Modelling the $^{S}CO_2$ power cycle of a generic dual-coolant fusion reactor with RELAP5-3D. Preliminary results and findings.

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Acknowledgments

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- INL has provided the UPC with a RELAP5–3D university license. Special thanks go to Paul Bayless and Cliff Davis for they feedback and support.

Contents of the presentation

- Brief introduction to our research activities
- Context: Spanish and European research on Nuclear Fusion
- Supercritical CO_2 power cycles
- Layouts proposed for the cycles
- Simulation of these layouts using RELAP5-3D (strengths and weaknesses identified)
- Conclusions

The ANT Research Group

- Since 2003, the Thermal-Hydraulics Studies Group (GET) of the UPC has been using RELAP5-3D.
- Now, GET is part of the Advanced Nuclear Technologies Research Group (ANT RG), of the Department of Physics and Nuclear Engineering.
- Main activities of ANT RG:
  - Nuclear data measurement
    - BEta deLayEd Neutron (BELEN) detector
    - n_ToF collaboration: neutron Time-of-Flight facility is located at CERN
  - Thermalhydraulics and safety
  - Fusion Technology

} ***GET*** (Thermalhydraulics and safety; Fusion Technology)

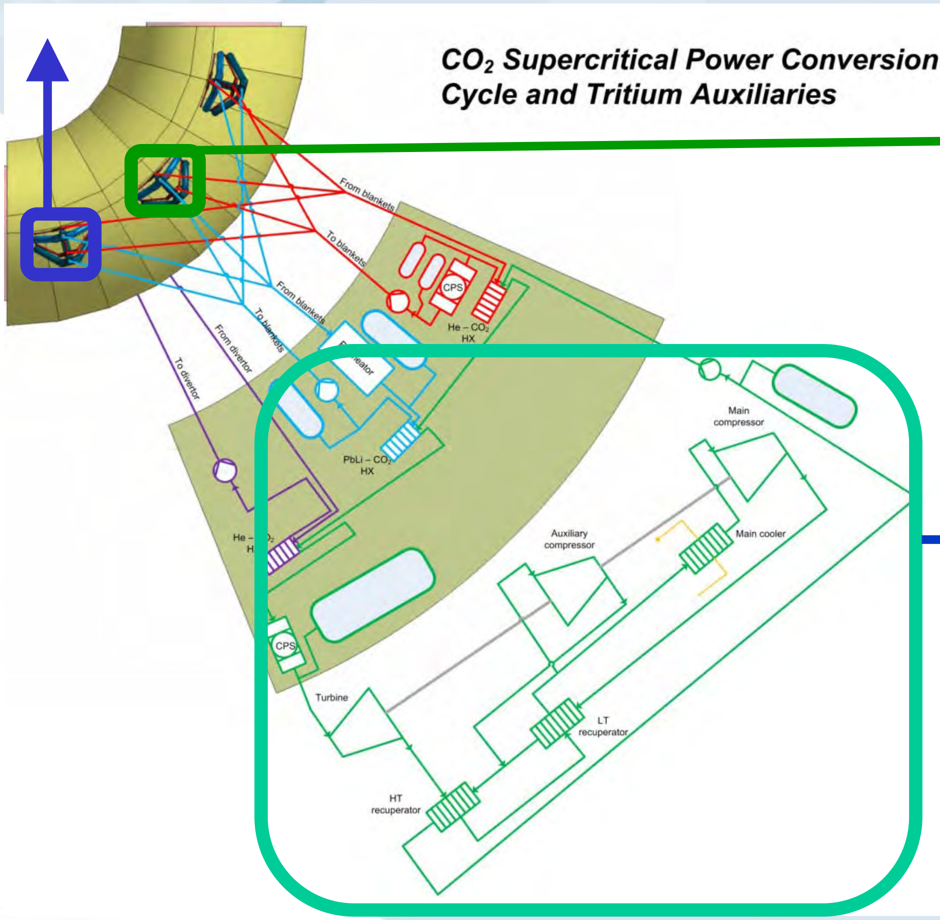
BELEN-20 detector at IGISOL (Jyväskylä University - Finland)

ANT activities in the field of FT

Microscopic description of He nucleation

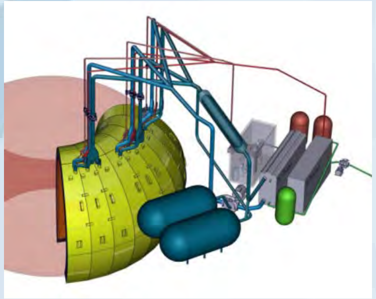
tritium **MHD**

Analysis of Breeding Blanket thermal-hydraulic performance with CFD support

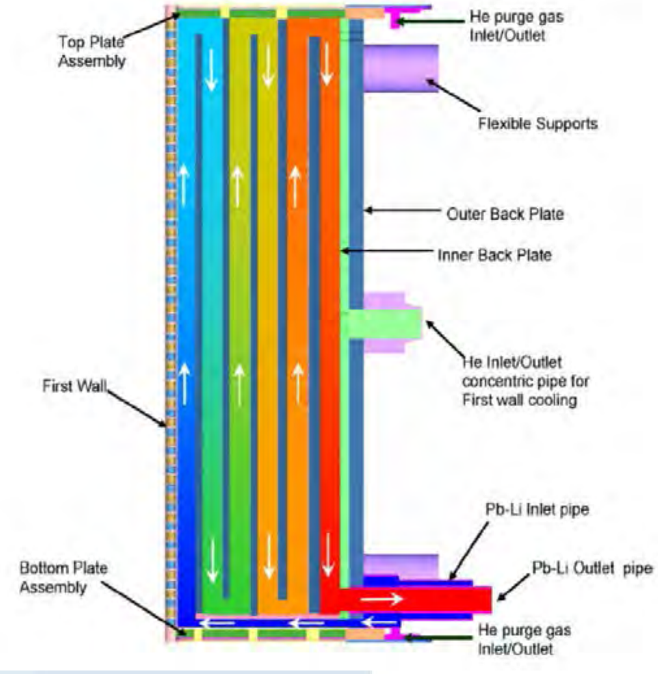


Integral system analysis

TH system code RELAP5-3D/ATHENA, developed by the INL.



ANT activities in the field of FT

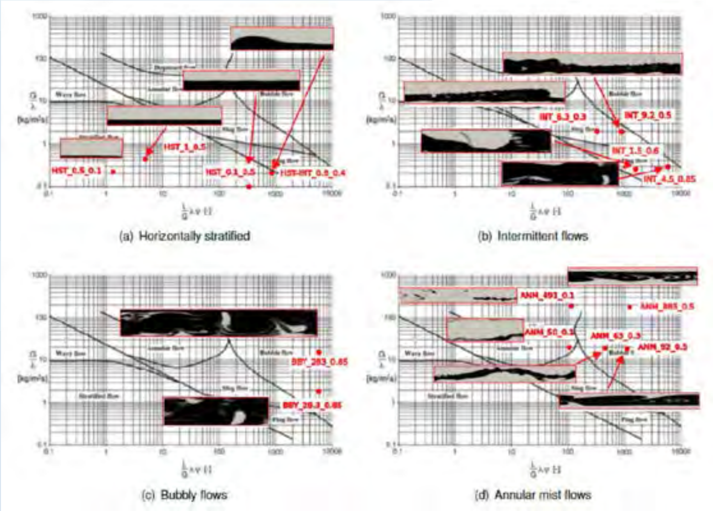


Institute for Plasma Research (IPR), India, is involved in the design and development of the Indian Test Blanked Module for ITER. Indian concept is a Lead-Lithium cooled Ceramic Breeder (LLCB). The first wall is cooled by helium.

RELAP/SCDAPSIM/MOD4.0 will be used for TH safety analyses. For some of the postulated off-normal events, a need exist to **simulate the mixing of He and LiPb fluids**.

UPC is cooperating with IPR to implement the necessary changes in the code to allow for this mixing.

The code two-phase flow equations structure has been modified to allow the existence of two phases, liquid LiPb and **dry** Helium in the **gas phase**.



A preliminary flow regime map has been developed on the basis of numerical simulations with the OpenFOAM CFD toolkit. Code modifications have been verified for vertical and horizontal configurations.

More details in Perez et al. (2015) and Freixa et al. (2015)

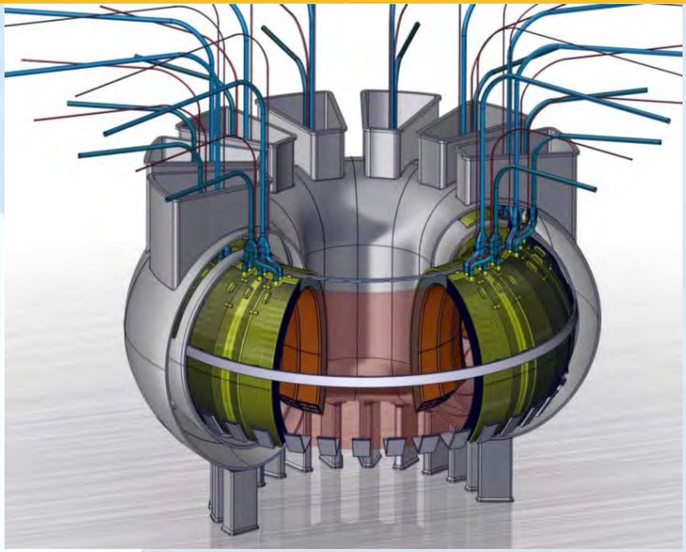
Spanish Fusion Program. TECNO-FUS

Major I+D objectives of the program (2009-2012):

Build-up the capabilities to design and engineer dual coolant breeding blankets (LiPb/He) and associate advanced auxiliary systems aimed at the conception of nuclear fusion reactors (DEMO).

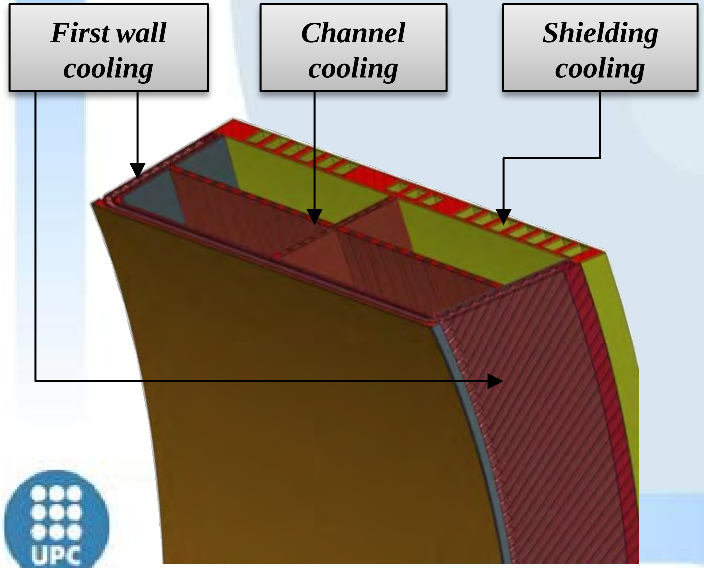
- Development, consolidation and integration of key engineering and computation capabilities.
- Conception and design of units, processes and systems for hydrogen isotopes.
- Development of instrumentation.
- Detail Engineering developments for in- vessel reactor components (blanket), and for auxiliary systems.
- Achievement of technological capabilities in production and qualification of key materials.

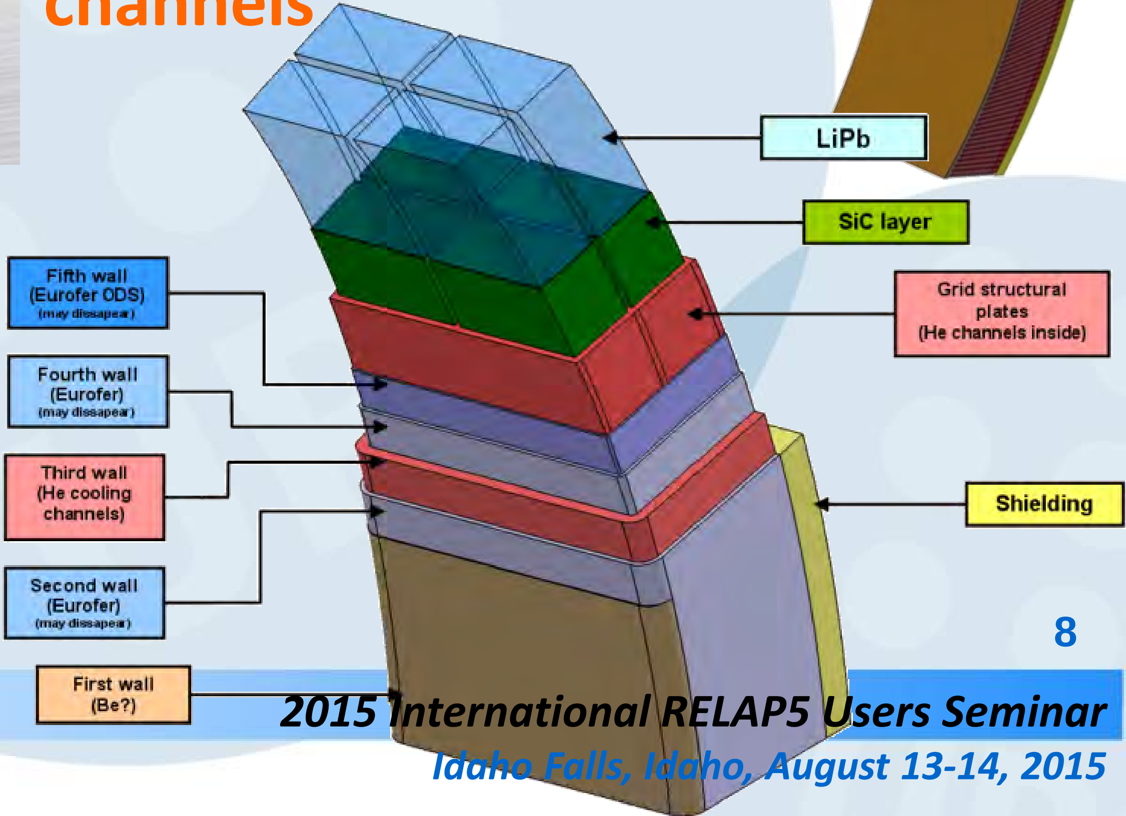
TECNO-FUS proposal for DEMO



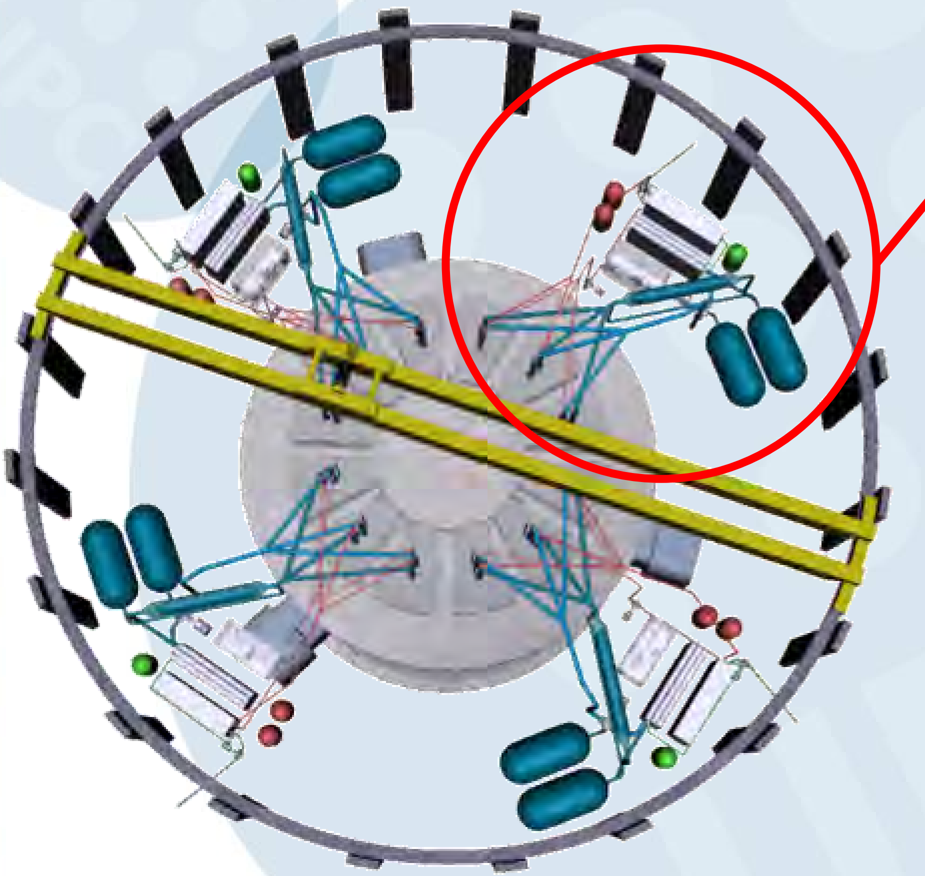
TECNO-FUS design option:

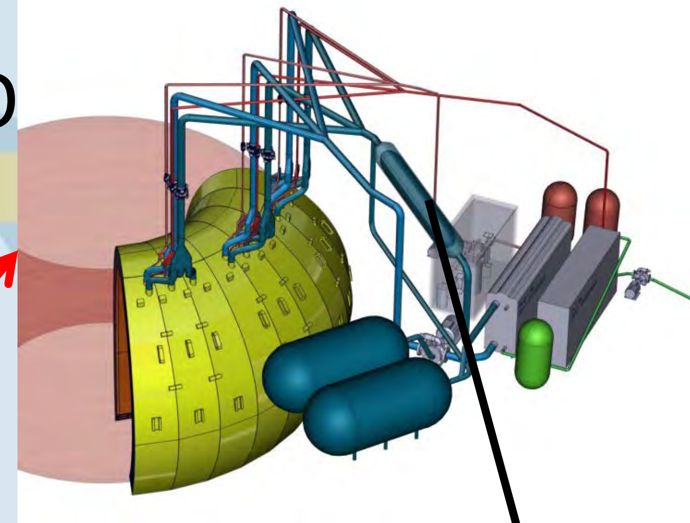
Vertical banana -shaped dual coolant blanked channels

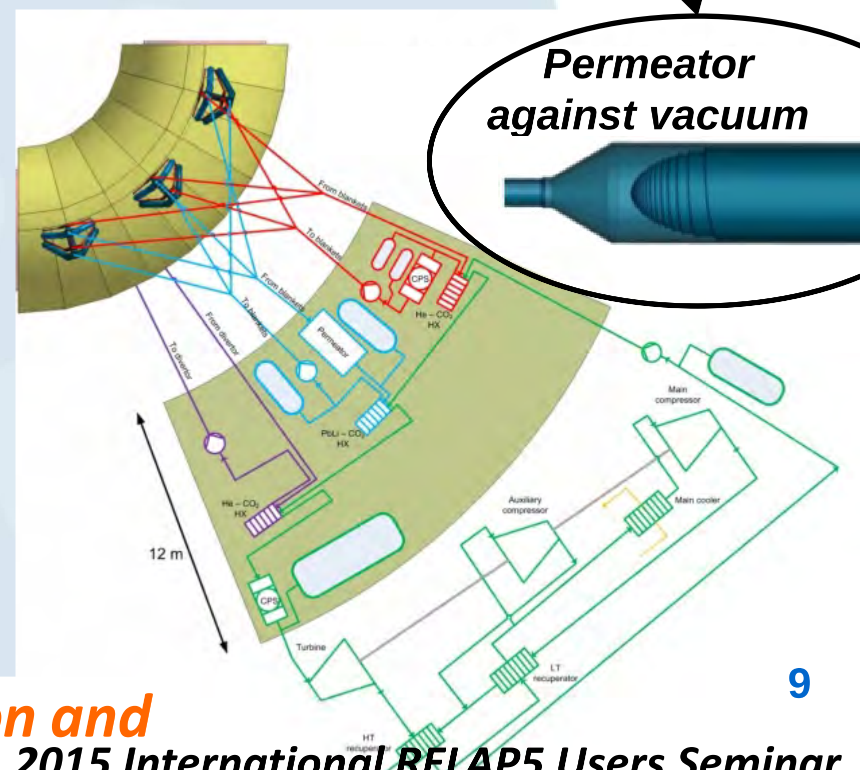




TECNO-FUS proposal for DEMO

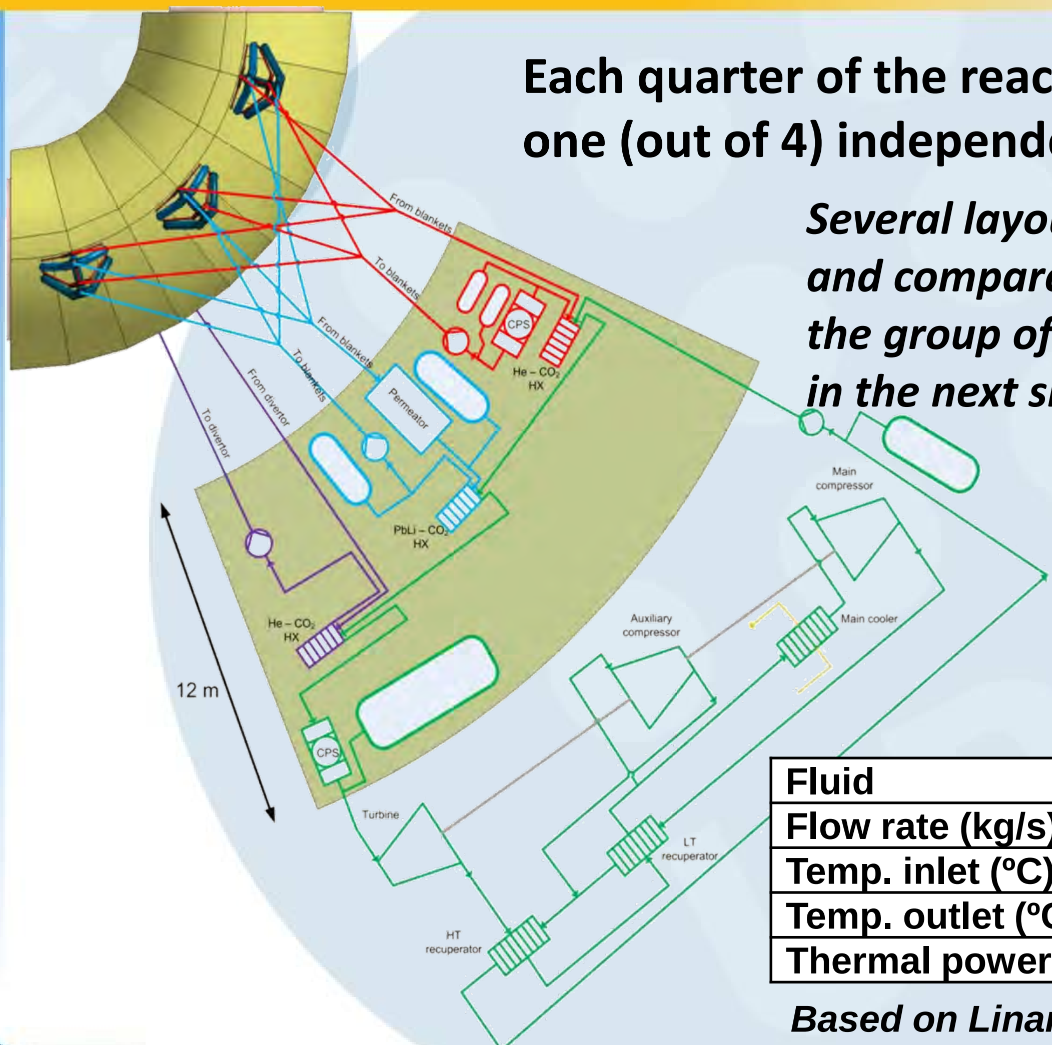






Advanced concepts for power conversion and tritium extraction systems

$^{S}CO_2$ recompression Brayton cycle



Each quarter of the reactor supplies thermal power to one (out of 4) independent power conversion units.

Several layouts have been proposed, analyzed and compared within the Spanish program by the group of COMILLAS (some references given in the next slides).

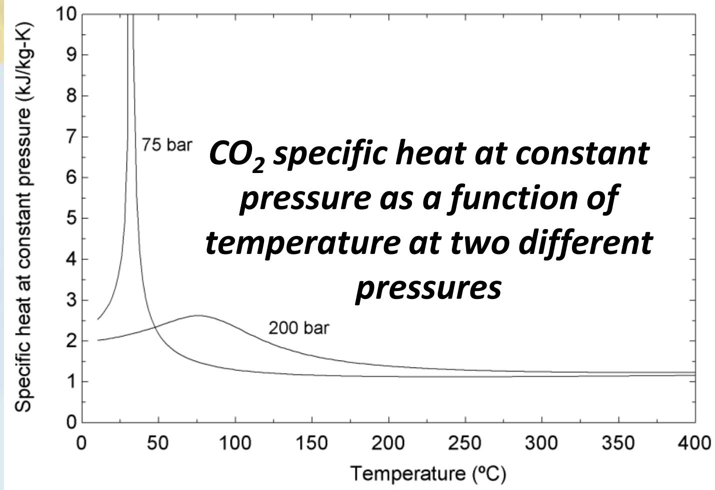
Thermal sources from one quarter of reactor considered in the TECNO-FUS DEMO design.

	Blanket		Divertor	
	BNK	LM	LDIV	HDIV
Fluid	He	LiPb	He	He
Flow rate (kg/s)	382	11500	118	119
Temp. inlet (ºC)	400	700	700	800
Temp. outlet (ºC)	300	480	566	700
Thermal power (MW)	198	494	82	62

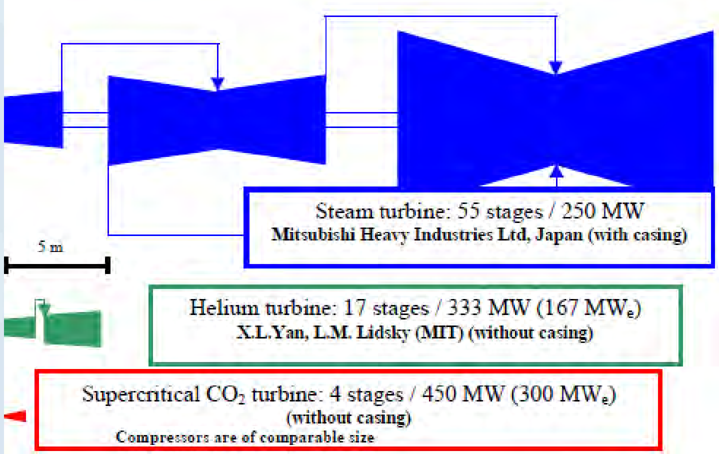
Based on Linares et al., 2010

$^{S}CO_2$ recompression Brayton cycle

- It has been shown that a recompression regenerative Brayton cycle can overcome the pinch-point problem that arises from the large heat capacity of CO2 at near critical pressures and temperatures compared with heat capacity at higher pressures or temperatures (Angelino 1968, Dostal et al. 2004).
- This type of cycle is the most efficient for the ranges of temperature to be found in the primary coolant of future fusion reactors (Dostal et al. 2004, Ishiyama et al. 2008, Linares et al. 2010).
- It presents other advantages as compared with H_2O or He cycles: size, cost, tritium management.

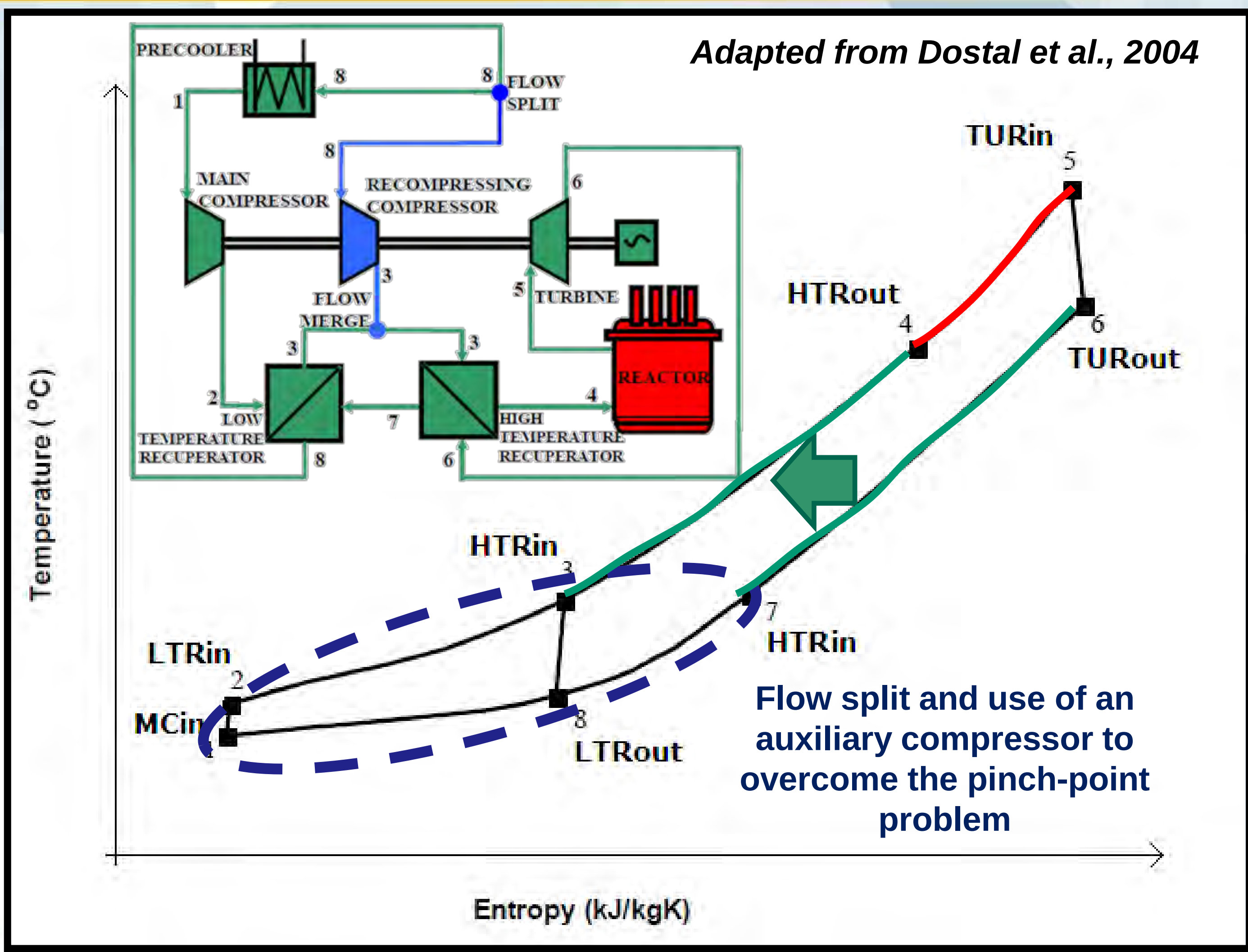


CO_2 specific heat at constant pressure as a function of temperature at two different pressures

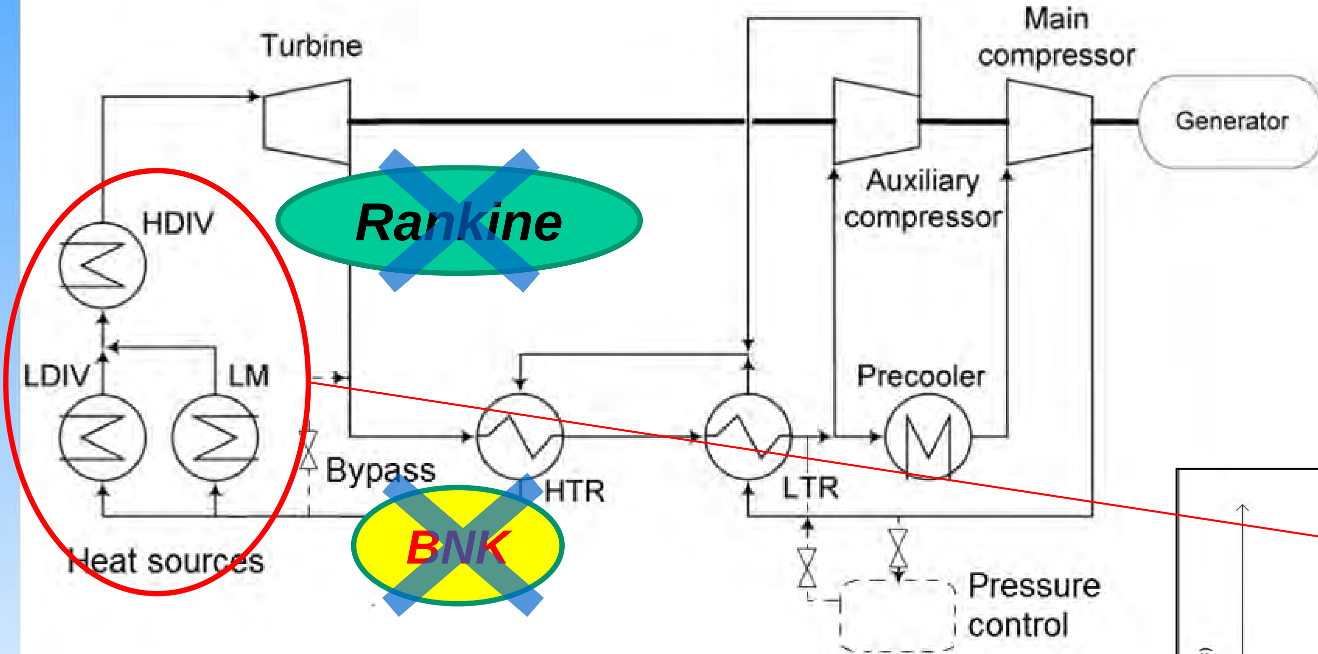


Comparison of turbine sizes (Dostal et al. 2004)

$^{S}CO_2$ recompression Brayton cycle

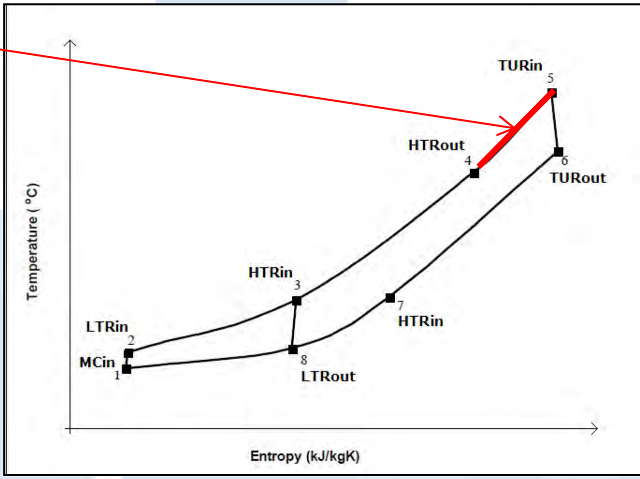


$^{S}CO_2$ cycle layout proposals



3 layouts were first proposed by **Linares et al. (2011)** in the framework TECNO-FUS. All of them use the **HDIV, LDIV** and **LM** heat sources.

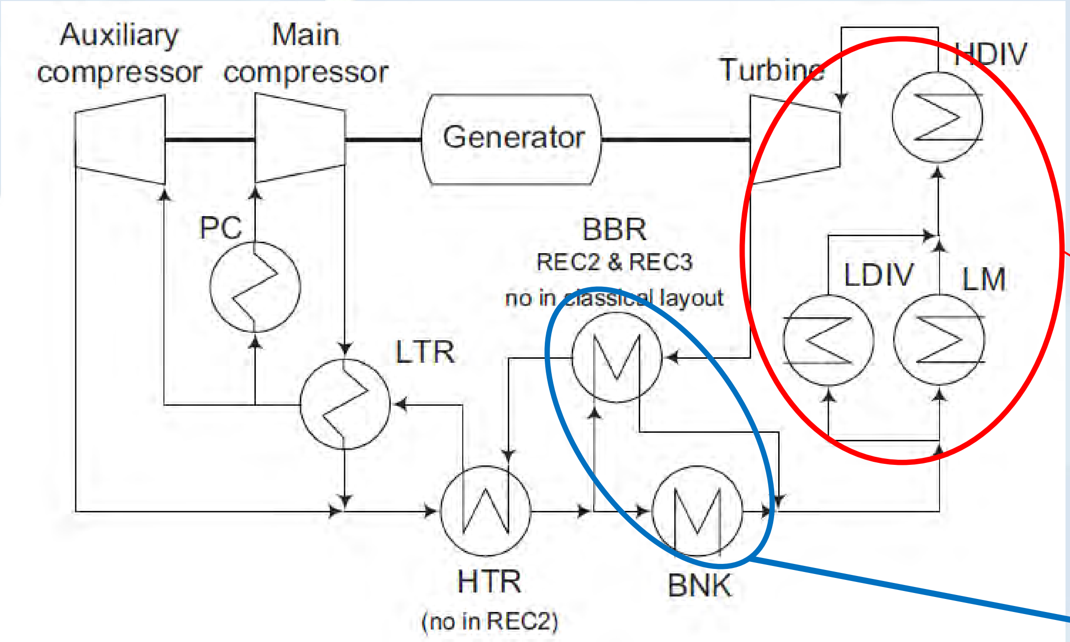
They differ in the use of the **BNK** heat source.



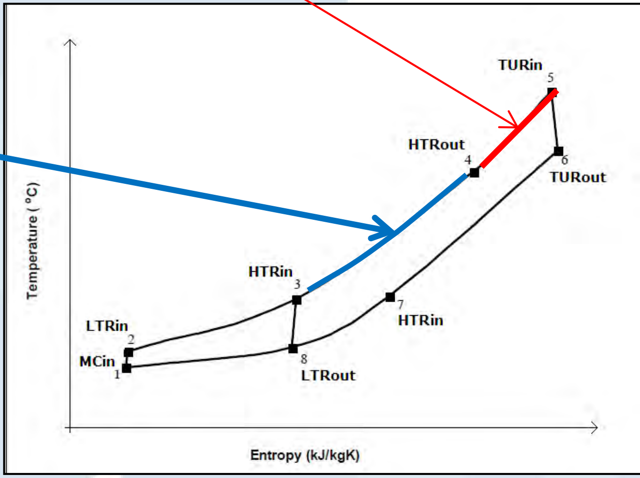
The low exergy of BNK makes it convenient either to recycle part of the CO_2 heat (after the turbine) by means of a Rankine cycle in a combined cycle configuration, or to use the BNK heat in a separate cycle (dual configuration).

Is the latter layout the one that has been modelled

$^{S}CO_2$ cycle layout proposals



The layout was further refined (**Serrano et al., 2014**).



Designs **REC2** and **REC3** were proposed, where the low-exergy **BNK** source is used **in parallel** with part or all the heat recovered after the expansion in the turbine.

Work in the modelling of REC2 layout is still ongoing. No results to show thus far.

$^{S}CO_2$ cycle layout proposals

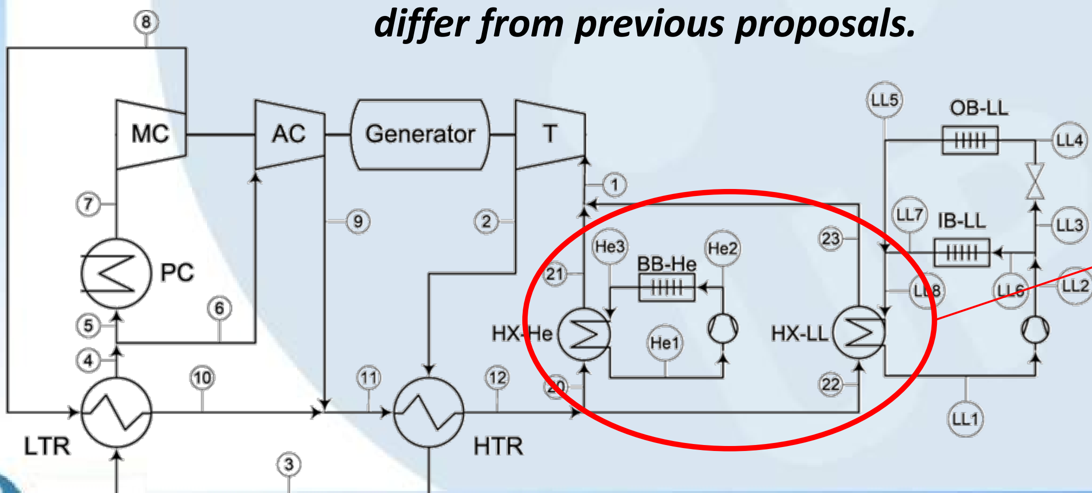
One of the Work-Packages in which we participate is the Balance of Plant (more precisely in the ***Considerations on alternative secondary coolants***).

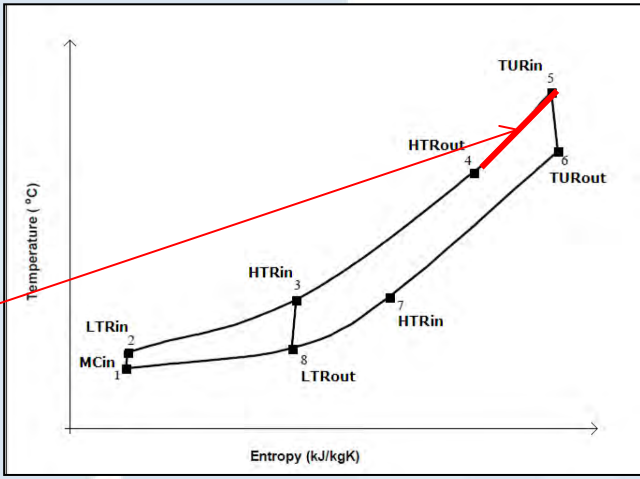
Within this WP a few layouts have been proposed for a $^{S}CO_2$ cycle. We have modelled the baseline layout (Linares et al., 2014).

UPC is participating (as a third party) in the EUROfusion project, aimed at the implementation of the *Roadmap to Fusion* (EFDA, 2012) during Horizon 2020 through a Joint Program of the members of the EUROfusion consortium.

In this case BNK and LM sources are used but not the divertor heat sources.

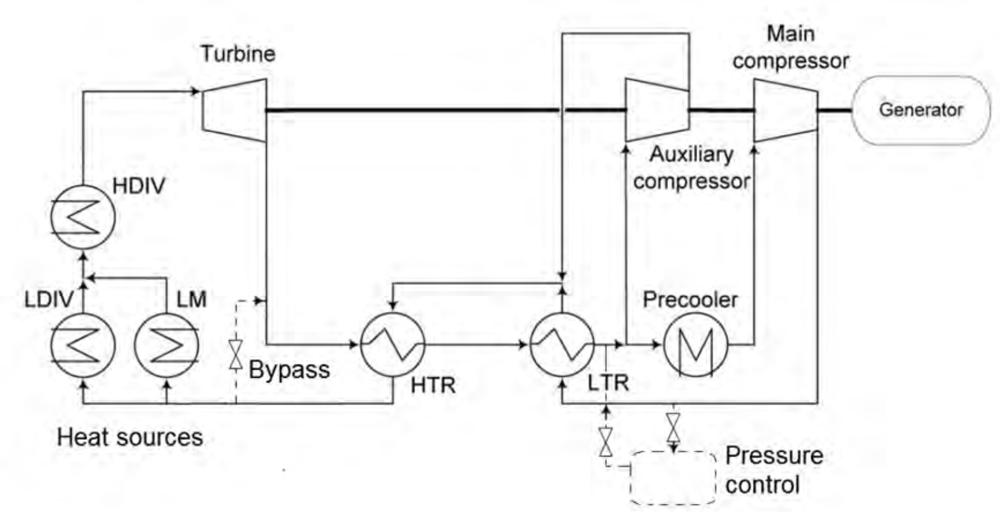
Working pressures and temperatures differ from previous proposals.





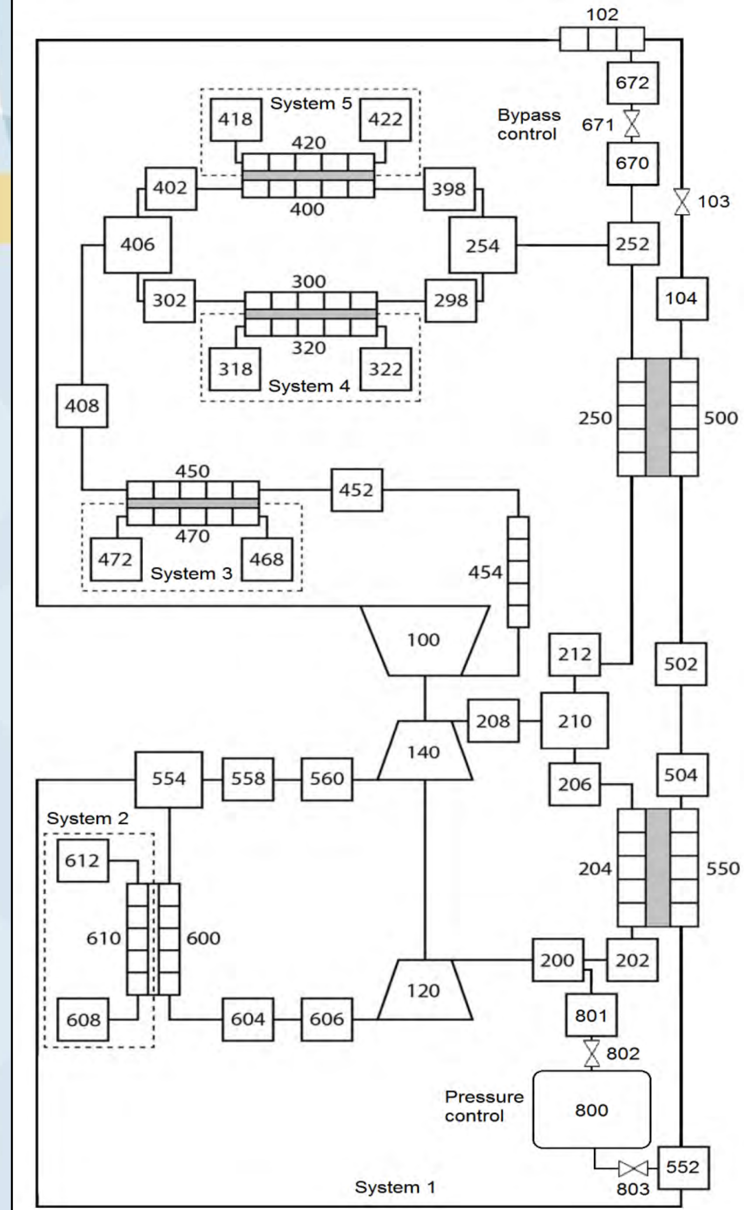
Modelling the cycle with R5-3D

TECNO-FUS layout "I" RELAP5-3D model



The application of RELAP5–3D to TH of fusion reactors takes advantage of the availability of many working fluids, a MHD pressure drop model (and of past developments related to the GFR (Davis et al., 2005):

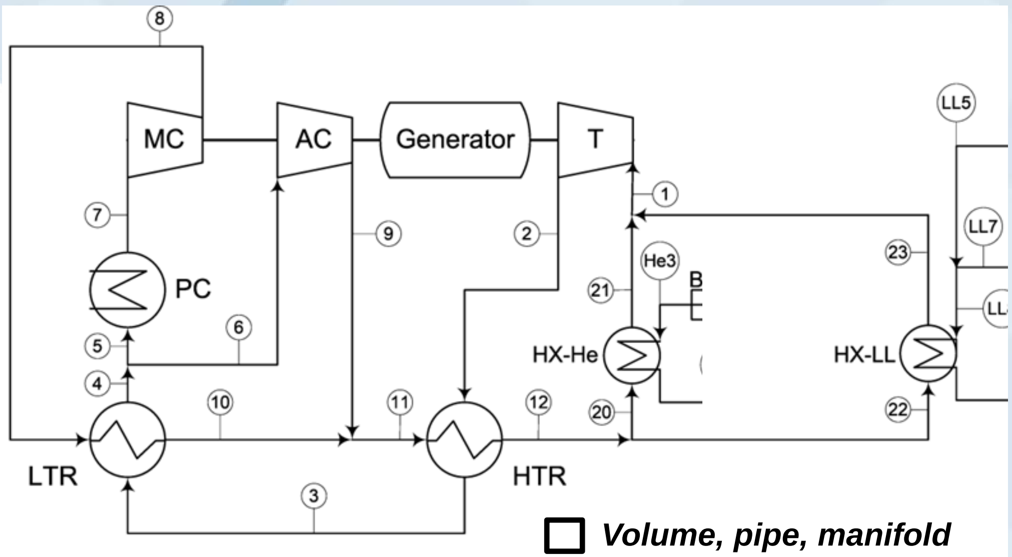
- ***addition of CO_2 properties,***
- ***Gnielinski (1976) heat transfer correlation,***
- ***enhanced turbine model***
- ***new compressor component (Fisher and Davis, 2005).***



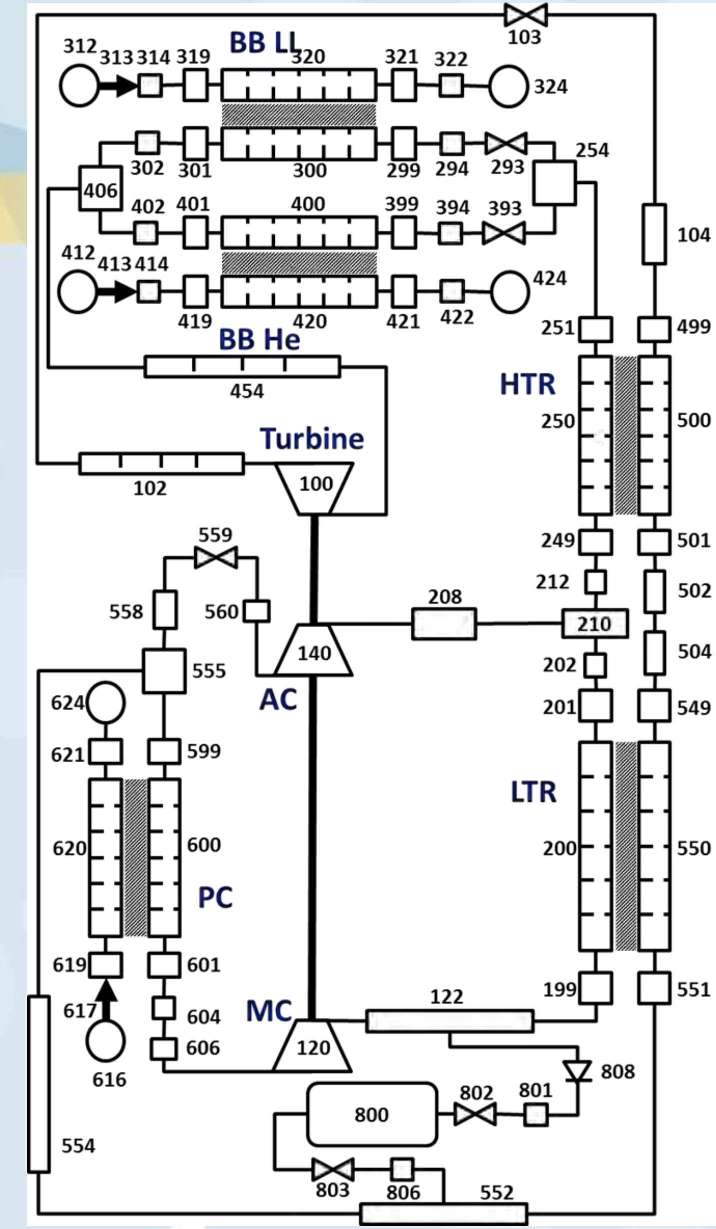
More details in Batet et al. (2014)

Modelling the cycle with R5-3D

RELAP5-3D representation (nodii) of the EUROFusion baseline layout



Volume, pipe, manifold
Boundary condition
Heat structure

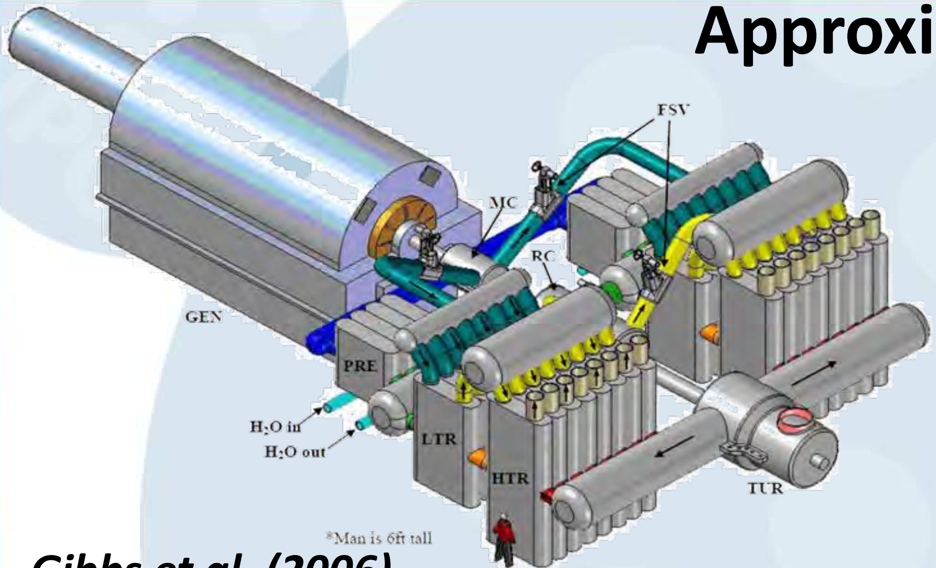


In both cases, only the thermodynamic CO_2 cycle has been modeled.

Heat sources are simulated as controlled flows through the primary sides of HX.

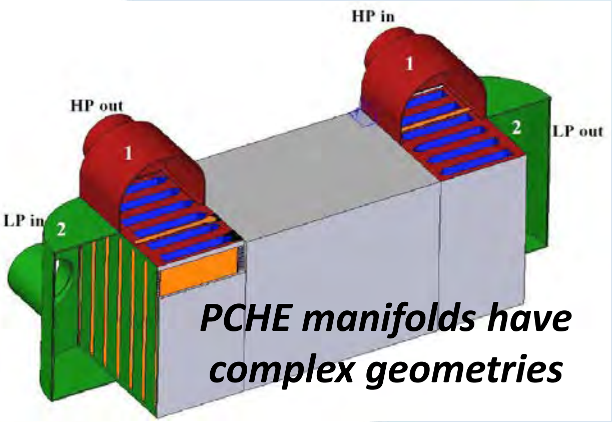
Modelling the cycle with R5-3D

Approximation to reality

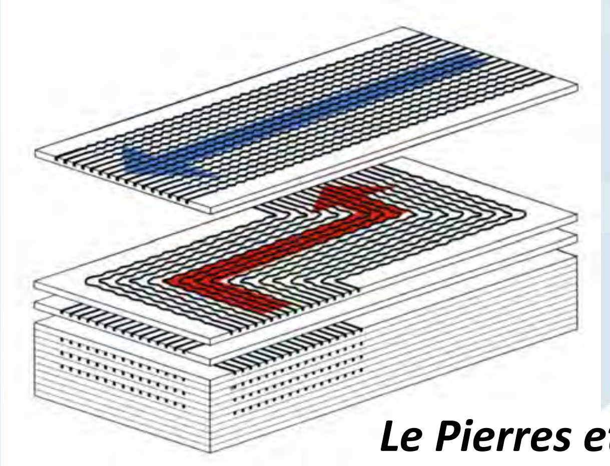


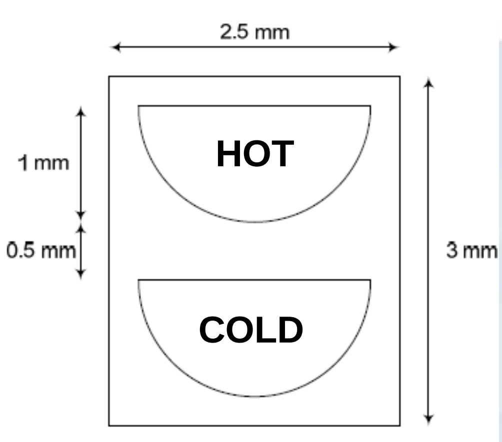
Gibbs et al. (2006)

It is **difficult to model** the exact geometry of the ***Printed Circuit Heat Exchangers (PCHE)***, *and* to capture the **pressure drops**.



PCHE manifolds have complex geometries





Le Pierres et al. (2011)

Simulation of layout “I“ (TECNO-FUS)

Some features of the model

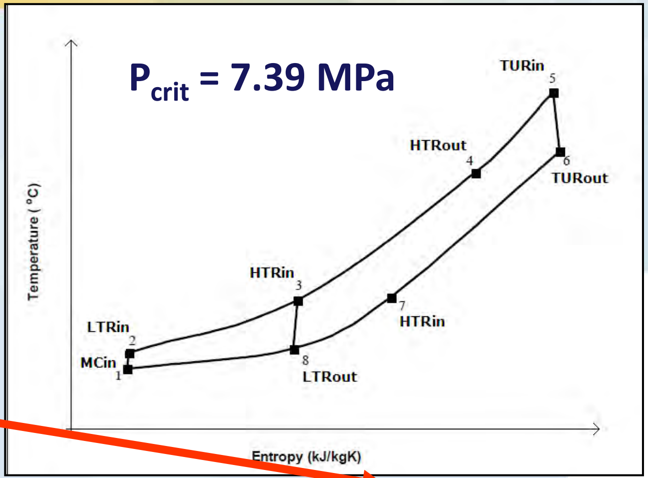
- Compressors’ models (components 120 and 140) prepared after the realistic compressor’s input deck supplied with the code (Davis et al., 2005), modifying it to meet the working conditions of each of the two compressors.
- Simplistic turbine model (constant isentropic efficiency).
- Pressure and bypass control systems have been designed
- Controllers aimed to stabilize some plant parameters in steady state and transient simulations have been designed:
  - Control of the pressure at the main compressor inlet.
  - Control of the temperature at the main compressor inlet (through the control of the water flow in the pre-cooler)
  - Control of power (bypass system).
  - Control of the flow from the thermal (LiPb and He) sources so as to maintain stable the turbine’s inlet temperature.
- The model has 168 volumes in total and 168 junctions and 59 Heat slabs (295 mesh points)

More details in Batet et al. (2014)

Simulation of layout "I" (TECNO-FUS)

Steady state results

State	P (MPa)	T (ºC)
Turbine inlet	19.42	544.5
Turbine outlet	7.63	430.4
HTR outlet (low pressure)	7.54	257.0
LTR outlet (low pressure)	7.44	134.2
MC inlet	7.42	40.0
MC outlet	20.13	118.1
LTR outlet (high pressure)	19.85	238.4
RC outlet	19.97	235.6
HTR outlet (high pressure)	19.68	396.7



***Chosen high enough to avoid calculation problems in the vicinity of the critical temperature* (31.1 °C)**

The model does not exactly reflect the real geometry of HX manifolds. Pressure drops in HX are thus to be taken with caution.

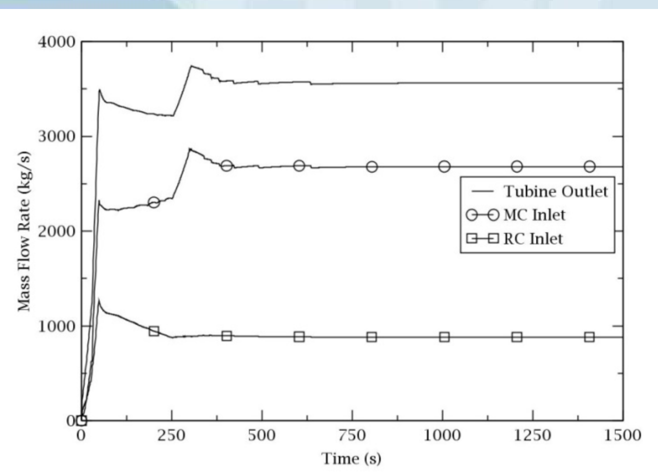
Main parameters of the model in Steady State

MC flow rate	**2684.3 kg/s**
RC flow rate	**882.0 kg/s**
Thermal power LM	**500.7 MW**
Thermal power LDIV	**91.3 MW**
Thermal power HDIV	**60.3 MW**
Electric Power	**259.0 MW**
Cycle efficiency	**39.7 %**

Simulation of layout "I" (TECNO-FUS)

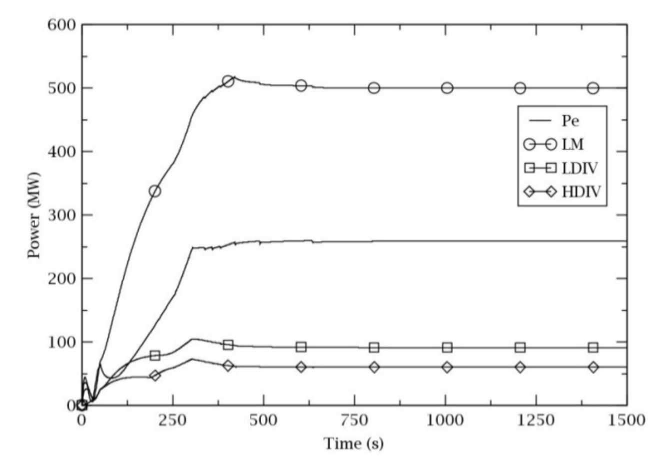
Transient calculation results

Contrary to other tools used in BOP calculations, RELAP5's nature makes it suitable for **dynamic analysis**. Moreover, the code allows the **simulation of plant controls**, and it's robustness make it possible to run cases imposing only a **few boundary conditions** (normally real plant conditions beyond the scope of the simulation).



Example of capabilities: plant startup.

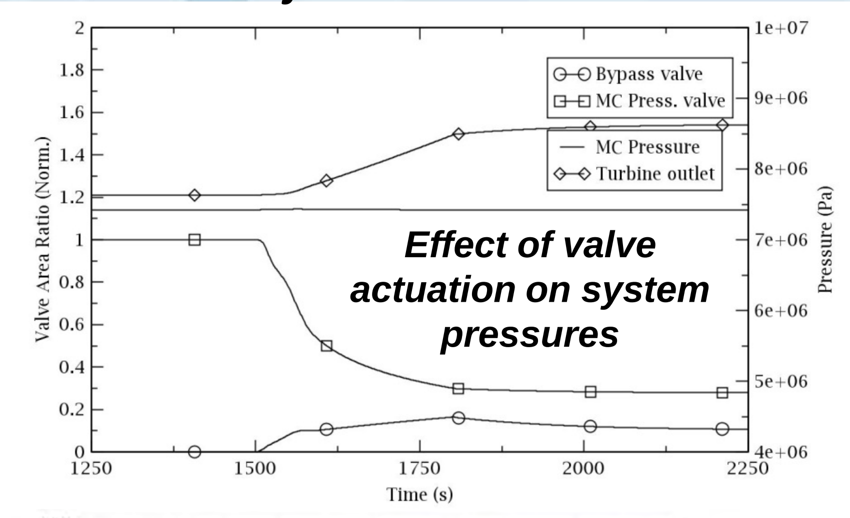
External increasing **torque** applied until synchronism velocity is achieved (in less than 50 s); in this moment, the **generator is connected to the grid** and shaft velocity remains constant. **Mass flow rate through the primary of HX** follows a ramp (5 min in the case of LDIV and HDIV and 7 min in the case of LM).

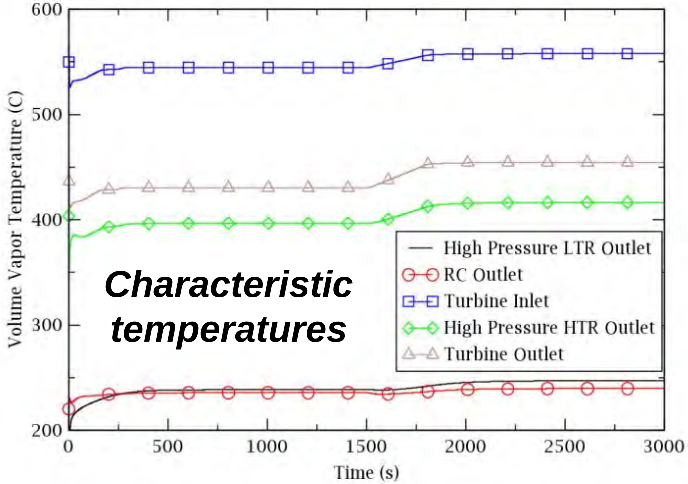


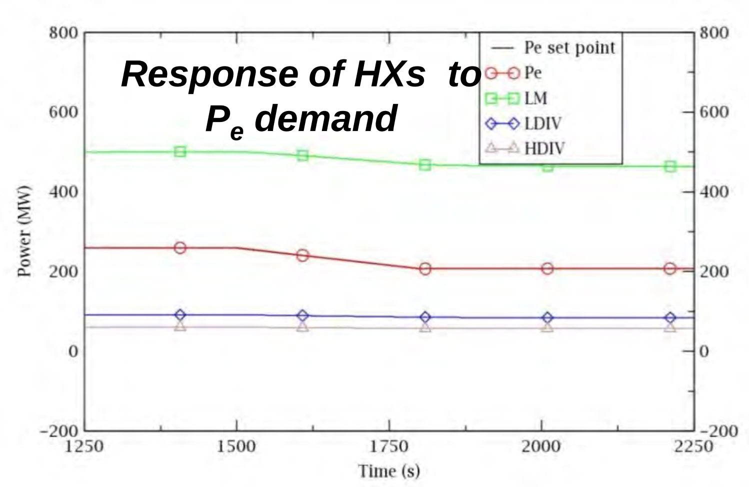
Simulation of layout “I“ (TECNO-FUS)

Transient calculation results

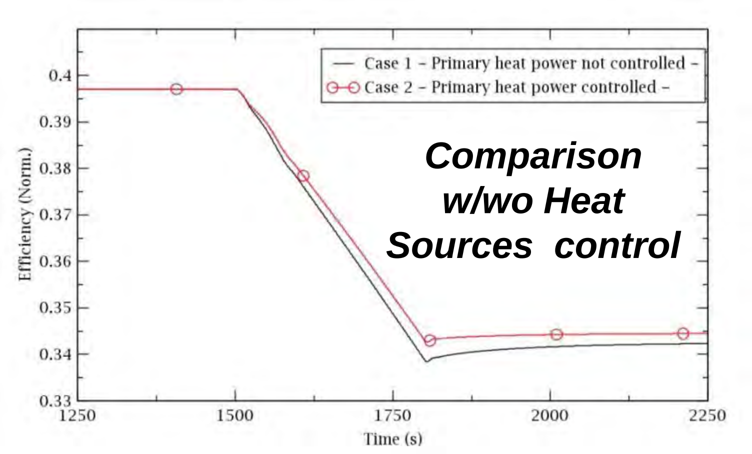
Load reduction to 80 % (ramp 4% /min) without control of heat sources







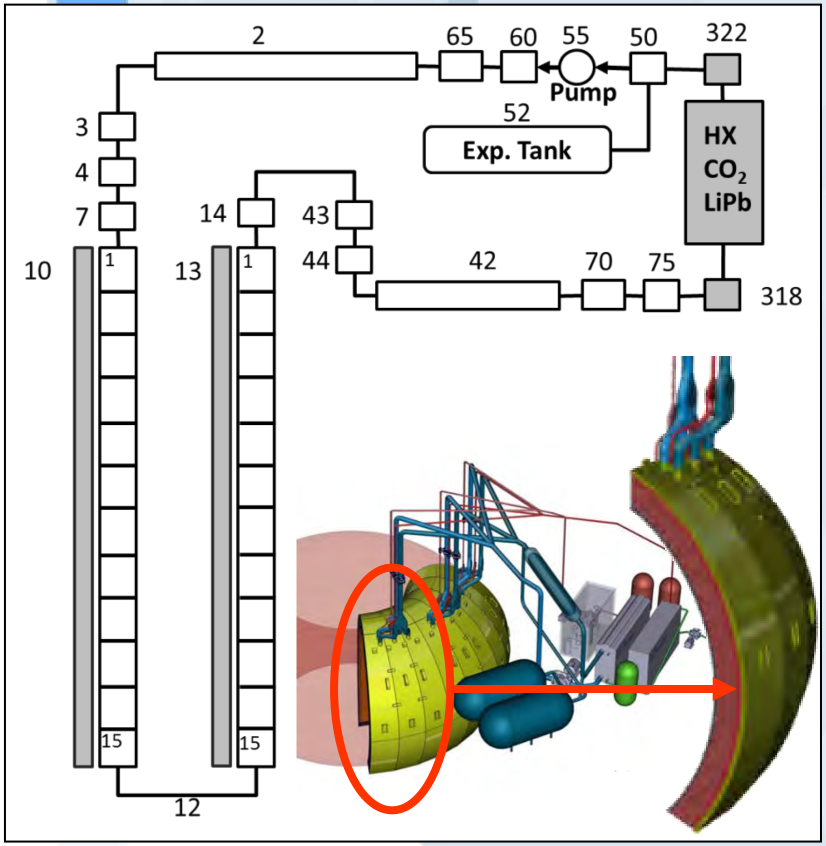
Load reduction results in an overall increase of temperatures. So, the model was later equipped with a control of the primary flows in the LM, LDIV HXs, to stabilize turbine’s inlet temp.



Simulation of layout "I" (TECNO-FUS)

Simplified RELAP5–3D model of the blanket

It represents the LM loop in the breeding blanket and the divertor (He) loop.

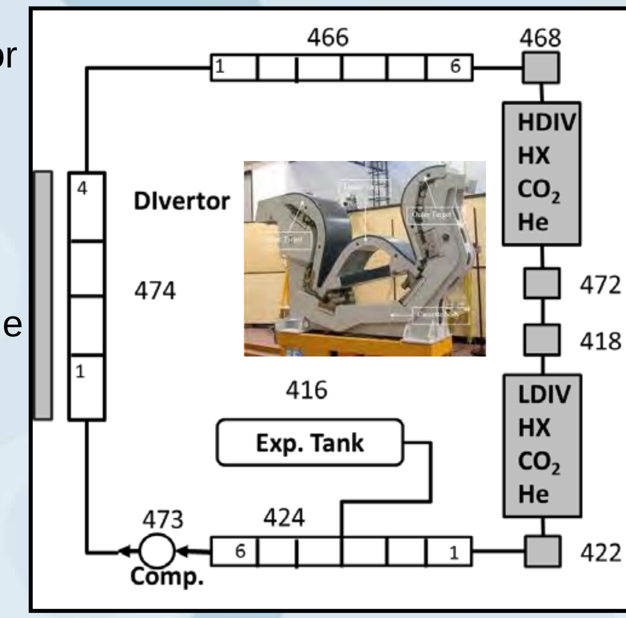


RELAP5-3D nodalization of the Liquid Metal loop model

Pump (55) and compressor (473) simulated using TMDPJUN.

LiPb expansion tank (55), modelled by means of a single volume and a flexible wall SNGLFW that simulates the pressure of He above the liquid.

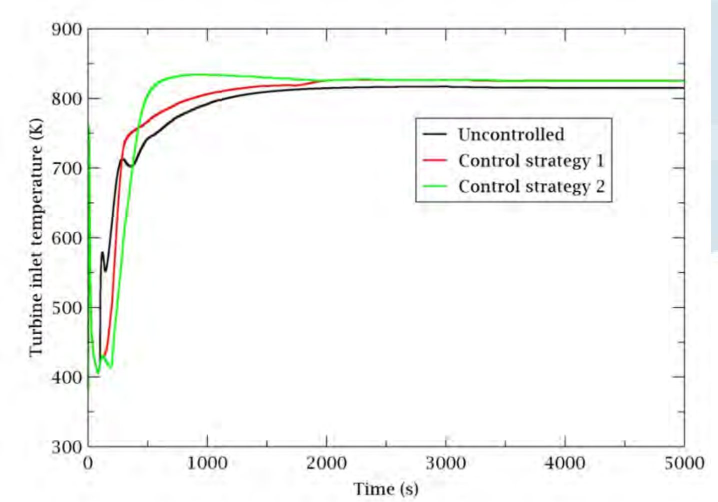
He expansion tank simply simulated as a constant pressure TMPDVOL.



RELAP5-3D nodalization of the He divertor loop model

Heat structures are used to simulate the thermal power from plasma and the heat exchange between the primary loops and the CO_2 cycle

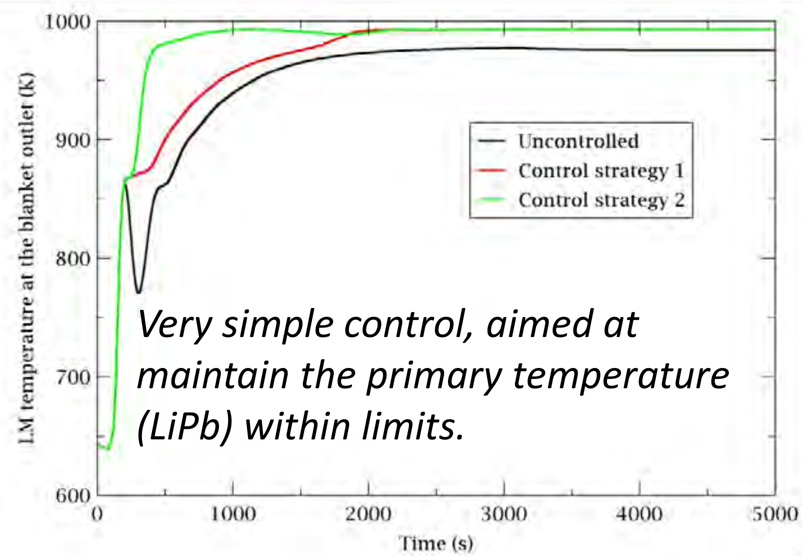
Simulation of layout “I“ (TECNO-FUS)



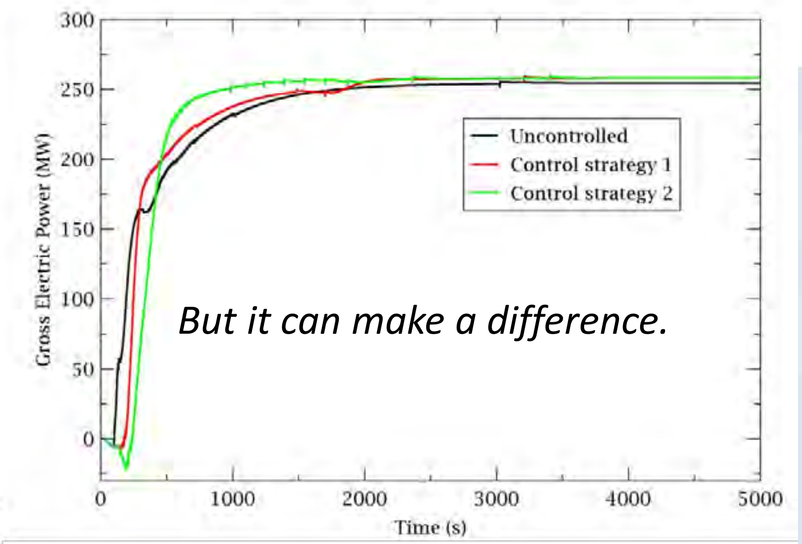
Simplified RELAP5–3D model of the blanket

Another plant start-up calculation

An external torque is applied until synchronism is achieved. Before it occurs, the reactor stars (at 80 s). The thermal inertia of the systems causes a decrease of efficiency during the initial minutes of operation (before steady state is reached). The **automatic control of CO_2 mass flow rate improves the performance.**



Very simple control, aimed at maintain the primary temperature (LiPb) within limits.



But it can make a difference.

Simulation of EUROFusion baseline layout

Main features of the model:

CO_2 system:

- *186 volumes (including pipes, heat exchangers, manifolds, compressors and turbine)*
- *189 junctions (including regular junctions and valves).*

In total:

- *88 heat structures (440 mesh points in total).*
- *242 volumes (Including CO_2 system , HX-LL, HX-He and PC)*
- *242 junctions*

Assumptions and simplifications :

- Passive heat structures or heat losses **not** simulated (lack of detailed description of lengths and thicknesses of piping and other structures)
- Length of piping connecting the several heat exchangers and components has been set somehow arbitrarily and has not been checked for consistency.
- Dimensions of HX slightly modified from analytical values so as to better reproduce the design temperature profiles. Water flow rate through PC is regulated so as to obtain a CO_2 temp. of 30°C at the MC inlet. All the heat exchangers are modeled as made of SS 316/316L.
- Diameters of pipelines between 0.6 m and 1.0 m. Pipes combined in parallel to get reasonable velocities. Pressure loss coefficients have been given default or typical values. Roughness has been set at 4.5 10^{-5} m in pipes, plenums and collectors, and at 1.0 10^{-6} m in the channels of HX

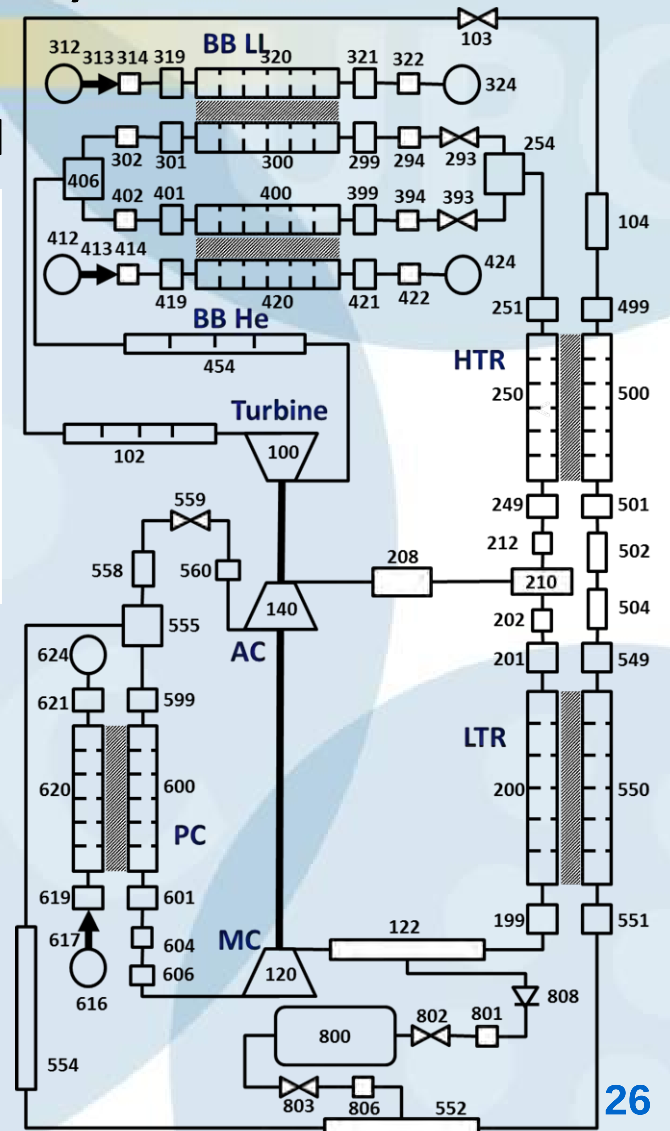
Simulation of EUROFusion baseline layout

Main parameters of the HX in the RELAP5-3D model

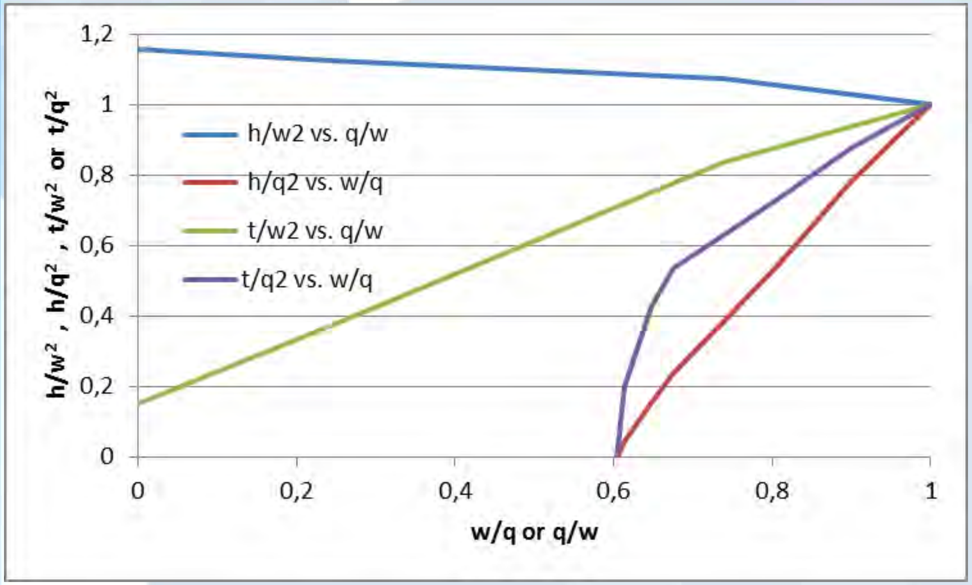
	Length [m]	Number of nodes	Flow area in each side [m²]	Exchange surface [m²]	Volume [m³]
HX-LL	0.90	10	3.75	4,500	13.5
HX-He	1.16	20	5.73	21,758	31.7
PC	0.68	10	5.81	12,922	18.8
LTR	4.56	40	35.59	531,185	774.8
HTR	0.36	8	12.06	14,215	20.7

Dynamic performance of compressors and turbine:

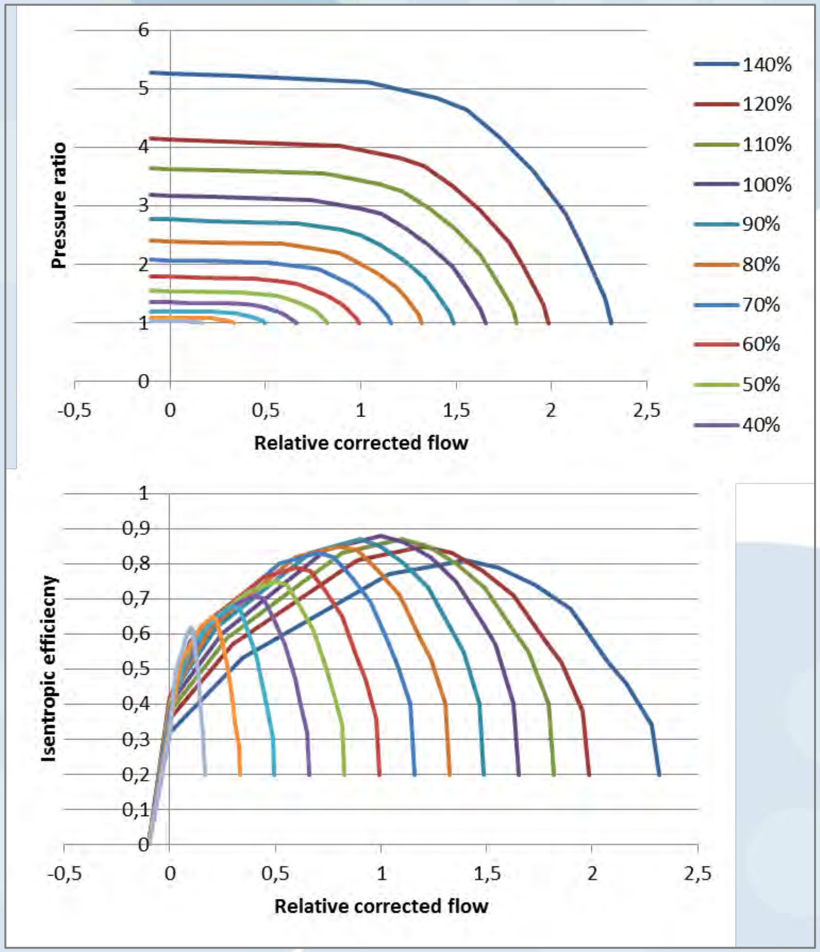
- Turbine modeled as a constant efficiency device
- MC modelled using a PUMP component. Presently the code does not allow liquid in the COMPRESSOR component (CO_2 at 30°C is understood as liquid even at supercritical pressure) . Pump's homologous curves constructed from scratch to reproduce a typical compressor's behavior.
- AC performance curves constructed from scratch to reproduce a typical compressor's behavior.



Simulation of EUROFusion baseline layout



***Homologous curves for the MC simulated as a R5-3D PUMP component.** h: normalized head, w: normalized rotational velocity, q: normalized flow rate.*

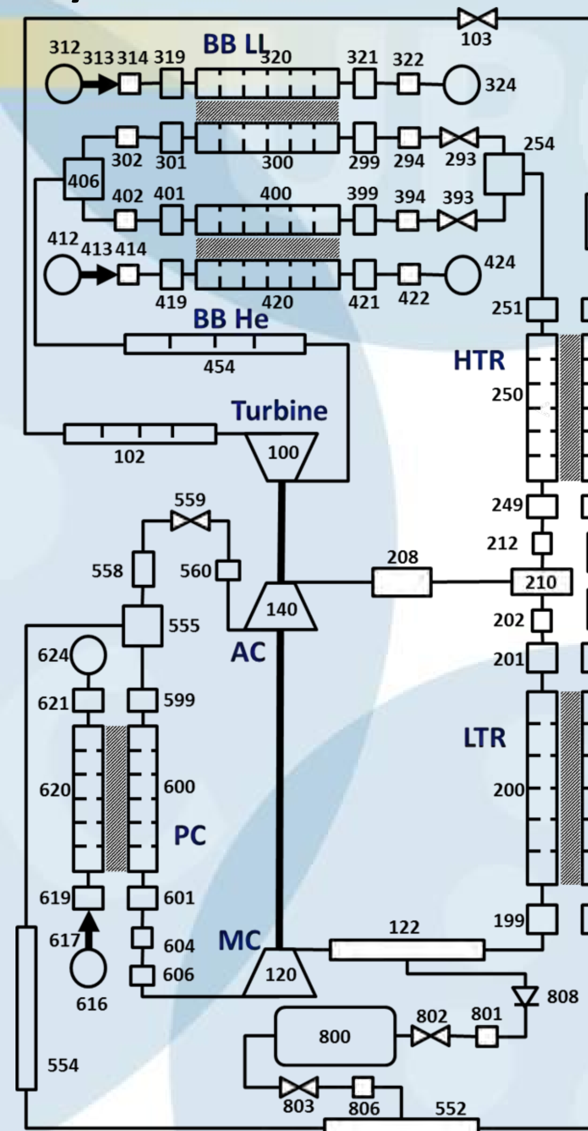


***Performance curves for the AC simulated as a R5-3D COMPRESSOR component,** as a function of the relative corrected rotational velocity.*

Simulation of EUROFusion baseline layout

A few control features have been introduced in the model:

- The control of LL flow rate and temperature (components 312 and 313) set as boundary conditions.
- The control of He flow rate and temperature (components 412 and 413) set as boundary conditions.
- The control of the water temperature (component 616), set as a boundary condition, and flow (component 617), controlled so as to bring the temperature of volume 604 to its set-point value (namely 30 °C).
- The flow areas of valves 293 and 393, that control the flow rate through HX-LL and HX-He heat exchangers respectively so as to achieve de desired outlet CO_2 temperature.
- The flow area of valve 559, to obtain the proper flow splitting between MC and AC
- The flow area of valve 103 (necessary in case of loss of load transients, not activated yet).
- A system pressure control consisting of a large inventory tank (volume 800) and controlled valves that inject (803) or absorb (802) CO_2 into/from the system.

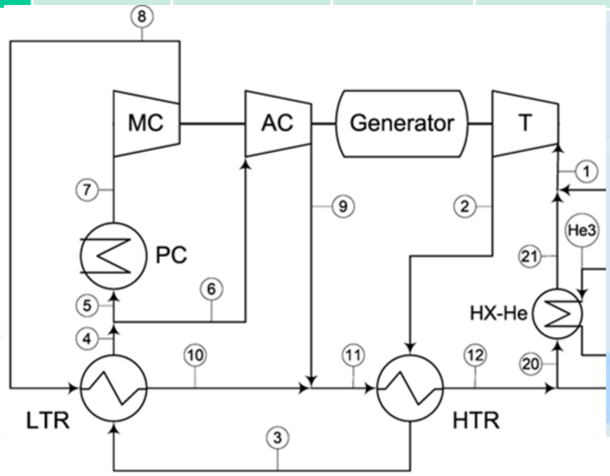


Most of these controls were already implemented in the model of layout "I".

Simulation of EUROFusion baseline layout

Steady State results

	Nominal values		R5-3D values	
State	p [bar]	T [° C]	p [bar]	T [° C]
1	250.0	390.0	250.3	389.9
2	86.2	274.1	86.5	273.6
3	85.8	218.8	86.0	219.6
4	85.4	61.8	85.4	62.1
5	85.4	61.8	85.3	62.0
6	85.4	61.8	85.4	62.1
7	85.0	30.0	85.1	30.0
8	251.2	54.8	252.3	55.1
9	250.8	156.4	252.0	158.1
10	250.8	211.8	251.8	211.6
11	250.8	193.8	251.9	194.5
12	250.4	237.9	251.6	237.6



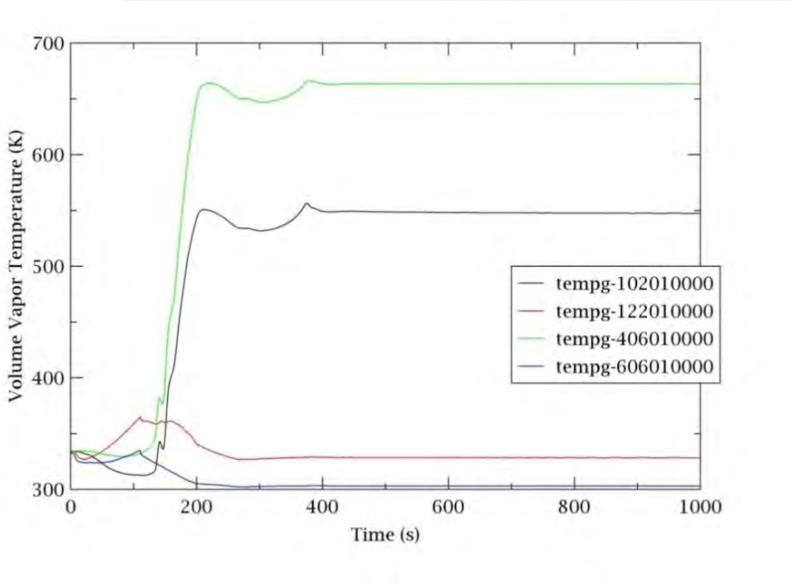
Parameter	RELAP5-3D model	Design value
Turbine power [MW)	1,038	1,082
MC power [MW]	171	165
AC power [MW]	185	182
Cycle power [MW]	681	735
Heat input in HX-LL [MW]	1,156	1,167
Heat input in HX-He [MW]	749	757
Heat released at PC [MW]	1,198	1,189
Heat exchanged in LTR [MW]	2,026	2,018
Heat exchanged in HTR [MW]	604	618
Pressure drop HTR hot side [bar]	0.52	0.40
Pressure drop LTR hot side [bar]	0.58	0.40
Pressure drop PC [CO_2] [bar]	0.47	0.40
Pressure drop LTR cold side [bar]	0.59	0.40
Pressure drop HTR cold side [bar]	0.26	0.40
Mass flow rate in the turbine [kg/s]	9,839	9,831
Mass flow rate in the MC [kg/s]	6,869	6,814
Mass flow rate in the AC [kg/s]	2,969	3,017

Simulation has only been possible by activating option 11 in card 1, which modifies the coding of the fluid for metastable states near the critical point and uses linear interpolation.

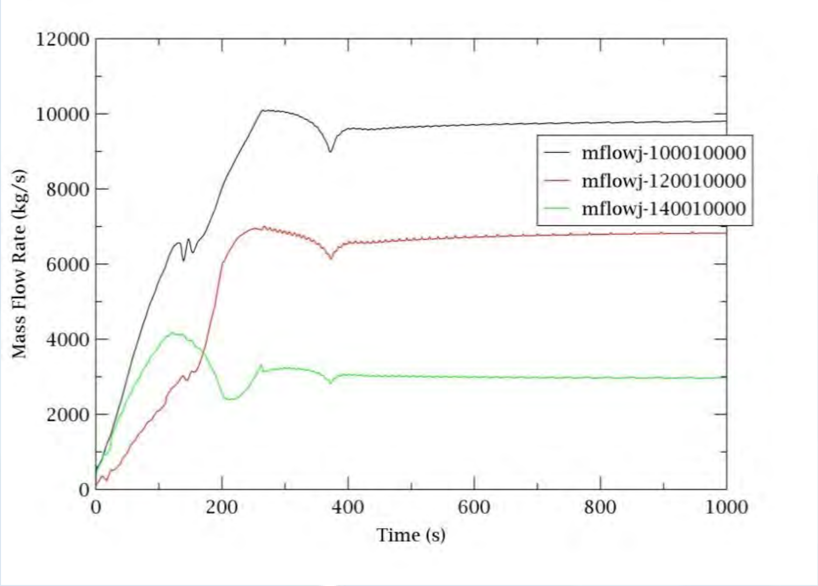
Simulation of EUROFusion baseline layout

Transient results. Start-up

The steady state values have been obtained after a start-up transient, useful to test the capabilities of the model and the robustness of the code.
Initial CO_2 conditions set at 85 bar, 61°C (except in the BB-LL HX, where T= 250 °C). Heating power ramped from 100s to 200s. Valve 293 is initially fully closed to avoid the freezing of the LiPb.



Evolution of Temp. in selected points of the CO_2 cycle: turbine inlet (406) and outlet (102) and MC inlet (606) and outlet (122).

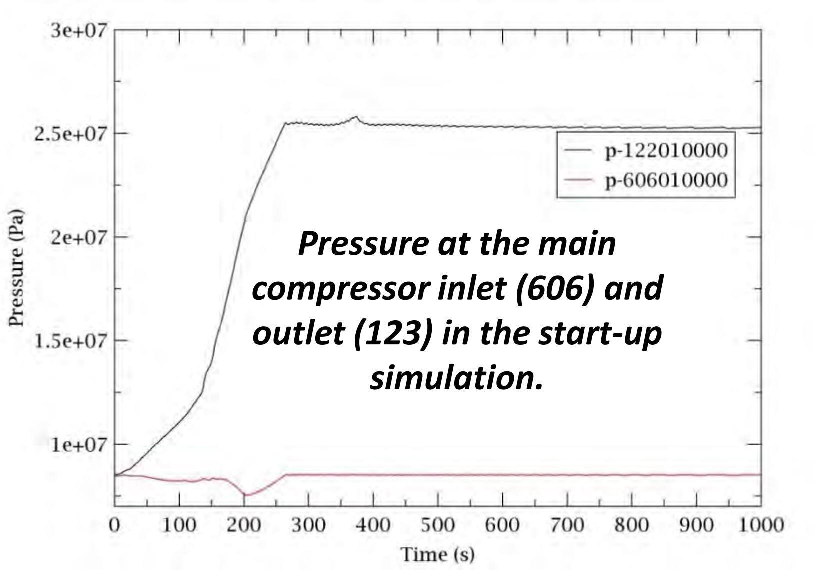


Evolution of the flow rates in the CO_2 cycle: turbine (100), MC (120) and AC(140).

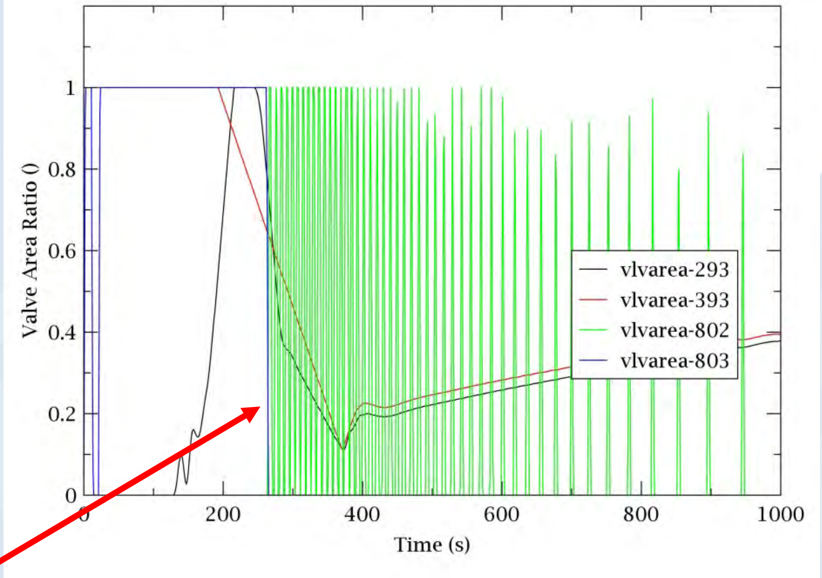
Simulation of EUROFusion baseline layout

Transient results. Start-up

Pressures are established at around 250 s (some 2 minutes after the synchronism speed has been reached). At the beginning, it is necessary to inject CO_2 to the system (valve 803 opens). Afterwards, when temperatures rise along the system and the gas expands, valve 802 operates in order to maintain the pressure. Valves 293 and 393 act with the aim of keeping turbine inlet temperature at the design value.



Pressure at the main compressor inlet (606) and outlet (123) in the start-up simulation.



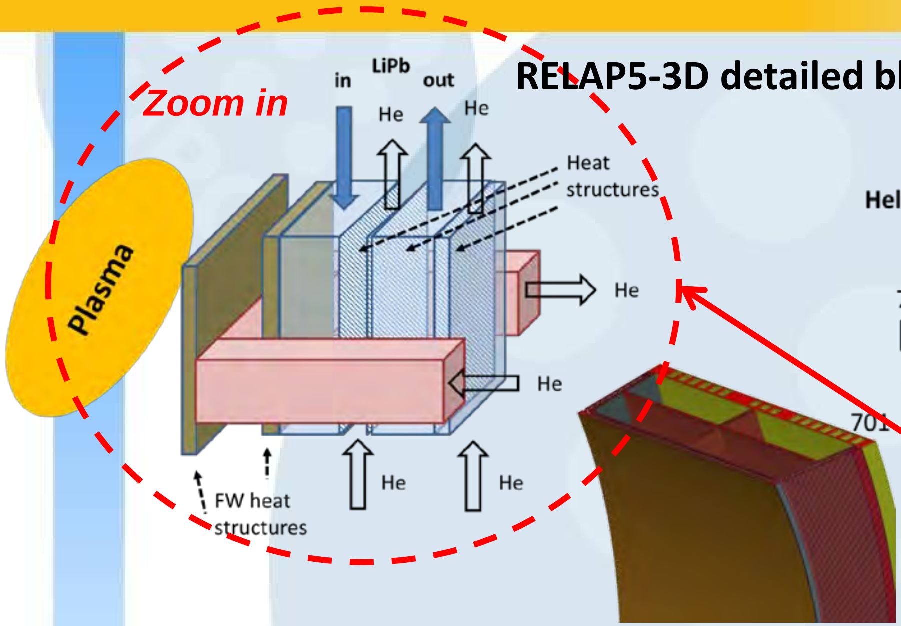
Operation of the controlled valves, expressed as the normalized flow area.

System's performance isn't smooth during the transient. Even when the plant has stabilized, valve 802 is still acting.

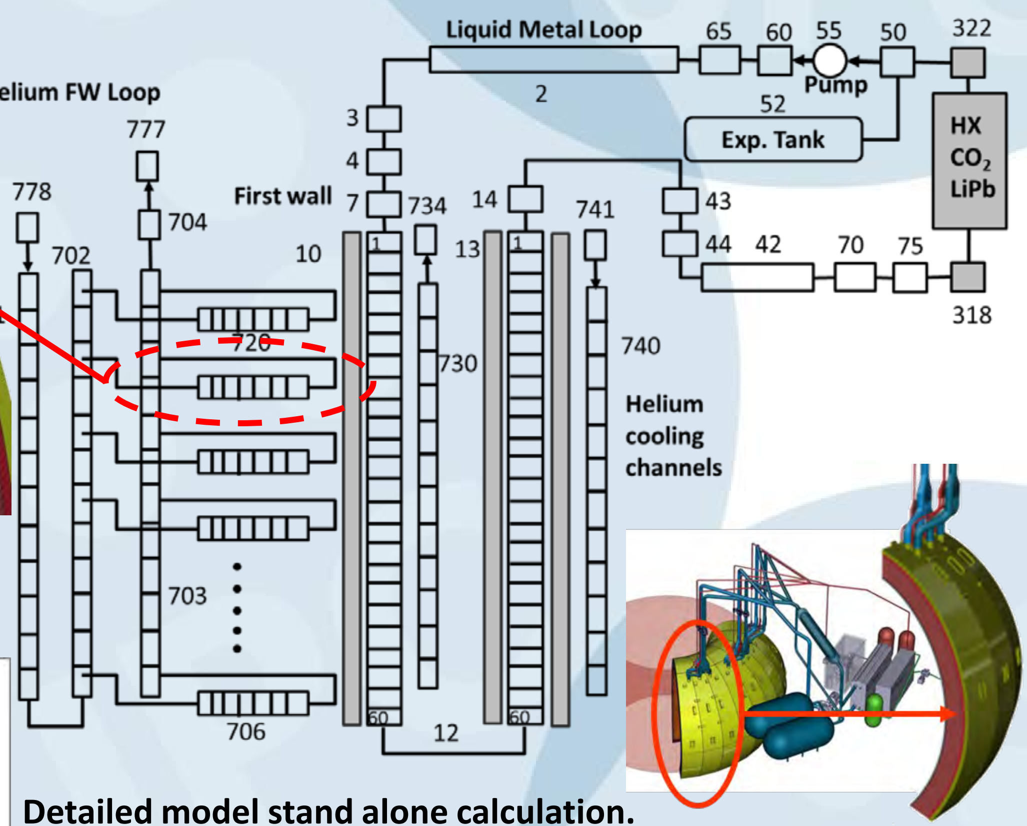
Simulation of EUROFusion baseline layout

- Steady state results are quite good considering the degrees of freedom of the system. With MC and AC simulated realistically, the flow rate through the system is regulated by their performance curves and pressure drops are self-adjusted by the model depending on the geometry and the flow rate.
- Transient results suggest that the dynamic model is able to simulate the behavior of a real plant provided the proper control system is modelled.
- Some difficulties encountered in plant stabilization, related to the control strategy. They point out:
  - the difficulties that a real plant will face
  - the opportunities that the dynamic simulation offers for control design
- A possible reason for the difficulties encountered is the different behavior of the PUMP component at off-nominal values as compared with the COMPRESSOR. This different performance is one cause of instabilities in the simulation of the plant start-up.
- The performance of the pressure control system is another reason of instabilities. An improved design of this system must be engineered in subsequent versions of the model.

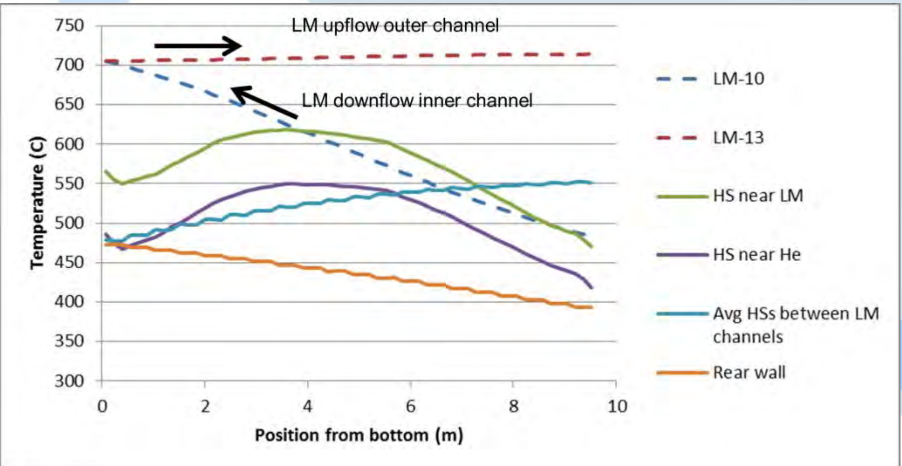
Detailed RELAP5–3D model of the blanket



RELAP5-3D detailed blanket nodalization including LM and BNK (He) circuits



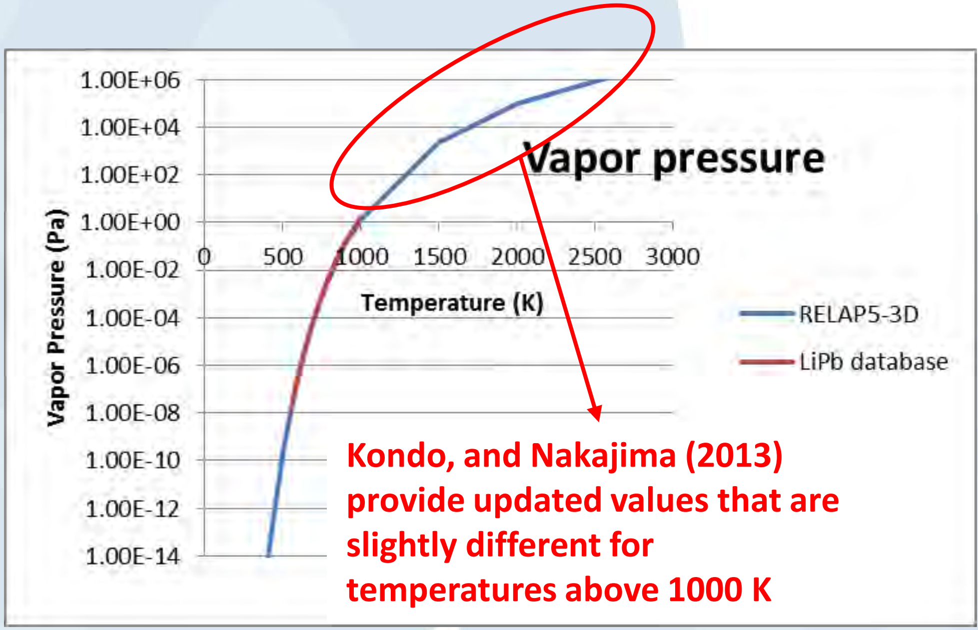
The complex multilayered, multi-material 3D –flux heat structure has been modelled by means of RELAP5-3D regular HS grouped in conduction enclosures.



Detailed model stand alone calculation.
Average temperatures along the poloidal direction in different zones of the breeding blanket (values have been smoothed in regions near horizontal helium channels)

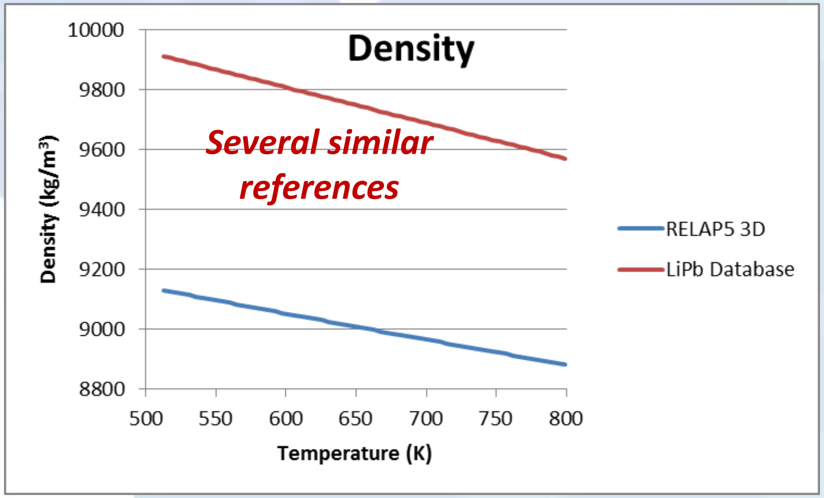
Comments on the LiPb properties library

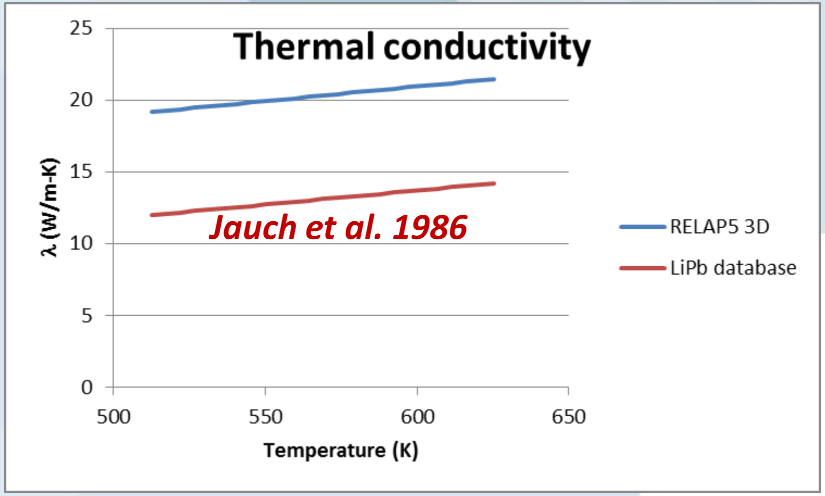
- A discrepancy has been found in the liquid metal loop: R5-3D results didn't match the nominal values; flow rates need to be adjusted in order to maintain thermal power and temperatures.
- So, an analysis has been done of the LiPb properties as implemented in the R5-3D properties library.
- R5-3D properties have been compared with values given in Mas de les Valls et al., Lead–lithium eutectic material database … (2008). *See the article for details on the references and comments on the quality of the referenced data*.

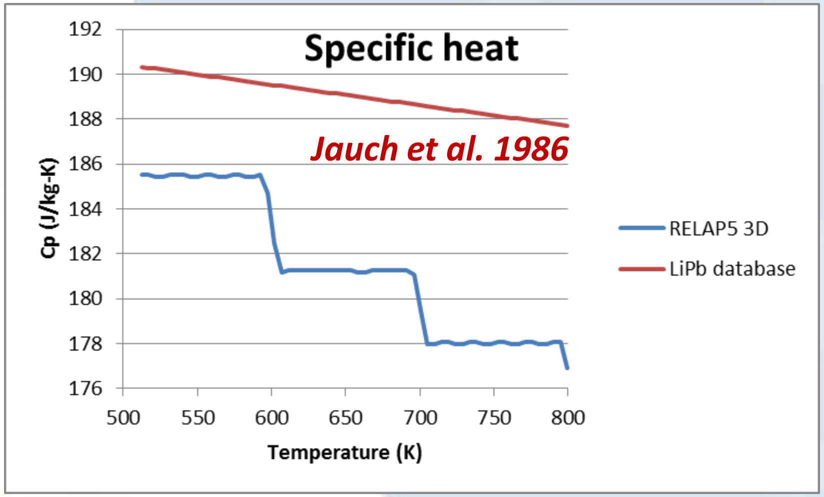


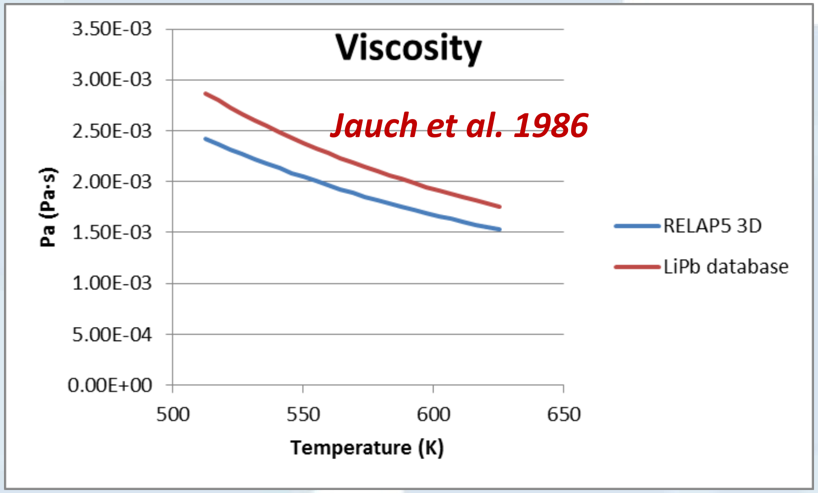
Vapor pressure (P_v) can be calculated combining the single species P_v and their respective chemical activities.

Comments on the LiPb properties library









RELAP53D Cp values computed as $\Delta h/\Delta T$

Comments on the LiPb properties library

Excerpts from RELAP5-3D man. vol.1 (INEEL-EXT-98-00834,Revision 4.1 Sept. 2013):

- The basic properties for lithium-lead […] are calculated from optional […]thermodynamic tables[11, 24, 28, 30, 31] […]. These tables are based on Young's soft sphere model formulation. The formulation used was based on fits to data from Young[24], Blink[30], and Nesmeyanov[28].
- […], formulations and least square fits to data from Vargaftik[14] and the Handbook of Chemistry and Physics[54] are used for these transport properties[…].

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54. R. Weast, editor, Handbook of Chemistry and Physics, 54th Edition, Cleveland: CRC Press, 1973

Modelling issues

- To ensure energy conservation at junctions in branches where flow area changes are abrupt, it has been necessary to activate the corresponding flags in the input deck (e = 1; modified PV term).
- The present model simulates only 1D heat transfer across heat exchangers. PCHE's geometry suggests that heat transfer follows a complex non-1D pattern.
- Regarding the HX, to avoid small dt (courant limit), the number of hydrodynamic nodes is small in the HX linking the primary heat sources and the CO_2 cycle. This leads to an underestimation of the heat flux (can be compensated for by increasing the effective heat transfer area). The alternate heat structure-fluid coupling model (5xxx) should be used whenever possible. Unfortunately, it is not possible to use it in the liquid sides (H_2O, LiPb), although Cp is almost constant there.
- Modelling options for the Inlet and outlet collectors of PCHE should be investigated, in order to improve the estimation of the pressure drop.

Conclusions

- RELAP5–3D is able to simulate the $^{s}CO_2$ cycle of a fusion power plant in a dynamic way.
- RELAP5–3D appears as a powerful tool for the design and testing of controls for the conceptual plant and power cycle designs. It allows the comparison of different control strategies within a relative short time.
- Provided the adequate control features are incorporated into the model, the simulations may help understand the performance of the plant in different situations and adjust the parameters of the control systems of a real plant.
- The model of the full plant can be used to perform relatively fast sensitivity analysis on important design parameters while helping understand the dynamic coupled behavior of the whole system.

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