UPDATED COMPARISON OF ECONOMICS OF FUSION REACTORS WITH ADVANCED FISSION REACTORS*

CONF-901007--2

DE90 017740

J. G. Delene

Engineering Technology Division
Oak Ridge National Laboratory

To be Presented at

Ninth Topical Meeting on the Technology of Fusion Energy

Oak Brook, Illinois

October 7-11, 1990

* Work sponsored by the Office of Fusion Energy, U. S. Department of Energy under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Updated Comparison of Economics of Fusion Reactors With Advanced Fission Reactors*

J. G. Delene
Oak Ridge National Laboratory
Oak Ridge, TN 37830
(615) 574-0316

ABSTRACT

The projected cost of electricity (COE) for fusion is compared with that from current and advanced nuclear fission and coal-fired plants. Fusion cost models were adjusted for consistency with advanced fission plants and the calculational methodology and cost factors follow guidelines recommended for cost comparisons of advanced fission reactors. The results show COEs of about 59-74 mills/kWh for the fusion designs considered. In comparison, COEs for future fission reactors are estimated to be in the 43-54 mills/kWh range with coal-fired plant COEs of about 53-69 mills/kWh ($2-3/GJ coal). The principal cost driver for the fusion plants relative to fission plants is the fusion island cost. Although the estimated COEs for fusion are greater than those for fission or coal, the costs are not so high as to preclude fusion's competitiveness as a safe and environmentally sound alternative.

I. INTRODUCTION

The ultimate viability of the fusion option for power generation will depend on its economic competitiveness with other options available in the same time frame. Fusion must either be directly competitive or offer sufficiently attractive economics so as to be a reasonable alternative in the event the more economic options become unacceptable. Although there are other possible sources of electric power on the horizon (i.e., solar, biomass), the principal alternatives for future large-scale base-load power generation should remain nuclear fission and coal-fired technologies. These technologies, however, have environmental and safety concerns which may eventually make them unacceptable. Advanced fission concepts now under development may reduce some of these concerns with their "passive safety" features. Such concepts include the Modular High-Temperature Gas-Cooled Reactor (MHTGR), Advanced Light Water Reactors (ALWRs) and Liquid Metal Reactors (LMRs). These concepts offer the prospect of reduced costs in addition to improved safety and environmental impact.

The analysis presented in this paper compares projected power costs from better current experience and advanced fission reactors and for an advanced fluidized bed coal-fired plant with projected costs for fusion power. Costs for the other advanced fission concepts (i.e., MHTGR and LMR) were not quantified in this study, but are expected to be in the same range as for the ALWRs. The analysis was performed using a consistent economic methodology developed for fission plant studies. In order to obtain a valid comparison between fission and fusion cost models, the non-fusion island costs for the fusion plant were adjusted for consistency with the fission costing assumptions.

II. ANALYSIS PROCEDURES

The general procedure was to apply the same costing methodology and cost factors used in the advanced fission reactor programs to fusion reactors and thereby obtain a consistent comparison.

A. General methodology

The general method used to estimate cost of electricity (COE) follows that recommended in the Nuclear Energy Cost Data Base[1] (NECDB) and in the Cost Estimating Guidelines (CEG) for advanced nuclear fission power technologies[2]. The NECDB methodology was developed for fission reactor studies and provides a basis for consistent comparisons between fusion and the alternatives. The recently published CEG follows the NECDB in general methodology and provides uniform procedures for developing cost estimates and guidelines for various cost factors including contingency and owner's cost. The CEG was

* Work sponsored by the Office of Fusion Energy, U. S. Department of Energy under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

developed to provide comparable cost estimates for advanced fissi·n reactor concepts.

B. Plant types

Nuclear fission plant designs used for the comparison include one consistent with the Better Experience for today's Pressurized Water Reactor (PWR) fission plants (PWR-BE); a large size (1200 MWe) evolutionary Improvement to the PWR-BE plant (IPWR); and a smaller (600 MWe) Advanced, passively safe plant (APWR). The Energy Economic *Data Base* (EEDB) *Phase X update*[3] includes construction cost models for these plants. The IPWR plant incorporates the effect of plant standardization and increased modularization of plant systems and equipment as well as the improved construction practices and regulatory reform implicit in the PWR-BE cost model. The APWR is a smaller reactor and includes application of passive safety features including related innovative design and construction features in addition to the assumption for the IPWR. The cost models for the IPWR and APWR are for Nth of a kind (NOAK) plants.

The coal-fired plant considered is also of advanced design. The cost model for this Atmospheric Circulating Fluidized Bed coal-fired plant is also based on an EEDB cost model[4].

Cost models for two fusion reactor concepts were included. The first is for the ESECOM studies[5] "point of departure" reactor, V-Li/TOK. This reactor represents a moderately advanced to advanced design and served as a reference point in the ESECOM study. The second fusion cost model is based on an ARIES design[6]. For the purposes of this cost comparison, both the ESECOM basecase and the ARIES plant were assumed to have a level of safety assurance equal to 3. The level of safety assurance (LSA) was defined in the ESECOM study, where a level 3 reactor is passively safe as long as there is no violation of small-scale geometry such as the rupture of a major coolant pipe. The passively safe APWR should also have an LSA factor of three, whereas the PWR-BE and IPWR have LSA factors of 4, which means that active safety systems are required.

C. Costing

All costs were updated to 1990 dollar cost levels for the comparison. The fusion plants' fusion island costs were not modified from previous estimates[5,6] other than for inflation. The fusion reactor's balance-of-plant costs were adjusted for consistency with the costs for similar items associated with the advanced fission plants. Thus, the turbine plant equipment cost model, etc., for the fusion plants are based on models developed for fission reactors. Costs were adjusted assuming that the IPWR is an LSA = 4 reactor and that the fusion reactors are both LSA = 3 as is the APWR. The costing algorithms in the Generomak code[7] were modified and the ESECOM basecase was rerun using the new costing. For the ARIES design, the starting point was a cost output from the ARIES study. Here, each cost account was adjusted using the same algorithms used for the ESECOM Basecase. The original ARIES fusion island costs, the cost for structures and site improvements, and the replacement costs were adjusted for inflation only. The reactor building is the major component in the structures account and insufficient information was available here for use with the cost algorithm.

Table 1. Technical and financial parameters

Plant size, MWe	1200
Levelization period, years	30
Reference cost year	1990
Year of plant startup	2025
Average inflation rate, %	5
Applicable tax law	TRA-86[b]
Cost of money during construction, %	11.35(6.05)[a]
Effective cost of money (discount rate), %	9.57 (4.35)[a]
Capacity/Availability factor, %	75

[a] Real, inflation adjusted rates in parenthesis
[b] Tax Reform Act of 1986

Technical and financial parameters used in the comparison are shown in Table 1. All plants are assumed to start operation in the year 2025. The PWR-BE, IPWR and both fusion plants are single 1200 MWe units. The APWR and coal-fired plant consist of two-600 MWe units. All cost models were scaled to the reference plant sizes for consistency. A 30-year levelized 1990 dollar COE was estimated. In performing the analysis a 5%/year inflation/cost escalation rate is assumed. The cost of money during construction and the effective cost of money during operation (adjusted to account for tax deductibility of debt interest) are those recommended in the NECDB. Both the nominal rates, with inflation, and the "real" rates, with inflation removed, are shown.

Cost factors used in the calculations are given in Table 2. A 2-year design plus 4-year construction lead time is assumed for the fusion plants. This is consistent with lead times projected for the advanced fission and coal-fired plants. The current "better experience" plants have total lead times of about 8 years or more.

Table 2. Cost factors

Plant	Lead Time (Years)	Indirect cost Factor	Contingency Factor	IDC Factor[a]	Fixed Charge Rate[a]
Fusion	6	0.431	0.184	1.189	0.0962
PWR/BE	8	0.764	0.196	1.283	0.0972
IPWR	6	0.479	0.195	1.189	0.0962
APWR	6	0.455	0.186	1.189	0.0962
Coal-fired	6	0.380	0.15	1.175	0.0983

[a] Constant 1990 dollar values

A breakdown of the Total Indirect cost factor is shown in Table 3 for the PWR-BE and Fusion plants. The fusion plant indirect costs are consistent with those for the IPWR and APWR after adjusting for unit size and LSA factor. The owner's cost factor is applied to total direct + other indirect costs and is specified in the CEG as 15%.

Table 3. Indirect cost factors (%)

Account	PWR-BE	Fusion (LSA-3)
91 Const. services[a]	19.1	12.8
92 Eng. & home off. serv.[a]	22.4	5.2
93 Field superv. & serv.[a]	11.9	6.4
94 Owner's cost[b]	15.0	15.0

[a] % of total direct costs
[b] % of total direct costs plus other indirect costs

The CEG also specifies the use of a 25% contingency factor for nuclear-safety grade construction and 15% for normal industrial construction. The 18.4% factor for fusion plant contingency represents a 25% reduction in the nuclear grade portion of these plants compared to an IPWR. The Interest During Construction (IDC) factor accounts for the cost of construction money. It is applied to the total of direct costs, indirect costs and contingency allowance to obtain the total capitalized plant cost. The IDC factor was calculated using the quarterly accounting procedure recommended in the CEG. Other construction profiles, such as that used in the ESECOM study, will give somewhat different capitalization factors. This factor depends on the total lead time and time pattern of construction expenditures. The fixed charge rate is a factor which when multiplied by the initial capitalized investment will give an equivalent annual cost of capital. The nominal dollar (including inflation) rate is approximately 0.165. The constant dollar fixed charge rates shown give an equivalent annual cost of capital in constant 1990 dollars. The rate will vary somewhat with plant type and lead time because of income tax considerations.

III. RESULTS

Capital investment cost breakdowns for the PWR-BE and for the ESECOM V-Li/TOK basecase with both LSA = 3 and LSA = 4 assumptions are given in Table 4. Although there are some differences between the costs for the PWR-BE and the LSA = 4 V-Li/TOK in nearly all accounts, the principal difference is in the "so-called" nuclear island costs with lesser differences for the heat transfer system and reactor building costs.

Table 4. Capital investment (million 1990 dollars)

Account description	PWR-BE	V-Li/TOK	
	LSA=4	LSA=4	LSA=3
Land and land rights	10	10	10
Struct. and impr.	259	381	313
Reactor bldg & hot cells	84	199	191
Other struct. & impr.	175	183	122
Reactor plant equipment	364	1014	965
Nuclear island	62[a]	536[b]	499[b,c]
Heat transfer syst.	85	271	271
Other react. plt. eq.	217	207	195
Turbine plant equipment	272	253	253
Electric plant equipment	102	127	107
Misc. plant equipment	57	53	49
Heat reject system	61	58	58
Total direct costs	1124	1896	1755
Indirect costs	853	917	757
Contingency	387	549	462
Total overnight cost	2364	3362	2794
Interest charge	669	589	521
Total capital cost	3033	3950	3495

[a] Excludes initial fuel charge, cost including initial fuel = $145 million.
[b] Excludes replaceable components such as blankets
[c] Cost including initial replaceable components = $800 million.

The heat transfer system difference is caused by the difference in cooling system; the PWR-BE is water cooled whereas the fusion plant is cooled with liquid lithium and requires an intermediate heat exchanger. The larger, lower energy density fusion reactor also requires a larger containment building and hot cells are included whereas they are not required for the PWR-BE. The nuclear island for the PWR-BE includes the reactor vessel and its internals. The initial nuclear fuel will cost an estimated additional $84 million. The fusion plant nuclear island cost for the V-Li/TOK includes only permanent components. The costs of non-permanent components, such as the blanket, are included with replacement costs in the same way that initial fuel load is included with fuel costs for fission reactors. If the blankets and other replaceable items were included as initial investment instead of as an operating cost, the total capital cost would be about $300 million more. The ARIES cost estimate, however, includes the initial blanket with the capital cost.

A summary of the investment costs for all plants is given in Table 5. It should be noted that the costs for the IPWR, APWR and ARIES are still preliminary and will most likely be modified in future cost models. The projected capital costs for the advanced fission plants are close to that for the coal-fired plant.

The estimated levelized COE for each concept is shown in Table 6. Costs are for the reference 1200 MWe plant size, however, costs are also shown for a single 600 MWe unit ALWR and coal-fired plant. The total capitalized cost multiplied by the fixed charge rate (Table 2) and divided by the annual electric power delivered to the grid, gives the levelized cost from capital investment. This is shown in the first cost column of Table 6.

Table 5. Capitalized investment costs
(Million 1990 Dollars)

Plant[a]	Direct Cost	Indirect Cost	Contingency	IDC Cost	Total Cost
V-Li/TOK	1755	757	462	521	3495
ARIES	2449	1054	644	727	4875
PWR/BE	1124	853	387	669	3033
IPWR	1033	495	298	346	2172
APWR	1119	446	291	351	2207
COAL	1164	411	236	317	2128

[a] 1200 MWe plant size

The Operation and Maintenance (O&M) costs for fission power plants have increased in recent years. The O&M costs used in this analysis are based on an ORNL study[8]. The procedures in that study were extended to provide cost models for improved fission plants and for fusion plants. An O&M cost increase for fusion relative to fission plants due to their greater complexity is compensated by reduced security needs and reduced radiation cleanup and protection.

The initial blanket is included in the fuel/replacement cost category for the V-Li/TOK plant, whereas it is included with capital for ARIES. The fission plants use high burnup, low leakage fuel cycles. A uranium cost of $130/kg U ($50/lb. U_3O_8) and an enrichment cost of $60/SWU are assumed for the second quarter of the next century. Coal prices are assumed in a range from $2-3/GJ with the fuel cost shown for an average of $2.50/GJ.

Table 6. Levelized cost of electricity
(1990 $ Mills/KWh)

Plant Type	Units-size MWe	Capital	O & M	Fuel	Decommissioning	Total COE
V-Li/TOK	1-1200	42.7	8.7	7.5*	0.5	59
ARIES	1-1200	59.0	8.7	5.9	0.5	74
PWR-BE	1-1200	37.6	9.2	7.1	0.5	54
IPWR	1-1200	26.5	9.2	7.2	0.5	43
APWR	1- 600	31.1	13.0	7.5	0.8	52
	2- 600	26.9	9.8	7.5	0.8	45
Coal	1- 600	29.7	9.8	24.2	0.1	64
	2- 600	26.5	7.4	24.2	0.1	58

* Includes blanket replacement.

IV. DISCUSSION OF RESULTS

The total cost of electricity (COE) for each power plant is shown in the last column of Table 6. Based on the plants and unit sizes considered, a COE range of 59-74 mills/kWh is indicated fusion; whereas the range for nuclear fission is 43-54 mills/kWh and that for coal-fired plants is 53-69 mills/kWh ($2-3/GJ coal price). There are both prospects for large cost increases in the fusion plants as designs are better defined and problems more understood and for cost decreases resulting from technological advances. The principal cost driver for the fusion plants relative to fission plants is the cost of the fusion island. This cost of about $800 million for the ESECOM basecase compares to about $145 million for the PWR-BE reactor vessel, internals and initial fuel. A more expensive heat transfer system, larger containment building and the internal electric requirements also contribute to the fusion cost disadvantage. The main design characteristics leading to lower COE are a high degree of safety assurance, improved physics, compact design, improved coils, and advanced energy conversion coupled with the use of advanced fuels.[9,10,5]

On the other side, the cost reductions projected for the advanced reactor may not be fully realized, or fission reactors may not be acceptable by the public or electric utilities at any price. Although fission power is considered safe by nearly all of the technical community, the events at Three Mile Island, Chernobyl, and the continuing controversy surrounding high level waste disposal create a negative public perception. Coal is also not immune to uncertainty. Future regulations of coal-fired plants pertaining to acid rain and potential CO_2 problems could raise power costs from this source appreciably and even eliminate it as a future source of power if global warning becomes a serious threat. Uncertainty in the future cost of coal is also very large with large variations from region to region.

V. CONCLUSION

Although the COE for fusion estimated in this study is greater than that for advance fission reactors, the costs are not so high as to preclude future competitiveness based on advanced designs and technological breakthroughs. In addition, fusion offers a safe and environmentally sound alternative in the event the more economic alternatives become unacceptable.

REFERENCES

1. "Nuclear Energy Cost Data Base, A Reference Data Base for Nuclear and Coal-Fired Power Generation Cost Analysis," U.S. Department of Energy, Office of Nuclear Energy DOE/NE-0095 (1988).

2. J. G. Delene and C. R. Hudson II, "Cost Estimate Guidelines for Advanced Nuclear Power Technologies," Oak Ridge National Laboratory Report ORNL/TM-10071/R2 (1990).

3. United Engineers & Constructors, Inc., "Phase X Update (1988) Report for the Energy Economic Data Base Program EEDB-9," U.S. Department of Energy, Office of Nuclear Energy (to be published 1990).

4. United Engineers & Constructors, Inc., "Energy Economic Data Base (EEDB) Program Phase IX Update (1987) Report AHS5-AF Supplement," Oak Ridge National Laboratory Report ORNL/Sub/87-86004/4 (1988).

5. J. P. Holdren, et. al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," Lawrence Livermore Laboratory Report UCRL-53766 (1989).

6. "Executive Summary of ARIES Reactor Design," University of California, Los Angeles Report UCLA-PPG-1300 (to be published 1990).

7. J. G. Delene, et. al., "Generomak Fusion Physics, Engineering and Costing Model," Oak Ridge National Laboratory Report ORNL/TM-10728 (1988).

8. H. I. Bowers, L. C. Fuller, M. L. Myers, "Cost Estimating Relationships for Nuclear Power Plant Operation and Maintenance," Oak Ridge National Laboratory report ORNL/TM-10563 (1987).

9. J. G. Delene and R. A. Krakowski, "Economic Implications for Fusion Derived from ESECOM Study," Fus. Technol. 15 (1989) 1225.

10. R. A. Krakowski and J. G. Delene, "Connections Between Physics and Economics for Tokamak Fusion Power Plants," J. Fus. En. 7 (1988) 49.

The Ultimate Viability of Fusion will Depend on its Economic Competitiveness with Other Available Electric Generation Options

- Nuclear Fission
- Coal-fired

Economics May be Tempered by Safety and Environmental Concerns

There are Advanced Fission Concepts Under Development Which Offer Prospects for Cheaper Power and Enhanced "Passive" Safety

- Improved Light Water Reactors (IPWR)
- Advanced Light Water Reactors (APWR)
- Modular High-Temperature Gas-Cooled Reactors (MHTGR)
- Advanced Liquid Metal Reactors (ALMR)

Improved Coal-Fired Technologies are also on the Way

- Advanced Fluidized Bed Combustion (AFBC)
- Advanced Gas-Turbine Combined Cycle (CCGT)

In Other Words -- The Competition is Not Standing Still

This Study Updates the Comparison of Fusion Costs with the Alternatives by Considering Advanced Fission and Coal-fired Technologies

- PWR-BE (Today's Better Experience Plant)
- IPWR
- APWR
- AFBC Coal-fired plant

For the Comparison, two Fusion Plants were Considered:

- ESECOM's V-Li/TOK
- ARIES-I

Fusion Balance of Plant Costs were updated for Consistency with the Advanced Fission Plants

The Methodology and Basic Cost Information were from Fission Reactor Program Sources

- Fission and Coal-fired Plant Capital Cost Models are from the Energy Economic Data Base (EEDB)

- General Levelized Cost Methodology, Financial Parameters and Fission and Coal cost Information from Nuclear Energy Cost Data Base (NECDB).

- Various Other Cost Factors from the "Cost Estimate Guidelines for Advanced Nuclear Technologies" (CEG).

Technical and Financial Parameters are Based on the 1988 Revision to the Nuclear Energy Cost Data Base

Plant Size, MW(e)	1200
Levelization Period, Years	30
Reference Cost Year	1990
Year of plant startup	2025
Average Inflation Rate, %	5
Applicable Tax Law	TRA-86[b]
Cost of Money during Construction, %	11.35 (6.05)[a]
Effective Cost of Money (Discount Rate), %	9.57 (4.35)[a]
Capacity/Availability Factor, %	75

[a] Real, inflation adjusted rates in parenthesis
[b] Tax Reform Act of 1986

Indirect Costs, Contingency Allowance and Interest Charges Must be Added to Direct Construction Costs to Obtain the Total Capital Cost

Plant	Lead Time (Years)	Indirect cost Factor	Contin-gency Factor	IDC Factor[a]	Fixed Charge Rate[a]
Fusion	6	0.431	0.184	1.189	0.0962
PWR/BE	8	0.764	0.196	1.283	0.0972
IPWR	6	0.479	0.195	1.189	0.0962
APWR	6	0.455	0.186	1.189	0.0962
Coal-fired	6	0.380	0.15	1.175	0.0983

[a] Constant 1990 dollar values

Indirect Cost Factors for Advanced Plants Reflect Standardized Nth-of-a Kind (NOAK) Plant Assumption

Account	Factors, %		
	PWR-BE	APWR	Fusion
91 Const. Services[a]	19.1	13.6	12.8
92 Eng. & Home Off. Serv.[a]	22.4	6.0	5.2
93 Field Superv. & Serv.[a]	11.9	6.9	6.4
94 Owner's Cost[b]	15.0	15.0	15.0

[a] % of total direct costs
[b] % of total direct costs plus other indirect costs

The 15 % Owners Cost Adder is Specified in the Advanced Fission Reactor Costing Groundrules

Capital Cost Differences Between Fission and Fusion are Primarily in the Nuclear Island, Reactor Building and Heat Transfer System.

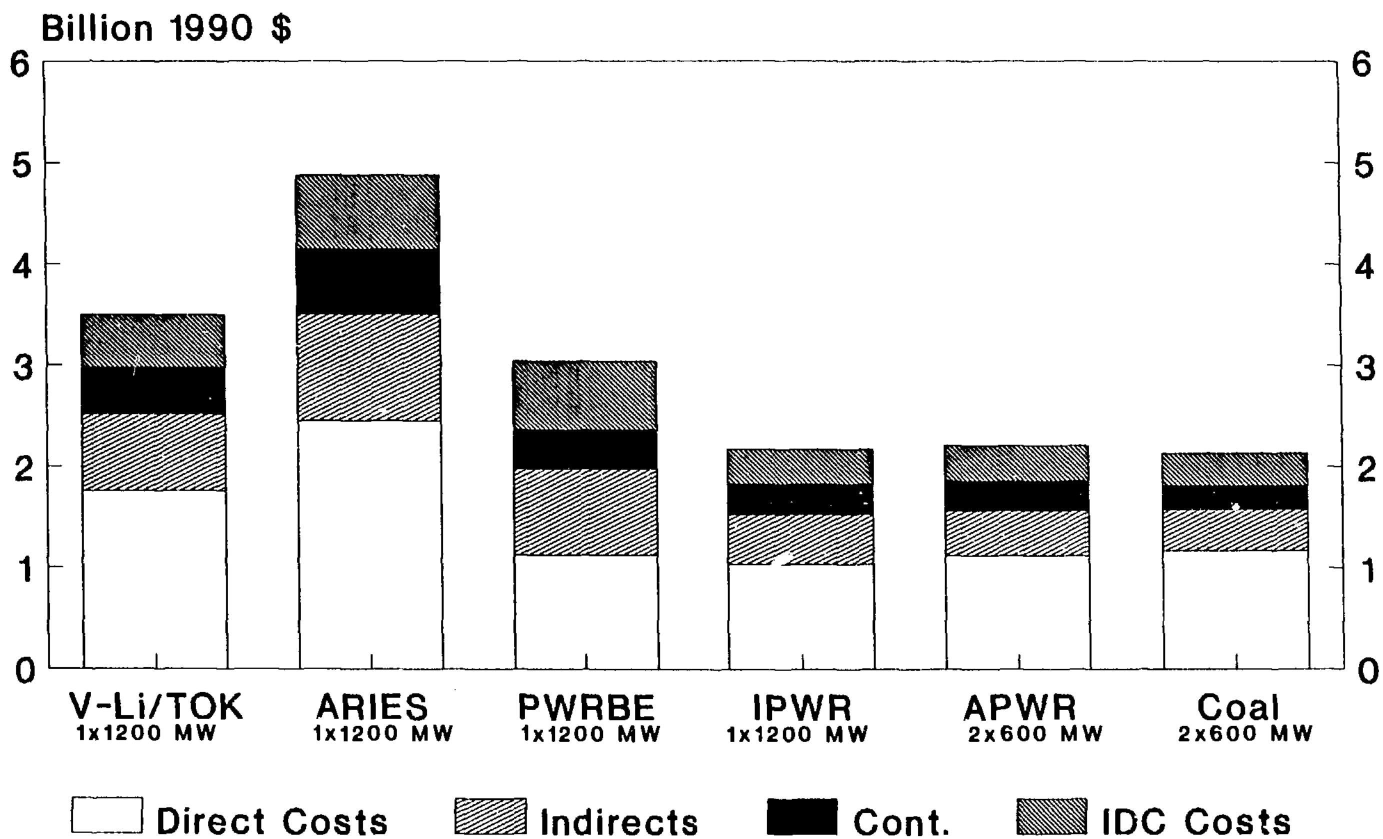
Account description	PWR-BE		V-Li/TOK LSA=4		V-Li/TOK LSA=3	
	Capital Investment Cost, Million 1990 $					
Land and land rights		10		10		10
Struct. and Impr.		259		381		313
Reactor Bldg & hot cells	84		199		191	
Other Struct. & impr.	175		183		122	
Reactor Plant Equipment		364		1014		965
Nuclear island	62[a]		536[b]		499[bc]	
Heat Transfer syst.	85		271		271	
Other react. plt. eq.	217		207		195	
Turbine plant equipment		272		253		253
Electric plant equipment		102		127		107
Misc. plant equipment		57		53		49
Heat reject system		61		58		58
Total direct cost		1124		1896		1755
Indirect costs		853		917		757
Contingency		387		549		462
Total overnight cost		2364		3362		2794
Interest charge		669		589		521
Total capital cost		3033		3950		3495

[a] excludes initial fuel charge, cost including initial fuel = $ 145 million.

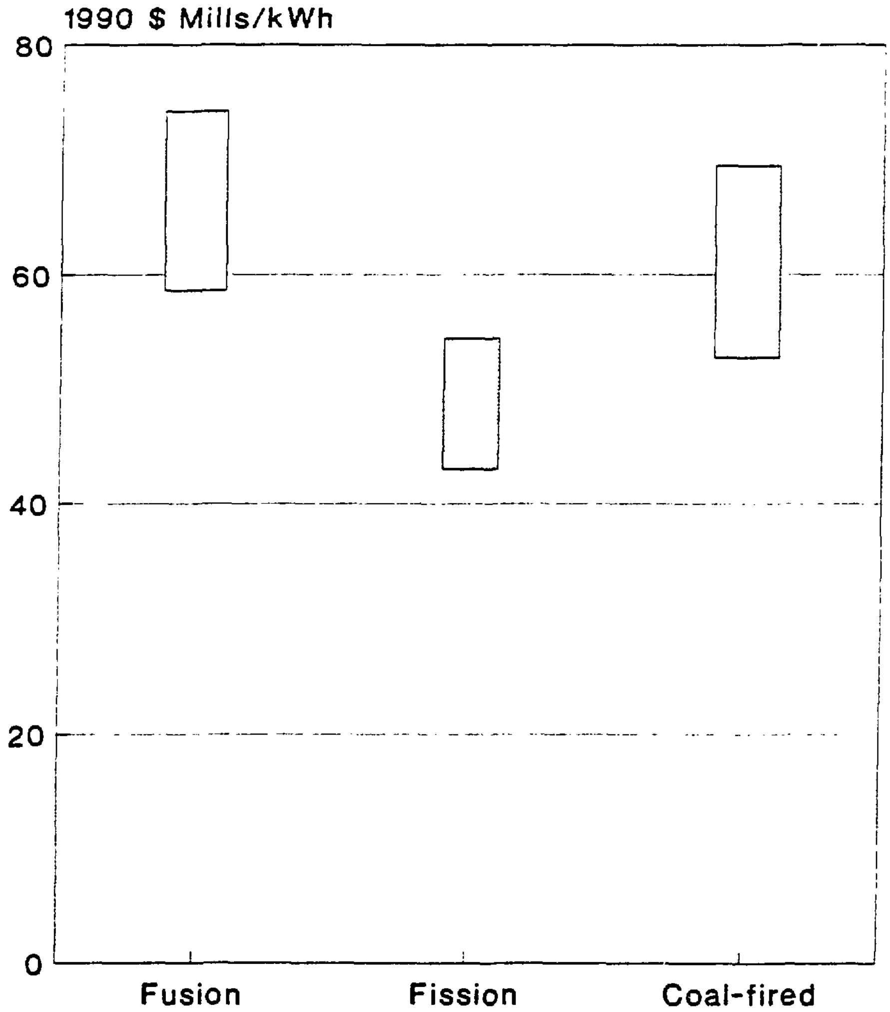
[b] excludes replacable components such as blanket.

[c] cost including initial replacable components = $ 800 million.

The Capital Investment Costs for the Fusion Plants are Significantly Higher than those for Advanced Fission and Coal-Fired Plants



The Cost of Electricity from the Fusion Options Was Found to be Higher than those from Fission, and in the Upper Range of Coal COEs.



The Higher Capital Charges are the Principal Cause of Fusion's Higher Cost of Electricity.

[1990 $ Mills/KWh(e)]

Plant Type	Units-size MW(e)	Capital	O & M	Fuel	Decommiss-ioning	Total COE
V-Li/TOK	1-1200	42.7	8.7	7.5[a]	0.5	59
ARIES	1-1200	59.0	8.7	5.9	0.5	74
PWR-BE	1-1200	37.6	9.2	7.1	0.5	54
IPWR	1-1200	26.5	9.2	7.2	0.5	43
APWR	1- 600	31.1	13.0	7.5	0.8	52
	2- 600	26.9	9.8	7.5	0.8	45
Coal	1- 600	29.7	9.8	19-29[b]	0.1	59-69[b]
	2- 600	26.5	7.4	19-29[b]	0.1	53-63[b]

[a] Includes blanket replacement.

[b] Coal Price Range of $2 - $3/GJ.

In Conclusion:

Although the COE for Fusion is Greater than for the Alternatives, The Cost is not so High as to Preclude its Future Competitiveness

- Use of Advanced Designs
- Technological Breakthroughs

Fusion Offers a Safe and Environmentaly Sound Alternative in the Event the More Economic Alternatives Become Unacceptable