Jackson Hole 2005 RELAP5 I ATHENA Seminar

A Study of Power Conversion Cycle for the Small-Modular 4S Sodium Cooled Fast Reactor

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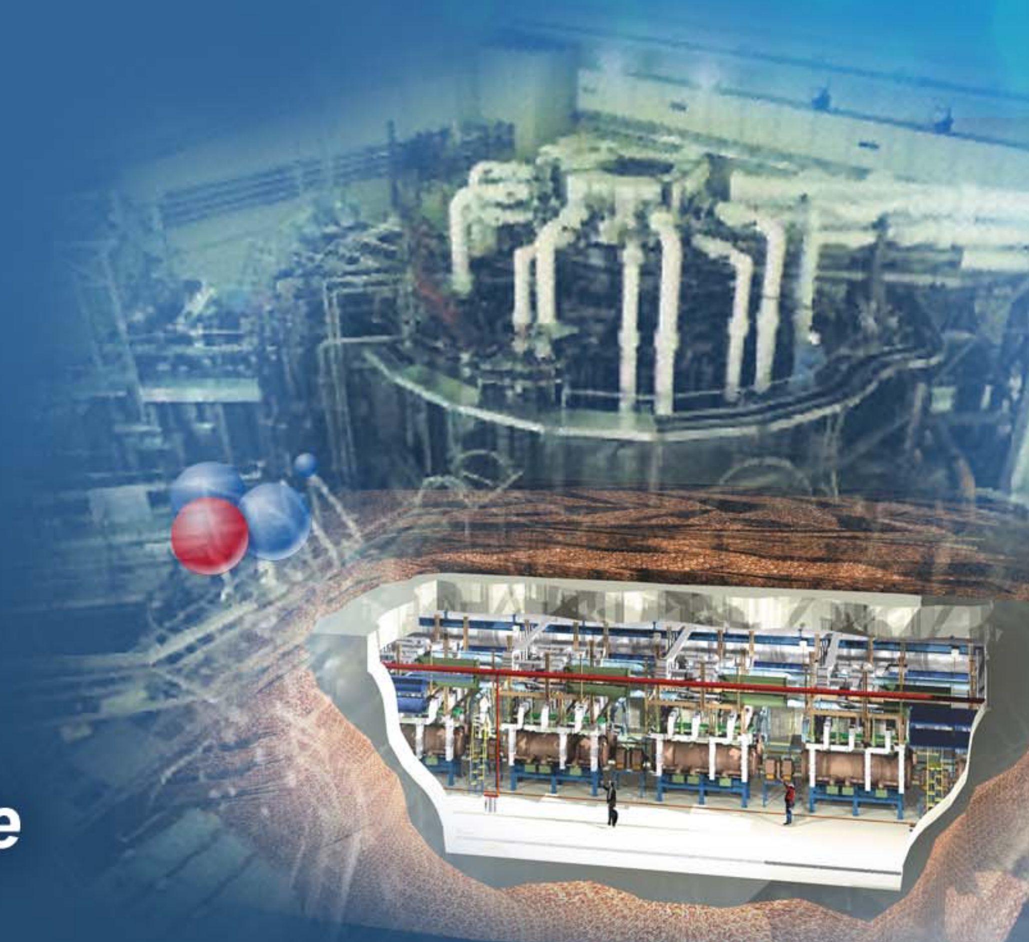
and
Philip Moor



Burns and Roe

Objective:

Find criteria to decide about optimum power conversion cycles for next generation nuclear power plant designs. BREI has been developing small-sized modular nuclear Power facilities (<100 Mwe) for the needs of distributed energy and multi-purpose applications.

A conceptual design utilizing the Japanese 4S (Super-safe, Small and Simple) sodium cooled fast reactor.

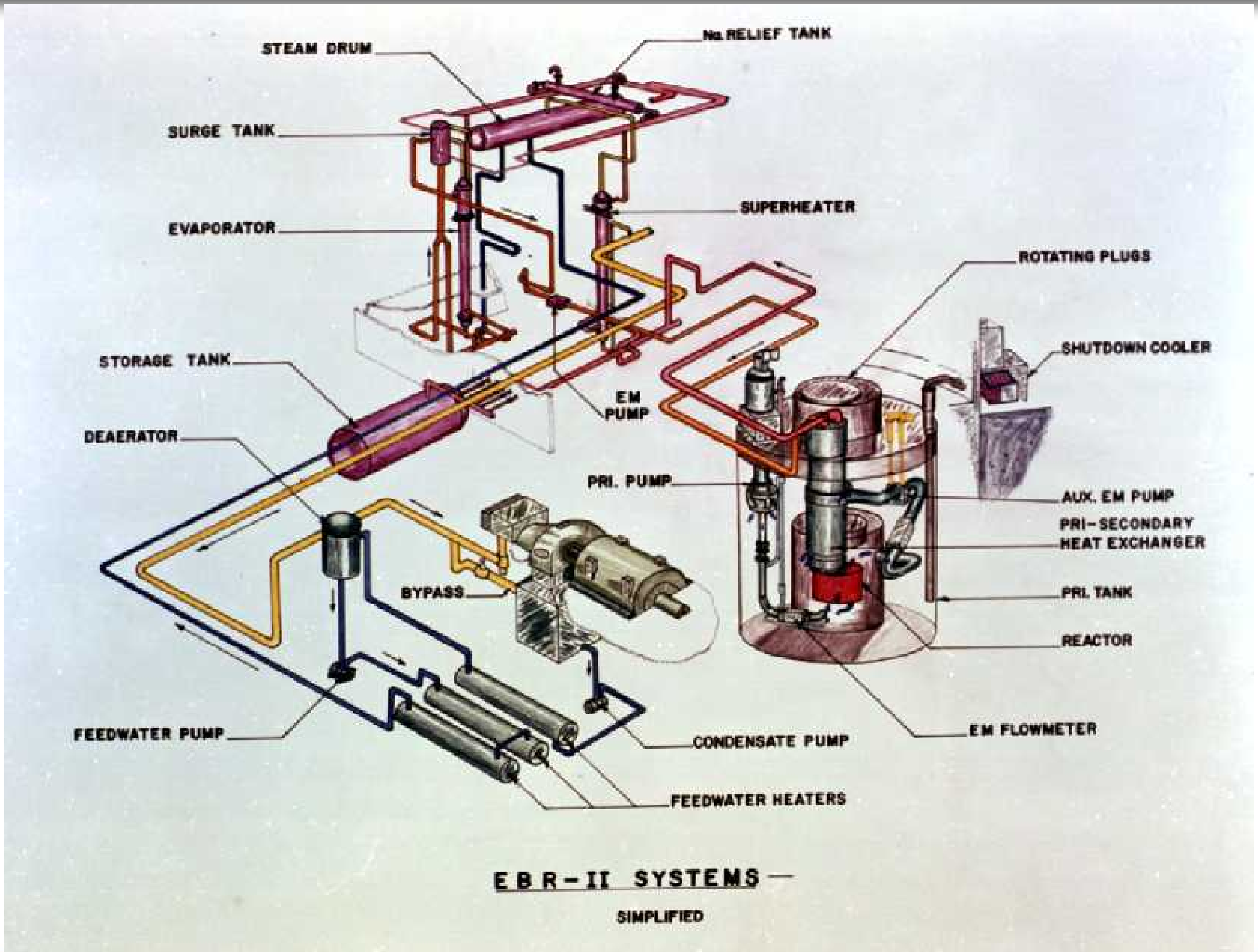
References:

1. The Experimental Breeder Reactor-II (EBR-II) http://www.anlw.anl.gov/anlw_history/reactors/ebr_ii.html
2. Introduction to the ALMR/PRISM http://www.nuc.berkeley.edu/~gav/almr/01.intro.html
3. Advanced 4S (CRIEPI A.MINATO, TOSHIBA N.HONDA) file:1172.pdf
4. Passive Reactor Dynamics and Load Characteristics of 4S (CRIEPI N.UEDA, TOSHIBA T.YOKOYAMA), 11th ICONE file:36539.pdf
5. An Optimization study on the Reflector (CRIEPI , TOSHIBA), 11th ICONE file:36284.pdf
6. 4S Current Status, April 2004 Alaska, TOSHIBA Presentation
7. STEMPRO Heat Balance Program by Thermoflow, version 11 dated 3/31/2003.

Introduction

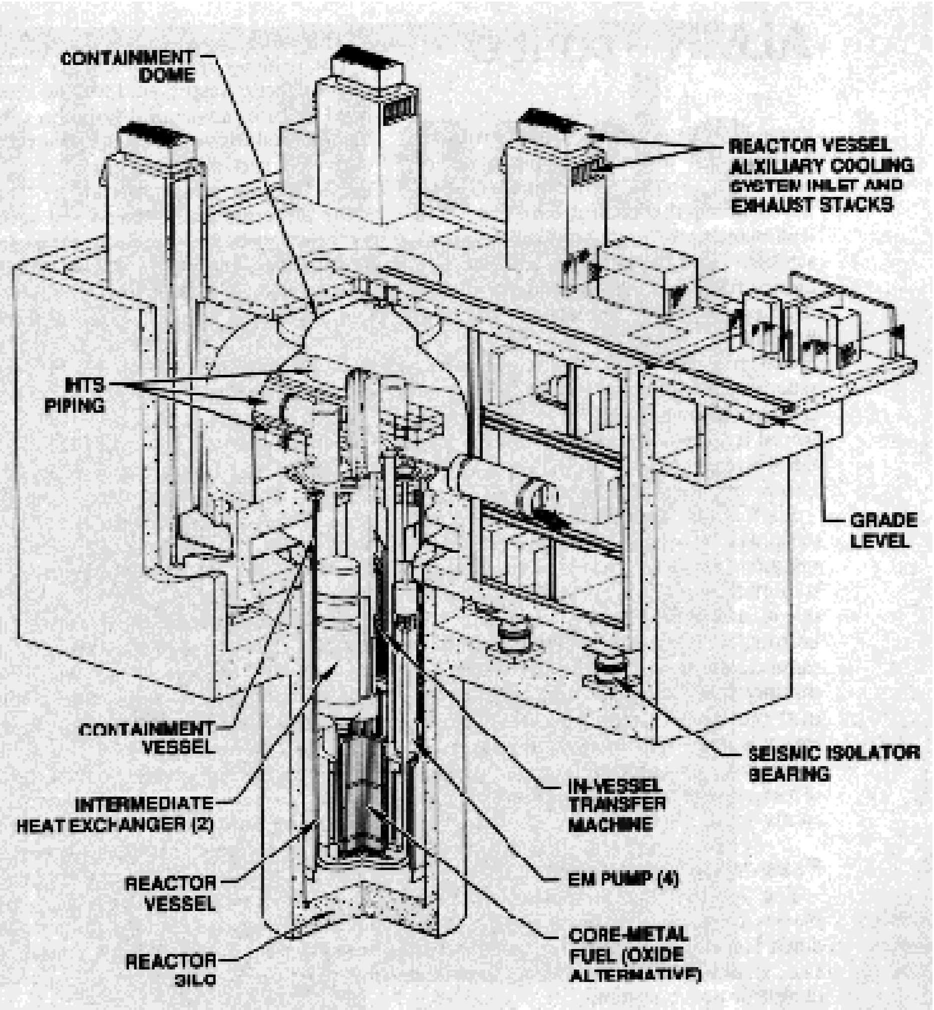
- Background (Ref. # 1)
  - The Experimental Breeder Reactor-II (EBR-II) stopped operation in 1994.
  - The tests and experiments that have been conducted in EBR-II have contributed heavily to national and international Fast Breeder Reactor technology
  - EBR-II pool type design was utilized by the Japanese 4S (Super-Safe, Small and Simple)

(Ref. # 1)


STEAM DRUM
Na RELIEF TANK
SURGE TANK
SUPERHEATER
EVAPORATOR
ROTATING PLUGS
SHUTDOWN COOLER
STORAGE TANK
EM PUMP
DEAERATOR
PRI. PUMP
AUX. EM PUMP
PRI-SECONDARY HEAT EXCHANGER
BYPASS
PRI. TANK
REACTOR
FEEDWATER PUMP
CONDENSATE PUMP
EM FLOWMETER
FEEDWATER HEATERS
EBR-II SYSTEMS
SIMPLIFIED

Background (Ref. # 2)

- The acronym ALMR stands for Advanced Liquid Metal Reactor.
- Substantial work has been done by General Electric, with the help of Argonne National Laboratory, in designing a reactor of this type.
- Their design is called the PRISM.
- PRISM stands for Power Reactor Innovative Small Module.
- A power block consists of three of these modular reactors, thus the use of the word Module in PRISM.
- Each reactor produces 160 MWe of power.
- The fact that each reactor is licensed separately and that reactors on a power block can start producing electric power before the other reactors are even built.



– 4S Major Features have been conceptualized by CRIEPI and or Toshiba (Ref. # 3, 6)

  - No refueling for 30 years
  - Passive safety
  - Transportability
  - Reasonable cost for distributed power supply

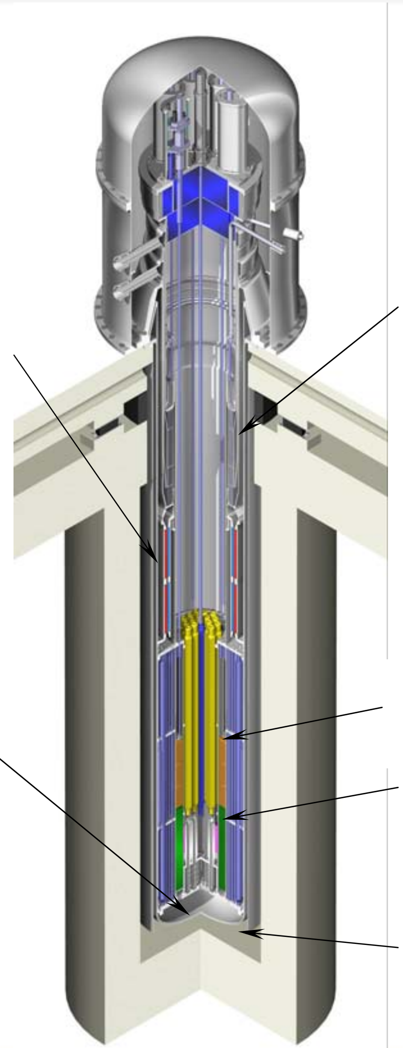
Main core design specification of 4S reactor (Ref. # 4,5)

Thermal output (MWt)	135
Coolant	sodium
Primary condition inlet / outlet temperature (^{o}C)	510 / 355
Secondary condition inlet / outlet temperature (^{o}C)	475 / 310
Core pressure drop (MPa)	~0.1

4S Reactor

EMP:Two electromagnetic pumps in series annular type

IHX: Intermediate Heat Exchanger, annular type



Double boundary: RV & GV

Reactor Vessel

Guard Vessel

Core with ultimate shutdown rod

Reflector Reactivity Control for Operation, Start-up,Shut down

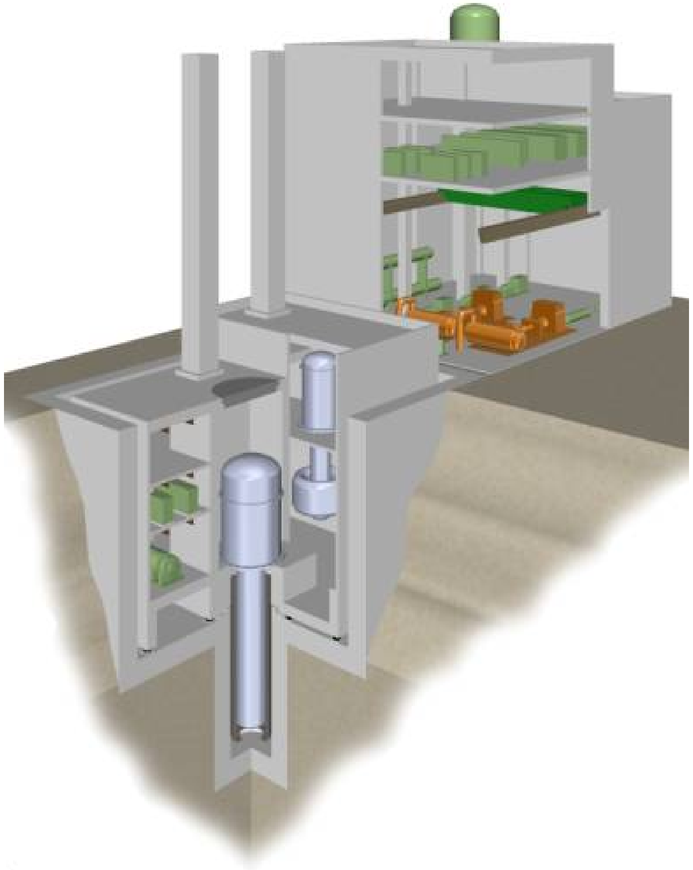
RVACS: Reactor Vessel Auxiliary Cooling System

Ref. # 6

– Power Conversion Cycle Goals

- The development of simpler, safer and more reliable nuclear power plant
- The reactor and components of Nuclear power plant will be factory assembled and shipped to site in modules
- Nuclear power plant with 4S reactors are aimed for installation in remote areas of the world
- Maximizing thermal efficiency and minimizing capital cost
- All Power conversion cycle components are either commercially available or within current design capabilities

4S Nuclear power plant

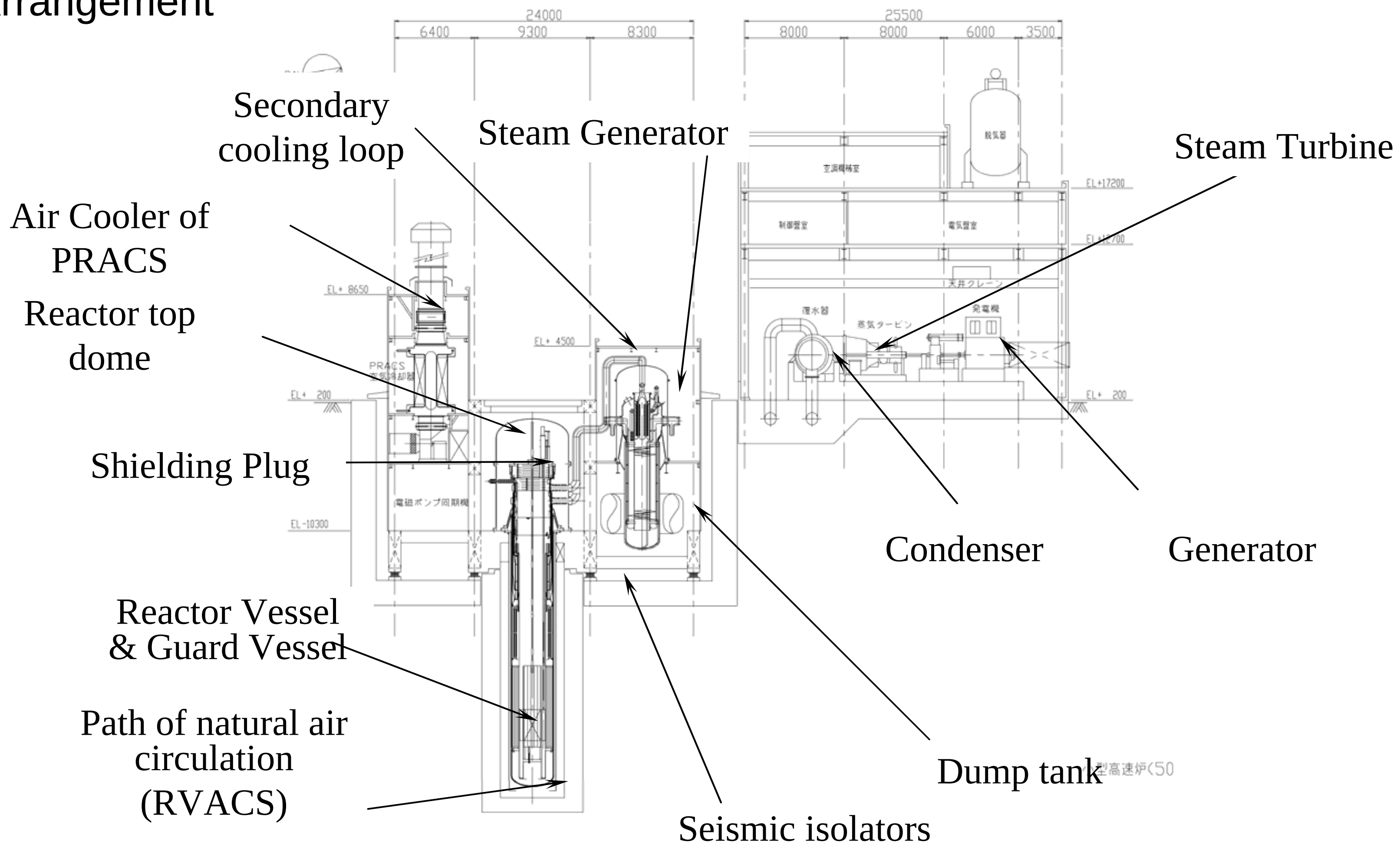


Ref. # 6

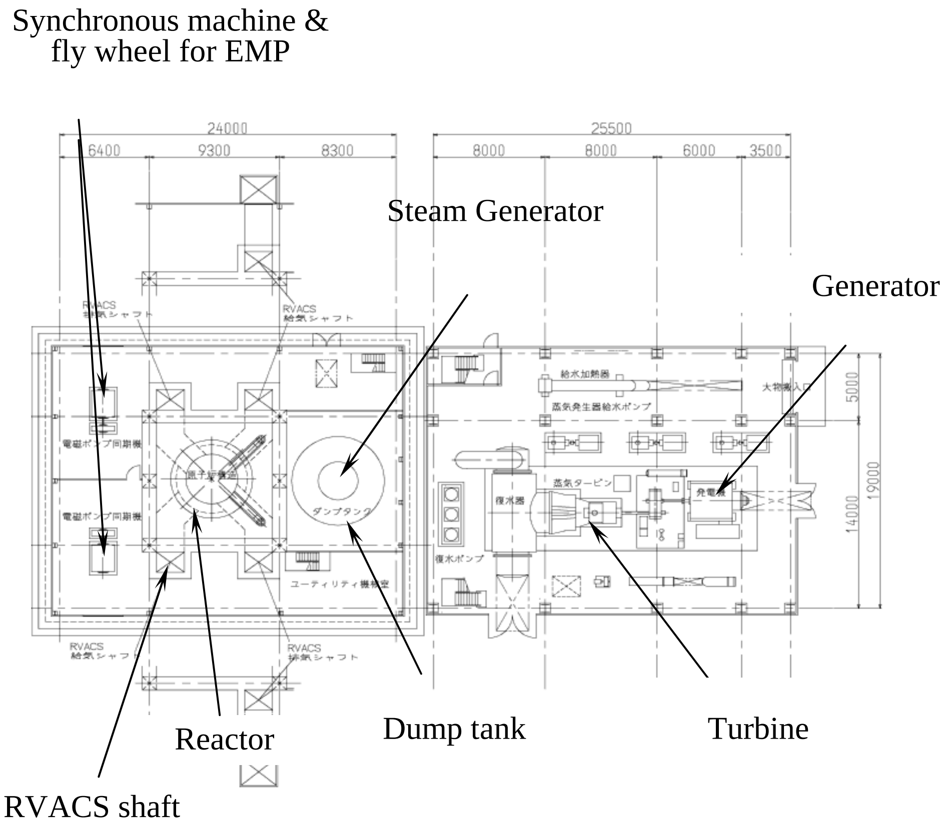
Boundary Conditions for the Heat Balance Calculation for Nuclear Cycle performance and for identification of the main components (Ref. 5)

Steam Generator inlet / outlet temperature (ºC)	253 / 453
Steam Generator inlet / outlet pressure (Mpa)	11.20 / 11.50
Electric Power (MW)	50

4S Plant Arrangement
(Ref. # 6)



4S Plant Arrangement (Ref. # 6)



Computational Tools Used for the Study

STEAMPRO (Ref. # 7)

- Both sub and supercritical cycles with up to two reheats and up to 10 shaft/casing layout can be modeled.
- The turbine expansion path is comprised of up to 20 dissimilar stage groups, with design-point efficiencies automatically estimated for each group from cycle conditions using industry-standard, published methods. The estimated efficiency is then adjusted in STEAMPRO for consistency with the steam turbine efficiency improvements that took place between 1974 and 1999. The adjustment produces turbine efficiencies, which are in the middle of the scatter-band of real turbine data based on machines from various manufacturers.
- STEAMPRO allows up to 12 stages of feedheating with any practical combination of heater types. Types include open (contact) heaters and closed (tubular) heaters, desuperheaters and drain coolers.
- STEAMPRO allows modeling air-cooled and water-cooled condensers and cooling tower models allow various dry and wet cooling arrangements to be used.

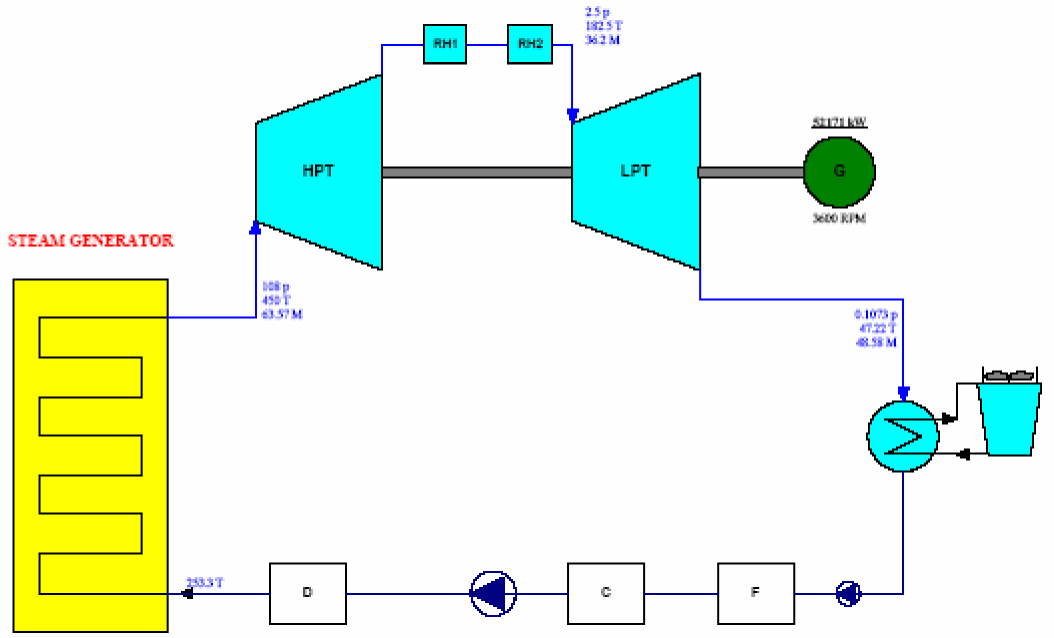
Design Choices

- Rotation speed 3600 rpm
- Single-shaft turbine-generator
- One HPT/IPT and one LPTs
- One main steam lines
- MSR between the HPT/IPT and the LPTs
- Three feedwater heaters
- Electrical-driven feedwater pumps
- Condenser cooling with mechanical draft cooling tower

REFERENCE DESIGN

Plant net power	50063	kW
Aux. & losses	2107.6	kW
Turbine heat rate	9629	kJ/kWh
Steam cycle heat rate	9349	kJ/kWh
Steam cycle efficiency	38.5	%

Ambient
0.97 p
27.78 T
34.93% RH



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p [bar] T [C] M [kg/s]

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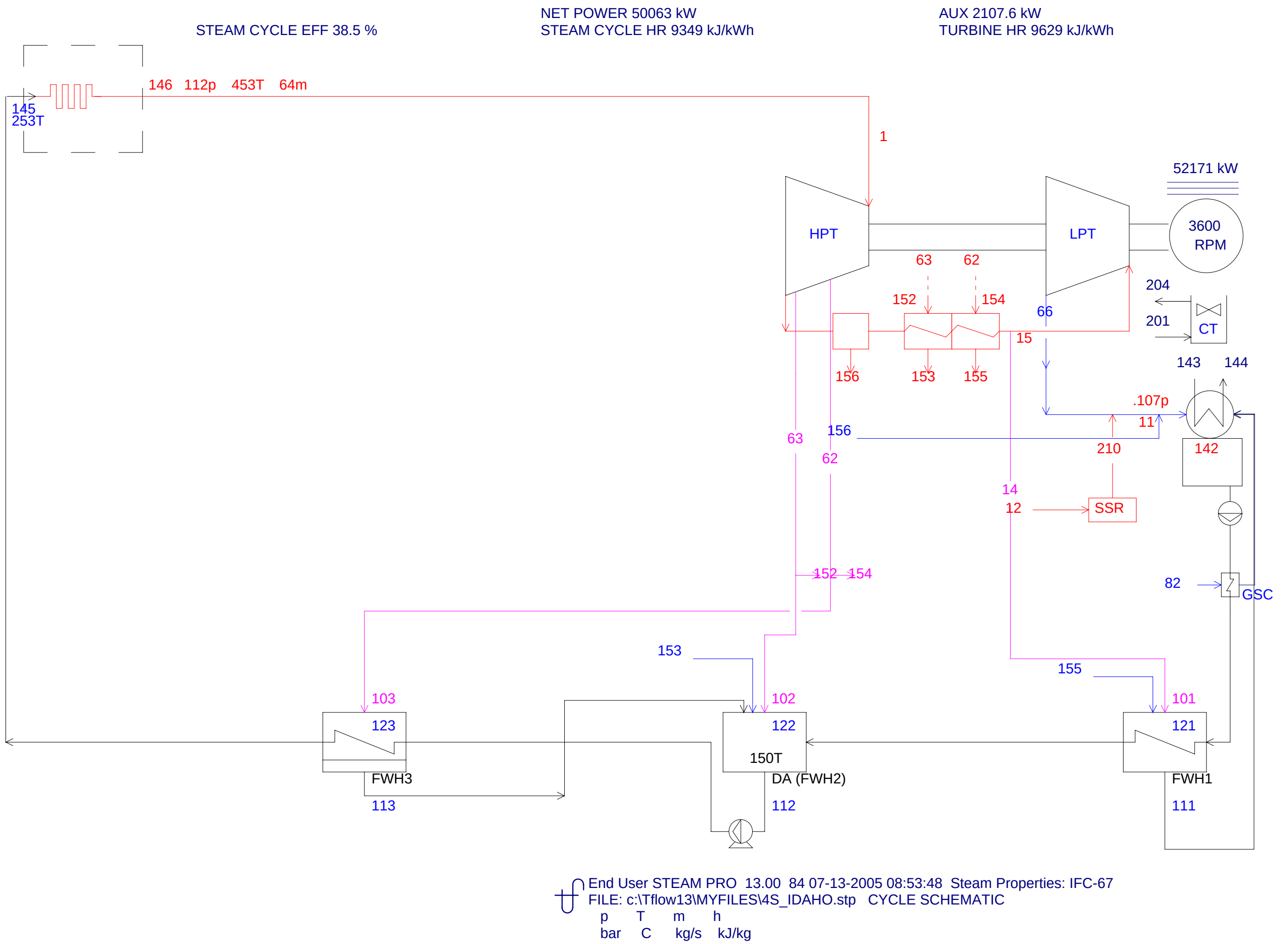


REFERENCE DESIGN

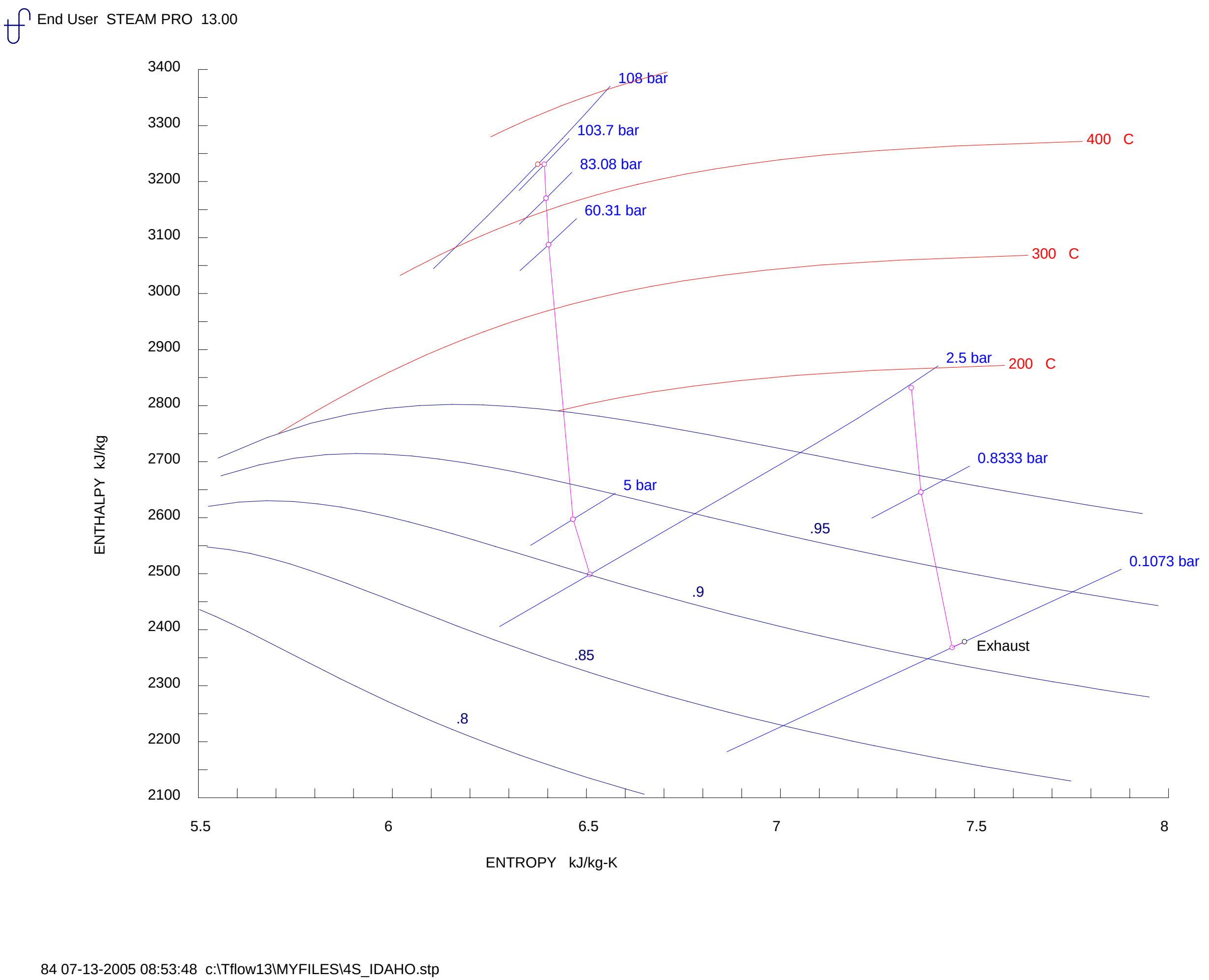
Stream	p [bar]	T [C]	M [kg/s]	h [kJ/kg]
1 Throttle or initial condition outside ST	108.00	450.0	63.57	3230.7
6 PIPT ahead of intercept valve	2.50	127.4	40.63	2706.6
11 Condenser (LPT exhaust)	0.11	47.2	36.26	2378.4
12 SSR Inlet	1.24	348.8	0.10	3172.5
14 After 2nd RH	2.50	171.8	6.62	2809.9
15 LPT Crossover	2.50	182.5	36.20	2832.0
62 Add / extr of ST group 2	60.31	365.2	13.20	3087.4
63 Add / extr of ST group 3	5.00	151.8	3.16	2597.1
66 Add / extr of ST group 6	0.11	47.2	36.20	2378.4
82 Stream to GSC	0.83	N/A	0.04	3172.5
101 Heating steam at FWH1	2.32	170.1	6.62	2807.6
102 Heating steam at FWH2	4.81	150.4	2.78	2594.8
103 Heating steam at FWH3	57.99	362.3	11.84	3085.0
111 Drain liquid at FWH1	2.32	125.0	7.98	524.8
112 Drain liquid at FWH2	4.81	150.4	63.57	633.7
113 Drain liquid at FWH3	57.99	158.1	11.84	670.2
121 Feedwater into FWH1	7.31	47.9	48.58	200.9
122 Feedwater into FWH2	4.81	122.2	48.58	513.4
123 Feedwater into FWH3	115.17	153.1	63.57	652.2
142 Feed water leaving condenser	0.41	47.2	48.58	197.6
143 Cooling water into condenser	2.52	27.3	1195.35	114.5
144 Cooling water leaving condenser	2.09	43.9	1195.35	184.0
145 Feed water into boiler	114.71	253.3	63.57	1101.8
146 Steam leaving superheater	112.32	453.3	63.57	3233.0
152 Heating steam of 1st RH	5.00	151.8	0.38	2597.1
153 Drain of 1st RH	N/A	N/A	0.38	559.2
154 Heating steam of 2nd RH	60.31	365.2	1.37	3087.4
155 Drain of 2nd RH	N/A	N/A	1.37	581.6
156 Moisture separator drain	N/A	N/A	4.30	535.3
201 Cooling tower inlet air	N/A	27.8	651.83	N/A
204 Cooling tower exit air	N/A	40.6	680.60	N/A
210 SSR to condenser	1.24	348.8	0.10	3172.5
Valve Stem leak 1 => LPcrs	N/A	N/A	0.18	3230.7
Valve Stem leak 2 => SSR	N/A	N/A	0.00	3230.7
HPT HP leak 1 => LPcrs	N/A	N/A	2.00	3170.2
HPT HP leak 2 => SSR	N/A	N/A	0.09	3170.2

REFERENCE DESIGN

NOTE:

Turbine expansion to ‘vacuum’

Uses most of core outlet enthalpy



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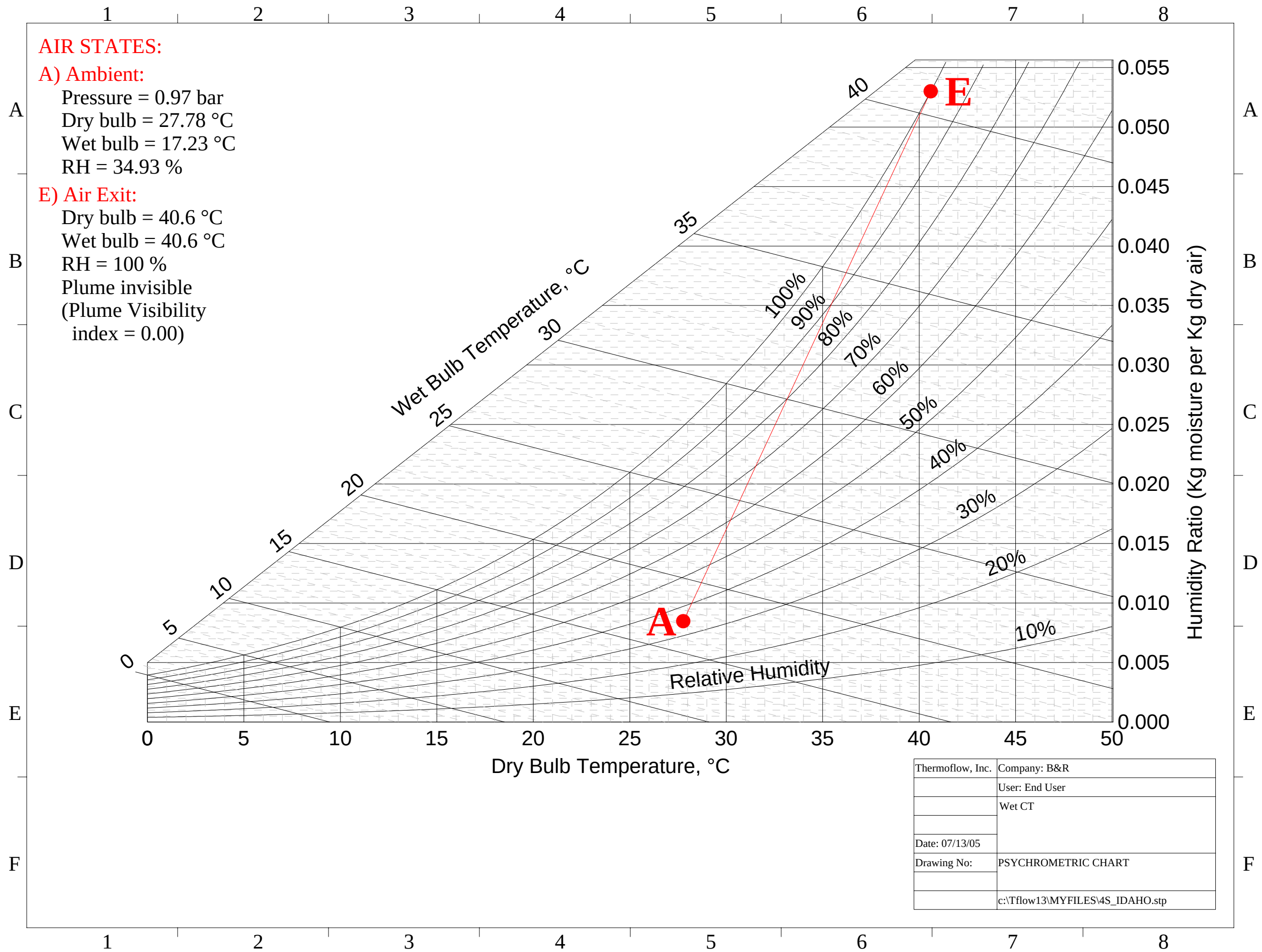

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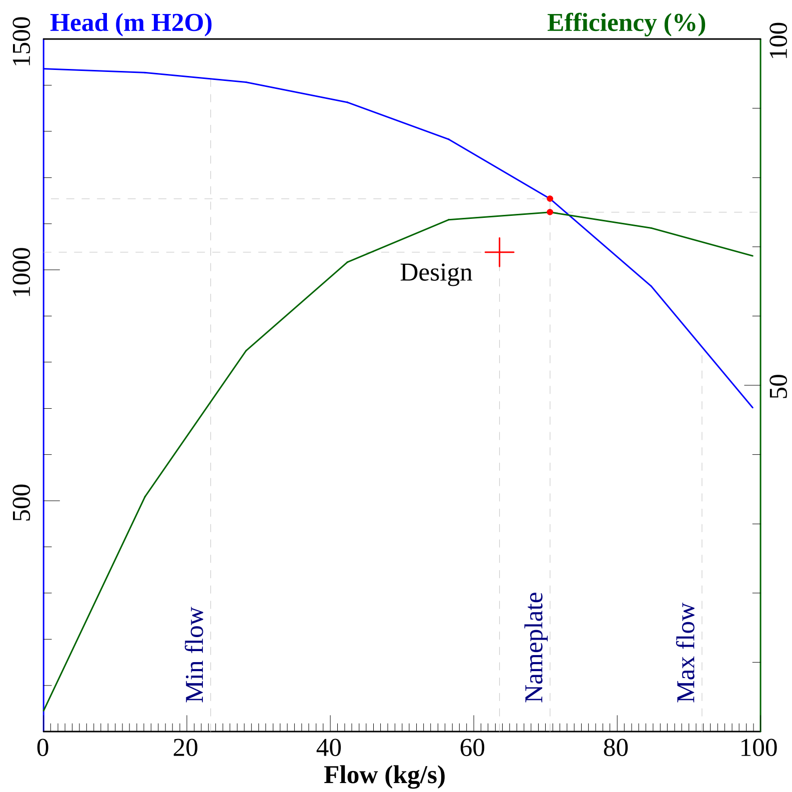
REFERENCE DESIGN

Boiler Feed Pump



No. of pumps	2
No. operating pumps	1
Nameplate flow	70.64 kg/s
Nameplate head	1153.9 m H2O
Nameplate flow (nominal)	4921 lpm
Nameplate head (nominal)	1158.3 m H2O
Nameplate RPM	3600
Design flow	63.57 kg/s
Design head	1038.5 m H2O
Design RPM	3600
Minimum continuous flow	23.31 kg/s
Maximum continuous flow	91.83 kg/s

Thermoflow, Inc.	Company: B&R
	User: End User
	Boiler Feed Pump
Date: 07/13/05	
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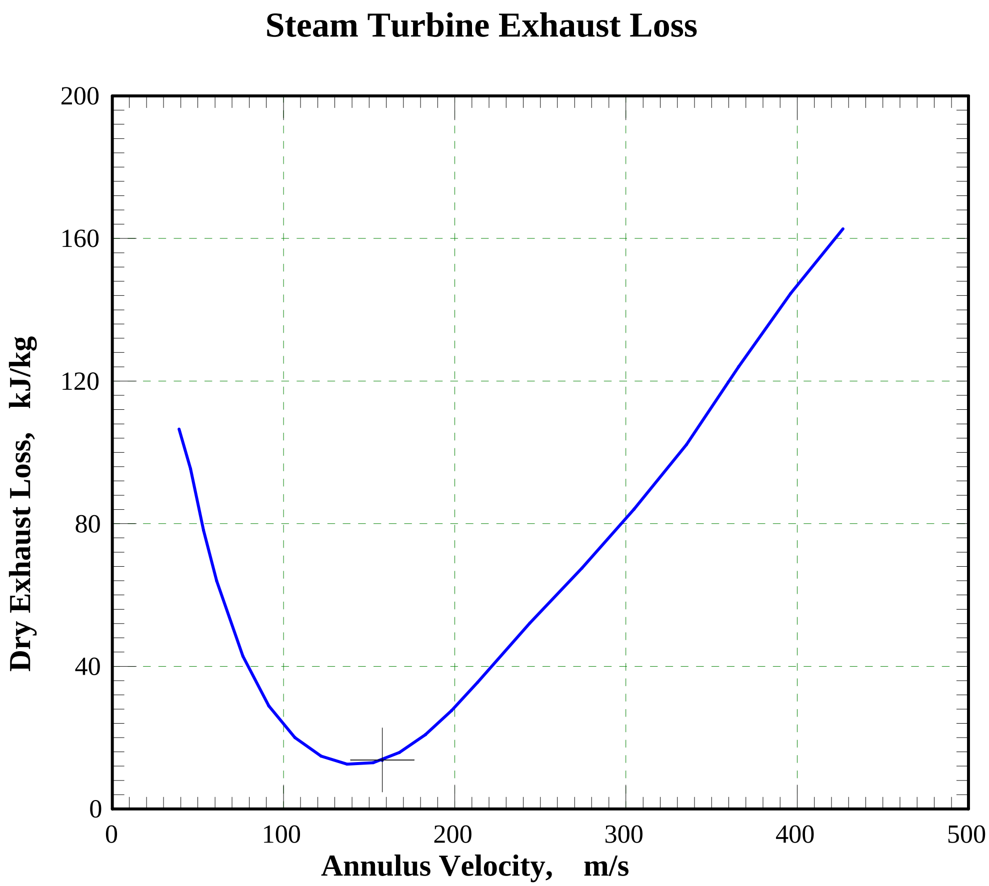

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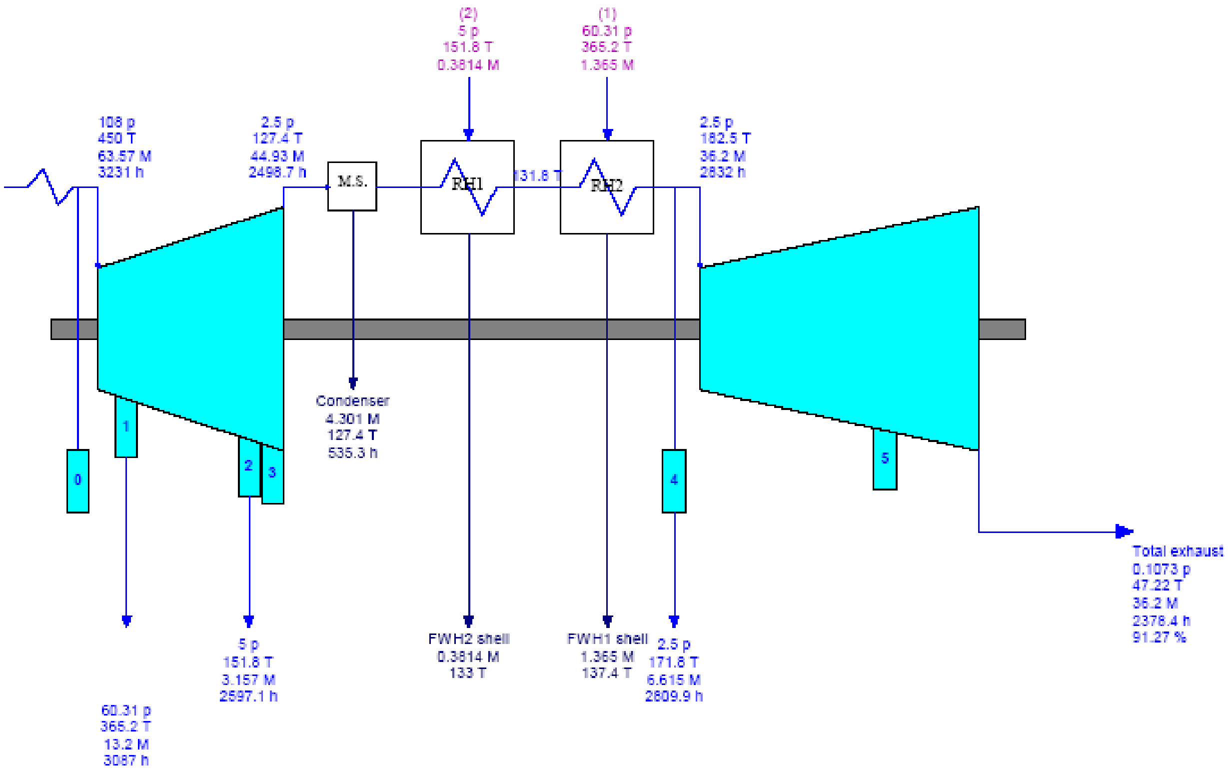
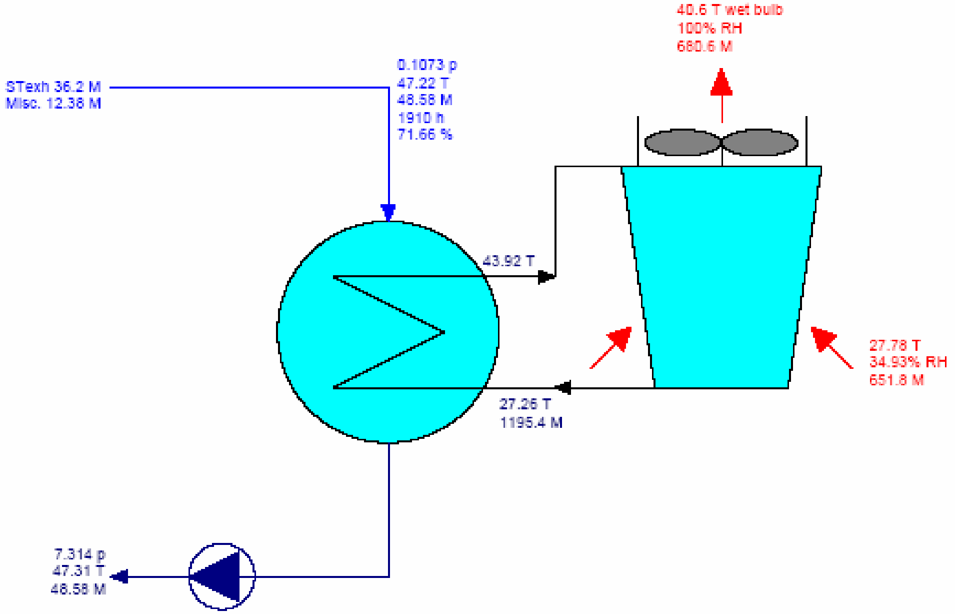
REFERENCE DESIGN

Expansion power	53328	kW
Mechanical loss	296.4	kW
Generator loss	861	kW
Generator power	52171	kW



REFERENCE DESIGN

Condenser heat rejection	83188	kJ/s
Condensate pump power	56.97	kW
CW circulation pump power	255.5	kW
Cooling tower fan	181.1	kW
CW blowdown	7.194	kg/s
CW makeup	35.97	kg/s



Miscellaneous assumptions:

- Pressure ratio for steam turbine expansion step: 1.1
- Condensation quality (Wilson line): 0.97
- Moisture efficiency penalty: 0.75
- Internal moisture separators with moisture/steam reach point: 0.5%
- HPT stop valves and throttle pressure drop (dP/P): 4%
- LPT intercept valve pressure drop (dP/P): 2%
- Throttle pressure/first stage exit pressure: 1.3
- Seal steam regulator pressure: 1.241 bar
- Gland steam condenser pressure: 0.8274 bar
- Transformer losses (% total power): 0.5%

Miscellaneous assumptions (continued):

- Generator rated power/nominal output: 1
- Generator power factor: 0.9
- Steam Generator feed pump isentropic efficiency: 90%
- Condenser circulating pump isentropic efficiency: 80%
- Condenser cleaning factor: 90%
- Head loss in cooling water piping: 6.1 m (w.c.)
- Number of condenser passes: 1
- Condenser pump isentropic efficiency: 80%
- Miscellaneous drain pumps isentropic efficiency: 80%

Miscellaneous assumptions (continued):

- Pressure/enthalpy loss in HPT inlet piping: 5% / 2.326 kJ/kg
- Pressure/enthalpy loss in reheater steam piping: 1% / 2.326 kJ/kg
- Pressure/enthalpy loss in extraction piping: 4% / 2.326 kJ/kg
- Feed pump turbine condenser cleaning factor: 90%

Burns & Roe has also sized all piping, feedwater heaters, reheat heaters and all pumps, etc. (information available upon request)

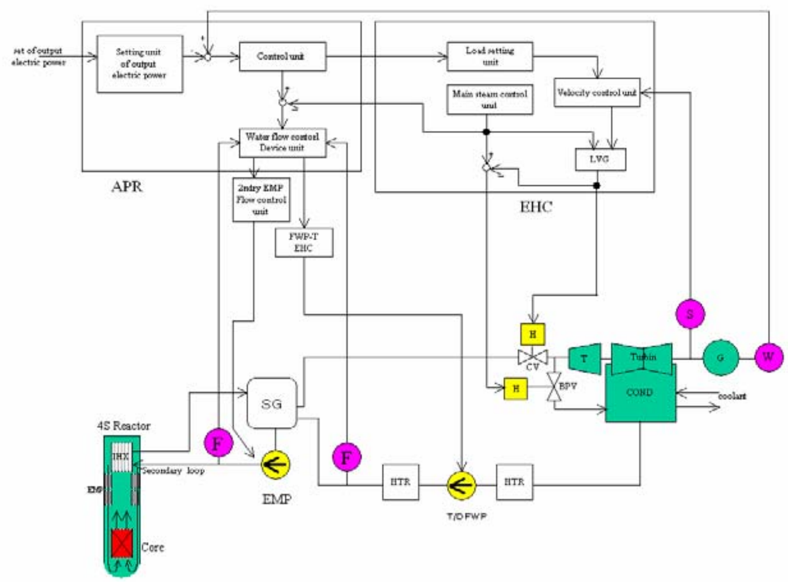
Materials in the 4S BoP

Component		Fossil	4S	Comments
Steam lines		P91 P92	P91 P92	Based on fossil experience New alloys
Turbine	**Casing**	cast 0.5%CrMoV 1.25Cr-0.5Mo 2.25Cr-1Mo P122 (HCM12A)	cast 0.5%CrMoV	current developmental
	Valves	cast 0.5CrMoV Cast P91 Cast mod P91+WCoNbB	cast 0.5CrMoV	current developmental (EPRI) developmental (VGB)
	Bolting	1%Cr-Mo-V Type 422: 12%Cr Nimonic 80A	1%Cr-Mo-V 12%Cr	current current current
	Rotor & discs	1%Cr-Mo-V forged NiCrMoV A469 Class 8 NiCrMoV A470 Class 8 NiCrMoV A471 Class 8 Type 422: 12%CrMoV mod 12%CrMoV 9%Cr-Co-Mo-W-V-Nb-N-B	1%Cr-Mo-V	current, low-alloy, bainitic steels currently used in Europe developmental
	Blades	forged Type 403: 12Cr Type 422: 12Cr	Type 403 Type 422	current
Condenser	**Tubes**	Carbon steel, Duplex stainless steels, Titanium	Carbon steel, Duplex stainless steels, Titanium	Based on fossil experience where SCC on coolant side is an issue
	Body	Carbon steel	Carbon steel	Based on fossil experience*
Demineralizer/deareator		Carbon steel	Carbon steel	Based on fossil experience
High and low pressure feedwater heaters		Carbon steel	Carbon steel	Based on fossil experience
Condensate and feedwater pumps		F304L	F304L	Based on fossil experience

Power controlled by feed-water flow rate, & core reactivity controlled without direct feedback. (Load-following), Ref.# 6

(1) Feed water controlled by Proportional & Integral system (*)

feed-water flow can change the reactor power through the temperature change of secondary sodium loop.



(2) Reactor power

Reactor power will decrease by the negative reactivity of core support plate expansion and coolant coefficient.

(*)This Plant control (4S design) system: Set parameters are output of electric power and main steam pressure. **BREI comments:** Why Primary Sodium Flow Control not receive input of flow demand?

Conclusions

- A complete heat balance model for the 4S power conversion cycle has been performed
- Balance of plant match to 4S NSSS platform
- The plant generates 50 MWe with 38.5% thermal efficiency (net electric power to the grid / fission power)
- The turbine-generator module is feasible with existing technology
- Candidate materials for all components of the power conversion cycle have been identified
- Future work will provide Results of the facility transient analysis during a variety of load conditions utilizing these inputs. Results will be obtained by using the RELAP-5 code with Power Conversion Cycle for all transient conditions