Balance of plant – Status and plans

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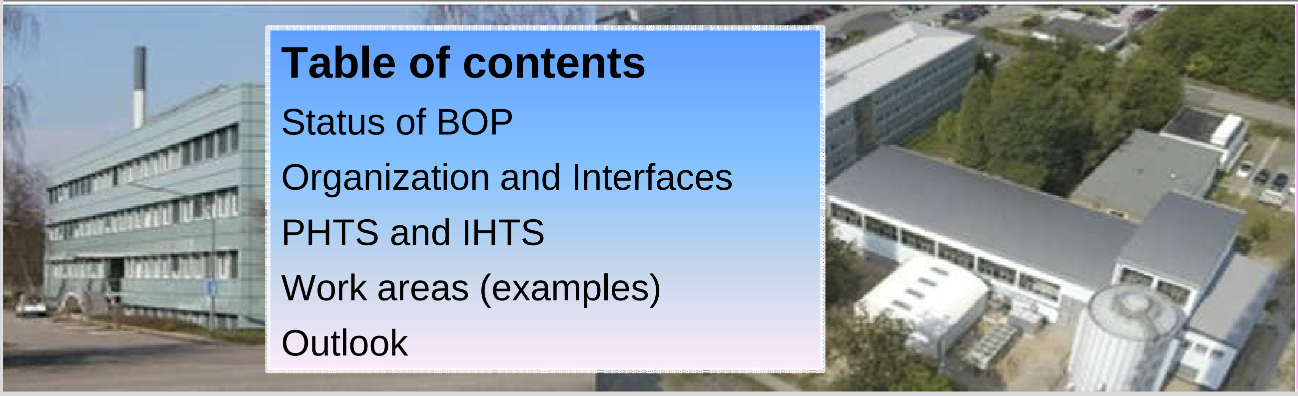
Workshop on DEMO Physics and Technology R&D

IPP Garching, September 2nd and 3rd , 2014

Institute for Neutron Physics and Reactor Technology



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WBOP

INR started 2010/11 into BOP
coming from design and safety for helium and liquid metal cooled systems

Wolfgang Hering, System engineer and safety liaison officer
Evaldas Bubelis, Systems engineer

EUROFUSION funding:
- PHTS & BoP Engineering: 0,2 ppy
- Modelling & analyses: 0,3 ppy
- Industry: 0,2 ppy

Starting situation: DEMO/FPP for what?

Important for BOP to define priorities for DEMO (2040+) and to develop systems further to FPP (2050+)
Recently new requirements are coming from:
Grid-operators, industry, renewables, transport, private fields

- Grid-operator: stability, load balancing
- Industry: stable power supply, predictable market prices
- Renewables: still high priority?
- Transport: trains, electric highways (trucks), airplanes(?)
- Private fields: increased volatile power production
  mobility (E-bikes, E-cars to be loaded after work!)
  IT-demand (smartTV, PC, Server, …)

→ **Plant concept still up-to-date for market to come?**

Work Programme BOP (2014-18)

1. **Simulation**
   Both water-cooled and helium-cooled BoP are designed, modeled, analyzed, and evaluated using appropriate tools

2. **Technology**
   Review and benchmarks on some of the DEMO/FPP key issues (T-control in HX, pulsed operation, BoP component failure modes, etc.)

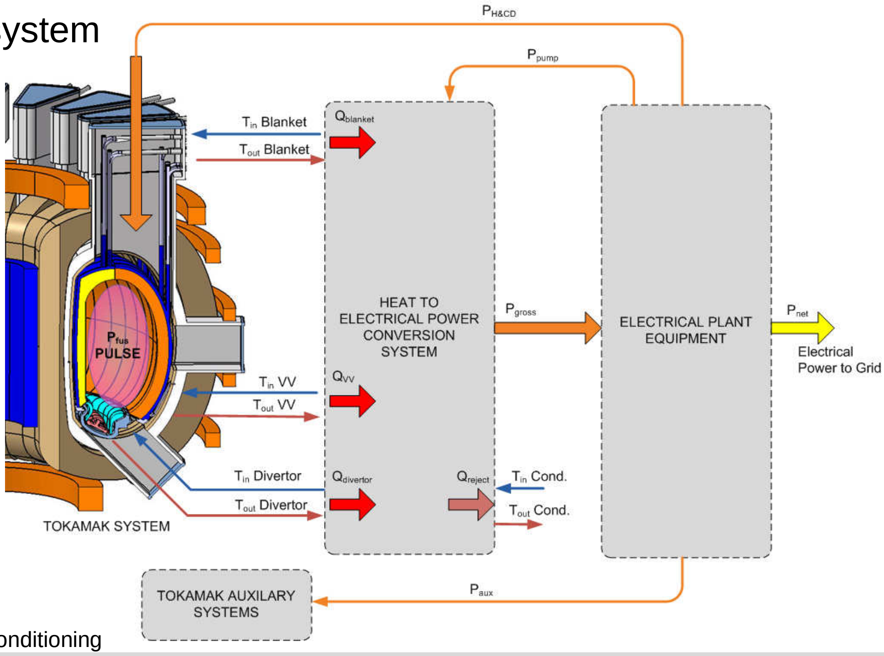
3. **Optimization**
   Optimize cooling and power conversion system (PCS) for
   a. continuous mode (steady state)
   b. pulsed mode (different duty cycle)

4. **Industry**
   Involvement focused on PCS components (high efficient power block)

BoP includes:

Main systems

- Heat Transport & Storage Systems (PHTS, IHTS)
- Power conversion system



Support systems

- Electrical Power distribution
- Auxiliary systems
- Fire Protection
- HVAC Systems

HVAC: Heating Ventilation and Air Conditioning

BoP tasks: Design and optimization

- Heat Transport System
  - PHTS and IHTS,
  - Power conversion system (Power block) from industry
- Support systems
  - Component Cooling System
  - Service Water System
  - Circulating Water System
  - Water Treatment Plant
  - Compressed Air System
  - Chemical and Volume Control System
- Electrical Power Supply
- I&C and Safety Systems [SAE]
  - Fire Protection
  - Filter and trapping devices
- HVAC System

HVAC: Heating Ventilation and Air Conditioning

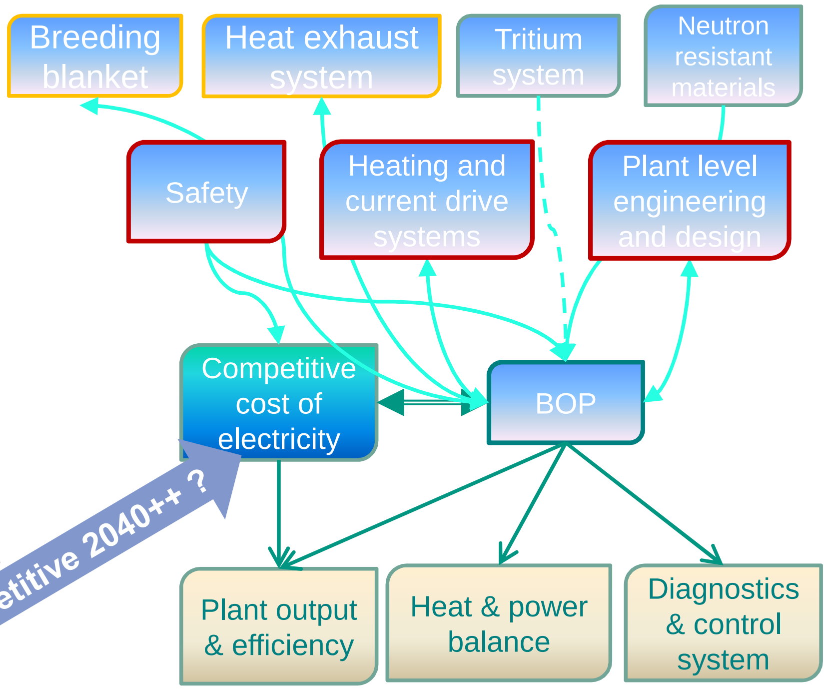
Interfaces: heat and electrical energy

Heat sources

- Primary:
  1. Blanket
  2. Divertor
- Secondary:
  1. Vessel cooling
  2. Gyrotron cooling
  3. …

Energy sinks:

1. Pumps and blowers
2. Magnets & Cryo plant
3. Plasma heating systems
4. Cooling system
5. …



But: what is competitive 2040++ ?

Organization

WPBOP (Mission 6) is managed by Emilio Cipollini (Ansaldo):

Responsibilities / Tasks:

- ***BOP2.1.1-01-02-03 & BOP2.1.2-01-02-03***

  System Requirements Document (PHTS, BOP)
- ***BOP2.1.3-01 Safety Requirements Document (KIT)***
- ***BOP-3.1.1-01-02-03 APROS Model*** *(CCFE)*
- ***BOP-3.1.2 Alternative Secondary Coolants*** *(S-CO_2, CIEMAT)*

Activities in BOP (2013/14)

Design

- Confirm indirect / direct cycle approach (Rankine/Brayton)
- **Develop Intermediated Heat Transfer and Storage System (IHTS)**
- Together with PIM: Identify needs for:
  - **Redundancy in PHTS components**
  - and level of their independency

Safety

- Requires dynamical tool for TH (high priority) and energy flow (low priority) simulations:
  → **Assess with SAE the applicability of the ASTEC code** (+BOP)
- PHTS to PCS pressure levels (tritium safety)
- Max. volume of coolant lost following LOCA [BB,SAE]
- Confirm safety classification approach [SAE]

Hierarchical approach

1. Operation mode of DEMO: stationary / **pulsed**
2. Define topology for BOP
   1. Interfaces of BOP for:
      - Internal power balance (Plasma restart ?)
      - Timing constraints
      - Heat production/cooling needs to be balanced within DEMO
   2. Parameter studies with EBSILON on:
      - Duty cycle
      - Storage size
3. Dynamic plant model to design and optimize:
   1. Components
   2. Loops, Fluiddynamics (PHTS, IHTS)
   3. Reliability, Efficiency and Safety
4. Fix of design and interfaces

*IHTS: Intermediate heat transfer and storage

Reference conditions for benchmark study

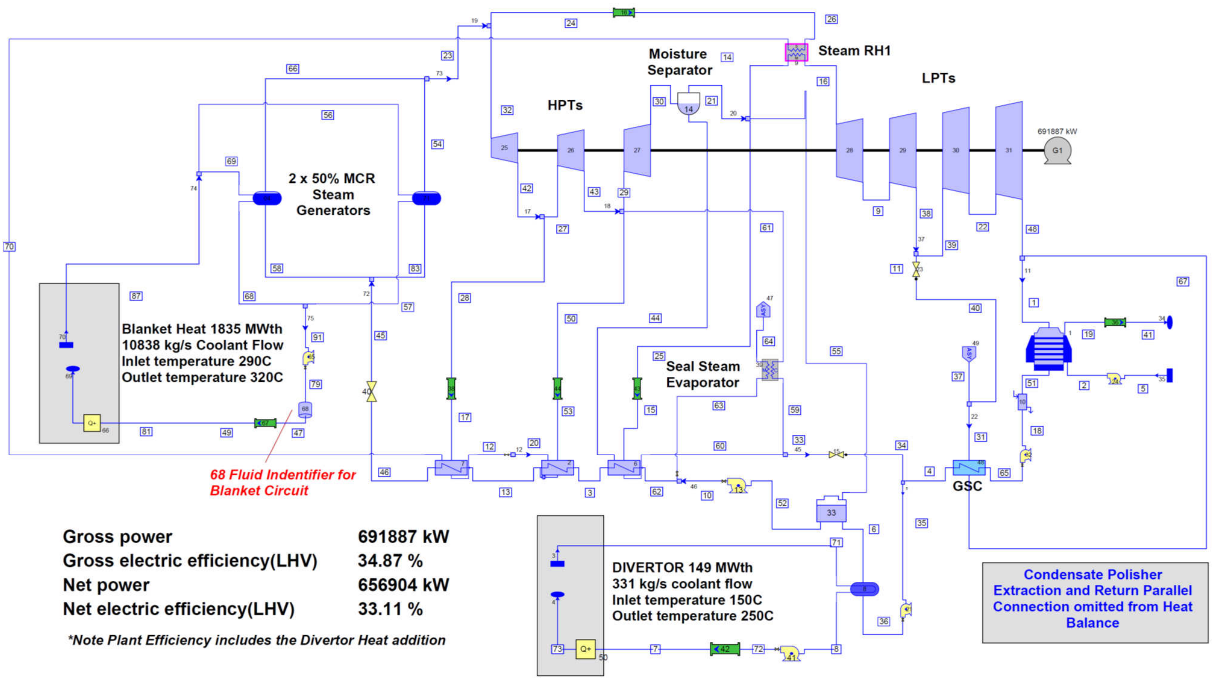
Blanket coolant	Blanket coolant outlet temperature	Secondary coolant	Blanket heat (MW)	Divertor heat (MW)	vessel heat (MW)	Gross electric power (MWe)	Pumping power (MWe)			other power requirements for Rankine cycle (MW)	Net electric power[a] (MWe)	Net efficiency[b]
							blanket, divertor & vessel coolant	working cycle	heat rejection circuit			
Water	320°C	steam	1835	149	not included	691.9	10.2	13.5	2.1	9.5	657 (666[c])	33.1% (33.6%[c])
Helium	500°C	S-CO_2	1835	149	34.6	878.9	162.2	26.4	12.5	not included	678	34.2%
Helium	500°C	S-steam	1835	149	34.6							

[a] The pressure drops assumed in the blanket may not be realistic.

[b] Vessel heat is neglected when calculating efficiency.

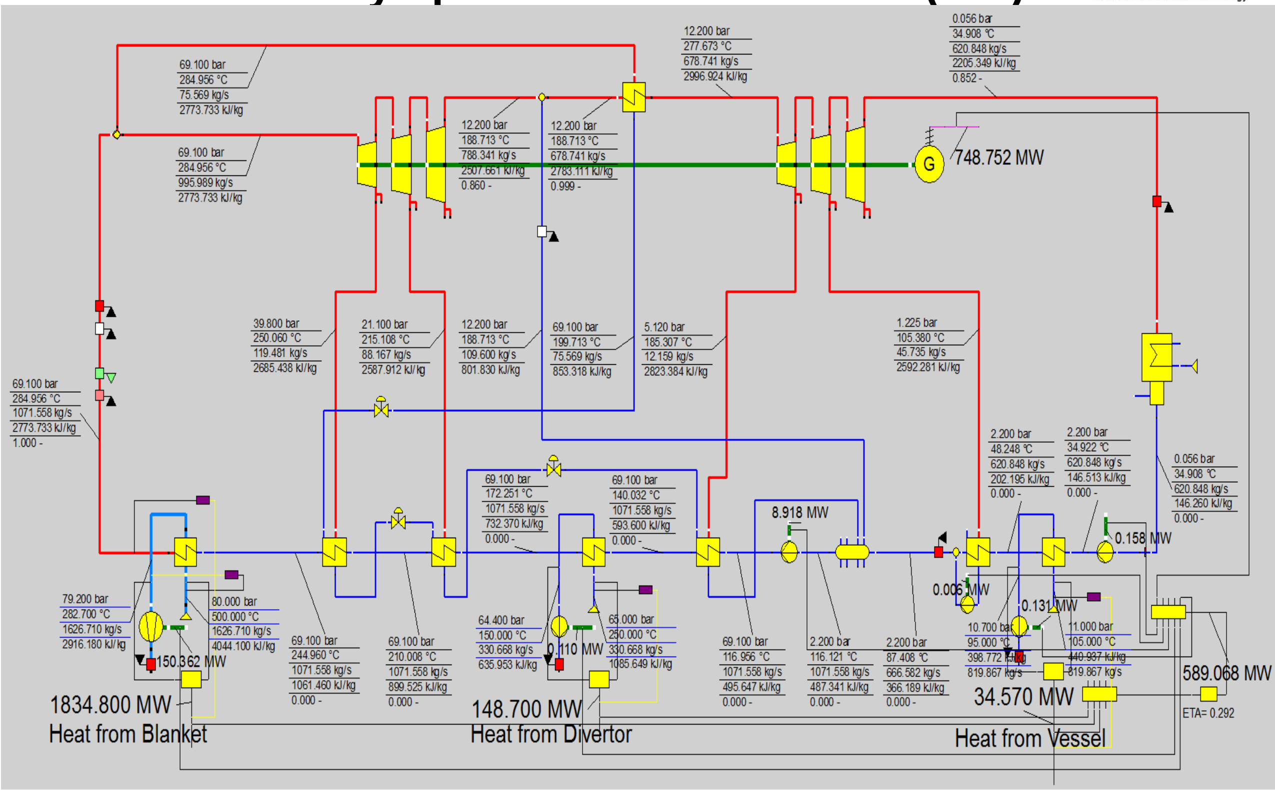
[c] Neglecting "other power requirements for Rankine cycle."

DEMO stationary operation:
PHTS: Water (CCFE)



Cycle diagram for Thermoflow model: Rankine cycle of water-cooled reactor (CCFE: https://user.efda.org/?uid=2MC3W9)

DEMO stationary operation: PHTS: Water (KIT)



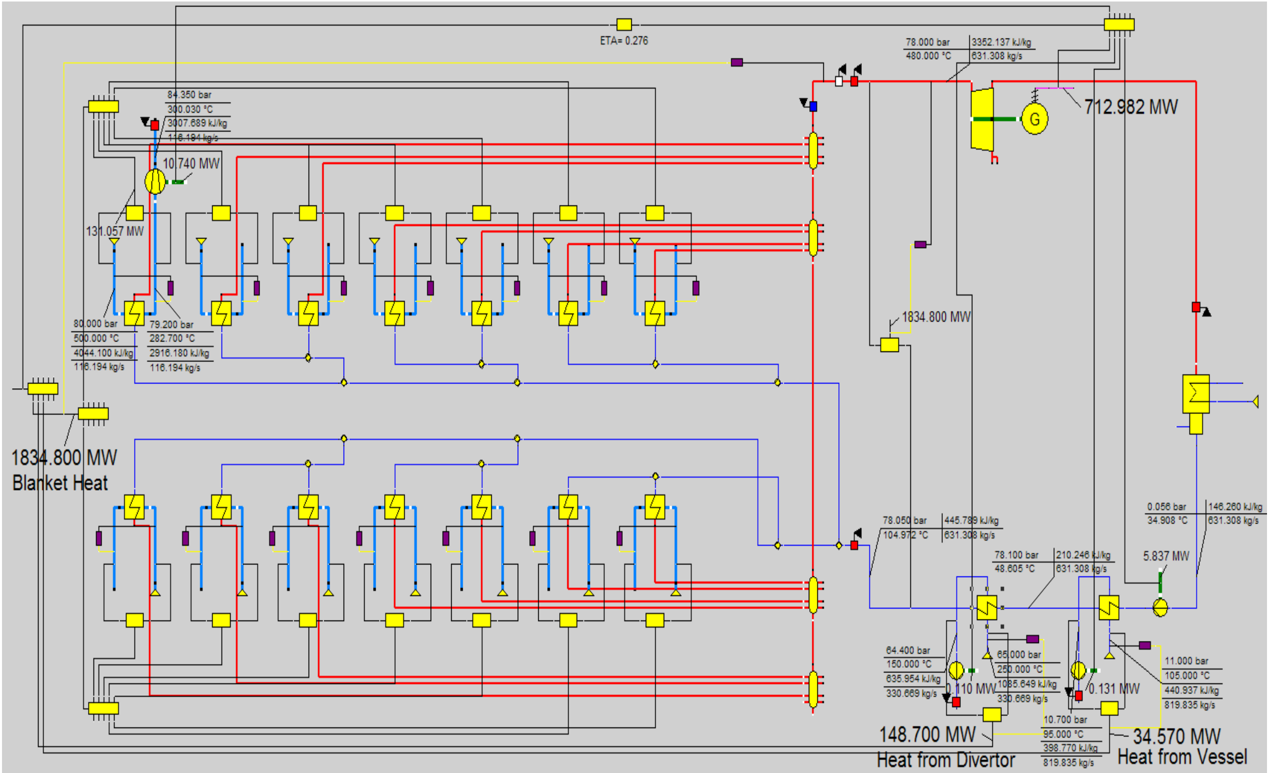
Benchmark on stationary operation

- Dymola (Modelica) (CCFE) versus EBSILON Professional (KIT)
- Most of the coolant parameters at different locations of the simulated DEMO BoP scheme agreed well
- Only slight difference of ~5.9 MW (< 1%) obtained in gross electrical power
- Thermal efficiency of such a cycle was estimated to be 36.7 %.

  → no further risk expected:
  design to be optimized and fixed

Assumed Isentropic Efficiencies	Helium PHTS	Water PHTS
of the turbine	0.88	---
of the low pressure turbine	---	0.90
of the high pressure turbine	---	0.85
of all modelled pumps	0.85	0.85
of helium blowers	0.82	---
Assumed generator efficiency	0.97	1.0 (idealized conditions)

DEMO stationary operation: PHTS: Helium



Demo pulsed operation analyses

- Analysis of energy flow and power demand along duty cycle
- Assess TES* storage sizes for 4:1 duty cycle:
  1. Water
  2. Helium
- Influence of dwell time on TES storage size

*TES: Thermal Energy Storage

BOP: Power balance along pulse complete?

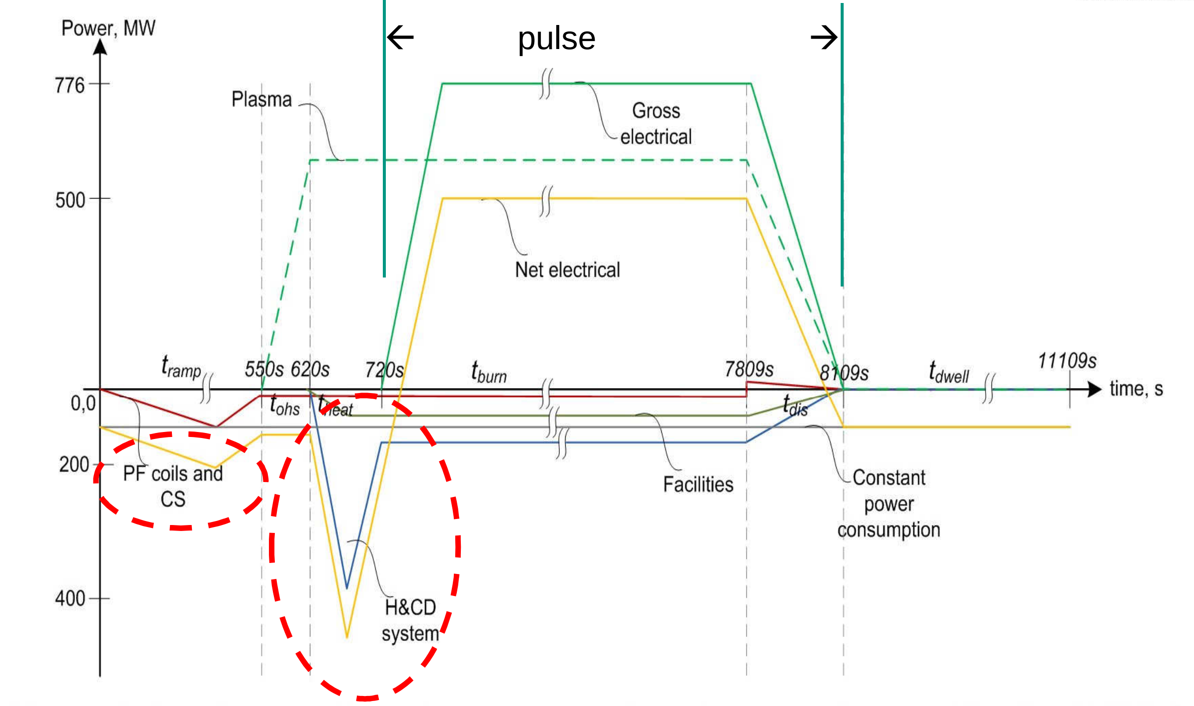


Figure 3. Rough estimation of power generation / consumption profiles for DEMO 1 scenario.¶

Source: TA WP13-DAS-08-T04, 2013, (IREC)

Storage vs. power supply costs

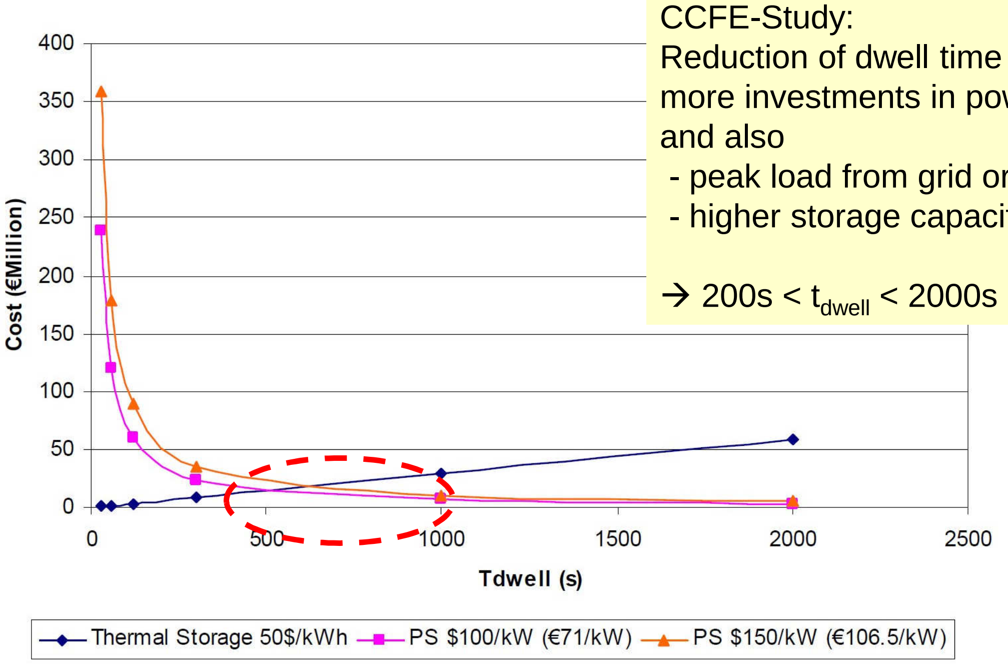


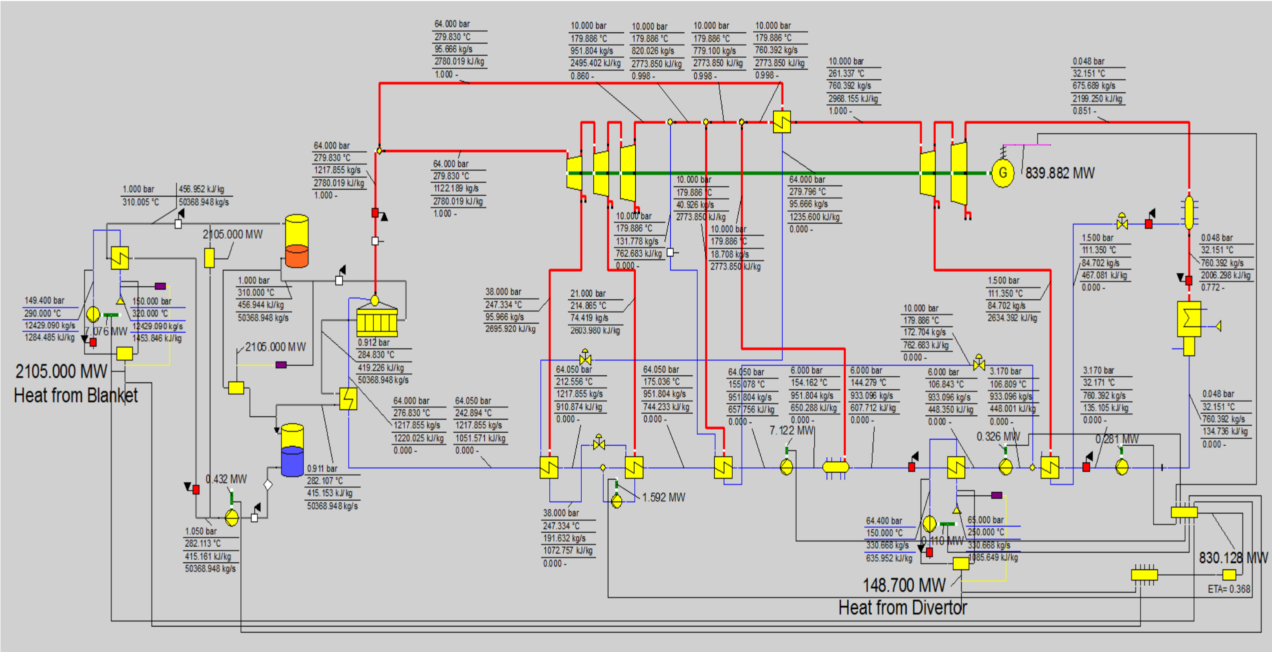
Fig. 7.5: Salt storage & power supply (PS) cost vs dwell time

CCFE-R(12)17, Jan. 2010

CCFE-Study:
Reduction of dwell time requires more investments in power supply and also
- peak load from grid or
- higher storage capacity

→ 200s < t_{dwell} < 2000s (t.b.c.)

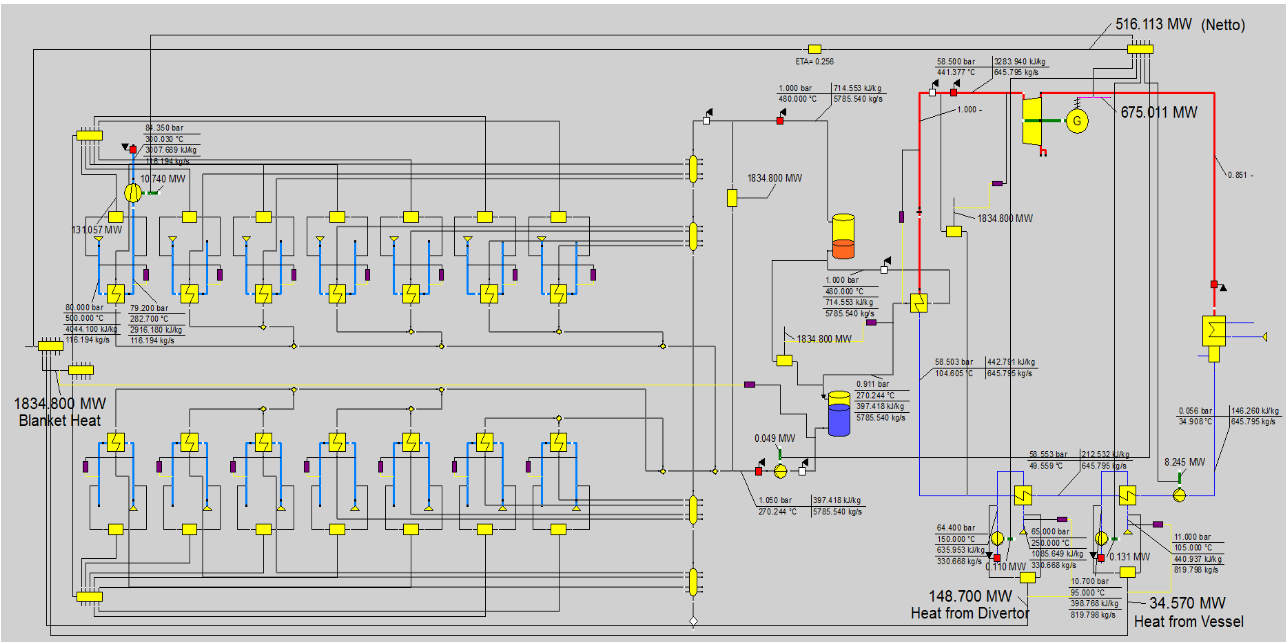
TES size for: Water + IHTS (solar salt)



DEMO BoP scheme for water cooled blanket concept with the integrated intermediate heat storage loop as modelled by KIT

*TES: Thermal Energy Storage

TES size for: Helium + IHTS (solar salt)



DEMO BoP scheme for helium cooled blanket concept with the integrated intermediate heat storage loop as proposed by KIT

*TES: Thermal Energy Storage

Pulsed operation: TES* size (water / helium)

- Both conceptual design configurations for DEMO intermediate heat storage loop are extended by a TES device coupled via an intermediate cooling loop to PHTS:
  - water cooled concept
  - helium cooled concept
- DEMO duty cycle for analysis: 4:1 (pulse time: 2h, dwell time: 0.5h)
- Results following PHTS boundary conditions
  - Water: Tin= 320 °C
    ~71300 t of solar salt, which amounts to (71300 t x 0.49 $/kg) 34.9 M$
  - Helium: Tin 500 °C
    ~8200 t of solar salt, which amounts to (8200 t x 0.49 $/kg) 4.0 M$

→ reason: **low usable ΔT in case of water**

*TES: Thermal Energy Storage

Pulsed operation: TES* size = f(t_{dwell})

Ebsilon results (no decay heat taken into account)

Dwell-time	Storage	Delta storage	Total costs, M$	Delta costs, M$
20 min	5800 tons	-2400 tons	2.842	-1.176
30 min	8200 tons	(Base case)	4.018	
40 min	10300 tons	2100 tons	5.047	1.029

Ebsilon results (decay heat taken into account, 10% Pnom blanket)

Dwell-time	Storage	Delta storage	Total costs, M$	Delta costs, M$
20 min	5200 tons	-2000 tons	2.548	-0.980
30 min	7200 tons	(Base case)	3.528	
40 min	9100 tons	1900 tons	4.459	0.931

Ebsilon results (decay heat taken into account, 10% Pnom blanket)

Dwell-time	Storage	Tank height	Tank diameter (cylinder)	Tank diameter (conservative value)*
20 min	5200 tons	17 m	14.51 m	14.78 m
30 min	7200 tons	17 m	17.07 m	17.39 m
40 min	9100 tons	17 m	19.19 m	19.55 m

*TES: Thermal Energy Storage

Pros & Cons

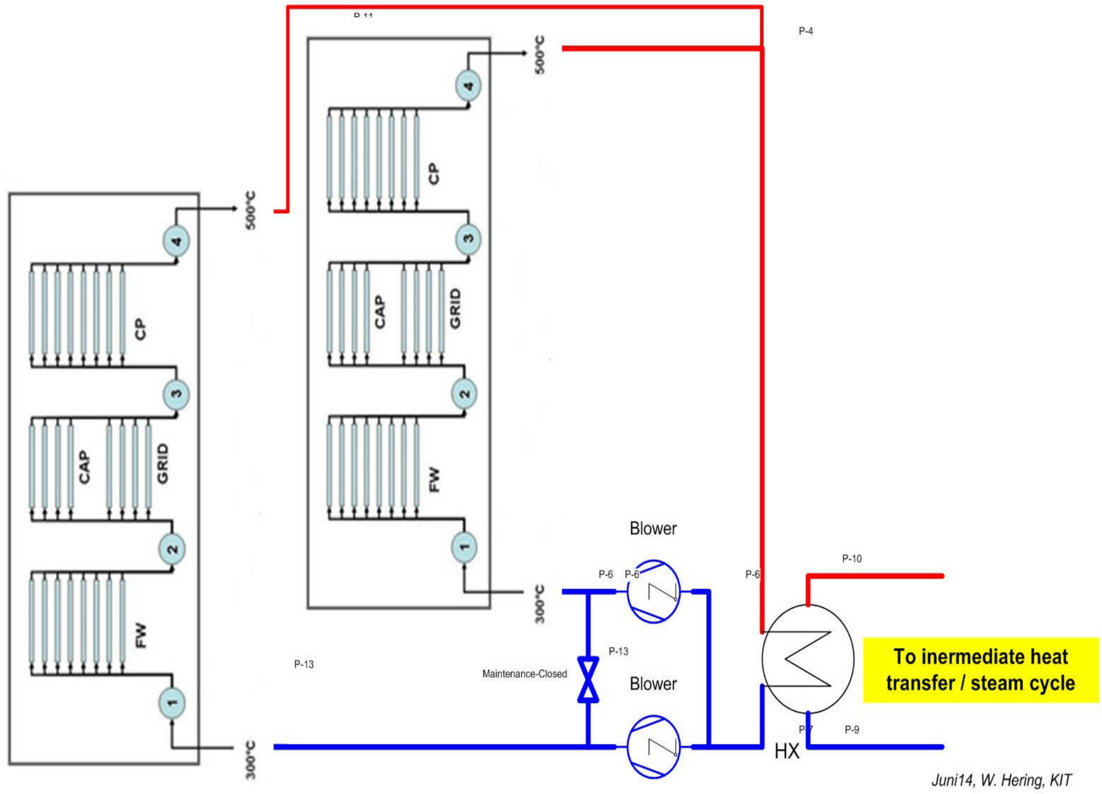
PROS:

- Storage size for He reasonable
- Decoupling high pressure He (with H^3) from PCS
- Enhances lifetime of power block
- Allows for in-house power and plasma restart
- Allows for certain grid stabilisation

CONS:

- Additional fluid
- Additional pumping power
- IHX for high heat fluxes

Safety: Proposal for PHTS redundancy



Summary (status 2014)

- Continuous plasma operation:
  - Water and Helium are feasible
  - Load following capacity limited (plasma stability!)
  - What about long pulse operation?
- Pulsed plasma operation
  - Required TES volume (and costs) for water >> helium
- Solar salt → 400°C, Saltstream™ 565 → ~500°C, >500°C Liquid metals
  - Dimensioning of TES allows:
    - Lowest size: in-house power level
    - Medium size: Plant/plasma restart
    - Large size: Load following level
    - Full size: Full power operation

    → Allows to adapt FPP to needs of the market
  - T behaviour in heat transfer fluid to be assessed → enhances safety ?
  - Optimization of duty cycle depending on design and cost options

Summary

- Duty cycle: Storage size dependency on:
  - dwell time and
  - power block efficiency.
- Safety: PHTS redundancy under discussion
- Thermal storage: Start: 2-tanks as used in commercial CSP plant; goal: thermocline Monotank (TMT)
- Power balance: Autonomous plasma-restart option feasible (Black-start-up?)
- Power output: Address needs of grid topology in 2040 / 2050

Outlook 2015

- High priority:
  - BOP-interfaces:
    time dependent flows of heating, cooling, and energy: volume and time dependency
  - Parametric studies with EBSILON with up-to-date power block (industry)
  - Dynamic simulation:
    definition of a common DEMO BOP and SAE system code to use synergetics (e.g. ASTEC-FUSION)
    If YES:
    - Perform dynamic simulations (without power block)
    - Extend ASTEC with a TES module
    - Couple ASTEC to PROCESS code (?)
- Low priority:
  - Continuous mode
  - Heat usage

Literature

1. Personal communication with Mr. Chris Harrington (CCFE)
2. E. Bubelis, W. Hering, “Selection of coolant for the heat storage system of DEMO BoP, analysis of Dwell time influence on the heat storage capacity requirements, cost and storage dimensions, and analysis of the potential to provide the needed in-house electricity needs for DEMO”, INR 10/14 – FUSION 446, August 2014
3. E. Bubelis, W. Hering, “Conceptual design configuration definition for DEMO intermediate heat storage loop, assuming both water and helium as primary coolants”, INR 11/14 – FUSION 447, August 2014.
4. T. N. Todd, R. Clarke, H. Kalsi, M. Kovari, A. Martin, A. Muir, Z. Vizvary, The Key Impacts of Pulsed Operation on the Engineering of DEMO, CCFE-R(12)17, 2010
   → (Solenoid spec: 200s < T_{dwell} < 2000s)
   → Dwell time analysis: 200-2000s range
   → The dwell time does not take into account the time after ramp-up and before ramp-down where there is insignificant fusion output power. This will increase the demands upon the thermal storage.
5. R. W. Bradshaw, N. P. Siegel, Molten nitrate salt development for thermal energy storage in parabolic trough solar power systems, ES2008-54174, Proceedings of ES2008 Energy Sustainability 2008, August 10-14, 2008, Jacksonville, Florida, USA
6. Dylan Grogan, Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants, Abengoa Solar Sunshot Conference, Project Review, April 24, 2013, (http://energy.gov/sites/prod/files/2014/01/f7/csp_review_meeting_042413_grogan.pdf)
7. C. Séropian, M. Barrachin, J.P. Van Dorsselaere, D. Vola, Adaptation of the ASTEC code system to accident scenarios in fusion, Fusion Engineering and Design 88 (2013) 2698–2703.
8. POWER PLANT CONCEPTUAL STUDY PPCS – STAGE III Final Report, Task Order EFDA 93/851 JK, June 2005
9. F. Díaz González, M. Cruz Zambrano, M. Sanmarti Cardona (IREC), Design assessment of pulsed power profiles in relation to Primary Heat Transfer and Balance of Plant systems, TA WP13-DAS-08-T04, 2013

HTF / sensible TES

GEMASOLAR RESULTS
Liquid Sodium compared to Solar Salt

METRIC	SOLAR SALT	LIQUID SODIUM	DIFFERENCE (%)
Annual Energy [MWh]	108,765	108,190	-0.53
$LCOE_{real}$ [c$/kWh]	14.00	13.31	-4.93
$LCOE_{nominal}$ [c$/kWh]	**17.33**	**16.48**	**-4.91**
Total installed cost/net cap. [$/kW]	11,319	10,626	-6.13
Gross to net conversion factor	0.8805	0.8802	-0.03
Internal Rate of Return (IRR) [%]	19.90	19.94	0.20
Net Present Value [million $]	21,6	20,5	-5.65
Total Installed Cost [million $]	**197**	**185**	**-6.13**

- **Saving** in total installed cost ≈ **12** million dollars (6.13%)
- **TES**: Current 27 $/kWh → 40 $/kWh (+50%)
- **Direct TES**: uneconomical
- **Indirect TES**: +20% in TES (3.73%)
  → Saving in total installed cost ≈ **7.35** million dollars
  → LCOE: 16.84 c$/kWh (2.83% lower)
  → O&M: Current 65 $/kW-yr → 86 $/kW-yr (+32.3%)

15 May 09 2014 Pilar Albar Bello Institute for Nuclear and Energy Technologies KALLA

PHTS Data (2013)

	Nuclear Heating [MW]	Inlet temperature [C]	Outlet temperature [C]	System pressure [bar]	Mass flow rate [kg/s]	Pressure drop [bar]	Enthalpy out* [kJ/kg]	Enthalpy in* [kJ/kg]
He cooled blanket	1705	300	500	80	1643,37	4.5***	4043,2	3005,7
H2O cooled blanket	1705	290	320	150	10070,88	3***	1454	1284,7
H2O cooled divertor	148,7	150	250	65	330,61	2**	1085,7	635,92
Vessel	37,45	95	105**	11	888,70	1**	441	398,86

*http://webbook.nist.gov/chemistry/fluid/
** D. Carloni, L.V. Boccaccini: Vessel/In-Vessel components Primary Heat Transfer System description, May 2013
*** Based on Antonella's emails

EBSILON®*Professional*

- EBSILON®*Professional* is a system that simulates thermodynamic cycle processes and is used to engineer, design, and optimize plants.
- EBSILON®*Professional* supports the engineering process — from feasibility studies to detailed dimensioning of the plant.
- Because of the broad flexibility of the system and the universality of the approach to solutions, it is possible to simulate virtually any thermodynamic cycle process.
  - Maximize the benefits of repowering and retrofitting actions by letting the EBSILON®*Professional* model do the simulation.
  - Design a performance-optimized plant for your application scenario by introducing the specific parameters into the model.
  - Calculate the effects of component contamination, various load cases, and changes in environmental conditions.
  - Simulate the operation of newly developed components in a cycle.
- EBSILON®*Professional at KIT also* includes a module for CSP / TES

BB data sheet

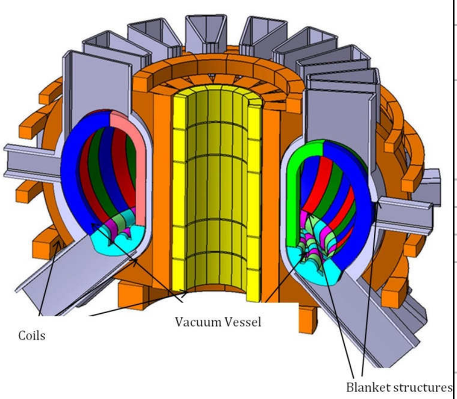


Figure 2.1 EFDA CAD model

		HCPB	HCLL	WCLL	DCLL	
Type of breeder/multiplier materials		Li4SiO4 Cer/ Be MM (separate pebble beds)	Lead-Lithium	Lead-Lithium	Dual coolant Lead-Lithium	
Coolant type		Helium	Helium	Water	Helium	Lead-Lithium
Pressure	[MPa]	8	8	15,5	8	0.1-2
Working Temperature Range	[°C]	300-500	300-500	285-325	250-450	300-500
Coolant Density	[kg/m³]	6	6		6	9726
Mass Flow Rate	[kg/s]	2165	2165	9310	707.4	29140.8
Specific heat of coolant	[J/kg-K]	5.20E+03	5.20E+03	1257-1484	1.00E+03	40
estimated pressure loss of the Blanket System	[MPa]	0.4	0,4		0.12	0.8-1.8 (*)
Piping Size	DN	t.b.d.	t.b.d.	t.b.d.	t.b.d.	t.b.d.
OB		500	500		110	80
IB		500	500		100	70
Height of the VV interface above the Tokamak Equatorial Plane	[m]	12	12	N/A	10,5	(?)
Volume of coolant at VV Interface	[m³]	450	450	N/A	N/A	N/A