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SUMMARY OF THE U.S. SENIOR COMMITTEE ON ENVIRONMENTAL, SAFETY, AND ECONOMIC ASPECTS OF MAGNETIC FUSION ENERGY (ESECOM)

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ABSTRACT

ESECOM has completed a recent assessment of the competitive potential of magnetic fusion energy (MFE) compared to present and future fission energy sources giving particular emphasis to the interaction of environmental, safety, and economic characteristics. By consistently applying a set of economic and safety models to a set of MFE concepts using a wide range of possible material choices, power densities, power conversion methods, and fuel cycles, ESECOM finds that several different MFE concepts have the potential to achieve costs of electricity comparable to those of fission systems, coupled with significant safety and environmental advantages.

1. INTRODUCTION

Organized in late 1985, the ten-member Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) has recently completed a comprehensive assessment [1] of the potential for magnetic fusion energy (MFE) providing energy with attractive economic, environmental, and safety, characteristics compared to present and future fission energy sources. We explored the interaction of environmental, safety, and economic characteristics of a variety of fusion and fission cases listed in Section 2, using consistent economic and safety models. Our findings in Section 3 indicate that several MFE candidates have the potential to achieve costs of electricity (COE) comparable to those of present and future fission systems, and with significant safety and environmental advantages. These conclusions rest on key assumptions about plasma performance and improvements in fusion technology, which are optimistic but defensible extrapolations from current achievements. In contrast, a recent report of the Scientific, Technological Options Assessment (STOA) office of the European Parliament [3] proposes criteria for assessment of future MFE reactor safety and economics, which are generally much more restrictive than criteria used in the ESECOM study, with respect to allowing assumptions of future technology improvement. ESECOM, however, has taken the long view that the time horizon for MFE commercial application is the year 2015 at the earliest, and more probably beyond 2030. Accordingly, ESECOM chose to analyze MFE cases assuming advances of new technologies (e.g., materials) that are only in the beginning stages of development. ESECOM's work thus clarifies the promising areas for future fusion research and development. Due to lack of space, only selected portions of the ESECOM work are discussed here. For more details on all areas covered by ESECOM, the reader is referred to the published technical summary [1] of this work and to the larger main report [2].

2. COMPARATIVE ANALYSIS OF FUSION AND FISSION CASES

ESECOM selected a set of fusion, fission, and fusion-fission hybrid reactor cases for comparative analysis, listed in Table I. These cases were selected to span a wide range of technical characteristics based on reasonable extrapolation from present knowledge, permitting exploration of the impacts on safety and economics of different materials and coolant choices, power densities, energy conversion schemes, and fuel cycles.

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

Table I: Reference cases analyzed by ESECOM.

Fusion Cases	
1.	A "point-of-departure" D-T fusion reactor using a tokamak configuration, with vanadium-alloy structure and liquid lithium as the coolant/breeder.
2.	A helium-cooled variant of the case 1 tokamak with reduced activation ferritic steel (RAF) structure and Li_2O solid breeder.
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.
4.	Another high-power-density RFP with a V-Li blanket minimally modified from that of the point-of-departure tokamak.
5.	A "low-activation" tokamak with silicon carbide (SiC) structure, helium coolant, and Li_2O breeder.
6.	A "pool"-type tokamak with vanadium structure and molten-salt (FLiBe) coolant/breeder.
7.	An advanced conversion variant of the point-of-departure tokamak with synchrotron-radiation-enhanced magnetohydrodynamic (MHD) conversion.
8.	An advanced fuel, water-cooled tokamak based on the D^3He fuel cycle with direct conversion of microwave synchrotron radiation.
Fusion-Fission Hybrid Cases	
9.	A "baseline" fusion-fission hybrid tokamak with RAF structure, lithium coolant, beryllium neutron multiplication, and thorium metal as the fertile material.
10.	An "advanced technology" hybrid tokamak with stainless-steel structure, helium coolant, and Li-F-Be-Th molten-salt blanket.
Fission Cases	
11.	A "best present experience" and "medium experience" pressurized water reactor (Westinghouse) (PWR-BPE), (PWR-ME).
12.	The Large-Scale Prototype Breeder (LSPB) (Electric Power Research Institute/DOE).
13.	The Power Reactor Inherently Safe Module (PRISM) Breeder design (General Electric).
14.	A modular high-temperature gas reactor (MHTGR) (GA/Gas-Cooled Reactor Associates).

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 numbers 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^3He fuel cycle to reduce neutron activation and tritium problems—are currently 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. For similar reasons we included advanced fission cases (PRISM—case 13 and MHTGR—case 14) as possible future competitors to fusion.

2.1. Economic Analysis

ESECOM analyzed, in a consistent framework, the economic, environmental, and safety characteristics of the cases in Table I, including, in some cases, examining the effects of varying the plasma performance, scale, and power density within an otherwise fixed design. The fusion and hybrid breeder cases were developed and analyzed with the assistance of the Generomak magnetic fusion physics/engineering/costing model [4] 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.) 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_T and a, the toroidal field in the plasma B_ϕ, and the plasma current I_ϕ, corresponding to the desired net electric power taken to be 1200 MW(electric) in all cases. 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. As an example, some of the main physics and engineering parameters of the point-of-departure tokamak (case 1) are given in Table II. This reactor case assumes advances in beta and current-drive efficiency beyond those considered for the current design of the International Thermonuclear Experimental Reactor (ITER). We examined sensitivity of the case 1 capital cost and COE to variations in these and other critical parameters. Reducing the beta to 0.06, or the current-drive efficiency by a factor of five (while increasing T_e to 25 keV), for example, increased COE by 15%.

The economics part of the Generomak model uses the physics and engineering parameters to calculate the direct capital costs of the fusion island, based on unit costs supplied to the model for fabricated material (e.g., \$400/kg for reactor parts fabricated from V-Cr-Ti 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 [5], updated to the 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.

Costs of the blanket, limiter, coolant, and other major items that turn over on a short time scale compared to 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 [6]. Calculation of other operation and maintenance costs also follows the NECDB model. Following standard engineering-economics techniques, as embodied in the NECDB, we then obtain a levelized constant dollar COE, in units of 10^{-3} U.S. dollars (1986) per kilowatt hour, or mills/KW·h.

The results of the basic economic calculations are shown in Table III. 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-yr construction period (adjusted to 1986 dollars). The additional fission case (11′ PWR-ME) in Table III is the "median experience" PWR and provides a second reference point for the U.S. (The design and construction lead time for this case is 12 yr, and the indirect costs are 100% instead of 37.5%.) Particularly noteworthy in these results is that the COEs for the best experience and median experience PWRs bracket the range of costs estimated for the various fusion, hybrid breeder, and advanced fission cases.

2.2. *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) oc-

Table II: Parameters of the ESECOM point-of-departure reference fusion reactor.

	V-Li/TOK
Aspect ratio, A	4.0
Plasma elongation, κ	2.5
Total plasma beta, β	0.1
Safety factor, q_ψ	2.3
Maximum field at coil, $B_{\phi c}$ (T)	10.0
Toroidal field in plasma, B_{phi} (T)	4.29
Major radius, R_T (m)	5.89
Plasma current, I_ϕ (MA)	15.8
Neutron wall loading (MW/m^2)	3.20
Fusion power (MW)	2862.
Blanket thickness (m)	0.71
Blanket/shield gap (m)	0.10
Shield thickness (m)	0.83
Neutron energy multiplication	1.27
Tritium breeding ratio	1.28
Total thermal power (MW)	3563.
Primary coolant inlet, T_i (°C)	300.
Primary coolant outlet, T_o (°C)	550.
Thermal conversion efficiency	0.404
Recirculating power fraction	0.12
Net electric power [MW(electric)]	1200.
Volume of fusion power core (m^3)	2669.
Mass of fusion power core (tonne)	11482.
Mass power density [kW(electric)/tonne]	105.

cupational and public exposures to radiation in routine operation, and (d) unwanted links to nuclear weaponry.

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 [7–10]. These codes operated on cylindrical approximations to our toroidal blanket configurations.

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 wt%. The activation calculations performed by the ORLIB averaging code using the ACTL cross-section library accounted for impurities to levels below 1 ppm by weight. The constituent and impurity compositions used in these calculations came mainly from the BCSS [11] and, in a few instances, from the design groups working on particular blankets. 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 (FPY) 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 FPY, as was the entire blanket of the D^{3}He case.

For purposes of assessing accident potential and occupational hazards, reactor radioactivity

Table III: Comparative costs without safety assurance credits (1986 U.S. dollars).

Case	Unit capital costs [$/kW(electric)]			COE (mill/kW·h)			
	Direct	Overnight	Total	Capital	Fuel and other O&M	Fission 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	43.5
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-D^3He/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[a]	40.3
10. SS-He/HYB	1343	2123	2305	34.1	21.7	−16.0[a]	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[b]	16.7[b]	43.2
13. PRISM[c]	996	1575	1710	25.3	18.5[b]	18.5[b]	43.8
14. MHTGR[c]	885	1400	1520	22.6	19.4	0.0	42.0

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

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

[c]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.

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 FPY of operation, including all changed-out components.

Estimates of tritium inventories in the fusion cases were based on the BCSS [11] and on subsequent design studies, and included tritium in structure, coolant, breeder, and neutron multiplier materials.

To facilitate analysis of accident hazards associated with radioactive materials of different degrees of inherent mobility, we divided the radioactive inventories of fusion and fission reactors alike into five mobility categories:

1. Elements gaseous or extremely volatile under thermochemical conditions of normal operation.

2. Elements somewhat volatile under thermochemical conditions of normal operation.

3. Elements somewhat to highly volatile under conditions likely to be encountered in an accident.

4. Elements somewhat volatile under conditions that may be encountered in severe accidents.

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

Case and mobility categories	Inventories (MCi)		Release fraction that would produce 200-rem critical dose from plume at 1 km		Release fraction that would produce 25-rem 50-yr ground dose at 10 km	
	First wall	BOFC	First wall	BOFC	First wall	BOFC
Case 1: V-Li/TOK (Fusion)						
I	5	0.077	52.	7100.	15.	260.
I-II	10	6.0	6.3	5.0	0.78	0.82
I-III	10	560.	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 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	

BOFC = Balance of fusion core (other than first wall).

5. Elements resistant to volatilization even under extreme accident conditions.

Given the radioactive inventories and the mobility-based classification scheme just described, we can calculate the off-site doses that would result from release of 100% of the radioactive inventory in each mobility category for each design. Then we can deduce how large the actual release fractions of these materials would have to be to produce any particular dose of interest. We calculated for each design, for example, what fractions of the radioactive inventories in each mobility category and each reactor component would have to be released in order 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); we also calculated such "dose threshold release fractions" corresponding to a 50-year dose of 25 rem from ground contamination at a distance of 10 km from the reactor. (For conversion of dose units, use 1 rem = 10^{-2} Sv.) The higher these dose-threshold release fractions are, the better, since 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.) Table IV gives dose-threshold release fractions by mobility category for the point-of-departure tokamak (case 1) and the PWR fission (case 11). The dose-threshold-release fractions for the fusion case 1 are larger than those for the PWR fission case in all mobility categories. The isotope contributing most of the mobility category I dose for fusion is tritium.

When we take 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. Table V gives estimates of the maximum plausible release fractions based on analysis at MIT by Kazimi, combined with test data from INEL on volatilization from the vanadium and steel alloys used in the fusion cases.

ESECOM found it useful to work with a classification of safety levels that defines four levels of "safety assurance," given in Table VI, based in substantial part on the work of Piet [12]. These level are based on differences in the extent and nature of dependence on passive versus

Table V: 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 to 0.7
III	0.05	0.1 to 0.7	0.2	0.2 to 0.4
IV	5×10^{-4}	0.01 to 0.1	2×10^{-3}	0.05 to 0.1
V	5×10^{-4}	1×10^{-4} to 1×10^{-3}	2×10^{-4}	0.003 to 0.05

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

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

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

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

active design features needed in a given design to provide assurance of public safety—more specifically, to preclude 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 versus 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 containment buildings with many doors and controlled penetrations.

ESECOM concluded that high "levels of safety assurance," (low LSA numbers) as described above, could be the basis for reduced requirements for expensive "nuclear-grade" materials and components compared to the requirements imposed in fission power plant construction in the U.S. today. To give cost credit to low LSA-numbered ESECOM fusion reactor cases, we used a set of cost-reduction factors for various reactor subsystems developed by Perkins in the MINIMARS study [13] to estimate the potential cost savings associated with the use of non-nuclear grade materials and components. Reactor cases with LSA = 1 received 100% of maximum credits of reference 12, those with LSA = 2 received 50%, those with LSA = 3 received 25% and those with LSA = 4 receive no safety assurance cost credits. The maximum cost credits amount to approximately 30% reduction in COE. Table VII lists the LSA rating and corresponding COE of the ten fusion cases for optimistic, nominal, and conservative evaluations. All fission cases were rated LSA = 4, except for the PRISM (case 13) and MHTGR (case 14), which designs included passive safety features, for LOCA accidents, and included cost reductions for the passive safety features estimated by their designers.

3. ESECOM FINDINGS AND CONCLUSIONS

Some of the most important findings of the ESECOM analysis are summarized in the following sections. For brevity, we have not included all of the findings or supporting analysis, for which we refer the reader to our longer reports [1,2].

Table VI: Definition of ESECOM's levels of safety assurance (LSA).

LSA	Concise description	Accident class: Large-scale reconfiguration	Accident class: Small-scale violation of geometry [e.g., loss-of-coolant accident (LOCA)]	Accident class: Transient without violation of geometry [e.g., loss-of-flow accident (LOFA)]
I	Inherent safety	If event occurs, material properties suffice to prevent fatal release.	If event occurs, material properties suffice 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 design features.	If event occurs, material properties and passive mechanisms suffice to prevent fatal release or escalation to next class.	If event occurs, 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 mechanism suffice to prevent fatal release or escalation to next class.
IV	Active protection	There are events in one or more of these categories that, if they occur, require active systems to preclude an off-site fatality, and that cannot be made incredible by passive design measures alone.		

3.1. The Potential of Magnetic Fusion Energy

Our analysis indicates that MFE 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. The most important potential advantages of fusion with respect to safety and environment are as follows:

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 an active safety systems and the performance of containment buildings.

2. substantial amelioration of the radioactive waste problem by eliminating or greatly reducing the inventories of radioactive isotopes with long half-lives. Under current U.S. waste-management regulations, fusion could greatly reduce or eliminate high-level wastes that require 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).

Table VII: Levels of safety assurance (LSA) and COE with safety assurance cost credits.

	Case	COE (mill/kW·h) and (LSA in parenthesis)			
		Optimistic concept evaluation	Nominal design estimate	Conservative concept evaluation	No safety assurance credits
1.	V-Li/TOK	46.2 (2)	49.7 (3)	53.1 (4)	53.1
2.	RAF-He/TOK	42.6 (2)	42.6 (2)	45.6 (3)	48.5
3.	RAF-PbLi/RFP	35.7 (3)	37.7 (4)	37.7 (4)	37.7
4.	V-Li/RFP	35.2 (3)	37.3 (4)	37.3 (4)	37.3
5.	SiC-He/TOK	40.3 (1)	40.3 (1)	47.5 (2)	54.6
6.	V-FLiBe/TOK	38.0 (1)	42.9 (2)	42.9 (2)	47.9
7.	V-MHD/TOK	31.0 (3)	35.4 (4)	35.4 (4)	35.4
8.	V-D^3He/TOK	34.9 (1)	41.3 (2)	41.3 (2)	47.8
9.	RAF-Li/HYB				
	With LWR clients	39.1 (3)	39.4 (4)	39.4 (4)	39.4
	With MHTGR clients	40.1 (3)	40.3 (4)	40.3 (4)	40.3
10.	SS-He/HYB				
	With LWR clients	38.4 (3)	38.8 (4)	38.8 (4)	38.8
	With MHTGR clients	39.4 (3)	39.8 (4)	39.8 (4)	39.8
11.	PWR-BPE	33.4 (4)	33.4 (4)	33.4 (4)	33.4
12.	LSPB	43.2 (4)	43.2 (4)	43.2 (4)	43.2
13.	PRISM	43.8 (3)	43.8 (3)	(4)	
14.	MHTGR	42.0 (3)	42.0 (3)	(4)	

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.

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.

3.2. Technology and Economics

The design characteristics offering the most important potential benefits for reducing fusion costs are as follows:

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

2. high level of safety assurance, 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 (BOP) 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 could be even larger.

The fusion cost estimates we have derived necessarily embody many uncertainities. The magnitudes of these cost estimates relative to one another are more informative than their absolute values, and serve to indicate promising areas of research to improve fusion.

3.3. Environment, Safety, and Economics

We believe the categorization of different designs into four levels of safety assurance, 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.

There is a potential conflict between pursuing higher neutron wall loading to reduce cost through higher power density, and pursuing the economic, regulatory, and public acceptance benefits of high levels of safety assurance.

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.

Active inventories of tritium in current reactor designs are small enough that even complete release under adverse meteorological conditions would not produce any prompt fatalities off-site.

Proper choice of fusion reactor structural materials can reduce or eliminate formation of the most troublesome long-lived activation products, and therefore can significantly reduce radioactive waste hazards, compared to fission.

An electricity supply system based on MFE 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 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, however, they will need to be subjected to international safeguards.

3.4. Implications for MFE R&D

Far more system level design and analysis work than has been conducted so far is needed to better define 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 levels of safety assurance, high mass power density, direct conversion, and design simplicity for reliability and ease of maintenance.

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.

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 International Thermonuclear Experiment Reactor (ITER), 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.

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