is independent of costs related to construction and operation of the power plant. Reactor designs show a consistent trend towards increased MPD as studies have matured and economics is emphasized. The studies indicate that an MPD value of about 100 kWe/tonne of fusion-power-core is an important target value and that further increases yield only a moderate improvement [17]. All confinement concepts, which have been examined to date, exhibit the potential to meet this minimum figure-of-merit target, and the RFP systems appear to have an intrinsically high MPD value [9].

Achieving a high MPD value requires efficient use of the applied magnetic field. This efficiency is measured by the quantity beta (β), the ratio of the plasma kinetic pressure to the magnetic pressure associated with the applied field. Beta is limited by plasma physics constraints. If beta is low, then high MPD can only be achieved by operating at high values of the externally produced magnetic field. One early tokamak design study [18], using the understanding of beta limits at that time, adopted superconducting magnets operating at high field (16 T). The result was a very large value of stored magnetic energy (250 billion joules, or 250 GJ). Not only did this field strength strain the limits of credibility at the time, but the stored energy represented a substantial financial risk if the magnets should fail. Both physics and technology programs responded to these concerns. Physicists developed a theory showing that lower fields (higher β) could be used if the plasma shape were elongated. The STARFIRE tokamak study used plasma shaping and achieved a more attractive system with 11 T magnets and a total stored magnetic energy of only 50 GJ. Since then, highly successful experiments (e.g. JET, DIII-D) have verified the benefits of plasma shaping. More recently, plasma theory suggests that further increases in beta may be possible. A recent study [19] of reactor operation in this “second stability regime” with β values of 20% (compared with 3% to 10% earlier) suggests that maximum fields of only 7 T and a stored energy of just 8 GJ would be possible. This exciting prospect is a stimulus to present experimental programs in machines such as TFTR, PBX-M, and DIII-D.

Meanwhile, the worldwide magnet development effort mobilized to demonstrate the design goals identified in reactor studies. The international Large Coil Task [20] successfully constructed and tested an 8 T magnet set arranged in a torus with 1 GJ of stored energy. Other programs [21] are developing small magnets at higher fields (12 T). Reactor studies have identified other key magnet development issues including high strength structural materials, better radiation-resistant insulators, and higher
current density superconductors. The High Field Compact Tokamak Reactor study [22] focused attention on a reactor with 13 T magnets having 40 GJ of stored energy.

Both the tokamak and RFP concepts would be limited to pulsed plasma operation if only inductive techniques were available to sustain the plasma current. System studies suggest that steady-state operation will be safer, more reliable, and more economical than pulsed operation. Fortunately, other techniques for sustaining the plasma current have been developed for both the tokamak and the RFP. Although too simplistic, the current-drive technique proposed in the early Mark I tokamak reactor study [23] stimulated theoretical studies of neutral beam (NB) and radio frequency (RF) approaches to current drive. Grounded on a firmer theory, STARFIRE [7] explored the benefits of steady-state operation. Worldwide experimental effort soon verified the prospects for steady-state operation. The main technical issue now concerns the efficiency of the current-drive system. In tokamaks, there is an inherent current drive called the “bootstrap current” which will greatly reduce the circulating power. The bootstrap current has now been experimentally observed and verified in the TFTR and JET tokamaks. The attractiveness of steady-state operation is a goal of the International Thermonuclear Experimental Reactor (ITER) [16]. Other technology development programs [e. g., cooled waveguides, negative-ion-based NB, high-power electron-cyclotron-resonance (ECR) sources] assist in meeting the steady-state goals.

The auxiliary power required for steady-state operation can also provide the external power needed to reach ignition temperatures in fusion plasmas. Early reactor designs considered, for example, neutral beam (NB) and electron-cyclotron resonance RF heating (ECRH) technologies. On the basis of such studies, important directions were identified for technology development. Conventional NB systems are not viewed as attractive for reactors. They are physically large and the penetrations needed make tritium and radiation containment difficult. An alternative NB technology based on negative-ion sources appears to be preferable. For ECRH, gyrotron technology seems impractical if the sources are limited to modest power (100 kW per unit). High power sources at unit sizes above 1 MW [e. g., advanced gyrotrons at 1 MW, cyclotron auto resonance masers (CARMS), or free electron lasers at up to 5 MW per unit] are now under development.

The nuclear performance of a fusion reactor is determined primarily by the blanket materials. Many material combinations have been proposed and early studies focused on achieving an adequate tritium-breeding ratio (> 1.1 tritons produced per triton consumed). Subsequent designs examined thermal-mechanical issues, accident and safety in design, and environmental impact. There are now several desirable choices for breeding materials, structural materials, and coolants in blanket applications. The breeder materials include solid lithium-bearing ceramics or liquid metals; structural materials include low-activation steels, vanadium alloys, and low-activation ceramic composites; coolants include gases, water, and liquid metals. The choice of energy conversion scheme is closely coupled with the choice of blanket materials. The emphasis in reactor studies has been on thermal energy conversion, but several studies of advanced fusion fuel cycles have considered direct energy conversion. Direct conversion can result in dramatic simplifications to the balance-of-plant for fusion reactors [24].

Perhaps the most challenging aspect of MFE reactor design is associated with plasma impurity control and helium and impurity exhaust. In this context, magnetic diversion of helium “ash,” impurities, and unburned fuel is the most commonly adopted approach. Unfortunately, the large magnet coils required for diversion can impede reactor maintenance and can also significantly increase the capital cost. Nevertheless, magnetic divertors remain the primary approach in the experimental program, particularly because of recently discovered benefits to plasma energy confinement, namely “H-mode” operation. On a smaller scale, some novel impurity control and exhaust schemes proposed in reactor studies are being investigated experimentally. These include the pump limiter [7] and the self-pumped limiter concept [19].

In summary, MFE reactor studies have identified the technical features, the development needs, and the prospects for MFE systems. Attractive solutions for
many problems have been found, and proposed solutions are being examined within the physics and technology programs.

Inertial Confinement Fusion Reactor Technology And Design

Inertial confinement fusion (ICF) [25,26] refers to the approach in which laser or charged particle beams deliver energy to compress and ignite small capsules of deuterium and tritium fuel. The ICF power plants will consist of a driver to implode and ignite the pellet target, a target factory to manufacture and deliver the targets to the center of the reactor core, one or more reaction chambers in which the targets are burned, and the balance of plant in which the fusion energy is converted to electricity. The schematic elements of an ICF reactor plant are shown in Fig. 2. The reaction chamber includes components for energy recovery, tritium breeding, and radiation shielding [27,28]. Differences between ICF and MFE power reactors make some technological issues easier and others more difficult to solve. Design flexibility is gained in ICF systems because of the relaxed vacuum requirements in the reaction chamber and in the separability of the driver, the fusion target manufacture, and the design issues of the reaction chamber. On the other hand, the extreme pulsed nature of ICF's energy production (i.e., three to four 1 GJ explosions per second in a 1000-MWe plant), the very large yields anticipated per shot (up to 1 GJ or 1/4 ton of TNT equivalent) and the manufacture and emplacement of target capsules are design challenges which differ from those of MFE systems. Also, at present, details of the design and operation of ICF fuel targets is classified. A power plant using classified targets is probably unacceptable so that progress on this unique ICF issue is needed. Thus, while ICF shares many technological development issues with MFE, it truly represents a very different approach to commercial fusion energy.

A number of drivers are possible for ICF power reactor applications including heavy ion beams, light ion beams, KrF, and solid-state lasers [29]. While some former driver candidates have been eliminated because of poor target results (e.g., pulsed electron beams and CO₂ lasers), proposals for other new drives (e.g., free electron lasers, compact torus accelerators, and other laser concepts) have taken their place. Two types of targets are in contention: indirect drive target (whose detailed design is classified and in which the drive energy is converted to X-ray energy before interacting with the fuel capsule) and direct drive targets [30,31] in which the fuel capsule is directly illuminated. There has been much work on target fabrication but only cursory attention has yet been paid to the design of a target factory (since the basic target design is still in question), and to target injection, tracking and positioning. In principle, any of the drivers could be used with either target type, illustrating the separability of driver and target issues.

Target performance in general does not depend on the surrounding chamber configuration. (This is not entirely true for pulsed power techniques.) Thus, many reaction chamber concepts have been developed to deal with the effects of target explosions. Also, the large number of driver, target, and chamber combinations, and the evolving emphasis on various design criteria (reliability, practicality, safety, environmental impact, and cost) have led to a large number of reactor studies over nearly two decades. A review of ICF reactor studies through 1984 is given in Reference [29].

Early ICF studies established two main themes: (1) there are several ways to deal with the very large peak-power-density incident on the first wall of the chamber as a result of the target explosion; and (2) self-consistent power plant concepts can be developed for each of the candidate drivers. In an ICF capsule, the energy is produced in a few tens of picoseconds (i.e., ~ 3 x 10⁻¹¹ s). Thus, for a capsule yield of 1 GJ, the instantaneous power is ~ 3 x 10¹⁹ W, far above the average fusion power of about 10 GW. This fact requires that the ICF reactor first-wall structure be very different from those in magnetic fusion reactors. The ICF first wall will either be at a very large radius, or it must be designed to tolerate ablation. Most designs have followed the latter principle in order to keep the size of the reaction chamber moderate, consistent with anticipated economic goals. Designs have been proposed in which the permanent
structure is protected by a variety of self-renewing first walls. Materials suggested for use between the target and the chamber structure include gases, liquid sprays, thin liquid-metal layers (i.e., wetted walls), thick liquid-metal layers (i.e., liquid lithium falls), and thick cascading layers of sand-like granules.

In all the liquid and solid first-wall reactors, some material will be vaporized with each pulse (up to a few kg). The material just beyond the vaporized region must be energy absorbing so that large shocks will not be transmitted to the permanent structure. Recondensation of the vaporized material before the next pulse (to reestablish the vacuum needed to inject the next target pellet and to propagate the driver beams to the target) is needed and has been identified as a critical issue for all these designs. The early studies indicated (largely through calculations) that self-renewing layers could be designed which would lengthen the effective time of the short energy pulse so that the peak power on the permanent structure is tolerable. In most studies, however, a paucity of experimental data is noted.

Vacuum requirements in ICF reactors, set by the driver beam propagation, are not stringent (1 to 1000 Pa). Therefore, even hot liquid-metals can be used inside the chamber (i.e., their vapor pressure is not too high). Once this fact was fully appreciated, many studies in the late 70s and early 80s moved the entire energy transport and tritium-breeding blanket inside the reaction chamber, providing far more material than was needed to stretch the short X-ray and debris pulses. In fact, enough cascading material is included in the chamber to stop essentially all the high energy neutrons produced. Advantages of this arrangement include more efficient deposition of thermal energy in the working fluid, better tritium-breeding ratio, lower activation of materials and, most importantly, much longer lifetime of the permanent structure. Previous fusion studies found that the first-wall structure lifetime will be, at most, a few years because of neutron damage. The HYLIFE study [32] showed that with a thick liquid-lithium layer, all structures could be made to last the assumed 30-year lifetime of the plant.

The ICF reactor studies also revealed the basic characteristics of self-consistent reactor concepts for each major driver candidate. Many characteristics proved to be independent of driver type but some differences remain. Vacuum requirements to transport the various types of beams to the target vary, being most stringent for heavy ions (about 10^{-3} Pa) and least for light ions (indeed about 1 kPa of gas is needed) with lasers in between (at about 10 Pa). When the advantages of tolerating a higher background chamber pressure became apparent [33], the heavy ion advocates sought and found ways to propagate their beams through it [34]. In the light ion designs [35], the higher chamber pressure required for beam propagation automatically protects the first wall from the effects of the X-rays and debris. All this energy is deposited in the chamber gas where the fireball created releases the energy to the first wall at an acceptably slow rate.

On the other hand, the ability to transport heavy ion and laser beams over long distances without significant losses allows the drivers to be located in a separate building, away from the reactor chamber itself. This has several advantages: it provides greater flexibility in designing the reactor chamber (i.e., very large chambers are possible) and makes maintenance of the driver easier. In turn, reliability should be improved and high-cost driver components are not in a radiation environment. It is also possible for one driver to service several reaction chambers, making modular construction possible as well as lowering the unit driver cost. Finally, separability of driver and target chamber reduces the target containment chamber volume.

In the mid-to-late 1980s, ICF system studies represented either an evolution of earlier concepts or more radical approaches that went beyond first generation designs. The earlier studies attempted to show that ICF reactors can be practical. The studies assumed the simplest designs and as much existing technology as possible. They showed that once high target gain is achieved, a practical power reactor can be built with existing technology. Nonetheless, design difficulties became apparent. The reactors were relatively expensive in both cost of electricity and capital requirements, they produced induced radioactivity at significant levels, and they raised safety issues because of the large tritium inventory and the large amount of liquid metal used. Present work has focused more on the use of advanced ceramic and composite
materials (granules, fabrics, and structures) [36-38], but their viability must be established.

Major unresolved issues for ICF reactors are a cost-effective rep-rated driver that can deliver 2 to 10 MJ to a target, and a target which will yield an energy gain of at least 100. The four major candidates at this time are solid state-lasers, KrF lasers, heavy ion beams, and light ion beams. Of these, only solid-state lasers have actually been used to implode ICF capsules. Recent systems studies [39] and new experimental work [40,41] indicate that conceptual solid-state-laser reactor-driver designs are plausible based on identified technologies. The solid-state laser's natural ability to achieve the high peak-power densities necessary to drive a capsule, its flexible frequency-conversion ability, and its operation at a frequency at which optical materials have a high damage threshold are some of the features that make it attractive as a driver, while rep-rate ability and cost are key outstanding issues. KrF lasers are being actively pursued [42] because of attractive features that include good energy coupling to the target, the use of a gaseous lasing medium, and the potential to be rep-rated. Issues of concern for KrF lasers include efficiency, cost, and optical complexity and size (associated with techniques such as optical multiplexing to shorten and shape the pulse). Heavy ion beams are the favorite candidate of some because of their naturally high wall-plug-to-beam conversion efficiency and their demonstrated, reliable repetitive-pulse operation. Recent systems work [43] showing the ability to generate and accelerate beams of multiply-charged ions reduces the cost of this option, although it still remains high. Light ion beams (lithium ions) generated by pulsed power techniques are being pursued because they are highly efficient (25% to 40%) and are low cost. Light-ion-beam reactor-systems work [35] has focused successfully on identifying plausible pulsed power elements which have the potential of repetitive operation and to transport and focus very high-current light-ion beams. All drivers except solid-state lasers must yet demonstrate that they can successfully drive ICF capsule implosions. A key open issue is whether any laboratory driver is able to attain the threshold energy to achieve high gain.

ECONOMIC ASSESSMENT OF FUSION ENERGY SYSTEMS

The development of an energy policy is subject to large uncertainties [44] in supply-and-demand forecasts for energy end-use, in environmental considerations (e.g., global warming and waste disposal), in variations among national regulations, and in the characteristics of future, competitive energy sources. Accordingly, the ability to project the timing of the market penetration and cost competitiveness of a new energy source for coming decades is difficult. Nevertheless, it is important to make the effort. The search for cheaper, more abundant fuels in recent times has led to systems (such as fission reactors) where the fraction of total cost devoted to buying the fuel is reduced but the cost to implement the technology is increased. Fusion’s fuel costs will be negligibly small but the technology could turn out to be excessively costly or complex, or the potential environmental advantages may be offset by difficulties in implementing the technology. Because of this, recent reactor studies have emphasized simplicity and reliability as well as safety and capital-cost improvements.

Several dozen economic assessments of both MFE and ICF central-station electric-power plants have included capital-cost estimates (based on various levels of detail), cost-of-electricity (COE) projections (based on capital costs, operation and maintenance (O&M) costs, fuel-and-other-consumables costs, decommissioning costs, and assumed plant availability), assessments of potential resource needs, development of energy-payback-time models, and comparisons with competitive energy technologies. Such economic assessments contribute to the identification of attractive avenues for magnetic or inertial confinement fusion research.

The present status of the fission power industry (in the USA), as well as future projections [45], provide lessons for fusion. Problems in the fission power industry can be traced to the increased technological sophistication needed to reduce from 50% (coal) to 30% the fraction of the total energy cost attributable to fuel and, in the U.S., to the large number of independent utilities, each specifying individual power-plant
requirements. Now, improved and safer fission power plants are being emphasized in the U.S. [45]. Their features include: (1) passive stability to uncontrolled energy releases; (2) simplification to reduce the number of plant components; (3) ruggedness of design to enhance critical design margins and extend plant longevity (>60 years); (4) ease of operation to reduce the “human factor” as was seen at the 1979 Three-Mile-Island accident; and (5) improved licensing through greater design margins, passive-safety features, factory fabrication/construction, standardization, and reduced probability of a severe accident (both in terms of public safety and investment protection).

Fusion-reactor fuel costs are expected to be less than the fuel costs of both present-day fossil fuel and nuclear-fission plants. The total plant capital costs, however, will likely be greater since the reactor costs associated with the heat-generating fusion power core (reaction chamber, blanket, shield, magnets or target driver, and structure) will probably be larger than the counterpart systems in fossil-fuel or fission-power plants. Plasma-current drivers (e.g., neutral beams or RF) for tokamak or RFP MFE systems or implosion drivers (e.g., heavy/light ion beams or KrF/solid-state lasers) and target factories for ICF systems contribute additional significant costs. Furthermore, most conceptual ICF designs require 10% to 20% of the gross electric power to be used within the plant to supply power to the driver system. This will yield a correspondingly larger balance-of-plant (BOP) and increase the unit’s capital cost.

Table 1 is a comparison of estimates of future fission reactor costs and estimates made for magnetic fusion based upon conceptual reactor designs. Cost estimates for ICF reactors have also been made, but the designs are at an earlier stage and the cost basis is different. For both MFE and ICF reactors, the results indicate that fusion reactors will be capital intensive and, with significant developments, can provide economically acceptable power [46]. We emphasize, however, that fusion’s most attractive attributes as a central station power source are its environmental and safety characteristics.

More broadly-based studies (including the recent ESECOM study [47,17]) point the way to economically competitive and environmentally acceptable fusion power through a careful choice of enhanced mass power density (MPD), blanket materials, and reactor configurations, together with improvements in plasma physics performance and the development of efficient plasma sustainment systems (heating, current drive, magnets, etc.).

Pending detailed conceptual design of fusion reactors for which systematic "bottom-up" costing analysis can be performed, the MPD (kWe/tonne) is suggested [48] as a useful indicator of progress in reactor design, provided recirculating power costs are kept to acceptable levels (e.g., <10% to 20%). Figure 3 is a plot of the mass power density (MWe/m³) in the fusion power core (FPC) as a function of the MPD for a number of fusion reactor designs and a typical PWR fission reactor. The MPD values for the UWMAK-I tokamak reactor study (1973), the STARFIRE design (1980), and the ESECOM/GENEROMAK Li/Li/V base case (1988) [47] tokamak designs are, respectively, 20, 50, and 106 kWe/tonne. Although the latter value exceeds the target value of 100 kWe/tonne, it remains below the 500-1000 kWe/tonne values that characterize PWR fission systems. Fusion's more massive (costly) system can be tolerated in economic terms only to the extent that its reduced fuel-cycle costs and improved environmental, licensing, and safety characteristics lead to competitive overall costs.

Advances in plasma physics (e.g., higher beta) and in engineering (e.g., higher power density blankets, high-field coils, efficient ICF drivers, etc.) can lead to high values of MPD and, hence, to competitive costs. Studies such as the recent TITAN Reversed-Field-Pinch (RFP) Study [9] (MPD = 760 kWe/tonne) and the ongoing ARIES Tokamak Study [49] (MPD ~ 84 kWe/tonne) continue this trend to higher MPD (see Fig. 3). Achievement of MPD values in excess of 100 kWe/tonne can be expected to result in lowering the FPC cost below one half the total plant capital costs, reducing the leverage of the most speculative aspect of the fusion plant. This conclusion assumes that the cost of a steam-cycle balance-of-plant is well understood.
Table 1. PROJECTED COSTS a OF FISSION AND FUTURE MAGNETIC FUSION POWER STATIONS

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<td>Total</td>
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b. Refs. 3,4: Pressurized-Water Reactor, Median Experience (Today's fission)
c. Refs. 3,4: Pressurized-Water Reactor, Better Experience (Today's fission, but with regulatory and improved construction practice).
d. Refs. 3,4
e. Ref. 7
f. Ref. 8: High-field, first stability regime.
Figure 3. Mass power density for various magnetic reactor designs showing a trend towards systems with MPD values > 100 kW/tonne of fusion power core. The HTGR and PWR are thermal fission reactors. MARS is a tandem mirror fusion design, TITAN is a reversed filed pinch (RFP) fusion design, and the remainder are fusion designs based on the tokamak system.
and comparable to those of fission and fossil plants of similar power output. The MPD may also be a useful figure-of-merit for ICF reaction chambers, although the dominance of the implosion-driver system and target costs have historically led to an emphasis on improving the pellet gain, G, and driver efficiency, \( \eta \) (see reference [32]).

Cost estimates in mills per kWeh for magnetic fusion reactors are given in Fig. 4 from various reactor design studies as a function of mass power density. More recent studies have higher values of MPD. The general trend has been towards higher MPD designs with lower values of COE as both designs and knowledge have advanced. The cost comparison (shown in Fig. 5 of tokamak reactors designed to produce 1200 MW of electricity as a function of the aspect ratio of the device) is indicative of progress that can still be made. The aspect ratio is the ratio of the major and minor radii of the torus. The cost shown is relative and excludes the cost of the balance-of-plant. However, it does include the effect of recirculating power to maintain a steady-state system. The curves in Fig. 5 are for two assumptions on the maximum attainable toroidal magnetic field at a coil, 14 T versus 24 T. Clearly, lower cost systems favor higher field systems at larger aspect ratio.

In summary, fusion power continues the historical trend towards more capital-intensive power-generating systems that use less expensive, more abundant fuel and have additional advantages in areas such as safety, air pollution, waste disposal, and other environmental and licensing features (see Section 4). Cost studies show fusion energy for central-station electric power may come at a premium relative to advanced fission or coal. However, fusion's safety and economic prospects appear to exceed those of either fission or coal by a substantial margin. Recent studies are emphasizing safety and environmental benefits through a broader selection of materials, fuel-cycles, configurations, and energy-conversion schemes. The achievement of a passively-safe reactor can lead to a significant cost credit [47,50] for both MFE and ICF systems.

SAFETY, ENVIRONMENT, AND LICENSING ASSESSMENT OF FUSION ENERGY SYSTEMS

One of the main incentives for investing in the development of fusion energy is the prospect that the safety and environmental (S&E) characteristics of fusion will be less troublesome, both in fact and in public perception, than those of fission and fossil fuels have been. This expectation of S&E advantages for fusion is not a guarantee however (i. e., tritium, neutrons, and neutron-activation products in fusion reactors represent radiological hazards similar in kind if not in magnitude to those of fission reactors). Assuring that fusion technology is developed in ways that exploit the potential for minimizing these hazards deserves high priority. Furthermore, the developers of fusion must address the need to minimize non-nuclear risks (e. g., chemical hazards, exposures to non-ionizing radiation, thermal impacts, etc.).

Background

The first substantial analyses of the safety and environmental characteristics of fusion reactors appeared in the period 1969-70 and focused mainly on tritium hazards in routine operation and in accidents [51], with secondary attention given to problems posed by neutron-activation products [52]. By the mid-1970s, activation-product hazards (occupational radiation doses, radioactive-waste problems, and possibilities for release in reactor accidents) were receiving attention comparable to that given to tritium [53]. Reactor-design studies featuring “low-activation” materials were being conducted [54], and fusion S&E issues had become the focus of international working groups and reviews sponsored by the IAEA [55].

The evolution of fusion S&E studies in the second half of the 1970s reflected the influence of several trends that had been taking place in S&E assessments of other energy options. The first was a trend toward increasing comprehensiveness in the kinds of energy related activities and environmental phenomena included in S&E assessments meant, for fusion, examining not only the most obvious radiological hazards but also the occupational and public hazards of fuel acquisition and transportation, accident risks to workers in component fabrication and power-plant
Figure 4. Estimated cost of electricity reported by different magnetic fusion reactor design studies carried out over the years, plotted in 1988 dollars as mills/kWhe versus the mass power density.
Figure 5. Relative costs of tokamak reactors as a function of aspect ratio for two different values of achievable maximum fields at the coils. The $\beta$-limit is that of first stability. The $(B_o,I)$ values are the on-axis magnetic field in Tesla and the plasma current in megamperes, respectively.
construction, chemical hazards in fusion technology, and magnetic-field hazards [56]. A second trend toward comparative assessment of technologies with similar applications, in light of recognition that estimates of S&E risks and impacts are meaningful only in relation to the risks and impacts of alternative ways to obtain the same societal benefits, led to comparative S&E assessments of fusion and fission—perhaps most notably the study of the S&E characteristics of fusion and fission fast-breeder reactors conducted under the auspices of the International Institute for Applied Systems Analysis in 1975-77 [57]. Finally there was a trend, in the study of fission-reactor accident hazards toward analysis of physically plausible pathways by which radioactive material could be released and estimation of radiation doses that could actually result (as opposed to indices based on inventory alone) [58]. This trend led to a similar focus on accident phenomenology in fusion-reactor safety assessments [59,60]. The findings of the fusion S&E assessments by the late 1970s, while obviously preliminary and incomplete, were not wholly reassuring regarding issues such as tritium inventory, accident analysis, and waste disposal.

Expanded efforts have taken place in the 1980s to ensure that fusion’s safety and environmental potential is maximized. These efforts included a more accurate characterization of the radiological hazards of fusion technology through the use of more detailed reactor designs [61], new experimental data on accident phenomenology [62], and more sophisticated analytical models (including computer simulation) of accident conditions, mobilization of radioactivity, and pathways to human exposure from reactors as well as from waste repositories [63,64,65]. This work was used to construct indices of relative hazard (or relative assurance of safety) that strike a reasonable balance between clarity and comprehensiveness, that lend themselves to inter-design and inter-source comparisons, and that convey some information about probability of harm (albeit far short of what would be contained in a full probabilistic risk assessment) [64-66]. More extensive studies of the feasibility of low-activation structural materials [67] and advanced (low-neutron) fuel cycles [68] are being carried out and there is a trend towards the systematic exploration of the trade-offs in fusion-reactor blanket design, among traditional performance criteria, minimization of tritium inventories, and maximization of safety margins against mobilization of activation products in accidents [69]. Finally there is a trend towards the integration of the results from the preceding elements, together with engineering-economic modeling of overall system performance and costs [70] to investigate the potential of a range of fusion-reactor concepts to achieve combinations of environmental, safety, and economic characteristics that are attractive compared to those of contemporary and advanced fission-energy systems [47,71,72].

The thrust of the results of the more recent studies can be summarized as follows:

- Fusion reactors of contemporary design will have advantages over fission reactors with respect to the consequences of severe accidents and the magnitude of radioactive-waste burdens, even in the relatively unfavorable case (for fusion S&E characteristics) of stainless-steel structure and liquid-lithium coolant/breeder.

- The magnitude of these advantages becomes more impressive for fusion-reactor designs that employ lower-activation structural materials and/or contain less stored energy than the stainless-steel/liquid-lithium combination. (Examples of lower-activation materials, in order of increasing S&E attractiveness and, but decreasing assurance of technological feasibility, are: elementally tailored ferritic steel, vanadium alloy, and silicon carbide. Coolant and breeders with less stored energy than liquid lithium include FLiBe molten salt, lead-lithium alloy, and helium coolant combined with a solid ceramic breeder material such as Li2O).

- For some fusion-reactor designs, it appears that avoidance of off-site deaths from acute radiation syndrome in severe accidents can be assured without reliance on active safety systems or containment buildings. Increased experience in the last several years with the handling and control of tritium supports the belief that fusion will be able to meet the same tight standards on routine emissions with which fission reactors now comply.

- Fusion-energy systems will present smaller problems than fission in respect to unwanted links to nuclear weaponry: fusion systems (other than fusion-fission hybrids) would contain no fissile material, and the introduction of means to
produce it will be relatively easy to detect.

- Fusion will create certain non-nuclear risks and impacts similar to those of other energy sources (e.g., waste heat, hazards of materials transportation and facility construction, chemical hazards to workers) and at least one non-nuclear hazard not shared by other sources [intense magnetic fields in MFE reactors (powerful pulses of laser light or particle beams in ICF)], but none of these issues currently appears to be serious enough to weigh importantly in societal decisions about fusion's attractiveness compared to other energy options.

- The present detailed nuclear-power-plant licensing regulations are strongly tied to fission reactor designs and will not be applicable to fusion. The underlying regulations in the U.S. for radiation protection (10CFR20, 10CFR50, and 10CFR100), however, are quite general and are expected to apply. It appears that fusion reactor designs can readily satisfy these regulations.

- Fusion has the potential to guarantee the safety of the public by limitations on radioactive material and stored energy inventories. This is expected to result in capital cost savings due to fewer licensing requirements for nuclear-stamp components. The potential for achieving a demonstrably safer reactors may also reduce the time and costs associated with the licensing process.

More information about the results on which these conclusions rest is provided in references [47] and [73]. The following section draws on the work in reference [73].

Hazards In Fusion Energy Systems

The discussion in the following subsections cover: tritium, activation products, radioactive waste management, and accident pathways.

Tritium

Tritium (H\textsuperscript{3}, in the fusion literature often denoted T) is radioactive with a half-life of 12.3 years, emits a beta particle of rather low energy (maximum 18 keV), and yields stable helium-3 (He\textsuperscript{3}). Tritium will occur in necessarily sizable quantities as an ingredient of the fuel in fusion reactors operating on the deuterium-tritium (D-T) reaction, and in smaller quantities as the product of D-D reactions in "advanced fuel" systems that contain deuterium. It is also formed as the result of neutron bombardment of light elements that may be present in fusion-reactor components.

The tritium in a D-T fusion reactor will reside in two quite different inventories. The "active" inventory consists of T in the plasma, tritium-breeding blanket, tritium-extraction system, impurity-control and vacuum-pumping system, fuel injectors, and any pipes and intermediate reservoirs linking these components. The magnitude of the active inventory depends on the characteristics of all these subsystems, including especially the mean residence time of T in the breeding blanket and the fraction of injected T that burns on each pass through the plasma. The "inactive" tritium inventory is that part kept in storage for use in the event of breakdown of the tritium extraction system or for eventual shipment to start up other reactors. Its magnitude is a matter of choice, but since it can be kept separate from the fusion power core and very well confined and protected, it usually is not given much attention as a source of routine emissions or accidental releases.

Estimates of the active tritium inventory in various designs for D-T reactors range from around 200 g to several kgs [15,28,47,69,74]. A D-T-fueled fusion reactor operating continuously at 4000 thermal megawatts (1200 to 1500 electrical megawatts) burns about 500 g of tritium per day. At this burn rate, a fractional burnup of 0.1 corresponds to an injection rate of 5 kg/d of T and a fractional burnup of 0.01 corresponds to 50 kg/d. Estimates of the amount of tritium in the breeding blanket have tended to fall over the years as designs of blankets and tritium-removal systems became more sophisticated. However estimates of the inventory in MFE systems that recycle tritium from the plasma have been growing recently because of physics results that imply a low fractional burnup in tokamak reactors. Estimated fractional burnups around 0.3 for ICF reactors lead to lower tritium throughput and, therefore, inventories. Fusion reactors based on advanced fuels (D-D or D-He\textsuperscript{3}) should be able to achieve T inventories below 100 g [47,65,75].
An objective is to keep the tritium inventory in the range of 100 to 2,000 g. This would correspond, at tritium's specific activity of 9700 curies (Ci) per gram, to between 1 and 20 megacuries (MCi). Issues are radiation exposure to workers inside the plant and to members of the public off site, in normal operation as well as in accidents.

International guidelines, as well as national regulations in most countries, limit occupational radiation exposures to 50 mSv (5 rem) per year to an individual worker [76,77]. The corresponding Recommended Concentration Guidelines (RCG) for tritiated water in air for continuous occupational exposure is 5 MCi/m³ [76]. (HTO is about 20,000 times more hazardous per curie than HT gas and is usually assumed to be the form present unless there is good reason to believe otherwise. The HT is converted to HTO in air with a variable characteristic time ranging from hours to days.) If follows that 3 Ci of HTO (representing on the order of 10⁻⁶ to 10⁻⁷ of the active T inventory) would be enough to contaminate all the air in a 5,000,000 m³ reactor building to the RCG. There is already considerable capability for and experience with tritium cleanup indicating that these problems are manageable [78].

National regulations in most countries limit the radiation exposure by airborne effluents to a hypothetical member of the public who spends full time at the boundary of a nuclear-energy facility to about 50 microsieverts (µSv) per year [77]. For a boundary at a distance of 1 km from the reactor, and considering annual average meteorological conditions at typical sites, complying with such regulations implies restricting routine releases of airborne tritium to the range of 100 to 200 Ci of HTO per day, which represents on the order of 10⁻⁵ to 10⁻⁴ of the plant inventory [79]. (Releases of other forms of radioactive material, of course, would reduce the releases of tritium that could be permitted.) Recent experience with handling large quantities of tritium in fusion-technology test facilities (e.g., the TSTA [78] indicate that the required degree of tritium control is indeed feasible.

Tritium, either as HT gas or as HTO liquid or vapor, is highly mobile even under normal operating conditions, and under accident conditions it would surely be one of the more likely radioisotopes to escape in quantity. How large a release of tritium would be tolerable in an accident depends on the “threshold” dose to the most-exposed member of the public that one must not exceed. One such dose threshold used by regulatory authorities in many countries is a 50-year dose commitment of 100 mSv (10 rem) [75], which corresponds approximately to an increase of 1% in the exposed individual’s pre-existing probability of dying of cancer. This dose could be received by an individual remaining for several days at the site boundary, 1 km from an accidental release of 100 to 200 g of tritium as HTO under highly unfavorable weather conditions (accounting for inhalation and skin absorption, resuspension of ground-deposited tritium, and a quality factor of 2 Sv/Gy in computing the dose per curie of tritium intake [77,79]). Such a release is in the range of 10% to 100% of the active tritium inventory in recent fusion-reactor designs.

How much tritium could be released in an accident without exceeding the 2 Sv critical-dose threshold below which no fatalities from acute radiation syndrome would be expected [26]? (The critical dose is that received in the first 7 days from the beginning of exposure plus half of that received in the 8th through the 30th days; it correlates well with acute radiation effects [58].) Taking into account that the critical dose from an accidental exposure to tritium is about half of the 50-year dose commitment, the tritium release (as HTO) corresponding to a critical dose of 2 Sv to an individual at the site boundary, 1 km away from the reactor is 4 to 8 kg, neglecting the possibility of evacuation. If the individual leaves within the first few hours after the accident, the release needed to give a critical dose of 2 Sv is 2 to 3 times as large, say 10 to 20 kg.

Thus, a key conclusion is that even a 100% release of the active tritium inventory in a fusion reactor could not produce an off-site dose large enough to lead to early fatalities unless that inventory exceeds 3-4 kg (no evacuation from the site boundary) and more probably 10 to 20 kg (most exposed individual leaves the site boundary after a few hours).
Activation Products

Neutron-activation products are formed when fusion neutrons (at 14 MeV from every D-T reaction and at 2.5 MeV from about half the D-D reactions) strike the main constituents and impurities in the reactor structure, coolant, tritium breeder (if any), neutron-multiplier materials (if any), and reactor-building atmosphere. The variety of neutron-activation reactions and resulting isotopes is very large when one takes into consideration the diversity of materials that may be found in fusion reactors, as well as the multistep reactions in which activation products or their decay products are themselves bombarded by further neutrons. On the other hand, the array of activation products that actually arise is controllable by design through the choice of structural and other materials to be used in the reactor (subject to other criteria these materials must satisfy).

The types and quantities of neutron-activation products that will be present in a fusion reactor can be predicted with considerable confidence using computer programs that have been improved and checked against experiments over a period of many years [80]. The neutron activation calculations reveal that typical D-T MFE reactors of contemporary design, built of metals such as austenitic or ferritic steels or refractory-metal alloys, and sized to deliver 1200 MWe, would contain in the range of 0.6 to 4 GCi of activation products when shut down after a long period of operation, and 3 to 10 times less a day after shutdown [47,61,69]. A low activation D-T MFE reactor with SiC structure would have comparable activity to the metal structure systems at shutdown but $10^2$-$10^3$ times less than these more conventional systems a day after shutdown [47]. The Cascade ICF reactor design, using a variety of SiC components, has a calculated inventory of 0.24 GCi at shutdown and 0.008 GCi a day later [28]. A fusion reactor design using the harder-to-ignite D-He$^3$ reaction has been predicted to have an activation product inventory of about 0.04 GCi at shutdown (the neutrons in this case come from D-D side reactions) [47].

Between 15% and 60% of the activation-product inventory in typical fusion-reactor designs will be embedded in the solid first wall separating the plasma chamber from the rest of the tritium-breeding and energy-absorbing blanket, with most of the remainder in the other solid- blanket components and the radiation shield. Some ICF D-T reactor designs achieve a substantial reduction in total activation-product inventory by interposing a flowing layer of low-activation liquid- or granular-coolant/ breeder material between the reaction zone and the innermost solid structure [28,81].

The total activation-product radioactivity inventories for a typical 1200 MWe D-T fusion reactor at shutdown are 1 to 10 times smaller than the $5 \times 10^9$ Ci of fission products in a fission reactor with the same electrical output. Use of the D-D fuel cycle brings little or no advantage in the quantity of activation [57,28], but the inventory in a D-He$^3$-fueled fusion reactor could be 3 to 100 times smaller than that of its fission counterpart [47,75].

Hazard Measures Relating to Accidental Releases

Table 2 presents a number of measures of the accident hazard associated with the inventories of radioactivity in fusion and fission reactors. The measures are arranged in ascending order of informatives, starting with numbers of curies. (The more informative the indicator, unfortunately, the more difficult it is to calculate.) The estimates shown are drawn largely from references [47], [65], and [82].

The integrated risk is by far the most informative hazard measure but also the most difficult to obtain. Very detailed design information and extensive operating experience are needed in order to catalog all the possible accident modes and to predict their probabilities of occurrence; and separate consequence calculations must be carried out for all the accident modes [58].

The maximum plausible doses (MPD) from “worst-case” accidents are of considerable interest (to the public and to licensing authorities) and are easier to calculate
Table 2. SOME QUANTITATIVE MEASURES OF ACCIDENT HAZARD[60,74,87]

<table>
<thead>
<tr>
<th>Measure</th>
<th>Units</th>
<th>Fission/Fusion Ratios&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radioactivity Inventory</td>
<td>Ci</td>
<td>1.2 to 8, various D-T 100, V-alloy D-He&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Biological Hazard Potential</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>5 to 20, steel D-T 15 to 80, V-alloy D-T</td>
</tr>
<tr>
<td>Complete Release Dose Potential</td>
<td>Sv</td>
<td>2 to 4, stainless steel D-T 3 to 6, ferritic steel D-T 40 to 20, V-alloy D-T 20 to 100, SiC D-T 200, V-alloy D-He&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Partial Release Dose Potentials, e.g., for 100% of T (as HTO) and noble gases</td>
<td>Sv</td>
<td>10 to 100, various D-T&lt;sup&gt;b&lt;/sup&gt; 300, V-alloy D-He&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum plausible release fractions&lt;sup&gt;c&lt;/sup&gt; for all isotopes (giving maximum plausible dose, MPD)</td>
<td></td>
<td>4, ferritic steel D-T 6 to 100, V-alloy D-T 50 to 100 SiC D-T 150, V-alloy D-He&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Integrated risk (probability x population dose summed over all possible accidents)</td>
<td>man-S&lt;sub&gt;v&lt;/sub&gt; per reactor/yr</td>
<td>not yet available</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on LMFBR characteristics in the numerator and characteristics of indicated fusion-reactor types in the denominator.

<sup>b</sup> Assumes active T inventories from 200 to 2000 g and 0.2 Sv critical dose at 1 km per kg of T released as HTO.

<sup>c</sup> Based on division of elements into 5 mobility categories with maximum plausible release fractions = 1.0, 0.3, 0.1, 0.03, and 0.01, respectively, for both fusion and fission; some fusion designs (and some future fission designs) may warrant smaller MPRFs for given elements.60
than the integrated risk, but doing so convincingly still requires detailed analysis of specific designs combining sophisticated models of accident phenomenology and experimental data on mobilization of radioactivity under extreme conditions [60,62,73,86]. Estimates of MPDs can be obtained by dividing the radioactive inventories into categories according to the relative mobility of the associated elements under accident conditions and associating each category with a maximum plausible release fraction (MPRF) based on whatever mobilization data and analysis are available for the relevant materials and configuration [47]. For the most preliminary comparisons of different reactor types, one may choose to use a common, conservatively defined “envelope” of MPRFs for all of the designs considered (as in Table 2).

In addition to such approaches to estimating maximum permissible doses, it is useful in preliminary safety assessments to be able to characterize in a general way the relative ease or difficulty of accident prevention in different reactor designs. Some important conclusions are:

a) Fusion reactions and the fusion plasma are rather easy to quench, and the amount of fusion fuel in the reaction chamber at one time is small, so designing fusion reactors to preclude nuclear reactivity excursions large enough to do serious damage should not be very difficult.

b) The chemical energy of liquid lithium is a troublesome source of stored energy in D-T fusion reactors that use this material as the coolant and tritium breeder. This contribution to accident risk can be greatly reduced by using lithium-lead alloy in place of liquid Li and can be avoided altogether by using solid or molten-salt Li compounds as the tritium breeder (or by using advanced fuel cycles that do not need to breed tritium). Liquid Li should only be used in combination with structural materials highly resistant to the release of activation products at temperatures attainable in lithium fires. Lithium-lead unfortunately creates some activation problems.

c) Apart from liquid Li, the most potentially troublesome source of stored energy in fusion reactors is the decay heat from structural activation products. Decay heat from the radioactivity in fission reactors is the major source of concern about core melt in loss-of-coolant accidents (LOCAs) and the reason for requiring engineered emergency-core-cooling systems in fission reactors of current types. For most fusion-reactor designs and materials, however, the afterheat power levels and power densities are enough lower than those in fission to substantially ease the emergency cooling problem. In fact, with suitable attention to this point in materials selection and design, D-T fusion reactors can be designed so that passive mechanisms of heat removal alone suffice to prevent structural damage and significant radioactivity releases in LOCAs; and D-He\(^3\) fusion reactors should be able to achieve this desirable characteristic with ease.

d) The energy stored in the confinement system (magnets for MFE reactors, lasers or particle beams in ICF reactors) and its power supplies will be sufficient to damage the reactor if released suddenly. (Such releases could generate projectiles capable of breaking coolant pipes or damaging other safety-related barriers.) These systems can probably be designed, however, with passive mechanisms to dissipate their energy gradually in accidents [47,28].

A useful way to summarize the most important safety-related characteristics of a given fusion-reactor or fission-reactor design is the level-of-safety-assurance (LSA) concept developed by Piet [66] and applied in the U.S. ESECOM study [47]. The LSA evaluations are based on the extent and nature of passive versus active design features in a reactor in order to assure public safety, perhaps most importantly to assure that early off site fatalities from release of radioactivity are precluded. An LSA value of 1 means that safety is assured by the sizes of the radioactivity inventories and stored energy sources alone without reference to any specifics of reactor configuration or accident scenario; an LSA of 4 means that assurance of safety requires demonstrating that active-safety systems will perform satisfactorily; and the intermediate LSA values mean assurance of safety depends on demonstrating that passive-design features can

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maintain the large-scale configuration of the reactor (LSA = 2) or that they can maintain both large-scale and small-scale configuration (LSA = 3). Although LSA = 4 systems may be adequately safe, lower LSA values mean that safety is easier to prove and, therefore, that siting and licensing should be easier.

The ESECOM study concluded that many D-T fusion reactor designs could achieve LSA = 2 or 3 and that use of very-low-activation materials (such as silicon carbide) or advanced fuels (such as D-He³) could bring LSA = 1 within reach [47].

Measures Relating to Radioactive Waste Management

Radioactive wastes from fusion reactors will consist mainly of activated structural material, part of it leaving the reactor when fusion-core components are replaced at intervals during the reactor’s lifetime and part of it resulting from the dismantling of the reactor at the end of its service. This material will total between 400 and 3000 m³ over a 1200 MWe reactor’s nominal life cycle of 30 years, compared to perhaps 400 m³ of “high-level” (>10,000 Ci/m³) fission-product and structural waste from an LMFBR of the same output [21,47,28]. Associated with the reprocessing plant and fuel fabrication plant for the LMFBR, however, will be another 100 to 400 m³/y of “medium-level” (0.1 to 10,000 Ci/m³) and transuranic contaminated wastes [57,88] that will require long-term management. Both the fusion and LMFBR fuel cycles will generate solid and liquid low-level wastes (<10,000 Ci/m³) amounting to perhaps 1000 m³/y [57,71], which are more easily managed.

In any case, other measures convey much more information about the relative difficulty of the waste management task than volumes do. Two such measures are [47,65]:

(i) The integrated biological hazard potentials (IBHP), obtained by dividing curies of each isotope by its RCG [83] for public water supplies, multiplying by its mean life, and summing over all isotopes in the wastes (units are m³/reactor year).

(ii) The annualized intruder hazard potentials (IHP) [86], obtained from standardized scenarios of the consequences of inadvertent intrusion into shallow burial sites after periods of 100, 500, and 1000 years (rem·m³/reactor year).

Some ratios of these indices for fission and fusion reactors are presented in Table 3. Use of the shallow burial scenarios provide a systematic way to account for the relative mobilities and toxicities of the constituents of wastes of different types. That wastes from some fusion reactor designs would qualify for shallow burial under current U.S. regulations [47] is an impressive indicator.

Hazard Measures Relating to Routine Emission and Exposures

Most of the activation products in a fusion reactor remain embedded in solid structure during routine operation. Only the far smaller quantities of activated material in the coolant and the building atmosphere have any chance of escaping to the environment under these normal conditions, and various studies have indicated that the doses expected from these sources can easily be held within the range of 10% to 50% of the total exposure guidelines (50 µSv/y each from airborne and aqueous effluents) for the most exposed individual at a 1-km site boundary [71,73,74]. This would leave room for the anticipated levels of tritium emissions without exceeding the guidelines.

Activation products will pose larger problems for the control of worker exposures inside the power plant. Approximate calculations of the contact dose rates to be expected at the surfaces of various fusion reactor components [47] give values exceeding the usual guidelines for unlimited hands-on maintenance (0.025 mSv/h contact dose rate) by seven to ten orders of magnitude at the first wall at 1 hour after shutdown and by four to nine orders of magnitude at 1 year after shutdown. Even at the shield, the factors are four to eight orders of magnitude at 1 hour and three to seven orders of magnitude at 1 year. Clearly, all maintenance in the immediate vicinity of the fusion power core will have to be done remotely. Proper choice of coolant,
Table 3. SOME MEASURES OF RADIOACTIVE WASTE HAZARD[55,74]

<table>
<thead>
<tr>
<th>Measure</th>
<th>Units</th>
<th>Fission/Fusion Ratios(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated (BHP_w)</td>
<td>(m^3\cdot\text{yr})</td>
<td>5,000, D-T stainless steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10,000, D-T ferritic steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100,000, D-T V-alloy</td>
</tr>
<tr>
<td>Annualized Intruder Hazard</td>
<td>(\text{rem} \cdot m^3)</td>
<td>250 to 1,000, D-T ferritic steel(^b)</td>
</tr>
<tr>
<td>Potential</td>
<td>(\text{per yr})</td>
<td>50,000, D-T tailored(^c) ferritic steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10,000 to 100,000, D-T V-alloy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300,000 D-T silicon carbide</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,000,000, V-alloy D-He(^3)</td>
</tr>
</tbody>
</table>

\(^a\) Based on LMFBR characteristics in the numerator and characteristics of indicated fusion-reactor types in the denominator.

\(^b\) The lower figure comes from a design with a lithium-lead blanket.

\(^c\) HT-9 ferritic steel modified to replace molybdenum with tungsten.
however, may allow hands-on maintenance of some parts of the coolant system; and use of low-activation structural material can also expand the scope for limited contact maintenance.

Non-nuclear Hazards

Previous studies of the fuel cycles of coal, fission, fusion, and renewable energy sources have indicated that, aside from emissions and accident risks from power plant operations, the highest risks to health and safety tend to be those of more-or-less routine accidents in fuel and materials acquisition, processing, manufacturing, and transport. These hazards for fusion systems appear to be in the same range as those of the renewable electricity sources, hydropower and wind, and well below those of coal [89]. Fusion reactors and fuel-cycle operations would not release significant quantities of greenhouse gases or acid-rain precursors, and fusion's land-use requirements would be smaller than those of most fossil and renewable energy sources [89]. Thermal pollution from D-T fusion reactors would not be significantly different in proportion to electrical output than that from fossil or fission plants. Advanced-fuel fusion reactors with a high proportion of the reaction energy carried by charged particles have the potential for significantly increased conversion efficiencies and thus of markedly reduced thermal pollution [68].

CONCLUDING REMARKS

Fusion energy has the potential to be a safe and environmentally attractive power source at economically acceptable levels. The safety and environmental advantages are substantial enough that they are a major part of the rationale for fusion development: fusion would have no counterpart to the problems of mining, air pollution, acid rain, and climate change associated with coal use; it offers the prospect of increased assurance of safety against major accidents; it has diminished linkages with military applications; and it presents a smaller waste-management task than fission. Achieving the full potential of fusion will not happen automatically but will require success in plasma physics and the technology of magnets and ICF drivers, the development of low-activation materials for the construction of reactors, and the development of low- tritium inventory designs. The size of the challenge and the present inadequacy of the resources make the task formidable. It also underlines the importance of increased international coordination and collaboration to optimize the utilization of diverse national resources in the common goal to achieve practical fusion energy.

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REFERENCES


56. The most impressive example is the 19-volume assessment, "An Environmental Analysis of Fusion Power to Determine Related R&D Needs," prepared in 1976 under the direction of J. R. Young at the Battelle Pacific Northwest Laboratories for the Energy Research and Development Administration; in addition to the overview and fusion technology survey (BNWL-2010, -2011, -2013, -2014), the reports cover fuel procurement (BNWL-2012), siting issues (BNWL-2015), materials availability (BNWL-2016), thermodynamic efficiencies (BNWL-2017), tritium and radiocarbon releases and effects (BNWL-2018, -2020, -2022), non-tritium radioactive wastes (BNWL-2019, -2023), magnetic-field issues (BNWL-2021), safety (BNWL-2024), transportation requirements (BNWL-2025), social impacts (BNWL-2026), comparisons with nonfusion energy systems (BNWL-2027), and environmental cost/benefit analysis for fusion (BNWL-2028).


73. In addition to other references cited on particular points, the reader will find a wealth of detailed information on many of these issues in two comprehensive reviews from the mid-1980s: J. B. Cannon, Ed., "Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy," Office of Energy Research, U.S. Department of Energy report DOE/ER-0170 (1983); and Fusion Safety Status Report IAEA-TECDOC-388 (International Atomic Energy Agency, Vienna, 1986). Data presented here and not otherwise attributed to a specific source are from these volumes.


83. RCGs for all important fission products have long been available from official bodies (et al., U.S. Code of Federal Regulations, Title 10, Chap. 1, Pt. 20, U.S. Government Printing Office, Washington, D.C. 1975), but performing useful fusion-fission comparisons using BHPs became possible only after Fetter developed a consistently calculated set of RCGs for fusion-relevant isotopes not encountered in fission applications (see Note [59]).


