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CHARACTERIZATION OF ALTERNATIVE ELECTRIC GENERATION TECHNOLOGIES FOR THE SPS COMPARATIVE ASSESSMENT: VOLUME 1, SUMMARY OF CENTRAL-STATION TECHNOLOGIES

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1.0 INTRODUCTION AND BACKGROUND

Essentially all economic sectors of our society depend in some part on electric power generation. Until the early 1960's, electric power was generated from hydroelectric and fossil fueled generating facilities. Hydroelectric potential has become fully utilized, with the exception of very small facilities (low head hydro). Fossil fuels are not renewable and, with the exception of coal, are rapidly being depleted. Alternative fuels and electric energy sources from renewable resources must be developed to preserve our present levels of activity and society as we know it. One such alternative electric energy source concept being pursued is the Satellite Power System (SPS)* - a photovoltaic facility orbiting earth and transmitting its generated power back down to earth.

A major element of the SPS Concept Development and Evaluation Program** is the characterization and comparative analysis of future terrestrial-based alternatives to SPS. A significant portion of this effort is the selection and characterization of six terrestrial central station electric generation systems that may be viable alternatives to SPS in the year 2000 and beyond. The objective of this report is to *complete and document the physical and cost characterizations of six electric generation technologies of designated capacity.*

The characterizations that follow this technical summary provide a detailed description of selected year 2000 power plant designs. It is im-

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*U.S. Department of Energy and NASA, SPS CDEP Reference System Report, DOE/ER-0023 (October 1978).

**Satellite Power System (SPS) Concept Development and Evaluation Program Plan, DOE/ET-0034 (February 1978).

portant to keep in mind that these plant designs represent only a certain sampling of concepts associated with each technology and that a realistic "best" design truly characteristic of a year 2000 technology cannot exist at this point in time. The technologies selected are technologically dynamic and hence may undergo rapid evolutionary as well as revolutionary change before the year 2000.

The technologies selected for the detailed characterization were:

Solar Technology

- Terrestrial Photovoltaic (200 MWe)

Coal Technologies

- Conventional high sulfur coal combustion with advanced flue gas desulfurization (1250 MWe)
- Open cycle gas turbine combined cycle plant with low Btu gasifier (1250 MWe)

Nuclear Technologies

- Conventional light water reactor (1250 MWe)
- Liquid metal fast breeder reactor (1250 MWe)
- Magnetic fusion reactor (1320 MWe)

2.0 APPROACH

Numerous studies and reports exist which characterize various electric generation technologies. Rather than restudy these technologies, the approach taken for this report was to rely on existing data and make it comparable. A consistent and traceable set of technological and cost characterizations of reference design systems were developed for the following technology configurations and nominal generating capacities:

- Terrestrial Central Station Photovoltaic
  - Without Storage - 200 MWe
- Conventional Coal with Improved Environmental Controls - 1250 MWe
- Light Water Reactor with Improved Fuel Utilization - 1250 MWe
- Liquid Metal Fast Breeder Reactor - 1250 MWe
- Magnetic Confinement Fusion - 2 @ 660 MWe

The basis for the technological and cost characterizations was the information and data in the preliminary reports prepared by TRW and United Engineers and Constructors, augmented by additional technical literature, expert opinion, and engineering judgment, as necessary. Consistency was established on an inter-technology basis by independent calculations of technology component sizes or capacities and by accounting for modifications necessary to consider a consistent fuel type or other factors designated.

Included in the characterizations were the following:

- Physical System Design and Operating Characteristics
- Capital and Operating Costs
- Operational Reliability and Availability
- Natural and Human Resource Requirements
- Environmental Residuals

Since the characterizations are of facilities for operation in the year 2000, the designs assumed were based on as yet undemonstrated technologies (e.g., the NUWMAK fusion machine, Wellman-Lord scrubbers, etc.). Each characterization addresses these assumed advances.

3.0 DISCUSSION AND SUMMARY

The reference plant studies have been normalized to 1250 MWe with the exception of the fusion and photovoltaic plants. The design studies from which the reference characterizations were taken had plant power production levels other than 1250 MWe. Normalization to 1250 MWe was accomplished by the scaling of plant parameters of the original design studies using the ratio of 1250 MWe to the original design capacity. A brief technical summary of each power plant design is provided below.

Terrestrial Photovoltaic Power Plant

The reference photovoltaic power plant is a nominal 200 MW size. There is no economy of scale beyond the 200 MW size as there is in conventional thermodynamic power plants. The plant characterization provided here assumes that progress in solar cell technology has resulted in high efficiency (19.3%) cells which are fabricated directly to rectangular shape. The cell cost has been projected for the year 2000 to be $\$35/m^2$, which is much less than current costs of about $\$1000/m^2$.

The solar photovoltaic power plant is the earth bound counterpart of the SPS. It uses the same advanced solar cell technology. It does not store energy. Due to the fact that the solar photovoltaic power plant is earthbound there are differences. The solar photovoltaic power plant on earth has a variable output due to the diurnal sunlight cycle and an erratic pattern of sunlight loss due to bad weather (clouds, fog, haze, etc.). The connection to the power grid on earth is straightforward, involving direct electrical connection.

The solar photovoltiac power plant supplies power to the grid on an "as available" basis. The grid may have storage in the form of batteries, fly-wheels, superconducting magnets, pumped hydroelectric, or compressed air storage; or it may have virtual storage in the form of hydroelectrical plants which are used for peaking. The grid treats the availability of electric power from the solar photovoltaic plant as a variation in the amount of power which must be supplied from the other sources.

The solar photovoltaic plant uses a large array of solar cells mounted on tilted frames pointed at the sun to generate high voltage d.c. The high voltage d.c. is then converted to high voltage a.c. and fed through trans-mission lines to the grid just as any other power plant operates.

Although large land areas seem to be covered by the solar photovoltaic power plant, the areas normally required for the mining, processing, and transporting of coal for a coal fired plant can be much larger over the lifetime of the plant.

It should be noted that operation of a solar photovoltaic power plant involves negligible environmental impact other than the plant land area. Key plant parameters are presented in Table 1.

Table 1. 25 MW Solar Photovoltaic Central Plant Array Key Parameters*

Parameter	Silicon Cell	Module
Size (Area)	6 x 6 cm	(1447m x 283m) = .4095 km^2
Cells	1	48,902,400
Panels		122,256
Rows		144
Sectors		2
Modules		1
Output at 100 MW/cm^2		
Current (Amperes)	1.24	2,598.4
Voltage	.50	$\pm$5.25K (a.c.)
Power (Watts)	.620	27.28 MW
Efficiency		
Item Efficiency	17.22%**	98%
Inefficiency Source	Basic Cell-Cover Glass	d.c./a.c. Converter
Cumulative Efficiency	17.22%	15.51%
Residuals		none
Resource Requirements		
Land		4,022 km^2
Construction and Operating Characteristics		
Operations Staff		25
Direct Capital Costs ($1000)		117,194
Indirect Capital Costs ($1000)		19,994
O&M Costs ($1000/yr)		1,678

* (Modeled somewhat after Table K-2 p. K-15 EPRI-ER-685)

** Solar Cell Efficiency 19.03% Bare at AM1

Total Module Cell Area = .176 km^2

Panel Area = .182 km^2

Conventional High Sulfur Coal Combustion with Advanced Flue Gas Desulfurization

The reference plant design was based on a 1232 MWe plant design by United Engineers and Constructors (UEC). The original design used limestone scrubbers. This design has been modified to include the Wellman-Lord Advanced Scrubbing System which is currently in the commercial demonstration phase. The Advanced Scrubbing System meets EPA's new source performance standard.

The reference plant uses Eastern Bituminous coal with a higher heating value of 11026 Btu/lb. at a rate of 541 tons/hr at nominal 1250 MWe operation. The net plant heat rate is 9546 Btu/kWh with a thermal power production of 3528 MWe, auxiliary use of 115 MWe and an overall plant efficiency of 35.75%. The capacity factor is 72.

Combustion of coal generates steam at a temperature of 1010°F and pressure of 3845 psig. This steam drives a cross compound two-parallel-shaft turbine generator before delivering heat to two mechanical draft wet cooling towers. Flue gases are processed through electrostatic precipitators to remove 99.7% of the flyash particulates and through a Wellman-Lord SO_2 removal system before being reheated with an in-stack, steam to flue gas heat exchanger, and discharged to the atmosphere through a 750 foot high, steel-lined stack.

The primary coal plant site occupies 500 acres with an additional 550 acres required over 30 years for solid/sludge waste disposal. The water consumption is 70×10^6 gallons/day at normal operation with 48×10^6 gallons/day required by the Wellman-Lord Scrubber System. Key plant parameters are presented in Table 2 and the thermodynamic cycle is shown in Figure 1.

Table 2. Key Plant Parameters - 1250 MWe High Sulfur Coal Plant

PARAMETERS	OPERATING DESCRIPTION
Steam Generator	Supercritical pressure, single reheat with Pressurized Furnace
Steam Flow	
Normal Superheater Outlet, 10^6 lb/hr	9.69
Steam Pressure/Temperature	
Superheater Outlet, psig/^oF	3,845/1010
Reheater Outlet, psig/^oF	650/1000
Fuel Type	Eastern Bituminous Coal @ 11026 Btu/lb, 10.29% ash, 3.2% sulfur
Fuel Firing Rate, Ton/hr at full load	541.1
Number of Precipitators	3
Precipitator Efficiency, in percent	99.7
Turbine Configuration	Cross-compound, 8 flow
Steam Pressure/Temperature at HP Turbine Inlet, psia	3,515/1000
Gross Generator Output, MWe	1,364.7
Net Station Output, MWe	1,250.0
Net Station Heat Rate, Btu/kWh	9,546
Net Plant Efficiency, in percent	35.75
Environmental Residuals	
Ash Sludge, lb/hr	97,372
$Na_2 SO_4$	4,200
Elemental Sulfur, lb/hr	21,818
SO_2, lb/hr	4,848
NO_x, lb/hr	5,012
Resource Requirements	
Water, 10^6 gallons/day	70
Natural Gas, 10^3 Scf/hr	156.0
Land, acres	
Plant	500
Wastes	550
Construction & Operations Characteristics	
Construction Labor Hours	9,306,700
Operations Staff	259
Capacity Factor, in percent	70
Availability, in percent	72
Direct Capital Cost ($1000)	452,078
Indirect Capital Costs ($1000)	90,706
O&M Costs ($1000/yr)	23,465

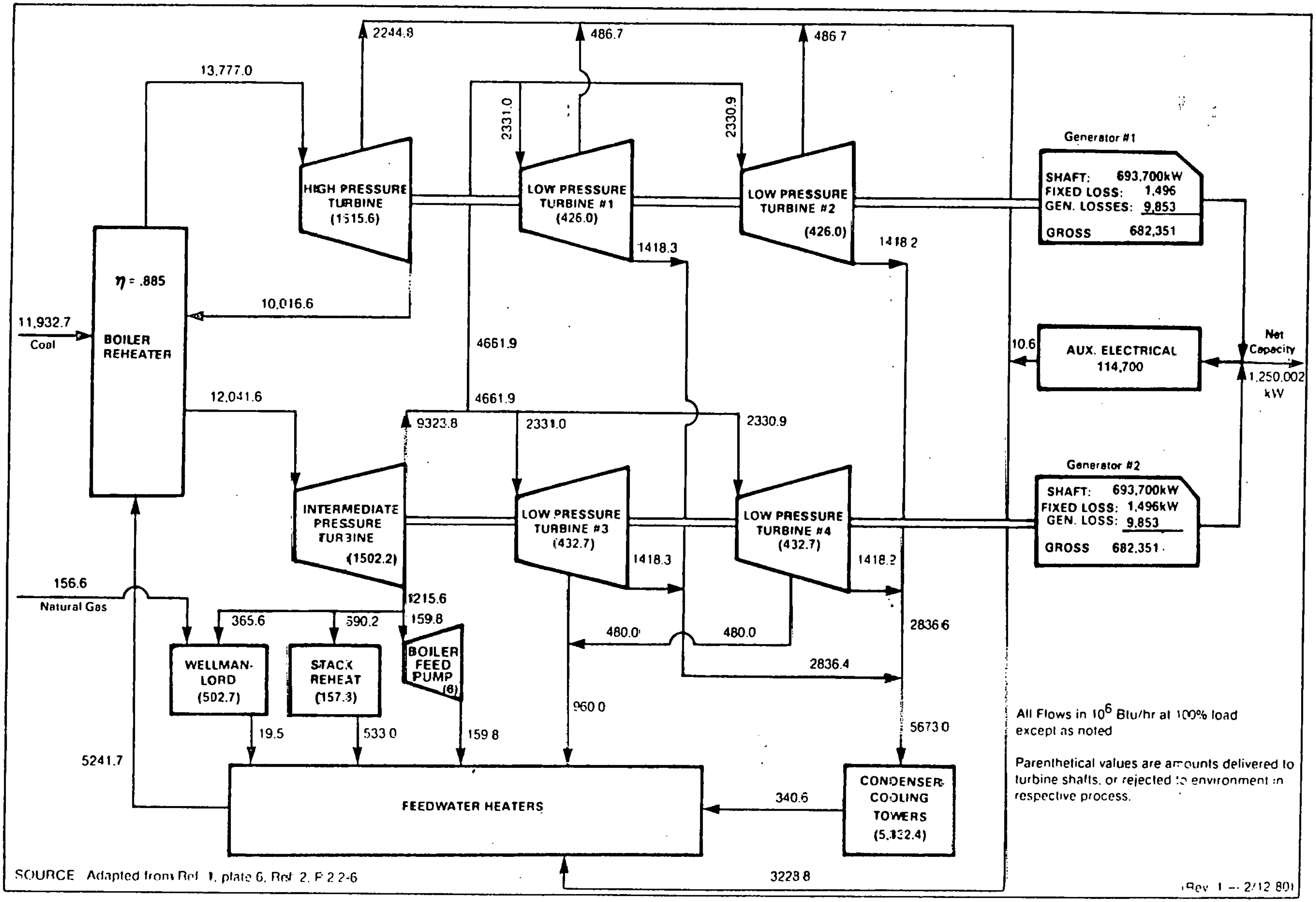

Figure 1. Coal Plant Simplified Thermodynamic Cycle

Open Cycle Gas Turbine Combined Cycle Plant with Low Btu Gasifier

The reference plant design is modeled after a 579 MWe plant described in the Energy Conversion Alternatives Study (ECAS, 1976). This plant meets the more stringent EPA new source performance standards. Ninety-eight percent removal of sulfur compounds occurs using the Alkazid process with an attendant Claus recovery system.

The reference plant uses Eastern Bituminous coal with a higher heating value of 11026 Btu/lb, at a feed rate of 502 tons/hr. and at nominal 1250 MWe operation. The net plant heat rate is 8,865 Btu/kWh, with 874 MWe produced by the prime cycle gas turbine, and 428 MWe produced by the steam bottoming cycle. The total gross output is 1301 MWe with auxiliary losses amounting to 51 MWe. Net plant efficiency is 38.5% with a 70% capacity factor.

Crushed coal is gasified, cleaned, and then combusted to directly drive eight air cooled gas turbines with a 2400^{o}F firing temperature. The turbine gas discharge is inputted into a steam bottoming cycle with turbine inlet temperature and pressure of 950^{o}F and 1800 psig, respectively. One steam turbine serves each of four heat recovery steam generator units. Low Btu gas cleanup is accomplished through the Alkazid-Claus process which removes H_2S from product gas and converts it to elemental sulfur.

The combined cycle plant site occupies 132 acres with an additional 32 acres required for waste disposal over a 30-year plant lifetime. The total water consumption per day is 12.5 x 10^6 gallons, over half of which comes from cooling tower evaporation.

A simplified thermodynamic cycle is shown in Figure 2. Key plant parameters are shown in Table 3.

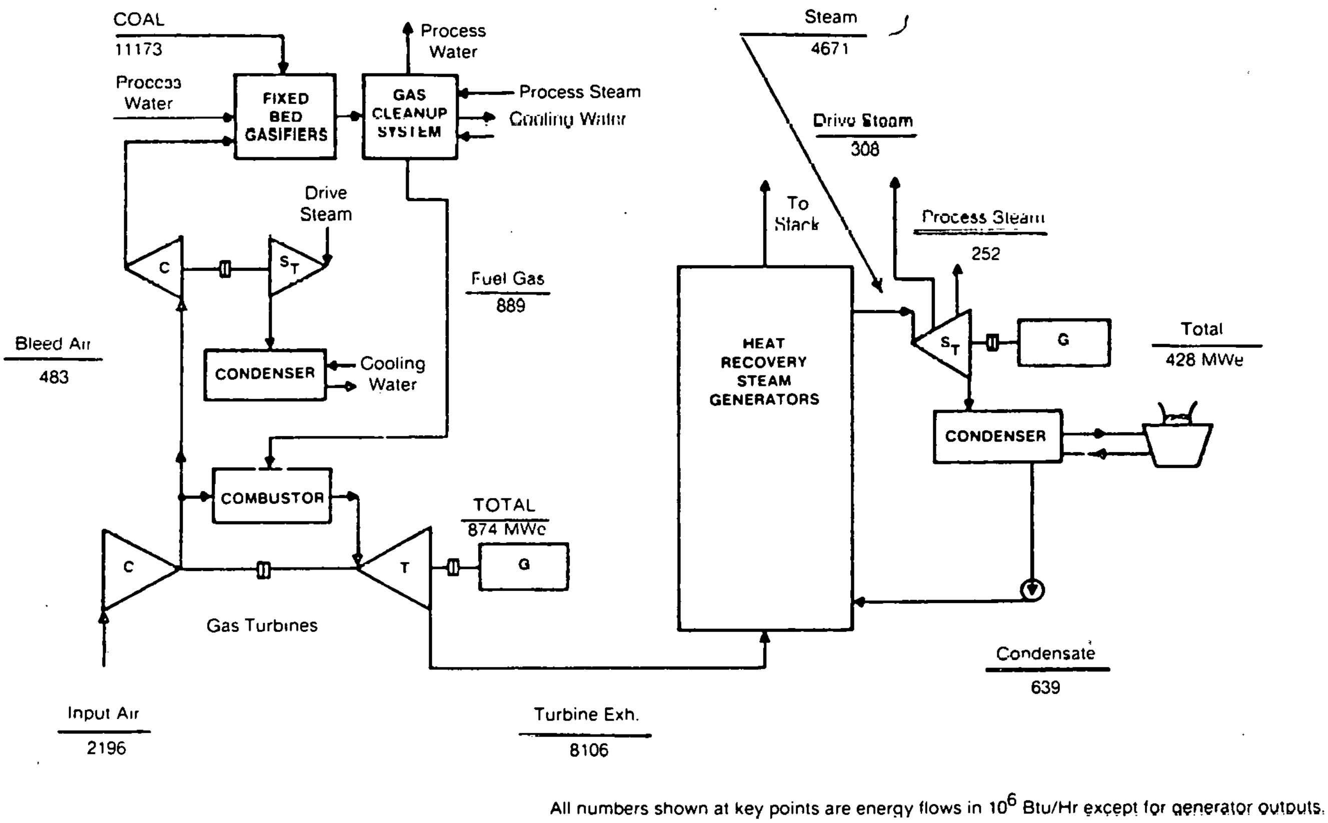

Figure 2 . Simplified Schematic Diagram of Open Cycle Gas Turbine Combined - Air Cooled - LBtu Gasifier

Table 3 . Summary of Design Parameters - Open Cycle Gas Turbine Combined Cycle with Low Btu Gasifier

(Full Load Conditions)

ENVIRONMENTAL IMPACT	1250 MWe Plant (Total Plant)
FUEL	
LBtu Gas (wet basis)	HHV = 2959 Btu/lb, LHV = 2745 Btu/lb*
Composition by Weight	
S (as H_2S + COS)	0.05%
GASIFIER	
Type	Fixed Bed
Operating Pressure (psia)	263
Cleanup System	Alkazid + Claus for H_2S Removal
	COS Hydrolyzer and NH_3 Removal
PRIME CYCLE	
Gas Turbine	Air Cooled
Turbine inlet temp (°F)	2400
Working fluid	Combustion gas
Turbomachinery configuration	Axial-flow
HEAT EXCHANGER	
Heat Recovery Steam Generator	
Vapor generator pinch point	
ΔT (°F)	18
Exit ΔT (°F)	84
BOTTOMING CYCLE	
Steam Bottoming Cycle	
Throttle temp (°F)	950
Throttle pressure (psi)	1800
HEAT REJECTION	
Wet Cooling towers	16 cells
Stack temperature (°F)	312
COS Hydrolysis Eff. (%)	100
NH_3 Removal Eff. (%)	97
Alkazid Removal Eff. (%)	95

* Data on "dry equivalent" not supplied for standard conditions.

Table 3 . Summary of Design Parameters - Open Cycle Gas Turbine Combined Cycle with Low Btu Gasifier (Continued)

(Full Load Conditions)

ENVIRONMENTAL IMPACT	1250 MWe Plant (Total Plant)
Claus Removal Eff. (%)	95
Sulfur By-Product Production (Elemental) (lb/hr)	29,917
Wellman-Lord Eff. (%)	90
Wet Scrubber Eff. (Process Gases) (%)	85
Plant Heat Rate (Btu Coal/kWh)	8,865
Plant Efficiency (%)	38.50
Environmental Residuals	
Ash (tons/day)	1240
Sulfur (tons/day)	359
Ammonia (tons/day)	108
Sludge (tons/day)	51
Air Emissions (tons/day)	56
Resource Requirements	
Land, acres	346
Water (10^6 gallons/day)	12.5
Limestone (tons/day)	20.4
Sodium Carbonate (tons/day)	2.2
Construction & Operation Characteristics	
Direct Construction Labor Hours (1000 hrs)	8,100
Operations Staff	336
Direct Capital Costs ($1000)	537,374
Indirect Capital Costs ($1000)	132,717
O&M Costs ($1000/yr)	20,660

Light Water Reactor

The reference light water reactor design is a single unit pressurized water reactor modeled after the Westinghouse 3425 MWt unit described in RESAR-35 and coupled with the balance-of-plant concept developed by UEC. The overall design of the unit was based on the licensing, design, construction and operation criteria, standards, codes, and guidelines in affect about January, 1976. The characterization represents the current state of technology in the late 1970's but projected to the year 2000.

The reactor uses low-enriched uranium oxide fuel (4.15% ^{235}U) in approximately 193 fuel assemblies. The nuclear steam system produces approximately 3750 MWt at full power yielding a generator output of 1309 MWe. Auxiliary power requirements come to 59 MWe leading to a net plant efficiency of 33.4%. The station heat rate is 10,224 Btu/kWh at a capacity factor of 70%.

The reactor core is cooled by pressurized water (2250 psia). The pressurized water flows to a steam generator which generates steam at 1100 psia and 556^{o}F. This steam then drives a tandem compound, six flow turbine generator. The turbine exit steam is condensed and heat is delivered to the atmosphere via three mechanical draft wet cooling towers.

The primary plant site requires about 500 acres. The water requirements are primarily from evaporative cooling and are about 23 x 10^{6} gallons/day. Key plant parameters are provided in Table 4 and a simplified thermodynamic cycle is shown in Figure 3.

Table 4 . Key Parameters, Nuclear Steam Supply System
1250 MWe Pressurized Water Reactor Plant

PARAMETERS	OPERATING DESCRIPTION
NSSS Warranted Power, MWt	3,750
Steam Flow, 10^6 lb/hr	16.62
Steam Pressure, psia	1,100
Power Density - Avg., kW/liter	104
Coolant Flow, 10^6 lb/hr	165.2
Coolant Inlet Temp. °F	563.8
Avg. Delta T through Vessel, °F	61.1
Coolant Pressure - Outlet psia	2,250
Turbine Output, MWe	1,309
Auxiliary Power, MWe	59
Net Power to Transformer, MWe	1,250
Net Station Heat Rate, Btu/kWh	10,224
Plant Efficiency %	33.4
<u>Environmental Residuals</u>	
Radioactive Solid Waste (ft^3/day)	119.4 to 133.8
Radioactive Gaseous Releases of all types (Ci/yr)	3×10^3
Waste Water Effluents, Tons/day	7
<u>Resource Requirements</u>	
Land, acres	500
Water (10^6 gallons/day)	23.2
<u>Construction and Operation Characteristics</u>	
Direct Construction Labor Hours (1000 hrs)	15,524
Operation Staff	215
Direct Capital Costs ($1000)	485,916
Indirect Capital Costs ($1000)	197,109
O&M Costs ($1000)	16,898

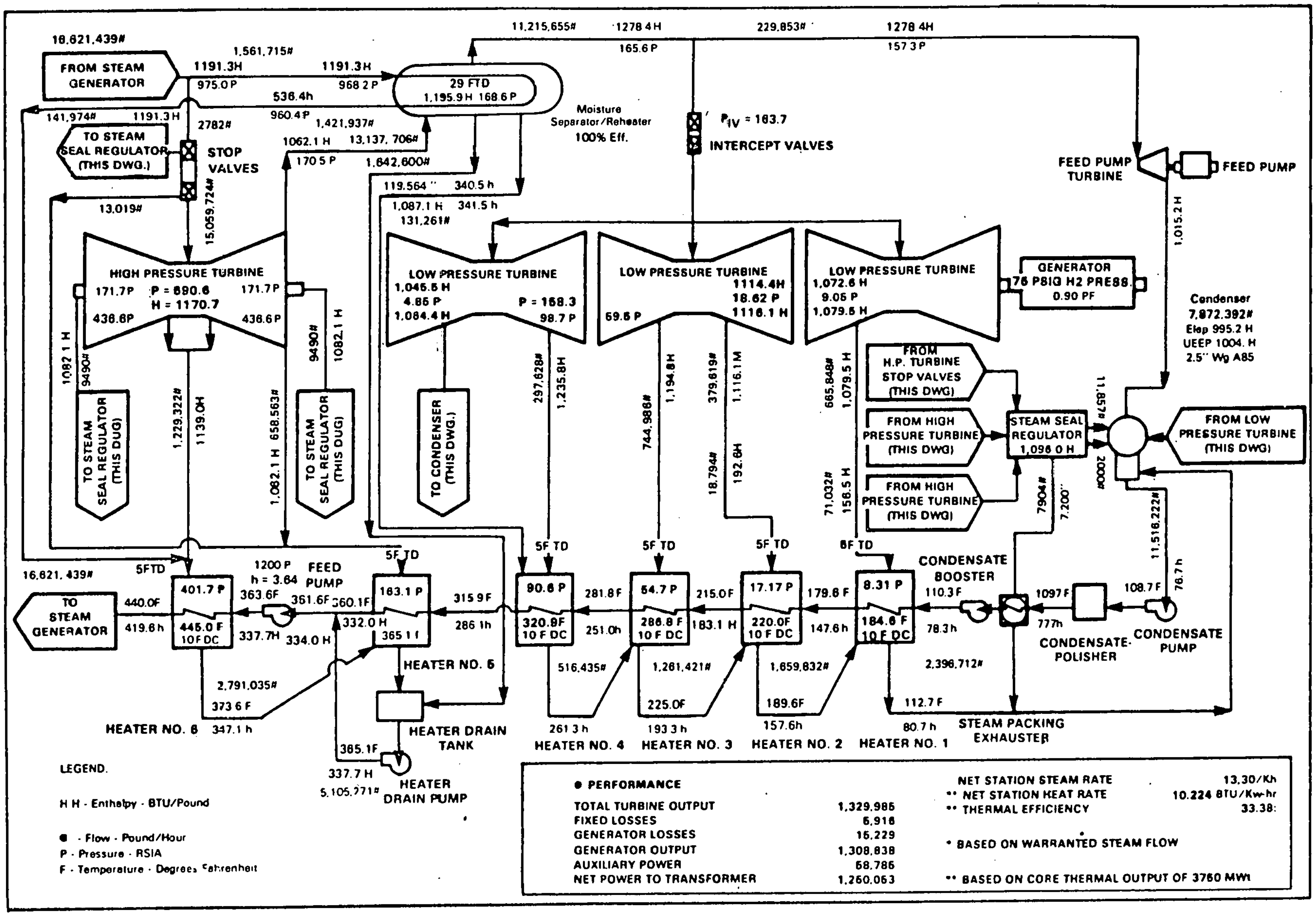

Figure 3. Light Water Reactor Facility Thermodynamic Cycle

Liquid Metal Fast Breeder Reactor

The reference liquid metal fast breeder reactor (LMFBR) is a single unit plant that represents an envelope of the currently available design thinking for commercial plants of the five principle U.S. manufacturers of nuclear LWR plants, Atomics International, Babcock & Wilcox, General Electric, Westinghouse, and Combustion Engineering. The basic nuclear plant is coupled to a balance-of-plant concept designed by United Engineers and Constructors (UEC).

The reference plant uses a uranium-plutonium oxide fuel for the core and depleted uranium breeding material in both the radial and axial blankets. The plant produces 1313 MW gross with auxiliary losses of 63 MWe. The plant efficiency is 36.6% with a 70% capacity factor.

The reactor core is cooled by liquid sodium which circulates through an intermediate heat exchanger generating steam. The turbine inlet steam conditions are 2200 psig pressure and 850°F temperature. The turbine exit steam is condensed and the residual heat is given up to the atmosphere via three mechanical draft wet cooling towers.

The LMFBR site occupies 500 acres and the plant requires about 20.8×10^6 gallons/day of water for cooling at nominal operation. Most of the water requirement (over 2/3) is for cooling tower evaporation.

Key plant parameters are shown in Table 5 and a simplified thermodynamic cycle is shown in Figure 4.

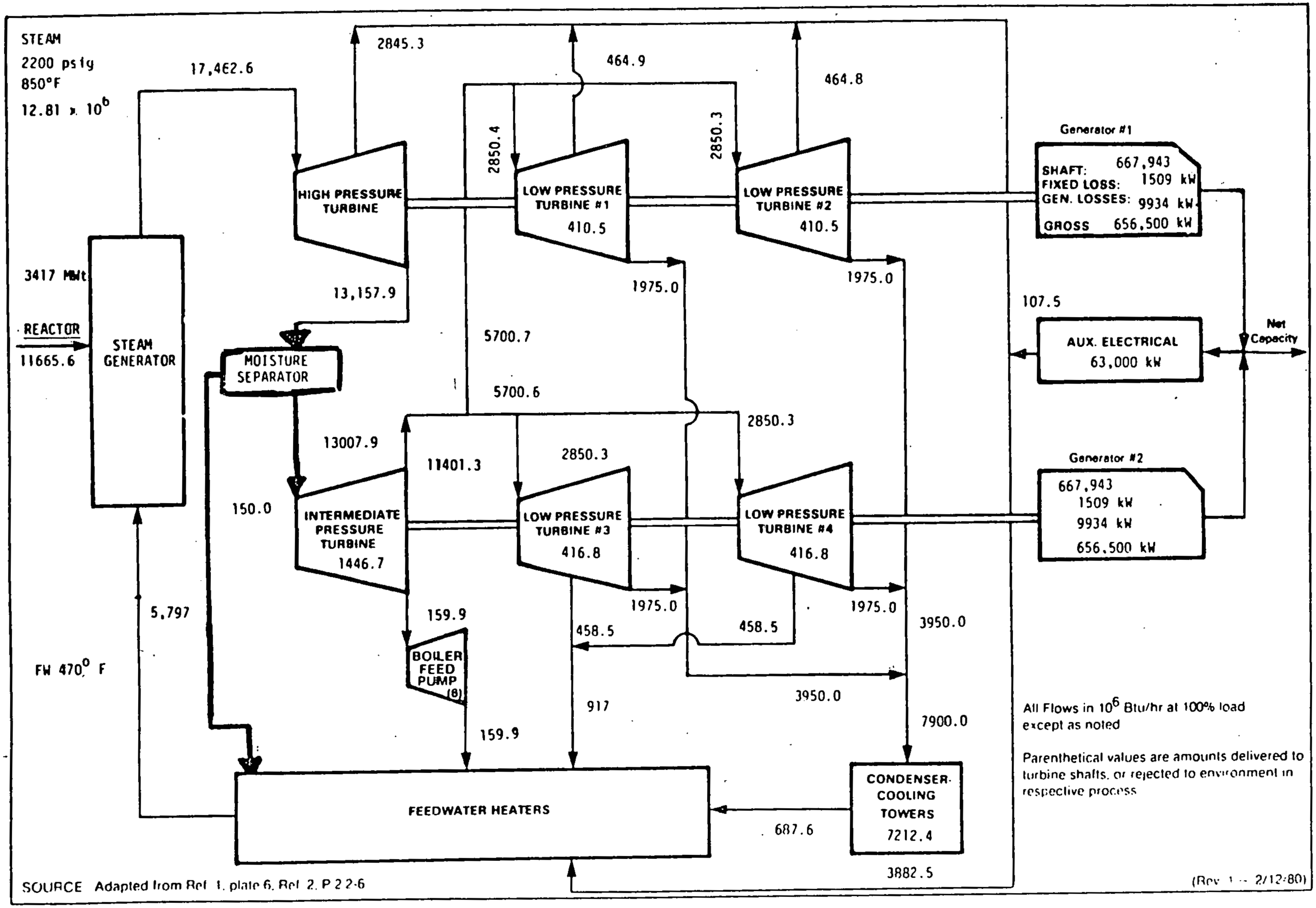

Figure 4 . Simplified Thermodynamic Schematic - 1250 MWe Reference LMFBR Facility

Table 5. Key Plant Parameters, Liquid Metal Fast Breeder Reactor

PARAMETER	VALUE
Thermal Power, MWt	3417
Electric Power, MWe (gross)	1313
Electric Power, MWe (net)	1250
Plant Efficiency, Percent	36.6
Steam Pressure, psig/ Temperature, °F	2200/850
Turbine Steam Flow, 10^6 lb/hr	12.81
Number of Coolant Loops	
Primary/Intermediate	4/4
Sodium Flow Rate, 10^6 lb/hr	
Primary (total/loop)	128.8/32.2
Intermediate (total/loop)	120.1/30.0
Number of Fuel Elements	
Core Fuel	678
Axial Blanket	678
Radial Blanket	420
Fuel Type	Oxide Fuel
Initial Core (Average)	
Discharge Burnup	45,983 MWD/MTHM
Core Loading	22.668 MTHM
Replacement Core Loadings	
Discharge Burnup	67,590 MWD/MTHM
Core Loading	23.316 MTHM
Axial Blanket	
Loading	19.038 MTHM
Pu Discharged	22.691 kg/MTH_i
Radial Blanket	
Loading	44.796 MTHM
Pu Discharged	20.895 kg/MTH_i
Resource Requirements	
Land	500 acres
Water (10^6 gallons/day)	20.8
Construction & Operation Characteristics	
Direct Construction Labor Hours (1000 hrs)	12,680
Operations Staff	225
Direct Capital Costs ($1000)	702,865
Indirect Capital Costs ($1000)	262,590
O&M Costs ($1000)	21,985

Magnetic Fusion Power Plant

The characterization of a fusion power plant presented here is based on the NUWMAK power plant design developed by the University of Wisconsin Fusion Engineering Program of the Nuclear Engineering Department and published in March, 1979. The NUWMAK power plant produces electricity through a boiling water reactor (BWR) power cycle with heat supplied by a Tokamak fusion reactor. One plant produces 660 MWe net. The power facility characterized here consists of two NUWMAK reactors and produces a net power of 1320 MWe operating at an overall thermal efficiency of 31.5%.

The NUWMAK is a newer and more realistic design than the UWMAK series developed by the University of Wisconsin. The design philosophy in NUWMAK has been to make mechanical design and maintainability easier. The power density in NUWMAK is increased to about 10 W/cm^3 as compared to 0.5 to 2 W/cm^3 in earlier designs. The NUWMAK design does not use a divertor to control impurities, thereby considerably simplifying the reactor design and allowing easier access and maintenance. Instead, impurity control in NUWMAK is achieved through a system using gas puffing (which also serves to partially fuel the reactor). Heating of the plasma is achieved via radio-frequency (RF) heating rather than by neutral-beam injection, simplifying the engineering. The reactor blanket employs phase change energy storage, reducing the need for and simplifying external energy storage systems. Titanium alloys replace stainless steel as structural materials for the first wall and blanket of the reactor, in order to increase material life under neutron bombardment and reduce the impact on mineral resources.

Schematically, Figure 5 shows a simplification of the power cycle for a NUWMAK Tokamak power plant. Although many technical questions remain concerning the NUWMAK design, the NUWMAK design is an improvement over earlier fusion reactor designs. Key plant parameters are shown in Table 6.

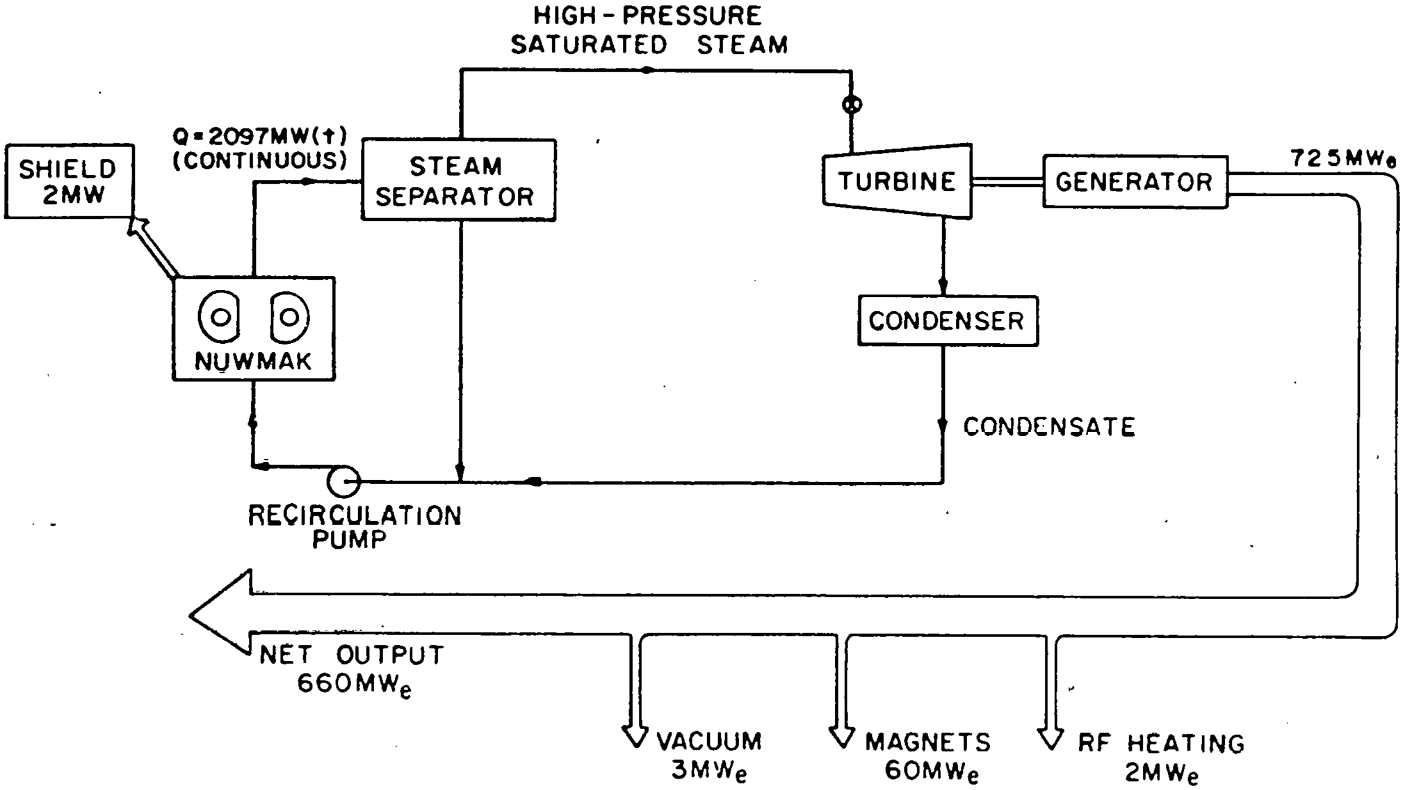

Figure 5 . Power Flow Diagram for NUWMAK

Table 6 . Key Plant Parameters for One NUWMAK Reactor

Parameter	Value
Power Output (During Burn)	2283 MW
Blanket Energy (Continuous)	1900 MW
Neutron Wall Loading	4.34 MW/m^2
Plasma Burn Time	225 Seconds
Plasma Down Time	20 Seconds
Structure	Ti Alloy
Breeding Material	$Li_{62}Pb_{38}$ Eutectic
Energy Storage Material	$Li_{62}Pb_{38}$ Eutectic
Coolant	Boiling H_2O
Coolant Temperature	300°C = (572°F)
Coolant Pressure	8.6 MPa = (1250 psi)
Net Power Output (Continuous)	660 MWe
Net Thermal Efficiency	31.5%
<u>Environmental Residuals</u>	
Tritium	< 10 Ci/day
Solid Waste	The blanket will be replaced every two years
<u>Resource Requirements</u>	
Land	500 acres
Water (est.) (10^6 gallons/day)	23
<u>Cosntruction & Operation Characteristics</u>	
Direct Construction Labor Hours (1000 hrs)	21,300
Operations Staff	300
Direct Capital Costs ($1000)	1,533,241
Indirect Capital Costs ($1000)	628,628
O&M Costs ($1000)	57,903

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