Nested Pebble Bed Blanket (NesPeB)

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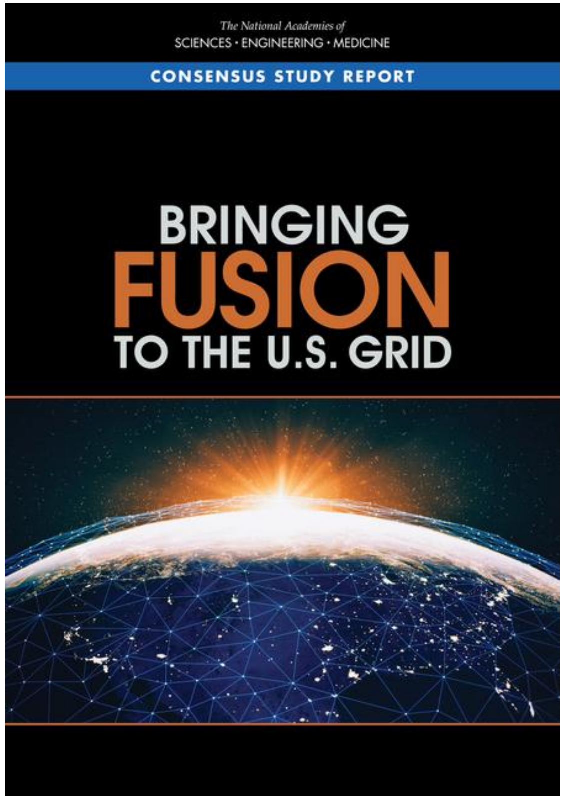
FERMI Team

07/09/2025

Patent Awarded: V. Badalassi, “Fusion Reactor Having Nested Pebble Bed Blanket” #12,254,994 B1

NASEM Fusion Pilot Plant requirements

- “Sufficient tritium self-production in a pilot is needed because the available world’s supply of tritium is of the same order as a D-T pilot plant’s annual tritium consumption.”
- Pilot plant should demonstrate TBR > 0.9 in its second phase
- “Advancing blanket technology readiness is required in order to select the blanket concept for a fusion pilot plant.”



- My further comment: the use of natural Lithium is key as there is no large Lithium-6 enrichment capability in US and EU

Motivation

	Liquid Metal (Li)	Liquid Metal (PbLi)	Solid (Ceramics)	Molten Salt (FLiBe)	NesPeB
TBR > 1.15	No ^6Li enrichment	^6Li enrichment	Be multiplier and ^6Li enrichment, structure minimization	Be multiplier and ^6Li enrichment	No ^6Li enrichment
Melting point	180 C	235 C	>1200 C	460 C	>1200 C
Material compatibility/ pairing	Vanadium alloy or RAFM steel, at high T requires coatings	RAFM steel or SiC - at high T requires coatings	RAFM steel and He or H_2O coolant, Best material compatibility	Corrosion and high T, no clear solution	RAFM steel, Helium and Neon coolants
Working pressure	High coolant pressure if gases are used	High coolant pressure if gases or water are used	High coolant pressure if gases or H_2O are used	Atm pressure	High coolant pressure as gases used
MHD effects	Electrical insulators required for MFE	Electrical insulators required for MFE	No MHD effects	Small MHD effects	No MHD effects
Tritium extraction	High tritium solubility/inventory, different extraction techniques needed	High tritium solubility/inventory, various extraction techniques needed	Simple & mature tritium extraction	No mature tritium extraction technology	Simple & mature tritium extraction
Safety	Very high chemical reactivity with H_2O and air	Lower chemical reactivity than pure Li	Reactivity with H_2O. Less severe reactivity with air.	Low reactivity with air. Generation of tritium fluoride gas	Risk of reactivity with H_2O is minimized
Breeder replacement	Fluid inlet/outlet	Fluid inlet/outlet	Replacement of the ceramic pellets. Relevant evolution under irradiation	Fluid inlet/outlet	Pebbles inlet/outlet
Neutron multiplier replacement	No need of neutron multiplier	No need of neutron multiplier	Replacement of the beryllium pellets/plates	Replacement of the beryllium plates	Pebbles inlet/outlet
TRL	2	2	2	2	2

Current blanket concepts are not satisfactory & there is the need of a breakthrough
Nested Pebble Bed Blanket

ARPA-E funds: $3.15M
Cost share: 5%

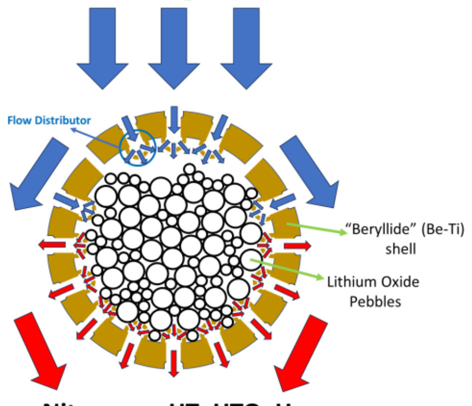
Nested Pebble Bed Blanket (NesPeB)

Oak Ridge National Laboratory

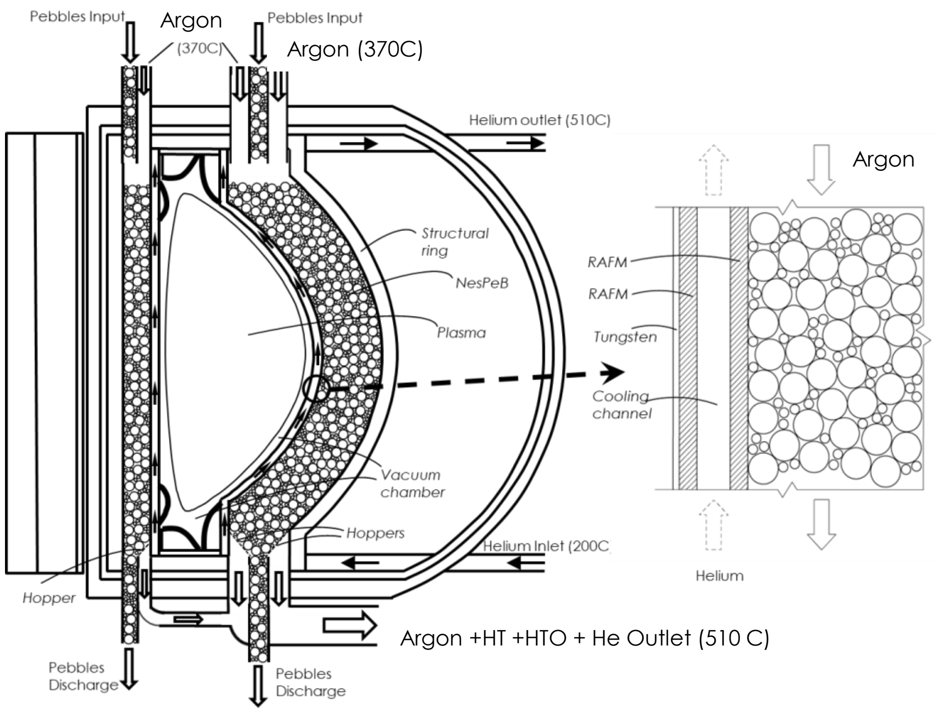
Vittorio Badalassi, PhD (ORNL)
Prof. Raymond Cao, Ohio State University

- **Patent awarded** (30 claims allowed, #12,254,994 B1)
- Design will be proven in a nuclear research reactor in representative conditions. **First time comprehensive nuclear blanket test.**
- **Final Deliverable**: **TRL=5-6** breeding blanket with an unprecedented combination of features. This TRL level for a blanket is unprecedented.
- **Tie to Vision OPEN Goal:** it addresses current blanket concepts' flaws and technical immaturity, accelerating fusion plants development.

NESTED PEBBLE

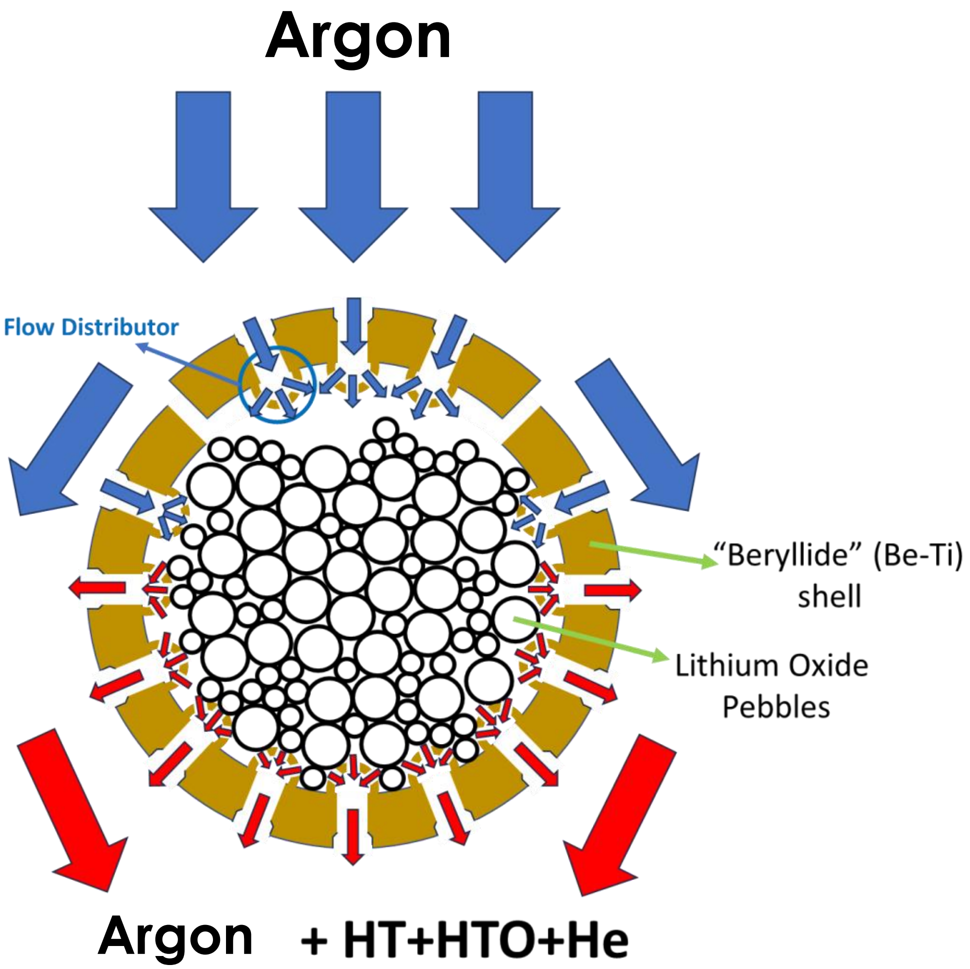


NESTED PEBBLE BED BLANKET (NesPeB)



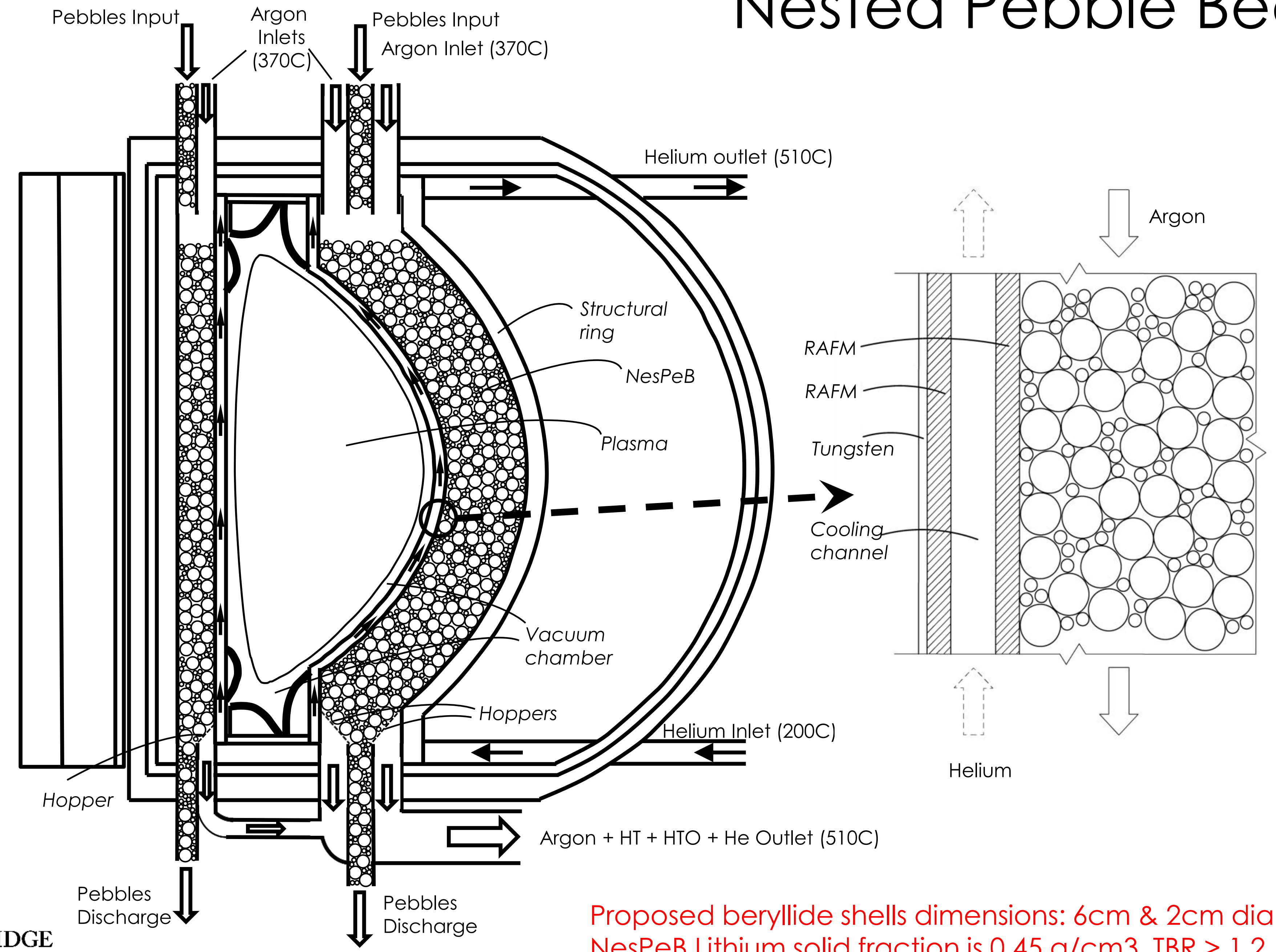
Metric	State of the Art	Proposed Target
TRL Breeding Blanket for a Fusion Power Plant	TRL=2-3	TRL=5-6
Solid breeder blanket Tritium Breeding Ratio with natural Lithium isotopic composition	0.9	1.2
Breeding Blanket proven features combination: no MHD effects, low corrosion, easy breeder and neutron multiplier replacement, low activation, mature tritium extraction technology, low reactivity	None	Proven up to TRL=5

What is a Nested Pebble?

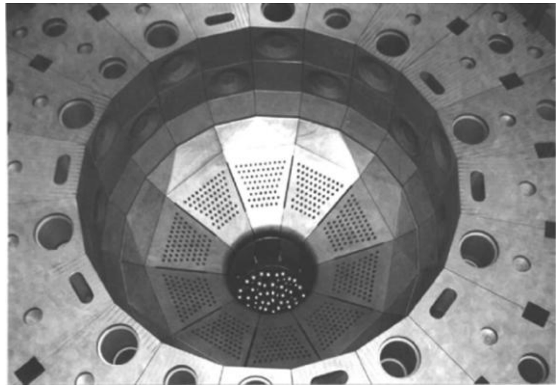


Beryllium best neutron multiplier, Beryllide: Beryllium + Vanadium (or Titanium) to eliminate Be deformation under n irradiation
Lithium Oxide: Lithium ceramic with the highest Lithium content (0.93 g/cm3, higher than the pure liquid lithium 0.51 g/cm3)
Why Argon as a coolant? The rate of diffusion of a gas is proportional to its partial pressure within the total gas mixture
Proposed dimensions lithium oxide pebbles: 0.8mm-2.4mm diameter, proposed beryllium shells diameters 2-6cm

Nested Pebble Bed Blanket



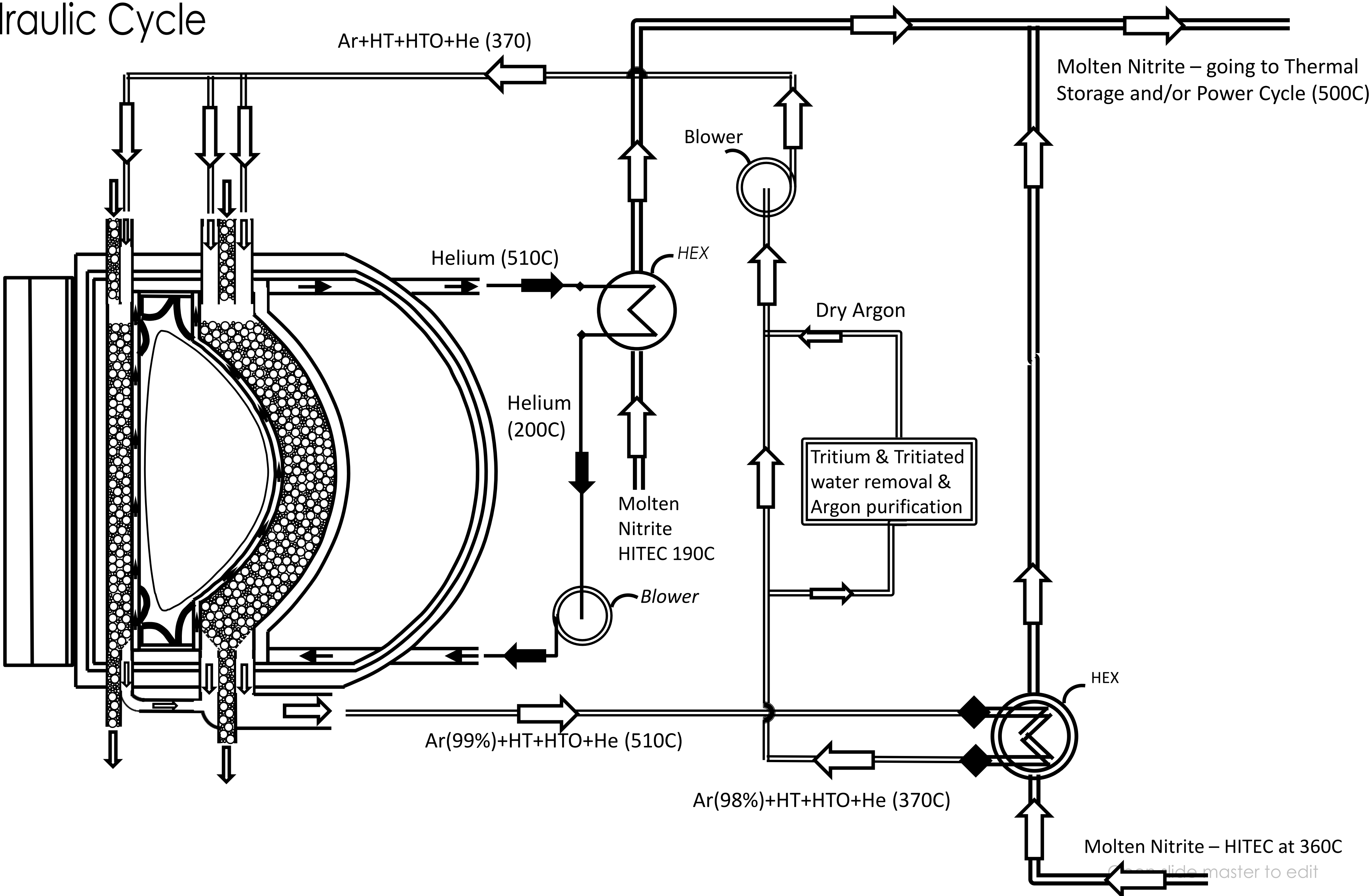
THTR-300 (Germany)



HTR-300 (China)

Proposed beryllide shells dimensions: 6cm & 2cm diam.
NesPeB Lithium solid fraction is 0.45 g/cm3, TBR > 1.2

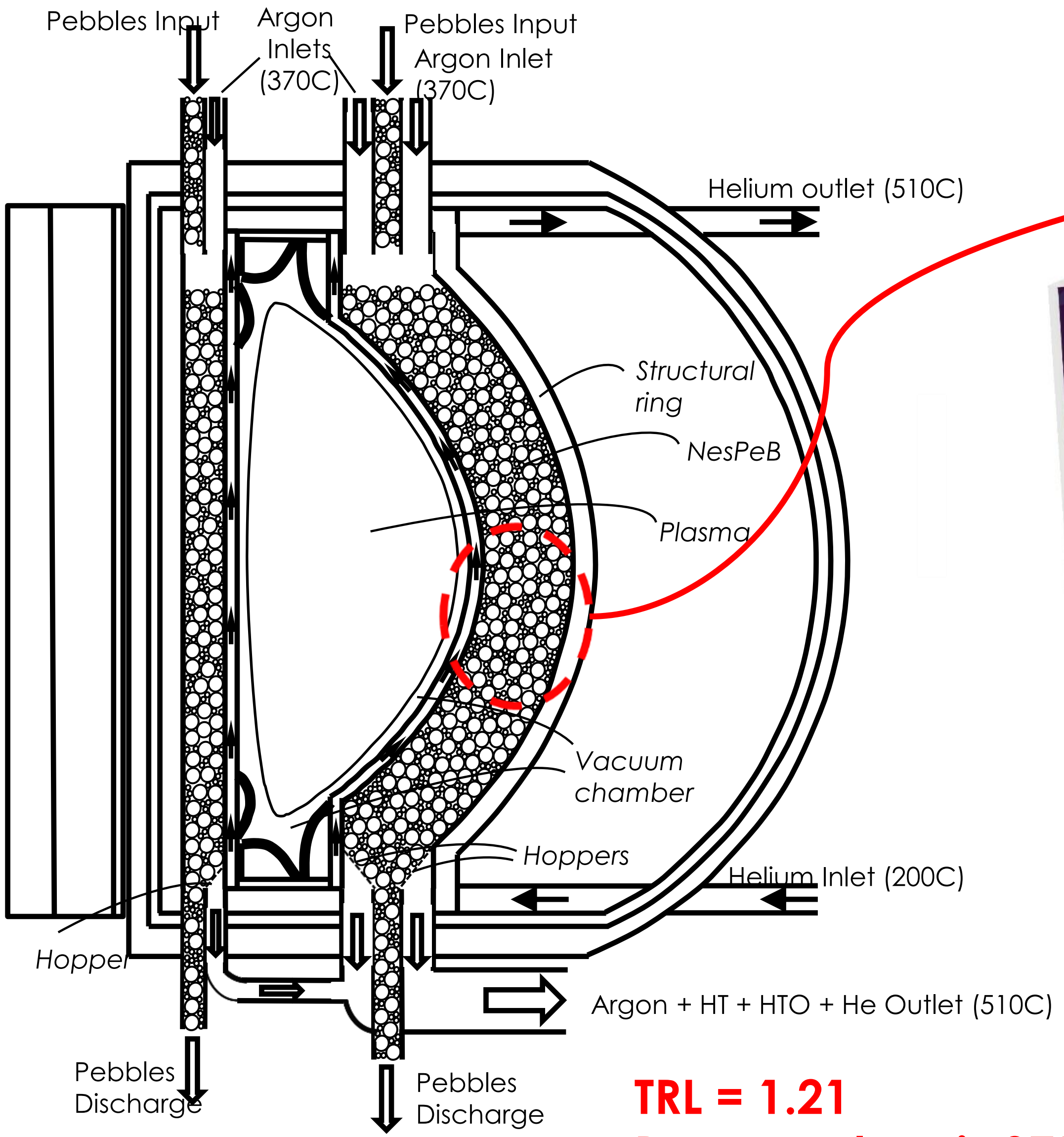
Thermal-Hydraulic Cycle

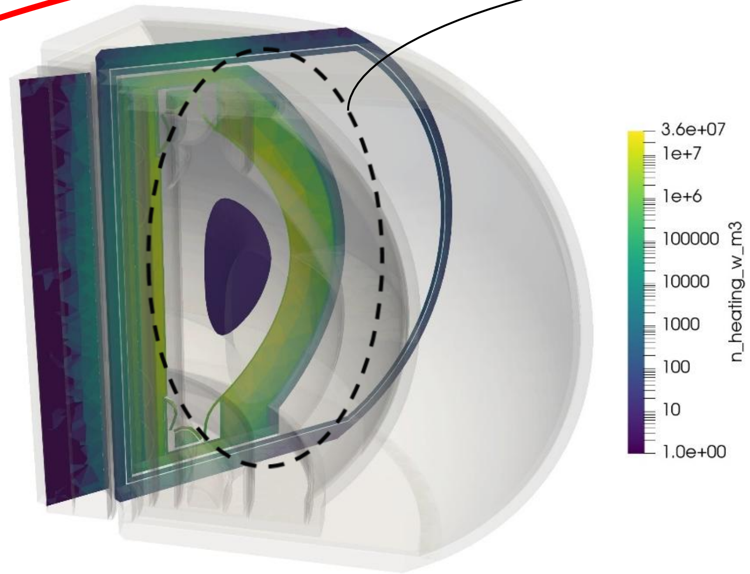


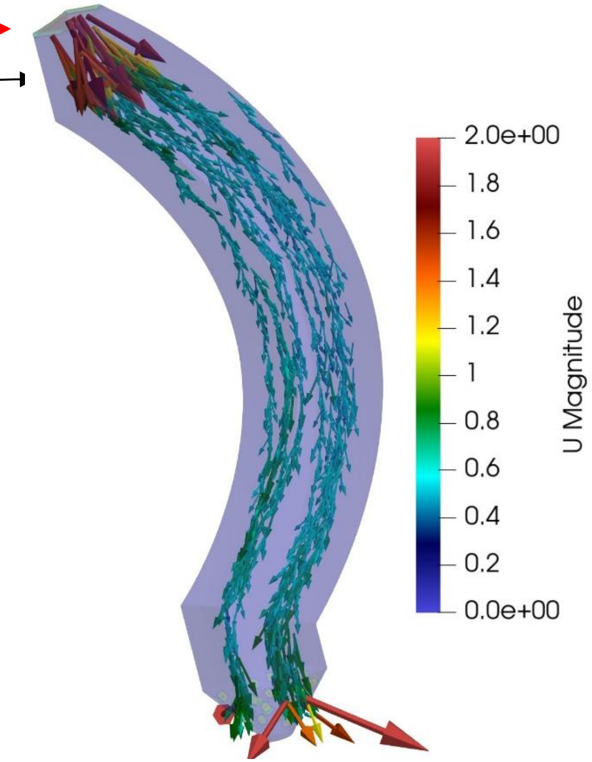
Technology Readiness Level of Blankets Designs?

TRL	Defense Acquisitions Definitions		PbLi Blanket		NesPeB (current)		NesPeB PROJECT GOALS
1	Basic principles observed and formulated.		Explorations since the 1980's		Solid breeder blankets physics explored since 1980s		
2	Technology concepts and/or applications formulated.		Many conceptual designs exist.		Technology concept formulated and patented		
3	Analytical and experimental demonstration of critical function and/or proof-of concept.		Single effects: LMMHD modeling and experiments, corrosion, tritium, heat flux, materials, neutronics	75%	Simulations with FERMI Single pebble irradiation and cooling in a research reactor	50%	
4	Component and/or bench-scale validation in a laboratory environment.		Multiple effects, increasing design details.	25%	Multiple pebbles irradiation in a research reactor		
5	Component and/or breadboard validation in relevant environment.	Path to FPP	Multiple effects testing at high temperature, high field strength, etc.		Multiple pebbles irradiation and cooling in a research reactor		
6	System/subsystem model or prototype demonstration in a relevant environment.		Integrated systems testing at relevant parameters.		Needs a blanket test facility with also FW 14MeV irradiation & cooling		50%
7	System prototype demonstration in an operational environment.		VNS/FNSF testing with integrated modeling		Needs a Fusion Pilot Plant		
8	Actual system completed and qualified through test and demonstration.		Blanket and systems qualification, installation in a Fusion Pilot Plant		Needs a Fusion Pilot Plant		
9	Actual system proven through successful mission operations.		Successful operation of a Fusion Power Plant: power production, T, RAMI, lifetime, safety.		Needs a Fusion Power Plant		

Preliminary FERMI Simulations – TRL & pressure drop

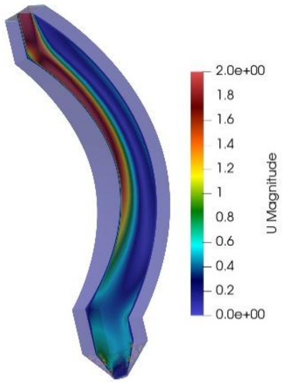




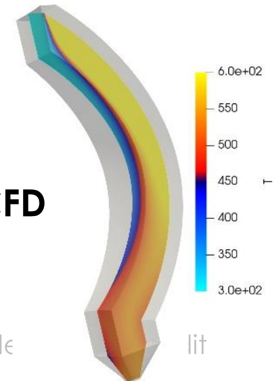


FNSF reactor: Heat deposition from neutronics calculations

TRL = 1.21
Pressure drop is 375.5 kPa (4.65% of total)



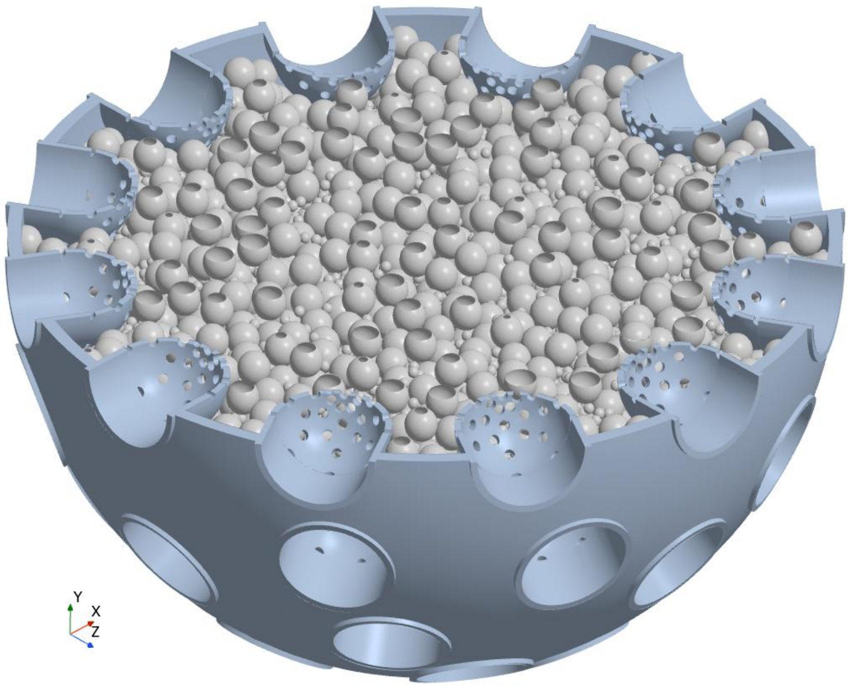
Velocity and temperature profiles from CFD calculations

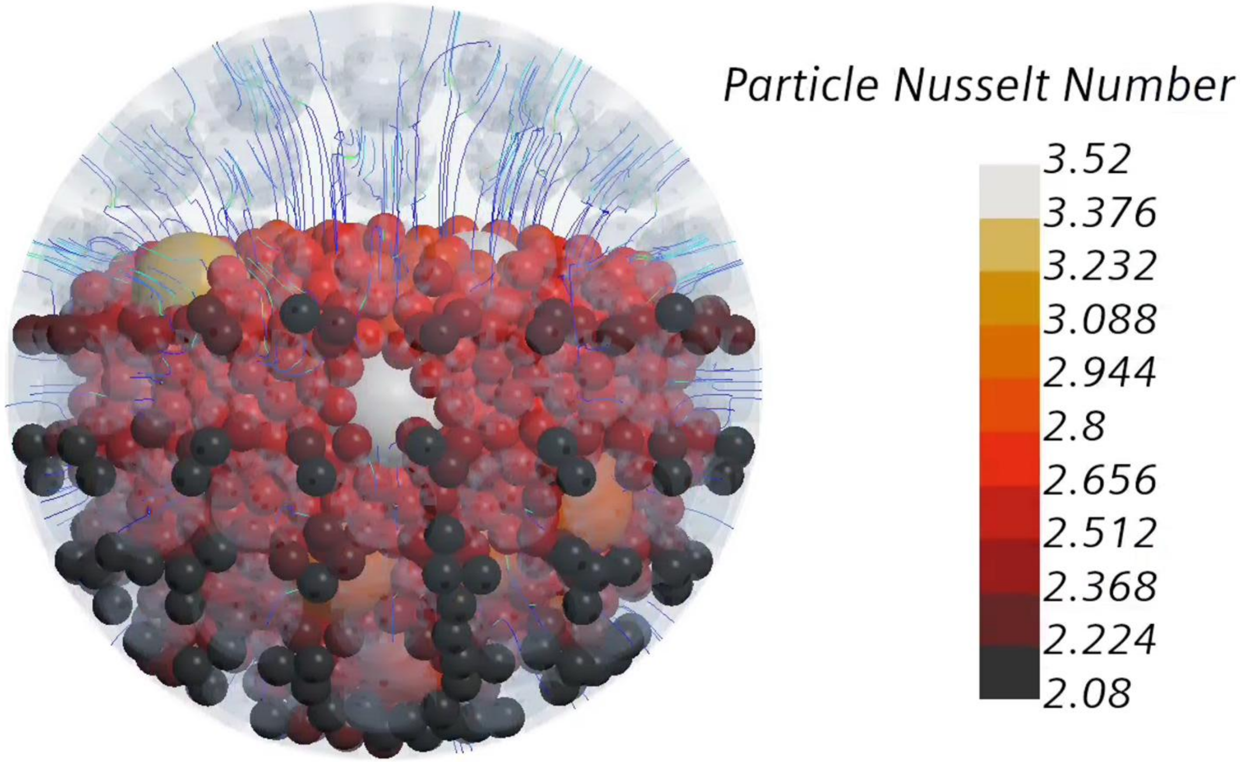


OAK RIDGE National Laboratory

Preliminary FERMI Simulations – single pebble

- Pebble heat transfer & temperatures are within design ranges





NesPeB Design Goals & FERMI Analysis

	Metric	Project Goal	Design Outcome	FERMI
1	NesPeB Tritium Breeding Ratio with natural Lithium isotopic composition	1.2	Fusion self sufficiency	1.21
2	Blanket pressure drop	< 5% of the total inlet pressure	Power efficiency	4.68%
3	Optimal Temperature range for breeding pebbles and shells	350-700C for Li2O 350-650 for the Beryllium shells	Optimal, reliable tritium production Acceptable Beryllium shell deformation	√
4	Lithium hydroxide (LiOH) concentration	< 70 ppm	Low corrosion	TBD
5	Stability and integrity of the shells coating (Titanium Nitride)	Coating does not peel off nor degrades meaningfully under irradiation	Nested Pebbles can move against each other	TBD
6	Integrity of the breeding pebbles (Lithium Oxide)	Acceptable swelling, no failures	Reliable tritium production	TBD
7	Integrity of the Beryllium (Aluminum) shell	No failures allowed	Integrity of the Nested Pebble Bed	TBD

FERMI simulations of NesPeB will need to be validated with experiments in the Ohio research reactor to reach TRL=5-6 – main goal of the NesPeB project

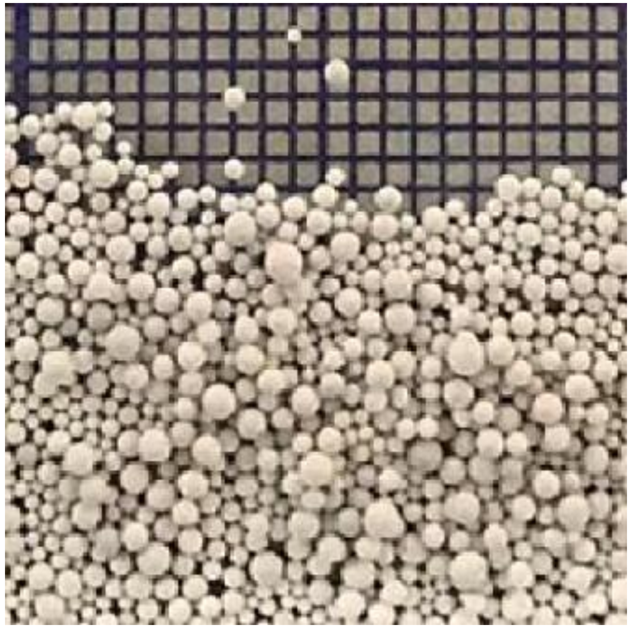
Proven Manufacturing

Proposed manufacturing techniques & technologies (all proven):

1) Laser drilling for the Be shell and flow distributors
2) Physical vapor deposition (PVD) for the Titanium Nitride coating
3) Hatch to open/close the Be shell can be screwed
4) Li2O pebbles manufactured by wet process
5) Tritiated water can be extracted by a condensation process
6) Tritium can be extracted by copper catalysts and others (HTGR)

Beryllium spherical shell
from gyroscopes (1.5 inch diam.)

Lithium Oxide pebbles



Titanium Nitride coating

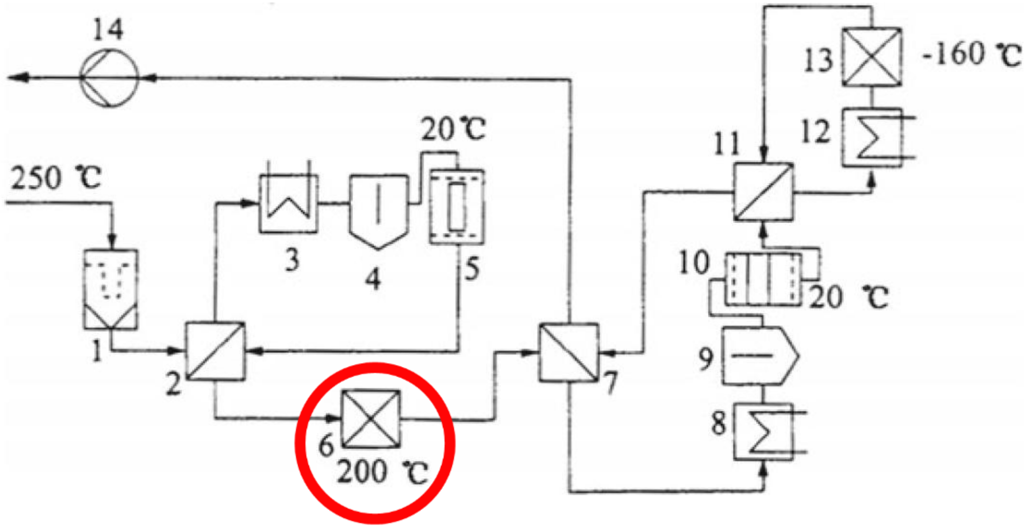
Proven Tritium & T. Water Extraction & Argon Purification

The purification and tritium, tritiated water and other impurities plant needed by NesPeB is almost identical to HTGR fission reactors (already tested and currently running in China i.e. with **TRL=9**)

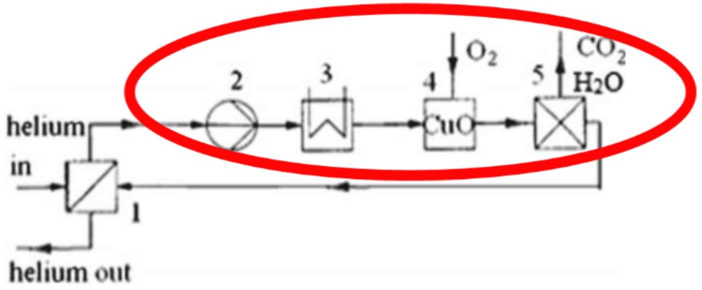
The picture represent the purification and extraction plant of **THTR-300 (300MW)** than run in the 80s for several years and is almost a twin of the currently running Chinese HTR-PM.

Gas separated from Helium by the THTR:
Hydrogen
Water
Carbon monoxide & dioxide
Oxygen
Incondensable heavy fission gases
Lithium hydroxide will be removed by the dust filter

HTGR 300 MW purification plant could separate up to 76g/day of hydrogen; a fusion reactor of same power needs 75 g/day of tritium, almost the same(!)



1: dust filter, 2: recuperator, 3: cooler, 4: separator, 5: activated charcoal filter, 6: copper oxide catalyst, 7: recuperator, 8: cooler, 9: separator, 10: molecular sieve, 11: recuperator, 12: cooler, 13: activated charcoal filter, 14: helium compressor



1: recuperator, 2: helium circulator, 3: cooler, 4: CuO catalyst, 5: molecular sieve

TRL & MRL LEVELS

TRL	1	2	3	4	5	6	7	8	9
Nested Pebble									
Nested Pebble bed concept									
Pebble bed concept (Fission)									
Pebbles conveyors (Fission)									
Fuel Cycle									
Thermodynamic cycle									
Tritium extraction									

MRL	1	2	3	4	5	6	7	8	9	10
Beryllium shell										
Lithium oxide pebbles										
Titanium Nitride Coating										