APPENDIX C

INERTIAL FUSION ENERGY REACTOR DESIGN STUDIES

COST BASIS

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INTRODUCTION

The economic basis for the Prometheus IFE Reactor Design Studies is presented in this Appendix C. One of the major tasks of the study was to conduct an economic assessment of the two reactor designs developed. In order to provide compatibility with other fusion and fission reactor design studies, the groundrules and estimating guidelines were established to allow consistency in the study comparisons. The IFE Reactor Study Oversight Committee provided the study team with a recommended set of guidelines[1]. Chapter 3 of the study final report documented all the technical and economic guidelines and recommendations which were implemented. The economic guidelines will be repeated here for completeness.

The analyses and methodologies used herein were outgrowths of reactor design studies conducted in the late 1970s and early 1980s, such as UWMAK and STARFIRE studies. Later studies have built upon those early efforts and have improved the overall methodology. However, realistic economic assessments of a future technology cannot be accomplished with a high degree of fidelity due to the degree of extrapolation over many years. Many tools are used to account for proper modeling of tax structures, depreciation, cost of money, fixed charge rates, and inflation rates. References 2 and 3 have significantly improved these economic models. The latest MFE reactor design studies, the ARIES series, have contributed toward normalization of such economic factors as noted in Reference 4.

Table C-1 presents the economic requirements and criteria employed in the Prometheus IFE Reactor Design Studies. These data have been coordinated with the Oversight Committee (Robert Krakowski), ARIES (Ron Miller), and the other parallel IFE reactor design study[5] (Wayne Meier). The factors used for the plant lifetime, lead time, and general economic and tax factors have generally been proposed by Delene[3] and accepted by the fission and fusion energy community. Delene (and the Oversight Committee) has also recommended the indirect cost factors be adjusted depending upon the LSA factor. A trade study on this factor was discussed in Section 6.13 of the Prometheus final report.

The cost for operations and maintenance cost was adopted from the ARIES study. The magnitude of the scaling coefficient was increased to bring the ARIES 1988$ cost basis to the study guideline of 1991$. As noted in Table C-1, the Gross National Product Implicit Price Level Deflators were used as the basis for inflating/deflating specific cost values. Table C-2 presents specific deflator data from 1980 to 1991.

Decommissioning costs were addressed in the recommended guidelines for the study, namely a range of 0-1 mill/kWh with an LSA dependency. Treatment of these costs were addressed in detail in a subsequent section in this Appendix.

Table C-1 Economic Requirements and Criteria

Plant Operating Lifetime, yrs	30				
Plant Construction Lead Time, yrs	6				
Contingency Factor, Project and Process	See below, may add risk factor				
Spare Parts Multiplier	1.0 (no spares)				
Constant Year Dollars	1991				
Nominal Year Dollars	1997				
Inflation Rate	.05				
Escalation Rate	.05				
	Average	Tax-Adjusted			
Effective Cost of Money, Nominal Dollars	.1135	.0957			
Effective Cost of Money, Constant Dollars	.0605	.0435			
Fixed Charge Rate, Nominal Dollars	.1638				
Fixed Charge Rate, Constant Dollars	.0966				

Indirect Cost Factors		LSA 1	2	3	4
91 Constr Serv & Equipment	(x TDC)	.113	.120	.128	.151
92 Home Office Engr & Services	(x TDC)	.052	.052	.052	.052
93 Field Office Engr & Services	(x TDC)	.052	.060	.064	.087
94 Owners Cost	(x TDC+91+92+93)	.150	.150	.150	.150
95 Process Contingency	(x TDC+91+92+93+94)	.000	.000	.000	.000
96 Project Contingency	(x TDC+91+92+93+94)	.1465	.173	.184	.195

	Constant $	Nominal $
97 IDC Factor	.1652	.3178
98 EDC Factor	-0	.2436

Operations and Maintenance Cost [$91]	$78.9x(L^*)\ (P_E/1200)^{0.5}$
LSA Factor, L*	0.7[1]; 0.85[2]; 0.952[3]; 1.0[4]
Decommissioning Allowance, mill/kWeh	0-1 (LSA-dependent)
Deuterium Fuel Cost, mill/kWeh	-0.05
Learning Curve	85-90% on fusion systems, 75-100% on non-fusion systems
Quantity Assumption	10th of kind commercial plant + Prototype and Demo if applicable
Other Factors Influencing the Economics	
Plant Availability/Capacity	Value derived from design approach. Will use typical MCF values (.75) as a starting value
Cost Adjustment Factor up to 1991$	Use Gross National Product Implicit Price Level Deflators [1982 Basis]

Table C-2 Commerce Department Gross National Product Implicit Price Level Deflators (1982 Basis Year)

Year	Annual Deflator	Rate of Change Change
1980	85.7	9.0
1981	94.0	9.7
1982	100.0	6.4
1983	103.9	3.9
1984	107.7	3.7
1985	110.9	3.0
1986	113.8	2.6
1987	117.4	3.2
1988	121.3	3.3
1989	126.3	4.1
1990	131.5	4.1
1991	138.1*	5.0 (assumed 5% Inflation)

Another of the Oversight Committee's recommendations was the use of common costing accounts[1]. The set given to the two design teams was developed by ARIES. This set was slightly modified for the Prometheus study to include IFE-specific equipment as shown in Table C-3. One of the changes was to incorporate the Target Manufacturing Plant Equipment and the Driver Plant Equipment into separate main Accounts 26 and 27. The Driver Plant Equipment has unique account names for several subaccounts, such as Ion Source or Driver Optics. Other driver accounts are common such as Pulsed Power Systems. Buildings were added in the Structures and Site Facilities Account for these new systems. Most other accounts were suitable with minor changes.

Table C-3 Prometheus Plant Cost Accounts

Number	Title
20.00	Land and Land Rights
20.01	Land and Privilege Acquisition
20.02	Relocation of Bldgs, Util, etc.
21.00	Structures and Site Facilities
21.01	Site Improvements and Facilities
21.01.01	General Yard Improvements
21.01.03	Transportation Access
21.01.02	Waterfront Improvements
21.02	Reactor Building
21.02.01	Basic Building Structures
21.02.02	Building Services
21.02.03	Containment Structures
21.02.04	Architectural
21.03	Driver Building (incl Tunnels/F.Focus/Pwr Supply)
21.03.01	Basic Building Structures
21.03.02	Building Services
21.03.03	Architectural
21.04	Turbine Building
21.04.01	Basic Building Structures
21.04.02	Building Services
21.04.03	Architectural
21.05	Heat Rejection Structures
21.05.01	Intake Structures
21.05.02	Discharge Structures
21.05.03	Unpressurized Intake & Discharge Conduits
21.05.04	Recirculating Structures
21.05.05	Cooling Tower Systems (See 23.03 for Cooling Towers)
21.06	Auxiliary Building
21.06.01	Basic Building Structures
21.06.02	Building Services
21.06.03	Architectural
21.07	Target Manufacturing Building
21.07.01	Basic Building Structures
21.07.02	Building Services
21.07.03	Architectural

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
21.08	Tritium and Waste Processing Building
21.08.01	Basic Building Structures
21.08.02	Building Services
21.08.03	Architectural
21.09	Miscellaneous Buildings
21.09.01	Administration Building
21.09.02	Control Room Building
21.09.03	Diesel Generator Building
21.09.04	Service Building
21.09.05	Cryogenics Building
21.09.06	Ventilation Stack
21.09.07	Misc Structures and Building Work
21.98	Spare Parts Allowance
21.99	Contingency Allowance
22.00	Reactor Plant Equipment
22.01	Reactor Equipment
22.01.01	First Wall and Blanket
22.01.01.01	First Wall Material and Structure
22.01.01.02	Blanket Structure and Cooling Tubes
22.01.01.03	Breeding Material
22.01.01.04	Attenuators, Reflectors, and Multipliers
22.01.01.05	Other
22.01.02	Shield and Vacuum Vessel
22.01.02.01	Vacuum Vessel Structure
22.01.02.02	Shielding Material (Bulk and Beamline)
22.01.02.03	Cooling Plumbing
22.01.03	Primary Structure
22.01.03.01	Reactor Support Structure
22.01.03.02	Equipment Support Structure
22.01.03.03	Cavity Support Pedestal
22.01.04	Cavity Vacuum
22.01.04.01	Helium Liquifier-Refrigerators
22.01.04.02	Vacuum Pumps
22.01.04.03	Backing Pumps
22.01.04.04	Vacuum Plumbing
22.01.04.05	Plenum Chamber
22.01.04.06	Other
22.01.05	Target Injection and Tracking
22.01.05.01	Accelerating Tube System
22.01.05.02	Sabot Retrieval System
22.01.05.03	Cryogenic System
22.01.05.04	Target Tracking System
22.01.05.06	Target and Sabot Storage System
22.02	Main Heat Transfer and Transport Systems
22.02.01	Primary Lead Coolant Subsystem
	Pumps and Motor Drives
	Piping
	Heat Exchangers, Steam Generators, Superheaters, Reheaters
	Tanks (Dump, Makeup, Clean-up...)
	Coolant Cleanup and Tritium Extraction System
	Thermal Insulation, Piping, and Equipment

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
	Tritium Extraction
22.02.02	Primary Helium Coolant Subsystem
	Pumps and Motor Drives
	Piping
	Heat Exchangers, Steam Generators, Superheaters, Reheaters
	Tanks (Dump, Makeup, Clean-up...)
	Coolant Cleanup and Tritium Extraction System
	Thermal Insulation, Piping, and Equipment
	Tritium Extraction
22.02.03	Primary Driver Waste Heat Coolant Subsystem
	Pumps and Motor Drives
	Piping
	Heat Exchangers, Steam Generators, Superheaters, Reheaters
	Tanks (Dump, Makeup, Cleanup...)
	Coolant Cleanup and Tritium Extraction System
	Thermal Insulation, Piping, and Equipment
22.02.04	Intermediate Coolant Subsystem (Not Used)
22.02.05	Secondary Coolant Subsystem (Not Used)
22.03	Auxiliary Cooling System
22.03.01	Shield and Structure Cooling Subsystem
	Pumps and Motor Drives
	Piping
	Heat Exchanger Equipment
	Tanks
	Pressurizing Equipment
	Cleanup Equipment
22.03.02	Final Optics and Beamline Cooling Subsystem
	Pumps and Motor Drives
	Piping
	Heat Exchange Equipment
	Tanks
	Pressurizing Equipment
	Cleanup System
22.03.03	Cryogenic Cooling Subsystem
	Helium Liquefier - Refrigerator
	LHe Transfer and Storage
	He Gas Storage
22.03.04	Other Cooling Subsystems
	Pumps and Motor Drives
	Piping
	Heat Exchange Equipment
	Tanks
	Pressurizing Equipment
	Cleanup System
22.04	Radioactive Waste Treatment and Disposal System
22.04.01	Liquid Waste Processing & Equipment Subsystem
22.04.02	Gaseous Wastes & Off-gas Processing Subsystem
22.04.03	Solid Waste Processing Equipment Subsystem
22.05	Fuel Cycle System
22.05.01	Chamber Exhaust Gas Processing (incl Beamlines gases)
22.05.02	Breeder Purge Gas Processing

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
22.05.03	Impurity Processing (Incl Lead Coolant Stream)
22.05.04	Water Processing
22.05.05	Isotope Separation System
22.05.06	Tritium and Deuterium Storage
22.05.07	Atmospheric Tritium Recovery
22.05.08	Waste Products Handling and Storage
22.06	Reactor Plant Maintenance
22.06.01	Reactor Cavity Maintenance Equipment
22.06.02	Hot Cell Maintenance Equipment
22.06.03	Final Optics Maintenance Equipment
22.07	Reactor Plant Instrumentation and Control System
22.07.01	Reactor Instrumentation & Control Equipment
22.07.02	Radiation Monitoring Systems
22.07.03	Isolated Indicating & Recording Systems
22.08	Other Reactor Plant Equipment
22.08.01	Special Heating Systems
22.08.02	Coolant Receiving, Storage and Makeup Systems
22.08.03	Gas Systems
22.08.04	Building Vacuum Systems
22.98	Spare Parts Allowance
22.99	Contingency
23.00	Turbine Plant Equipment
23.01	Turbine-Generators
	Turbine-Generators and Accessories
	Foundations
	Standby-Exciters
	Lubrications Systems
	Gas Systems
	Reheaters
	Shielding
23.02	Main Steam System
23.03	Heat Rejection System
	Water Intake Common Facilities
	Circulating Water Systems
	Cooling Towers
	Other Heat Rejection Systems
23.04	Condensing Systems
	Condensers
	Condensate System
	Gas Removal System
	Turbine By-pass Systems
23.05	Feed Heating System
	Regenerators & Recuperators
	Pumps
	Tanks
23.06	Other Turbine Plant Equipment
	Turbine Auxiliaries
	Auxiliaries Cooling System
	Makeup Treatment System
	Chemical Treatment and Condensate Purification System
	Central Lubrication Service System

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
23.07	Turbine Plant Instrumentation & Control
	Process Instrumentation & Control
	Automatic Monitoring and Control
	Isolated Indicating and Recording Gauges, Meters and Instr
23.98	Spare Parts Allowance
23.99	Contingency
24.00	Electric Plant Equipment
24.01	Switchgear
	Generator Circuits
	Station Service
24.02	Station Service Equipment
	Station Service & Startup Transformers
	Low Voltage Unit Substation & Lighting Transformers
	Battery System
	Diesel Engine Generators
	Gas Turbine Generators
	Motor Generator Sets
24.03	Switchboards, including Heat Tracing
	Main Control Board for Electric Systems
	Auxiliary Power and Signal Boards
24.04	Protective Equipment
	Generating Station Grounding System
	Cathodic Protection
24.05	Electrical Structures and Wiring Containers
	Concrete Cable Tunnels, Trenches and Envelopes
	Cable Trays and Support
	Conduit
	Other Structures
24.06	Power and Control Wiring
	Generator Circuits Wiring
	Station Service Power Wiring
	Control Wiring
	Instrument Wiring
	Containment Penetrations
24.07	Electrical Lighting
	Reactor Building Lighting
	Turbine Building Lighting
	Electric Plant Equipment Building Lighting
	Miscellaneous Plant Equipment Buildings Lighting
	Target Manufacturing Plant Building Lighting
	Driver Building Lighting
	Yard Lighting
24.98	Spare Parts Allowance
24.99	Contingency
25.00	Miscellaneous Plant Equipment
25.01	Transportation and Lifting Equipment
	Cranes, Hoists, Monorails and Conveyers
	Railway
	Roadway Equipment
	Watercraft
	Vehicle Maintenance Equipment

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
25.02	Air and Water Service Systems
	Air Systems (Excl Piping)
	Water Systems (Excl Piping)
	Auxiliary Heating Boilers
25.03	Communications Equipment
	Local Communications Systems
	Signal Systems
25.04	Furnishings and Fixtures
	Safety Equipment
	Shop, Laboratory, and Test Equipment
	Office Equipment and Furnishings
	Change Room Equipment
	Environmental Monitoring Equipment
	Dining Facilities
25.98	Spare Parts Allowance
25.99	Contingency Allowance
26.00	Target Manufacturing Plant Equipment
26.01	Capsule Fabrication
26.02	Indirect Case Fabrication
26.03	Fuel Filling
26.04	Indirect Target Mating
26.05	Target Storage
26.06	Target Manufacturing Plant Instrumentation and Control Equipment
26.07	Target Manufacturing Plant Maintenance Equipment
26.98	Spare Parts Allowance
26.99	Contingency Allowance
27.00	Driver Plant Equipment
Heavy Ion Driver	
27.01	Ion Source/Injector System
27.02	Accelerating Structures
	Insulators, Cores, Structure
27.03	Focusing Magnet System
27.04	Cryogenics and Cooling System
27.05	Storage Rings
27.06	Transport/Final Focus System
Laser Driver	
27.01	Front End System
27.02	Discharge Laser System
27.03	Raman Accumulator System
27.04	Stimulated Brillouin System
27.05	Excimer Gas System
	Gas Flow System
	Gas Conditioning System
27.06	Driver Optics Systems
	Front End Optics
	Discharge Laser Windows
	Discharge Turning Mirrors
	Raman Input Windows
	Raman Secondary Mirrors
	Raman Output Windows
	SBS Polarizer

Table C-3 Prometheus Plant Cost Accounts (Cont.)

Number	Title
	SBS Quarter-Wave Plate
	SBS Chirper Crystal
	SBS Cell Window
	SBS Cell Mirror
	Vacuum Interface Windows
	Turning Mirrors
	Focusing Mirrors
	Grazing Incidence Mirrors
	Spares
	Mounts
Common Driver Systems	
27.07	Pulsed Power System
27.08	Driver Vacuum System
27.09	Driver Instrumentation & Control Equipment
27.10	Driver Maintenance Equipment
27.11	Miscellaneous Systems
27.98	Spare Parts Allowance
27.99	Contingency Allowance
28.00	Special Materials
	Initial Supply of Special (Non-fuel and Non-structural) Materials, Fluids, Gases and Liquids which require non-standard indirect costing or fixed charge rate accounting.
	Reactor Coolants
	Turbine Working Fluids
	Driver Fluids and Gases
	Reactor Building and Beamline Cover Gases
91.00	Construction Facilities, Equipment and Services
	Temporary Facilities
	Construction Equipment
	Construction Services
92.00	Home Office Engineering and Services
	Systems Engineering
	Management Services
	Quality Assurance
	Safety and Environmental Engineering
93.00	Field Office Engineering and Services
	Construction Management
	Inspection
	Pre-Operational Training
94.00	Owners Cost
	Project Administration
	Staff Training and Plant Startup
	Inventories and Spares Administration
95.00	Process Contingency
96.00	Project Contingency
97.00	Interest During Construction (IDC)
98.00	Escalation During Construction (EDC)

C.1 DEVELOPED ECONOMIC STUDY GUIDELINES

The Introduction Section discusses many of the important economic guidelines which significantly affect the total capital cost (including the indirect costs) and the cost of electricity. Although there is some controversy on the best technique to represent the ultimate capital and operating cost with a high degree of fidelity, the salient point is that all practitioners should conform to the same, pre-established groundrules to insure valid comparisons between studies.

This section will discuss some of the groundrules which have a higher degree of uncertainty, more controversy, and perhaps, a higher impact on the overall final economic results.

Level of Safety Assurance - The ESECOM study[6] introduced the concept of Level of Safety Assurance (LSA) to describe and categorize varying degrees of safety. The ESECOM study associated costs with those prescribed levels. Delene[3] further proposed additional costs or credits based upon the LSA determination. As noted in Table C-1, the indirect costs are scaled according to the plant LSA values. Delene also recommended scaling direct capital costs according to the LSA values. In the Prometheus studies, only the indirect costs, the O&M costs, and the decommissioning costs were scaled by the LSA values. It was felt that the means to obtain the lower LSA rating depends, in part, upon the selection of certain materials or designs. This decision significantly impacts the direct costs and we could not justify modifying the direct costs depending on the LSA rating. Section 6.13 describes a trade study of varying levels of LSA, with no decrease in the direct capital costs of the plant. In fact, if a plant were judged to have a higher LSA rating, presumably a lower cost of materials and processes would have been utilized, somewhat offsetting the LSA penalties.

Learning Curve - The recommended economic guidelines[1] suggested the use of learning curves to estimate the cost reduction possible with quantity purchases of like components or subsystems. Indeed, this practice has been instituted beginning with the STARFIRE study. The concept is well documented in many industries. However the application in reactor studies has been somewhat inconsistent. In the STARFIRE economic analysis, Waganer attempted to apply differing learning curves to subsystems as appropriate, with some systems having no learning (i.e., 100%) and others which were judged to be labor intensive, to have a high degree of learning (~80%). Since the STARFIRE analyses, other reactor designs have continued to use the technique of learning curves. But the practice has deteriorated with less emphasis on justification and more on a broad-brush treatment, perhaps with a single learning curve value for all accounts. The Oversight Committee recommended the Prometheus study follow the example of ARIES in establishing economic guidelines and indeed many of the guidelines are taken from ARIES study. A rough draft of an ARIES System Studies report[7] indicated the ARIES economic analysis would use a universal learning curve of 75%. If applied to large quantity purchases, a 75% learning curve is a very powerful cost reduction technique. For example, the cost of a tenth of a kind would be 38% of the first unit cost and the 100th would be 15% of the first unit cost, see Figure C-1 Only a small portion of documented cases[8] would support such an overall level of cost improvement.

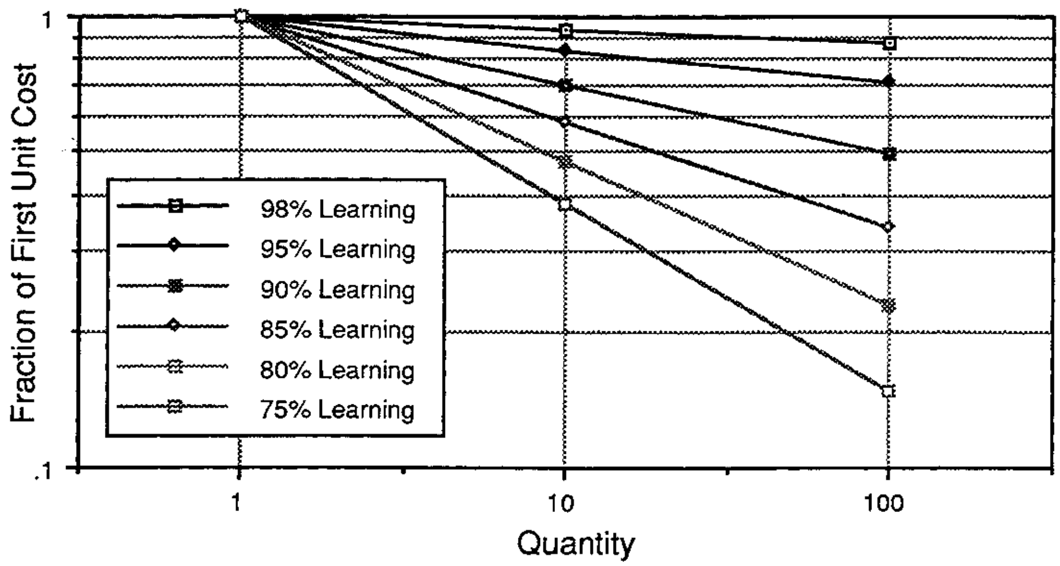

Figure C-1. Log Linear Unit Cost Curves

In the Prometheus economic analysis, it was felt that each system, subsystem, and in some cases, the components must be examined individually to determine which learning curve should be applied. Table C-4 illustrates the learning curves applied to each of the reactor cost accounts. No learning was applied to the Structures and Site Facilities because these would largely constructed on site with local labor. Many of the components would be unique to this site. Some of the interior building systems, i.e., HVAC and lighting fixtures, would experience learning effects, but they would be considered as high quantity purchases from many other construction projects and therefore, any incremental learning effects on this estimate would be negligible.

In the Reactor Plant Equipment, each system and subsystem was viewed independently with regard to the amount of labor (subject to learning) and to materials (weakly influenced by learning). Another factor was if the system would be constructed on-site or off-site in a factory. The quantity to be purchased was used in the learning curve analysis, along with an estimate of how many identical prior units would have been constructed for demonstration units or other purposes. The First Wall and Blanket is estimated to have a 85% learning curve. The Shield is estimated at 90% because an increased percentage of the construction cost would occur at the site location. The Main Heat Transfer and Transport System is estimated at 75% because of the large number of like components, such as pipes, valves, pumps, and storage tanks. Many of these would be new and unique to this application, especially the SiC plumbing within the reactor bulk shield region. The Reactor Radioactive

Table C-4 Application of Learning Curve by Cost Account

Cost Acct	IFE Reactor Plant Cost Accounts	Lrn Crv
20.00	Land and Land Rights	
21.00	Structures and Site Facilities	
21.01	Site Improvement and Facilities	1.00
21.02	Reactor Building	1.00
21.03	Driver Building	1.00
21.04	Turbine Building	1.00
21.05	Heat Rejection Structures	1.00
21.06	Auxiliary Building	1.00
21.07	Target Manufacturing Building	1.00
21.08	Tritium and Waste Processing Bldg	1.00
21.09	Miscellaneous Buildings	1.00
22.00	Reactor Plant Equipment	
22.01	Reactor Equipment	
22.01.01	First Wall and Blanket	0.85
22.01.02	Shield and Vacuum Vessel	.90/.85
22.01.03	Primary Structure	0.85
22.01.04	Cavity Vacuum	0.85
22.01.05	Target Injection and Tracking	0.85
22.02	Main Heat Transfer and Transport Sys	
22.02.01	Primary Lead Coolant Subsystem	0.75
22.02.02	Primary Helium Coolant Subsystem	0.75
22.02.03	Driver Waste Heat (See Acct 23)	
22.03	Auxiliary Cooling System	
22.03.01	Shield and Structure Cooling Subsystem	0.85
22.03.02	Final Optics and Beamline Cooling Subsys	0.85
22.03.03	Cryogenic Subsystems, Reactor Plant	
22.03.04	Other Cooling Subsystems	
22.04	Radioactive Waste Treatment and Disposal	1.00
22.05	Fuel Cycle System	0.85
22.06	Reactor Plant Maintenance System	0.85
22.07	Reactor Plant Instrumentation and Control	.90
22.08	Other Reactor Plant Equipment	1.00
23.00	Turbine Plant Equipment	1.00
24.00	Electric Plant Equipment	1.00
25.00	Miscellaneous Plant Equipment	1.00
26.00	Target Manufacturing Plant Equipment	0.90
27.00	Driver Plant Equipment	
27.01	Front End System (L)	0.90
	Ion Source/Injector System (HI)	0.90
27.02	Discharge Laser System (L)	0.90
	Accel Modules and Power Supplies (HI)	0.90
27.03	Raman Accumulator System (L)	0.90
	Focusing Magnet System (HI)	0.90
27.04	Stimulated Brillouin System (L)	0.90
	Cryogenics and Cooling Systems (HI)	0.90
27.05	Excimer Gas Flow System (L)	0.80
	Storage Rings (HI)	0.90
27.06	Driver Optics (L)	0.90
	Transport/Final Focus System (HI)	0.90
27.07	Driver Pulsed Power System	0.90
27.08	Driver Vacuum System	0.90
27.09	Driver I&C Equipment	0.90
27.10	Driver Maintenance Equipment	0.85
27.11	Miscellaneous Systems	0.90
28.00	Special Materials	1.00

Waste Treatment and Disposal system is considered to not have any learning effects. It was felt that this system would continue to evolve throughout the first to the tenth unit and learning curves would be inappropriate.

No learning curve effects are applied to the Turbine Plant Equipment, Electric Plant Equipment, and the Miscellaneous Plant Equipment. The rationale is that these systems are relatively common to other large power plants and any learning effects may be offset with site- and plant-specific effects. The Target Plant Equipment is estimated with a 90% learning curve because this equipment would be unique to this type of IFE plant and a limited degree of learning would be anticipated. The Driver Plant is generally costed with a 90% learning curve. The number of components in this system are generally larger that those present with the other major systems. For the KrF laser driver, there are 960 laser amplifier modules that are coupled into 60 Raman accumulators using 960 sets of comparable optical components. There are 60 beamlines with associated optical elements and support equipment. In the heavy ion driver, there are a large number of like coils, pulse power equipment, vacuum equipment, and storage ring equipment. Even though there will be demonstration or prototype equipment which would represent the first of a kind costs, the cost reduction with a large number of equipment purchases is significant.

Plant Availability/Capacity Factors - The canonical plant availability which has been derived or assumed in most MFE reactor design studies is 75% plus or minus a few percentage points. Our team was fortunate to have SPAR as a subcontractor to specifically examine the factors contributing to availability (or lack of availability). The major plant systems were examined for mean times to failure and mean times to repair. These data, along with the anticipated scheduled maintenance period, were used to determine the plant availability. The results for the laser-driven plant is 79.4% and the heavy ion-driven plant is 80.8%. Section 6.3.3 of the final report explains the methodology and analysis to derive these values. These values are higher than those estimated for MFE reactor power plants, but we believe they are justified due to the simpler and longer-lived IFE first wall and blanket system. Moreover, the two drivers examined in the Prometheus study are highly reliable which also contributes to the higher availability. A new system in the IFE plants which is not present in MFE plants is the Target Manufacturing Plant. Since redundancy is required to assure a constant supply of high quality targets, this plant equipment is specified to have a very high degree of reliability. The net result of the higher plant availability is roughly a 6% lower cost of electricity for an equivalent annual capital cost.

C.2 OVERALL COSTING AND ECONOMIC METHODOLOGY

Cost of Electricity - The main economic evaluation parameter is the ultimate cost of electricity (COE) as expressed either in constant year dollars or nominal year dollars. Constant year dollars assumes the purchasing power of the dollar remains constant over time, i.e. no inflation. Even with no inflation, there remains a certain cost of capital (~6.05% in the study guideline). In the nominal dollar accounting technique, a nominal inflation rate is assumed (5% per annum) and the cost of money is inflated accordingly.

All the direct capital cost accounts, 20 through 28, were estimated in 1991 dollars. If the cost estimate or cost estimating relationship (CER) were accomplished in a prior year, the data in Table C-2 were used to escalate the cost to 1991 dollars. Spare parts are usually incorporated in the direct costs, but the recommended guidelines specified that the spare parts would be assumed to be zero. The typical indirect cost accounts (91-94) were estimated using the agreed upon percentages shown in Table C-1. The specific values are dependent upon the specific LSA of the power plant designed. Process contingency was assumed to be zero and the project contingency 14.65% of the previous subtotal. And again the percentage value is dependent upon the LSA value. All of these data are in 1991 dollars. This is sometimes referred to as the "Overnight Costs" referring to the plant being constructed in zero time with no interest or escalation charges.

In actual practice, a power plant requires time for construction. A 6-year construction schedule is assumed for Prometheus, which is very optimistic in today's environment. However, it is not inconceivable that future plants could be constructed in this time span. And by the time a tenth identical plant is constructed, it may be the norm. At the end of the construction period the interest on the borrowed money has contributed to the outstanding debt. If inflation is present, then items purchased and wages in the latter stages of the construction period will further increase the cost of the plant due to the effects of escalation. The IDC (Interest During Construction) factor assumes a typical expenditure curve and expected rates of return of capital available from different sources. The IDC factor of 0.1652 accounts for those effects in a constant money scenario. For the nominal dollar case, the IDC factor increases to 0.3178. If there is no inflation, the EDC (Escalation During Construction) is zero, but for a nominal 5% inflation, the EDC factor is 0.2436. See Reference 3 for more discussion on this topic. The above methodology is intended to transform the overnight construction costs in 1991 dollars to those associated with the end of construction and the start of plant operation.

The cost of electricity is usually quoted for the first year of operation. The plant Total Capital Cost is converted into an annual cost by multiplying with a fixed charge rate which accounts for the rate of return on capital and tax law implications. Two different

Fixed Charge Rates are quoted for either the constant dollar or the nominal dollar accounting. Other annual costs include Operations and Maintenance (Plant O&M), Scheduled Replacement of large components such as the First Wall and Blanket modules, Target Manufacturing O&M, Fuel, and an allowance for the eventual decommissioning of the plant (also LSA dependent). For the constant year dollars, no escalation is applied to the operating costs, whereas for the nominal dollar case, the escalation rate is compounded for the construction period and the result applied to the operating costs.

There are several other factors contributing to the plant COE. The following equation displays the formulation of the COE:

$$COE = \frac{[\text{Annualized Capital Cost} + \text{Yearly Operating Cost}]}{\text{Net Power} \times \text{Plant Availability}}$$

$$COE = \frac{[\text{Annualized Capital Cost} + \text{Yearly Operating Cost}]}{[\text{Thermal Power} \times \text{Efficiency} - \text{Auxiliary Power}] \times [1 - \text{Scheduled Downtime} - \text{MTBF} \times \text{MTTR}]}$$

The Annual Costs in the numerator have generally been discussed in the previous paragraphs. More detail on this subject will be discussed in a later section of this appendix. The net electric power output will provide the income source to offset the annual expenses. The nominal output for the Prometheus designs was intended to be 1000 MWe. However, the process to arrive at the net power output is iterative. A nominal fusion power is chosen which in turn causes choices in driver energy, target gain and yield, and plant repetition rate. Meanwhile, the design of the energy collection and transformation systems in the First Wall, Blanket, Main Heat Transport, and Energy Conversion is proceeding. Only after the entire energy system is defined and overall efficiencies are established, can a preliminary new output be estimated. To adjust the net output closer to the desired value, assumptions and designs are modified and the process repeated. In Prometheus, the design for the laser plant achieved 972 MWe and the heavy ion plant achieved 999 MWe.

There is an economy of scale to be considered in scaling the size of the plants. The study was instructed to design and evaluate a 1000 MWe plant, recognizing that the COE would be more favorable if the plant size were larger. In Section 6.13 of the main report this economy of scale is discussed in detail. The COE is presented for plants of 500, 1000, and 1500 MWe. Detailed designs were not developed for these three cases, but the system code performance and cost estimating relationships were developed over a range of size parameter space, thus enabling the trade study.

The net electric power output discussed above is the nominal plant capacity. Over the period of a year, there are some number of scheduled and unscheduled outages which contribute to a loss of productive power output. The Plant Availability factor accounts for this decrement in productive output. Section 6.3.3 of the main report discusses this factor. The determined Availability for the Prometheus-L is 79.4% and Prometheus-H is 80.8%.

Costing Basis - The cost basis for the Prometheus Reactor Plants is in 1991 dollars. The design task leaders and the cost analysts developed the cost estimate for today's cost to purchase and install the system. If a cost estimate or cost estimating relationship was developed in a prior year, the estimate was updated to 1991 dollars by applying the appropriate inflation rates shown previously in Table C-2. The level of technology varied somewhat over the plant subsystems. Most of the systems and components were state-of-the-art and were costed thusly. Some systems or components were considered to advance the state-of-the-art. Some judgment was applied to determine what that system would cost today.

The costs reported in this report, principally in Section 6.13 and in this appendix, were based upon data generated within the ICCOMO systems code. Likewise, the cost estimating relationships (CERs) reported in the following sections are those used by the code to generate the cost data. These CERs are based upon the historical or developed cost bases. Many of the CERs use other data generated within the systems code. These data are generated or developed based upon general models within the code for the purposes of trade studies over wide parameter ranges. These general models in the systems code were continuously updated to conform to the most current embodiment of the reactor design approach. However, in the area of the reactor power balance, the systems code was not updated to handle and report the power balance exactly the same manner as the final Ebasco power balance calculations. To do so would have required recomputing all the study's economic trade study results which would have been a formidable task. The reported power balance in the reactor design parameter list reflects the final Ebasco thermal heat balance data; however, the power balance data in the systems code is not identical. Thus, power data taken from the reactor parameter list and used in the CERs to determine system cost will show slight discrepancies as compared to the reported costs.

C.3 CAPITAL COST ACCOUNTS

The cost accounting format used in the Prometheus design studies conforms to the cost accounts shown in Table C-3. This is very similar to that used by MFE in the most recent design studies, ARIES as well as several other IFE design studies. This format will assist in evaluating the plant systems relative cost impact. This will also allow commonalty in comparison of other alternative design approaches. The accounts reflect all the systems and facilities required to produce busbar electricity.

The following sections will present a brief synopsis of the supporting cost basis for the presented costs. More detail on the content in each account is provided in Table C-3.

C.3.1 Land and Land Rights (Account 20)

The cost of the land, land rights, and relocation of buildings is the major cost in this account. STARFIRE[9] estimated the size of the site to be 1000 acres costing $3.3M in 1980 dollars (~$5.3M in 1991 dollars). This plant site would likely be somewhat larger and siting of power plant have become more complex, both of which would indicate a higher cost would be suggested. ARIES assumed a $10M land cost for their plant. Prometheus is estimated to have similar land cost at $10M; therefore C_{20} = $10M.

C.3.2 Structures and Site Facilities (Account 21)

This account covers all direct costs associated with the physical plant buildings such as the reactor, driver, turbine, electrical equipment, cooling system structures, and site improvements and facilities. All provisions cooling, site access, and security will be provided. The total cost of Structures and Site Facilities, Account 21, is $376.66M for the laser option and $322.41M for the heavy ion option.

C.3.2.1 Site Improvements and Facilities (Account 21.01) - This account encompasses all site improvements and facilities necessary for the complete power plant. This includes the general site improvements including site work, fencing, storm sewer, earth moving equipment, tank and pump foundations, fire protection, and sanitary sewers. Transportation access is provided by highway and railway access, but no waterfront improvement were considered. The STARFIRE[9] and EBTR [10] estimates were $11.15M (1980$), which would convert to $18M in 1991$. HIFSA[11] estimated the site improvements at $17M in 1986$ which would convert to $20.5M in 1991$. ARIES estimated this account at $11.85M in 1990$. It is thought the Site Improvements and Facilities costs would continue to escalate and $21M would be a more appropriate cost estimate for both sites. See Table C-5 for account details.

Table C-5. Site Improvements and Facilities Costs

Category	Costs, ($ M)
General Site Improvements	
Site Work, Fencing, Storm Sewer	6.70
Earth Moving Equipment	7.00
Tank and Pump Foundations	1.00
Fire Protection	1.40
Sanitary Sewer	1.50
Transportation Access	
Highway	1.40
Railway	1.90
Total Site Improvements and Facilities, $C_{21.01}$ =	21.00

C.3.2.2 Reactor Building (Account 21.02) - The reactor building and other BOP facilities are described in the main report, Section 6.10. Ebasco helped develop these costs contained herein along with comparable estimates from past design studies. The Ebasco cost estimate was from a similar sized fission reactor building. Some design features were modified to account for changes associated with the Prometheus reactor designs. The volume of the Prometheus-L reactor building is roughly similar to STARFIRE[9] and EBTR[10], but the Prometheus-H building is much smaller. The Ebasco cost reference was of a comparable size to the Prometheus-L building design, but it had a free-standing containment structure. The Prometheus building designs use a steel liner inside the concrete building structure which would be a less expensive option. Scaling these data, the cost for the Prometheus-L building would be $106.06M and the smaller heavy ion reactor building would be $60.88M. These may seem low when compared to MFE reactor buildings, but the comparable MFE reactor buildings would include the functions contained in both the IFE reactor buildings and the driver buildings and, in some part, the target manufacturing buildings.

The cost estimating relationships for the reactor building assumed a cost based upon a volume relationship. The radius of the laser reactor building was 43 meters scaled to the ratio of the thermal power to the nominal thermal power of 3091 MW raised to the 0.5 power. The radius of the heavy ion reactor building was normalized to a 31.5 meter radius and using the same thermal power ratio to 3091 MW raised to the 0.3 power. The building height used similar relationship with the coefficients of 71.5 m for the laser reactor building and 64.0 m for the heavy ion reactor building. The differences in the nominal coefficients account for the building differences due to beam enclosure requirements whereas the lower heavy ion scaling coefficient is meant to reflect a weaker dependence of the thermal power in this type of reactor building. The building cost was scaled from the Ebasco estimate by assuming a fixed cost of $25.5M plus a variable cost of $194/m^3.

Radius, Reactor Bldg = 43.0 x $(P_t/3091)^{.5}$ (Laser)
Height, Reactor Bldg = 71.5 x $(P_t/3091)^{.5}$ (Laser)

Radius, Reactor Bldg = 31.5 x $(P_t/3091)^{.3}$ (Heavy Ion)
Height, Reactor Bldg = 64.0 x $(P_t/3091)^{.3}$ (Heavy Ion)

Volume, Reactor Bldg = π x Radius^2 x Height

Cost, Reactor Building, $C_{22.01}$ = \$194 x volume + \$25.5 M

C.3.2.3 Driver Building (Account 21.03) - The costing basis for the Laser Driver Building for Prometheus-L is similar to the costing basis for the Power Supply Building for STARFIRE[9]. This building is priced on a volume basis with an approximate volume of 415,000 m^3. The escalated cost basis is \$88/m^3 which results in a laser building cost of \$36.52M. The heavy ion driver building is largely below ground building, just sufficiently wide to accommodate both legs of the accelerator. The costing basis is \$120/ft^2 tunnel floor area plus \$50/ft^2 floor area of the above-ground, pulse-forming network (PFN) building. The tunnel floor area is assumed to equal the LINAC length multiplied by five times the maximum induction core radius. The PFN building is assumed to be half the tunnel width. The total cost of the heavy ion beam driver enclosure is \$38.27M.

C.3.2.4 Turbine Building (Account 21.04) - The Turbine Building houses the turbines and all the auxiliary equipment for the turbines. The economic basis is the ARIES cost estimating relationship, $C = \$53.9M \times (P_{gross}/1246)^{0.5}$. This results in a cost of \$57.18M for the laser option and \$52.79M for the heavy ion option.

C.3.2.5 Heat Rejection Structures (Account 21.05) - These structures support the heat rejection systems. The main elements in this account are the Intake Structures, the Discharge Structures, the Unpressurized Intake and Discharge Conduits, the Recirculating Structures, and the Cooling Tower Earth Work. The Cooling Towers are not included in this account, rather are covered in Account 23.03, Heat Rejection Systems. The economic basis is the ARIES CER. This results in a cost of \$11.48M for the laser system and \$10.69M for the heavy ion option.

$$C_{21.05} = \$11.48M \times \left(\frac{(\text{Power to Conversion System} - P_{gross})}{1860} \right)^{0.5}.$$

C.3.2.6 Auxiliary Building (Account 21.06) - This building houses the HX pumps, ancillary systems, and maintenance facilities for the Reactor Plant Equipment, including the Hot Cell Facilities. The cost basis is the ARIES[7]. This results in a cost of \$15.54M for the laser option and \$14.81M for the heavy ion option.

$$C_{21.06} = \$15.0M \times \left(\frac{P_{gross}}{1246} \right)^{0.3}.$$

C.3.2.7 Target Manufacturing Building (Account 21.07) - This building handles the processed DT fuel from the Fuel Processing System and fabricates either the direct drive targets for the laser-driven reactor or the indirect drive targets for the heavy ion-driven reactor. As described in Section 6.4, the Target Manufacturing Building is divided into different zones according to the tritium handling requirements and the cryogenic processes. The nominal cost was derived by Ebasco with appropriate scaling by grams of tritium used/day as recommended by ARIES[7]. This results in a cost of $46.92M for the laser option and $44.92M for the heavy ion option.

$$C_{21.07} = \$47M \times \left(\frac{T_{usage}}{1500} \right)^{0.3} .$$

C.3.2.8 Tritium and Waste Processing Building (Account 21.08) - This building is similar in size and function to the Target Manufacturing Building. Thus the same CER is used to estimate the building cost.

$$C_{21.08} = \$47M \times \left(\frac{T_{usage}}{1500} \right)^{0.3} .$$

C.3.2.9 Miscellaneous Buildings (Account 21.09) - The CER for this category of Miscellaneous Buildings is taken from the ARIES report as

$$C_{21.09} = \$35M \times \left(\frac{P_{net}}{1000} \right)^{0.3} .$$

This results in a cost of $35.03M for the laser option and $35.11M for the heavy ion option.

C.3.3 Reactor Plant Equipment (Account 22)

This account summarizes all the fusion Reactor Plant Equipment (RPE). The systems contained herein are usually designed uniquely designed for the fusion application or have been tailored to accommodate the fusion systems. In the IFE application, this account only encompasses the reactor cavity and its systems, the heat transport and transfer systems, auxiliary cooling, radioactive waste, fuel cycle, reactor plant maintenance, reactor plant I&C and other reactor plant equipment. The functions of the driver and the target manufacturing plant are contained in other accounts at this same level. Because of this separation of function, the costs associated with this account will be less than that associated with the RPE for MFE reactor designs. The total RPE costs for the laser option is $700.43M whereas the heavy ion option is $568.34M. The bulk of this difference is traceable to the larger laser reactor cavity, higher power handled by the laser option systems, and the different beamline shielding approach and requirements. These are explained separately below.

C.3.3.1 Reactor Equipment (Account 22.01) - The costs in the account cover the components of the first wall and blanket, shield and vacuum vessel, primary structure, cavity vacuum, and target injection and tracking. These accounts represent all the functions contained within the reactor cavity as a whole to contain the fusion blast and debris, breed the tritium, and convert and capture the fusion energy. Each of these accounts are important and will be discussed separately. The cost of the laser option is $391.82M and the heavy ion option is $271.64M.

C.3.3.1.1 First Wall and Blanket (Account 22.01.01) - The standard approach for estimating this account in most or all fusion reactor design studies is to estimate the volume and mass of each type of material required in subsystem and then multiply by an average cost per unit mass. This average cost accounts for the material cost of the components, assuming for bulk purchases in a mature manufacturing environment. Likewise the labor cost for the fabrication, inspection, assembly, and installation and checkout have been factored into the overall unit cost for the material.

Figure C-2 is a modified version of a figure presented in Section 6.8 which illustrates the radial build of the First Wall/Blanket/Vacuum Vessel/Plena/Shield of the reactor cavity. This figure displays the radial thicknesses assumed, the volumetric density, and the materials used. The geometry of the cavities are right circular cylinders with hemispherical ends. The specific geometry is defined in Section 6.3. Using these data, the cost of each layer of the radial build was estimated. The unit cost of materials used is noted in Table C-6. The fabricated costs for the First Wall, Blanket and Shield have always been a topic of great debate, mainly because the materials are usually exotic, of currently-limited supply, and leading the state-of-the-art in fabrication. Thus the estimated costs involve extrapolation in time, quantity, fabrication methods, supply, and demand. The unit cost values quoted in Table C-6 are representative of those currently quoted by comparable studies and are not considered to be out of the realm of feasibility. The learning curve for this type of construction would be approximately 85%. However it is anticipated that a previous demonstration plant would have been built and learning would have begun with that unit. The cost basis for the unit cost have been assumed for the first commercial unit, thus the cost of the Demo plant (first of a kind) will have to be increased by 1/.85 and the cost computed for the 11th unit (for the 10th commercial plant). The resultant learning curve is 0.6705 for the 10th commercial First Wall and Blanket.

Silicon carbide (SiC) composite material is used to a great extent in the reactor cavity—in the first wall, blanket structure, reflector material, in the plena region as piping for the lead and helium coolants, and in the shield as one of the shielding materials. Several different costs are assumed for this material depending the usage and the fabrication and quality requirements as shown in Table C-6. The high quality SiC material is costed at $400/kg whereas the bulk granular material is $70/kg for neutron multiplier and $20/kg for bulk shield material. Currently SiC can be purchased at prices much lower than $20/kg, but the required level of purity will increase the cost.

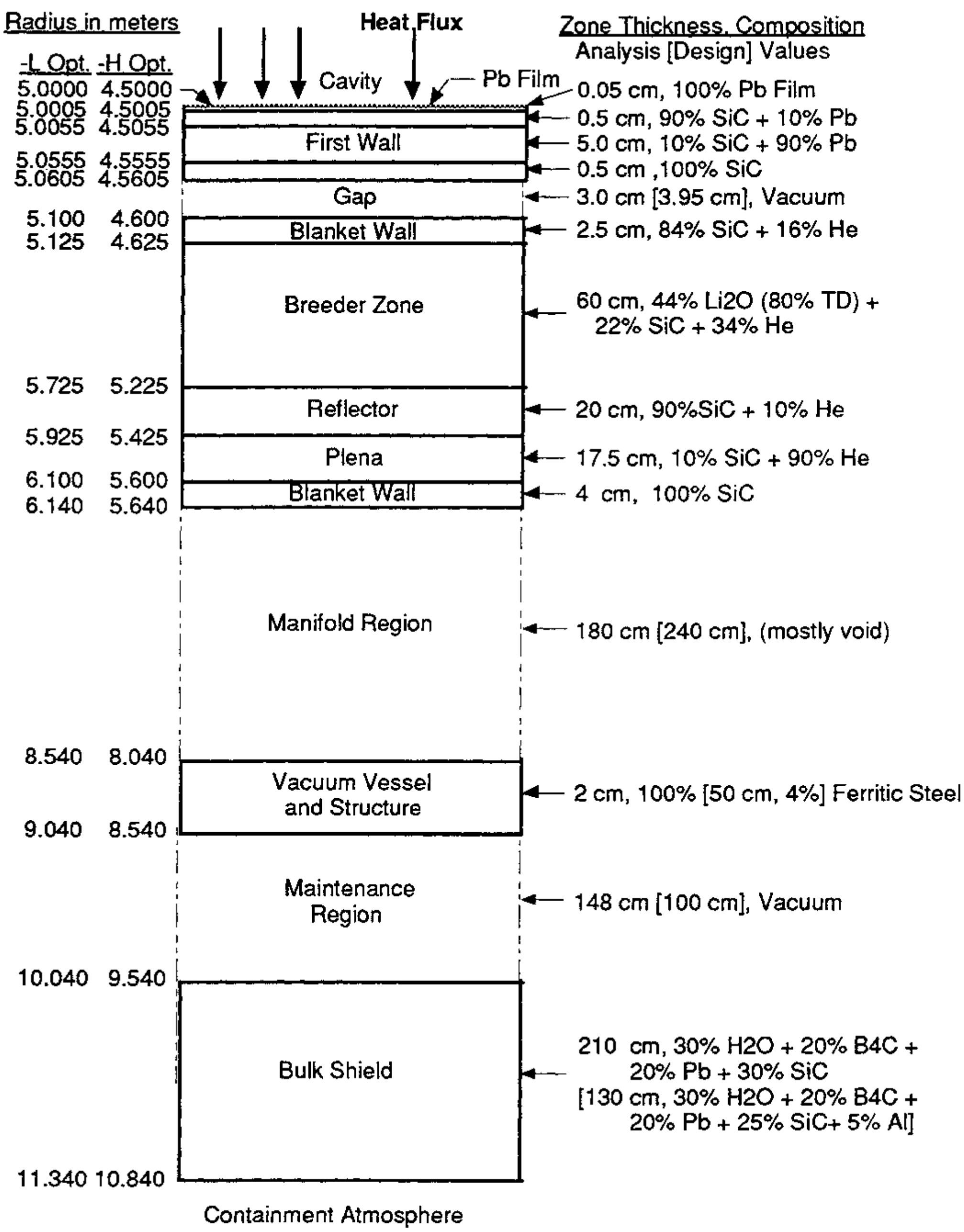

Figure C-2. Radial Build of the First Wall, Blanket, and Shield Subsystems

Table C-6 Cost of Materials Used in the FW/B/S Systems

Material	Special Properties/Usage	Installed Cost, $/kg
SiC	Composite, Structural, Complex/First Wall, Blanket, Headers	400
SiC	Solid Bulk Material/Neutron Reflector	70
SiC	Powdered Bulk Material/Shield Component	20
Li_2O	Pebble-Sized Material/Breeder	210
Pb	Liquid with Low Bi Impurity/Protectant, Coolant, N. Multiplier	2.2
Pb	Solid Granules with Low Bi Impurity/Shield Component	2.2
F. Stl	Structural, Moderate Complexity/Vacuum Vessel, Structure	30
Al	Structural, Moderate Complexity/Shield Structure	30
B_4C	Solid Granules, High Purity/Shield Structure	40
Concrete	High Purity Concrete/Alternate Shield Material	4
Steel	Structural, Low Complexity Liner	15

The ceramic breeding material, Li_2O, also has a nebulous cost basis in that it and other breeding materials have not been used in quantity over a long time period. But this cost data is representative of cost estimates used by other contemporary studies. The cost of lead is significantly higher than current applications, but the need to lower the bismuth impurities will cause the cost increase.

Table C-7 summarizes the material cost of the First Wall and Blanket subsystem for the two reactor concepts. In the Prometheus reactor concepts, the cost of the first wall is a rather insignificant portion of the overall cavity cost. The cost of the blanket is approximately 30 times more expensive than the first wall component. The cost of the silicon carbide in the blanket is the dominate cost element, as it is an expensive material and is used for the structural material, coolant tubes, and plenum region piping. The cost of the breeding material is a moderate cost element. The lesser cost of the heavy ion options is attributable to the smaller cavity radius and height and is roughly proportional to the square of the cavity radius (surface area). If the cavity blanket could be further optimized, the cost of the heavy ion reactor cavity would be reduced.

Table C-7 First Wall and Blanket Material Costs

Component Material		Laser Reactor (M$)	Heavy Ion Reactor (M$)
First Wall			
SiC		5.92	4.81
	Subtotal	5.92	4.81
Blanket			
SiC		118.96	98.38
Li_2O		32.15	26.43
	Subtotal	151.11	124.81
	Total	157.03	129.62

Note: The lead and helium coolants are treated as a special materials and are costed in Account 28.

C.3.3.1.2 Shield and Vacuum Vessel (Account 22.01.02) - During the conduct of the study, a trade study of two shield approaches were conducted with two different sets of shielding materials. Table C-8 illustrates the materials considered, their densities, and the respective cost per kilogram. The type #1 shield reflects the composite shield approach with aluminum, water, lead, B_4C, and SiC, whereas Type #2 shielding uses concrete and steel. All the materials are carefully graded and selected to assure the proper shielding performance. This selection and quality requirement adds to the material cost. The cost of the concrete is not just the bulk cost of common construction grade concrete. The materials will have to be carefully screened to assure a radiation resistant concrete with a carefully known composition, blended especially for shielding. Other charges are included to forms, scaffolding, equipment charges, labor, finishing costs, and wastage.

Table C-8 Cost of Shield Materials Comparison

			Type #1 Shield, Composite			Type #2 Shield, Concrete		
Material	Density kg/m^3	Cost $/kg	Usage	Mass/Vol kg/m^3	Cost/Vol $/m^3	Usage	Mass/Vol kg/m^3	Cost/Vol $/m^3
Alum	2,700	30.0	0.05	135	4,050			
Water	1,000	NC	0.30	300	0			
Lead	11,350	2.2	0.20	2,270	4,994			
B_4C	2,500	40.0	0.20	500	20,000			
SiC	3,200	20.0	0.25	800	16,000			
Concrete	2,240	4.0				0.87	1,948.8	7,795
Steel	7,860	15.0				0.08	628.8	9,432
	Total or Avg.			4,005	45,044		2,577.6	17,227
	Avg. Cost/kg				11.25			6.68

The cost information from Table C-8 indicates that the concrete shield is less expensive than the composite shield on a equal volume basis. However, thicknesses need to be adjusted to have an equally effective shield. As is discussed in Section 6.8.4, the composite bulk shield should be 1.3 meters thick and the concrete would have to be 1.7 meters thick. This would equate to a shielding cost per square meter of $14.63/m^2 for the composite shield and $11.35/m^2 for the concrete shield.

From the data in Table C-8, it was determined that the lesser cost shield would be the concrete option. However due to activation concerns and waste disposal considerations, it was decided the more responsible decision would be to adopt the slightly more expensive, but environmentally attractive, composite material shield option. Table C-9 summarizes the shield and vacuum vessel costs for the two options. As noted in Sections 6.8.4 (Primary Shielding and Beamline Shielding) and 6.5.3 (Common Subsystems), the shielding approach is designed to closely contain the radiation volumes and not allow irradiation access to the large reactor building or ancillary equipment. The Bulk Shielding and the Vacuum Vessel costs are influenced by the reactor cavity size of the two options. The much smaller cost for the vacuum port enclosures reflects the reduced vacuum requirements for the heavy ion cavity. The cost of the 60 laser beamline shields is the dominate cost factor. The cost of the heavy ion beamlines is still significant but the HI beamlines are fewer in number and in size than the laser option. If the channel transport concept proves not to be feasible, the cost of heavy ion shielding would increase significantly.

Table C-9 Total Shielding and Vacuum Vessel Costs

Component		Laser Reactor (M$)	Heavy Ion Reactor (M$)
Bulk Shielding		128.55	117.25
Vac Port Enclosure		23.50	6.09
Beamline Shielding		48.34	3.22
	Subtotal	200.39	126.56
Vacuum Vessel		3.43	3.02
	Total	203.82	129.58

Learning curve factors are used to arrive at the data illustrated in Table C-9. Some reduction in the composite shielding costs is expected. The aluminum containment vessel would probably be fabricated in a remote factory and assembled and filled with the composite material at the site. Thus the overall composite learning curve was estimated at 90% with no prior units assumed. Ten units were used for the bulk shield whereas the vacuum port has three enclosures per reactor and the laser has 60 beamlines. The number of purchased units influences the resultant learning factor. The heavy ion reactor has a slightly different number of units of vacuum enclosures and beamlines.

If the shield beamlines were constructed of concrete, it would not be prudent to use a learning curve because the shield would be constructed mostly with on-site labor. This would have nullified any cost advantage for the concrete shield.

The Vacuum Vessel is thought to be constructed with more off-site labor, thus it is costed at ten units and a learning curve of 85%.

C.3.3.1.3 Primary Structure (Account 22.01.03) - This account considers the reactor structure to support the inner wall, blanket, and vacuum vessel as well as the beamline supports and the vacuum pump enclosures. It is assumed the bulk shielding is self-supporting and the cost of any structural function is included in the shielding account, except for the beamline shield supports.

The structure would likely be constructed with either steel or aluminum, both of which would be costed at $30/kg installed, with no prior units and an 85% learning curve applied. There was no detailed design developed for these components, so an estimating technique was used. It was assumed the mass of the inner structure between the blanket subsystem to the vacuum vessel would be 1/10 of the supported first wall, blanket, and lead coolant weight. The resultant structure would be approximately 0.123×10^6 kg for the laser option. The structure between the laser reactor vacuum vessel to the bulk shield was also estimated with the same technique, adding the incremental weights of the first wall, blanket, coolant, FW/B structure and vacuum vessel. The vacuum vessel to bulk shield structure would weight 0.155×10^6 kg. In as similar fashion, the resultant weights of the beamline support structure and the vacuum pump enclosure were estimated. Table C-10 summarizes the supported and structural weights and the resultant costs.

Table C-10 Primary Structure Weights and Costs

Components	Supported Wt kg $\times 10^6$	Structural Wt kg $\times 10^6$		Component Cost M $
Laser Option				
Blanket/VV Structure	1.229	0.1229		2.15
VV/Bulk Shield Str	1.425	0.1425		2.71
Beamline Structure	7.175	0.7175		12.55
Vac Pump Encl Str	3.19	0.319		5.58
			Total	22.99
Heavy Ion Option				
Blanket/VV Structure	1.013	0.1013		1.77
VV/Bulk Shield Str	1.287	0.1287		2.25
Beamline Structure	0.410	0.0410		0.72
Vac Pump Encl Str	0.827	0.0827		1.45
			Total	6.19

C.3.3.1.4 Reactor Cavity Vacuum (Account 22.01.04) - This account includes the vacuum system costs for the reactor cavity including the vacuum pumps and all roughing pumps, liquifiers and cooling systems, plenum chambers and ancillary equipment. The cost is based upon the base pressure requirement of the non-condensable cavity atmosphere. The laser system has a lower base pressure (~3 mtorr compared to ~100 mtorr for the HI case) so its vacuum system is more expensive.

	Cavity Pumping		Beamline Pumping
Heavy Ion	$\$0.5M \times (h_{usage}/2420)$	+	$2 \times \$2.0M \times (nbft/7)^{.5}$
Laser	$\$6.0M \times (h_{usage}/2420)$		

The independent parameters are h_{usage} which is hydrogen usage in g/d and nbft is the number of beams for final transport per cavity side. The system cost for the laser option is \$4.54M and the heavy ion option is \$3.51M.

C.3.3.1.5 <u>Target Injection and Tracking (Account 22.01.05)</u> - This system includes all the injection system costs for the injection acceleration system (either electromagnetic or pneumatic), the timing and tracking system outside the reactor cavity and possibly a tracking system within the reactor cavity. This cost was based upon the HIFSA[11] database of $7.9M for a target injection and tracking system based upon 10 targets per second. The CER is $7.9M x Repetition rate/10 Hz times the learning curve factor for 85% (.8528). The cost of the laser system is estimated at $3.44M for a repetition rate of 5.65 Hz and $2.74M for a repetition rate of 3.5 Hz. The related computer system would not be included in this account.

C.3.3.2 Main Heat Transfer and Transport Systems (Account 22.02) - These systems encompass all the main coolant systems which transport the usable heat from the reactor cavity. Specifically the coolant systems are the liquid lead for the first wall coolant and protectant and the gaseous helium coolant for the blanket. In the case of the laser reactor system, the waste heat from the laser amplifiers is used as supplemental heating for the steam generator (feedwater heating and supplemental heating). The system contained a heat exchanger which transferred the heat from the KrF amplifier gas into a helium coolant, which was used in the main helium coolant system steam generation. The cost for these are treated in Cost Account 23.05. The heavy ion driver systems have high enough efficiency that it was judged not economical to process the lesser amount of waste heat from the heavy ion driver. Intermediate or secondary coolant systems were not used in the Prometheus designs.

As shown in Table C-3, the elements of the heat transfer and transport include pumps and motor drives, piping external to the reactor cavity, heat exchangers, steam generators, superheaters, reheaters, tankage, coolant cleanup, tritium extraction from the coolants, and insulation.

The cost estimating basis for this system is derived from several sources—ARIES[7] (which seems to have some lineage back to STARFIRE[9] and MARS[12]) and some historical data from Ebasco in work they had previously estimated or current estimates on steam generators. The learning curve factor applied to this system was judged to be 75% which represents a system with a high degree of learning (lots of new technology, high labor content in factory conditions, and opportunity for significant improvement). The 75% learning over 10 units reduces the first commercial lot cost to 0.3846 of the estimated cost. The summarized first unit costs and the 10th unit costs are shown in Table C-11.

Ebasco estimated the cost for the first commercial steam generator, sized for the laser system. An average cost was obtained for the first six units used in a single plant, $76.8M for the lead steam generators and $132.6M for the helium steam generators (first lot of commercial units). These were scaled by thermal power raised to the 0.8

power (per ARIES[7] recommendation) to obtain the costs for the heavy ion system costs.

The cost of the steam-driven helium circulators was estimated by Ebasco for a trade study during the conduct of the Prometheus study. The cost of the laser system was $47.53M with a scaled cost of $43.54M for the heavy ion system (first lot costs). Associated costs of the 108" diameter helium piping was estimated to be $165.59M for the laser system and $151.69M for the heavy ion system. Helium coolant makeup costs from the BCSS[13] study would be $9.88M and $9.05M based upon the scaled thermal power.

Ebasco did not specifically estimate the cost of the lead piping or pumps. The best reference for the lead pumps and piping was that generated by TRW in conjunction with the MARS[12] study and subsequently used in the BCSS[13] study. MARS used $Li_{17}Pb_{83}$ coolant, 2081 MW of thermal power, and four main loops with a flow rate of 22,750 kg/s per loop. The Prometheus lead loops have a lower flow rate of 9229 kg/s. If the TRW data are scaled to 91$, and adjusted for the flow rate to the 0.8 power, the cost for the pumps are $16.73M for the laser and $15.42M for the heavy ion systems. The MARS pipe size was 0.762m whereas the Prometheus size is 0.609 m. If the costs are adjusted to 91$, the thermal power to the 0.8 power, and the pipe size to the 0.85 power, the resultant costs are $63.10M for the laser and $58.88M for the heavy ion.

The lead coolant makeup and cleanup system is estimated at $4.13M for the laser system and $3.34M for the heavy ion system. Table C-11 summarizes all Main Heat Transfer and Transport System costs.

Table C-11 Main Heat Transfer and Transport System Costs

Component	Laser Reactor w/o Learning	Laser Reactor w/ Learning	Heavy Ion Reactor w/o Learning	Heavy Ion Reactor w/ Learning
Primary Lead Coolant System				
Steam Generators	76.80	29.54	71.66	27.56
Pumps	16.73	6.43	15.42	5.93
Piping/Valves	63.10	24.27	58.88	22.65
Coolant Cleanup	4.13	1.59	3.34	1.28
Subtotal	160.76	61.83	149.30	57.42
Primary Helium Coolant System				
Steam Generators	132.60	51.00	121.47	46.72
Pumps	47.53	18.28	43.54	16.74
Piping/Valves	165.59	63.68	151.69	58.34
Coolant Cleanup	9.88	3.80	9.05	3.48
Subtotal	355.60	136.76	325.75	125.28
Total	516.36	198.59	475.05	182.70

C.3.3.3 Auxiliary Cooling System (Account 22.03) - In the Prometheus reactor designs, there are only two major subsystems in the Auxiliary Cooling System. These are the Shield and Structure Cooling Subsystem and the Final Optics and Beamline Cooling Subsystem. Cryogenic Cooling would be a candidate subsystem, but in the Prometheus designs, the costs are contained within the Cavity Vacuum account under the Reactor Equipment, Account 22.01.04. No other requirements exist for cryogenics within the Reactor Plant Equipment. The Driver Plant will need cryogenics, but this is covered under the Driver Plant Equipment.

Both the Shield and Structure Cooling Subsystem and the Final Optics and Beamline Cooling Subsystem were assumed to have learning applied at 85% over 10 units. The basis for the Shield and Structure Cooling Subsystem is the ARIES[7] CER for the Primary or Intermediate Cooling (H_2O) system, which was \$0.103M x $Pth^{0.8}$ x escalation factor. With shield waste heat of 43 MW and 38 MW for the laser and heavy ion cases, this CER yields \$8.36M and \$6.06M. With 85% learning applied, the laser cost is \$1.96M and the heavy ion cost is \$1.77M for Account 22.03.01.

For laser case, the Final Optics and Beamline Cooling system covers the cooling of the 60 composite shield beamline structures and neutron apertures as well as the cooling of the final optics. This is a low grade heat system, not suitable for energy production. This system was not specifically defined, so an allowance of \$5M was allocated for this system (which would equate to \$2.91M after the learning curve factor was applied). The heavy ion beamlines would also be shielded in the two large beamline enclosures. Cryogenic cooling of the final magnets are handled in the driver costs. An allowance of the beamline cooling was assumed to be \$3M before learning and \$1.75M after learning.

The total cost for Account 22.03 is \$4.87M for the laser option and \$3.52M for the heavy ion reactor.

C.3.3.4 Radioactive Waste Treatment and Disposal System (Account 23.04) - This account handles all the liquid, gaseous, and solid waste processing and disposal for the reactor plant equipment. The cost basis for this account is the ARIES[7] study. When scaled for the thermal power handled for the two reactors and the year of the estimate, the cost for the laser reactor was \$5.68M and for the HI option was \$5.41M. No learning curve (LC =1.0) was applied to this account because it was felt this system would continue to evolve from the first commercial unit continuously to the final unit. Continuing regulation and environmental concerns would prevent the benefits of producing a common design over the several units.

C.3.3.5 Fuel Cycle System (Account 22.05) - The cost of the Fuel Cycle System is based upon the flow rate of the hydrogen isotopes used in the fuel cycle. The cost for the deuterium and tritium processing are determined from the tritium flow rate. Because the IFE targets are comprised of CH compounds, additional hydrogen flow rates must be handled by the Fuel Cycle System. There is a difference in that the direct drive targets contain only target capsules whereas the indirect targets contain both capsules, radiation cases, and internal support structures. Other compounds and elements are in these targets, such as carbon and lead, but these will be collected in the first wall protectant and disposed of in the Waste Processing System. Only the excess hydrogen will influence the Fuel Cycle System with the heavy ion reactor and indirect target design having a significantly higher hydrogen flow rate. See Section 6.7 for details on the Fuel Cycle System and the estimated flow rates.

The cost estimating relationship used for the Fuel Cycle System is \$20M x (hydrogen usage/2420)$^{0.5}$ + \$60M x (tritium usage/1500)$^{0.5}$ x learning. The usage values are expressed in grams/day. The final costs with 85% learning included are \$48.15M for the laser system and \$55.38M for the heavy ion system. The heavy ion option has a lower tritium flow rate, but the hydrogen flow rate is much higher, which yields a more expensive system.

C.3.3.6 Reactor Plant Maintenance (Account 22.06) - This account covers the Reactor Cavity Maintenance Equipment, the Hot Cell Maintenance Equipment and the Final Optics Maintenance. The maintenance equipment for the driver systems are associated with that major account. SPAR Aerospace estimated the cost of the first commercial system for the laser option to be \$22.7M for the Reactor Building Maintenance and \$13.45M for the Hot Cell Maintenance Equipment for a total of \$36.15M. Table C-12 for details on these costs. Scaling these costs by thermal power raised to the 0.5 exponent yields an estimated cost of \$33.36M for the heavy ion case. Note that the 0.5 exponent only weakly scales the cost to the thermal power. After application of an 85% learning curve, the laser option total cost is \$21.07M and the heavy ion option is \$19.44M.

C.3.3.7 Reactor Plant Instrumentation and Control (Account 22.07) - STARFIRE[9] estimated I&C costs for the Reactor I&C, Monitoring Systems, and Instrumentation and Transducers at \$23.41M which escalates to \$37.69M. ARIES[7] had the identical cost values for their instrumentation and control systems. HIFSA[11] had lower costs, around \$10M which was probably too low. Thus the STARFIRE costs would be adopted with a 90% learning applied. The final cost I&C cost for both reactor plants is estimated at \$26.60M with learning curve effects applied.

C.3.3.8 Other Reactor Plant Equipment (Account 22.08) - This account covers special heating systems, coolant receiving, gas systems and building vacuum systems. No detailed estimates were conducted on these systems and allowances were used in concert with previous estimates. No learning curve effects were used because of the lack of detailed estimates.

Table C-12 Reactor Plant Maintenance Equipment Costs
First Unit Costs

Item Description	Number	Cost, $ M
Reactor Cavity Maintenance Equipment		
Upper Manipulator	1	2.5
Deployable Heavy Lift Manipulator	1	1.5
Mobile Heavy Duty Manipulator	2 @ $1M	2.0
Bi-arm Manipulators	2 @ $1M	2.0
Small Power Manipulator, 100 kg	4 @ $0.1M	0.4
Helium Steam Generator Robot	1	1.3
Lead Steam Generator Robot	1	1.3
Pump Room Manipulator	1	1.0
Contaminated Lead Manipulator	1	1.0
Viewing Equipment (lights, stems, etc.)		1.0
Measuring Tools		0.5
General Tools		3.0
Flask Handling Buggy		0.5
Crawlers		0.25
Crane Maintenance Equipment		1.0
Strongbacks, Fixtures		1.0
Welding Units	3	0.45
Radiation/contamination Detection Tools		2.0
	Total (Laser)	22.70

Note: Main Cranes, Small Cranes and Transporter are costed in Account 25.01

Item Description	Number	Cost, $ M
Hot Cell Maintenance Equipment		
Bi-arm Manipulator	2 @ 1M	2.0
Payload Manipulator	2 @ 0.1M	0.2
Heavy Duty Manipulator	1	1.0
Flask Handler	1	0.5
Tools		2.0
Assembly Fixtures		3.0
Crane Maintenance Equipment		0.75
Viewing Equipment		0.5
Radiation/contamination Detection Tools		2.0
Decontamination Equipment (incl Tanks)		1.5
	Total (Laser)	13.45
	Total (Laser)	36.15
	Total (Heavy Ion)	33.36*
With Learning	Total (Laser)	21.07
	Total (Heavy Ion)	19.44

* Scaled by thermal power$^{0.5}$

Special heating equipment will be require to assure the lead coolant can be added and removed from the reactor piping and first wall components. An allowance of $3M is provided for this system.

Coolant Receiving from STARFIRE[9] had been estimated at $0.24M which when escalated would be approximately $0.4M.

Gas Systems will be required due to the CO_2 inert atmosphere in the Reactor Building. The estimated cost would be $0.15M.

The Building Vacuum Systems to provide vacuum to other subsystems requiring vacuum conditions. This does not imply the building is under a vacuum, rather the building is nominally at atmospheric pressure, inerted with CO_2. Detritiated for the Reactor Building is handled under Account 22.05.07. A small allowance of $0.10M is provided for the Reactor Building Vacuum System.

The total cost of the Other Reactor Plant Equipment is $3.65M.

C.3.3.9 Reactor Spare Parts (Account 22.98) - The project recommended guidelines[1] specified that all spare costs should be set to zero for this analysis. Therefore Cost Account 22.98 = $0.0.

C.3.3.10 Contingency (Account 22.99) - The cost contingency for this account is accounted at a higher level, namely Account 96.00. Thus the contingency cost at this level is $0.0.

C.3.4 Turbine Plant Equipment (Account 23)

This account summarizes all the turbine plant equipment (TPE). The account usually parallels the equipment contained in most power plant cost accounts, i.e., turbine generators, main steam, heat rejection, condensing systems, feed heating and other TPE systems. Listed below are the cost estimating relationships for the major systems. The costs are assumed to be mature with no learning curve reductions applied. Ebasco data were used on the accounts 23.1 and 23.3 with the remainder being obtained from the ARIES study cost basis. The nominal costs shown below in Table C-13 differ slightly from that shown in the final cost tabulation. This is due to slight differences in the handling of the power values within the code. The CERs described in the following sections are those used in the code.

Table C-13 Turbine Plant Cost Estimating Relationships

Account	Cost Relationship	Nominal Costs Laser	Nominal Costs Heavy Ion
23.01	140 x (Gross Elect/1400)$^{.7}$	138.74	124.87
23.02	7.73 x (Gross Thermal/2860)	8.82	7.51
23.03	58.68 x ((Gross Ther-Elect)/1860)$^{.8}$	59.37	50.19
23.04	(Condensing is in Heat Rejection Account)		
23.05	12.16 x (Gross Thermal/2860) + 11.13 x (Waste Power recovered/193)	26.28	13.03
23.06	65.85 x (Gross Electric/1000)$^{.6}$	79.96	73.06
23.07	12.6 x (Gross Electric/1000)$^{.3}$	13.88	13.27
	Nominal Total	327.05	281.93
	Reported Total Costs	327.13	282.98

C.3.5 Electric Plant Equipment (Account 24)

The subaccounts in the Electric Plant Equipment include Switchgear, Station Service, Switchboards, Protective Equipment, Electrical Structures and Wiring Containers, Power and Control Wiring and Electrical Wiring. The cost estimating relationship for this account is 71.5 + 67 x (Gross Electric Power/1000). The amount shown in the final cost table is calculated using the internal code power balance which is slightly different from the power balance data calculated by Ebasco which is shown in the data parameter list. The reported Electric Plant Equipment cost for the laser option is $165.46M and the heavy ion version is $151.59M. There were no learning curve cost factors applied to this account.

C.3.6 Miscellaneous Plant Equipment (Account 25)

This account included Transportation and Lifting Equipment, Air and Water Service Systems, Communications Equipment, Furnishings and Fixtures. This account is weakly scaled to the gross electric power. The account cost estimating relationship is 57.1 x (Net Electric Power/1000)$^{.3}$. The costs for the laser version is $57.15M and the heavy ion version is $57.27M. Since the plant design did not exactly iterate on the exact value of 1000 MWe, this cost for the Miscellaneous Plant Equipment varied slightly from one version to the other. There were no learning curve cost factors applied to this account.

C.3.7 Target Plant Equipment (Account 26)

This account included all facilities to manufacture and store the targets used in the reactor plant. The extraction and processing of the fuel elements is contained within and is costed in the reactor plant. Likewise the injection of the targets is also a function of the reactor plant. All other target preparation facilities are in this account. This would include capsule fabrication for both the direct and indirect targets and the related fuel filling. The indirect drive target case fabrication will be included in the cost account along with the mating of the fuel capsule, the support structure, and the outer case structure. Facilities will be provided for temporary storage of the target structures sufficient for the inventory needs. Support equipment will include instrumentation, control, and maintenance services. Section 6.4 explains the necessary equipment in more depth.

An approximation of the capital cost of target plant can be developed from the following parameters and the general cost relationship shown in Table C-14.

Table C-14 Target and Target Plant Cost Factors

Target Type	Nominal Capital	Repetition Rate	Reject Fraction	Target Matl Cost	Matl Usage
Laser DD	$127 M	5.65	.02	$0.010	0.75
Laser ID	$157 M	Not Determined	.04	$0.012	0.75
Heavy Ion ID	$182 M	3.54	.05	$0.014	0.75

$$\text{Number Targets / Yr} = \frac{\text{Repetition Rate} \times 3.155 \times 10^7}{(1 - \text{Reject Fraction})}$$

$$\text{Target Factory Cost} = \text{Nominal Capital Cost} \times \left[\frac{\text{Number Targets / Yr}}{10^8}\right]^{.7}$$

The above values determine the first unit cost for a target factory. It is assumed the factory capital cost follows a 90% learning curve (0.7047).

This yields $134.94M for the direct drive laser target factory and $143.62M for the heavy ion indirect drive target factory.

C.3.8 Driver Plant Equipment (Account 27)

This account is unique from other all major accounts in that the drivers are completely different from each other. These unique accounts for the Heavy Ion Driver are the Ion Source and Injector, Accelerating Structures, Focusing Magnet Systems, Cryogenics and Cooling Systems, Storage Rings and Transport and Final Focus Systems. For the Laser Driver, the analogous subsystems are the Front End Systems, the Discharge Laser System, the Raman Accumulator System, the Stimulated Brillouin System, the Excimer Gas Flow System, and the Complete Optics System including the Final Focus and Grazing Incidence Mirrors.

There are some common types of accounts which support both types of driver systems. These are the Pulsed Power Systems, the Driver Vacuum Systems, the Instrumentation and Control System, Driver Maintenance System, and Miscellaneous Systems.

Learning curves were applied to these accounts. The majority of the accounts are assumed to learn at the rate of 90%. The Laser Gas Flow system is expected to have a higher learning rate of 80% due to the large amount of mechanical equipment in the system. The Heavy Ion Storage Rings is also expected to exhibit a 80% learning also due to the large number of like mechanical and electrical components. The common maintenance account is expected to have an 85% learning curve.

The costs for the Driver Subsystems are noted below in Table C-15. See Table 4.1.2-2 for more detailed cost data on the HI driver and Tables 4.1.1-2, 4.1.1-3, and 4.1.1-4 for the laser driver systems and subsystems.

Table C-15 Driver Plant Equipment Costs

Account No	HI Driver Title	Cost, $ M	Laser Driver Title	Cost, $ M
27.01	Ion Source/Injector	7.05	Front End System	10.25
27.02	Accelerating Struct	70.84	Discharge Lasers	44.91
27.03	Focusing Magnets	43.25	Raman Accelerators	4.65
27.04	Cryogenic System	8.67	SBS Cells	1.27
27.05	Storage Rings	13.05	Gas Flow System	33.91
27.06	Final Transport	53.72	Optics Systems	106.18
27.07	Pulsed Power	150.98	Pulsed Power	142.14
27.08	Driver Vacuum	9.66	Driver Vacuum	0.00
27.09	Driver I&C	19.00	Driver I&C	20.00
27.10	Driver Maintenance	19.29	Driver Maintenance	16.66
27.11	Miscellaneous Systems	7.60	Miscellaneous Systems	18.31
	Totals	403.11	Totals	398.28

C.3.9 Special Materials (Account 28)

This account accrues the costs of the special materials necessary at the start up of the reactor. These are generally fluids or gases which are non-fuel and non-structural. These will only need be purchased at the time of the initial checkout phases and do not need to be acquired during the early phases of the plant construction. The general classes are the reactor coolants (helium and liquid lead), the turbine working fluids, the driver working fluid (KrF gases), and reactor building and laser building cover gases.

The allowance for the special materials is $1.62M for the laser driver reactor and $1.32M for the heavy ion. The higher cost for the laser is due to the larger size reactor cavity and the inclusion of the KrF gases and the driver beamline cover gas.

C.3.10 Indirect Cost Accounts (Accounts 91 through 98)

The economic guidelines for these accounts were agreed upon by the two contractors and approved by the DOE IFE Reactor Design Study Economics Working Group. The resulting formulations for each indirect cost account are shown in Table C-1. There is a Level of Safety Assurance dependence on each account. Prometheus was assessed to be at the LSA Level One for both reactor types.

Table C-16 summarizes the Indirect Costs for the two Reactor Plant Designs with an LSA rating of one.

Table C-16 Prometheus Reactor Plant Cost Factors in Constant 1991 Dollars LSA = 1

	Cost Account	Prometheus-L		Prometheus-H	
		CYD*		CYD*	
	Total Direct Cost	2171.67		1940.64	
91	Constr Serv & Equip	245.40		219.29	
92	Home Office Engr & Serv	112.93		100.91	
93	Field Office Engr & Serv	112.93		100.91	
94	Owners Cost	396.44		354.26	
95	Process Contingency	0.00		0.00	
96	Project Contingency	445.27	NYD**	397.90	NYD**
97	Interest During Constr	575.66	1107.41	514.42	989.60
98	Escalation During Constr	0.00	848.68	0.00	758.55
	Total Capital Cost	4060.29	5440.90	3628.34	4862.07

* CYD (Constant 1991 Dollars)
** NYD (Nominal 1997 Dollars)

C.4 COST OF ELECTRICITY ACCOUNTS

The cost of electricity (COE) is defined as the cost of delivering a kilowatt of energy to the busbar. The cost is projected to the first year of operation. The cost elements of the COE are the annualized plant capital cost, annual operations and maintenance (O&M) cost, scheduled replacement cost, target manufacturing O&M cost, fuel cost, and decommissioning cost. The remaining elements which determine the energy production include the plant availability factor and the net plant capacity. Table C-17 summarizes these elements in millions of dollars for both current dollars and nominal year dollars for Prometheus-L and Prometheus-H.

Table C-17 Cost of Electricity Accounts for the Prometheus Reactor Plants

Cost Account		Prometheus-L		Prometheus-H	
		CYD	NYD	CYD	NYD
	Annual Capital	392.22	891.22	350.50	796.41
40-47	Plant O&M	49.71	66.61	50.39	67.53
50	Sched Replacements	24.29	32.55	20.17	27.03
	Target Mfg O&M	12.32	16.51	11.80	15.81
2	Fuel	4.08	5.47	5.60	7.50
	Decommissioning	4.56	6.11	4.56	6.11
Total Annual Operating Costs		94.96	127.25	92.52	123.98
Total Annual Costs		487.18	1018.47	443.02	920.39
Plant Availability Factor, %		79.4	79.4	80.8	80.8
Plant Capacity, MWe		972	972	999	999
Cost of Electricity, mills/kWh		72.0	150.5	62.6	130.0

Each of these elements are discussed in following sections.

C.4.1 Annual Capital Cost

The cost of capital to construct the Prometheus plants are accumulated over the construction period along with the interest charges. The payback of this borrowed capital begins at the initial operating date and continues for the economic lifetime of the plant. These costs are levelized on an annual basis. Fixed charge rates are determined to take into rate of return of capital and the tax law provisions. Section C.2 provides additional information. The constant and nominal fixed charge rates are 0.0966 and 0.1638 respectively. See Table C-2 for the complete economic guidelines. Two different fixed charge rates are provided to account for the constant year dollars or the nominal year dollars. Table C-17 illustrates the annual cost values for the two reactor plants and the two charge rates. Prometheus-L is slightly more expensive by approximately 10% than the heavy-ion version. This effect is largely due to the larger structures, the larger Reactor Plant Equipment, and the larger-sized

Electric and Plant Equipment for the laser system. The Driver Plant Equipment costs are nearly identical in both cases.

C.4.2 Annual Operating Cost

The summary of the Annual Operating Cost shown in Table C-17 notes that the costs are nearly identical with compensating small factors. Scheduled replacement costs are slightly higher for the laser system but the fuel target costs are more expensive in the case of the heavy ion system. All annual operation costs are estimated in 1991 dollars. The nominal year dollar data is escalated at a 5% annual rate to the initial operating date.

C.4.2.1 Plant O&M Cost - This account includes staff, materials, scheduled and unscheduled activities, and general supplies for the entire reactor plant except for the target plant which has unique maintenance requirement above and beyond those of a typical MFE power plant. For consistency with other fusion reactor design studies, the Economics Working Group recommended[1] the usage of a cost estimating relationship used by ARIES[4] on this project. The equation was escalated from the ARIES 1988$ baseline to Prometheus baseline of 1991$. The Plant O&M cost is defined by $78.9 x LSA factor x $(Pe/1200)^{0.5}$ for the constant year dollars, see Table C-1. This results in similar O&M costs due to the nearly identical plant power outputs. This result is reasonably correct at the level of detail developed in these studies. On a relative basis, it would be expected the laser-driven plant would exhibit a slightly higher O&M plant cost due to more maintenance on the driver and the more involved reactor plant equipment arrangement.

C.4.2.2 Scheduled Maintenance Cost - The costs accrued in this account provide for periodic replacement of significant cost items with a finite and predictable lifetime. In the case of the two Prometheus reactors, the replacement cost of the first wall and the blanket modules were included. The life of the first wall is estimated to be five years and the blanket, ten years. The margin of error on these components are significant, but these values are reasonable estimates for today's technology. The replacement costs of the final mirrors and the grazing incidence metal mirrors were considered for inclusion, but the estimated lifetime ranged from life-of-plant down to 5-10 years. Thus these were not included in this cost category. The plant and target plant O&M cost accounts do include all costs associated with the remaining periodic and periodic maintenance activities.

Since the laser-option first wall and blanket components are more expensive, this is reflected in the higher Scheduled Maintenance cost for the laser option.

C.4.2.3 Target O&M Cost - This account includes staff, materials, scheduled and unscheduled activities, and general supplies associated with the Target Plant. The data is based upon the previous work done by Pendergrass[15]. More specific detail is shown in Table 6.4.3-1 regarding the Target Factory O&M cost assumptions and bases. The higher number of the laser direct drive targets required per day slightly offset the individually higher cost of each indirect drive heavy ion target.

C.4.2.4 Fuel Cost - These fuel costs are associated with the manufacturing of the direct drive and indirect drive targets. Included are the material and processing costs of the targets. These cost data are derived from the work of Pendergrass[15] and modified as required for the year of the estimate, the materials used, and the target parameters. See Section 6.4.3 for more specific details. The cost of the fuel materials is $C_{MATL} = C_{MATL_i} \times \left(\frac{E_{Beam}}{3MJ}\right) \times \frac{(N/yr)}{USAGE}$. C_{MATL} is cost of target materials. USAGE is a factor which represents losses in the fabrication process. Both C_{MATL_i} and USAGE data are shown in Table C-14. The cost of the indirect drive, heavy ion target results in a more expensive fuel cost than the direct drive laser target. The difference is not an important factor in the overall annual cost and is not a determining factor in the decision between the two options.

C.4.2.5 Decommissioning Allowance Cost - An allowance will have to be provided for the decommissioning of any power-producing plant. The guideline document for this study[1] recommended the use of a methodology similar to that proposed by NECDB[2] and used by the ARIES project[3,4]. Specific to decommissioning costs, the guidelines recommended a range of costs from 0 to 1 mill/kWh dependent upon the level of safety assurance (LSA) with no specific values given. The cost estimate for ARIES did not explicitly define what values they were using, but Reference 3 estimated a value of 0.5 mill/kWh for ARIES and other fusion plants and 0.8 mill/kWh for an advanced passively safe fission plant. Reference 2 estimated and referenced decommissioning costs for fission plants which ranged from average cost of $166M to $191M in 1991$. The U.S. Council for Energy Awareness[14] assumed the decommissioning cost for a fission plant would be $2100M and a coal plant would be $26M in 1991$. It is anticipated that fusion plants will be more environmentally attractive and entail less decommissioning costs, especially those plants which are designed to achieve low LSA values. On the other hand, the trend is toward providing a higher level of protection for the environment which steadily provides additional cost to any environmental cleanup operations. Thus for this analysis it is estimated that for the LSA = 1 case, approximately $200M in 1991$ will have to be provided for decommissioning. Furthermore, LSA levels of 2, 3, and 4 are estimated at $400M, $600M, and $800M each.

The envisioned method of providing adequate funds for decommissioning a plant is to contribute to a sinking fund from power revenues. This sinking fund will accumulate until the plant's useful lifetime has expired (30-40 years). The Nuclear Energy Cost

Data Base[2] suggested the accruing interest rate should be assumed to be 2.4%/year real dollars based on long term U.S. Government obligations. If the sinking fund is accruing at the rate of 2.5% per annum for 30 years, an allowance of 0.68 mill/kWh would be adequate for a 1000 MW, LSA = 1 plant operating at 75% availability to accumulate $200M. If the plant LSA were judged to be at higher levels, proportionately higher allowances would need to be provided. For the Prometheus designs, this results in an annual allowance of $4.56M for decommissioning.

C.4.3 Cost of Electricity Summary

The cost of electricity (COE) is the ultimate measure of the viability of a competitive power plant. The design of Prometheus has been optimized to produce a high level of power, long life components, low cost systems, and low operations and maintenance costs. All these elements are combined into the figure of merit called the cost of electricity.

The capital costs for the laser option is roughly 10% higher than the heavy ion option mainly due to the more expensive buildings and reactor plant and the requirement to produce more power to offset a slightly lower plant efficiency. The operating costs for both plants are virtually identical with the heavy ion option having a slight advantage due to the cost of replacement parts. By intent, both power plant were designed to produce nominally 1000 MWe net of electricity. Due to the differences in plant efficiencies, the laser plant must be sized slightly larger to produce the same net output. The final factor is the plant availability which slightly favors the heavy ion plant design. This results in a lower COE for the heavy ion plant (62.6 mills/kWh versus 72.0 mills/kWh). The capital cost is the determining factor in this case.

As is discussed in the main body of the report, this difference should not be viewed as a significant difference. Many of the contributing factors have sizable error bands on the data. New developments are occurring which influence the outcome. If a particular option is selected for further development, significant advances can be obtained. The analyses included in this report attempted to be midway between conservative and optimistic.

The final result is that both Prometheus reactor designs economically compare favorably with existing fossil, fission, and MFE fusion power plants. The economics of inertial fusion power plants will not be the deciding factor for the development of this energy option.

References for Appendix C

1. Ronald C. Davidson, et. al., "Inertial Confinement Reactor Design Studies Recommended Guidelines", September 1990.

2. "Nuclear Energy Cost Data Base: A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Coat Analysis, "U.S. Department of Energy Report DOE/NE-0095 (September 1988).

3. J. G. Delene, "Updated Comparisons of Economics of Fusion Energy," 9th Topical Meeting on Technology of Fusion Energy (Oakbrook, Illinois, 7-11 October 1990)

4. R. L. Miller, "Options and Optimizations for Tokamak Reactors: ARIES, " 9th Topical Meeting on Technology of Fusion Energy (Oakbrook, Illinois, 7-11 October 1990)

5. W. R. Meier, et al., OSIRIS and SOMBRERO IFE Reactor Design Study Final Report, 1991

6. J. P. Holdren et al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," LLNL Report URL-53766, 25 September 1989.

7. Ronald L. Miller, Robert A. Krakowski, David A. Ehst, ARIES System Study Results (Draft), 15 February 1991.

8. Linda Argote and Dennis Epple, "Learning Curves in Manufacturing," Science, Vol. 247, pg. 920-924, September 1990.

9. C. C. Baker, M. A. Abdou, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1, September 1980.

10. C. G. Bathke, et al, "ELMO Bumpy Torus Reactor and Power Plant Conceptual Design Study," LA-8882-MS, August 1981.

11. D. S. Zuckerman, et al., "Induction LINAC Driven Heavy Ion Fusion System Model," Fusion Technology, Vol. 13, #2, 1986.

12. B. G. Logan, et. al., "Mars, Mirror Advanced Reactor Study," LLNL report UCRL-53480, July 1984.

13. M. A. Abdou, et al., "BCSS, Blanket Comparison and Selection Study," Final Report ANL/FPP/84-1, September 1984

14. "Advanced Design Nuclear Energy Plants: Competitive, Economical Electricity," U.S. Council for Energy Awareness, January 1991.

15. J. H. Pendergrass, et al., "Heavy Ion Fusion Target Cost Model," Fusion Technology, Vol. 13, pg. 375, 1988.