Fusion Reactor Design Studies- Standard Unit Costs and Cost Scaling Rules

**S. C. Schulte
W. E. Bickford
C. E. Willingham
S. K. Ghose
M. G. Walker**

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FUSION REACTOR DESIGN STUDIES-
STANDARD UNIT COSTS AND COST
SCALING RULES

S. C. Schulte
W. E. Bickford
C. E. Willingham
S. K. Ghose(a)
M. G. Walker(a)

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Pacific Northwest Laboratory
Richland, Washington 99352

(a) Bechtel National, Inc.
San Francisco, California 94119

FOREWORD

In preparation of this document, the DOE Office of Fusion Energy and the Pacific Northwest Laboratory arranged for the user community to review and agree to the content of the document. The utility of the document is based on this common satisfaction of the diverse needs and approaches of the user community.

To maintain this utility, this document should not be revised without first obtaining the concurrence of the Office of Fusion Energy that any proposed revision will be compatible with the current needs and procedures of the magnetic fusion power development program.

ABSTRACT

This report establishes standard unit costs and scaling rules for estimating costs of material, equipment, land, and labor components used in magnetic confinement fusion reactor plant construction and operation. Use of the standard unit costs and scaling rules will add uniformity to cost estimates, and thus allow valid comparison of the economic characteristics of various reactor concepts.

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INTRODUCTION

The Department of Energy and its contractors are engaged in the economic evaluation of fusion power reactor concepts. This document describes an economic evaluation format to be utilized in the evaluation of magnetic confinement fusion power reactor concepts. The format was developed by Battelle at the Pacific Northwest Laboratory for the Department of Energy. Use of the format will result in cost estimates that are generated on a uniform and consistent basis.

The evaluation format was developed in two phases. Phase I established standard cost estimate reporting accounts and a standard method for translating estimates of plant capital investment costs, operating and maintenance costs, scheduled component replacement costs, and fuel costs into an estimate of leveled energy cost. The reporting accounts and translating method are described in Fusion Reactor Design Studies - Standard Accounts for Cost Estimates, (PNL-2648, May 1978). Phase II established standard unit costs and cost scaling rules for estimating capital investment, operating, and fuel costs. These unit costs and scaling rules are described in this report.

PURPOSE

The evaluation format will provide the fusion community with a tool that will make cost estimates produced at different times and by different estimators comparable. This report defines uniform unit costs and scaling rules that will allow estimators to estimate costs based on identical assumptions and unit cost relationships. This report also defines a price level index that will allow cost estimates made in different years to be uniformly normalized to account for inflation. Using these rules, cost estimates can easily be made comparable.

SCOPE

The cost estimating rules are applicable to commercial magnetic confinement fusion reactor power plant concepts constructed and operated in a mature fusion economy. The rules define standard unit costs and cost estimating relationships for estimating direct capital investment costs, engineering and

administrative costs, and interest and escalation costs. Also defined are relationships for estimating operating and maintenance costs, scheduled component replacement costs, and fuel costs. The rules define a price level index for inflating the standard cost estimating relationships to reflect later year price levels. A reference plant construction schedule is also provided for use in those cases where the organization performing a reactor study does not have a better basis for estimating the length of construction.

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STANDARD UNIT COSTS AND COST ESTIMATING RULES

The contents of this report consist of standard unit costs, cost scaling rules and reference plant subsystem cost estimates. Unit costs are installed costs per unit quantity (e.g., \$/kg, \$/lb). Reference plant subsystem cost estimates are generic balance of plant subsystem cost estimates.

The unit costs and cost scaling rules are established for a cost estimating level of detail commensurate with the level of detail currently achieved in fusion reactor cost estimating. If too many unit costs and scaling rules are established, application of the data by different estimators may result in non-uniform costing of identical subsystems. If too few unit costs and scaling rules are established, the cost estimating process may not be flexible enough to permit the identification of significant cost differences.

This report is intended to be used for estimating installed costs for commercial fusion power reactor components constructed and operated in a mature fusion economy. The unit costs and cost scaling rules are based on July 1979 price levels. However, costing data for use in subsequent years can be generated by applying the process outlined on Page 5 of this report.

The standard unit costs and cost scaling rules are arranged as follows:

<u>Cost Account</u>	<u>Index</u>
Land and Land Rights (Account 20)	Standard unit costs for land and land rights are listed in Appendix A.
Site Improvements and Facilities (Account 21.01)	
Reactor Building (Account 21.02)	Standard unit costs for site improvements and facilities, and reactor building are listed in Appendix A.
Turbine Building (Account 21.03)	
Cooling System Structures (Account 21.04)	A cost estimate for building and cooling structures associated with a reference 1,000 MWe turbine plant is listed in Appendix C. Cost estimating rules for scaling this cost estimate to power conversion systems in the range from 800 to 1,400 MWe are given in Appendix D.

Cost Account	Index
Power Supply and Energy Storage Buildings (Account 21.05)	
Miscellaneous Buildings (Account 21.06)	
Ventilation Stacks (Account 21.07)	Standard unit costs for power supply and energy storage buildings, miscellaneous buildings and ventilation stacks are listed in Appendix A.
Reactor Plant Equipment (Account 22)	Standard unit costs for reactor plant equipment are listed in Appendix A.
Turbine Plant Equipment (Account 23)	A cost estimate for turbine plant equipment associated with a reference 1,000 MWe turbine plant is listed in Appendix C. Cost estimating rules for scaling this cost estimate to power conversion systems in the range from 800 to 1,400 MWe are given in Appendix D.
Electric Plant Equipment (Account 24)	A cost estimate for electric plant equipment associated with a reference 1,000 MWe turbine plant is listed in Appendix C. Cost estimating rules for scaling this cost estimate to power conversion systems in the range from 800 to 1,400 MWe are given in Appendix D.
Miscellaneous Plant Equipment (Account 25)	A cost estimate for miscellaneous plant equipment associated with a reference 1,000 MWe turbine is listed in Appendix C. Cost estimating rules for scaling this cost estimate to power conversion systems in the range from 800 to 1,400 MWe are given in Appendix D.
Special Materials (Account 26)	Standard unit costs for special materials are listed in Appendix G.
Construction Facilities, Equipment, and Services (Account 91)	
Engineering and Construction Management Services (Account 92)	
Other Costs (Account 93)	Cost estimating rules for construction facilities, equipment and services, and for engineering and construction management services and other costs are given in PNL-2648.
Interest During Construction (Account 94)	
Escalation During Construction (Account 95)	Cost estimating rules for interest and escalation during construction are given in PNL-2648.
Spare Parts Allowance	
Design Allowance	
Contingency Allowance	Cost estimating rules for spare parts, design and contingency allowances are listed in Appendix E.
Operating and Maintenance (Account 40-47)	
Scheduled Component Replacement (Account 50-51)	Standard unit costs for operating and maintenance and scheduled component replacement are listed in Appendix F. Gross cost estimating rules are given in PNL-2648.
Fuel (Account 02-03)	Standard unit costs for fuel are listed in Appendix G.

ESCALATION METHODOLOGY

Fusion reactor component costs will change over time in response to general price level change (i.e., inflation), changes in market conditions (i.e., supply and demand), and technological changes. As a result, the standard unit costs and cost estimating rules will require periodic updating. The escalation methodology defined in this report will provide estimators with a tool to uniformly update the standard cost estimating rules. The updating mechanism will allow 1) cost estimates to be based on current year price levels (and not just mid-1979 price levels) and 2) estimates developed in different years to be put on a same year price level basis and, therefore, made comparable.

The escalation methodology utilizes price level index inflation factors. A single index is designated for use with each unit cost or cost estimating rule. Cost estimates developed during calendar year 1979 should utilize the standard unit costs and cost scaling rules as they are stated in this report. Cost estimates developed in later years should utilize escalated costs (i.e., costs that have been updated via the designated inflation factors to reflect price levels for the year in which the cost estimate is performed). The year for which the cost estimate is made should be stated in the cost estimate.

The inflation factors (price level indexes) are contained in the following publications:

- The Handy Whitman Index of Public Utility Construction Costs. Whitman, Requardt, and Associates, Baltimore, MD. (Electric Utility Construction for the North Central Region.)
- Survey of Current Business. United States Department of Commerce, Bureau of Economic Analysis, Washington, DC. (General Business Indicators, national income and product implicit price deflators, gross national product.)

The sources of inflation factors (price level indexes) to be used with each unit cost or cost estimating rule are shown in Table 1. All unit costs and cost estimating rules reported under the same major reporting account utilize the same index.

TABLE 1. Sources of Price Level Indexes (Inflation Factors)

<u>Cost Account</u>	<u>Index</u>
Land and Land Rights (Account 20)	<u>Survey of Current Business</u> <u>Implicit Price Deflators</u>
Structures and Site Facilities (Account 21)	<u>Handy-Whitman Index</u> Structures and Improvements (18)
Reactor Plant Equipment (Account 22)	<u>Handy-Whitman Index</u> Reactor Plant Equipment (19)
Turbine Plant Equipment (Account 23)	<u>Handy-Whitman Index</u> Turbogenerator Units (12)
Electric Plant Equipment (Account 24)	<u>Handy-Whitman Index</u> Total Distribution Plant (42)
Miscellaneous Plant Equipment (Account 25)	<u>Handy-Whitman Index</u> Miscellaneous Power Plant Equipment (14)
Special Materials (Account 26)	<u>Survey of Current Business</u> <u>Implicit Price Deflators</u>
Construction Facilities, Equipment, and Services (Account 91)	None
Engineering and Construction Management Services (Account 92)	None
Other Costs (Account 93)	None
Interest During Construction (Account 94)	None
Escalation During Construction - Optional (Account 95)	None
Spare Parts Allowance	None
Design Allowance	None
Contingency Allowance	None
Operating and Maintenance (Account 40-47)	<u>Survey of Current Business</u> <u>Implicit Price Deflators</u>
Scheduled Component Replacement (Account 50-51)	<u>Survey of Current Business</u> <u>Implicit Price Deflators</u>
Fuel (Account 02-03)	<u>Survey of Current Business</u> <u>Implicit Price Deflators</u>

Application of the inflation factors will only approximate cost data in future years. Over time, major reporting account inflation factors will not adequately reflect changes in unit costs and cost estimating rules. For this reason, price level index inflation factors should not be utilized after fiscal year 1982.

An example of the application of a price level index inflation factor is given below:

EXAMPLE

Objective

Determine Turbine Generator and Accessories Cost (23.01.01) for a July 1981 cost estimate

Given

Turbine Generator and Accessories Cost (1979 dollars) = \$64.5 million

Appendix C

Inflation Factor Index = Handy Whitman Turbogenerator Units

Table 1

Handy Whitman Cost Index Number - July 1981 = 460

Hypothetical

Calculations

Current year cost =

$$\frac{\text{inflation factor index (current year)}}{\text{inflation factor index (July 1979)}} \times \text{cost (July 1979)}$$

July 1981 Turbine Generator and Accessories Cost =

$$\frac{460}{388} \times \$64.5 \text{ million} = \$76.5 \text{ million}$$

METHODOLOGY FOR ESTABLISHING CONSTRUCTION SCHEDULE

The purpose of this section is to provide guidelines for estimating fusion reactor plant construction schedules. A reference fusion plant construction schedule is established for use in studies in which there is no specific basis for establishing construction schedule. It should be understood that these guidelines serve to provide approximations in the absence of detailed data on design, engineering, procurement, and construction. Power plant construction schedules are generally considered to cover the entire time period during which capital expenditures are made in direct support of a power plant project. Thus, the schedule includes project-specific preliminary design studies, construction permit and licensing activities, detailed design and engineering, procurement, construction, fuel loading, testing, and startup.

The importance of properly estimating schedule durations is apparent from inspection of the magnitude of the time-related elements of capital costs. The combination of escalation during construction and interest during construction through an extended construction schedule can account for more than half the entire capital cost of a large power plant project.

For the purpose of estimating schedule requirements for a fusion reactor power plant, an 11 year length of construction should be utilized. Due to institutional and market uncertainties and the early state of fusion reactor designs, a typical Light Water Reactor (LWR) construction schedule was assumed to approximate fusion reactor plant construction schedule. The reference schedule is shown in Figure 1.

FIGURE 1. Reference Schedule

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APPENDIX A

STANDARD UNIT COSTS

Land/Structures and Site Facilities/
Reactor Plant Equipment

STANDARD UNIT COSTS - Land, Structures and Equipment

"Installed cost consists of material and equipment purchase expense, fabrication/assembly expense, transportation/purchasing/testing expense, direct and indirect installation expense, and associated overhead expense."

	Installed Cost (7/79 Price Levels)
20. <u>LAND AND LAND RIGHTS</u>	
Land and Land Rights	\$2500/Acre
21. <u>STRUCTURES AND SITE FACILITIES</u>	
Excavation	\$3.40/cu yd
Fill and Compaction	\$3.60/cu yd
Concrete Work (in place)	\$230/cu yd
Reinforcing Steel	\$300/cu yd
22. <u>REACTOR PLANT EQUIPMENT</u>	
22.01 Reactor Equipment	
22.01.01 Blanket and First Wall	
Wall Modifiers (coating, liners, etc.)	
Carbon/graphite (woven cloth, ~100 μ m thick)	\$ 220/kg
Carbon/graphite (plain liner thin squares, ~1 cm thick)	\$ 25/kg
Pyrolytic graphite (.5 cm thick liner)	\$3000/kg
SiC (1 cm thick, radiating panels)	\$ 265/kg
Tungsten (plates sintered from powder)	\$ 80/kg
Al ₂ O ₃ (1 cm thick liner)	\$ 25/kg
Graphite (honeycomb structure)	\$ 300/kg
First Wall	
Tubular (thin wall, 2.5 cm OD, ~0.06 cm wall)	
SS-316	\$ 14/kg
PE-16	\$ 20/kg
V20-Ti	\$ 184/kg
TZM	\$ 170/kg
Nb	\$ 88/kg
Other	

Installed Cost
(7/79 Price Levels)

First Wall (contd)

Sheet (segmented torus, no support)

SS-316	\$ 25/kg
V20-Ti	\$ 200/kg
Nb	\$ 150/kg
TZM	\$ 190/kg
Inconel-718	\$ 49/kg
Other	

Modular or Bucket Shells
(complicated fabrication, thin wall,
rigid quality control and testing)

SS-316	\$ 32/kg
V20-Ti	\$ 250/kg
Inconel-718	\$ 60/kg
TZM	\$ 240/kg

Blanket

Highly machined components,
forgings, castings (lattices,
seats, locking rings)

SS-316	\$ 25/kg
Inconel-718	\$ 49/kg

Blanket structure (fabricated
from heavy plates/beams by
welding, cutting, bolting)

SS-316	\$ 15/kg
Inconel-718	\$ 26/kg
Nb	\$ 90/kg
TZM	\$ 169/kg
Other	

Breeding Material (assume reactor
grade lithium)

Liquid Lithium (natural ${}^6\text{Li}$)	\$ 30/kg
Liquid Lithium (90% enriched ${}^6\text{Li}$)	\$1000/kg

Installed Cost
(7/79 Price Levels)

Breeding Material (contd)

Solid Li Compounds (natural
in SS cans, 10-25 cm OD)

LiH	\$ 35/kg
LiAlO ₂	\$ 40/kg
LiAl	\$ 40/kg
Li ₇ Pb ₂	\$ 45/kg
Li ₄ SiO ₄	\$ 8/kg
LiD (D ₂ at \$1100/kg)	\$ 250/kg
Li ₂ O	\$ 33/kg
Other	

Solid Li Compounds (natural,
in SS pins or rods ≤3 cm OD)

LiH	\$ 52/kg
LiAlO ₂	\$ 60/kg
LiAl	\$ 60/kg
Li ₇ Pb ₂	\$ 68/kg
Li ₄ SiO ₄	\$ 12/kg
LiD	\$ 375/kg
Li ₂ O	\$ 50/kg
Other	

Solid Li Compounds (90% enriched
⁶Li, in SS cans, 10-25 cm OD)

LiAlO ₂	\$ 160/kg
Li ₄ SiO ₄	\$ 54/kg
LiAl	\$ 160/kg
LiD	\$1020/kg
Li ₂ O	\$ 500/kg
Other	

Solid Li Compounds (90% enriched
⁶Li, clad in SS pins or rods
≤ 3 cm OD)

LiAlO ₂	\$ 234/kg
Li ₄ SiO ₄	\$ 81/kg

	Installed Cost (7/79 Price Levels)
Breeding Material (contd)	
LiAl	\$ 234/kg
LiD	\$1500/kg
Li ₂ O	\$ 750/kg
Other	
Attenuators, Reflectors and Multi- pliers (in SS cans or bulk quantities)	
C	\$ 6/kg
Be	\$ 220/kg
Pb	\$ 3/kg
Other	
Attenuators, Reflectors and Multi- pliers (clad in SS pins or rods ≤3 cm OD)	
C	\$ 9/kg
Be	\$ 330/kg
Pb	\$ 5/kg
Other	
22.01.02 Shield (primary and secondary)	
C/graphite (blocks)	\$ 6/kg
B ₄ C (in cans or bulk quantities)	\$ 56/kg
Pb (sheets)	\$ 3/kg
SS-316 (sheets)	\$ 15/kg
SS-316 (pellets)	\$ 10/kg
Concrete	\$ 265/kg ³
Lead Cement	\$ 2/kg
Borated Water	\$ 15/kg
22.01.03 Magnets	
Stabilizer	
OFHC Cu (plain ribbon)	\$ 5/kg
OFHC Cu (stamped for cooling)	\$ 10/kg

	<u>Installed Cost</u> <u>(7/79 Price Levels)</u>
Stabilizer (contd)	
OFHC Cu (complex machining)	\$ 25/kg
Al	\$ 11/kg
Other	
Superconductor	
NbTi (copper matrix 1:1)	\$ 50/kg
Nb ₃ Sn (Nb ₃ Sn to bronze ratio, 1:3)	\$ 100/kg
Other	
Conductor Bonding to Stabilizer	
Soldering, Brazing (one surface)	\$ 3/kg
Wrap around with soldering (multiple surfaces)	\$ 6/kg
Insulators	
Micarta	\$ 4/kg
Epoxy	\$ 12/kg
Super Thermal Insulation	\$ 90/m ²
Other	
Internal Conductor Support	
SS-316 (D shaped or circular discs with machined grooves for conductor)	\$ 25/kg
SS-316 (spool or bobbin for solenoid type coil)	\$ 20/kg
SS-316 (Yin-Yang)	\$ 30/kg
Fabrication (includes fixtures, winding and assembly)	
Yin-Yang in shop	\$ 50/m
Toroidal, D or circular in shop	\$ 45/m
Toroidal or circular in field	\$ 60/m
Liquid He Dewar, see 22.03.01, Magnet Cooling	
Dewar Vacuum Tank, see 22.01.06, Reactor Vacuum System	

		<u>Installed Cost</u> <u>(7/79 Price Levels)</u>
22.01.04	Supplemental Heating (includes power supply equipment)	
	RF Heating (based on output power)	
	Electron cyclotron resonance	\$ 5/W
	Lower hybrid resonance heating	\$ 1/W
	Ion cyclotron resonance heating	\$.50/W
	Neutral Beam (based on output power)	\$ 1.50/W
22.01.05	Primary Structure and Support	
	External Coil Supports	
	SS-316 Toroidal, Circular, Distributed Structure	\$ 20/kg
	Blanket and Shield Support	
	Simple Structure SS-316	\$ 20/kg
	Machined or fabricated SS-316	\$ 25/kg
	Hardware 316-SS	\$ 16/kg
	PCRV (prestressed, reinforced concrete)	\$ 0.50/kg
	Other	
	Direct Converter Vacuum Tank Support	
	SS-316 Support	\$ 12/kg
	Concrete Support	\$ 260/cu yd
22.01.06	Reactor Vacuum System	
	Plasma Chamber Vacuum	
	Main Pumping System (includes valving and piping)	
	Cryopumps ($\sim 10^5$ liter/sec/m ² pump speed down to 10^{-8} torr)	\$3000/m ²
	Turbomolecular (up to 5×10^3 liters/sec, backup for cryopumps)	\$150,000/unit

		Installed Cost (7/79 Price Levels)
Reactor Vacuum System (contd)		
Backup Pumps		
Roots blower (2500-3000 liter/sec)		\$12,000/unit
Other		
Roughing Pumps (~100 liters/sec)		\$ 6,000/unit
Supplemental Heating		
Cryopumps (10^5 liter/sec/m ² speed, pulsed, high gas loads)		\$ 3,000/m ²
Direct Converter Vacuum		
Vacuum Tank (SS-316)		\$ 13/kg
Pumps (cryopumps)		\$ 3,000/m ²
Vacuum Exhaust Ducts		
200 cm diameter SS-316		\$20,000/m
100 cm diameter SS-316		\$15,000/m
~75 cm diameter SS-316		\$10,000/m
22.01.07	Power Supply Switching and Energy Storage	
Supplemental Heating (see 22.01.04)		
Pulsed Coil Applications:		
Flywheels (with AC-DC generator motor set)		\$ 500/MJ
Capacitor		\$350,000/MJ
D.C. Homopolar		\$ 16,000/MJ
Steady-State Coil Applications:		
D.C. Solid State		\$ 40/kW
22.01.08	Impurity Control	
Wall Treatment		
Low Z liners (see 22.01.01, Wall modifiers)		
Honeycomb (see 22.01.01, Wall modifiers)		

	Installed Cost (7/79 Price Levels)
Impurity Control (contd)	
Gas Blanket (based on first wall area covered)	\$ 100/m ²
Divertors (poloidal or toroidal)	
Coils - included in 22.01.03 magnets	
Particle collectors (including structures, slots, etc.)	
Lithium Systems	
Wetted Screen and Horn	\$ 200/m ²
Surface using Flowing Liquid Li	\$ 60/m ²
Solid Surface Deposition	
Zr Getter Foil	\$ 45/kg
Nb Slab	\$ 300/m ²
22.01.09 Direct Converter	
Vacuum Tank SS-316, 1 cm thick	\$ 13/kg
D.C. Modules	
Single-stage	\$ 4,000/m ²
Two-stage	\$ 7,000/m ²
Three-stage	\$ 4,000/m ²
Thermal Shields	\$ 3,500/m ²
Cryopumps (liquid He)	\$ 3,000/m ²
Liquid Nitrogen Refrigerators (based on power needed to operate liquefier)	\$ 40,000 x (kW) ^{.7}
Liquid Helium Refrigerators (based on power needed to operate liquefier)	\$ 40,000 x (kW) ^{.7}
Power Conditioning (output from D.C. modules)	\$ 44/kW

Installed Cost
(7/79 Price Levels)

22.02 Main Heat Transfer

22.02.01 Primary Coolant System

Pumps and Motor Drives

He Circulators ($\sim 5 \times 10^4$ kg/hr at 800 psi)	\$3,500,000/unit
Liquid Metal ($\sim 2 \times 10^6$ kg/hr at 40 psi)	\$1,000,000/unit
Liquid Metal ($\sim 1 \times 10^7$ kg/hr at 40 psi)	\$2,000,000/unit

Piping (includes insulation)

Stainless Steel for He, 800-900 psi	
150-200 cm diameter	\$ 100,000/m
<150 cm diameter	\$ 80,000/m
Stainless Steel for Liquid Metal	
50 cm diameter	\$ 150,000/m

Heat Exchangers

Li $\rightarrow$ Na	\$25/kW _{th}
He $\rightarrow$ Na	\$15/kW _{th}

Tanks (SS-316, 400 m³ capacity)

Dump, Make-up or Hot Storage	
Water	\$115/m ³
Na	\$950/m ³
Li	\$1,100/m ³

Cleanup System

Circulating He (based on mass of coolant)	\$2/kg
Circulating Liquid Metals	
Na (based on mass of coolant)	\$5/kg
Li (based on mass of coolant)	\$12/kg

Installed Cost
(7/79 Price Levels)

22.02.02 Intermediate Coolant System

Pumps and Motor Drives

Water ($\sim 10^5$ kg/hr)	\$175,000/unit
($\sim 10^4$ kg/hr)	\$ 25,000/unit

Liquid Metal

$\sim 10^5$ kg/hr	\$300,000/unit
$\sim 10^4$ kg/hr	\$ 40,000/unit

Piping (includes insulation)

Water (SS-316, ~ 50 cm diameter)	\$ 8,000/m
Water (carbon steel, ~ 50 cm diameter)	\$ 3,500/m
Liquid Metal (<50 cm diameter)	\$ 16,000/m

Heat Exchangers (steam generators)

He $\rightarrow$ Steam	\$21/kW _{th}
Li $\rightarrow$ Steam	\$15/kW _{th}
Na $\rightarrow$ Steam	\$14/kW _{th}
Water $\rightarrow$ Steam	\$ 8/kW _{th}

Tanks (SS-316, 400 m³ capacity)

Dump, Make-up or Hot Storage

Water	\$ 115/m ³
Na	\$ 950/m ³
Li	\$1100/m ³

Cleanup System (based on mass of coolant)

He System	\$ 2/kg
Na System	\$ 5/kg
Li System	\$12/kg

22.03 Auxiliary Cooling System

22.03.01 Magnet Cooling

	Installed Cost (7/79 Price Levels)
Magnet Cooling (contd)	
Superconducting Coil Dewar: (SS-316 double wall vacuum and coolant tank)	
Yin-Yang, SS-316	\$ 30/kg
D or Circular Shape	\$ 35/kg
Liquid He Storage Dewar	\$3.00/liter
Liquid N ₂ Storage Dewar	\$2.50/liter
Refrigeration	
3 kW, 4.2K He Refrigerator	\$2,000,000/unit
Piping	
5 cm OD SS-316 Schedule 40	\$120/m
22.03.02 Shield and Structure Cooling	
Cooling (based on kW deposited)	
Water	\$4/kW _{th}
He	\$6/kW _{th}
Piping (SS-316 Schedule 40)	
5 cm OD	\$120/m
2 cm OD	\$100/m
Pumps and Drives	
Water ($\sim 10^5$ kg/hr)	\$7/kW _{th}
He ($\sim 10^4$ kg/hr)	\$25/kW _{th}
Heat Exchanger	
He → Water	\$10/kW _{th}
Purification	\$1.5/kW _{th}
22.03.03 Supplemental Heating; Cooling	
Injector Cooling (per kW deposited)	\$20/kW _{th}
Piping (2 cm OD, SS-316 Schedule 40)	\$100/m

		<u>Installed Cost (7/79 Price Levels)</u>
Supplemental Heating; Cooling (contd)		
	Pumps (water, $\sim 10^4$ kg/hr)	\$2/kW _{th}
	Purification	\$2.50/kW _{th}
22.03.04	Power Supply Cooling	
	Pumps, Piping, Cooling	\$3/kW _{th}
22.04	Radioactive Waste Treatment and Disposal (based on reactor thermal output)	
	Liquid Waste Processing (concrete and ultimate disposal of tritiated water)	\$150/MW _t
	Gaseous Waste and Off-Gas Processing Systems	\$400/MW _t
	Solid Wastes Processing Equipment	\$300/MW _t
22.05	Fuel Handling and Storage Systems	
	Fuel Purification (based on daily hydrogen mass flow rate)	\$1,000/kg-day
	Fuel Preparation and Injection System	
	D-T Pellet Fabrication (based on daily flow)	\$12,000/kg-day
	Gas Liquefiers	\$3,800/kg-day
	Fuel Storage	\$80,000/tank
	20 kg T ₂ capacity	
	20 kg D ₂ capacity	
	Fuel Preparation (20 kg/day)	\$60,000/machine
	Fuel Injectors (20 kg/day)	\$250,000/injector
	Emergency Air Detritiation	\$30/gram/T
	Facility Atmosphere Cleanup (based on flow rate in the equipment)	\$400/cfm

APPENDIX B

REFERENCE POWER CONVERSION PLANT DESCRIPTION

REFERENCE POWER CONVERSION PLANT DESCRIPTION

1000 MWe GROSS

[For qualifications regarding this appendix, refer to Appendix C.]

B.1 INTRODUCTION

Reference 1000 MWe gross power conversion plants are described in this appendix. The reference plants are assumed to represent typical power conversion plants that can be integrated with magnetically confined fusion reactors and their associated heat transport systems.

The conceptual designs developed to date for this class of fusion reactors and their heat transport systems cover a wide spectrum of plant capacity, reactor heat source, coolant type, and coolant temperature. Examples of typical variation of these parameters are shown below:

<u>Parameter</u>	<u>Range of Variation</u>
Plant Capacity	800 MWe to 2000 MWe
Heat Source	Blanket, Divertor, Direct Convertor, etc.
Coolant Type	Lithium, Helium, Water, etc.
Coolant Temperature (reactor outlet)	440°C to 980°C

These wide variations have resulted in wide variations in the heat transport systems and power conversion systems in the conceptual fusion plant designs. The power conversion systems adopted in these designs range from state-of-the-art low temperature, saturated steam cycles to advanced systems like the closed cycle gas turbine (Brayton) cycle and the potassium cycle. In these advanced systems, attempts were made to utilize the high temperature available from fusion reactors to achieve high thermodynamic efficiencies. But, considering the adverse economics, lowered reactor first wall life, reliability and plant availability, technology development requirements, etc.,

imposed by high coolant temperatures, the current design trend has been to use lower temperatures. Low coolant temperatures have favorable impacts on these considerations.

Considering the trend toward lower temperatures, the reactor coolants are categorized into two groups for the purpose of standardizing power conversion systems for fusion conceptual design studies. These two groups are gas coolants (helium, steam, etc.) and liquid coolants (lithium, water, molten salt, etc.). The primary motivation for categorizing the coolants in this manner is to take advantage of the power conversion technologies already developed or being developed for the light water reactor (LWR), liquid metal fast breeder reactor (LMFBR), and gas-cooled fission reactor systems.

Representative heat transport systems with the associated power conversion systems for the two groups of coolants are shown in Figures B-1 and B-2. The saturated steam cycle has been largely used with moderate temperature liquid coolants, whereas the superheat steam cycle has been used mostly with high temperature gas coolants. The saturated cycle has been used in the LWR and LMFBR designs, while the superheat cycle has been used in LMFBR and gas-cooled reactor designs. Thus, for the fusion plants, two reference power conversion cycles are assumed -- a saturated steam cycle and a superheat steam cycle. The descriptions of the two cycles and the conversion plant arrangements are given in the following sections.

B.2 SATURATED CYCLE

A schematic diagram of the saturated cycle conversion system is shown in Figure B-1. The steam cycle selected for energy conversion is similar to that for LWR and LMFBR designs. Steam conditions at the turbine inlet are 6.9 MPa and 285°C (1000 psia and 545°F).

The turbine-generator selected is a tandem compound 1800 rpm unit operating with a saturated cycle. The unit consists of one high pressure (HP) cylinder, four moisture separator-reheaters, two low pressure (LP) cylinders, and one generator.

FIGURE B-1. Typical Heat Transport and Energy Conversion Systems for Liquid-Cooled Concepts

FIGURE B-2. Typical Heat Transport and Energy Conversion Systems for Gas-Cooled Concepts

The conversion system also includes a condensate system and a feedwater heating system. The function of the condensate system is to condense the steam exhausted from the low pressure cylinders of the turbine-generator unit. The condensate system schematically consists of a steam condenser and a condensate pump which delivers the condensate to the feedwater heating system. The condensation is accomplished by circulating cold water through the condenser.

The function of the feedwater heating system is to preheat and pressurize the condensate and deliver it to the steam generator at the required temperature and pressure conditions. The system schematically consists of a feedwater pump(s) and feedwater heater(s). The pump is driven by a steam turbine. The heating of feedwater is accomplished by extracting steam from the turbine at different stages and passing it through feedwater heaters.

A large amount of heat is rejected from the energy conversion system while condensing the turbine exhaust steam in the steam condenser. This rejected heat amounts to approximately 65% of the total heat generated in the reactor. This is caused by the thermodynamic inefficiency of the Rankine Cycle used in the conversion system.

The function of the heat rejection system is to reject this waste heat to an ultimate heat sink. This function is accomplished by transporting the heat rejected in the condenser to cooling towers where it is ultimately rejected to the atmosphere. The system schematically consists of a circulating water pump and a cooling tower as shown in Figure B-1. The circulating water pump draws cold water from the cooling tower and delivers it to the condenser to cool the condensing steam. The effluent hot water from the condenser then flows back to the cooling tower and exchanges heat with air.

A schematic heat and mass balance diagram of the conversion system is shown in Figure B-3.

FIGURE B-3. Heat and Mass Balance Schematic of 1,000 MWe Steam Plant Conversion System: Saturated Steam Cycle

EQUIPMENT LIST

Major equipment along with their capacity ratings for the saturated cycle are listed below:

Main Steam Turbine

Type	TC-4F-43 LSB
Rating, kW	1,000,000
Speed, rpm	1,800
Inlet conditions, MPa/°C	6.9/285
Outlet conditions, cm HgA	6.35/4.19
Steam flow, kg/sec	1501.7

Generator

Type	4 pole, 3 phase, 60 Hz
Rating, kVA/kV	1,167,000/25
Hydrogen pressure, MPa	0.62
Power factor	0.9

Feedpump Turbine

Type	Multistage, variable speed
Number	2
Rating, kW	8,400
Steam flow, kg/sec	12.75
Inlet conditions, MPa/MJ/kg	1.45/2.97

Moisture Separator Reheater

Type	Two-stage steam reheat, shell, and tube
Number	4

Turbine Condensers

Type	Two shell, dual pressure, surface condenser
Duty, MWt	1,900
Heat transfer surface, m ²	69,700
Tube material	90-10 Cu Ni
Cooling water flow, kg/sec	31,500

Circulating Water Pumps

Type	Vertical-centrifugal wet-pit
Number required	4
Capacity, kg/sec	8,000

EQUIPMENT LIST (contd)

Circulating Water Pumps (contd)

Rated head, m	32
Motor rating, kW	3,400

Cooling Tower

Type	Mechanical draft, wet cooling towers
Number of rows	3
Number of cells/row	14
Design bases, ambient WB, °C rated load	15.6
Approach, °C/range, °C	8.3/14.4
Total rating, MWt	1,960
Total flow, kg/sec	31,500

Feedwater Heater

Type	Closed horizontal shell and tube
Number, HP/LP	2 pairs/4 pairs
Final feedwater temperature	217.8°C
Material	Stainless steel tubes Carbon steel shells

Condensate Pumps

Type	Vertical canned centrifugal
Number	3
Capacity, kg/sec	555
Head, m	360

Feedwater Pumps

Type	Horizontal centrifugal
Number	2
Capacity, kg/sec	830
Head, m	810
Driver	Steam-turbine

B.3 SUPERHEAT CYCLE

Figure B-2 shows the schematic diagram of the superheat cycle. This steam cycle is similar to that considered in Gas-Cooled Fast Reactor designs. Steam conditions at the turbine inlet are 9.24 MPa and 534°C (1340 psia and 994°F). The turbine-generator selected is a tandem compound 1,800 rpm unit operating with a superheat cycle, and it consists of one high pressure (HP) cylinder, one intermediate pressure (IP) cylinder, two low pressure (LP) cylinders, and one generator. This cycle does not use a moisture separator-reheater.

Figure B-4 shows the schematic heat and mass balance diagram of this conversion system. The condensate system, feedwater heating system, and heat rejection system are the same as described in Section B.2 of this appendix.

FIGURE B-4. Heat and Mass Balance Schematic of 1,000 MWe Steam Plant Conversion System: Superheat Steam Cycle

LEGEND
Kg - FLOW - Kg/sec.
P - PRESSURE MPa
H - ENTHALPY MJ/Kg
T - TEMPERATURE °C

NAME PLATE RATING
1,000,000 KW TURBINE GENERATOR UNIT
9.24 MPa, 534°C, 6.4 cm HgA
1169,000 KVA, .90 PF
1800 RPM

B.13

NO.	DATE	REVISIONS	BY	CHE	DESN	ENGR	PROJ.	CLIENT
SCALE	NONE	DESIGNED	DRAWN	S. LOUIE				
BECHTEL CORPORATION SAN FRANCISCO								
1,000 MWE STEAM PLANT								
TURBINE HEAT BALANCE SUPERHEAT STEAM CYCLE								
BCHTEL	JOB NO.	DRAWING NO.	REV.					
	13480	D-4	0					

EQUIPMENT LIST - FIGURE B-4

Major equipment along with their capacity ratings for the superheat cycle are listed below:

Main Turbine Data

Rating, kW	1,000,000
Speed, rpm	1,800
Throttle steam pressure, MPa	9.24
Throttle steam temperature, °C	534
Steam flow, kg/sec	1010.6
Condenser pressure, cm Hg.A	6.4

Generator

Type	4 pole, 3 phase, 60 Hz
Rating, kVA/kV	1,169,000/22
Generator pf	0.9
Hydrogen pressure, MPa	0.52

Cooling Tower

Type	Induced draft
Flow rate, kg/sec	21,500
No. of cells (total)	24 (12 cells per tower)
Approach, °C	4.4
Range, °C	17.3
No. of Fans	24

Turbine Condenser

Quantity	1
Type	Dual pressure - 2 shells
Surface area: m ²	57,728
Tube material	Admiralty Brass
Duty, MWt	1558
Cooling Water Flow, kg/sec	21,500

Circulating Water Pump

Quantity	3
Type	Vertical wet pit
Capacity, kg/sec	7,200
Head, m	26
Driver, kW	Electric motor, 2,600

EQUIPMENT LIST (contd)

Condensate Pump

Quantity	3
Type	Vertical
Capacity, kg/sec	340
Head, m	380

Feedwater Pumps

Quantity	2
Type	Horizontal barrel
Design Capacity, kg/sec	340
Head, m	2450

Feed Pump Turbine

Quantity	2
Type	Multistage, variable speed
Rating, kW	17,500
Steam Flow, kg/sec	48.6
Inlet conditions, MPa/MJ/kg	1.2/2.99

Feedwater heater

Type	"U" Tube
Number, HP/LP	2 pairs/4 pairs
Final Feedwater Temperature	211°C
Material	304SS tubes
	Carbon steel shells

B.4 PLANT ARRANGEMENT

Turbine Building Arrangement

A general arrangement of the steam turbine building was developed for each of the saturated and superheat steam cycle cases. In each case, a plan view and a cross-sectional view of the turbine building was prepared. Drawings B-5 and B-6 are respectively the plan and cross-sectional views of the saturated cycle case. Drawings B-7 and B-8 are the respective plan and cross-sectional views of the superheat cycle case. These drawings show the arrangement of the major equipment and piping in the turbine building. The major equipment includes the turbine-generator, moisture separator-reheater, condenser, feed-water heater, and feed pump. It is to be noted that the superheat cycle does not require a moisture separator-reheater as may be seen in the heat balance diagram (Figure B-4) and the arrangement drawings (Drawings B-7 and B-8) for this cycle.

Plot Plan

In addition to the turbine building arrangement drawings, a plot plan was prepared (Drawing B-9) showing the relationship between the turbine building, the cooling towers, and other facilities associated with the steam plant. This plot plan is intended to show the relative location of the various structures and facilities of a power plant. It is to be noted that the plot plan does not show the reactor building, heat exchanger building, and other related buildings as these were not addressed in this appendix (Appendix B). However, a general area is indicated for these buildings in the plot plan.

H
G
F
E
D
C
B
A

A vertical scale with labels A, B, C, D, E, F, G, and H from bottom to top, representing a concentration gradient.

FIGURE B-8. Cross-Sectional Arrangement of Equipment in the Steam Turbine Building: Superheat Steam Cycle

APPENDIX C

REFERENCE POWER CONVERSION PLANT COST ESTIMATE

REFERENCE POWER CONVERSION PLANT COST ESTIMATE

[The estimates and scaling rules presented herein are based largely on adaptations and extrapolations of previous design studies of fission and fusion plants performed by Bechtel, particularly the 1000 MWe (gross) Prototype Large Breeder Reactor (PLBR) study developed by General Electric Company and Bechtel Corporation. The estimate for the PLBR plant was based on general arrangement drawings, electrical single-line diagrams, system flow diagrams, and a plot plan for a hypothetical site. Materials and equipment were prices at January 1976 cost levels, with manual labor at \$13.75 per hour, representing an appropriate mix of construction crafts. Adequate skilled labor was assumed to be available to support a straight time single shift work week. More recent PLBR cost studies provided information comparing saturated and superheated steam cycles. The PLBR estimates and cost studies were escalated to 1979 dollar levels, and allocated to the appropriate fusion plant cost accounts from PNL-2648. Caution should be exercised when applying these results. The system being scaled should represent systems similar in design, scope and interface to the reference designs (Appendix B); the scaling rules of Appendix D should be applied within the applicable ranges as indicated for the rules. The application of these results should be limited to conceptual design studies].

SATURATED STEAM CYCLE

CAPITAL COST DETAIL
(1979 Dollars)

<u>Accounts</u>		<u>\$ Million</u>
21	<u>STRUCTURES & SITE FACILITIES</u>	29.6
.03	<u>Turbine and Control Buildings</u>	25.4
.01	Basic Building Structures	16.2
.02	Building Services	<u>9.2</u>
.04	<u>Cooling System Structures</u>	4.2
23	<u>TURBINE PLANT EQUIPMENT</u>	134.9
.01	<u>Turbine Generators</u>	62.5
.01	Turbine Generator & Accessories	60.6
.02	Foundations	<u>1.9</u>
.02	<u>Main Steam System (Piping)</u>	4.8
.03	<u>Heat Rejection Systems</u>	18.5
.01	Water Intake Common Facilities	1.0
.02	Circulating Water Systems	5.5
.03	Cooling Towers	<u>12.0</u>
.04	<u>Condensing System</u>	13.1
.01	Condensers	9.1
.02	Condensate System	3.5
.03	Gas Removal Systems	<u>0.5</u>
.05	<u>Feed Heating System</u>	9.5
.01	Regenerators & Recuperators	3.5
.02	Pumps	5.9
.03	Tanks	<u>0.1</u>
.06	<u>Other Turbine Plant Equipment</u>	10.0
.01	Turbine Auxiliaries	0.4
.02	Auxiliaries Cooling System	3.4

SATURATED STEAM CYCLE (contd)

CAPITAL COST DETAIL

(1979 Dollars)

<u>Accounts</u>		<u>\$ Million</u>
.06	<u>Other Turbine Plant Equipment (contd)</u>	10.0
	.03 Make-up Treatment System	2.2
	.04 Chemical Treatment System	3.4
	.05 Central Lubrication System	<u>0.6</u>
.07	<u>Instrumentation & Control</u>	16.5
24	<u>ELECTRIC PLANT EQUIPMENT</u>	117.6
.01	<u>Switchgear</u>	8.7
	.01 Generator Circuits	1.3
	.02 Station Service	<u>7.4</u>
.02	<u>Station Service Equipment</u>	11.4
	.01 Station Service & Start-up Transformer	1.6
	.02 Low Voltage Substations & Transformer	2.4
	.04 Diesel Engine Generators	2.8
	.07 Main Power Transformers	<u>4.6</u>
.03	<u>Switchboards</u>	0.1
.04	<u>Protective Equipment</u>	1.3
.05	<u>Electrical Structures & Wiring Containers</u>	52.1
	.01 Concrete Cable Tunnels & Envelopes	1.8
	.02 Cable Trays & Support	12.7
	.03 Conduit	<u>37.6</u>
.06	<u>Power & Control Wiring (including heat tracing)</u>	41.9
	.01 Generator Circuits Wiring	3.0
	.02 Station Service Power Wiring	28.0
	.03 Control Wiring	<u>10.9</u>

SATURATED STEAM CYCLE (contd)

CAPITAL COST DETAIL

(1979 Dollars)

<u>Accounts</u>	<u>\$ Million</u>
.07 <u>Electric Lighting</u>	2.1
25 <u>MISCELLANEOUS PLANT EQUIPMENT</u>	15.5
.01 <u>Transportation & Lifting Equipment</u>	3.3
.01 Cranes, Hoists, Monorails, Conveyors	<u>3.3</u>
.02 <u>Air & Water Service Systems</u>	9.4
.01 Air Systems	1.0
.02 Water Systems	<u>8.4</u>
.03 <u>Communications Equipment</u>	1.6
.01 Local Communication Systems	0.9
.02 Signal Systems	<u>0.7</u>
.04 <u>Furnishing & Fixtures</u>	1.2
.01 Safety Equipment	0.1
.02 Shop, Laboratory & Test Equipment	<u>1.1</u>

SUPERHEAT STEAM CYCLE

CAPITAL COST DETAIL
(1979 Dollars)

<u>Accounts</u>		<u>\$ Million</u>
21	<u>STRUCTURES & SITE FACILITIES</u>	30.6
.03	<u>Turbine and Control Buildings</u>	26.4
.01	Basic Building Structures	17.2
.02	Building Services	<u>9.2</u>
.04	<u>Cooling System Structures</u>	4.2
23	<u>TURBINE PLANT EQUIPMENT</u>	140.7
.01	<u>Turbine Generators</u>	66.4
.01	Turbine Generator & Accessories	64.5
.02	Foundations	<u>1.9</u>
.02	<u>Main Steam System (Piping)</u>	5.9
.03	<u>Heat Rejection Systems</u>	11.9
.01	Water Intake Common Facilities	0.6
.02	Circulating Water Systems	3.5
.03	Cooling Towers	<u>7.8</u>
.04	<u>Condensing System</u>	13.1
.01	Condensers	9.1
.02	Condensate System	3.5
.03	Gas Removal Systems	<u>0.5</u>
.05	<u>Feed Heating System</u>	16.9
.01	Regenerators & Recuperators	6.2
.02	Pumps	10.5
.03	Tanks	<u>0.2</u>
.06	<u>Other Turbine Plant Equipment</u>	10.0
.01	Turbine Auxiliaries	0.4
.02	Auxiliaries Cooling System	3.4
.03	Make-up Treatment System	2.2

SUPERHEAT STEAM CYCLE (contd)

CAPITAL COST DETAIL
(1979 Dollars)

<u>Accounts</u>	<u>\$ Million</u>
.06 <u>Other Turbine Plant Equipment (contd)</u>	10.0
.04 Chemical Treatment System	3.4
.05 Central Lubrication System	<u>0.6</u>
.07 <u>Instrumentation & Control</u>	16.5
24 <u>ELECTRIC PLANT EQUIPMENT</u>	122
.01 <u>Switchgear</u>	8.7
.01 Generator Circuits	1.3
.02 Station Service	<u>7.4</u>
.02 <u>Station Service Equipment</u>	11.4
.01 Station Service & Start-up Transformer	1.6
.02 Low Voltage Substations & Transformer	2.4
.04 Diesel Engine Generators	2.8
.07 Main Power Transformers	<u>4.6</u>
.03 <u>Switchboards</u>	0.1
.04 <u>Protective Equipment</u>	1.3
.05 <u>Electrical Structures & Wiring Containers</u>	54.4
.01 Concrete Cable Tunnels & Envelopes	1.8
.02 Cable Trays & Support	13.3
.03 Conduit	<u>39.3</u>
.06 <u>Power & Control Wiring (including heat tracing)</u>	44.2
.01 Generator Circuits Wiring	3.0
.02 Station Service Power Wiring	29.7
.03 Control Wiring	<u>11.5</u>

SUPERHEAT STEAM CYCLE (contd)

CAPITAL COST DETAIL
(1979 Dollars)

<u>Accounts</u>	<u>\$ Million</u>
.07 <u>Electric Lighting</u>	2.1
25 <u>MISCELLANEOUS PLANT EQUIPMENT</u>	15.5
.01 <u>Transportation & Lifting Equipment</u>	3.3
.01 Cranes, Hoists, Monorails, Conveyors	<u>3.3</u>
.02 <u>Air & Water Service Systems</u>	9.4
.01 Air Systems	1.0
.02 Water Systems	<u>8.4</u>
.03 <u>Communications Equipment</u>	1.6
.01 Local Communication Systems	0.9
.02 Signal Systems	<u>0.7</u>
.04 <u>Furnishing & Fixtures</u>	1.2
.01 Safety Equipment	0.1
.02 Shop, Laboratory & Test Equipment	<u>1.1</u>

APPENDIX D

REFERENCE POWER CONVERSION PLANT COST ESTIMATE
SCALING RULES

SCALING RULES - REFERENCE POWER CONVERSION PLANT COST ESTIMATE

[Caution should be exercised when applying these rules. The system being scaled should represent systems similar in design, scope and interface to the reference designs (Appendix B); scaling rules should be applied within the applicable ranges as indicated for the rules. The application of these results should be limited to conceptual design studies. For further qualifications, see Appendix C].

The data presented in this appendix provide means for adjusting the Reference Power Conversion Plant Cost Estimate (Appendix C) to reflect different design conditions than those outlined in the Reference Power Conversion Plant Description (Appendix B). For each account, cost/design relationships are discussed together with scaling factors that apply to the costs in that account. These cost relationships are applicable to the total cost of the account within a limited range of deviations from the reference plant design if noted in the discussion of that account, and in any case within an overall plant range from 800 MWe to 1400 MWe (gross). They are not appropriate for preparing original estimates of substantially different design.

21.03 Turbine Building (including Control Room, Heater Bay, Diesel Generator and Auxiliary Equipment Areas)

This account may be adjusted by applying the appropriate building volume unit cost for each of the major building functions: for the Turbine Building area, \$83/m³ of enclosed space; for the Control Room area, \$197/m³; for the Diesel Generator and Auxiliary Equipment areas, \$177/m³. These unit costs apply to differences in volume from the reference design case which is based on volumes for these functional areas as follows: Turbine Building 182,500 m³, Control Room 7,400 m³ and Diesel Generator and Auxiliary Building areas, 49,000 m³. These building volumes are consistent with recent nuclear plant designs which require approximately 200 m³/MWe to 250 m³/MWe for these types of buildings. It is expected that fusion plants will have similar requirements.

21.04 Cooling System Structures

The reference design employs a closed condenser cooling system, thus no intake, discharge or unpressurized conduit systems are included. Recirculating structures (Account 21.04.04) and Cooling Tower System Earthwork (Account 21.04.05) may be adjusted by the following relationship:

$$C_1 = C_R \left[\frac{MWe_1}{MWe_R} \right]^{.3}$$

where C_1 = adjusted cost

C_R = reference cost

MWe_R = rating of reference turbine equipment (Appendix B)

MWe_1 = rating of new turbine equipment

23.01 Turbine-Generator

The turbine-g Generator account includes the purchase and installation of the turbine-generator and associated auxiliary equipment and piping as well as the turbine pedestal. The account may be adjusted in relation to the gross generating capacity of the equipment by means of the following relationship:

$$C_1 = C_R \left[\frac{MWe_1}{MWe_R} \right]^{.7}$$

This relationship is applicable in the case of saturated steam conditions within the temperature range of 500°F to 750°F, and within the pressure range of 900 psi to 1200 psi. The same relationship is applicable in the case of superheated steam conditions within the temperature range of 800°F to 1000°F, and within the pressure range of 1800 psi to 2400 psi.

23.02 Main Steam System (Piping)

The main steam system cost is largely affected by the steam flow through the turbine generator as well as the length of steam piping as determined from the plant arrangement. Alterations from the reference facility can be calculated from the expression:

$$C_1 = C_R \left[\frac{MWt_1}{MWt_R} \times \frac{LF \text{ Main Steam Piping}}{6,400 \text{ LF}} \right]$$

where: LF = total linear feet of piping, including expansion loops
 MWt_R = thermal rating of the reference plant (Appendix B)
 MWt₁ = thermal rating of the new plant

23.03 Heat Rejection Systems

The heat rejection system, composed of the facilities associated with the circulating water pumps and motor drives, and the waste heat cooling tower, is sensitive in cost mainly to the amount of heat rejected. Given a constant plant efficiency, adjustment of the cost from the reference plant can be determined from the expression:

$$C_1 = C_R \left[\frac{MWt_1}{MWt_R} \right]^{.8}$$

23.04 Condensing System

The steam condensing system cost is affected primarily by the size of the condenser, and is related to the steam flow through the turbine and the amount of heat rejected. A direct relationship of cost per MWe gross generator output is sufficiently accurate for adjusting condensing system cost:

$$C_1 = C_R \left[\frac{MWe_1}{MWe_R} \right]^{.9}$$

23.05 Feedwater Heating System

The feedwater heating system, composed of pumps, heat exchangers, piping, valves, and miscellaneous equipment is sensitive in cost mainly to the feedwater flow and temperature rise. The cost relationship to the flow, however, is less than linear, and the expression

$$C_1 = C_R \left[\frac{MWt_1}{MWt_R} \right]^{.6}$$

may be used to adjust this account for differences in gross plant heat transport capacity.

23.06 Other Turbine Plant Equipment

This account may be related to plant capacity by the expression:

$$C_1 = C_R \left[\frac{MWe_1}{MWe_R} \right]^{.6}$$

23.07 Instrumentation and Control Equipment

This account includes instrumentation and control equipment for the turbine plant balance of plant facilities, and undergoes modest change in cost within the range of plant sizes between 800 MWe and 1400 MWe (net). Its cost may be estimated from the reference plant cost by the expression:

$$C_1 = C_R \left[\frac{MWe_1}{MWe_R} \right]^{.3}$$

24. Electric Plant Equipment

The electric plant accounts consist mainly of equipment and materials required to distribute power to the in-plant loads associated with the reactor plant, the turbine plant and other balance of plant equipment. Therefore, the total auxiliary load required to operate equipment throughout the entire plant is one important parameter of electric plant cost, the other being building sizes, which affects the average run lengths and quantities of wire, cable, conduit, etc.

The electric plant accounts provide for equipment and feeder cabling to the reactor power supply area, but do not include reactor power supply equipment, conductors, switches or protective devices beyond the first transformer feeding the reactor power supply equipment.

24.01, 24.02, 24.03. Major electrical equipment accounts may be assumed to vary in cost, in direct relationship to the auxiliary loads required by the plant mechanical equipment. Thus, adjustments to those accounts may be made by use of the expression:

$$C_1 = C_R \left[\frac{MWaux_1}{MWaux_R} \right]$$

where $MWaux_1$ and $MWaux_R$ are plant auxiliary loads (exclusive of power loads required by the reactor power supply equipment) for the adjusted and reference plants, respectively.

24.04 Protective Equipment (General Station Grounding Systems and Cathodic Protection)

The cost of grounding and cathodic protection systems is composed mainly of the station grounding grid and ground connecting cables. Adjustments to the cost of this account may be related to the plot area requirements for all buildings by the expression:

$$C_1 = C_R \left[\frac{A_1}{A_R} \right]$$

where A_1 and A_R are the total plot area requirements for all buildings in the new and reference plants, respectively, and C_1 is held within the range of 10% less than C_R , to 200% greater than C_R . For the reference case, the A_R is 14,000 m².

24.05 and 24.06. The estimated costs for these accounts are influenced by the plant auxiliary load requirement, which impacts numbers and sizes of cabling runs; and building sizes, which impacts average run lengths. Adjustments to cost may be estimated with equal weight to each of these parameters by means of the expression:

$$C_1 = 0.5 C_R \left[\frac{MW_{aux1}}{MW_{aux2}} + \frac{A_1}{A_R} \right]$$

The estimated costs in Accounts 24.05 and 24.06 include allowance for electric heat tracing of primary and secondary liquid metal heat transport system piping. For gas cooled reactor designs where tracing of heat transport lines is not required, \$2 million should be deducted from Account 24.05 and \$4 million from Account 24.06 before making the adjustments described above. Adjustments to Accounts 24.05 and 24.06 by means of the expression above should be limited to values of C_1 which are within the range of 20% less than C_R to 100% greater than C_R . If the formula indicates values beyond this range, independent assessment of the value is necessary.

24.07 Electric lighting may be adjusted in direct proportion to total volume of all buildings:

$$C_1 = \left[C_R \frac{V_1}{V_R} \right]$$

where V_1 and V_R are total volumes of all buildings (in accounts 21.02, 21.03, 21.05 and 21.06) for the adjusted and reference plants, respectively, V_R being 700,000 m³.

25. Miscellaneous Plant Equipment

Miscellaneous plant equipment may be left unadjusted, except for Account, 25.01, Transportation and Lifting Equipment. With this account, \$800,000 represents an allowance for purchase and installation of the reactor building crane. For special fusion reactor configurations, special reactor building cranes are to be estimated independently and substituted for this \$800,000 allowance.

APPENDIX E

COST ESTIMATING RULES

Spare Parts Allowance/
Contingency Allowance/
Design Allowance

COST ESTIMATING RULES

Design allowances, contingency allowances and spare parts allowances are dollar amounts added to estimates to account for costs expected to be incurred during the course of a project, but which are not adequately accounted for in the body of the estimate.

DESIGN ALLOWANCE

A design allowance is usually employed in an estimate of a particular piece of equipment or system for which a quotation was received or an estimate was made at an early stage of the design of that item. The allowance represents the difference between the simpler concept envisioned at the time the estimate was made and the mature design expected to be developed ultimately. It may be considered as equivalent to change orders to a supplier if a purchase order was written when the estimate was made.

For a fusion plant estimate, accounts 21, 23, 24, and 25 represent facilities and systems that are similar to such facilities and systems in a conventional fission plant and which are well understood in concept. Therefore, no design allowance for these accounts is recommended.

However, for a fusion plant estimate, account 22 represents equipment and systems that are not conventional in design. Therefore, a design allowance of 10% of estimated costs is recommended.

CONTINGENCY ALLOWANCE

The contingency allowance is an amount added to an estimate to account for the difference between the sum of individual items estimated and the total amount that is reasonably expected to be spent, considering the degree of uncertainties in the estimated quantities, prices, labor productivity, etc. embodied in the estimate details. Due to the nature of estimating, which is generally to assign values to known quantities, unknown quantities and other uncertainties usually tend to produce a net increase from the estimated costs. Thus, with all estimates there is the risk that in the course of design and construction, actual costs will be greater than the estimate. The contingency allowance is added to an estimate to reduce the risk of overrun to an acceptable level. The magnitude of the allowance must be considered based on a thorough understanding of the methods and bases of the estimated costs.

For the conceptual level of design for fusion plant accounts 21, 22, 23, 24, and 25, a contingency allowance of 15% of estimated costs is recommended.

SPARE PARTS ALLOWANCE

Although the types and numbers of spare parts to be provided in inventory at the startup of a power plant is decided by the owner of the plant, common practice indicates that a reasonable cost allowance for the value of spares in inventory falls in a fairly consistent range of percentages of major equipment costs. This allowance may also be expressed as a function of total cost of installed equipment and materials, since the relationship between major equipment cost and total cost of equipment and materials remains relatively constant.

Spare parts allowances of 2% of estimated costs for account 21, 2% of estimated costs for account 22, 2% of estimated costs for account 23, 4% of estimated costs for account 24, and 3% of estimated costs for account 25 are recommended.

APPENDIX F

STANDARD UNIT COSTS

Operating and Maintenance/
Scheduled Component Replacement

STANDARD UNIT COSTS - Operation and Maintenance

	<u>Annual Cost Per Staff Member^(a) (7/79 Price Levels)</u>
Management Personnel	\$75,000
Operations Personnel	\$55,000
Maintenance (Routine) Personnel	\$40,000
Maintenance (Special) Personnel	\$55,000
Technical Personnel	\$40,000
Clerical and Services Personnel	\$30,000

(a) Includes fringe benefits, insurance, and overhead expense burdens.

APPENDIX G

STANDARD UNIT COSTS

Fuel/Special Materials

STANDARD UNIT COSTS - FUEL/SPECIAL MATERIALS

Purchase Cost (price)
(7/79 Price Levels)

02.-03 FUEL

26. SPECIAL MATERIALS

26.01 to 26.04 Fuel and Coolants

Deuterium (99.75% pure)

D₂O \$ 225/kg

D₂ \$2000/kg

Tritium (current market price) \$5000/g

Tritium (mature fusion economy) \$ 0/g

Lithium (reactor grade) \$ 30/kg

Helium

Small shipments \$3.25/liter

Bulk quantities \$2.00/liter

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Atomics International
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