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Summary of the Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy

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Preface

The Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) was organized under the administrative auspices of the Magnetic Fusion Energy Division of the Lawrence Livermore National Laboratory with financial support from the Office of Fusion Energy (OFE) of the U.S. Department of Energy (DOE). The Committee, however, is national in composition and independent in its mode of operation. Its members have served as individuals, not as representatives of their institutions, and the members alone are responsible for the findings presented here.

The members of ESECOM are: J. P. Holdren (Chair), University of California, Berkeley, Calif.; D. H. Berwald, Grumman Aerospace Corporation, Bethpage, N.Y.; R. J. Budnitz, Future Resources Associates, Berkeley, Calif.; J. G. Crocker, Idaho National Engineering Laboratory (INEL), Idaho Falls, Idaho; J. G. Delene, Oak Ridge National Laboratory (ORNL), Oak Ridge, Tenn.; R. D. Endicott, Public Service Electric and Gas Company, Newark, N.J.; M. S. Kazimi, Massachusetts Institute of Technology (MIT), Cambridge, Mass.; R. A. Krakowski, Los Alamos National Laboratory (LANL), Los Alamos, N. Mex.; B. G. Logan, Lawrence Livermore National Laboratory (LLNL), Livermore, Calif.; and K. R. Schultz, GA Technologies Inc., San Diego, Calif.

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ABSTRACT

The Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) has assessed magnetic fusion energy's prospects for providing energy with economic, environmental, and safety characteristics that would be attractive compared with other energy sources (mainly fission) available in the year 2015 and beyond. ESECOM gives particular attention to the interaction of environmental, safety, and economic characteristics of a variety of magnetic fusion reactors, and compares them with a variety of fission cases. Eight fusion cases, two fusion-fission hybrid cases, and four fission cases are examined, using consistent economic and safety models. These models permit exploration of the environmental, safety, and economic potential of fusion concepts using a wide range of possible materials choices, power densities, power conversion schemes, and fuel cycles. The ESECOM analysis indicates that magnetic fusion energy systems have the potential to achieve costs-of-electricity comparable to those of present and future fission systems, coupled with significant safety and environemntal advantages.

INTRODUCTION

In many ways, fusion is the ultimate energy source: it is the fire that lights the sun and the rest of the stars; it is the source of the elements that constitute the universe; it can wring from a gram of deuterium fuel as much energy as the combustion of 10 tons of coal, enabling the trace of deuterium in each gallon of sea water to provide as much energy as 300 gallons of gasoline. It is also so difficult to harness for meeting civilization's energy needs that more than three decades of intensive scientific and engineering effort have not sufficed to accomplish the task.

Today, several experimental fusion-energy machines that are in the early stages of operation or the advanced stages of construction are within reach of demonstrating the scientific feasibility of the magnetic-confinement approach to harnessing fusion. (That is, they are close to attaining a combination of fuel temperature and confinement quality capable of yielding a fusion-energy release equal to the energy requirement for heating the fuel.) Yet U.S. public and governmental support for pursuit of long-term energy options is imperiled by a combination of overall budgetary stringency, competing claims

on research funds, and an oil-glut-induced complacency about the future of energy supply. The time is therefore ripe to reexamine the goals, potentials, and priorities of fusion-energy development, both as an aid to planners shaping the future of fusion research and development after the scientific-feasibility milestone is attained, and as a progress report to a larger community that is understandably concerned about the priorities and payoffs in energy R&D.

The goals of the fusion energy program encompass more than understanding the physics and technology of heating and confining fusion fuels; more than applying this understanding to the construction of devices that can convert fusion energy into the forms civilization needs (such as electricity and fluid fuels); and more than unlocking the nearly inexhaustible energy resources that such devices could use. For if fusion is to make an important contribution to civilization's energy needs, it is not enough that fusion energy systems work--they must do so with economic, environmental, and safety characteristics that are attractive compared with those of other energy sources available in the same time frame.

The Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) was organized in late 1985 to provide an up-to-date assessment of magnetic fusion energy's prospects for meeting this last requirement. We have given particular attention to the interaction of environmental, safety, and economic characteristics in fusion-reactor design, and to identifying those directions within fusion technology that seem most likely to lead to combinations of these characteristics that would make fusion an attractive long-term energy source compared with (or in symbiosis with) fission and other options. We have not considered inertial-confinement fusion explicitly, although, inevitably, some of our findings could be applied to the inertial-confinement as well as to the magnetic-confinement approach.

This summary presents our findings in compact form. The reader interested in more detail and documentation should consult the much longer main report.[1]

THE RATIONALE FOR DEVELOPING MAGNETIC FUSION ENERGY

As background for our assessment, it is appropriate to discuss briefly the overall rationale for developing magnetic fusion energy (MFE)--that is, the combination of possible characteristics of MFE and possible

characteristics of the energy future that could lead to an important role for MFE technologies.

The scientists and engineers working to develop MFE have long considered the attractions of achieving their goal to be self-evident: the attainment of an energy supply for civilization that would be at once safe, clean, affordable, and inexhaustible. But safety, cleanness, affordability, and inexhaustibility are all relative attributes, not absolutes. The yardsticks by which these attributes are measured--and society's weighing of their importance relative to one another--depend on the context: the time horizon of interest, the projected energy demands in that time frame, the characteristics of all the energy sources potentially available to meet those demands, and the priorities given to economic vs environmental and safety concerns.

The time horizon for large-scale commercial application of MFE is, at the earliest, the year 2015 and beyond, and more probably 2030 and beyond. The energy break-even or scientific feasibility demonstration expected in the next few years will need to be followed by an intensive program of technological development aimed at demonstrating engineering feasibility (the actual generation of significant net energy from D-T fuel) in a device that can operate more or less continuously and can convert the fusion energy into electricity and/or other usable forms. The challenges of establishing engineering feasibility for MFE (including especially materials issues, magnet design, plasma current drive, fuel handling, impurity removal, tritium control, and remote maintenance of neutron-activated components) are different in character than the scientific-feasibility challenges that have taken more than 30 years to overcome, but it is entirely possible that they will require as much or more money and effort.

Assuming that funding for MFE R&D in the U.S., Europe, Japan, and the Soviet Union combined remains at or above its 1985 level of about $1.5 billion (U.S.) in 1985 dollars per year, it is reasonable to suppose that establishing the engineering feasibility of MFE by constructing and operating a demonstration power reactor at near-commercial scale will require another 20 years beyond the proof of scientific feasibility. Just how much this timetable could be accelerated by substantially increasing the funding for fusion R&D is controversial. There is little doubt, however, that the attainment of a successful demonstration reactor will be delayed if funding is reduced.

The establishment of engineering feasibility for MFE in the form of a working large-scale demonstration reactor--say, by 2010--still will not ensure this technology's commercial success. Passing the further threshold of commercial feasibility requires that the solutions to the scientific and engineering challenges of MFE be combined in ways yielding economic, environmental, and safety characteristics that are attractive compared to those of other energy options capable of meeting the same societal needs. Whether and when commercial feasibility of MFE actually will be achieved depends, therefore, not only on the characteristics of future fusion technologies that cannot be completely described today; it also depends on the characteristics of several alternative technologies that may be available to fill a similar niche in the energy futures of the U.S. and the world.

Early in the period of fusion's potential availability, its competitors may include coal-fired power plants, light-water and advanced-convertor (nonbreeder) fission reactors, and early fission breeders. In the longer term, the list of possible competitors expands to include advanced fission breeders and large-scale solar-electric plants. The possibilities in the early part of fusion's potential availability (as well as later) also include a symbiosis between fusion and fission systems, in which fusion reactors would breed fissile fuel for "client" fission convertor reactors.

Although more is known about the costs and other characteristics of the near-term technologies competing with fusion than about those of the longer-term possibilities, significant economic and environmental uncertainties are associated with near-term and long-term alternatives alike[2-4]:

1. Coal. Recoverable coal resources amount to perhaps 5000 terawatt-years (TW-yr) worldwide, or about 500 times civilization's annual use of all industrial energy forms in the mid-1980s. But mining, transporting, processing, and burning this coal pose environmental problems that may prove expensive to abate, and the potentially intolerable climatic impacts of accumulating atmospheric carbon dioxide from fossil-fuel combustion may put a lid on coal use altogether.

2. Nonbreeder Fission Reactors. Use of the world's high-grade uranium resources in nonbreeder fission reactors might yield as little as 1000 TW-yr or as much as 5000 TW-yr of thermal energy, convertible to a third as much electricity. In the U.S., this technology has been costlier than projected in monetary terms, and its future costs are subject to uncertainty and dispute. It has also been controversial with respect to safety, environment (including

waste management), and links to nuclear weapons, and its continued public acceptability in some countries can be questioned.

3. Fission breeder reactors. This technology could stretch uranium resources a thousandfold or more (a factor of 50 - 100 from better utilization of the high-grade resources and the rest from rendering lower-grade resources of uranium economically exploitable). But the economics of breeders are more uncertain and the safety and environmental controversies potentially more acute than for conventional (nonbreeder) fission reactors.

4. Biomass and Hydropower. The renewable energy sources most heavily used today, biomass and hydropower, provide about 2 TW-yr/yr worldwide. Whether this figure could be expanded by more than a factor of 2 or 3 is highly uncertain in view of competing uses for the resources and rising environmental as well as monetary costs.

5. Sunlight. More abundant renewables, most notably the 88 000 TW-yr/yr of sunlight reaching Earth's surface, are more dilute and, so far, more costly than hydropower or biomass to convert to electricity or fluid fuels. The eventual cost of large-scale production of electricity or fluid fuels from sunlight is uncertain by at least a factor of 3, and some of the approaches for doing so may have significant environmental costs.

In addition to these uncertainties about the supplies, costs, and acceptability of alternatives to fusion, there is great uncertainty about future energy demand: studies of the potential worldwide demand for energy around 2030, for example, have generated estimates ranging from about 10 TW-yr/yr (about the same as in 1985) to more than 30 TW-yr/yr (Refs. 5,6). What fraction of future energy demand will be provided by centrally generated electricity or other energy forms that could be supplied by fusion technologies is also uncertain. (Electricity generation accounts for 30 to 35% of primary energy use in most industrial nations today.)

Against the backdrop of so uncertain an energy future, what are the potential attractions of fusion that might justify the continuing investments needed to bring it about? Different attractions pertain to different time frames and scenarios:

1. Most obviously, the energy-supply potential of fusion is huge: a hundred million TW-yr based on oceanic lithium as the limiting ingredient in a D-T fuel cycle, a few hundred billion TW-yr based on the D-D fuel cycle.[7] In the very long term (more than a few thousand years), only fission breeder reactors and large-scale use of solar energy will be able to compete with

fusion-electric generation (or fusion breeding of fissile fuels) as mainstays of civilization's energy supply.

2. There is a good chance that fusion will be cheaper than large-scale solar-energy technologies, and possibly it will be less disruptive environmentally. There is a good chance that fusion will be safer than fission breeders, and cheaper if safety advantages can be translated into lower costs. Given sufficient margins in these respects, fusion would become the clear choice as civilization's primary inexhaustible option for central-station electricity supply and fluid-fuels production.

3. In the near term, the competitors for fusion are more diverse--but so are their liabilities. Environmental-control requirements could increase fossil-fuel costs to well above today's levels, and the CO_2 problem could limit fossil-fuel use altogether; fission could be deemed unacceptable by the public because of concerns about reactor safety, waste management, and weapons links; technologies for large-scale harnessing of solar energy could remain very expensive. If all (or even most) of these potential problems come about, then having an affordable, safe, and environmentally attractive fusion option available at the earliest possible date would become extremely important.

4. Even if the possibility of debilitating shortcomings in nonfusion energy alternatives is excluded, fusion technology might achieve a combination of versatility and economic, environmental, and safety characteristics so attractive that fusion would displace previously satisfactory energy sources and, perhaps, transform patterns of energy use in ways that cannot be foreseen in detail.

5. Finally, if the above-mentioned concerns about the economic, environmental, and safety characteristics of fission reactors do not foreclose the fission option, an important complementary role for fusion could materialize through the use of fusion-hybrid-breeder reactors to supply fission convertor reactors with fuel. This approach might be able to improve system economics (and, conceivably, system safety and proliferation resistance) compared with pure-fission systems, while providing a fusion-technology "stepping stone" toward pure-fusion electricity generation.

The case for giving high priority to R&D on MFE obviously depends not only on the possibility that such benefits will materialize but more importantly on the likelihood that they will. While that likelihood cannot be evaluated in a fully persuasive manner on the basis of current information, ESECOM viewed its task, broadly construed, as one of clarifying the prospects

for attaining these benefits by assessing the environmental, safety, and economic potential of an array of fusion-reactor possibilities derived from the existing knowledge base.

SCOPE OF ESECOM'S ANALYSIS

The Committee undertook to address the following sets of specific questions:

1. What will be the likely economic, environmental, and safety characteristics of magnetic-fusion reactors if such reactors are based on the D-T fuel cycle, the confinement schemes and design concepts most extensively studied to date, present leading-candidate materials, and extrapolation of power-plant construction practices from the fission industry? What trade-offs and interactions among economics, environment, and safety are evident under these circumstances?

2. What are the possibilities for improving fusion's performance with respect to economics, or environment, or safety, or (most importantly) the combination of these achievable in a single design, by using (a) alternative materials, (b) alternative blanket designs, (c) alternative energy-conversion schemes and outputs (such as fissile fuels), (d) alternative confinement schemes, (e) alternative fuel cycles, and (f) alternative balance-of-plant designs, construction practices, and siting arrangements made possible by such innovations? Can such reactors be designed to preclude fatalities from acute radiation exposure even under "incredible" circumstances, while remaining economically competitive?

3. What changes in present programs of MFE research and development might increase the likelihood of achieving improvements of these sorts?

4. How do the prospects of fusion with respect to environment, safety, and economics compare with those of its likely competitors? Are there promising symbioses between fusion and other energy sources?

Because of the limited time and resources available for this study, our analysis of fusion's potential competitors and symbionts has been confined mainly to fission technologies. Fission provides the most appropriate comparison because it is the most obvious and best understood competitor for fusion in the central-station electricity-generation niche in the long term. Fission is also the most obvious focus of an examination of potential symbiosis because of the much-studied possibility of using fusion-fission

hybrid breeders of fissile material to fuel client fission-converter reactors that might be cheaper and/or safer than self-sustaining pure-fission breeders. Examining fission has the further merit that the experience of the fission industry with power-plant engineering, construction, safety analysis, and regulation and licensing offers a number of insights about the possibilities for and difficulties with approaches aimed at reducing the costs of fusion.

In addition to confining our investigation of competition and symbiosis to fission, we further narrowed the scope of our undertaking by omitting from detailed consideration any potential applications of fusion energy other than central-station electricity generation and production of fissile fuel. Such applications could include production of synthetic chemical fuels, production of weapons materials for the nuclear stockpile, production of radioisotopes for industrial and medical applications, and use of fusion neutrons to transmute fission-reactor radioactive wastes into shorter-lived substances. Many of these applications have been reviewed recently elsewhere.[8,9]

Even with these restrictions in the scope of our work, the breadth and complexity of the assessment being undertaken were daunting. Clearly, such a task could only be attempted in so short a time by making the fullest possible use of other recent and ongoing work--in the national laboratories, in the universities, and in industry--on the possible shape of fusion technology and on its likely environmental, economic, and safety characteristics. In this connection, we have benefited particularly from: the work of the Department of Energy's (DOEs) "Low Activation Materials Panel"[10]; the STARFIRE[11] and MARS[12] design studies; the Blanket Comparison and Selection Study[13]; the work of Sheffield et al. at ORNL on the Generomak model[14]; the DOE/ORNL Nuclear Energy Cost Data Base[15]; the dissertations of Piet[16] and Fetter[17] on methods of safety and environmental assessment for fusion; the 1983 ORNL review of environmental implications of magnetic fusion,[18] and the review of this topic published by the IAEA in 1986[19]; the ongoing fusion-safety work at INEL and MIT[20,21]; the 1986 Brookhaven study of proliferation and safeguards issues in future technologies[22]; the studies of reversed-field-pinch reactors at LANL[23] and of low-activation ceramics at GA Technologies[24]; the fusion-fission hybrid studies coordinated by LLNL[25]; and the Technical Planning Activity (TPA) for MFE coordinated by the Argonne National Laboratory for the DOE.[26] We have also profited from comparing notes with the authors of studies being conducted more or less in parallel with ours in the European Community[27] and in Japan.[28]

At the same time, it must be emphasized that the impressive body of work from which we were able to draw, combined with such new analyses as will be described here, were together far from sufficient to provide convincing answers to all of the questions posed. It is too early in the evolution of fusion technology for that to be possible. Necessarily, then, our answers are incomplete rather than comprehensive, tentative more often than confident, and qualitative as often as quantitative. We think, nonetheless, that these findings illuminate some important dimensions of the topic, and we hope that they will provide a useful stepping stone in the ongoing process of understanding the prospects of MFE and steering research efforts toward achieving its highest potential.

ORGANIZATION AND REFERENCE CASES

ESECOM's work was organized in four phases:

1. **Identifying and describing a set of reference cases--fusion, fission, and fusion-fission hybrid reactors--selected to span a wide range of technical characteristics based on reasonable extrapolation from present knowledge.**

2. **Analyzing, in a consistent framework, the economic, environmental, and safety characteristics of these reference cases** (including, in some instances, the effects of varying plasma performance, scale, and power density within an otherwise fixed design).

3. **Integrating and synthesizing the findings from Phase 2 to provide a comparative assessment** of various fusion systems relative to one another and relative to the reference fission and fusion-fission hybrid breeder systems, and identifying trade-offs and symbioses among environmental, safety, and economic characteristics (including, for example, possible cost savings achievable through attaining different types and degrees of safety assurance).

4. **Developing conclusions about directions in MFE R&D that could improve** the prospects for achieving fusion's full potential with respect to economics, environment, and safety.

FUSION REFERENCE CASES

The ten fusion and fusion-fission cases were chosen to permit exploration of a wide range of variations associated with different materials choices, power densities, conversion schemes, and fuel cycles, subject to certain

obvious constraints: the total number of cases had to be kept within reason; the combination of cases had to be constructed as an interrelated array to permit comparisons among variations with something in common; and the cases chosen had to be describable in sufficient detail to permit the use of the kinds of economic and safety models capable of illuminating differences among the cases in a consistent and persuasive way.

The following set of ten cases emerged--over a period of months--from these considerations:

1. A point of departure D-T fusion reactor using a tokamak configuration, with vanadium-alloy structure and liquid lithium as the coolant/ breeder (denoted in figures and tables herein as V-Li/TOK);

2. A helium-cooled variant of the Case 1 tokamak, with reduced-activation ferritic steel (RAF) structure and Li_2O solid breeder (RAF-He/TOK);

3. A high-power-density, reversed-field pinch (RFP) with RAF structure, a water-cooled copper-alloy first wall and limiter, and self-cooled lithium-lead breeder (RAF-PbLi/RFP);

4. Another high-power-density RFP with a V-Li blanket minimally modified from that of the point-of-departure tokamak (V-Li/RFP);

5. A low-activation tokamak with silicon carbide (SiC) structure, helium coolant, and Li_2O breeder (SiC-He/TOK);

6. A pool type tokamak with vanadium structure and molten-salt (FLiBe) coolant/breeder (V-FLIBE/TOK);

7. An advanced-conversion variant of the point-of-departure tokamak with synchrotron-radiation-enhanced magnetohydrodynamic (MHD) conversion (V-MHD/TOK);

8. An advanced-fuel, water-cooled tokamak based on the D-He^3 fuel cycle with direct conversion of microwave synchrotron radiation (V-DHe^3/TOK);

9. A baseline fusion-fission hybrid tokamak with RAF structure, lithium coolant, beryllium neutron multiplication, and thorium metal as the fertile material (RAF-Li/HYB); and

10. An advanced technology hybrid tokamak with stainless-steel structure, helium coolant, and Li/F/Be/Th molten-salt blanket (SS-He/HYB).

The point of departure V-Li/TOK system and the RAF-He/TOK variant represent improvements on STARFIRE[11] technology using the two leading-candidate blankets from the Blanket Comparison and Selection Study.[13] These are steady-state, D-T fueled, superconducting tokamaks, for which Troyon-Gruber beta scaling[29] and current drive at an efficiency of 0.2 amp/watt have

been assumed; these latter assumptions hold for the other tokamak cases studied as well. The RFP cases rely heavily on early studies performed at the Los Alamos National Laboratory[23] and a more recent multi-institutional study being directed by UCLA[30]; these are resistive-coil machines with oscillating-field current drive and a nominal limit on beta that has been observed experimentally. The SiC-He/TOK blanket is based on work done at GA Technologies,[24] while the V-FLIBE/TOK pool design is the work of a group led by D.-K. Sze at Argonne National Laboratory.[31] The V-MHD/TOK and V-DHe^3/TOK advanced-conversion and advanced-fuel blankets are largely the work of B. G. Logan at LLNL,[32] stimulated in the latter case by innovative work at the University of Wisconsin on a possible solution to the problem of helium-3 availability.[33] The hybrid-breeder blankets are based on studies coordinated by LLNL over the past several years.[24,34] It should not be assumed, however, that any of the ESECOM cases are identical to the final designs in studies on which we drew: In many cases, we made modifications to maintain consistency among the ESECOM cases; in some cases, ongoing studies refined their own designs further after ESECOM's specifications were fixed; and in some cases, ESECOM did not require or use the level of design detail available because our analytical approaches were tailored to a lesser level.

The Committee's aim in selecting these particular cases was to provide a basis for exploring variations in environmental, safety, and economic characteristics that may follow from different combinations of materials choices, power densities, energy-conversion schemes, and fuel cycles. The circumstance that only tokamaks and RFPs were examined does not reflect any shared opinion about the prospects of other confinement schemes; rather, it resulted from the sheer convenience of being able to obtain consistently calculated cost estimates from a preexisting engineering-economics model that is restricted to toroidal geometries. The role of the RFP cases, in particular, was to permit investigation of higher-power densities than could be attained for tokamaks within the framework of the Generomak model.

The different cases do represent, of course, differing degrees of extrapolation from materials choices, physics parameters, and engineering features that might be considered reasonably certain to be attainable based on current knowledge. An examination that confined itself only to conceptual designs of fusion reactors that were solidly based on existing physics and engineering data bases could not claim to have addressed fusion's full potential, nor could such a study say much about directions worth

investigating in pursuit of markedly improved performance. Such cases as 5 through 8--featuring (respectively) ceramic structural materials to achieve extremely low activation, a pool-type design for passive cooling under nearly any accident conditions, enhanced MHD conversion to reduce balance-of-plant complexity and cost, and a D-He^3 fuel cycle to reduce neutron activation and tritium problems--are less credible than more conventional designs. But analyzing these cases, as examples of a much larger set of advanced approaches, has enabled us to avoid unduly constraining our assessment of fusion's long-range possibilities.

FISSION REFERENCE CASES

Four fission reference cases were selected for comparison (and for investigation of symbiosis with the fusion-fission hybrid breeders) as follows:

1. A "best present experience" pressurized-water reactor (PWR-BPE) (Westinghouse) (Ref. 14);

2. The large-scale prototype breeder (LSPB) (Electric Power Research Institute/DOE) (Refs. 35,36);

3. The power reactor inherently safe module breeder design (PRISM) (General Electric) (Ref. 37); and

4. A modular high-temperature gas reactor (MHTGR) (GA Technologies/Gas-Cooled Reactor Associates) (Ref. 38).

These cases were picked to serve different functions in the study. The PWR-BPE provides a reference point rooted in experience; it serves as a sort of calibration for the economic and safety indices of the advanced fission and fusion cases, as well as representing a minimum-performance fission client for the fusion-hybrid breeder. The LSPB and PRISM systems represent a standard and an alternative approach to fission breeding; they are potential direct competitors with fusion for the long-term, central-station, electricity-generation market. The MHTGR could be considered a competitor for fusion in the near future, before uranium has become costly enough to justify breeding, and as an advanced client for breeders of either the pure-fission or the fusion-hybrid varieties.

PLASMA/ENGINEERING/ECONOMIC ANALYSIS

The fusion and hybrid-breeder cases were developed and analyzed with the assistance of the Generomak magnetic-fusion physics/engineering/costing model,[14] modified appropriately for our purposes.

The physics/engineering part of the Generomak model accepts as input the desired values of net electric power output, plasma beta, aspect ratio and elongation of the toroidal plasma, Troyon coefficient, and maximum toroidal field at the coil. (The combination must be chosen to give an acceptable value of the edge-plasma safety factor, q_ψ.) These inputs are used together with chosen blanket/shield characteristics (materials, radial dimensions, densities, inlet and outlet temperatures), conversion-efficiency relations, and current-drive assumptions in an iterative calculation of the plasma major and minor radii, R and a, the toroidal field in the plasma, B_ϕ, and the plasma current, I_ϕ, corresponding to the desired net electric power. Also calculated in this process are plasma volume, plasma ignition margin, fusion power, neutron wall loading, reactor thermal power, overall thermal efficiency, current-drive and other auxiliary power, "fusion island" volume, and the masses of the blanket, reflector, shield, and coils. Some of the main physics and engineering parameters of the ten fusion and fusion-fission hybrid cases are summarized in Table 1.

The economics part of the Generomak model then uses these results to calculate the direct capital costs of the fusion island, based on unit costs supplied to the model for fabricated materials (e.g., 400 $/kg for reactor parts fabricated from vanadium/chromium/titanium alloy, 90 $/kg for superconducting coils) and for certain specific components (e.g., power supply for current drive is costed at 2.25 $/W). Most of these costs are based on those developed in the Starfire study,[11] updated to January 1986 dollars used as the cost basis throughout ESECOM's work. Some of the Starfire figures have been further modified based on the Committee's judgment that more recent information warranted changes.

Balance-of-plant costs in various categories (land, structures and improvements, heat transfer and transport equipment, turbine-plant equipment, and so on) are obtained by assuming that reference costs, updated from the Starfire study, scale with thermal power, electrical power, or fusion-island

Table 1. Selected physics and engineering parameters of fusion cases.

	V-Li TOK	RAF-He TOK	RAF-Li Pb/RFP	V-Li RFP	SiC-He TOK	V-FLIBE TOK	V-MHD TOK	V-DHe^3 TOK	RAF-Li HYB
Aspect ratio, A	4.0	4.0	6.0	6.0	4.0	4.0	3.6	3.6	4.0
Plasma elongation, K	2.5	2.5	1.0	1.0	2.5	2.5	2.5	2.2	2.5
Total plasma beta, β	0.1	0.1	0.1[a]	0.1[a]	0.1	0.1	0.12	0.12	0.1
Safety factor, q_ψ	2.3	2.3	0.02	0.02	2.3	2.3	2.1	2.1	2.3
Max field at coil, $B_{\phi c}$(T)	10.0	10.0	0.69	0.66	10.0	10.0	12.0	16.0	10.0
Torr field in plasma, B_ϕ(T)	4.29	4.25	0.43	0.42	3.88	4.61	5.98	10.12	4.27
Major radius, R_T(m)	5.89	6.07	4.69	4.69	7.02	5.12	5.05	8.56	4.99
Plasma current, I_ϕ (MA)	15.8	16.2	22.4	21.7	17.0	14.8	25.1	60.2	13.3
Neutron wall loading (MW/m^2)	3.20	3.18	16.6	14.6	2.53	3.70	3.74	0.09	2.64
Fusion power (MW)	2862	3027	3291	2896	3226	2504	2753	3258	1700
Blanket thickness (m)	0.71	0.70	0.60	0.32	0.79	1.20	0.40	0.45	0.76
Blanket/shield gap (m)	0.10	0.10	0.10	0.0	0.40	--	0.05	0.05	0.10
Shield thickness (m)	0.83	0.92	0.10	0.45	1.08	0.05	0.60	0.60	0.53
Neutron energy multiplication	1.27	1.27	1.33	1.272	1.20	1.30	1.30	1.10	2.44

Table 1. (continued)

	V-Li TOK	RAF-He TOK	RAF-Li Pb/RFP	V-Li RFP	SiC-He TOK	V-FLIBE TOK	V-MHD TOK	V-DHe^3 TOK	RAF-Li HYB
Tritium breeding ratio	1.28	1.11	1.03	1.28	1.06	1.20	1.05	0.0	1.02
Total thermal power (MW)	3563	3648	4216	3580	3827	3179	3414	3271	3725
Primary coolant inlet T_i(°C)	300	275	350	300	250	600	770	150	275
Primary coolant outlet T_o(°C)	550	510	500	550	500	650	1470	150	450
Thermal conv. efficiency	0.404	0.400	0.343	0.404	0.380	0.446	0.370	0.350	0.374
Recirculating power fraction	0.12	0.13	0.12	0.12	0.13	0.11	0.05	0.03	0.11
Net electric power (MW_e)	1200	1200	1200	1200	1200	1200	1200	1200	1200
Volume of fusion power core (m^3)	2669	2965	428	457	4573	2507	2490	4907	1635
Mass of fusion power core (Mg)	11482	12270	2663	2396	14348	4239	11268	19296	6614
Mass power density (kW_e/tonne)	105	98	451	501	84	283	107	62	181

[a]A total beta of 0.1 for the RFPs corresponds to a poloidal beta of 0.2.

volume raised to an appropriate fractional exponent. Thus, for example, the reactor building and hot cells (cost account 21.1) are costed at

$$C_{bldg}\ (M\$) = \$174.4 \times (V_{FPC}/2409)^{0.67} , \qquad (1)$$

where \$174.4 million is the updated Starfire figure for this component given a fusion-island volume of 2409 m^3. (The fusion island comprises the plasma chamber, first wall, blanket, shield, coils, and coil structure.) Total capitalized investment cost in 1986 dollars is obtained by multiplying the direct costs for the fusion island and balance of plant by factors accounting for indirect costs (proportional to design-and-construction lead time), contingency, and interest during construction.

Costs of the blanket, limiter, coolant, and other major items that turn over on a time scale that is short compared with the plant lifetime are treated analogously to fuel costs in the fission fuel cycle, following the methodology embodied in the Nuclear Energy Cost Data Base (NECDB) at ORNL.[15] Calculation of other operation and maintenance costs also follows the NECDB model. Following standard engineering-economics techniques, as embodied in the NECDB, then yields a levelized constant-dollar cost of electricity (COE). The unit costs, scaling factors, and other engineering/economics assumptions that enter the capital-cost and COE calculations are summarized in Table 2.

It should be clear from the description of this procedure that the COE will depend not just on the choice of blanket type, input unit costs, and economics conventions, but also on the initial choice of the combination of physics parameters--beta, aspect ratio, elongation, maximum toroidal field at the coil, and so on. It was essential for our purposes that the point-of-departure tokamak, which was to be the anchor or reference point from which the other tokamak cases would be developed, should be based on choices of the physics parameters that are not only reasonable in light of present knowledge of tokamak possibilities but also close to the values that would minimize the COE subject to this constraint of physical reasonableness. Accordingly, we determined the physics parameters for the point-of-departure case by using the Generomak model in an iterative mode, seeking a COE minimum.

Although the actual "marching variable" used in this iterative process was the maximum magnetic field at the primary coil $B_{\phi c}$, it is particularly informative to show the results as a function of the ratio of net electric

Table 2. Economics parameters and assumptions for fusion cases (all costs in 1986 dollars).

UNIT COSTS FOR FABRICATED MATERIALS:

V15Cr5Ti = \$400/kg; RAF steel = \$50/kg; PCA steel = \$50/kg; SiC (blanket) = \$100/kg; SiC (other) = \$30/kg; Fe1422 = \$20/kg; Fe2Cr1V = \$20/kg; coils (tokamak) = \$90/kg; coils (RFP) = \$50/kg; supporting structure = \$25/kg.

UNIT COSTS FOR COOLANT/BREEDER AND OTHER MATERIALS:

Liquid Li (unenriched) = \$45/kg; LiO_2 (unenriched) = \$45/kg; $Pb_{83}Li_{17}$ (80-90% enriched) = \$13/kg; FLiBe = \$70/kg; Be = \$500/kg; $LiF\text{-}BeF_2\text{-}ThF_4$ = \$50/kg; Cd = \$1600/kg; BeO = \$200/kg; He^3 =\$100,000/kg.

COMPONENT COSTS:

Auxilliary power (tokamak) = \$2.25/W; auxilliary power (RFP) = \$0.50/W; limiter = \$60 000/m^2.

SCALING RULES FOR DIRECT COSTS BY CATEGORY:

Cost account		Cost relation (million \$ 1986)
20	Land	\$ 5.0 M (not scaled)
21.1	Reactor bldg and hot cells	$\$174.4\ M \times (V_{FPC}[m^3]/2409)^{0.67}$
21.2	Other bldgs and improvements	$\$120.6\ M \times (P_{TH}[MW]/4085)^{0.50}$
22.1	Reactor plant equip: heat trans	$\$100.3\ M \times (P_{TH}[MW]/4085)^{0.60}$
22.2	Reactor plant equip: other-1	$\$162.4\ M \times (P_{TH}[MW]/4085)^{0.60}$
22.3	Reactor plant equip: other-2	$\$\ 44.1\ M \times (V_{FPC}[m^3]/2409)^{0.67}$
23	Turbine plant equipment	$\$230.7\ M \times (P_{EL}[MW_e]/1200)^{0.8}$
24	Electric plant equipment	$\$121.2\ M \times (P_{EL}[MW_e]/1200)^{0.4}$
25	Misc plant equipment	$\$\ 47.3\ M \times (P_{EL}[MW_e]/1200)^{0.3}$
26	Main condensor and heat rejection	$\$\ 59.1\ M \times (P_{TH}\text{-}P_{EL}[MW])/2885)^{0.8}$

Table 2. (Continued)

FINANCIAL ASSUMPTIONS:

Plant lead time = 6 yr; plant lifetime = 30 yr; indirect cost factor = 0.375; contingency factor = 0.15; real cost of money = 0.0283/yr; inflation = 0.06/yr; interest during construction (real, for S-curve investment pattern) = 0.0856; effective tax rate = 0.4816; tax depreciation life (plant) = 10 yr; tax depreciation life (replaceable blankets) = 5 yr; fixed charge rate = 0.165 (nominal $), 0.0844 (constant $).

OPERATION AND MAINTENANCE ASSUMPTIONS:

Capacity factor = 0.65, except V-MHD and V-DHe^3 tokamaks = 0.75 owing to absence of turbines; blanket lifetime = 20 MW-yr/m^2 of neutron fluence at the first wall (except 30 yr for D-He^3/TOK, 15 MW-yr/m^2 for RAF, 7 MW-yr/m^2 for PCA); 25% of auxilliary power supply replaced at same interval as blanket; annual coolant makeup = 2%; radwaste management charge = 1 mill/kW-hr; other operation and maintenance charges are 8.9 mills/kW-hr, with downward adjustments in cases with higher capacity factor He cooling and upward adjustment for extra guards (equal to fission plants) for hybrids.

power to the mass of the fusion power core--that is, mass power density (MPD, kW_e/tonne)--as in Fig. 1. Also shown are the results of a similar iterative process for an RFP with the same liquid-lithium/vanadium-alloy blanket type. In the RFP case, the lower limit on COE depends on the physically determined upper limit on peak neutron flux or heat flux at the first wall, with the actual COE minimum being dictated by the cost of frequent first-wall/blanket replacement (materials and downtime) at very high neutron wall loadings. The COE minimum for the tokamak case results from a capital-cost trade-off associated with low-power density at low fields and high-coil masses at high fields.

The Case 1 Li/V blanket also served as the basis for using the Generomak model to examine the connection between physics and economics for a variety of tokamak confinement assumptions ranging from the very conventional (low beta,

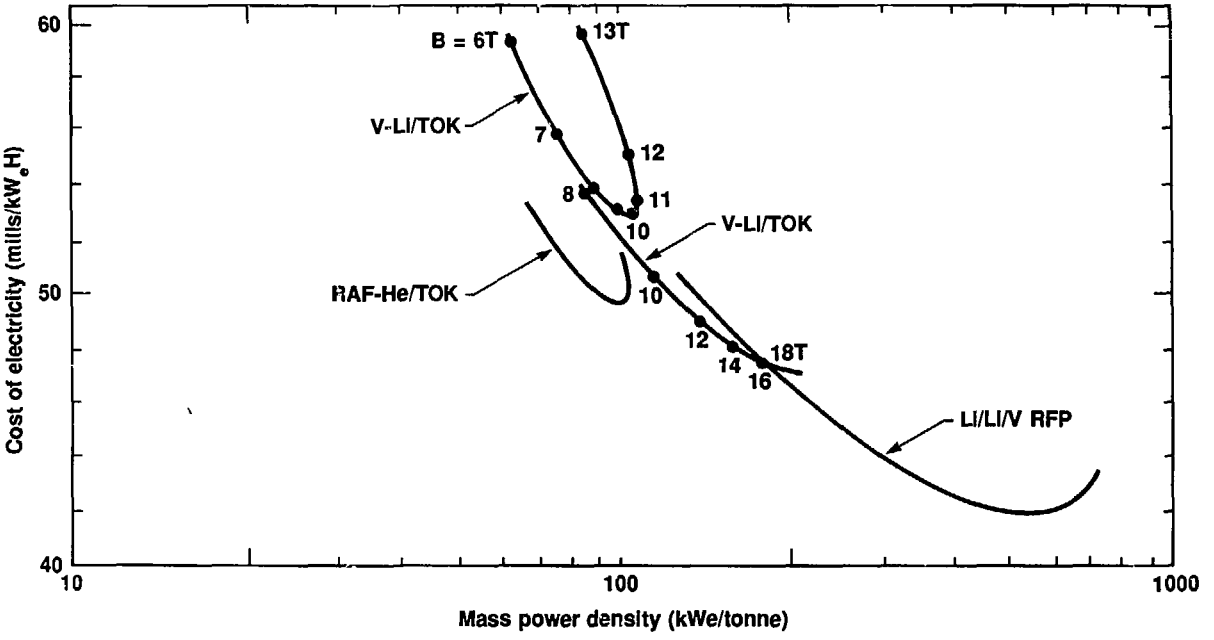

Figure 1. Cost of electricity vs mass power density for some ESECOM cases. The curves show the location of the economic-optimum design point as the maximum toroidal magnetic field is varied in two tokamak cases and as the neutron wall loading is varied in the V-Li/RFP. The effect of an improved superconducting coil design on the COE/MPD relation for the point-of-departure V-Li/TOK is also shown.

long pulsed) to the yet-to-be-achieved second-stability regime (high beta, low current). Some of these results are presented below in connection with our discussion of uncertainties, and more detail can be found in our main report.[1]

For the fission cases, engineering characteristics and capital-cost estimates were taken from the analyses of the vendors or designers,[15,35-38] modified in some instances according to the results of DOE reviews of these concepts. This information was then integrated into the NECDB methodology, with further modifications as necessary for consistency with the fusion calculations. For example, we use 6 years as the nominal design-and-construction lead time for the fission cases as well as for the fusion ones to avoid biasing the comparisons with the assumption that future fission systems will suffer the sorts of construction delays that have been prevalent in recent experience. The engineering characteristics and economic assumptions for the fission cases are summarized in Table 3.

The results of the basic economic calculations are shown in Table 4. Here the "overnight" costs include the application of indirect and contingency factors but not interest during construction; they are the costs that would result if construction were instantaneous. The total capital costs are obtained by accounting for interest during the assumed 6-year construction period (adjusted to 1986 dollars). The additional fission case (11' PWR-ME) in Table 4 is the median-experience PWR and provides a second reference point rooted in reality. (The design-and-construction lead time for this case is 12 years and the indirect costs are 100% instead of 37.5%.) Particularly noteworthy in these results is that the costs of electricity for the best experience and median experience PWRs bracket the range of costs estimated for the various fusion, hybrid-breeder, and advanced-fission cases.

All the costs estimated for fusion systems in Table 4 are based on the assumption that nuclear-grade construction is required throughout the plant, as has been the case with fission PWRs. The figures for the LSPB, PRISM, and MHTGR systems, on the other hand, incorporate some allowances for reduction of nuclear-grade requirement in consideration of the higher degree of passive safety that designers of these systems believe could be demonstrated in comparison with conventional fission plants. It is reasonable to suppose that those fusion systems with relatively low inventories of radioactivity and/or impressive passive barriers against release of these materials may also avoid the burdens of full nuclear-grade construction. A more systematic treatment

Table 3. Fission cases: engineering characteristics, economic assumptions engineering characteristics.

Case	Plant output (MW_e)	No. of reactors in plant	Primary fluid	Reactor exit temp. (°F)	Reactor exit press. (psig)	Thermal conversion effic.	Enrichment (%)
1 PWR-BPE	1139	1	H_2O	618	2250	0.339	3
2 LSPB	1320	1	Na	950	atm	0.377	24.4
3 PRISM	1245	9	Na	875	atm	0.325	25.9
4 MHTGR	558	4	He	1268	919	0.399	20

FINANCIAL ASSUMPTIONS:

Same as for fusion except indirect cost factor = 0.31 for MHTGR and 0.21 for PRISM (compare 0.375 for other fission and fusion cases), corresponding to <6-yr design-and-construction lead time claimed by designers for these modular plants.

FISSION FUEL-COST PARAMETERS:

U_3O_8 = \$50/lb; Th = \$35/kg; Pu = \$50/g; conversion = \$8/kgU; enrichment = \$60/SWU.

Fuel fabrication (per kg heavy metal): LWR (low-enriched U) = \$240; LWR (U/Pu mixed oxide) = \$730; HTGR (low-enriched U) = \$1750; HTGR (U233/Th) = \$1150; LWR (U233/Th) = \$1185; LMFBR (core) = \$2250; LMFBR (blanket) = \$330.

Spent-fuel shipping (per kg heavy metal): LWR = \$45; HTGR = \$300; LMFBR = \$110.

Table 3. (continued)

Reprocessing (per kg heavy metal): LWR (U/Pu) = $440; LWR (U233/Th) = $625; HTGR = $730; LMFBR = $700.

Radioactive-waste management = 1 mill/kWhr.

OTHER OPERATION AND MAINTENANCE ASSUMPTIONS:

Capacity factor = 0.65; nonfuel O&M charges = 7.1 mills/kWhr for PWR, 7.7 mills/kWhr for LSPB, 7.9 mills/kWhr for PRISM, 8.3 mills/kWhr for MHTGR.

of levels of safety assurance (LSA) in fusion and fission systems is offered below, along with a discussion of the economic ramifications of this issue.

The nature and magnitude of the uncertainties in our cost estimates will also be discussed below. Suffice it to say here that these figures are of greater interest for their magnitudes relative to one another than for their absolute values.

Table 4. Comparative costs without safety assurance credits (1986$).

Case	Unit capital costs ($/kW$_e$)			Cost of electricity (mil/kW-hr)			
	Direct	Over-night	Total	Capital	Fuel, other O&M	Fiss. fuel sales	Total
1 V-Li/TOK	1378	2178	2365	35.1	18.1	0.0	53.1
2 RAF-He/TOK	1387	2193	2380	35.3	13.2	0.0	48.5
3 RAF-LiPb/RFP	949	1501	1630	24.2	13.5	0.0	37.7
4 V-Li/RFP	963	1523	1655	24.5	12.8	0.0	37.3
5 SiC-He/TOK	1621	2563	2785	41.3	13.4	0.0	54.6
6 V-FLIBE/TOK	1184	1873	2035	30.1	17.8	0.0	47.9
7 V-MHD/TOK	873	1380	1500	19.2	16.1	0.0	35.4
8 V-DHe^3/TOK	1763	2787	3025	38.9	8.9	0.0	47.8
9 RAF-Li/HYB	1649	2608	2830	41.9	21.7	-23.2[b]	40.3
10 SS-He/HYB	1343	2123	2305	34.1	21.7	-16.0[b]	39.8
11 PWR-BPE	740	1170	1270	18.8	14.6	0.0	33.4
11' PWR-ME	980	2260	2620	41.0	15.6	0.0	56.6
12 LSPB	1040	1645	1785	26.5	----16.7----	[c]	43.2
13 PRISM[a]	996	1575	1710	25.3	----18.5----	[c]	43.8
14 MHTGR[a]	885	1400	1520	22.6	19.4	0.0	42.0

[a]Some safety-assurance credits were embedded in the vendor/designer estimates of PRISM and MHTGR capital costs and remain in the cost figures shown here.

[b]These figures for hybrid fissile-fuel sales are based on MHTGR clients.

[c]Fuel-sales credits for LSPB and PRISM are based on costs of reprocessing at central facilities (see Table 3) and sale of resulting plutonium at $50/g. Reprocessing costs may be higher for on-site reprocessing proposed by PRISM designers.

SAFETY/ENVIRONMENT ANALYSIS

ESECOM's analysis of environmental and safety characteristics included qualitative and, where possible, quantitative assessment of: (a) possibilities and consequences of major releases of radioactivity from reactor accidents; (b) magnitude of the radioactive-waste burden; (c) occupational and public exposures to radiation in routine operation; and (d) unwanted links to nuclear weaponry. Most of these analyses begin with the inventories of various types of radioactivity, to which we now turn.

DETERMINATION OF RADIOACTIVE INVENTORIES

The largest quantities of radioactivity in fusion reactors are in the form of neutron-activation products, most of which are embedded in solid reactor materials. Smaller quantities may circulate with coolant, having been formed in coolant materials or mobilized from structure by corrosion, and still smaller quantities formed by air activation or outgassing from solid materals can be present in the plant atmosphere. Different subsets of these inventories play key roles in routine exposures of plant workers to radiation, in defining the potential for radiation doses to the public in the event of major accidents, and in shaping the radioactive-waste-management task.

ESECOM's calculations of activation-product inventories were carried out at LLNL using the TART, ORLIB, and FORIG computer codes and their associated data bases.[17,39-42] These codes operated on cylindrical approximations to our toroidal blanket configurations, in which the area of the cylindrical inner wall was equal to that of the first wall of the toroid being represented and the thicknesses of the cylindrical layers were chosen to give approximately the volumes implied by the toroidal blanket design.

The Monte Carlo calculations employed by the TART code to determine the neutron and gamma spectra in the various layers of the blanket, manifold/reflector, and shield (and, in one case, magnets) used 20 samples with 5000 particles per sample. These spectrum calculations accounted for materials compositions down to the level of 0.1% by weight. The activation calculations performed by the ORLIB averaging code using the ACTL cross-section library took account of impurities to levels below 1 ppm by weight. The constituent and impurity compositions used in these calculations came mainly from the Blanket Comparison and Selection Study (BCSS) (Ref. 13) and, in a few

instances, from the design groups working on particular blankets. These compositions are shown in Table 5.

The inventories resulting from such calculations depend not only on the incident neutron fluxes and layer thicknesses and compositions, but also on the total irradiation times. Based on a neutron fluence limit of 20 MW-yr/m^2 at the first wall, it was assumed that solid blanket components in reactors with first-wall fluxes in the range of 3 MW/m^2 were changed after each 6 full-power years of operation, while those in reactors with first-wall fluxes around 15 MW/m^2 were changed after each full-power year of operation. Shields, magnets, and liquid constituents of blankets were assumed in most cases to be irradiated for 30 full-power years, as was the entire blanket of the very low neutron-flux (0.09 MW/m^2) D-He^3 tokamak.

For purposes of assessing accident potential and occupational hazards, reactor radioactivity inventories were evaluated at their maximum levels--that is, those attained just before blanket change-out. Radioactive-waste calculations were based on life-cycle waste quantities for 30 full-power years of operation, including all changed-out components. Component dimensions, irradiation times, and volumes for fusion Cases 1 through 6 and 8 are summarized in Table 6. (Because of lack of cross-section data for cadmium isotopes that are potentially dominant in the activation for Case 7--the V-MHD tokamak--activation calculations and the associated safety and environmental analyses were not performed for this case.)

Estimates of tritium inventories in the fusion cases were based on the BCSS (Ref. 13) and on subsequent design studies, and included tritium in structure, coolant, breeder, and neutron-multiplier materials. In addition, kilogram quantities of tritium (at 10 MCi/kg) ordinarily would be kept in vault storage as an operational reserve or for subsequent transfer to start up new reactors. This inactive tritium inventory is not likely to be released in ordinary accidents (or even in extraordinary ones), although it might be releasable by sabotage, act of war, or natural disaster exceeding those for which the system was designed. A third type of tritium inventory exists in vacuum pumps and tritium fuel processing and purification systems, typically 100 to 200 grams. This inventory can be largely contained in separate compartments from the reactor. Vulnerability to release is generally thought to be intermediate between the tritium in the reactor blanket, structure, and coolant (the most vulnerable) and the tritium reserve fuel stored in a vault (the least vulnerable). Although ESECOM considered only the most vulnerable

tritium (in the reactor) to be released in an accident, the additional tritium in the pumps and fuel processing equipment, even if released, would not be sufficient to significantly change any of the conclusions ESECOM derived from its accident analysis of fusion cases.

Fission-product inventories for the PWR and LMFBR cases were derived from figures in the Reactor Safety Study of the U.S. Nuclear Regulatory Commission

Table 5. ESECOM alloy compositions (weight fraction).

VCrTi: 0.798 V; 0.150 Cr; 0.050 Ti; 0.0003 Si; 0.0002 Al; 0.0001 N,O; 0.00005 C; 0.00004 Fe; 0.00003 P; 0.00001 S,Mo,Ta; 0.000004 Ni,Nb; 0.000002 Cu,As,W; 0.000001 Cl; 0.0000001 K.

Fe2CrlV: 0.9513 Fe; 0.024 Cr; 0.015 V; 0.003 Si,Mn; 0.0011 C; 0.0005 Ni; 0.00043 Al; 0.0004 Cu; 0.0002 Mo; 0.00015 N,S; 0.00007 P; 0.00003 Ti.

RAF: 0.8516 Fe; 0.11 Cr; 0.025 W; 0.0053 Mn; 0.003 V; 0.002 Si; 0.0015 C; 0.001 Ti; 0.00013 P; 0.00008 Al; 0.00007 O; 0.00006Ni; 0.00005 Co; 0.00004 S; 0.00003 Cu,Sn; 0.00001 B,N,Zr; 0.000005 Sb,Pb; 0.000004 Ta; 0.000003 K; 0.0000027 Mo; 0.000002 Ba,Tb,Ir,Bi; 0.000001 Nb,Cd; 0.0000009 Ag.

Li2O: 0.5333 O; 0.4658 Li; 0.00037 K; 0.00021 Ca; 0.0001 Cl,Fe; 0.00008 Pb; 0.00005 Na; 0.00002 Al,Mn,Ni; 0.00001 Si; 0.000006 Cu.

Cu: 0.9985 Cu; 0.0015 Zr; 0.000022 Fe; 0.000012 S,Ag; 0.000005 Ni,As,Sb,Pb; 0.000002 Se; 0.000001 Sn,Te,Bi; 0.0000005 Mn.

LiPb: 0.9922 Pb; 0.0068 Li; 0.001 Sr; 0.0005 P,Zn; 0.0003 S,K,As,Zr; 0.00026 O; 0.0001 Na,Ca,Fe,Ba,Bi; 0.00005 Al,Cd; 0.00003 Ti,V,Co,Mo,Sb; 0.00002 Cl,Cr; 0.00001 Be,B,N,Mg,Si,Mn,Ni,Cu,Ag,Sn.

PCA: 0.6488 Fe; 0.16 Ni; 0.14 Cr; 0.02 Mn,Mo; 0.005 Si; 0.003 Ti; 0.001 V; 0.0005 W; 0.0003 Al,Co,Nb; 0.0002 Cu,As; 0.0001 N,P,Ta; 0.00005 B,C,S,Zr,Sn; 0.00001 Sb,Ba,Tb,Ir,Pb,Bi; 0.000003 K; 0.000002 Cd; 0.000001 Ag.

SiC: 0.7005 Si; 0.2995 C; 0.000011 Fe; 0.0000003 Co.

Table 5. (Continued)

PE16 Ni: 0.43 Ni; 0.35 Fe; 0.17 Cr; 0.03 Mo; 0.01 Al,Ti; 0.005 Si,Mn; 0.001 V; 0.0005 W; 0.0003 Co,Nb; 0.0002 As,Cu; 0.0001 N,P,Ta; 0.00005 B,C,S,Zr,Sn; 0.00001 Sb,Ba,Tb,Ir,Pb,Bi; 0.000003 K; 0.000002 Cd; 0.000001 Ag.

FLiBe: 0.784 F; 0.13 Be; 0.086 Li; 0.000166 Fe; 0.000026 Ni; 0.000019 Cr; 0.000005 S; 0.000001 Mo.

NOTE: When a number is followed by more than one element, each of the elements listed is present at the indicated weight fraction.

(NRC)[43] and an LMFBR safety study conducted in the Federal Republic of Germany,[44,45] scaled to 1200 MW_e. As in the fusion cases, the inventories were evaluated both to give the maximum in the reactor at any one time (just before refueling in steady-state operation) and to give the 30-year life-cycle quantities of radioactive wastes. Coolant activation and isotopes with half-lives of a few seconds or less were not included. Fission-product and actinide inventories for the fusion-fission hybrid breeder cases were approximated by scaling from those calculated in earlier work for a somewhat similar blanket,[46] and activation-product inventories for the hybrids were estimated from related pure-fusion cases using a scaling devised by Fetter.[17]

ACCIDENT ANALYSIS

To facilitate analysis of accident hazards associated with radioactive materials of differing degrees of inherent mobility, we divided the radioactive inventories of fusion and fission reactors alike into five mobility categories, as indicated in Table 7. In the case of fission, the categorizations are based on estimates of releasibility under accident conditions from the Reactor Safety Study,[43] from more recent NRC and nuclear-industry reviews of the radioactive source term in light-water-reactor accidents,[47,48] from preliminary analyses of the release from the Chernobyl accident,[49] and from U.S. and German studies of LMFBR accidents.[44,50] In the case of fusion, the categorizations are based in part on limited experimental data on releases from candidate fusion alloys under conditions that might be

expected in accidents[20,21] and in part on generally available data on the melting points and boiling points of relevant elements and their oxides. The categorizations in Table 7 must be regarded as very approximate in any case, and differences of a single level should not be taken too seriously.

Table 6. Irradiation characteristics of fusion-reactor components.

Case (first-wall n flux) and component	Change-out time (full-power yr)	Layer Δr (cm)/Matl volume fraction (%)	Component volume (m^3)	Life-cycle volume (m^3)
Case 1: V-Li/TOK (3.20 MW/m^2)				
First wall VCrTi	6	5 / 20	6.9	34
Inner blkt VCrTi	6	35 / 7.5	19	96
Manifold VCrTi	6	35 / 10	28	140
Manifold Fe2Cr1V	6	35 / 80	230	1100
Shield Fe2Cr1V	30	30 / 80	220	220
Case 2: RAF-He/TOK (3.18 MW/m^2)				
First wall RAF	6	6 / 12	5	25
Inner blkt RAF	6	57 / 15	55	270
Inner blkt Li2O	6	57 / 50	330	1700
Manifold RAF	6	22 / 15	37	190
Shield Fe2Cr1V	30	30 / 90	220	220
Case 3: RAF-LiPb/RFP (16.6 MW/m^2)				
First wall Cu	1	1 / 50	0.58	17
First wall RAF	1	1 / 20	0.23	7
Inner blkt RAF	1	60 / 11.7	12	350
Inner blkt LiPb	30	60 / 88.3	86	86
Shield Fe2Cr1V	30	10 / 90	20	20

Table 6. (Continued)

Case (first-wall n flux) and component	Change-out time (full-power yr)	Layer Δr (cm)/Matl volume fraction (%)	Component volume (m^3)	Life-cycle volume (m^3)
Case 4: V-Li/RFP (14.6 MW/m^2)				
First wall VCrTi	1	1 / 30	0.35	11
Inner blkt VCrTi	1	32 / 5.6	0.60	18
Shield VCrTi	1	43.5 / 6.7	8.9	270
Shield Fe2Cr1V	1	43.5 / 83.3	72	2100
Magnet Cu	30	28 / 70	5.0	5.0
Magnet PCA	30	28 / 10	7.2	7.2
Case 5: SiC-He/TOK (2.53 MW/m^2)				
First wall SiC	6	1 / 100	6.8	34
Inner blkt SiC	6	49.1 / 16	58	290
Inner blkt Li2O	6	49.1 / 39.8	230	1200
Manifold SiC+	6	28.9 / 52	120	620
Shield Al+	30	108 / 89.1	970	970
Case 6: V-FLiBe/TOK (3.70 MW/m^2)				
First wall VCrTi	6	0.3 / 100	0.85	4.2
Inner blkt VCrTi	6	120 / 4	19	97
Inner blkt FLiBe	30	120 / 96	460	460
Shield PE16	30	14 / 100	75	75
Case 8: D-He^3/TOK (0.09 MW/m^2)				
First wall VCrTi	30	1 / 100	23	23
Inner blkt VCrTi	30	50 / 5	24	24
Shield Fe2Cr1V	30	60 / 70	1200	1200

Table 7. Categorization of radioactive isotopes by mobility under accident conditions.

Category Definition	Fusion	Fission
I: Elements gaseous or extremely volatile under thermochemical conditions of normal operation.	H,C,*N,Ar	H,C,*N, Ar,Kr,Xe
II: Elements somewhat volatile under thermochemical conditions of normal operation.	Mg,P,Cl,Ca, Ag,Cd,Re,Hg	I,Cs,Rb
III: Elements somewhat to highly volatile under conditions likely to be encountered in an accident.	Na,Mn,As,Sr, Mo,Cu,Ni,Tc, Tl,Po,Pb	Sb,Te
IV: Elements somewhat volatile under conditions that may be encountered in severe accidents.	K,Co,V,Pd, In,Sb,W,Te	Sr,Ru,Ba, Rh,Co,Mo, Tc
V: Elements resistant to volatilization even under extreme accident conditions.	Be,Al,Si,Sc, Ti,Fe,Y,Zr, Nb,Sn,La,Hf, Ta,Bi,Cr	Fe,Y,La, Zr,Nb,Ce, Pr,Nd,U, Th,Np,Pa Pu,Am,Cm

*From activation of air.

NOTES: These categorizations denote relative mobility of fusion elements compared with one another and of fission elements compared with one another; it should not be assumed that fusion elements in a given mobility cate/gory have the same likelihood of release, or the same release fraction in a severe accident, as elements in the same mobility category in the fission column.

Temperature ranges for fusion are defined as follows:
Normal operation: $T < 800$ K
Likely to be encountered in an accident: $800\ K < T < 1200\ K$
May be encountered in severe accidents: $1200\ K < T < 1800\ K$

We assume that the elements may come into contact with oxygen under accident conditions, so formation of volatile oxides has been taken into account.

Many of the categorizations for elements in fusion alloys are based on experimental data for V15Cr5Ti and HT9 ferritic steel. Relative mobilities in different alloys will not necessarily be the same in all cases.

Revisions in this or any similar scheme are inevitable as more data become available; this is especially so on the fusion side where available data are currently so scanty.

Given the radioactive inventories and the mobility-based classification scheme just described, it becomes possible to calculate the off-site doses that would result from release of 100% of the radioactive inventory in each mobility category for each design. One can then deduce how large the actual release fractions of these materials would have to be to produce any particular dose of interest. One can calculate, for example, what fraction of the radioactive inventory in a fusion-reactor first wall would have to be released to generate, under adverse weather conditions, an acute whole-body dose of 200 rem at a distance of 1 km from the reactor (corresponding approximately to the threshold below which no early fatalities would be expected); and one can calculate these dose-threshold release fractions for each different mobility category in each reactor type. The higher these dose-threshold release fractions are, the better, because a large figure indicates that the threshold dose will not be exceeded unless a large fraction of the inventory escapes. (A dose-threshold release fraction exceeding unity means that not even a 100% release of the inventory would suffice to produce the threshold dose.)

Where estimates are available of the actual release fractions that are plausible for materials in different mobility categories under severe-accident conditions, these estimates can be compared with the dose-threshold release fractions calculated as just described to clarify whether (and by how much) the threshold doses could be exceeded in credible events. (Estimates of maximum plausible release fractions in severe accidents are available for at least a few types of fission reactors, and ESECOM has made such estimates--necessarily in a very approximate way, but we believe very conservatively--for three of our fusion cases.) Even where estimates of the maximum plausible release fractions are not available, as is the case for most fusion systems and for the more advanced fission systems, direct comparison of the dose-threshold release fractions for the various mobility categories in different systems provides some basis for judgment about the relative potential of these systems to generate dangerous releases.

Table 8 summarizes our findings on inventories and dose-threshold release fractions for some of the fusion cases and for the PWR and LSPB fission cases.

Table 8. Dose-threshold release fractions by component and mobility category.

Case and mobility categories	Inventories (MCi)		Release fraction that would produce: 200 rem crit dose from plume @ 1 km		25 rem 50-yr ground dose @ 10 km	
	First wall	BOFC	First wall	BOFC	First wall	BOFC
Case 1: V-Li/TOK						
I	5	0.077	52	7100	15	260
I-II	10	6.0	6.3	5.0	0.78	0.82
I-III	10	60	5.1	0.027	0.55	0.00011
I-IV	95	670	3.7	0.027	0.021	0.00010
I-V	540	2400	0.036	0.015	0.0016	0.00009
Case 2: RAF-He/TOK						
I	1.7	0.040	160	2e4	56	4400
I-II	7.1	16	5.7	2.3	2.3	0.86
I-III	390	450	0.036	0.032	0.00011	0.00011
I-IV	510	670	0.035	0.028	0.00011	0.00010
I-V	1200	1300	0.033	0.027	0.00011	0.00010
Case 3: RAF-PbLi/RFP						
I	0.51	0.032	510	4e3	180	2200
I-II	21	20	1.9	0.63	0.70	0.076
I-III	120	480	0.031	0.011	0.00086	0.00019
I-IV	220	1300	0.028	0.011	0.00013	0.00017
I-V	2500	1600	0.028	0.010	0.00013	0.00010

Table 8. (Continued)

Case and mobility categories	Inventories (MCi)		Release fraction that would produce: 200 rem crit dose from plume @ 1 km		25 rem 50-yr ground dose @ 10 km	
	First wall	BOFC	First wall	BOFC	First wall	BOFC
Case 4: V-Li/RFP						
I	5.0	0.07	51	2e4	18	350
I-II	6.5	6.3	17	4	2.4	0.17
I-III	6.5	940	14	0.012	1.9	0.00010
I-IV	38	1100	8.1	0.011	0.031	0.00008
I-V	180	4600	0.099	0.0084	0.0047	0.00008
Case 5: SiC-He/TOK						
I	1.7	2.1	160	220	56	77
I-II	8.2	14	86	17	55	12
I-III	8.3	15	41	3.1	8.4	0.095
I-IV	8.0	230	41	0.13	2.9	0.016
I-V	800	1500	21	0.13	2.9	0.016
Case 6: V-FLiBe/TOK						
I	0.17	0.01	1600	1e5	560	5700
I-II	1.1	0.96	41	38	4.7	4.8
I-III	1.1	1.2	32	22	3.0	0.32
I-IV	17	16	19	14	0.90	0.060
I-V	110	220	0.20	0.21	0.0096	0.008
Case 8: V-DHe^3/TOK						
I	0.50	0.006	500	8e5	180	2e5
I-II	0.81	0.038	100	960	13	120
I-III	0.82	0.66	29	20	9.5	0.053
I-IV	6.8	1.2	26	20	6.3	0.052
I-V	62	4.7	0.58	4.4	0.027	0.043

Table 8. (Continued)

Case and mobility categories	Inventories (MCi) Fission core	Release fraction that would produce: 200 rem crit dose from plume @ 1 km Fission core	25 rem 50-yr ground dose @ 10 km Fission core
Case 11: PWR-BPE (fission)			
I	380	0.38	28
I-II	1300	0.017	0.00013
I-III	1500	0.011	0.00012
I-IV	2600	0.0058	0.000086
I-V	5600	0.0025	0.000048
Case 12: LSPB (fission)			
I	360	0.67	63
I-II	1000	0.024	0.00017
I-III	1200	0.015	0.00016
I-IV	2200	0.0071	0.000095
I-V	5300	0.0031	0.000042

NOTES: All figures scaled to a standard 1200-MW_e plant size.

BOFC = balance of fusion core = blanket other than first wall, manifold/reflector, shield, and magnets (if magnet activation is significant).

All of the tritium in the blanket is counted as if it were in the first wall, where it dominates the Category I inventory.

Dose-threshold release fractions greater than one mean that release of the entire inventory would not suffice to produce the threshold dose;these figuresthus represent multiples of the inventory.

The absence of cross-section data for certain cadmium isotopes made it impossible to perform accurate activation calculations for Case 7 (V-MHD/TOK), so no figures for this case are presented here.

Two different threshold doses have been used here, critical-dose and chronic-dose thresholds.

The critical dose threshold corresponds to a critical whole-body dose commitment of 200 rem delivered by passage of the radioactive plume to an individual standing 1 km from the release under meteorological conditions that tend to maximize this dose. Here critical is defined--as in the Reactor Safety Study[43]--to include all of the radiation dose delivered in the first 7 days after the exposure plus half the dose delivered in the 8th through 13th days. The mechanisms considered are external irradiation by suspended and ground-deposited material during plume passage, and internal irradiation from material inhaled while the plume is passing. A critical dose commitment of 200 rem represents the level below which no early fatalities would be anticipated. (Early fatalities are those resulting from acute radiation syndrome; when the dose is high enough to produce such fatalities, they occur within the first 60 days after the exposure.)

The chronic dose threshold corresponds to a 50-year whole-body dose of 25 rem from ground contamination at a distance of 10 km from the release. The calculation of this dose accounts for inhalation of resuspended material as well as for external irradiation by material on the ground, and it corrects for shielding attributable to surface roughness and to the exposed persons' being indoors part of the time. Potential doses from contamination of food and drinking water are not included. Under U.S. standards, a potential exposure of 25 rem in 50 years from ground contamination would require either evacuation or extensive cleanup procedures.

All doses were calculated assuming weather conditions highly adverse in respect to the critical dose at the plant boundary (Pasquill F stability, 1 m/s windspeed, inversion layer at 250 m, release at ground level with no thermal plume rise, and a deposition velocity of 0.01 m/s) and using the dose models developed by Fetter.[17]

The results in Table 8 indicate that all of the fusion cases shown have substantial safety advantages over fission reactors based on release fractions required to exceed threshold doses--even without assuming that the physically plausible release fractions might be smaller for fusion. The point of departure V-Li/TOK fusion case, for example, has more than a two-order-of-magnitude advantage over the LMFBR with respect to critical dose at 1 km in every mobility category from I to IV if one bases the comparison on the fusion first wall (which, with respect to after-heat power density, radioactivity

concentration, surface-to-volume ratio, and susceptibility to overheating as a result of reconfiguration or exposure to fire, represents by far the most vulnerable part of the fusion inventory to release). Even the highest power-density fusion system (the RAF-LiPb/RFP) has a significant advantage over the LMFBR with respect to critical dose at 1 km from mobility categories I through IV. The advantages of the low-activation and advanced-fuel fusion systems are much larger still.

If the whole balance of fusion core (BOFC) is included in the comparison, most of the fusion systems still retain an advantage of an order of magnitude or more over the fission cases with respect to critical-dose threshold release fractions in most mobility categories. With respect to chronic-dose threshold release fractions, as well, most of the fusion cases have significant advantages compared with fission whether the BOFC is included or not. The exceptions here are Cases 2 and 3, in which the manganese activation in the ferritic-steel blanket produces high potential for ground contamination, and Case 4, in which the manganese activation in the shield and cobalt-60 in the magnet supports pose similar ground-contamination potential. In general, the potential for significant ground contamination from fusion-reactor accidents (50-year ground doses well in excess of 25 rem at distances of tens of kilometers) is considerably greater than the potential for early fatalities. In nearly all cases, the main contributors in this respect are manganese and cobalt isotopes in mobility categories III and IV.

Table 9 gives a component-by-component breakdown of the critical-dose threshold release fractions in the fusion cases and indicates which specific isotopes are mainly responsible for the dose potential in each mobility category. These figures underline the safety attractions of some of the more advanced fusion cases--the SiC-He, V-FLiBe, and D-He^3 tokamaks. It is apparent that these systems cannot generate a prompt fatality off-site at all unless one can imagine an event that would release a substantial fraction of the Category V isotopes from the first wall (in the cases of the V-FLiBe and D-He^3 tokamaks) or a substantial fraction of the Category IV isotopes from the shield (in the case of the SiC-He tokamak).

When one takes the next step of comparing the release fractions needed to generate threshold doses with the fractions that may be physically plausible for isotopes in the different mobility categories in the fusion and fission cases, the advantage of fusion widens. This is shown in Table 10, where FSECOM's estimates of maximum physically plausible release fractions for the

Table 9. Critical-dose threshold release fractions and dominant isotopes. The figures shown are the fraction (or multiple) of the inventory in the stated component and mobility category that would produce a critical whole-body dose of 200 rem at 1 km from the release under pessimistic assumptions.

Case and mobility category	First Wall		Rest of inner blanket		Manifold/reflector		Shield	
	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes
Case 1: V-Li/TOK								
I	50	H3	2e4	H3	1e4	H3	3e5	H3
I-II	6	Ca45,Ca47	8	Ca45,Ca47	10	P32,Ca45	400	P32
I-III	5	Ca45,Na24	6	Ca45,Na24	0.03	Mn56,Mn54	0.6	Mn56
I-IV	4	Ca45,Na24	5	Ca45,Na24	0.03	Mn56,Mn54	0.6	Mn56
I-V	0.04	Sc48	0.04	Sc48	0.02	Mn56,Mn54	0.4	Mn56,Fe59
Case 2: RAF-He/TOK								
I	200	H3	2e4	H3	3e6	H3	3e4	H3
I-II	6	Re186,Re188	3	Re186,Re188	7	Re188,Re186	400	P32
I-III	0.04	Mn56,Mn54	0.03	Mn56,Mn54	0.9	Mn56,Mn54	0.7	Mn56,Mn54
I-IV	0.04	Mn56,Mn54	0.03	Mn56,Mn54	0.3	W187,Mn56	0.5	Mn56,Mn54
I-V	0.03	Mn56,Mn54	0.03	Mn56,Mn54	0.3	W187,Mn56	0.4	Mn56,Fe59
Case 3: RAF-PbLi/RFP								
I	500	H3	4e3	Ar41	NA	NA	5e6	H3
I-II	2	Re188,Re186	0.6	P32,Re188	NA	NA	400	P32
I-III	0.03	Cu64,Mn56	0.01	Po210,Mn56	NA	NA	0.7	Mn56
I-IV	0.03	Cu64,Mn56	0.01	Po210,Mn56	NA	NA	0.7	Mn56
I-V	0.03	Cu64,Mn56	0.01	Po210,Mn56	NA	NA	0.6	Mn56,Fe59
Case 4: V-Li/RFP								
I	50	H3	6e4	H3,N13	NA	NA	2e4	H3,N13
I-II	20	Ca45,Ca47	10	Ca45	NA	NA	7	P32
I-III	10	Ca45,Na24	7	Ca45,Na24	NA	NA	0.01	Mn56,Cu64
I-IV	8	Ca45,Na24	6	Ca45,Na24	NA	NA	0.01	Mn56,Cu64
I-V	0.1	Sc48	0.04	Sc48	NA	NA	0.01	Mn56,Cu64

Table 9. (Continued)

Case and mobility category	First Wall		Rest of inner blanket		Manifold/reflector		Shield	
	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes	Threshold release fraction	Dominant isotopes
Case 5: SiC-He/TOK								
I	200	H3	1e4	H3	1e8	C14	200	H3
I-II	90	Mg27,H3 Re188,Re186	40	P32,Mg27	9000	Mg27	30	
I-III	40	Na24,Mg27	20	P32,Mn54	8000	Mg27	4	Na24,Re188
I-IV	40	Na24,Mg27	10	P32,Mn54	1000	Co60,Mg27	0.1	W187
I-V	20	Al29,Na24	9	Al29,P32	500	Si31,Co60	0.1	W187
Case 6: V-FLIBE/TOK								
I	2000	H3	1e5	H3	NA	NA	2e8	H3
I-II	40	Ca45,Ca47	40	Ca45,P32	NA	NA	3e5	P32,Ca45
I-III	30	Ca45,Na24	20	Ca45,Na24	NA	NA	500	Mn56,Mn54
I-IV	20	Ca45,Na24	8	Ca45,Na24	NA	NA	100	Co60,Mn56
I-V	0.2	Sc48	0.2	Sc48	NA	NA	100	Co60,Mn56
Case 8: D-He3/TOK								
I	500	H3	1e6	H3	NA	NA	3e6	H3
I-II	100	Ca45,H3	1e3	Ca45	NA	NA	9e3	H3,P32
I-III	80	Ca45,Na24	800	Ca45,Na24	NA	NA	20	Mn54,Mn56
I-IV	60	Ca45,Na24	700	Ca45,Na24	NA	NA	20	Mn54,Mn56
I-V	0.6	Sc48	6	Sc48	NA	NA	20	Mn54,Mn56

Table 10. Estimates of maximum plausible release fractions.

Mobility Category	Fusion			Fission
	V-Li/TOK	RAF-He/TOK	V-Li/RFP	LWR, LMFBR
I	1.0	1.0	1.0	1.0
II	0.1	0.7	0.7	0.2-0.7
III	0.05	0.1-0.7	0.2	0.2-0.4
IV	5e-4	0.01-0.1	2e-3	0.05-0.1
V	5e-5	1e-4 to 1e-3	2e-4	0.003-0.05

NOTES: The time-temperature scenarios assumed in estimating the fusion release fractions are as follows:

V-Li/TOK: Lithium-air fire + decay heat produce 1300°C for 10 hours followed by 40 hours at 900°C.

RAF-He/TOK: Decay heat produces 900°C for 50 hours.

V-Li/RFP: Lithium-air fire + decay heat produce 1500°C for 10 hours followed by 40 hours at 1200°C.

V-Li and RAF-He tokamaks and the V-Li RFP are compared with corresponding estimates for fission. The fusion release fractions are based on analyses at MIT of maximum attainable temperatures in these systems, combined with data from INEL on volatilization from these alloys at those temperatures, and with no credit for the effects of active release-suppression measures or containment buildings. The fission release fractions have been compiled from Refs. 43 and 47-50.

LEVELS OF SAFETY ASSURANCE (LSA)

The fission and fusion communities have given considerable attention to the concept of inherent or passive safety. There is as yet no generally accepted technical definition of inherent safety, however, and if one were agreed upon there would be a danger of its being used, too simplistically, to divide the world of reactors into just two categories--those that possess this property and those that do not. We have found it useful to work with a more highly differentiated classification that defines four LSA, based in substantial part on the work of Piet.[51] These levels are based on differences

in the extent and nature of dependence on passive vs active design features for assurance of public safety--more specifically, for precluding any off-site early fatalities from release of radioactivity.

By passive design features we mean combinations of materials properties and configurations of structural components such that natural processes of energy removal (conduction, natural convection, radiation) suffice to limit accident sequences and the resulting radioactivity releases. Relevant materials properties include inventories of radioactivity, masses, heat capacities, strength vs temperature, melting points, vapor pressures (as functions of temperature), and susceptibility to formation of volatile oxides. By active design features, we mean pumps, valves, switches, sensors, and the like, as well as (more controversially) containment buildings.

We had two main reasons for categorizing containment buildings with active rather than passive means of assuring safety. First, containment buildings are typically complicated systems with many penetrations controlled by active means, and they can fail in many ways. Second, if one were to assert that a sufficiently stout containment building justifies the appellation of passive safety whatever the characteristics of the reactor inside, the concept of passive safety would lose most of its meaning: it would not offer any useful distinctions among degrees of "goodness" in the safety properties of the reactors themselves.

As discussed above, our quantitative threshold for avoidance of early fatalities off-site is a critical whole-body dose of 200 rem at the plant boundary, assumed to be at 1 km from the point of the release. If the "fencepost" critical dose does not exceed 200 rem, not only are no early fatalities from acute radiation syndrome to be expected among members of the public, but it can be shown as well that the total population exposure resulting from lower doses at larger distances will not exceed a few million person-rem. This figure implies an eventual number of excess cancer deaths in the range of a few hundred among the millions of people receiving a measurable dose, or considerably less than 0.1% of the cancer fatalities occurring in this population from other causes. (The dose of 200 rem to the hypothetical most-exposed individual translates to a 2 to 4% chance of dying of cancer, which is to be compared with an overall chance of 20 to 25% that a given individual in an industrial society will die of cancer from some other cause.)

The four LSA are arranged so that moving from Level 1 (the highest or most desirable level) to Level 4 (the lowest or least desirable level)

shrinks, at each step, the range of accident conditions in which materials properties and passive heat removal alone suffice to assure public safety, thus expanding the range of accident conditions that must be prevented by passive design features (Levels 2 and 3) or active ones (Level 4). More specifically:

1. In a Level 1 reactor, safety is assured by passive mechanisms of release limitation no matter what the accident sequence. The radioactive inventories and material properties in such a reactor preclude a fatal release regardless of the reactor's condition.

2. In a Level 2 reactor, safety is assured by passive mechanisms of release limitation as long as severe reconfiguration of large-scale geometry is avoided, and escalation to fatality-producing reconfigurations from less severe initiating events can plausibly be precluded by passive design features. In such a reactor, natural heat-transfer mechanisms suffice to keep temperatures below those needed--given its radioactivity inventories and material properties--to produce a fatal release unless large-scale geometry is badly distorted.

3. In a Level 3 reactor, safety is assured by passive mechanisms of release limitations as long as severe violations of small-scale geometry--such as a large break in a major coolant pipe--are avoided, and escalation to fatality-capable violations from less severe initiating events can plausibly be precluded by passive design features. In such a reactor, sufficiency of natural heat-transfer mechanisms to keep temperatures low enough--given its radioactivity inventories and materials properties--to avoid a fatal release can only be assured while the coolant boundary is substantially intact.

4. In a Level 4 reactor, there are credible initiating events that can only be prevented from escalating to fatality-capable boundary violations or reconfigurations by means of active safety systems.

Achievement of Level 1 is most readily apparent when it is based on inventory alone--that is, when one can show that the complete release of the radioactive inventory of the reactor would not produce a critical dose of 200 rem at the plant boundary. In cases where the inventory is too large to meet this condition, characterization of the reactor as Level 1 could still, in principle, be justified if persuasive information about the properties of the materials in which the radioactivity is embedded and about the quantities of energy that could be brought to bear on those materials showed conclusively that mobilization of a sufficient fraction of the inventory to produce a

critical dose of 200 rem at the plant boundary is impossible. In cases where this determination is not clear cut, however, Level 1 should not be claimed.

To warrant classification of a design as Level 2, it must be demonstrated that preservation of the large-scale geometrical aspects of the design in an accident is sufficient to ensure public safety without resort to active systems and that passive design features make failure of the large-scale geometric aspects required for safety incredible. For example, if maintenance of a pool geometry is necessary to provide cooling for radioactive components, then the integrity of that pool must be assured by passive means for all credible circumstances.

For classification as Level 3, it must be demonstrated that preservation of large-scale and small-scale geometric integrity together is sufficient to assure public safety without resort to active systems and that passive design features are sufficient to preserve the features of geometry needed to maintain this condition. For example, if failure of a piping system could drain required coolant or prevent required natural circulation and if such failure could lead to mobilization of sufficient radioactivity to cause an off-site early fatality, then failure of that system must be made incredible by passive means. Level 3 designs must tolerate, without resort to active systems, all anticipated faults such as station blackout, relief-valve failures, pump-seal failures, and so on.

For Level 4 designs, maintenance of the critical safety-related aspects of large- and/or small-scale geometry cannot be assured by passive means, or, even if assured, is not sufficient to preclude off-site early fatalities without reliance on containment or other active measures for release suppression. For such designs, active safety systems must be provided and shown to be of very high reliability if public safety is to be considered assured. This approach, which is the one employed in contemporary fission-reactor practice, requires a tremendous amount of safety analysis and testing as well as the acquisition of multiple active safety systems that are expensive in themselves. It is inherently difficult to analyze the responses of active systems to a wide range of low-probability events, and still more difficult to prove the adequacy of such analyses to the public and to licensing officials. Certainly Level 4 designs can be made sufficiently safe; but the costs of assuring their adequate safety tend to be high, and the demonstrability of adequate safety to the relevant audiences may be so difficult as to cause a further set of costs and burdens (through, e.g.,

prolonged licensing procedures, public hearings and lawsuits, and siting restrictions).

The definitions of the four LSA are presented in compact form in Table 11. Table 12 summarizes the LSA assignments arrived at by ESECOM for our reference cases. For each of the reference cases we show three values of the LSA, as follows:

1. The **optimistic concept evaluation** represents the highest safety-assurance potential of the concept in question. It is obtained by assuming favorable resolution of the uncertainties in the rudimentary safety analysis we used to make these assignments. This favorable resolution could result from better data on materials properties, from better modeling of accident conditions, from consideration of design features we did not take into account, or from a combination of these.

2. The **nominal design estimate** represents our best estimate, albeit leaning to the conservative side, under the prevailing limitations of design detail and safety-relevant data. Among other conservatisms mentioned below, we have tended to resolve any Committee disagreements about the nominal rating in favor of the more pessimistic value.

3. The **conservative concept evaluation** represents the lower-bound LSA concept. It is obtained by assuming unfavorable resolution of the main uncertainties in our analysis.

We define a concept in this connection to have the same choice of blanket materials and basic geometry as the corresponding ESECOM reference case, but allow the possibility of changes in shield materials and high-heat-flux components in considering the potential for improvement.

The procedure by which the LSA assignments in Table 12 were derived involves comparing the critical-dose threshold release fractions for various reactor components and mobility categories with the mobilization fractions that seem conceivable in the kinds of temperature transients predicted or postulated for the various designs in different classes of accidents. The dominant safety concerns in the different cases are listed in compact form in Table 12. The details of our assumptions and analyses concerning stored energy sources, patterns of release, resulting temperature transients, and mobilization of activated materials--based largely on work at MIT and INEL--can be found in our main report,[1] together with a fuller explanation of how these findings were integrated in the assignment of LSA values.

Table 11. The meaning of ESCCOM's LSA. The entries under each accident class indicate the basis of assurance that accidents in the class will not lead to an early fatality off-site.

LSA	Concise description	Accident class: Large-scale reconfiguration	Accident class: Small-scale violation of geometry (e.g., LOCA)	Accident class: Transient without violation of geometry (e.g. LOFA)
I	Inherent safety	If event occurs, material properties[a] suffice to prevent fatal release.	If event occurs, material properties suffice to to prevent fatal release.	If event occurs, material properties suffice to prevent fatal release.
II	Large-scale passive protection	Reconfiguration severe enough to lead to off-site fatality is made incredible using passive passive design features.	If event occurs, material material properties and passive mechanisms[b] suffice to prevent fatal release or escalation to next class.	If event occurs, material material properties and-passive mechanisms suffice to prevent fatal release.
III	Small-scale passive protection	Reconfiguration severe enough to lead to off-site fatality is made incredible using passive design features.	Violation severe enough to lead to off-site fatality is made incredible using passive design features.	If event occurs, material properties and passive mechanisms suffice to prevent fatal release or escalation to next class. class.

Table 11. (Continued)

LSA	Concise description	Accident class: Large-scale reconfiguration	Small-scale violation of geometry (e.g., LOCA)	Transient without violation of geometry (e.g. LOFA)
IV	Active	There are events in one or more of these categories protection that, if they occur, require active systems[c] to preclude an off-site fatality, and that cannot be made incredible by passive design measures alone.		

[a]Materials properties include inventories of radioactivity, heat capacities, melting points, vapor pressures versus temperature, and susceptibiilty to formation of volatile oxides, and are evaluated in the context of the energy sources that could be present.

[b]Passive mechanisms include natural convection, conduction, and radiation. The sufficiency of these mechanisms may depend on large-scale geometry and/or on the integrity of coolant boundaries.

[c]Active systems include pumps, valves, switches, sensors, and, in the view we have adopted here, containment buildings (some of the penetrations in which are managed by active means).

Although reactors classified at Levels I, II, or III would not need active systems to provide assurance against early fatalities off-site, they would presumably be equipped with such systems for protection of plant investment and abatement of other consequences of accidents.

Table 12. Levels of safety assurance for ESECOM reference cases.

Case	Level of safety assurance: Optimistic concept evaluation	Nominal design estimate	Conservative concept evaluation	Dominant safety concerns
1 V-Li/TOK	2	3	4	Lithium-air fire + decay heat, Mn mobilization from manifold
2 RAF-He/TOK	2	2	3	LOFA[a] and LOCA[b] with decay heat, Mn mobilization from blanket
3 RAF-PbLi/RFP	3	4	4	PbLi reaction, high decay heat, Cu from 1st wall, Po from PbLi
4 V-Li/RFP	3	4	4	Lithium-air fire plus high decay heat, Mn from shield, Cu from magnets
5 SiC-He/TOK	1	1	2	T release, water-air reaction with mobilization of W from shield
6 V-FLiBe/TOK	1	2	2	Decay heat, V-air reactions, Sc mobilization from blanket
8 V-DHe^3/TOK	1	2	2	V-air reactions, Sc mobilization from first wall, T release
9 RAF-Li/HYB	3	4	4	Lithium-air fire, LOCA/LOFA, mobilization of FP, actinides
10 SS-He/HYB	3	4	4	LOCA/LOFA, worse heat transfer than Case 9, similar releases
11 PWR-BPE	4	4	4	LOCA/LOFA, loss-of-power transient, mobilization of FP[c]

Table 12. Levels of safety assurance for ESECOM reference cases.

Case	Level of safety assurance: Optimistic concept evaluation	Nominal design estimate	Conservative concept evaluation	Dominant safety concerns
12 LSPB	4	4	4	Sodium-air fire, core transient mobilization of FP,[d] actinides
13 PRISM	3	3	4	Sodium-air fire, core transient mobilization of FP, actinides
14 MHTGR	3	3	4	Core transients, C reactions, mobilization of FP

[a]LOFA = loss-of-flow accident
[b]LOCA = loss-of-coolant accident
[c]FP = fission products

We believe we have erred rather consistently on the side of conservatism--that is, in the direction of overstating the potential releases--in our analyses and LSA assignments. The main conservatisms have been: the assumption that activated components are heated to the combustion-zone temperature in lithium fires rather than to the (lower) pool or air temperature; the neglect of heat removal by natural convection of air in thermal-transient calculations; ignoring any possibility of mitigating measures during postulated temperature transients of many hours' duration; and neglect of demobilization of activated material by condensation and plate-out within the reactor building. The actual quantities of activated material released in even the most serious fusion reactor accidents are likely to be considerably smaller than we have estimated here.

ROUTINE EMISSIONS AND EXPOSURES

As is the case with the fission fuel cycle, the normal operation of fusion power facilities will entail small emissions of radioactivity to the

environment--hence some exposure of members of the public to radiation--as well as routine exposures of workers to radioactivity and radiation at plant sites. As a basis for comparison, routine exposures from the contemporary LWR fuel cycle to members of the public in the current generation are in the range of 500 to 1500 person-rem (whole-body equivalent) per GW_e/yr: 25 to 70% from reprocessing plants (if plutonium recycle is practiced), 25 to 70% from uranium mining and milling, 7 to 20% from reactor operations, and less than 1% from other fuel-cycle operations including uranium enrichment, fuel fabrication, and radioactive-waste management.[52,53] (Population doses in person-rem are the sum of all the individual doses.) Exposures predicted to occur in future generations as a result of current operations of the nuclear-fuel cycle are in the range of 5000 person-rem per GW_e-yr, spread out over the next 20 000+ years, from emissions to 5770-year half-life carbon-14, and a dose as high as a million-person rem per GW_e-yr, spread out over the next several hundred thousand years, from leakage of radon from uranium-mill tailings if these are not managed so as to avoid this dose.[52,53]

Routine worker exposures from the LWR fuel cycle fall in the range of 1000 to 4000 person-rem per GW_e-yr: 50 to 70% at reactors, 2 to 50% at reprocessing plants, 5 to 20% in mining and milling of uranium, and less than 1% at other fuel-cycle steps (fuel fabrication and enrichment, waste management).[52,53] Early experience with high-temperature gas reactors (HTGRs) and LMFBRs suggests that the worker doses at such reactors may be much lower. The range of values for reprocessing is so large that experience with this technology has been limited and highly varied; the lowest figures are based on projections for large, modern plants that have not yet operated. Because there is even less experience with radioactive waste management at commercial scale (including the decommissioning of facilities at the end of their useful lives), the estimates cited for public and worker exposures from this activity must also be considered to be rather uncertain.

Using the usual linear hypothesis relation of one excess cancer death per 5000 to 10 000 person-rem, the 500 to 1500 person-rem public dose to the current generation translates to 0.05 to 0.3 excess death per GW_e-yr. The routine dose to the most exposed individual member of the public falls well below NRC guidelines of 5 mrem/yr each from gaseous and aqueous effluents, corresponding to less than a tenth of natural background radiation and an incremental probability of cancer death, on a strict interpretation of the linear hypothesis, on the order of 10^{-6} per year. Average individual worker

doses fall well below the NRC limit for routine occupational exposure of 5 rem/yr; the worker population dose translates under the linear hypothesis to 0.1 to 0.8 excess cancer deaths per GW_e-yr.

The significance of the doses to future generations, accumulated over huge time scales, has been questioned on the grounds that the dose rates involved are at all times tiny fractions of natural background radiation--indeed, tiny fractions of the geographic variations in the natural background--and any associated excess cancer deaths would likewise represent infinitesimal perturbations in the pattern of cancer deaths from other causes. It seems likely, nonetheless, that concern over these very long time scale, very low dose-rate exposures will lead to more stringent regulations governing carbon-14 emissions and management of uranium-mill tailings. (The quantity of tailings generated per GW_e-yr would be reduced by about a hundred-fold with the advent of breeding fuel cycles, in any event.)

Fusion-power technology, as contemplated, would have no counterpart to fission's sources of routine emissions and exposures in uranium mining and milling, nor any real counterpart to fission's reprocessing-plant emissions and exposures. The main fusion analog to reprocessing is tritium recovery, which is integral to reactor operations in current designs. Some reprocessing of particularly valuable activated structural, breeder, or neutron-multiplier material might be contemplated in future fusion systems, however. Concerning exposures associated with waste management, quantitative estimates for fusion would necessarily be even more uncertain than those for fission; to the extent that the indices of waste hazard summarized in the next section have any relevance to the potential for worker and public exposures, however, one may argue that such exposures should be smaller for fusion systems than for fission. The main focus of emissions control in fusion, then, presumably will be the power plant itself.

It is reasonable to suppose in any case that all fusion-power operations will be subject to the same standards governing routine exposures to workers and the public as apply in the fission industry. Observing these individual maxima will lead in the case of fusion--as it has with fission--to average exposures that are considerably smaller.

The key uncertainty that arises from lack of operating experience and design detail on the fusion side is what capital and operating costs will be associated with keeping occupational and public exposures from fusion reactors within whatever guidelines are in force. The best we can do at this stage of

fusion's development is to call attention to those characteristics of fusion power plants that will tend to determine those costs and to distinguish tentatively between aspects that seem amenable to inexpensive solutions and those that seem more problematical, hence potentially more expensive or at least more demanding of engineering innovation to avoid undue expense.

The most important such characteristics with respect to occupational exposures are: (a) the ease or difficulty of tritium control in a given fusion-reactor design; (b) the magnitude and spatial distribution of gamma-emitting activation products in reactor components; and (c) the nature of the distributed gamma source associated with coolant activation and coolant transport of activated corrosion products. The first and third items are also major determinants of potential emissions to the environment outside the plant, and hence of public exposures. Finally, an emission source of little significance to occupational exposures but potentially a major contributor to the long-term, global population dose is (d) carbon-14 produced by neutron reactions on nitrogen, oxygen, and carbon in structural materials, coolants, breeders, and plant atmosphere.

Tritium

Although analyzing tritium behavior and control without very detailed reactor designs is extremely difficult, we offer in Table 13 a tentative characterization of the tritium-control issue for the ESECOM reference designs. The levels of potential difficulty of tritium control presented in the table are calibrated against fission experience as follows: low corresponds to the magnitude of the tritium-control task in LMFBRs and HTGRs (where matters are simplified by the use of a primary coolant other than water); medium corresponds to the magnitude of the task in LWRs and heavy-water reactors (e.g., CANDU); and high refers to cases likely to prove more difficult than any fission experience. Much of the basis for these evaluations is the analysis of tritium-control issues provided in the Blanket Comparison and Selection Study,[13] augmented by more recent experimental results.[20,21] Other useful surveys of the literature of tritium-control in fusion reactors are found in Refs. 18 and 19.

Table 13. Tritium-Control Issues in ESECOM reference cases.

	Active tritium inventory (grams)	Dominant location of tritium	Difficulty of control	Key issues, comments
V-Li/TOK	500	coolant/ breeder	Low	High T solubility in lithium implies low mobility; higher than expected T implantation in V alloy may pose problems.
RAF-He/TOK	160	Breeder	Low to medium	T removal from primary loop may be difficult; losses into steam generator high unless T in helium is oxidized rapidly.
RAF-PbLi/RFP	60	Coolant	Medium to high	Low T solubility in PbLi means high mobility.
V-Li/RFP	500	Coolant/ breeder	Low	Same as V-Li/TOK.
SiC-He/TOK	160	Breeder	Low to medium	Similar to RAF-He/TOK.
V-FLiBe/TOK	15	Structure	Medium	Low tritium solubility in FLiBe poses problems; a chemical "fix" has been proposed.
V-MHD/TOK	Not estimated	Structure?	Medium?	FLiBe breeder has low T solubility. MHD blanket not well characterized as to T control.
V-DHe^3/TOK	60	Coolant	Low to medium	Less T handling since it need not be bred, but water as coolant gives some T difficulties.
RAF-Li/HYB	1000	Coolant/ breeder	Low	Similar to other liquid lithium systems.
SS-He/HYB	200	Structure	Low to medium	Similar to other helium-cooled systems.

Structural Activation

We have used the Remote Maintenance Rating Code[17] to compute surface contact dose rates from semi-infinite slabs with the activation-product composition of the ESECOM fusion-reactor components (first wall, blanket, manifold/reflector, shield, and in some cases magnets) at several times of interest--shutdown and 1 hour, 1 day, 1 week, 1 month, 1 year, and 30 years after shutdown. As in our accident analysis, the activation levels correspond to maximum irradiation for the respective components--that is, just before component change-out (e.g., after an irradiation of about 20 MW-yr/m^2 for first-wall and blanket components) or the assumed plant decommissioning (after 30-full-power years). The results are summarized in Table 14. These results of the semi-infinite-slab-approximation tend to overstate the actual dose rates to be expected from finite components. On the other hand, some locations in the reactor will be subject to the radiation fields from more than one component. In any case, the figures in Table 14 have the merit of having been calculated in a consistent fashion, and they can give at least a rough indication of the magnitude of the problems to which shielding, remote-maintenance equipment, and limited access will have to provide the solutions. The remote-maintenance equipment and techniques needed to cope with these problems have only begun to be developed. Success in this endeavor will be important not only in minimizing occupational exposures to radiation during maintenance, but also in keeping the costs of maintenance of fusion reactors to tolerable levels. Finally, the systems and capabilities developed for remote maintenance presumably will have considerable bearing on the ease or difficulty of decommissioning fusion reactors at the end of their useful lives--a problem whose potential for generating both costs and occupational exposures is not yet well understood for either fission or fusion systems.

Coolant Activity

Radioactive material occurs in coolants because of neutron-activation of constituents of the coolant itself and because of corrosion of activated (or

Table 14. Contact dose rates from activated components.

Case and component	Contact dose rate (mrem/hr) vs time after shutdown						
	t=0	1 hr	1 d	1 wk	1 mo	1 yr	30 yr
Case 1: V-Li/TOK							
First wall V15Cr5Ti	1.2e10	5.9e9	4.2e9	6.1e8	1.6e8	8.6e6	6.1e2
Inner blkt V15Cr5Ti	6.6e9	1.7e9	1.2e9	1.8e8	5.3e7	3.0e6	1.7e2
Manifold V15Cr5Ti	3.2e9	9.1e7	6.5e7	1.2e7	4.3e6	2.9e5	2.9e1
Manifold Fe2Cr1V	4.5e8	3.1e8	4.8e7	4.5e7	4.1e7	1.7e7	7.8e3
Shield Fe2Cr1V	6.2e7	2.3e7	2.1e6	1.9e6	1.4e6	3.2e5	3.6e3
Case 2: RAF-He/TOK							
First wall RAF	1.3e10	9.7e9	1.8e9	1.7e9	1.6e9	7.4e8	5.8e4
Inner blkt 1 RAF	2.4e9	1.8e9	3.4e8	3.1e8	2.9e8	1.4e8	3.3e4
Inner blkt 1 Li2O	3.9e9	1.5e6	4.7e5	2.6e5	2.4e5	9.2e4	2.9e2
Inner blkt 2 RAF	1.4e8	1.1e8	2.1e7	1.4e7	1.2e7	5.8e6	1.7e4
Inner blkt 2 Li2O	8.7e7	2.9e5	4.4e4	8.0e3	6.9e3	2.1e3	9.3e0
Manifold RAF	1.4e8	1.2e8	3.9e7	7.0e6	5.8e6	2.8e6	2.8e4
Shield Fe2Cr1V	3.4e7	1.3e7	1.5e6	1.4e6	1.1e6	3.2e5	1.0e3
Case 3: RAF-PbLi/RFP							
First wall Cu	1.3e11	4.7e10	1.5e10	2.7e9	2.6e9	2.3e9	5.0e7
First wall RAF	7.6e10	5.5e10	6.5e9	4.9e9	4.5e9	2.0e9	6.4e5
Inner blkt RAF	5.7e9	4.1e9	5.6e8	4.2e8	3.9e8	1.8e8	3.0e4
Inner blkt PbLi	3.4e7	2.4e7	1.8e7	9.7e6	6.9e6	5.0e6	8.6e5
shield Fe2Cr1V	4.3e8	2.0e8	1.6e7	1.4e7	1.0e7	1.4e6	6.2e2
Case 4: V-Li/RFP							
First wall V15Cr5Ti	8.2e10	4.3e10	3.0e10	4.4e9	1.1e9	5.7e7	1.8e3
Inner blkt V15Cr5Ti	4.4e10	1.4e10	9.9e9	1.5e9	4.0e8	2.2e7	4.0e2
Shield V15Cr5Ti	1.8e10	6.0e8	4.3e8	7.3e7	2.5e7	1.7e6	3.1e1
Shield Fe2Cr1V	2.6e9	1.8e9	1.9e8	1.7e8	1.5e8	6.1e7	7.4e3
Magnet Cu	6.7e8	5.7e8	1.6e8	1.5e6	1.4e6	1.1e6	2.7e4
Magnet PCA	5.6e8	4.4e8	6.0e7	5.4e7	5.1e7	4.0e7	8.7e5
Case 5: SiC-He/TOK							
First wall SiC	5.2e10	1.4e7	2.7e6	5.0e4	4.4e4	2.5e4	3.5e2
Inner blkt SiC	9.5e9	1.2e6	8.4e4	1.6e4	1.5e4	1.1e4	2.0e2
Inner blkt Li2O	4.1e9	1.4e6	4.8e5	2.8e5	2.5e5	9.8e4	3.1e2
Manifold all matls	1.2e8	2.1e4	1.0e4	1.0e4	9.9e3	8.7e3	1.9e2
Shield all matls	1.2e7	8.6e6	4.3e6	6.6e4	3.2e3	4.8e2	2.4e0
Case 6: V-FLiBe TOK							
First wall V15Cr5Ti	2.2e10	8.5e9	6.0e9	8.7e8	2.2e8	1.2e7	7.7e2
Inner blkt V15Cr5Ti	2.2e9	3.5e8	2.5e8	3.7e7	1.0e7	6.0e5	2.5e1
Inner blkt FLiBe	3.8e9	1.5e5	5.1e4	4.8e4	4.3e4	1.5e4	1.0e2
Shield PE16	1.4e5	1.1e5	7.0e4	6.5e4	5.8e4	2.7e4	5.5e2

Table 14. (Continued)

Case and component	Contact dose rate (mrem/hr) vs time after shutdown						
	t=0	1 hr	1 d	1 wk	1 mo	1 yr	30 yr
Case 8: V-DHe^3/TOK							
First wall V15Cr5Ti	5.0e8	1.1e8	7.7e7	1.1e7	2.9e6	1.6e5	1.6e1
Inner blkt V15Cr5Ti	2.4e7	1.1e7	7.7e6	1.1e6	3.2e5	1.8e4	1.6e0
Shield Fe2Cr1V	1.1e5	8.3e4	2.1e4	2.0e4	1.9e4	8.8e3	7.5e-1

activatable) material from the coolant-system walls. (In the case of fusion-fission hybrid systems, migration of fission products and actinides from the fuel into the coolant is an additional source of coolant activity.) This radioactive material, entrained in the coolant or deposited subsequently on the walls of pipes and in pumps and valves, poses threats to workers mainly during routine maintenance of coolant systems and during cleanup of coolant spills. Migration of coolant-borne activation products to other parts of the plant following spills may also lead to emissions to the environment outside the plant and hence to public exposures.

Problems of coolant-borne activity have been less thoroughly studied in the fusion community than either tritium problems or activation embedded in structure, and the data base from which to form judgments about the relative hazards of coolant activity in different fusion-reactor designs is rather scanty. The characterization provided in Table 15 is based mainly on reviews in Refs. 11, 13, 16, and 54-57. Here again, the indicated levels of potential difficulty are calibrated against fission experience: low corresponds to the level of precautions and countermeasures necessary in the fission system that is least troublesome from the standpoint of coolant activation, namely the HTGR; medium corresponds approximately to the greater level of effort required to cope with coolant activity in LWRs and LMFBRs; and high corresponds to a level of difficulty and complexity greater than that encountered in fission systems.

Carbon-14

The main carbon-14 production reactions of concern in fusion reactors appear to be $^{14}N(n,p)^{14}C$ on nitrogen in the plant atmosphere or present as

Table 15. Occupational exposure problems from coolant activity.

Coolant/ structure	Relevant ESECOM cases	Inventory (Ci)[a]	Fraction deposited on walls	Contact dose rate (rem/hr)[b]	Overall magnitude of problem
Li/steel	9	7e5	?	----/ 6,000	Medium to high
/V	1,4	7e5	?	?	Medium?
He/steel	2,10	3e4	99.9%	<0.1/------	Low
/SiC	5	?	99+%?	?	Low
H2O/steel	none	2e5	99.9%	>0.1/300	Medium
/V	8	?	99+%?	?	Medium?
/Cu	3	?	99+%?	?	Medium to high
PbLi/steel	3	6e8	?	100/90,000	High
FLiBe/V	6,7	7e7[c]	?	0.1/ 2,000	Low to medium

[a]Inventory values from calculations performed for the BCSS (Ref. 13) assuming wall loading of 5 MW/m^2 for 2 years.

[b]First estimate based on modeling of system; second estimate is BCSS index assuming an infinite slab of material continually exposed at the first wall.

[c]The FLiBe inventory decays within a day to 6e5 Ci, owing to the 110-minute half-life of the initially dominant F-18.

impurities in reactor materials, $^{17}O(n,alpha)^{14}C$ on the trace isotope oxygen-17 in oxygen, $^{13}C(n,gamma)^{14}C$ on the carbon-13 isotope in carbon, and a two-step chain in which this last reaction occurs on carbon-13 produced from the dominant isotope in oxygen by $^{16}O(n,alpha)^{13}C$. The long-term population dose commitment from carbon-14 is probably in the range of 500 person-rem per curie released,[18] extended over a few times the 6000-year half-life of this isotope. The activation calculations performed by ESECOM indicate production of carbon-14 in blanket and shield materials at rates of up to hundreds of curies per year. Most of this carbon-14 presumably remains immobilized in the structural materials in which it was formed, where because of its weak beta

emission its contribution to short-term radiological hazards compared to other activation products is very small. The question of the mobility of carbon-14 formed in different materials needs more attention, however. The large quantities of carbon-14 formed in Li_2O solid breeder material from n-alpha reactions on the oxygen may be of particular concern. This production is much larger than from the H_2O in water-cooled fusion reactors, apparently because of the effectiveness of lithium in slowing down fast neutrons through the reaction

$$^{7}Li + n\ (fast) \rightarrow T + {}^{4}He + n\ (slow) \quad . \qquad (2)$$

It is possible that special systems for capturing carbon-14 will be required in fusion reactors that use lithium-oxide or lithium-aluminate breeders.

Based on the foregoing considerations and on the more detailed treatments in our main report,[1] we provide in Table 16 a summary of the relative difficulties that may be expected in connection with managing the four main aspects of routine emissions and exposures in ESECOM's reference fusion reactors. We reemphasize that high degrees of difficulty may or may not translate into significant extra costs. The application of engineering ingenuity to difficult tasks may lead in some cases to inexpensive solutions. A relevant reference point is the cost of controlling routine emissions in fission power plants: Such controls in current LWRs account for at most a few percent of both capital costs and operating costs, and these costs in newer fission systems are expected to be comparable or lower.

RADIOACTIVE WASTES

The size of the radioactive-waste-management task was characterized quantitatively using the concept of intruder dose developed by the U.S. NRC in connection with its "10CFR61" criteria for shallow burial of fission-reactor wastes.[58] The intruder dose is the highest dose that could be received, between 100 years and 1000 years after shallow burial of the wastes, by (a) a worker excavating the site and constructing a dwelling there or (b) a farmer cultivating the site and eating the food grown there. Qualification for shallow burial requires--under specified assumptions about site design and waste form and packaging--that the calculated intruder dose not exceed 0.5 rem/yr.

Table 16. Relative difficulty of managing routine emissions and exposures for the ESECOM reference cases: A summary.

Case	Tritium (workers, public)	Structural activation (workers)	Coolant activity (workers, public)	Carbon-14 (public)
V-Li/TOK	Low	High	Medium?	Medium?
RAF-He/TOK	Low to medium	High	Low	High
RAF-PbLi/RFP	Medium to high	Very high	High	Medium
V-Li/RFP	Low	High	Medium?	Medium?
SiC-He/TOK	Low to medium	Low to medium	Low	High
V-FLiBe/TOK	Medium	Medium	Low to medium	Low
V-MHD/TOK	Medium?	NE[a]	NE	Medium?
V-DHe^3/TOK	Low to medium	Medium	Low?	Low?
RAF-Li/HYN	Low	High?	High?	NE

[a]NE = not evaluated.

ESECOM used computer codes developed by Fetter[17] for applying the 10CFR61 methodology (with correction of several errors in the original NRC work) to fusion as well as fission wastes. The results permitted us to characterize the wastes with four different indices: the life-cycle volume of the radioactive wastes from each 1200-MW_e, 30-year lifetime power plant; the intruder dose averaged for these wastes; the Annualized Intruder Hazard Potential (the sum of the products of intruder dose times annual waste volume for each reactor component), and the Deep Disposal Index (for the life-cycle wastes, the sum of the products of the volumes of components with intruder doses exceeding 0.5 rem times the ratios by which this threshold is exceeded).

In using the shallow-burial scenario and the intruder-dose concept as the basis for its scheme for characterizing radioactive-waste burdens, ESECOM does not intend to suggest that shallow burial is necessarily the best strategy for managing fusion wastes, or that fusion systems whose wastes do not meet the

present shallow-burial criteria are hopelessly handicapped. We simply believe that this calculational approach provides a consistent and illuminating way to rank the size of the radioactive-waste-management task for different systems.

The results of using this approach for some of our fusion and fission cases are shown in Table 17. The RAF cases reflect the benefit of using a

Table 17. Radioactive waste indices for ESECOM fusion reference cases.

	Life-cycle waste volume (m^3)	Intruder dose (rem)	Annualized intruder hazard potential ($R\text{-}m^3/yr$)	Deep disposal index (m^3)	Dominant isotopes
Case 1: V-Li/TOK					
First wall VCrTi	34	0.60	0.69	41	Nb94,Al26
Inner blkt VCrTi	96	0.47	1.5	0	Nb94,Al26
Manifold VCrTi	140	0.31	1.5	0	Nb94,Tc99
Manifold Fe2Cr1V	1100	0.20	7.6	0	Tc99,Nb94
Shield Fe2Cr1V	220	0.079	0.57	0	Tc99,C14
Total (average)	1590	(0.22)	12	41	
Case 2: RAF-He/TOK					
First wall RAF	25	0.66	0.55	33	Ag108m,Nb94
Inner blkt 1 RAF	130	0.26	1.2	0	Ag108m,Nb94
Inner blkt 1 Li_2O	1400	0.011	0.48	0	Ar39,C14
Inner blkt 2 RAF	140	0.066	0.31	0	Ag108m,Nb94
Inner blkt 2 Li_2O	310	5.6e-4	5.8e-3	0	C14,Ar39
Manifold RAF	190	0.054	0.33	0	Ag108m,Nb94
Shield Fe2Cr1V	220	0.044	0.33	0	Tc99,C14
Total (average)	2415	(0.039)	3.2	33	
Case 3: RAF-PbLi/RFP					
First wall Cu	17	9.0	5.3	306	Ag108m,Fe60
First wall RAF	7	0.8	0.18	11.2	Ag108m,Nb94
Inner blkt RAF	350	0.16	1.8	0	Ag108m,Nb94
Inner blkt PbLi	86	190	540	30,000	Bi208,Ag108m
shield Fe2Cr1V	20	0.039	0.026	0	Tc99,C14
Total (average)	480	(34)	550	33,000	
Case 4: V-Li/RFP					
First wall VCrTi	10	0.57	0.20	12	Nb94,Al26
Inner blkt VCrTi	72	0.45	1.1	0	Nb94,Al26
Shield VCrTi	180	0.29	1.7	0	Nb94,Tc99
Shield Fe2Cr1V	2100	0.19	14	0	Tc99,Mo93
magnet Cu	50	5.3	8.9	530	Ag108m
magnet PCA	7.2	56	13	806	Nb94,Tc99
Total (average)	2419	(0.48)	39	1300	

Table 17. (Continued)

	Life-cycle waste volume (m^3)	Intruder dose (rem)	Annualized intruder hazard potential ($R\text{-}m^3/yr$)	Deep disposal index (m^3)	Dominant isotopes
Case 5: SiC-He/TOK					
First wall SiC	34	0.018	0.021	0	Al26
Inner blkt SiC	290	3.9e-4	3.8e-3	0	Al26,C14
Inner blkt Li_2O	1200	0.011	0.42	0	Ar39,C14
Manifold all matl	620	1.1e-4	2.3e-3	0	C14,Be10
Shield all matl	970	2.5e-3	0.08	0	Al26
Total (average)	3114	(0.0053)	0.53	0	
Case 6: V-FLiBe/TOK					
First wall VCrTi	4.2	1.1	0.15	9.2	Nb94,Al26
Inner blkt VCrTi	97	0.2	0.64	0	Nb94,Al26
Inner blkt FLiBe	460	2.4e-3	0.037	0	C14,Tc99
Shield PE16	75	0.036	0.091	0	Nb94,Tc99
Total (average)	636	0.044	0.92	9.2	
Case 8: D-He^3/TOK					
First wall VCrTi	23	0.083	0.064	0	Nb94,Al26
Inner blkt VCrTi	24	5.7e-3	4.6e-3	0	Nb94,Al26
Shield Fe2Cr1V	920	8.3e-5	2.5e-3	0	Tc99,Nb94
Shield Pb and B_4C	264	6.3e-8	5.5e-7	0	Pb205,Bi208
Total (average)	1231	(2.4e-4)	0.071	0	
LSPB (fission)[a]					
fiss prod, actinides	120	34,000	140,000	8,200,000	Am241,Cs135
cladding, channels	120	11	44	2600	Nb94,Tc99
reactor vessel, etc	200	NC	NC	NC	

NC = not calculated

[a]Fission products and actinides are measured as reprocessed wastes, less cannisters, occupying 4 m^3 per 1200-MW_e reactor-yr. Volume of the radionuclides, without the chemical matrix they are embedded in during reprocessing is 10 times smaller. Reactor vessel and related components add about 200 m^3 of activated waste (40 - 50 000 Ci/m^3) at the time of decommissioning; we did not compute the intruder dose and related indices. The average activation will be less than that of the cladding and fuel-channel material removed from the core each year; the indices may be smaller than those listed in the cladding-channel category.

modification of the usual HT-9 ferritic steel in which tungsten has been substituted for molybdenum; this substitution eliminates the major source of the niobium-94, molybdenum-93, and technetium-99 activation products that otherwise would dominate the waste hazard from HT-9. Based on the two indices that we consider most illuminating--the Annualized Intruder Hazard Potential and the Deep Disposal Index--Table 17 shows that the worst fusion cases are superior to fission by more than two orders of magnitude and the better fusion cases enjoy even larger margins. In all but one of the fusion designs, the intruder dose averaged for all the life-cycle wastes falls below the 0.5 rem/yr threshold, meaning that this mixture would qualify for shallow burial under the current regulatory philosophy.

If, as many experts argue, the management of fission-power wastes proves to entail only modest contributions to fuel-cycle radiation exposures (on the order of the estimates cited in the preceding section) and to the monetary cost of electricity (on the order of the 1 mil per kW-hr we have assumed here), then it should be safe to conclude from the indices presented in Table 17 that waste management will also have only very modest effects on the overall environmental and economic costs of electricity from fusion. In other words, our assumption for the ESECOM economic calculations that fusion waste management will cost the same mil per kW-hr as fission waste management, should be conservative. If, on the other hand, the management of fission wastes should turn out to pose much more serious problems than the foregoing estimates suggest--as some critics of fission energy continue to assert may be the case--the margins between fusion and fission indicated in Table 17 are large enough to make plausible that fusion might escape these difficulties.

Concerning fusion hybrid breeders and the associated fuel cycles, we did not perform separate calculations of waste burdens. To first order, one would suspect from the dominance of fission-energy generation in a system of fission reactors supplied with fissile fuel by a hybrid breeder, and from the comparison of fusion and fission waste characteristics in Table 17, that the wastes from such a system would be dominated by those from the fission clients. Some closer attention may be warranted, however, to possible differences in the quantities of actinides associated with the wastes from a hybrid-fueled fission energy system.

UNWANTED LINKS TO NUCLEAR WEAPONRY

Just as countries that openly operate nuclear-weapons programs can use weapons-dedicated or dual-purpose (energy-weapons) fission facilities to produce the needed nuclear-weapons materials, it would also be possible to design fusion reactors to maximize tritium production for use in natural weapons programs and to design fusion-fission hybrid reactors to produce large quantities of weapons-grade plutonium for such purposes.[9,59] We do not consider these purely weapons-dedicted forms of fusion technology further here. We focus instead on ways in which pursuit of fusion technologies for energy-generation purposes may contribute to providing nuclear weapons capabilities to countries or groups that have not been able or willing to acquire such capabilities by other means; and we compare this problem with the corresponding one for fission energy technologies.

The main concern about facilitating nuclear weapons proliferation by fission energy technologies has been that these technologies would spread access to fissile materials--most importantly plutonium and highly enriched uranium. Lack of access to these materials has long been considered the principal technical barrier to the acquisition of fission weapons.[52,53,60,61] The potential vulnerability of a fission fuel cycle therefore can be characterized most compactly in terms of quantitatives of fissile material present at the point(s) in the fuel cycle where the physical, chemical, and isotopic barriers to its removal and use in nuclear weapons are lowest. A yardstick against which to measure the quantities of fissile material involved is the critical mass required to fashion a nuclear explosive. This information is provided in Table 18 for representative fission fuel cycles and for the RAF-Li/HYB fusion-fission hybrid breeder (Case 9) considered by ESECOM. Fission fuel-cycle flows are from the American Physical Society fuel-cycle study published by 1978 (Ref. 53) and from information provided to ESECOM for denatured high-temperature gas (HTG) fuel; critical masses are from the same study and from Willrich and Taylor.[61]

The rankings of "Relative Weapons Potential" shown in Table 18 are based on the nature of the barriers to diversion for weapons use at the indicated point(s) of greatest vulnerability, most importantly the need for isotopic enrichment, the need for chemical separation of plutonium from uranium or U-233 from thorium, the presence or absence of fission products, and the sophistication required in weapon design and fabrication using the indicated

Table 18. Fissile materials in fission and fusion-hybrid fuel cycles.

Fuel cycle	Point(s) of greatest vulnerability	Quantity of fissile material and dilutant(s) (per reactor-yr)	Relevant critical mass	Main remaining technical barrier to use in nuclear explosives	Relative weapons potential
PWR (once-through)	spent-fuel storage	250 kg Pu (69% fissile) in 26,000+ kg U + fission prod	5-10 kg fissile Pu	chemical separation from U & fission products	Low/medium
PWR (self generated Pu recycle)	reprocessing plant output	440 kg Pu (61% fissile), possibly mixed with U	5-10 kg fissile Pu	chemical separatopm from U if present	Medium/high
HIGR (U235/Th232/U233 fuel cycle)	enrichment plant output	350 kg 93.5% enriched U235	15-20 kg U235	no significant barrier	Very high
	reprocessing plant output	190 kg U233, 50 kg U235	5-10 kg U233	no significant barrier	Very high
LMFBR (natural U feed)	reprocessing plant output	2350 kg Pu (80% fissile), possibly mixed with U	5-10 kg fissile PU	chemical separation from U if present	High
RAF-Li/HYB (LWR clients)	reprocessing plant output with Th	3300 kg U233, probably mixed	5-10 kg U233	chemical separation from Th if present	High

NOTE: Critical masses are for metals and vary with isotopic composition and reflector. Critical masses of oxides are significantly but not prohibitively higher. "Coprocessing" so that fissile output from reprocessing is mixed with nonfissile uranium or thorium isotopes (meaning subsequent isotopic separation would be necessary in order to use material for weapons) is generally possible but not convenient. Hybrid breeder serves some 13 1-GW_e client LWRs, so fissile flow per system GW_e is much smaller than shown. LMFBR would serve 1 to 2 client LWRs (most plutonium produced is recycled to the LMFBR itself).

material. With respect to sophistication in weapon design and fabrication, we have assumed the following ranking of materials from easiest to most difficult[53,61,62]: U-235, U-233, plutonium with fissile content about 75%, plutonium with fissile content below 75%. The "Relative Weapons Potential" rankings in Table 18 do not take into account physical security barriers (guards, monitoring systems, possible collocation of facilities to minimize

transport of fissile materials, and so on) as opposed to the technical ones built into the choice of fuel cycle.

The annual flow of plutonium from a hybrid breeder operating on the Pu-239/U-238 fuel cycle would be similar to the U-233 figure shown for ESECOM's RAF-Li/HYB case in Table 18. The fissile content of hybrid plutonium would be in the vicinity of 90%--even higher than that for LMFBRs--and hence particularly well suited for use in nuclear explosives.[22] On the other hand, hybrid plutonium would contain more Pu-236 than that from LWRs or LMFBRs, leading to penetrating gamma emissions from the U-232 decay chain and tending to decrease the attractiveness of the material for bomb makers.

If the U-233/Th-232 fuel cycle had large antidiversion advantages over the Pu-239/U-238 alternative, this would constitute an important additional benefit derived from the ability of hybrid breeders to make the U-233/Th-232 cycle economically more attractive than with pure-fission breeders as the source of the U-233. A number of reviews have concluded,[53,59,62-64] however, that the antidiversion advantages sometimes claimed for the U-233/Th-232 fuel cycle--based mainly on radiological hazards to bomb makers and on the possibility of denaturing the U-233 to be used client reactors with U-238--are the modest usefulness at best, tend to be offset by corresponding disadvantages, and come at substantial cost in money and convenience.

Fusion-energy systems other than fusion-fission hybrid breeders would not ordinarily produce or contain fissile materials, so the weapons-linkage concern that is most acute for fission energy systems--that the technology would provide access to this limiting ingredient for producing fission weapons--would be far less acute for such fusion systems. The only remnant of this particular concern in pure-fusion reactors would be that fertile material not ordinarily present could be introduced into the reactor and exposed there to fusion neutrons to breed fissile isotopes--either openly or clandestinely.

If a government or major industrial concern in possession of a fusion reactor were to decide to undertake such a step openly, they certainly would be able to produce significant quantities of high-quality fissile material in a rather short time. In the Brookhaven study of proliferation and safeguards issues in future technologies,[22] it was estimated that insertion of uranium-carbide breeder modules at the first wall in the Starfire fusion reactor would yield about 14 kg of fissile plutonium per square meter per year, and that dissolving uranium in the reactor coolant could yield 160 kg of fissile plutonium per year. On the other hand, it would be extremely difficult if not

impossible for a government or industrial concern to achieve significant fissile material production clandestinely in an ostensibly pure-fusion reactor subject to frequent international monitoring of the sort that can be readily envisioned based on fission practice. The modifications to the fusion reactor and its operating procedures needed to make and extract fissile material would be easy to detect, especially given that one is looking for fertile or fissile material in an environment where none is expected (in contrast to looking for small discrepancies in large inventories, as is the case in monitoring fission or fusion-fission fuel cycles). Similarly, the necessary modifications would be too extensive and too obvious to escape detection by the operators of the plant if an attempt at clandestine fissile-materials production were being made by a subgroup of insiders; and because of the need for prolonged access as well as easily observed modifications of systems and procedures, outsiders would have no chance at all.

The next question that arises is whether the diversion of tritium from fusion reactors for use in thermonuclear weapons poses problems analogous to those of diversion of fissile material from fission reactors for use in fission weapons. It is true that tritium is used in a number of modern thermonuclear warhead designs[65]; that the inventories and throughputs of tritium in large D-T fusion rectors (typically kilograms in inventory and hundreds of grams per day in throughput) are more than large enough to be significant in the weapons context [the total tritium inventory in the U.S. weapons stockpile has been estimated to be about 70 kg (Ref. 66)]; and that fusion reactors could be rather readily modified to maximize net tritium output for weapons purposes. For these reasons, commercial fusion reactors presumably will be subject to materials accounting procedures and other safeguards designed to minimize the chance that reactor tritium will be misused for weapons. There are, nonetheless, some strong arguments for regarding the tritium safeguards issue as fundamentally less problematical for fusion than the fissile-material issue is for fission. Most importantly, tritium acquisition is not the limiting ingredient on thermonuclear-weapon construction in the way that fissile materials are the limiting ingredient on fission-weapon construction. Both the needed fission-bomb trigger and the technical insights required for design and fabrication of thermonuclear weapons are more important barriers than access to fusion fuels, and while access to tritium is convenient in thermonuclear-weapon construction, it is not necessary.

The spread of highly weapons-specific types of knowledge--as distinct from the spread of particular facilities and materials usable for weaponry--has not been given much weight in recent years as a liability of fission energy systems, in large part because the knowledge needed to build fission weapons (and most certainly those parts of this knowledge that are derivable from nuclear-power technology) is already so widespread. In the case of thermonuclear weaponry, by contrast, the much greater scientific and technological sophistication required is not so widespread, and the question logically arises whether the spread of fusion-energy technology would spread important insights relevant to thermonuclear weapons.

The major powers declassified their research programs on magnetic-confinement approaches to fusion energy in 1958, and they have maintained their field as an area of declassified and indeed highly internationalized research ever since. This strongly suggests that the important insights about thermonuclear weaponry have nothing in common with MFE. As is well known, however, there are connections between research in inertial-confinement fusion and insights relevant to the design and effects of thermonuclear weapons,[22,67] and these connections have been the basis for classification of many aspects of research on inertial confinement since the inception of such work. Because inertial-confinement fusion is not within the province of ESECOM and classification barriers would prevent a full discussion in any case, the weapons linkages of inertial-confinement fusion are not considered further here.

It needs to be emphasized, finally, that judgments about the weight to be given to unwanted weapons linkages in comparing fission and fusion energy options are very difficult because much of the weapons risk is dependent on institutional and political rather than technical factors. Little can be said now about the nature of these nontechnical elements 30 or 40 years in the future when large-scale use of fusion may have become a real possibility--the institutional and political incentives and restraints relating to acquiring nuclear weapons could be very different in the future--and without such information any estimates of the absolute impact of the weapons-linkage issue on either the fission or the fusion side must be highly speculative.

OTHER FUEL-CYCLE IMPACTS

In assessing the overall environmental and safety implications of any energy source, attention must be given to all associated activities, not only the operation of the power plant itself and the management of power-plant wastes. 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 (and, in the fission case, reprocessing-plant operations) and aside from weapons linkage, the biggest energy-associated risks to health and safety tend to be those of more-or-less routine accidents in fuel and materials acquisition, processing, manufacturing, and transport. For the most part, these hazards fall more heavily on workers than on the public. Of the public risks in these categories, the largest usually arise from transporting fuels and materials. Because the occupational hazards are also largely dependent on the quantity of fuel and nonfuel materials being handled, a crude but useful index for comparing other fuel-cycle impacts, both occupational and public, is the total mass associated with constructing and operating the various fuel cycles.

Estimates of these masses for fusion- and nonfusion-energy cycles are summarized in Table 19, with very rough figures for worker deaths in materials-related accidents, public deaths resulting from the transport of materials, and emissions of particulate matter in materials-related activities (as an index of air-pollution impact). These figures were adapted from a number of recent reviews[2,18,68-70]; a particularly detailed discussion of the conceptual and methodological issues arising in such calculations is found in Ref. 66.

Materials-related hazards in the indicated magnitudes have not excited much public or regulatory interest in the past and probably will not do so in the future. The main exceptions are the relatively high worker risks that come from coal mining (and, to a lesser extent, uranium mining) and the rather high public risk that comes from coal transport. Even this last problem, which objectively speaking is a rather serious impact of coal use, seems to be perceived more as a hazard of society's transport and transportation systems than of its energy system.

In any case, the materials-related hazards of fusion appear to be in the same range as those of fission and the most widely used renewable electricity sources of the present time, hydropower and wind, and well below those of

Table 19. Materials requirements and impacts in energy cycles.

Energy cycle	Thousands of tons of materials per GW_e-yr			Accidental deaths from materials activities,[a] per GW_e-yr		Particulate emissions from materials activities[a] tons/GW_e-yr
	Total metals	Concrete	Fuel (as ore)	Workers	Public	
Coal	1-2		5-7	3,500[b]	1-3	0.5-3 50-400
Fission	1-2	8-13	200[c]	0.3-1.3	0.03-0.06	80-800
Hydropower	1-2	13-70	--	0.15-0.3	0.03-0.2	130-2500
Wind	5-15	6-50	--	0.1-0.4	0.03-0.3	70-4500
Fusion	2-4	10-20	3.5[d]	0.3-0.7	0.03-0.1	100-2500

[a]Materials activities include mining, processing, manufacturing, and transport.

[b]Figure is for bituminous coal; range for lower-rank coals extends to about 2 times higher.

[c]Figure is for sandstone ore at 1000 ppm U_3O_8 feeding an LWR on a once-through fuel cycle. Plutonium and uranium recycle could reduce figure by 25 to 30%. Use of fast breeder reactors could reduce it fifty- to one-hundred-fold.

[d]Ore requirement is mainly seawater, plus 35 tons lithium-bearing brine.

coal. As a yardstick for assessing the meaning of 0.1 public death per GW-yr (the upper-limit public risk from transport of fusion materials), it is of interest that this figure amounts to about 0.001% of the risk from all causes--and 0.02% of the risk from all accidents--in a representative population of 1 million U.S. citizens whose annual electricity consumption amounts to about 1 GW-yr.

With this perspective, it is clear that the modest differences among different fusion systems in the hazards related to bulk materials requirements are not important. Occupational hazards of particularly toxic materials, such as beryllium, might be another matter; but they seem unlikely to be as difficult to handle as the radiological occupational hazards considered above, and we did not examine them. For further discussion of chemical hazards in

fusion reactors as well as of exposures to electric and magnetic fields (which also seem not to pose very difficult problems) see Ref. 18.

SYNTHESIS

In this section we treat the interaction of safety, environmental, and economic characteristics, and we discuss some of the uncertainties and omissions that bear on the interpretation of our results. We defer until the final section, "Findings in Brief," our comments on the implications of this study for directions in research and development on MFE.

INTEGRATION SAFETY, ENVIRONMENT, AND ECONOMICS

A premise of this study has been that environmental and safety characteristics of fusion reactors may significantly affect the cost of electricity from this energy source, and that early attention to the specific ways in which safety and environment could influence fusion's economics may be useful in steering the development of fusion technology in directions that enhance positive influences (reduce costs) and minimize negative ones.

The most obvious economic ramifications of environmental and safety issues in nuclear energy technologies would seem to be the construction and operating costs associated with specific safety-related or environmental-control subsystems--that is, subsystems whose functions are to prevent accidents, or to abate their consequences, or to prevent or reduce routine exposures of workers and the public to radioactivity and radiation. But tabulating the construction and operating costs of safety and environmental-control subsystems is difficult because of the complexity and degree of integration typical of power plants of any kind. Many components and subsystems have multiple functions, so that it is not always clear what should be classified as a safety or environmental-control subsystem and what should not. Most of the components in the plant are related to safety and environment in the looser sense that failure or improper functioning of the components could have safety or environmental consequences, which means in turn that safety and environmental factors must be taken into account in the design of the components and may well affect the costs of their construction and operation. And it is in the nature of a complex, integrated system that

the presence and characteristics of safety and environmental-control subsystems invariably will influence costs of other parts of the plant.

The problem of sorting out the economics of safety and environment is further compounded by the multiplicity of approaches to assuring safety and low routine exposures, some integrated into the design at the most basic level (e.g., passive safety based on materials compositions and certain large-scale geometric arrangements) and others added on as discrete subsystems (e.g., containment sprays and filtering systems). Added on approaches to safety and environmental control are by their nature associated with identifiable costs; designed in approaches may also add to costs in comparison to systems of comparable performance without the designed-in safety/environmental features, but this is not necessarily so, and in any case there may be offsetting gains in the form of reduced requirements for added-on systems.

There are, finally, some indirect but sometimes very large impacts of safety and environmental characteristics on economics that exert themselves through the processes of siting, licensing, and regulation. That is, as fission experience has demonstrated, if the safety and environmental characteristics of a plant or class of plants allow significant public uncertainty about their acceptability, the result can be difficulties and delays in siting and licensing, redesigns and retrofits during construction, and safety/environment-related shutdowns once commercial operation has commenced--all of which can be staggeringly expensive. These problems can arise even if a plant is, objectively, extremely safe; difficulty in demonstrating its safety can be enough to cause the problems.

The combination of difficulties just described has made it difficult to analyze what share of power-generating costs should be attributed to safety and environment, even the case of fission. Obviously, making such an estimate for fusion power technology at the present state of its development would be even less feasible. Charged, nonetheless, with the task of somehow illuminating this issue, ESECOM has used a mixture of quantitative and qualitative approaches to provide some partial insights.

On the quantitative side, we have assumed that high LSA, as described above, could be the basis for reduced requirements for nuclear grade materials and components compared to the requirements imposed in fission power-plant construction today. Much more than any extra quality or reliability actually built into such "N-stamped" materials and components, it is the layers of documentation and certification required to establish the pedigree of these

items and to accompany their installation in the power plant that account for the large cost increases associated with them (for example, a factor of 6 in cost for something as simple as piping). The conceptual basis for the N-stamp requirements in fission plants is the need for a wide range of components to function reliably under accident conditions if unacceptable public radiation exposures are to be prevented. Thus we believe that in fusion (or fission) reactor designs providing the same assurance more simply--for example, by virtue of fundamental materials properties and passive heat-transfer mechanisms in configurations that can be maintained without active safety systems--the layers of assurance provided by N-stamp certification of many plant components would not be required.

To apply this idea to the ESECOM fusion-reactor reference cases, we made use of a set of cost-reduction factors developed by J. Perkins in the course of the Minimars study[71] to estimate the potential cost savings associated with use of nonnuclear-grade materials and components. These cost-reduction factors are broken down into the standard cost accounts used in ESECOM's Generomak/NECDB economic model. They are shown in Table 20. The result of applying them account by account to a given fusion reference design represents a hypothetical minimum plant capital cost that would apply if no nuclear-grade materials and components were required in constructing that plant. The difference between this figure and the unadjusted capital cost (see Table 4) of a reactor is its hypothetical maximum safety assurance credit in our scheme.

This maximum credit amounts to about 30% of the unadjusted capital cost for the point-of-departure tokamak; since different designs have different distributions of their unadjusted costs among cost accounts, however, this percentage reduction varies slightly from case to case. As a check on our results, we repeated some of our calculations using a set of safety-assurance cost-reduction factors derived independently in a recent inertial-confinement fusion-reactor study.[72] Although the factors differed in detail, the overall cost reductions calculated were very similar.

It may be argued that, inasmuch as no fusion system is likely to be able to avoid nuclear-grade requirements entirely, such a figure tends to overstate the savings available even to systems with LSA = 1. On the other hand, potential savings from reduced licensing and construction times, from higher capacity factors attributable to fewer safety-related shutdowns, and, perhaps, from increased flexibility in siting--none of which savings we attempted to

Table 20. Cost-reduction factors for complete avoidance of N-stamp requirements. Figures multiply unadjusted costs to give costs if no nuclear-grade requirements applied. Entries denoted DDC are design-dependent composites of other categories.

Account number	and description	Multiplier
20	Land and land rights	1.0
21	Structures and site facilities	DDC
211	Site improvements and facilities	0.68
212	Reactor building	0.68
213	Turbine building	0.68
214	Reactor maintenance building	0.68
215	Tritium building	0.68
216	Electrical equipment building	0.68
217	Other buildings and structures	0.68
22	Reactor plant equipment	DDC
221	Reactor system	DDC
221.1	Vacuum vessel/first wall	0.5
221.2	Blankets	0.5
221.3	Nuclear shields	0.5
221.4	Structure	0.67
222	Magnet system	0.69
223	Auxiliary plasma heating	1.0
224	Vacuum-vessel pumping system	1.0
225	Magnet power conditioning	1.0
226	Heat transport	0.4
227	Plasma fuel handling	1.0
228	Instrumentation and control	1.0
229	Reactor maintenance equipment	1.0

Table 20. (Continued)

Account number and description		Multiplier
23	Turbine plant equipment	1.0
24	Electric plant equipment	0.57
25	Miscellaneous plant equipment	0.77
26	Heat rejection system	0.8
	Total direct cost	DDC
	Indirect costs[a]	*0.80*
	Total plant capital cost	DDC

[a]Multiplier for indirect-cost fraction of direct cost.

quantify--would add to those from reduced nuclear-grade construction. The size of further possible savings from elimination of some active safety systems in reactors with LSA = 1, 2, or 3 is very difficult to estimate; even where active systems are not needed for assurance against off-site fatalities, some of these systems presumably will still be desirable for protection of plant investment against smaller but nonetheless potentially costly accidents.

In any case, we did not assume that each fusion reactor design was entitled to the maximum hypothetical cost reduction calculated by the scheme described above. Instead, the savings actually credited were scaled to the LSA assigned to the design. Designs with LSA = 1 received 100% of the maximum credit, those with LSA = 2 received 50%, those with LSA = 3 received 25%, and designs with LSA = 4 received no safety-assurance credit. (Recall that Level 4 corresponds to contemporary fission-reactor practice and hence to the contemporary N-stamp requirements and construction costs that were the basis of the unadjusted cost calculations.)

The adjusted capital costs obtained by following this prescription were then combined with the calculated operating costs (assumed independent of LSA) to obtain COE figures. These are shown in Table 21 for ESECOM's ten fusion and hybrid-breeder reference cases; figures in each case are given for all three LSA evaluations--optimistic, nominal, and conservative--and the unadjusted figures (no safety-assurance credit) are shown for comparison. As can be seen

Table 21. Cost of electricity with safety-assurance credits.

Case		COE (mills/kWh) if safety-assurance credits correspond to: Optimistic concept evaluation	Nominal design estimate	Conservative concept evaluation	No safety assurance credit
1	V-Li-TOK	46.2	49.7	49.7	53.1
2	RAF-He-/TOK	42.6	42.6	45.6	48.5
3	RAF-PbLi/RFP	35.7	37.7	37.7	37.7
4	V-Li-RFP	35.2	37.3	37.3	37.3
5	SiC-He/TOK	40.3	40.3	47.5	54.6
6	V-FliBe/TOK	38.0	42.9	42.9	47.9
7	V-MHD/TOK	31.0	35.4	35.4	35.4
8	V-DHe^3/TOK	34.9	41.3	41.3	47.8
9	RAF-Li/HYB				
	w LWR clients	39.1	39.4	39.4	39.4
	w MHTGR clients	40.1	40.3	40.3	40.3
10	SS-He/HYB				
	w LWR clients	38.4	38.8	38.8	38.8
	w MHTGR clients	39.4	39.8	39.8	39.8

from Table 21, the effect of these adjustments is to narrow the range of COE values spanned by the reference cases, as well as to lower the average figure. The reason for the narrowing is that the fusion cases with higher unadjusted costs tended to earn better safety-assurance ratings, which is not surprising given that their higher unadjusted costs tended to result from advanced materials or from relatively low-power densities, both of which can contribute to the possibility of passive protection against major releases.

In addition to this necessarily very approximate approach to quantifying the potential benefits of achieving high LSA, we also attempted to qualitatively characterize some potential cost impacts of safety and environmental issues that are resistant to quantification at the present state of knowledge about fusion technology. Specifically, we identified a set of such issues that will have some bearing on reactor design, construction, and operation, but whose resolution is not clear enough to permit incorporation of

engineering details, operating procedures, and corresponding costs into the formal engineering/economic model ESECOM used. Two of these issues--seismic restraints and safety systems for chemically reactive coolants--relate to accident prevention/control; two others--tritium-control systems and remote maintenance--relate to control of radiological hazards in routine operation. These are not the only issues of this kind, of course, but they are surely four of the most important.

For each reference design, we assigned a potential economic impact rating of High, Medium, Low, or None to each of the four safety/environment issues, indicating its potential for leading to costs beyond those embedded in ESECOM's nominal costing evaluation: we consider High to represent a potential impact equivalent to a 20% increase in plant capital cost, Medium a 10% increase, and Low a 5% increase. Obviously these are very approximate categorizations. Indeed, we emphasize that we do not know that these costs will materialize at all; clever engineering solutions might be able to reduce or avoid them. We have used this scheme simply as a way of drawing attention to the possible magnitudes associated with safety/environment-related cost uncertainties that no one is really in a position to pin down more precisely. The ratings, which are based on safety and environmental considerations summarized above and treated in more detail in our main report,[1] as well as on engineering judgment concerning the technical problems involved,[1,13] appear in Table 22. If the four areas are considered together, the designs with the highest combined potential cost impacts (as percentages) are seen to be Cases 1, 3, 4, and 9, while those with the lowest are Cases 5, 6, and 8.

It has been widely supposed that there will be trade-offs between attractive economics and safety characteristics, partly on the basis of the economic costs of added-on safety systems and partly on the assumption that high-power density is as inimical to safety as it is favorable to low cost. Our work suggests that the relations are more complicated than this. As already noted above, LSA values of 1, 2, or 3 associated with basic materials properties and passive energy-removal mechanisms may lead to substantial savings through reduced N-stamp requirements, even if elaborate active safety systems remain desirable to protect plant investment. As for the putative economics/safety trade-off associated with power density, that relation is also complicated. Depending on details of confinement scheme, magnet capabilities, and materials properties (among other factors), the economic optimum power density may occur at levels below those where significant

Table 22. Potential cost impacts of some other safety/environment issues. High means a potential impact on COE equivalent to that of a 20% increase in plant capital costs, medium 10%, low 5%. Potential impacts may be reducible or avoidable by means of engineering innovations.

	Case	Seismic restraints	Reactive-coolant protection	Tritium-control systems	Remote Maintentance
1	V-Li/TOK	Medium	Medium	Low	High
2	RAF-He/TOK	Low	None	Medium	Medium/high
3	RAF-PbLi/RFP	Medium	Low	Medium	High
4	V-Li/RFP	Medium	Medium	Low	High
5	SiC-He/TOK	Low	None	Medium	Low/medium
6	V-FLiBe/TOK	Low	None	Medium	Medium
7	V-MHD/TOK	Low	Low	Medium	Medium/high
8	V-DHe^3/TOK	Low	None	Low	Medium
9	RAF-Li/HYB	Medium	Medium	Low	High
10	SS-He/HYB	Medium	None	Medium	High

adverse impacts on LSA would occur. Generalizations on this point are unreliable, as detailed technical specifications and a rather rigorous analysis of the thermal transients that could be encountered in realistic accidents are required to clarify the question for any given design. Also, compactness (associated with high power density or simplified magnetic topology, such as the RFP) may offer advantages for maintenance and accident-recovery, translating into economic benefits.

It is possible, finally, that there is an economics/safety trade-off associated with plant scale, wherein very large plants are favored by the scaling laws of fusion plasmas and other economies of scale, while safety assurance is imperiled at very large scale by the size of the radioactivity inventories present in a single device. Here, too, as the longer analysis in our main report suggests, the situation is more complicated than it first appears. Even without bringing safety into the picture, the economic-optimum scale is influenced by many factors, some of them poorly understood even for

fission plants and necessarily more so for fusion. The extent to which modularization, multiplexing, mass production, and learning effects could change the usual conceptions about nuclear-plant scale economies is unclear and needs further investigation; information being accumulated in the study of this issue for fission plants will eventually be helpful in assessing fusion's prospects, but attention will also have to be given to possible differences in the amenability of fission and fusion systems to modularization, multiplexing, and factory fabrication. The implications of all this for safety represent largely uncharted ground, and the already overambitious scope of this study in relation to the available resources left us little room even to begin mapping it.

UNCERTAINTIES AND OMISSIONS

We have mentioned in the foregoing summary many of the uncertainties that inevitably arise in a study of this kind. Most of them are attributable at least in part to the early stage of development of fusion technology. Some are connected with our assumptions about the performance of fusion plasmas and the surrounding systems; some affect our assessments of environmental and safety characteristics; and most influence one way or another our estimates of monetary costs.

It is useful to separate the uncertainties that affect our economic estimates into four classes, as follows:

1. Physics uncertainties, such as those associated with plasma performance, current-drive efficiency, maximum magnetic field strength, and so on;

2. Materials uncertainties, having to do with the key properties of structural materials in regard to strength at temperature, fabricability, maintenance of performance under neutron bombardment, and so on;

3. Technology uncertainties (including aspects related to environment and safety), such as those connected with tritium management, remote maintenance, energy conversion, and so on;

4. Institutional uncertainties, having to do with management practices, regulatory environment, interest rates, and so on.

The uncertainties in the physics and materials categories can easily be large enough, in the fusion cases, to become feasibility issues; that is, if the outcomes are unfavorable enough, particular approaches (and perhaps

fusion-electric systems in general) will not even be close to competitive. Put another way, it is not hard to show that outcomes still within the realm of possibility for combinations of these variables could drive up the cost of electricity to 2 times or more the nominal values estimated here. Most of us think that is unlikely, but it cannot be ruled out. (It can be added that the economic attractiveness of fusion hybrid breeders is less sensitive to such uncertainties than is the case for pure-fusion systems, both because the hybrid breeders are less demanding of fusion performance and because the impact of their cost on COE is diluted by the economics of the client reactors.)

In the technology category, the range of uncertainty is probably smaller: in the least well developed cases the cumulative uncertainty from all such effects may extend to 50% or so greater than our nominal COE values, and in the least uncertain cases perhaps to 25% or so greater than the nominal values. Still, it is conceivable that very adverse outcomes on combinations of major issues such as remote maintenance and tritium management could drive up costs by more than these tentative figures suggest.

In the institutional category, finally, it should be clear from fission experience that combinations of these management/regulatory/financial aspects can be responsible for cost impacts in the range of a multiplicative factor of 2. Many of these aspects would tend to affect different fusion designs--and indeed fission as well as fusion systems--approximately equally, although as already noted this might not be so for regulatory factors related to safety.

We present in Table 23 a necessarily judgmental evaluation of the relative sizes of the physics, materials, and technology uncertainties in the 14 ESECOM fusion, hybrid, and fission reference cases. The table was compiled by polling the members of ESECOM at a meeting in December 1986. The choices for each reactor type and uncertainty class were Negligible, Low, Medium, or High. The "votes" of the members were averaged numerically using a scale from 0 for Negligible to 3 for High. The fission PWR-BPE again serves as a calibration of this scale: it receives zeroes (negligible uncertainties) in each of these three categories. (It should be noted that the institutional uncertainties affecting the COE for PWRs would not be zero.) The pure-fusion system with the lowest across-the-board physics, materials, and technology uncertainties is the RAF-He/TOK; it is also the most attractive of the relatively low-uncertainty cases from the safety/environment standpoint.

Table 23. Judgmental relative uncertainties in ESECOM reference cases. Values obtained by averaging ratings of Negligible, Low, Medium, and High made by individual members of ESECOM. Numerical scale for averaging was Negligible = 0, Low = 1, Medium = 2, High = 3.

	Case	Averaged uncertainty ratings		
		Physics	Materials	Technology
1	V-Li/TOK	1.7	2.3	2.0
2	RAF-He/TOK	1.7	1.3	1.8
3	RAF-PbLi/RFP	2.3	1.8	2.6
4	V-Li/RFP	2.3	2.3	2.6
5	SiC-He/TOK	1.7	3.0	2.3
6	V-FLiBe/TOK	1.7	2.5	2.3
7	V-MHD/TOK	2.3	2.8	2.8
8	V-DHe_3/TOK	3.0	2.3	2.3
9	RAF-Li/HYB	1.1	1.8	2.0
10	SS-He/HYB	1.1	2.0	2.0
11	PWR-BPE	0.0	0.0	0.0
12	LSPB	0.1	0.6	1.0
13	PRISM	0.1	0.6	0.9
14	MHTGR	0.0	0.7	0.8

A more detailed characterization of economic uncertainties in the materials and technology levels was undertaken in connection with calculating the COEs for the fusion cases. (For this purpose, as already noted, the main physics uncertainties were assumed to have been resolved with rather favorable outcomes--typically 10% beta, plasma safety factor of 2.3, maximum field of 10 tesla at the coils, coil current density greater than 20 MA/m^2, and so on.) For each cost account and major subaccount used in calculating capital costs (e.g., turbine-plant equipment, nuclear-island/coils), and for each heading under operating costs (e.g., blanket replacement, other fuel-like expenditures), an economic uncertainty rating of Low, Medium, or High was assigned by consensus after committee discussion of the associated engineering and materials issues. This was done for each design, after accounting for the

safety-assurance credits corresponding to the nominal LSA evaluations. The ratings and the rationales for them can be found in our main report. It then became possible to compute for each design the fractions of the COE that are associated with low-uncertainty, medium-uncertainty, and high-uncertainty elements.

The results of this breakdown of COE according to uncertainty level are presented in Table 24. Figure 2 presents in graphical form the cost comparisons among all the ESECOM reference cases, using pie diagrams placed at the nominal COEs of the fusion designs to convey the uncertainty distributions from Table 24. Shaded bars denote the range from optimistic to conservative evaluations of LSA, and dotted arrows emphasize the existence of unquantified

Table 24. Distribution of COE by degree of uncertainty. Evaluations performed for nominal LSA.

Case	Nominal LSA	COE (mil/kWh)	Fraction of COE associated with: Low uncertainty	Medium uncertainty	High uncertainty	
1 V-Li/TOK	3	49.7	0.367	0.326	0.307	
2 RAF-He/TOK	2	42.6	0.459	0.377	0.164	
3 RAF-PbLi/RFP	4	37.7	0.368	0.281	0.350	
4 V-Li/RFP	4	37.3	0.409	0.392	0.199	
5 SiC-He/TOK	1	40.3	0.434	0.352	0.214	
6 V-FLiBe/TOK	2	42.9	0.323	0.337	0.338	
7 V-MHD/TOK	4	35.4	0.299	0.232	0.469	
8 V-DHe3/TOK	2	41.3	0.298	0.232	0.470	
9 RAF-Li/HYB	4					
stand alone		63.7	0.267	0.403	0.330	
with MHTGR clients		40.3	0.506	0.215	0.279	
10 SS-He/HYB	4					
stand alone		55.8	0.302	0.314	0.384	
with MHTGR clients			39.8	0.507	0.208	0.284

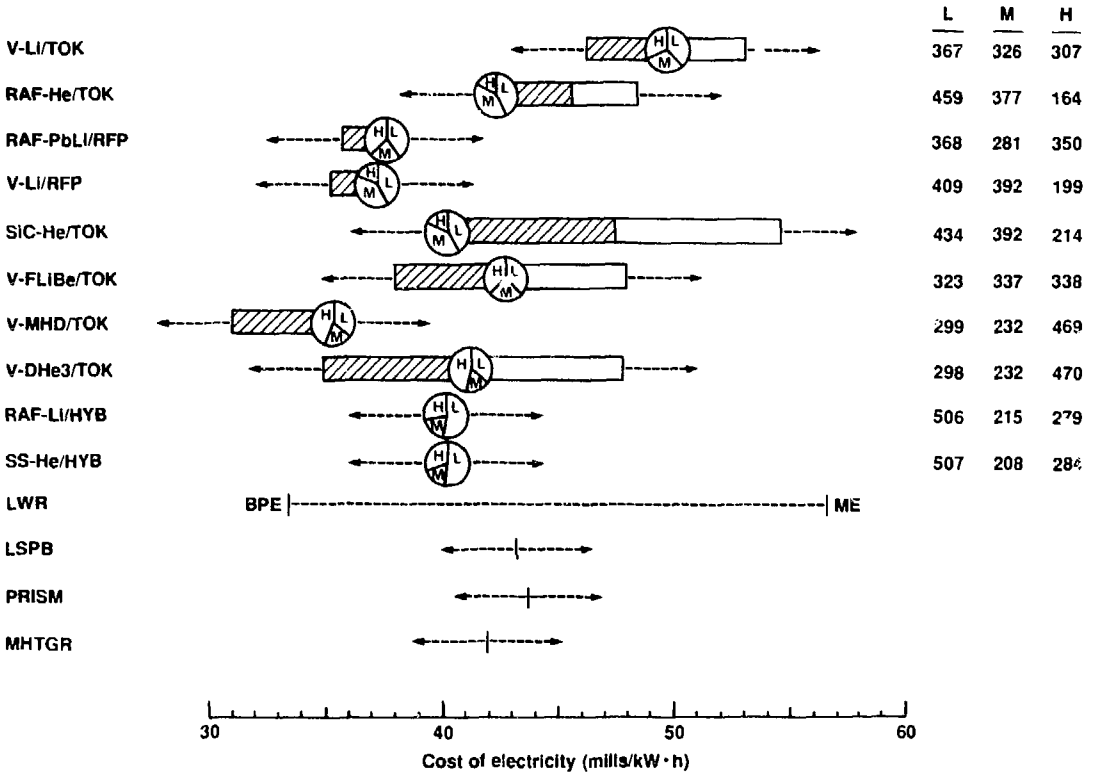

Figure 2. **COE estimates for ESECOM cases with and without safety assurance credits.** L, M, and H represent low, medium, and high cost uncertainties determined by assigning these designations to each cost account for each design. (See Table 24.) Where the conservative LSA rating is less than 4, a blank bar extends to the COE that would obtain at LSA = 4 (that is, without safety-assurance credits).

uncertainties associated with, for example, physics and institutional factors. Fission COEs are not broken down by uncertainty level because the disaggregated cost estimates needed to do so were not available to us for all the fission cases.

Although the emphasis in the preceding discussion has been on the possibility that fusion economics could be worse than ESECOM's estimates indicate, the economic uncertainties do cut in both directions. It is true that we have picked some key parameters (such as beta and current drive efficiency) toward the optimistic end of the ranges that are plausible based on present understanding, so that the uncertainties may not be symmetric; on the other hand, it is impossible to account in any comprehensive way for the array of potential discoveries that have not yet been made and that could extend the range in the optimistic direction.

Indicative of such possibilities is the concept of the second stability regime for tokamaks. Information that became available late in our study[73] made it possible for us to explore in at least a preliminary way, using the Generomak model, the potential impact on tokamak economics if the second stability regime actually turns out to be realizable. COE reductions in the range of 15 to 20% for the ESECOM point-of-departure V-Li/TOK were estimated for this eventuality. Another possibility with the potential for significant positive effects on MFE economics is advanced superconducting magnets. ESECOM's sensitivity studies indicated that application of the advanced magnets assumed for the D-He^3 case to the point-of-departure tokamak could reduce COE for the latter case by about 13%. These and some other results of our modeling of the sensitivity of COE to physics and technology assumptions are shown in Table 25.

The rapid pace of developments, late in our study, relating to higher-temperature superconductors[74] raises further magnet-related possibilities for savings, ranging from reduced refrigeration costs (a small-percentage effect) to substantially more compact designs (with conceivable savings in the 20 to 30% range). Much more work on the higher-temperature superconductors will be required before the likelihood of achieving these possibilities can be evaluated with any confidence.

Still other possibilities simply were not considered by ESECOM at all. For example, there exists a range of possible compact confinement schemes with improved magnet topology and field utilization and the potential for significant cost reductions; these extend beyond the RFP and include concepts

Table 25. Sensitivity of COE to variations in parameters. All figures are for variations on nominal values for point-of-departure V-Li/TOK.

	Change in COE (%)
Troyon coefficient, $\beta B_\phi a/I_\phi = 0.04$	
• Decrease from 0.04 to 0.03, giving $\beta = 0.075$	+ 7
• Make proportional to 1/k, with k = 2.5, $\beta B_\phi a/I_\phi = 0.016$, $\beta = 0.04$	+30
• Increase from 0.04 to 0.12 by schieving second stability regime, giving $\beta = 0.20$	-16
Plasma safety factor, $q_\phi = 2.3$	
• Increase from 2.3 to 4.0	
-- by decreasing β to 0.057	+10
-- by decreasing A from 4 to 2.7	+13
Plasma elongation, k = 2.5	
• Reduce from 2.5 to 2.0 with A = 3	+ 8
Current drive efficiency, $\gamma = 2.7$ A/m^{2}W ($I_\phi/P_{OD} = 0.2$ A/W)	
• Limit γ to 0.4 A/m^{2}W	+42
• Limit γ to 0.5 A/m^{2}W but increase plasma T to 25 keV	+14
• Sustain full $I_\phi = 15.7$ MA with bootstrap currents	- 8
Coil current density, $j_{\phi c} = 20.4$ MA/m^2	
• Improved coil design with $j_{\phi c} = 58$ MA/m^2, $B_{\phi c} = 18$ T	-13
Blanket unit cost, 190 $/kg	
• Decrease by 50 percent	- 6
Plant Lead Time, Y = 6 yr	
• Decrease fry 6 to 5 yr	- 3

such as the Spheromak, field-reverse configurations, and the dense Z-pinch.[75] These approaches were not amenable to investigation in the framework of our study, but they deserve attention. Another possibility not considered here is spin-polarization of fuel nuclei to increase their reaction rate. This technique has been rather extensively studied,[75] although its feasibility is still unclear. If it works, it could increase the reaction rate in D-T systems by a factor of perhaps 1.5, reducing the beta required for a given power density by the square root of that factor. The economic trade-off between the resulting cost savings and the added costs associated with accomplishing the polarization cannot be evaluated given current knowledge. A still less well understood possibility we did not analyze is "cold nuclear fusion" based on muon catalysis of the fusion reactions. Conceivably this process, which has been demonstrated at temperatures between a few kelvin and a few hundred degrees centigrade, can be made energetically and economically attractive, but if so the technology would be so different from that of MFE that our current study would be of little relevance in judging its potential.

FINDINGS IN BRIEF

Our most important and general conclusions follow under the first subheading. More detailed conclusions and recommendations are summarized in the subsequent subsections.

THE POTENTIAL OF MAGNETIC FUSION ENERGY

Our analysis indicates that magnetic fusion energy systems have the potential to achieve costs-of-electricity comparable to those of present and future fission systems, coupled with significant safety and environmental advantages. This conclusion is based on (a) assumptions about plasma performance and engineering characteristics that are optimistic but defensible extrapolations from current experience, and (b) consistent application of an elaborate set of engineering/economic and safety/environment models to a range of fusion and fission reference cases, with the known characteristics of fission light-water reactors as a benchmark. Fusion's potential economic

competitiveness does not depend on translating safety and environmental benefits into cost credits, but it would be enhanced if that occurs. The most important potential advantages of fusion with respect to safety and environment are:

1. High demonstrability of adequate public protection from reactor accidents (no early fatalities off-site), based entirely or largely on low-radioactivity inventories and passive barriers to release rather than on active safety systems and the performance of containment buildings;

2. Substantial amelioration of the radioactive-waste problem by eliminating or greatly reducing the high-level-waste category that requires deep geologic disposal;

3. Diminution of some important links with nuclear weaponry (easier safeguards against clandestine use of energy facilities to produce fissile materials, no inherent production or circulation of fissile materials subject to diversion or theft).

These advantages are potentially large enough to make a difference in public acceptability of MFE, as compared with fission.

The timing and intensity of the need for MFE will depend on future patterns of U.S. and world energy demand, as well as on the characteristics of other energy sources available to meet those demands. Future energy demand and the characteristics of alternatives to fusion in the time frame when it might be available--starting 20 to 30 years hence--are clouded by uncertainty. Given the potential damages to society from insufficient energy supply or excessive economic and environmental costs of obtaining it, however, and given the absence of any long-term energy source that is both reasonably assured technologically and free of potentially serious economic or environmental liabilities, it would be imprudent to assume that fusion energy would not be needed.

If efforts to continue to increase the efficiency of energy end use worldwide are less successful than hoped, if the expansion of coal use is constrained by the carbon-dioxide problem and other environmental liabilities, if fission energy cannot be expended owing to concerns about safety and links to nuclear weaponry, and if large-scale use of sunlight and biomass energy is impeded by high monetary costs or environmental impacts, then the need for fusion energy could be early and acute. Even if such severe problems with the alternatives do not materialize, fusion might offer sufficient benefits in its combination of fuel availability, economic cost, versatility, and

environmental safety characteristics to displace otherwise acceptable energy sources for significant societal advantage. Fusion's long-term potential includes a number of applications--among them synfuels production, isotope production, waste processing, and space propulsion--that may contribute to its attractiveness but were not evaluated by ESECOM.

Neither the economic competitiveness nor the environmental and safety advantages of fusion will materialize automatically. Economic competitiveness depends on attaining plasma and engineering performance--such as high beta, efficient current drive, and ease of maintenance consistent with high capacity factor--that are not yet assured. Achieving the potential environmental and safety advantages depends in large measure on designs specifically tailored to do so and on the use of low-activation materials whose practicality for fusion applications remains to be demonstrated. Research is needed to clarify these possibilities, and a commitment to pursuing fusion's highest potential is needed to ensure that the results of such research are embodied in the mainstream of fusion development.

In a world where large-scale use of fission energy had been deemed acceptable, fusion hybrid breeder reactors producing fuel for fission-reactor clients would have the potential to improve system economics (and, conceivably, system safety and proliferation resistance) compared to pure-fission systems, while providing a fusion-technology stepping stone toward pure-fusion electricity generation. The COE uncertainties of hybrids are lowe han for other fusion systems because cost and performance variations in the fusion breeder itself are distributed over a large number of fission client reactors with less uncertain economics. On the other hand, whether and when hybrids will be attractive at all depends strongly on very uncertain aspects of the world energy future, including the public acceptability of large-scale use of fission, the cost of uranium, and the characteristics of advanced fission breeders.

Although the technological feasibility of MFE has not yet been firmly established and the characteristics of a practical reactor therefore remain unclear in detail, it is completely appropriate--indeed essential--to undertake a systematic and cont'nuing assessment of fusion's potential to achieve attractive combinations of environmental, safety, and economic characteristics. Doing so at a relatively early stage of fusion's development has the advantage of steering R&D efforts in the directions of greatest promise, before one approach or the other has become locked in.

It is essential, in this connection, that sufficient R&D be devoted early to determining which of a variety of confinement schemes, structural materials, blanket types, and fuel-cycle/energy-conversion combinations can actually be made practical. Otherwise, the set of realistic possibilities for attractive combinations of environmental, safety, and economic characteristics will not be known, incurring the risk that fusion either will be developed in suboptimal directions or will not appear to be attractive enough to be developed at all.

TECHNOLOGY AND ECONOMICS

The fusion cost estimates we have derived necessarily embody many uncertainties. Experience suggests that even our estimates for fission-energy costs, based on better understood systems, should not be considered very accurate. The magnitudes of these cost estimates relative to one another are more informative than their absolute values. Although the overall COE uncertainties for our fusion and advanced fission reference cases probably exceed the typical differences between cases, we believe our use of consistent calculational techniques for all the cases justifies some confidence in our conclusion that MFE has the potential to be generally competitive with fission energy. Similarly, we have confidence that our relative COE figures convey real insights about the economic effects of particular types of design changes.

The uncertainties with the biggest effects on our estimates of COE for the fusion-electric cases are associated with achieving the assumed beta and current-drive efficiency and with attaining plant reliability and maintainability characteristics compatible with reasonable capacity factors. These are crucial issues for MFE competitiveness, they pose particular difficulties in tokamaks, and they will need much more experimental and design work before answers can be offered with high confidence. At the same time, it should be emphasized that improvements in some areas--for example, magnets--can offset shortfalls in others.

ESECOM'S ten fusion and hybrid-breeder reference cases were chosen to explore the implications of different choices of power densities, coolant/breeder combinations, structural materials, energy conversion schemes, and fuel cycles within a limited number of case studies. We do not claim, nor should it be assumed, that any one of these designs embodies the best

combination of choices that could be made based on current knowledge. Using ESECOM's findings and other recent work, it should be possible to generate new designs with improved performance by combining some of the best features of different reference cases.

The design characteristics offering the most important potential benefits for fusion COE are:

1. Compactness (including but not limited to high mass power density), which reduces the capital cost of the fusion power core, reduces, as a result, the sensitivity of COE to plasma performance, and may ease maintenance;

2. High LSA, meaning demonstrability of public safety based on low radioactive inventories and passive mechanisms for preventing releases, which should reduce costs for active safety systems and nuclear-grade components as well as facilitating siting and licensing;

3. Advanced energy-conversion systems, which should be able to reduce balance-of-plant costs and may increase capacity factors.

Each of these features has the potential to generate COE reductions in the range of 20 to 30%. If two or more of them can be combined in one design, the resulting COE reduction will be larger.

Advanced-fuel reactors, which offer significant environmental and safety benefits, may be able to reach economically competitive levels of COE with the help of direct conversion, advanced magnets, and simplified, long-life blankets. All of these features are either more feasible or more helpful in the case of advanced fuels than they are in the D-T case, thus partly offsetting the D-T advantage in plasma reactivity.

While strong economies of scale are expected to be associated with the scaling characteristics of fusion plasmas, other aspects of the economics of scaling in fusion (and other) power plants remain inadequately understood. It is possible that important diseconomies of scale--associated in some instances with reduced availability--will be encountered in important components (e.g., blankets, magnets). The possible trade-offs between scale economies and potential benefits of modularization and learning need more thorough exploration; experience being acquired with fission systems will be informative about fusion's prospects in this respect.

Among the specific reference cases examined by ESECOM, some of the most potentially attractive are those in which technological uncertainties or lack of design detail loomed largest--notably the SiC-He, V-FLiBe, V-MHD, and D-He^3 tokamaks. This observation underscores our recommendation for expanding

the R&D efforts directed at clarifying the feasibility of advanced design concepts.

ENVIRONMENT, SAFETY, AND ECONOMICS

We believe the categorization of different designs into four LSA--based on the extent to which assurance of public safety depends only on low inventories of radioactivity and passive mechanisms to prevent releases--is an informative way to characterize differences relevant to the interaction of safety and economics. Although reliance on active safety systems and/or the proper performance of containment buildings can provide adequate safety in terms of actual values of risk, relying instead on low radioactive inventories and on passive safety features tends to produce a still safer system. In addition, the passive approach greatly eases the problem of demonstrating the adequacy of safety, not only in the technical and regulatory communities but also to decision makers and the public. This advantage is likely to translate into cost savings through reduced expenditures on active safety systems, reduced requirements for nuclear-grade components, diminished siting and licensing problems, and fewer delays in construction.

Increases neutron wall loading contributes to (but is not the only basis for) high-mass power density and associated economic benefits; very high neutron wall loading, however, can reduce the chance of attaining high LSA. There is thus a potential tension between pursuing high wall loading to get the economic benefits and operational advantages of compactness, and pursuing the economic, regulatory, and public acceptance benefits of high LSA. The magnitude of neutron wall loading at which this tension becomes an actual trade-off is strongly design dependent, and detailed safety analysis is needed to determine it. It may be possible to alleviate this tension to economic advantage by careful choice of materials and other safety-related aspects of design.

With suitable choice of structural materials and blanket design, even a large lithium fire would not produce any prompt fatalities off-site. The potential destructiveness of lithium fires in terms of plant investment and public acceptability nonetheless dictates the use of special design features against such fires in plants that use liquid lithium as the primary coolant-breeder. These features should include avoiding the use of water cooling for limiters/divertors and other high-heat-flux in-vessel components, as well as

other measures to prevent lithium-water, lithium-air, and lithium-concrete fires in the event of a lithium spill.

Use of structural materials with low short-term activation is important in achieving high LSA. Such materials reduce the potential for off-site doses in accidents in two ways: reduction of the total amount of radioactivity potentially available for release, and reduction of the decay heat that can contribute to the mobilization of this material.

Active inventories of tritium in reactor designs are small enough that even complete release under adverse meteorological conditions would not produce any prompt fatalities off site. The blanket and coolant-breeder inventories of tritium in ESECOM's reference designs are in the range of 100 to 500 grams; release of the larger amount as tritiated water would produce a maximum whole-body critical dose in the range of 4 to 40 rem at the plant boundary. The inactive tritium supply stored at the plant, although larger, can be divided up and extremely well protected.

Releases of tritium in normal operation are likely to dominate other sources of routine radiation exposure to members of the public from fusion, but it is feasible to make these releases as low as regulations require. The economic costs of meeting tight standards on tritium releases will depend on reactor type and on the combinations of tritium-control technologies that are adopted. The design of tritium-control systems for different reactor configurations deserves continuing detailed investigation.

Carbon-14 constitutes another source of routine public radiation exposure of possible concern, and the sources and fate of this isotope in fusion reactors need closer investigation. Carbon-14 is formed by neutron activation of nitrogen, oxygen, and carbon isotopes in reactor materials. In some instances, the quantities produced and their potential mobility may require special control technologies to avoid the global population dose that accumulates over many thousands of years (at dose rates tiny compared to geographic variations in natural background) if this material is released.

Routine radiation exposures of plant workers will be a complicated function of in-plant tritium distribution, air and coolant activation, configuration and activation of solid reactor components, and maintenance procedures. This issue cannot be analyzed in satisfying detail at the current stage of knowledge about fusion-reactor design and operation. It is reasonable to suppose that designs and procedures will be configured in such a way as to avoid worker exposures in excess of the 500 to 1000 person-rem per

plant-year characteristic of commercial fission-reactor practice, but the cost of meeting this guideline is uncertain. It is already clear, however, that the contact doses from even the lowest-activation structural materials will be too high to permit hands-on maintenance of any components inside the shield within months of reactor operation.

Choice of fusion-reactor structural materials to reduce or eliminate formation of the most troublesome long-lived activation products leads to large reductions in the key indices of radioactive-waste hazards, compared to fission. In some of the reference designs examined by ESECOM, all of the radioactive wastes would qualify for shallow burial under the logic of current regulations. We do not conclude here that shallow burial is necessarily the best management scheme for fusion-reactor wastes, having made no systematic study of waste-management options. We simply offer the finding that fusion wastes would qualify for shallow burial in some cases--and would come close to qualifying in most of the others--as an illuminating indicator of the reduction made possible by fusion in the size of the waste-management problem.

An electricity-supply system based on magnetic fusion energy would be less likely than a fission-energy system to contribute to the acquisition of nuclear-weapons capabilities by subnational groups, and would also be easier to safeguard against clandestine use for fissile-material production by governments. Except for the special case of hybrid breeders, fusion reactors need not produce or contain any fissile material, and a fusion-based electricity-supply system would not circulate any. Because fusion reactors could be modified to produce fissile material, they will need to be subjected to international safeguards. On the other hand, using fusion reactors for fissile-material production would require prolonged control over the reactor (unlikely for subnational groups) and would be easier to detect by international safeguards (hence less likely to be judged an attractive option by governments) than is diversion from fissile fuel cycles. In principle, tritium in D-T fusion reactors could be stolen by subnational groups or diverted to weapons programs by governments, but the consequences of this vulnerability are less profound than those of fissile-materials vulnerability in fission energy systems: the sophistication in nuclear weapons design and construction needed to make use of tritium is likely to remain beyond the reach of subnational groups, and for governmental nuclear-weapons programs tritium can be useful but it is not an essential ingredient in the sense that fissile materials are.

IMPLICATIONS FOR MFE R&D

Far more system-level design and analysis work than has been conducted so far is needed to permit better definition of the economics and safety characteristics of fusion. Emphases in these systems studies should include:

1. Improved characterization of accident pathways and radioactivity release mechanisms;

2. Development of reactor designs combining high LSA, high mass power density, direct conversion, and design simplicity for reliability and ease of maintenance.

More detailed designs are needed to allow more sophisticated analyses of fusion safety, environmental characteristics, reliability, and economics; such analyses are needed, in turn, to permit more informed decisions on which fusion concepts should receive priority for development. The possible system-level advantages of advanced fuels have not been sufficiently evaluated and deserve further study. Fusion-hybrid studies should also continue, with particular emphasis on optimizing the choice of fuel cycle.

The ultimate viability and attractiveness of MFE depends so strongly on materials issues that a strong, sustained materials-development and testing program must be considered second only to confinement studies as a prerequisite for fusion's success. The materials program should be closely integrated with the systems studies called for above, as well as responding to the materials issues posed by current fusion devices. Because of the diversity of candidate materials and the international distribution of materials-science capabilities, coordination of materials development in the U.S. with corresponding programs in Europe, Japan, and the Soviet Union would be highly beneficial to all parties.

A balanced R&D program in both physics and technology is needed to realize the possibility of cost-competitive electricity. Our economic analysis indicates that a competitive tokamak reactor (40 - 50 mils/kW-hr) will require attainment of either (a) values of beta (10%) and current-drive efficiency gamma (greater than or equal to about 1.4) near the upper range of theoretical extrapolation from experimental values, or (b) advanced magnets good enough to relax these stringent requirements, or (c) full safety-assurance cost credits, or (d) inexpensive direct conversion to reduce balance-of-plant cost. Because none of these economics-related development

tasks will be easy or will guarantee success, a multiple-pronged R&D approach is only prudent.

Additional R&D effort should be focused on resolution of technology issues that affect the feasibility of particular fusion concepts. Any assessment of the relative safety and economic merits of different fusion cases depends on the credibility of engineering assumptions that require experimental verification. Such concept-feasibility issues arise for all of the ESECOM cases including the point-of-departure tokamak. A partial list of these issues includes: the extent of surface erosion of plasma-interactive components, limits of high surface-heat-flux removal in realistic component geometries, limits of blanket internal heat transfer using liquid-metal coolants in strong magnetic fields, tritium solubilities and penetrativities, feasibility of thorium-cycle fuel reprocessing for hybrid breeders, and operational and lifetime-reliability characteristics of MHD direct-conversion systems.

Notwithstanding the difficulty of the physics and engineering challenges that must be addressed in the next generation of fusion facilities--such as the compact-ignition TORUS and the engineering test reactor--it is important that these facilities also be used to develop and demonstrate the kinds of safety features that will be needed for commercial reactors. Postponing major attention to safety issues until more physics and technology issues have been resolved would reduce the chance of fusion's achieving its safety potential and could increase the chance of accidents at the experimental facilities themselves. (Such accidents could damage fusion's prospects as well as the devices, even in the absence of significant off-site radiation doses.)

The diversity of MFE confinement and blanket concepts, together with the inevitability of new ideas and new discoveries, call for a long-term R&D strategy aimed at developing successive, improving generations of fusion reactors. Results of near-term systems and materials studies should be used to select blanket candidates for separate effects tests over the next 10 years and for integrated tests in an international Engineering Test Reactor in the period 2000 to 2010, leading to an acceptable first-generation fusion reactor (exemplified in our study by the point-of-departure tokamak) that could become operational in the period 2010 to 2015. In parallel with these developments, more advanced confinement and blanket concepts should be pursued at a pace

appropriate to their evolving promise, aiming for improved second- and third-generation reactors for the period 2020 and later.

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