Accelerating Fusion Energy Industrialization through Process Standardization

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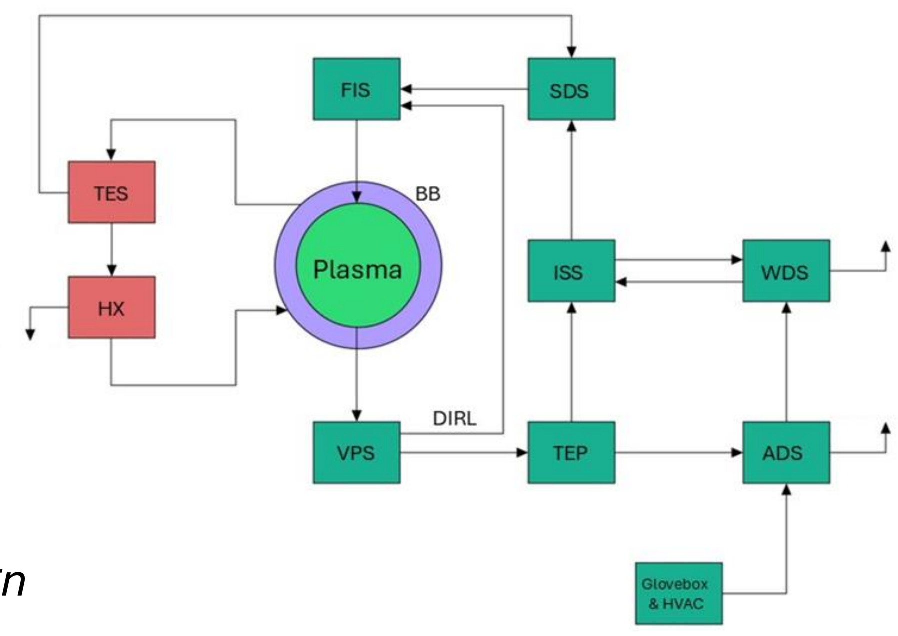
Breeding Blanket (BB) and Tritium Fuel Cycle are critical topics for ensuring the availability and operability of future fusion power plants. These areas could significantly benefit from **know-how and technology transfer**, as well as from **early-stage process standardization** rooted in Eni's industrial background. The following analyses are based on a high-field tokamak reactor, consistent with the design parameters proposed by CFS for an ARC-like reactor configuration [1].

Breeding Blanket

Due to the **interplay of multiple physical phenomena** within a BB, a stepwise approach has been adopted:

- **parametric analyses** have first been carried out **on individual physical domains,**
- **integrated analyses** to capture the combined effects.

The first analyses are based on the FLiBe-based Liquid Immersion Blanket (LIB) concept [2].

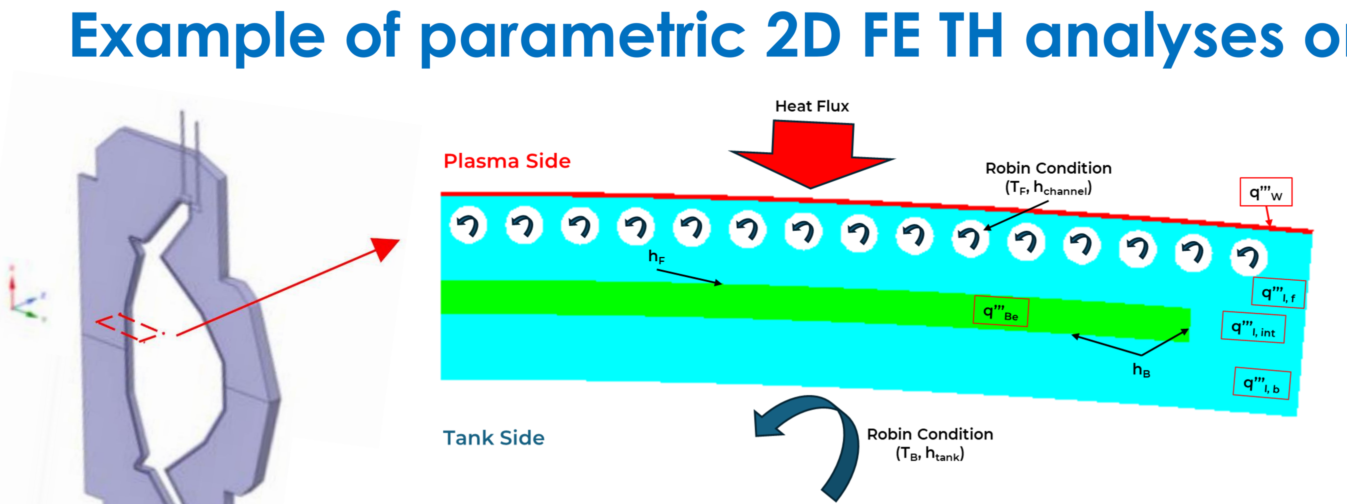


Simplified workflow employed for BB design

- Parametric Neutronic analyses
- Parametric Thermal-hydraulic analyses
- Parametric Thermo-mechanic analyses

→ CAD Integration → Integrated analyses: • Neutronics • Thermal-hydraulic • Mechanics → Preliminary design

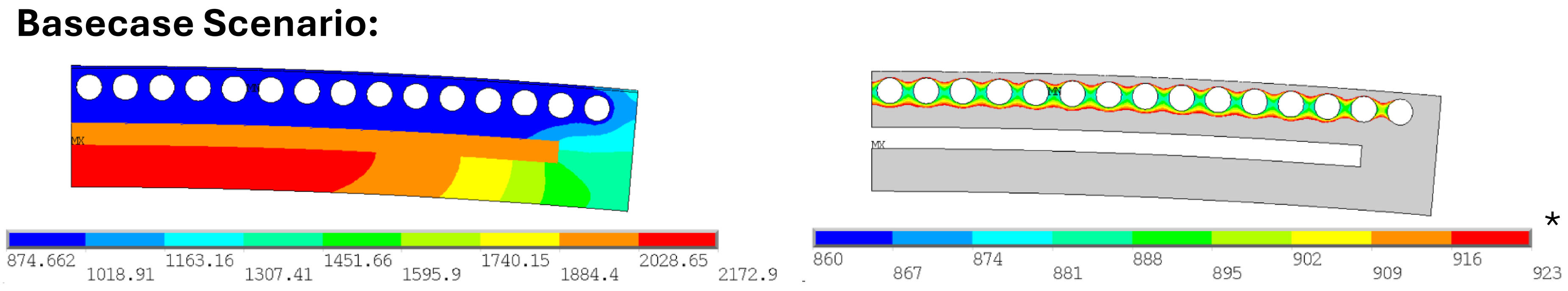
Example of parametric 2D FE TH analyses on a FW module



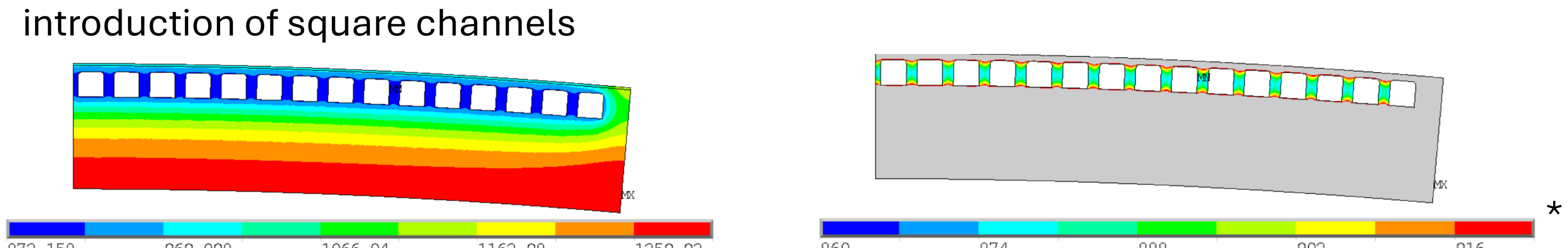
Ref. Material	
Red	Tungsten
Blu	Inconel 718
Green	Beryllium
Other options	
Red	Tungsten + Transitional material
Blu	Hastelloy N, V-Alloy
Green	Beryllide, Pb

Goal: Optimal cooling system design to maintain temperatures within material performance limits.

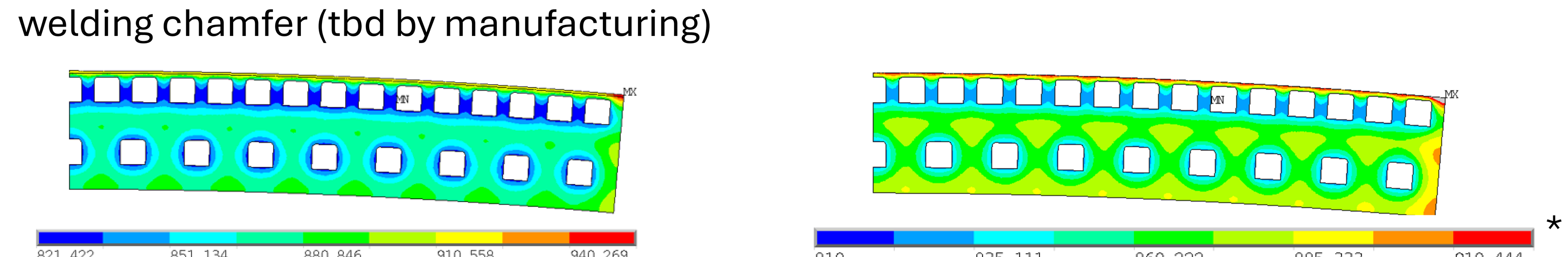
Basecase Scenario:



First Optimization: removal of beryllium (tbc by neutronic analyses) and introduction of square channels



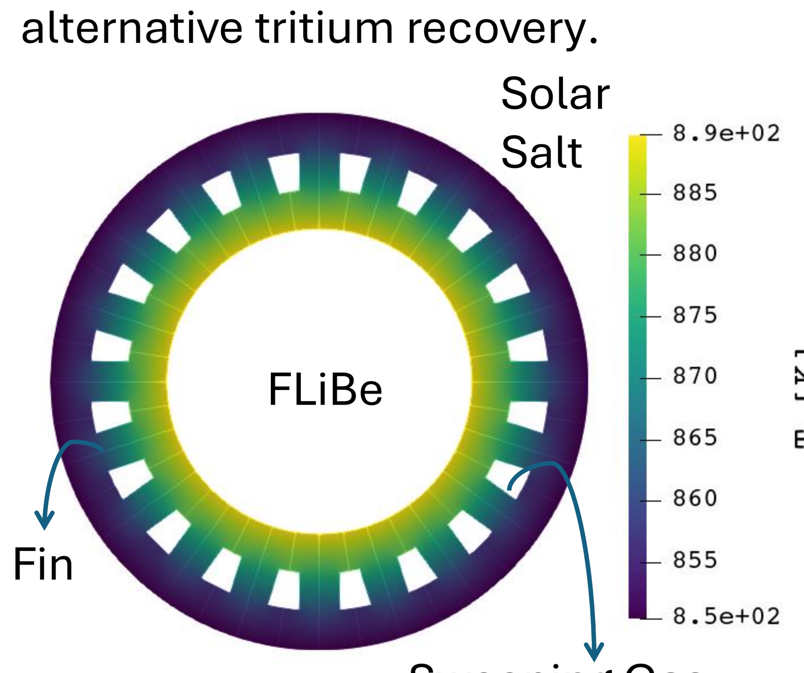
Further Optimization: double channel, reduction of ΔT and T_min, reduction of welding chamfer (tbd by manufacturing)



* Legend Max capped at T limit of Inconel 718 (923 K)

Double-Bundle Heat Exchanger

FLiBe is supposed to operate both as breeding blanket and primary heat transfer fluid. **The primary heat exchangers**, with heat transfer surfaces around 10^4 m^2, **could involve excessive tritium losses** to the environment. A Double-Bundle Heat Exchanger with integrated sweeping gas would minimize tritium permeation and allow alternative tritium recovery.



Cross Section of the Duoble-Bundle

- Lumped-parameter mass transport analyses / Thermal analyses with FEM
- → Multi-objective optimization algorithm to identify an optimal 2D section
- → Accurate mass transport analyses with CFD / Accurate thermal analyses with FEM
- → Final 2D design of the pipe cross section
- → Design of the full Heat Exchanger

Tritium Fuel Cycle

It involves the **continuous recovery, purification, and re-injection of tritium** into the plasma.

The Fuel Cycle has been **simulated with Aspen HYSYS®**, a chemical (system-based) process simulator widely adopted in the Oil & Gas sector, to assess the technical feasibility and integration of subsystems. **Add-ons have been implemented** to simulate unconventional equipment (e.g. vacuum pumps) or fluids (e.g. gas tritium or FLiBe). **The technologies with the highest TRL** have been selected.

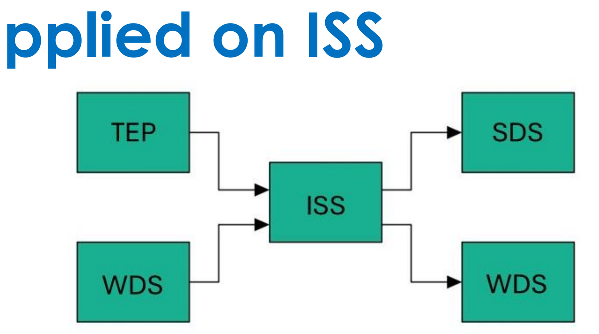
Iterative standardized workflow

1. Definition of the input data
2. Definition of the requirements
3. Creation of the PFD
4. Execution of the Process Simulation
5. Compilation of the equipment list
6. Assessment of Tritium Inventory

Example of workflow applied on ISS

1

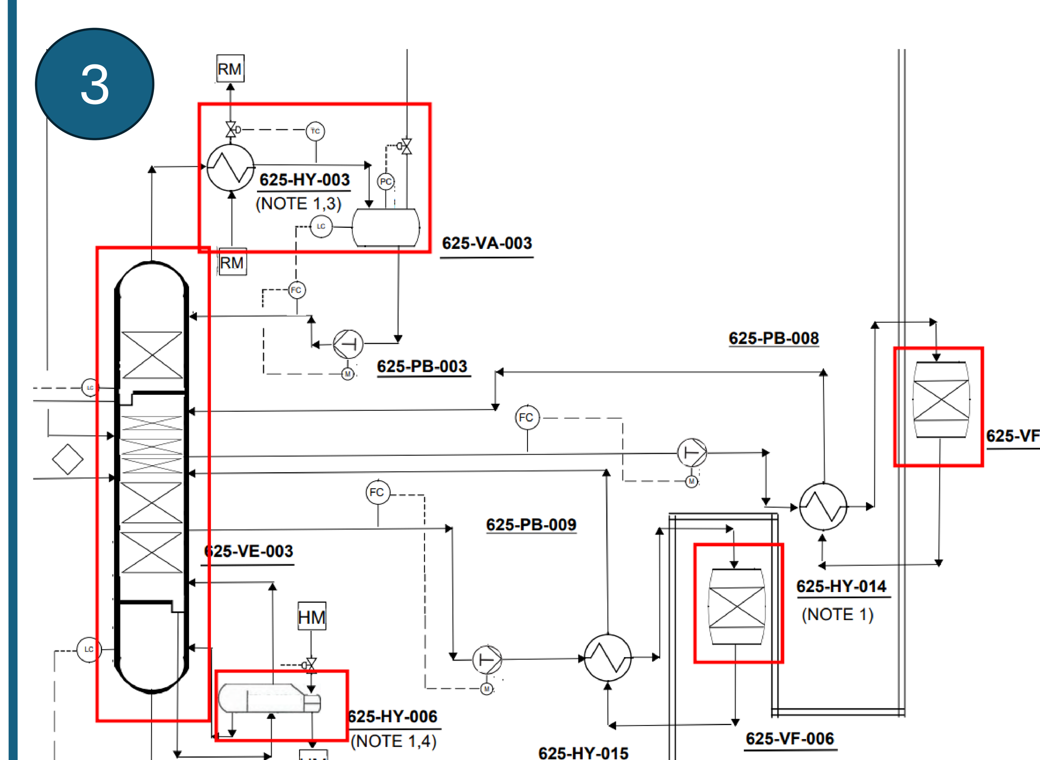
	Feed to Tritium ext. column	Feed to Protium ext. column
T [°C]	333	
P [kPa abs]	300	250
Flow Rate [mol/h]	109.2	199.4
H2 [mol%]	0.32	60.23
HD [mol%]	4.95	33.88
HT [mol%]	4.08	0.01
D2 [mol%]	22.29	5.85
DT [mol%]	44.80	0.01
T2 [mol%]	23.06	8E-5



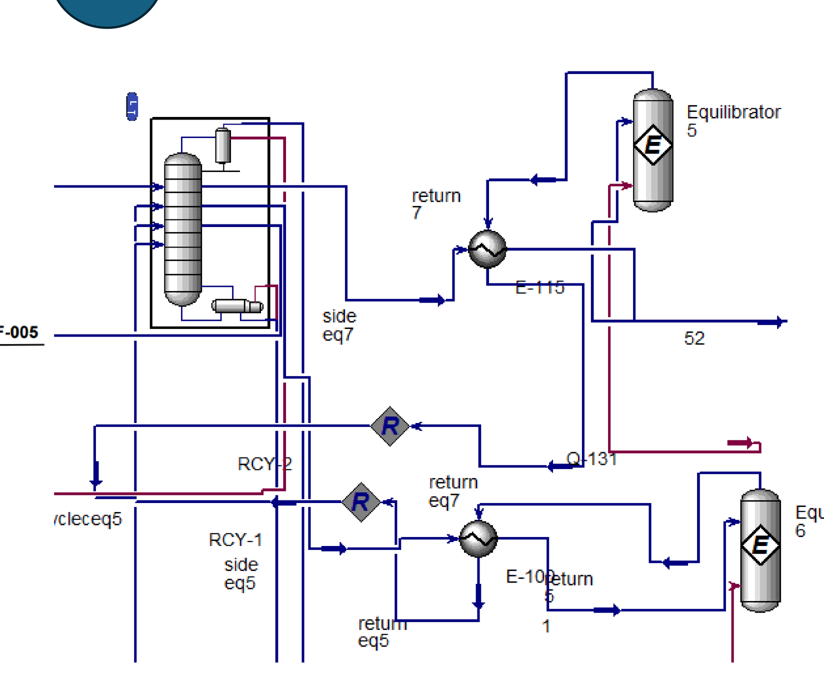
2

ID	Requirement
REQ_ISS_01	The ISS shall separate incoming hydrogen stream into T2, D2 streams
REQ_ISS_02	The ISS shall remove H2 from the torus hydrogen exhaust
REQ_ISS_03	Protium concentration at the outlet shall be below 1 %
REQ_ISS_04	T-rich stream shall be > 90% in T2
REQ_ISS_05	D-rich stream shall be > 90% in D2

3



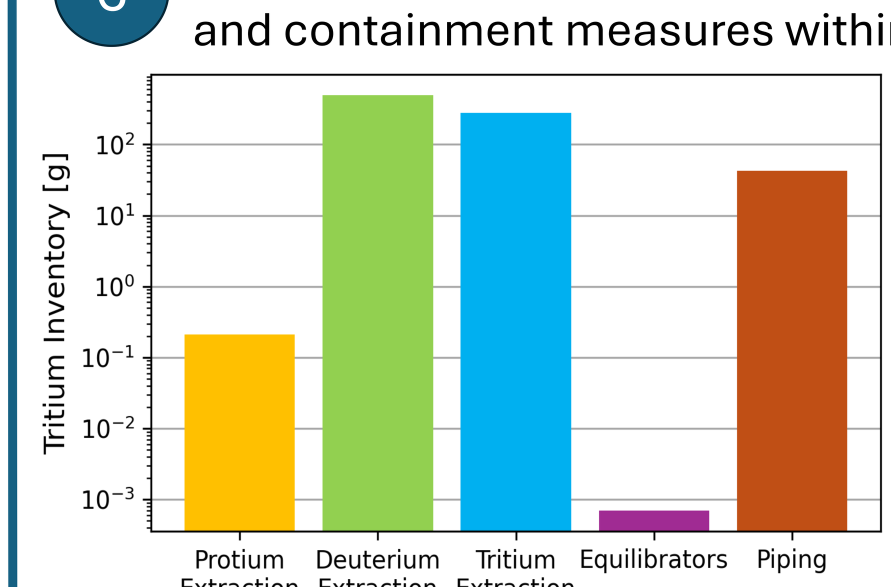
4 *Just Tritium Extraction Column reported*



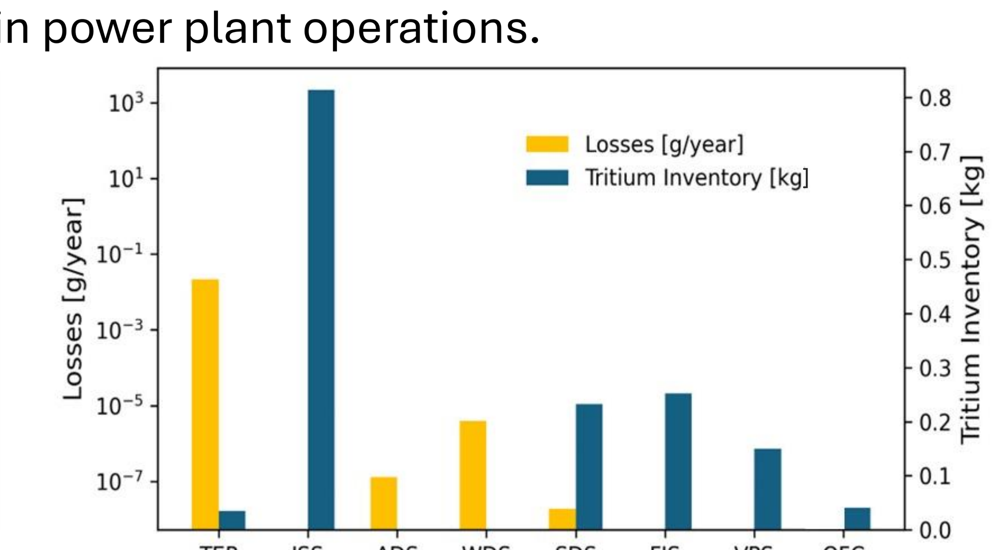
5 The **Equipment List** outlines key specifications – size, duty, el. power and operating conditions – crucial for **early-stage market analysis**.

ITEM TAG	Q.TY	DESCRIPTION	DIMENSIONS (mm) ID / W	DIMENSIONS (mm) L (T/T)	DIMENSIONS (mm) H (T/T)	CAPACITY / DUTY VALUE	CAPACITY / DUTY UNIT	ELECTRIC POWER VALUE	ELECTRIC POWER UNIT	TEMPERATURE (°C) DESIGN	TEMPERATURE (°C) OPERATING	PRESSURE (bar) DESIGN	PRESSURE (bar) OPERATING
350-VA-001	1	FIRST STAGE INLET BUFFER	300	-	1000					85 / -5	25	4,5 / FV	0,8 - 2 (1)
350-KP-001A/B/C/D/E/F	6	FIRST STAGE INLET COMPRESSOR	90 (1)	300 (1)	-	2.50	Nm3/h	n/a	kWe	454 / -5	25 (s) / 434 (d)	6	0,8 - 2 (s) / 4 (d)
350-HA-002	1	FIRST STAGE PERMEATOR REHEATER	200	300	150	0,16 743,6 (cold side) / 474,4 (hot side)	kWth g / h			420 / -5	C.S.: In: 25 °C, Out: 340 °C H.S.: In: 400 °C, Out: 35 °C	6 (cold side) 4,7 (hot side)	4 (cold side) / 1,5 (hot side)
350-HM-001	1	FIRST STAGE PERMEATOR ELECTRICAL HEATER	150	250	100	743.60	g / h	0.0375	kWe	420 / -5	340 / 400	6	3.3
350-XZ-001	1	FIRST STAGE PERMEATOR	100 (1)	1000 (1)		743.60	g / h			420 / '-5	400	6 / FV	2,5 feed 1,9 ret. side / 0,1 perm. side
350-KC-002A/B	2	FIRST STAGE SCROLL PUMP	180 (1)	253 (1)		2.12	Nm3/h	n/a	kWe	420 / '-5	400	4,5 / FV	0,1 (s) / 1,3 (d)
350-KP-002A/B	2	FIRST STAGE PERMEATE COMPRESSOR	90 (1)	300 (1)		2.12	Nm3/h	n/a	kWe	400 / -5	35 (s) / 312 (d)	5	1 (s) / 3 (d)
350-HC-003	1	FIRST STAGE RETENTATE COOLER	250	350	200	269,2	g / h	0.035	kWe	420 / '-5	400 / 25	6	1.8
350-VA-002	1	CATALYTIC STAGE INLET BUFFER	200		680					400 / '-5	25	4,5 / FV	1.2
350-KP-003A/B	2	CATALYTIC STAGE INLET COMPRESSOR	90 (1)	300 (1)		0.381	Nm3/h	n/a	kWe	400 / -5	25 (s) / 309 (d)	6	1 (s) / 4 (d)
350-HM-002	1	CATALYTIC REACTOR ELECTRICAL HEATER	300	500	250	2961	g / h	0.2610	kWe	500 / -5	25 / 480	6	4.5
350-VF-001	1	CATALYTIC REACTOR	70		180	2961	g / h			500	480	6 / FV	4
350-XZ-002	1	CATALYTIC STAGE PERMEATOR	63 (1)		1000 (1)	2961.04	g / h			420 / '-5	400	6 / FV	2,5 feed 1,8 ret side / 0,1 perm. side
350-HC-009	1	SECOND STAGE RETENTATE COOLER	300	400	250	2900	g / h	0.146	kWe	420 / '-5	400 / 25	6	1.8
350-KP-005A/B	2	RETENTATE RECYCLE COMPRESSOR	90 (1)	300 (1)		1.4053	Nm3/h	n/a	kWe	211 / -5	25 (s) / 191 (d)	6	1,3 (s) / 4 (d)
350-KC-004A/B/C/D	4	SECOND STAGE SCROLL PUMP	180 (1)	253 (1)		0.361	Nm3/h	n/a	kWe	420 / '-5	400	4,5 / FV	0,1 (s) / 1 (d)
350-KP-004A/B	2	CATALYTIC STAGE PERMEATE COMPRESSOR	90 (1)	300 (1)		0.361	Nm3/h	n/a	kWe	296 / -5	25 (s) / 276 (d)	5	1 (s) / 3 (d)

6 Inventory minimization plays a critical role in **meeting safety standards** and containment measures within power plant operations.



Tritium Inventory in ISS equipment



Tritium Inventory in Fuel Cycle and insights on Tritium losses
Losses to be calculated for VPS and OFC

References

[1] Hillesheim (2023) APS Division of Plasma Physics Meeting 2023, abstract id.JP11.115
[2] Sorbom (2015) 10.1016/j.fusengdes.2015.07.008