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ECONOMIC IMPLICATIONS FOR FUSION DERIVED
FROM ESECOM STUDY *

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ABSTRACT

The main conclusion of the ESECOM study is that commercial fusion power plants have the potential to be economically competitive with present and future alternatives, while at the same time promising significant environmental and safety advantages, if designed properly. Furthermore, a range of fusion reactor approaches was identified which appears to meet these economic, safety and environmental goals. Economic competitiveness is not automatic, but depends on achieving enhanced plasma and engineering performance, such as high beta with low transport losses, efficient current drive and improved high-field coils. The main design characteristics leading to lower cost of electricity are a high degree of safety assurance, compactness, improved coils, and advanced energy conversion coupled with the use of advanced fuels.

I. INTRODUCTION

To a great extent the ultimate viability of any fusion option will depend on its economics relative to all electric power-producing options available in the same time frame. The Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) was organized by Department of Energy, Office of Fusion Energy to provide an assessment of the prospect of magnetic fusion energy having attractive environmental and safety characteristics while simultaneously having reasonable assurance of being competitive. This paper presents principally the economic results and implications from the ESECOM study;[1] environmental and safety characteristics will be addressed only as the economics are affected.

Although large uncertainties exist, the principal conclusion of the ESECOM study[1] is that commercial fusion reactors have the potential to be economically competitive with present and future alternatives, while simultaneously promising significant environmental and safety advantages, if the reactor is properly designed. Furthermore, a range of fusion reactor approaches was identified that appears to meet these economic, safety and environmental goals.

II. MODELS

The engineering, physics and costing models used in the study are based largely on those given in Ref. 2 and implemented in the Generomak code described in detail elsewhere.[3] Specific trade-offs and sensitivities between cost and physics have been reported in Ref. 4 for the ESECOM, "point-of-departure" tokamak case.

Reactor plasma and engineering

In total, ten fusion reactor variants based principally on the tokamak were analyzed by the ESECOM study. A brief description of these ten cases is given in Table 1. These designs include systems that produce electricity by both conventional and advanced conversion schemes, as well as fission/fusion hybrid concepts. In addition to the tokamak concepts, high-power-density systems were investigated using the compact Reversed-Field Pinch (RFP)[5,6] as a sample reactor system for that regime. Although the Generomak model is approximate and is inappropriate for detailed design calculations, it provides a self-consistent, quantitative comparison between alternatives and can provide information about the direction and approximate magnitude of alternative design choices. The Generomak model, as it was used in the ESECOM study, represents an extrapolation of present physics and technology[4] insofar as high beta (10%), efficient current drive (0.2 A/W), 15-20 $MWyr/m^2$ blanket/shield lifetimes, pumped limiter impurity control and improved super-conducting

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Table 1. Fusion plant models

V-Li/TOK	- "Point-of-departure" tokamak with vanadium structure and liquid lithium coolant/breeder.
RAF-He/TOK	- He cooled variant with reduced activation ferritic-steel (RAF) structure and Li_2O solid breeder.
RAF-LiPb/RFP	- High-power-density Reverse-Field Pinch (RFP) with RAF structure, self-cooled lithium-lead breeder, and water-cooled first wall.
V-Li/RFP	- RFP with V/Li/Li blanket; RFP version of "point-of-departure" tokamak.
SiC-He/TOK	- "Low-activation" tokamak with silicon carbide (SiC) structure, helium coolant, and Li_2O breeder.
V-FLiBe/TOK	- "Pool-type" tokamak with vanadium structure and molten salt (FLiBe) coolant/breeder.
V-MHD/TOK	- Advanced-conversion variant with synchrotron-radiation enhance magnetohydrodynamic (MHD) conversion.
V-DHe^3/TOK	- Advanced-fuel variant with D-He^3 fuel cycle and direct conversion of microwave radiation.
RAF-Li/HYB	- Fusion-fission hybrid tokamak with RAF structure, lithium coolant, beryllium neutron multiplier, and molten-salt blanket.
SS-He/HYB	- Advanced hybrid tokamak with stainless-steel structure, helium coolant, and molten-salt blanket.

coil technology are assumed. Physics and engineering parameters for the Li-V/TOK basecase are shown in Table 2.

Table 2. Physics engineering parameters for Li-V/TOK tokamak basecase

Aspect ratio, $A = R_T/a$	4.0
Elongation, $\kappa = b/a$	2.5
Safety factor, q_ψ	2.3
Total beta, $\beta = 0.04 I_\phi / a B_\phi$	0.1
Plasma ion temperature, T_i(kev)	10
Plasma standoff, a_w/a	1.1
Current drive efficiency, I_ϕ/P_{CD} (A/W)	0.2
Net electric power, P_e (MWe)	1,200
Gross thermal conv. eff.	.404
Blanket/gap/shield thicknesses (m)	.71/.10/.83
Toroidal field coil (TFC) current density, $j_{\phi c}$(MA/m^2) =	$\frac{(96 - 6B_{\phi c})}{1+(B_{\phi c}/12)^{1.5}}$
Maximum field at TFC, $B_{\phi c}$(T)	10
Blanket fluence lifetime (MW yr/m^2)	20
Blanket-neutron energy gain, M_N	1.27

Table 3. Economic and financial parameters

Plant life (years)	30
Plant lead time (years)	6
Indirect cost factor	0.375
Contingency factor	0.15
Interest during construction factor	0.0856
Nominal capacity factor (%)	65
Effective cost of money[a] (%)	2.83
Inflation rate (%)	6.0
Effective tax rate (%)	48.16
Tax depreciation life (years)	
- overall plant	10
- replacement blankets, etc.	5
Fixed charge rate[a]	0.0844

[a] constant dollar rates excluding inflation

Costing

The general methodology used for estimating the cost of electricity (COE) follows that in the Nuclear Energy Cost Data Base (NECDB),[7] which gives the basis for consistent comparisons between alternatives. The method uses a year-by-year revenue requirements procedure together with levelization techniques to establish a single equivalent COE over the economic life of the plants. The procedure was developed for fission reactor studies, is mathematically consistent with basic engineering economic principles, and should produce consistent comparisons among alternate energy technologies, including fusion energy. Economic and financial parameters used are shown in Table 3.

Fusion-plant capital cost estimates were based primarily on those developed in the STARFIRE[8] tokamak reactor study updated to 1986 dollars with some modification for the different reactor types. The Generomak model computes the fusion-power-core (FPC) volumes and reactor powers on the basis of a self-consistent radial-build; the plasma power density computed to be consistent with the specified net electric power, recirculating power, and physics constraints. The blanket, coil, structure, and shield costs are calculated from the respective volumes together with the average densities and unit costs for each regions. The unit material costs used in the analyses are shown in Table 4. Resulting capitalized investment costs for each of the fusion plants, based on "nuclear-grade" construction, are shown in Table 5, which also includes the COE.

Present-day and advanced fission plants were analyzed for comparison. The fission reactor cases include a pressurized water reactor (PWR),[9] a modular high-temperature gas-cooled reactor (MHTGR),[10] a large liquid-metal breeder reactor,[11] and an advanced modular liquid metal reactor.[12] The reference PWR is

Table 4. Unit material costs ($/kg.)

V15Cr5Ti	400
RAF/PCA	50
Lithium/Li_2O (Nat.)	45
Beryllium metal	500
BeO	200
Silicon Carbide (first wall/structure)	100/30
FLiBe	70
Thorium Salt	50
PbLi	13
Cadmium	1600
Shield	20
Coils	
Resistive copy alloy (RFP)	50
Superconducting	90
Advanced, high field	130
Coil structure	25
Advanced coil structure	60
Auxiliary power, $/W	
Current drive (TOK)	2.25
Current drive (RFP)	0.50
Advanced systems,[a] $M	45
Limiter, $/m^2	60000

[a] V-MHD/TOK and V-DHe^3/TOK

based on a United Engineers and Constructor's cost model for a plant whose costs are consistent with recent better construction cost experience (PWR/BE) plants.[9] This plant cost model is being used for comparison in various fission reactor studies, and it reflects the potential effects of proposed improved construction practices, as well as regulatory and licensing reforms. For comparison purposes, the cost of the current median-experience (PWR/ME) plant is also included. The MHTGR is a design proposed by Gas-Cooled Reactor Associates.[10] The large liquid metal reactor is the Electric Power Research Institute/USDOE Large Scale Prototype Breeder (LSPB),[11] and the modular liquid metal reactor is the PRISM design proposed by General Electric.[12] The characteristics and cost estimates for these fission plants were based on architect-engineering studies, the analysis of concept proponents (as modified by DOE reviews), and adjustments for consistency with the costing ground rules adopted for the fusion plants in this study. Capitalized investment costs for the fission plants are also shown in Table 5. Unit fuel cycle costs for the fission plants were taken from the NECDB with U_3O_8 costed at $50/lb, enrichment charged at $60/SWU, and plutonium priced at $50/gram.

Table 5. Comparative costs without safety assurance credits (1986 dollars)

Plant	Unit capital costs ($/kWe)[a] Direct	Overnight[b]	Total[c]	COE (mills/kWh) Capital	Fuel and other O&M	Fissile fuel sales	Total
V-Li/TOK	1378	2178	2365	35.1	18.1	0.0	53.1
RAF-He/TOK	1387	2193	2380	35.3	13.2	0.0	48.5
RAF/LiPb/RFP	949	1501	1630	24.2	13.5	0.0	37.7
V-Li/RFP	963	1523	1655	24.5	12.8	0.0	37.3
SiC-He/TOK	1621	2563	2785	41.3	13.4	0.0	54.6
V-FLiBe/TOK	1184	1873	2035	30.1	17.8	0.0	47.9
V-MHD/TOK	873	1380	1500	19.2	16.1	0.0	35.4
V-DHe^3/TOK	1763	2787	3025	38.9	8.9	0.0	47.8
RAF-Li/HYB	1649	2608	2830	41.9	21.7	-23.2[e]	40.3
SS-He/HYB	1343	2123	2305	34.1	21.7	-16.0[e]	39.8
PWR/BE	740	1170	1270	18.8	14.6	0.0	33.4
PWR/ME	980	2260	2620	41.0	15.6	0.0	56.6
LSPB	1040	1645	1785	26.5	----16.7-----[f]		43.2
PRISM[d]	996	1575	1710	25.3	----18.5-----[f]		43.8
MHTGR[d]	885	1400	1520	22.6	19.4	0.0	42.0

[a] "Nuclear-grade" construction costs for 1200 MWe(net) plant size
[b] Includes direct cost + indirect cost + contingency allowance
[c] Overnight cost + interest during construction
[d] There is some safety assurance credits imbedded in PRISM and MHTGR costs
[e] Figures for hybrid fissile sales are based on MHTGR client reactors
[f] Central reprocessing and refabrication facilities and $50/gram fissile plutonium

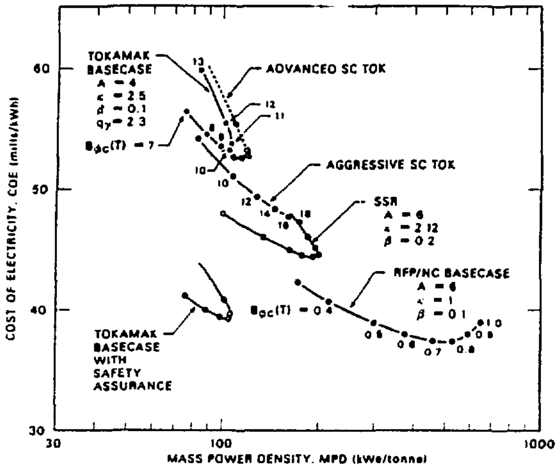

Fig. 1. Dependence of COE on masspower density, MPD (kWe/tonne) for the basecase tokamak, an advanced magnet design, a second-stability-region tokamak and a reverse-field pinch case.

III. RESULTS

Power-density trade-off

Figure 1 gives the dependance of COE as the magnetic field at the coil, $B_{\phi c}$, is varied. The minimum COE and optimal (maximum) mass power density (MPD) result because of a trade-off between increased engineering power density as $B_{\phi c}$ and the plasma power density are first increased; a decrease in COE results as the fusion power core volume decreases. As $B_{\phi c}$ increases above 9-11 T in the basecase tokamak, the decreasing current density causes the coil size and mass to increase, which in turn decreases MPD and increases cost. The COE minimum occurs at higher values of $B_{\phi c}$ and MPD, for the more aggressive magnet designs. The values for $B_{\phi c}$ used in the analyses were close to those producing minimum COEs for all cases. This minimum is sensitive to other physics (e.g., beta) and technology (e.g., coil current density versus maximum critical field) constraints. The impact on COE of the confinement concept per se is also shown on Fig. 1, including a second stability-region (SSR) tokamak and the RFP.

The basecase COE calculation for the fusion plants assumed full nuclear-grade construction, even though some of the concepts promise outstanding safety characteristics. Even with the requirement of full nuclear-grade construction, the range of COE for the fusion plants falls between those of the PWR/BE and PWR/ME plants (Table 5).

Safety trade-off

Based on the ESECOM safety and environmental assessment,[1] each concept was assigned a level of safety assurance (LSA) that within the context of the ESECOM study was determined primarily by materials of construction (kind of radioactivity) and the power density (probability of after-heat driven radioactive release). A favorable LSA rating (low LSA number) gave the basis for reduced nuclear-grade construction requirements with the best rating (LSA=1) associated with non-nuclear-grade materials and components. Cost reduction factors[13] were applied to a range of subsystems and weighted according to the LSA rating, with application of full LSA cost credits for non-nuclear construction achieving about a 25% reduction in COE. Table 6 gives the cost breakdown for the Li-V/TOK basecase and the impact of applying the full LSA cost credits. Since the different designs have different cost distributions, the overall cost reduction associated with full credits varies from plant to plant. The COE as a function of MPD, as $B_{\phi c}$ is varied, is also shown in Fig. 1 for the Li-V/TOK basecase with full LSA cost credits. The

Table 6. Cost reduction for V-Li/TOK if qualified for full Safety assurance credits.

Account description	Construction cost (M $) No credit		Full credit	
Land		5		5
Struct. and Impr.		320		218
Reactor bldg & hot cells	208		141	
Other struct. and impr.	112		77	
React. Plant Equip.		880		626
Shield	137		69	
Coils	191		133	
Structure	21		14	
Auxiliary power	133		133	
Heat transfer & transport	202		81	
Other reactor plant equip	197		197	
Turbine plant equipment		231		231
Electric plant equipment		121		69
Misc. plant equipment		45		35
Heat reject system		50		40
Total Direct Cost		1653		1224
Indirect Costs		620		367
Contingency		341		238
Total Overnight Cost		2614		1829
	Cost of Electricity (mills/kWh)			
Capital investment		35.05		24.53
"Fuel" related		9.21		5.88
Blankets	6.51		3.25	
Limiters	0.57		0.54	
Waste disposal	1.00		1.00	
Auxiliary power	0.78		0.73	
Other "fuel"	0.35		0.35	
Operation and Maintenance		8.87		8.87
Total COE		53.1		39.3

Table 7. Cost of electricity with safety assurance credits (mills/kWh)

	Nominal LSA	Without LSA credit	Nominal design estimate
V-Li/TOK	3	53.1	49.7
RAF-He/TOK	2	48.5	42.6
RAF-PbLi/RFP	4	37.7	37.7
V-Li/RFP	4[a]	37.3	37.3
SiC-He/TOK	1	54.6	40.3
V-FLiBe/TOK	2	47.9	42.9
V-MHD/TOK	4	35.4	35.4
V-DHe^3/TOK	2	47.8	41.3
RAF-Li/HYB	4		
stand-alone		63.7	63.7
with MHTGR client		40.3	40.3
SS-He/HYB	4		
stand-alone		55.8	55.8
with MHTGR client		39.8	39.8

[a]Another analysis of this design[6] predicts an LSA rating of 3

application of LSA cost credits does not affect the optimal value for $B_{\phi c}$ appreciably. The cost impact of the LSA ratings on each fusion plant is shown in Table 7. 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 cost credits. The LSA adjustments narrowed the COE range, since concepts with higher unadjusted costs usually had better LSA ratings. This result reflects a perceived trade-off through COE of power density and LSA rating.

Comparison with fission

The economic results of the ESECOM analyses, shown in Tables 5 and 7, imply that magnetic fusion energy has the potential to be competitive with alternative long-term energy sources. The range of costs for the fusion plants fall within the range of costs between present-day better-experience (PWR/BE) and median-experience (PWR/ME) fission reactors. This competitive potential does not depend on, but nevertheless is enhanced by, translating safety and environmental benefits into cost credits. Fusion plants with better safety assurance ratings tended to have advanced materials and relatively low power densities, both of which result in higher costs prior to adjustments related to LSA; the LSA adjustments tend to ameliorate these higher cost effects. The main design characteristics offering important benefits for lower COE are high LSA (SiC-He/TOK, RAF-He/TOK, V-FLiBe/TOK and V-DHe^3/TOK designs), compactness (RFP designs), improved coils (MHD and DHe^3 designs), advanced energy conversion (MHD and DHe^3 designs) and advanced fuels (DHe^3 design). The most potentially attractive cases considered by ESECOM were those involving the most physics and technology uncertainty, extrapolation, and/or (relatedly) lack of design detail.

Fusion/fission hybrids

The fusion hybrid breeder reactor was found to have potential as a first step in commercial deployment if fission reactors are available to provide a market for the fission materials produced. Fusion hybrid breeders have less COE uncertainty than systems based solely on fusion, because both cost and performance variations in the fusion breeder itself are distributed over a large number of client reactors with presumed less uncertain economics. Also, since the fusion breeder is primarily a fuel producer, its load carrying capability is not as important as for other fusion reactors. The fusion hybrid may also be economic in smaller unit sizes as demonstrated in Fig. 2. Although the COE of the stand alone fusion hybrid shows about the same economy of scale as the point-of-departure basecase, the combination of it with the constant size client fission reactors produce relatively stable average system (including client reactors) costs.

Physics trade-offs

The economic competitiveness of fusion is not automatic, however, but will depend critically on achieving the enhanced physics and engineering performance assumed in the study (Table 2). The economic importance of achieving enhanced plasma performance compared to conservative extrapolations of present-day parameters[14] indicates a 37% higher COE than the ESECOM basecase result[4] or about $135 million/year revenue requirements for a 1200 MWe plant. It is clear that fusion power based on the tokamak will not be competitive unless both physics and technological improvements are made. Lastly, the above conclusions that tokamak-based fusion with advanced physics may be economically competitive with fission must be tempered with a realization that, while both were assumed to operate with similar reliability, the fusion

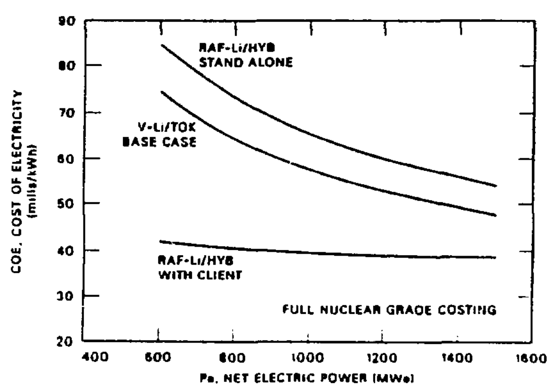

Fig. 2. Effects of plant size scaling on cost of electricity.

system, in addition to being constructed of more exotic (costly) materials, is subject to a wider range of operating environments. This system is an inherently more complex system and potentially can have both higher failure rates and longer time to repair.

Uncertainty analysis

It is realized that large uncertainty surrounds the cost results presented herein, not the least of which is system availability. The ESECOM study examined the effect on COE of a number of important engineering, physics, and operational uncertainties. These uncertainties were expressed quantitatively both by exploring the effect of the possible variable ranges using the Generomak model,[4] and by the more qualitative judgement of the committee as a whole. While physics uncertainties could result in "go/no-go" situations if some worse scenarios materialize, a more likely effect is a degradation of system performance and an increase in COE to uncompetitive levels. The ESECOM attempted to quantify the material and technological uncertainties, with the premise that the physics issues will be resolved at or near the reference values (Table 2). The committee assigned a high, medium or low economic uncertainty rating to each cost subaccount. It was then possible through this corporate value judgement to compute the fraction of COE for each design that is associated with each level of uncertainty. The results of this breakdown are shown in Fig. 3. The cost comparison for all ESECOM cases is shown, using pie diagrams placed at the nominal COEs of each fusion design indicating the uncertainty distribution. The percent of costs in each cost category is shown in tabular form. The shaded bars denote the ESECOM assessment of the range from optimistic to conservative evaluations of LSA. The blank bars extend the COE to that obtained without safety assurance credits. The dashed arrows indicate unquantified uncertainties related to physics and institutional factors.

The economic uncertainties extend in both directions, however. Physics or technological breakthroughs in the future, for instance, could extend the range in the optimistic direction; such a possibility is a second-stability regime for tokamaks.[4] A COE reduction for the "point of departure" V-Li/TOK in the range of 15-20% was estimated if the second-stability region is actually realized (Fig. 1). Other possibilities are advanced superconducting magnets and higher-temperature superconductors. Sensitivity studies performed as part of the ESECOM study indicate that application of the advanced (high field, high current density) magnets could reduce COE for the basecase by about 13%. These and other results of the ESECOM COE sensitivity analysis of various physics and technological assumptions are summarized in Table 8.

Table 8. Effect of uncertainty on basecase parameters[a]

	Change in COE (%)
Troyon coefficient, $\beta B_\emptyset a/I_\emptyset = .04$[o]	
Reduced from .04 to .03	+7
$\beta = .075$	
Proportional to $1/\kappa$+30	
$\beta = .04, \kappa = 2.5$	
$\beta B_\emptyset a/I_\emptyset = .016$	
Plasma safety factor, $q_\psi = 2.3$[b]	
Increase to $q_\psi = 4$	
Reduce β to .057	+10
Decrease A to 2.7	+13
Plasma elongation, $\kappa = 2.5$[b]	
Reduce elongation to 2 with A=3	+8
Blanket radiation life, 20 MW yr/m^2 [b]	
Decrease to 10 MW yr/m^2	+11
Current-drive efficiency, $\gamma = 2.7 A/m^2W$ ($I_\emptyset/P_{CD} = 0.2 A/W$)[b]	
Limit γ to 0.5 A/m^2W	+42
Limit γ to 0.5 A/m^2W and increase plasma temperature to 25 keV	+14
Include effect of bootstrap current	-8[c]
Use present-day, PCSR-E parameters[12]	+38
Eliminate nuclear-grade requirements	-25
Coil current density, $j_{\emptyset c} = 20.4$ MA/m^2 [b]	
Improved aggressive design $j_{\emptyset c} = 58$ MA/m^2, $B_{\emptyset c} = 18$T	-13
Plant lead time, 6 years[b]	
Reduce lead time by 1 year	-3
Blanket unit cost, 190 \$/kg[b,d]	
Reduce by 50%	-6
Achieve second stability	-16

[a] Changes are single-point variations from basecase(V-Li/TOK) parameters (Table 2)
[b] Basecase (V-Li/TOK) value
[c] Based on full 15.7 MA plasma current being sustained by bootstrap currents.
[d] installed cost

IV. CONCLUSIONS

The main economic conclusion of the ESECOM study is that magnetic fusion energy has the potential to be competitive with alternative long-range energy sources and that this potential is enhanced by translating safety and environmental benefits into cost credits. This potential, however, will not reach fruition unless physics and technology uncertainties are resolved favorably (i.e., Table 2). This favorable resolution will require a vigorous and sustained research and development program. While the ESECOM study represents a first broad step toward integrating economics with safety and environmental considerations, considerably more detailed work is needed. A continuing systematic assessment effort aimed at achieving attractive combinations of environmental,

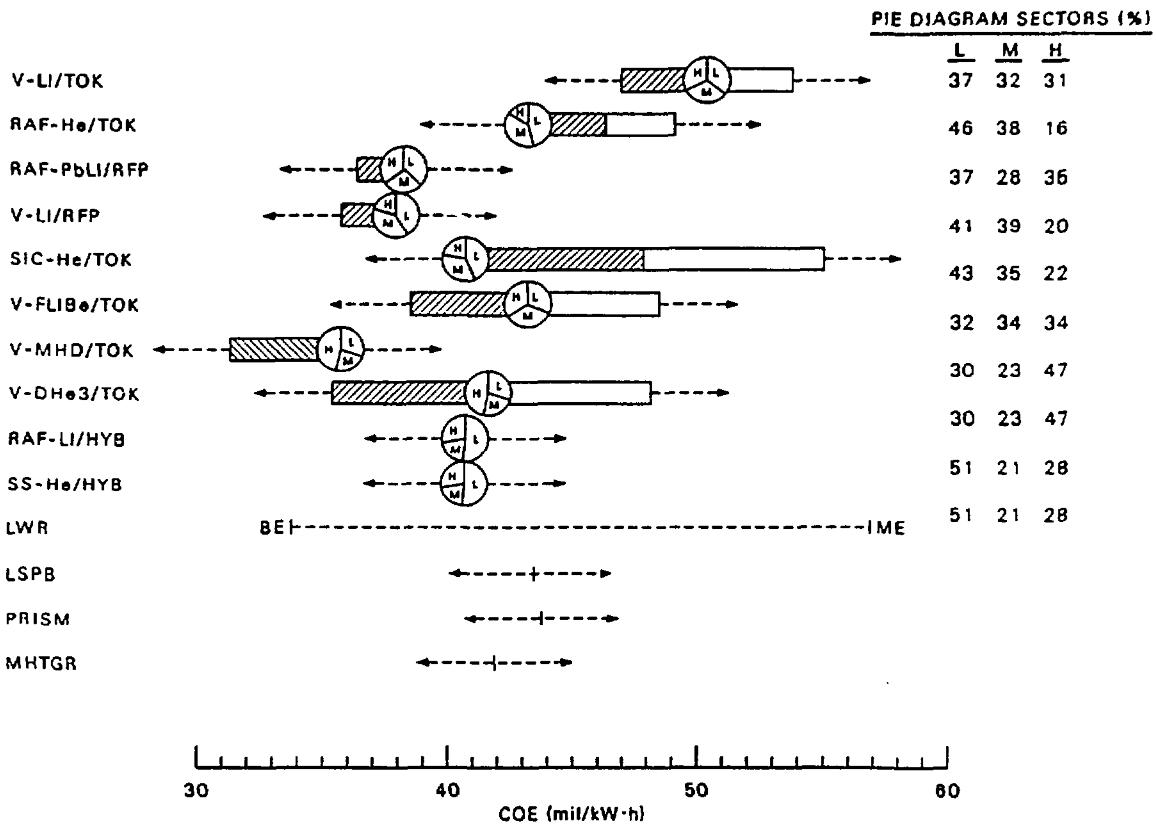

Fig. 3. The COE estimates for ESECOM cases with and without safety assurance credits. The pie diagrams are centered on the COE values corresponding to ESECOM's "nominal" LSA assignments. The pie slices labeled L, M, and H denote the fractions of these COEs associated with low, medium, and high cost uncertainties, as determined by assigning these designations to each cost account for each design. ESECOM did not do an uncertainty analysis broken down by cost accounts for the fission cases, so these have no pie diagrams. Where the "conservative" or "optimistic" LSA ratings differ from the nominal one, shaded bars span the corresponding cost range. Where the conservative LSA rating is <4, a blank bar extends to the COE obtained at LSA = 4 (that is, without safety assurance credits). The dashed arrows symbolize unquantified uncertainties in physics, materials, technology, and institutional factors. For the LWR, a dashed line spans the range between the "better-experience" and "median-experience" cases. All costs are in 1986 dollars.

safety, and economic characteristics is required; refinements in the costing model for each design should be made; and other designs/concepts that combine or enhance the better features of the various cases studied by ESECOM should be investigated.

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