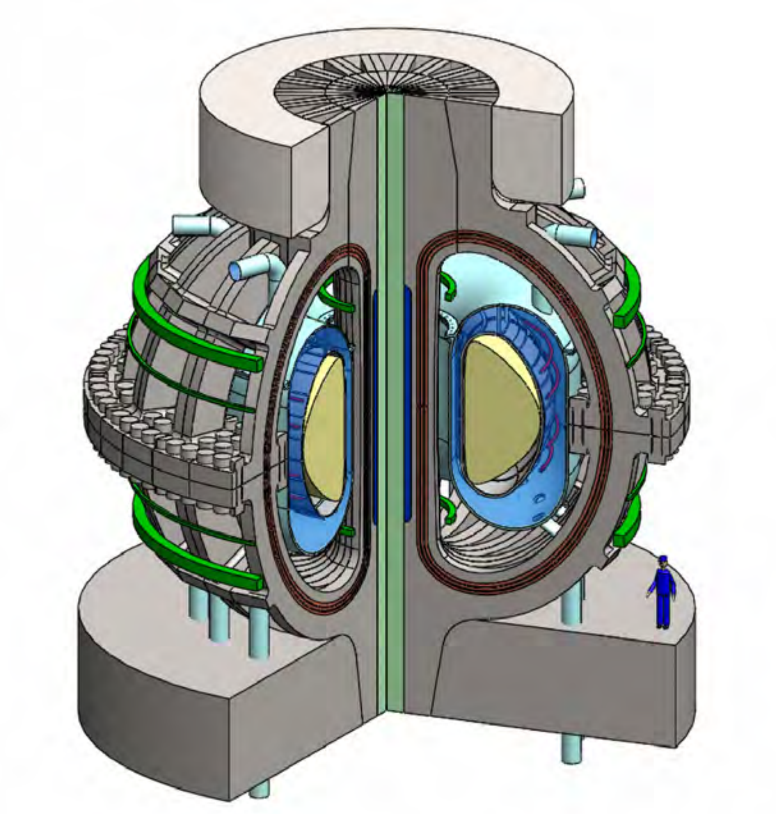
Liquid immersion blankets for fusion power plants



Brandon Nils Sorbom

Workshop on Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors, October 27, 2015

Thank you to all who contributed to ARC!

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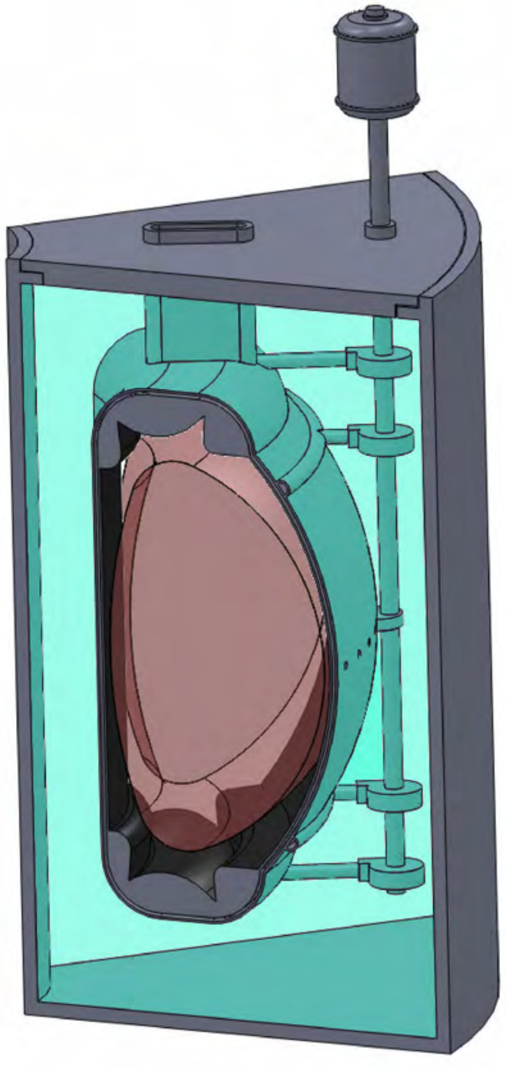
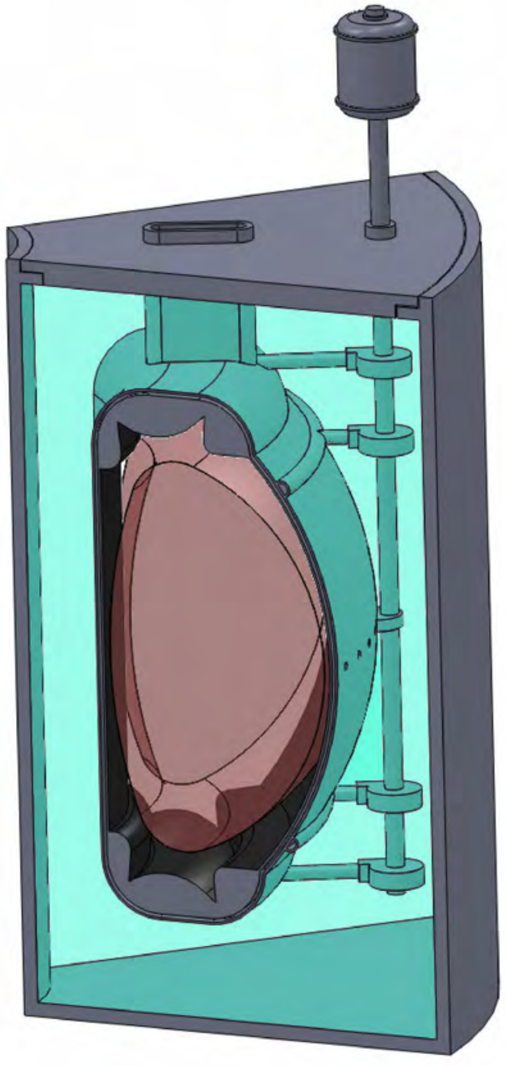
Outline



- What functions do a fusion blanket have to perform?
- Traditional blankets vs. the liquid blanket
- How well do liquid blankets perform?

Outline



- What functions do a fusion blanket have to perform?
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Fusion blanket systems must perform three main roles—two are different than for fission!

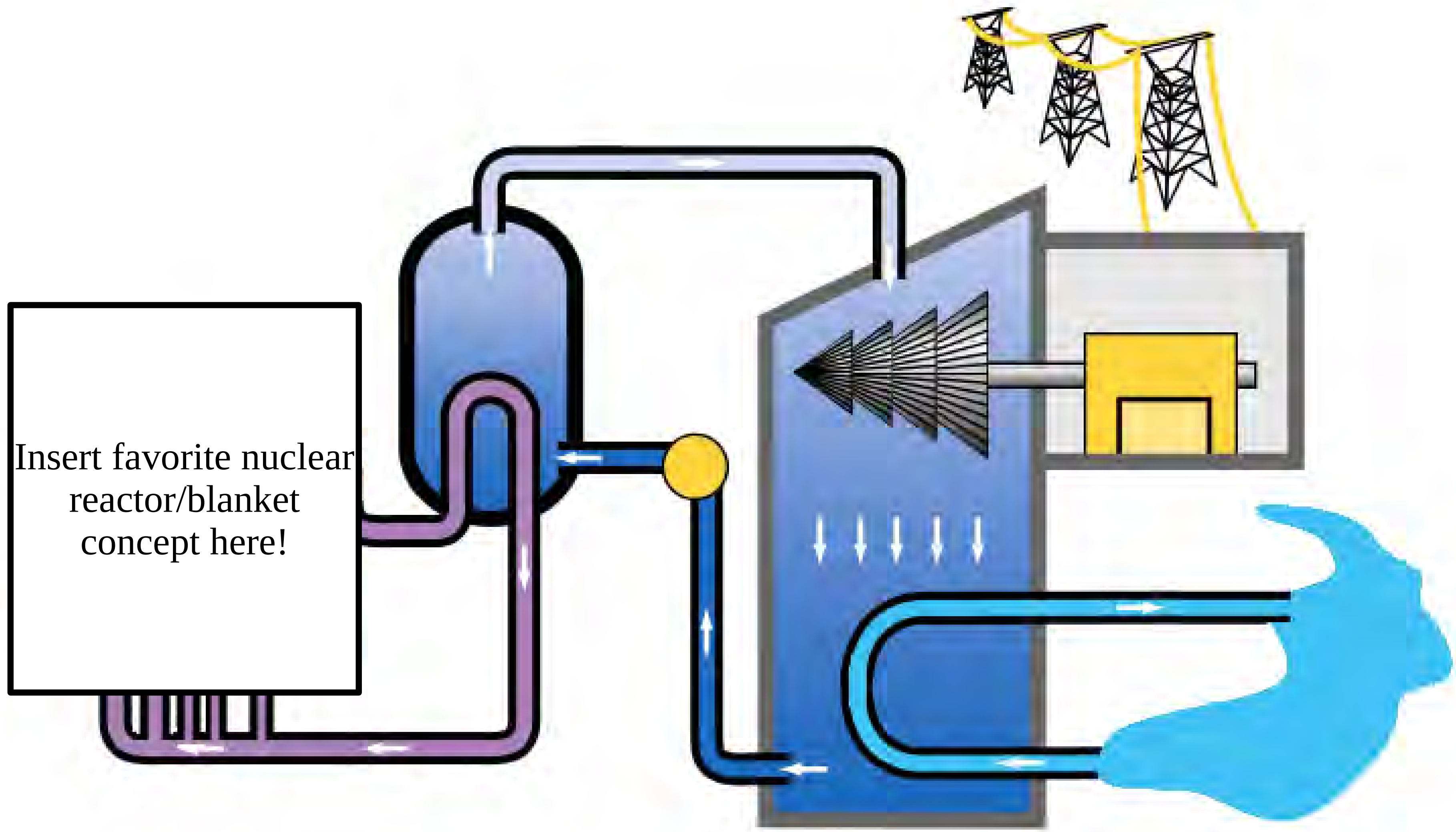
A blanket must:

1) Extract the energy from the fusion reactions in a useable form (same as fission)

2) Breed enough tritium to fuel the reactor

3) Shield the TF coils from high-energy neutrons

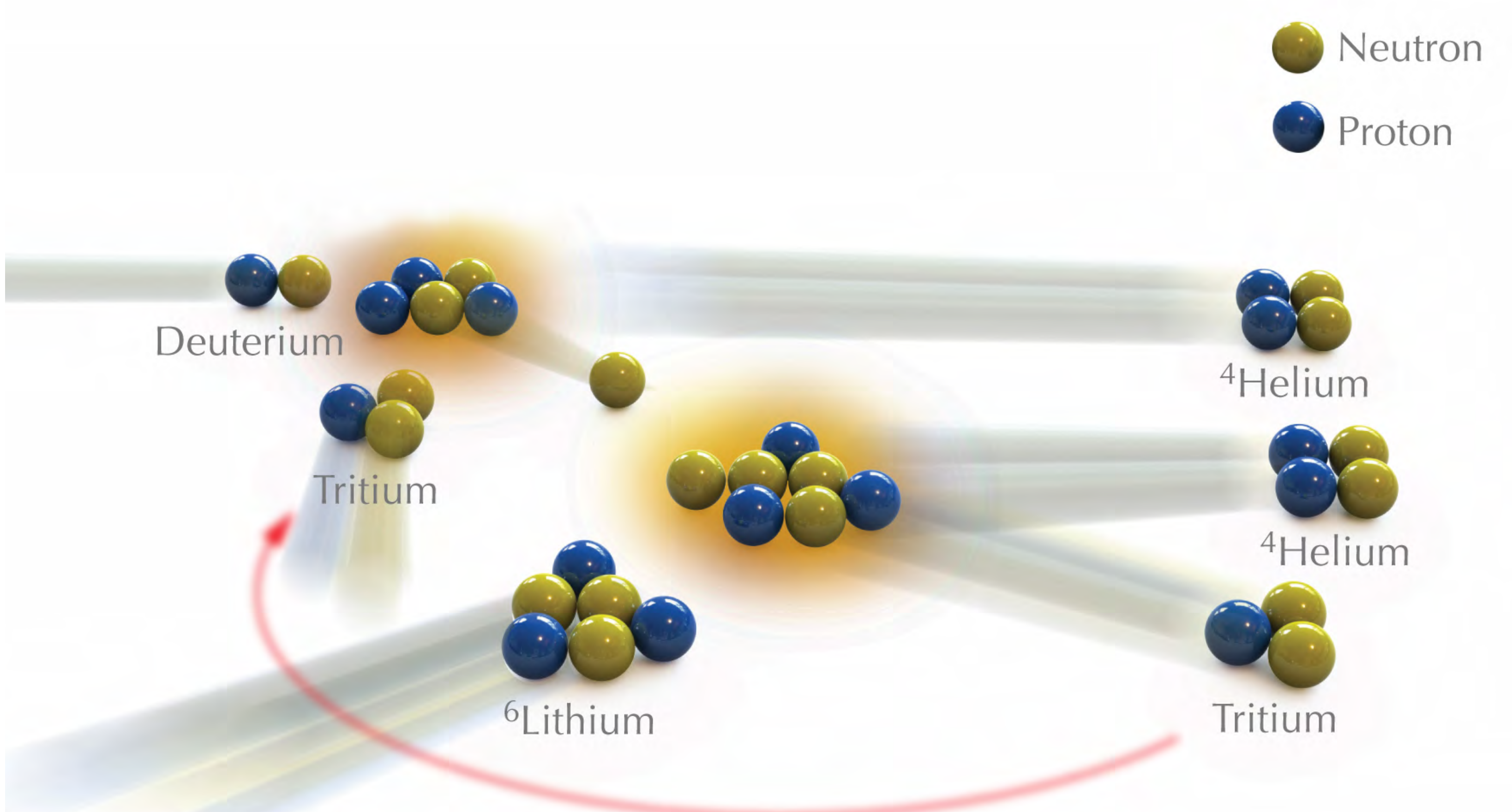
Blanket is used to extract useable energy from nuclear reactions



Energy extraction blanket requirements

- Should have favorable thermal-hydraulic properties
  - Low density and viscosity (easy to pump)
  - High heat capacity (efficient at removing heat)
  - High temperature operation (higher Carnot efficiency)
- Want something that looks like water, but at a higher temperature
- Only major difference from fission is that MHD effects in fluid become important (more on this later)

The blanket must breed fuel (tritium) for the reactor



https://www.euro-fusion.org/glossary/tritium-breeding/

Tritium breeding requirements

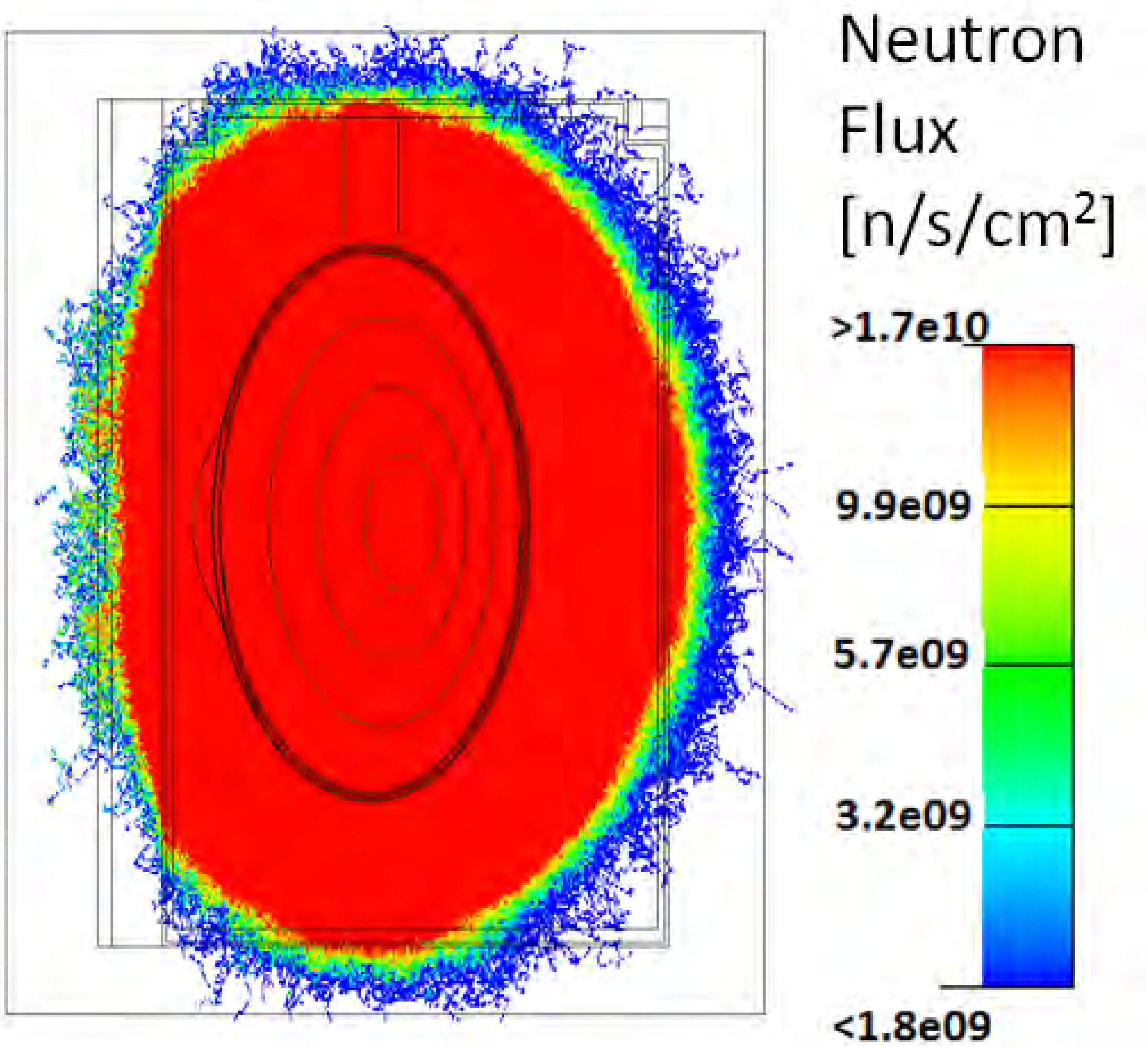
- 500 MWth ARC reactor consumes ~67 g of T *per day*
- Must provide a tritium breeding ratio (TBR) greater than 1, i.e. you get more tritium out of the blanket than you put into the reactor

$$TBR = \frac{Tritium\ Bred}{Tritium\ Consumed}$$

- We use the ARIES critera[1] to have TBR > 1.1 to account for deficiencies in nuclear data and uncertainties in exact reactor geometry
- Lithium is by far the best material to breed tritium, so blanket must have lithium in some form
- As a bonus, the blanket could have a neutron-multiplying isotope (such as beryllium) to increase the number of low-energy neutrons to interact with Li-6

1.) El-Guebaly, L. A., & Malang, S. (2009). Toward the ultimate goal of tritium self-sufficiency: Technical issues and requirements imposed on ARIES advanced power plants. Fusion Engineering and Design, 84(12), 2072-2083.

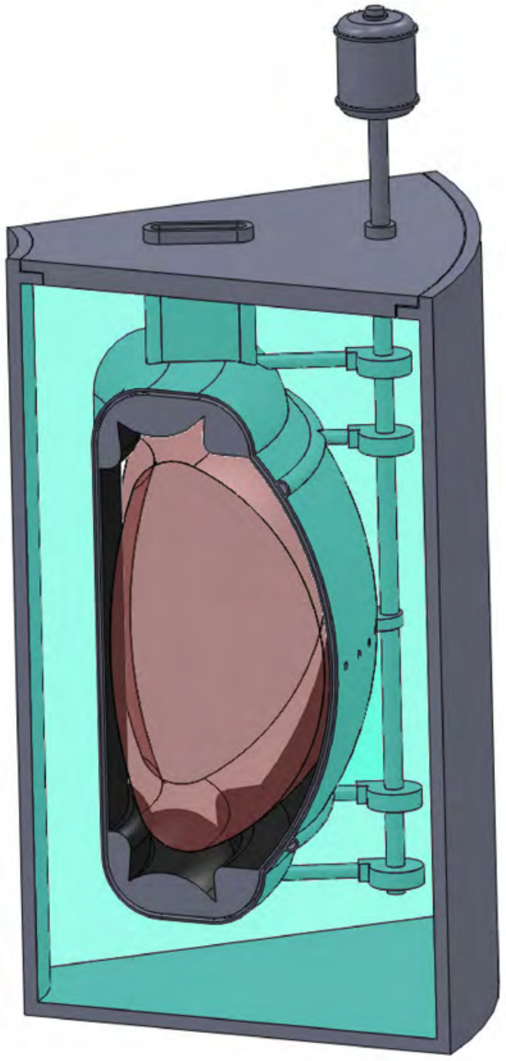
The blanket must effectively shield the TF coils from neutrons



Magnet Shielding Requirements

- All practical reactor designs utilize superconducting coils
- Critical current capability of superconductor degrades after a certain amount of damage from high-energy (> 0.1 MeV) neutrons
- REBCO high-temperature superconductors have not been tested to failure, but Nb_3Sn starts degrading around a neutron fluence of 3×10^{18} neutrons/cm^2 for high energy neutrons

Outline



- What functions do a fusion blanket have to perform?
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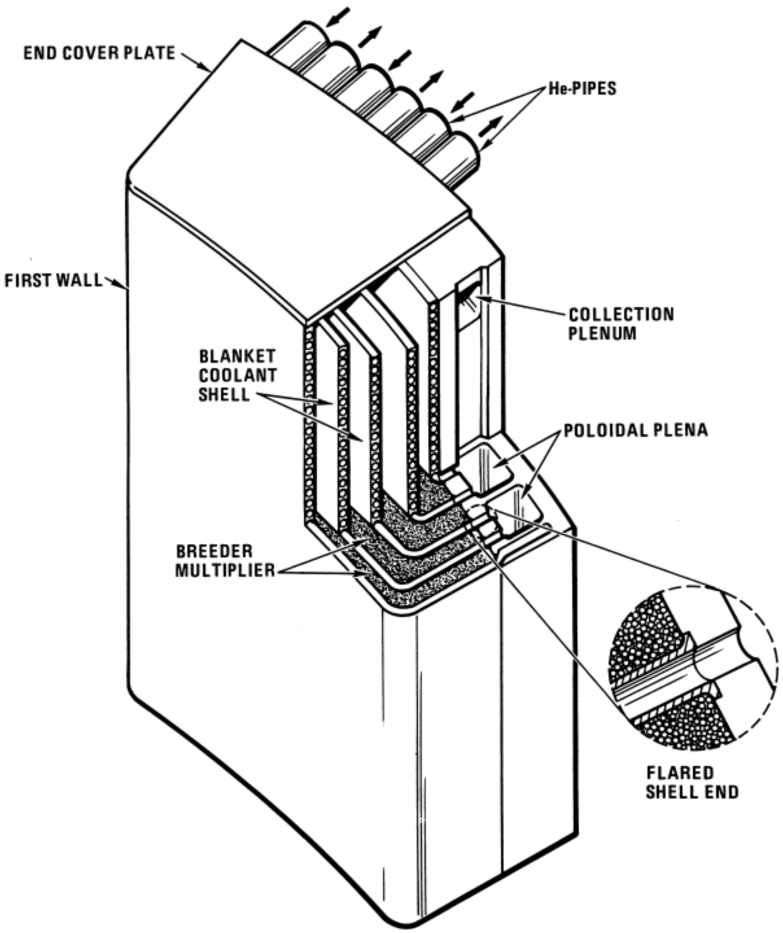
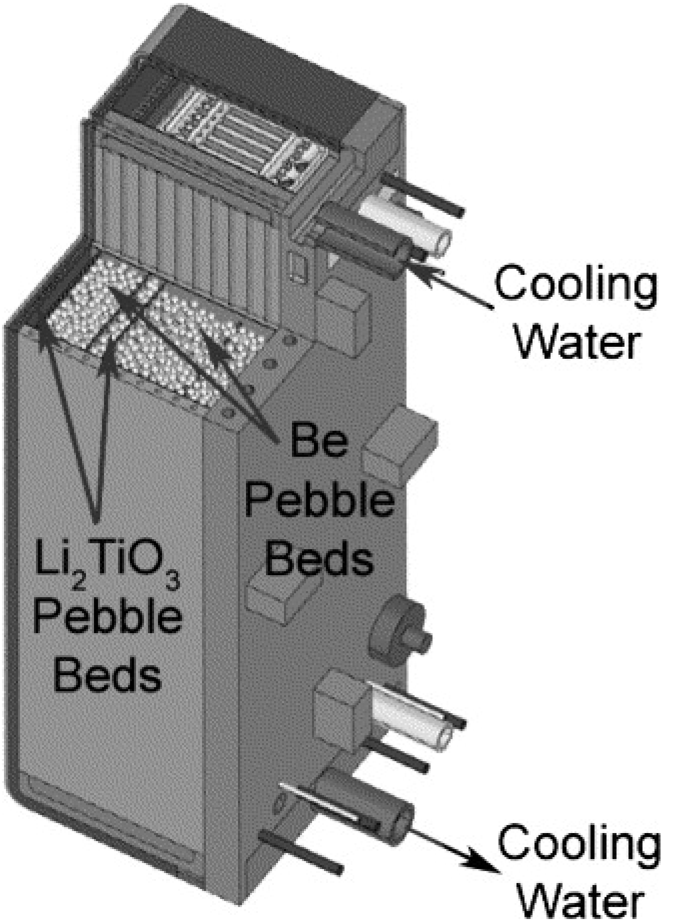
"Traditional" blankets utilize a large amount of solid material



ARIES-I Blanket

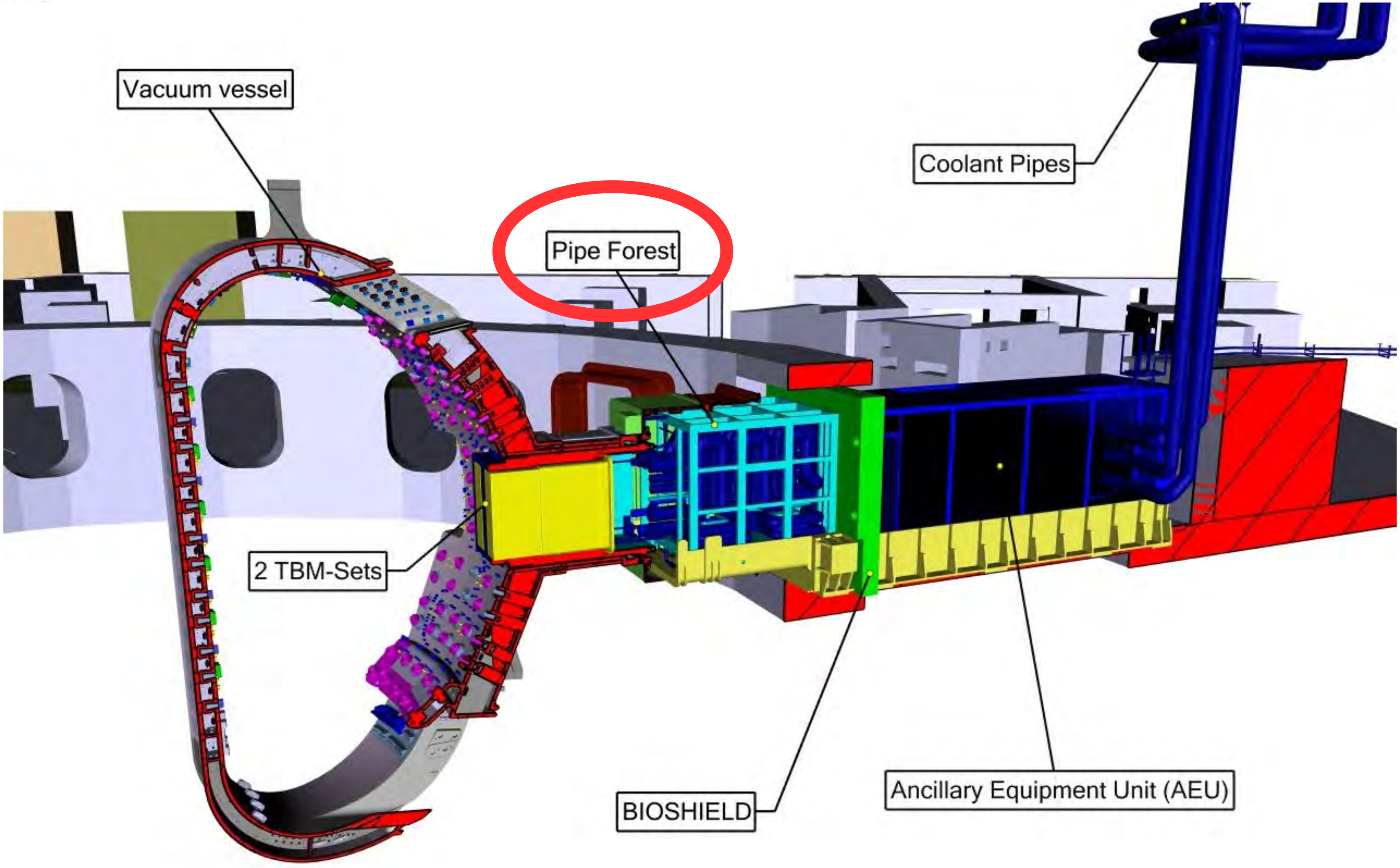


Japanese Tritium Breeding Module for ITER

Najmabadi, Farrokh, et al. "The ARIES-I Tokamak Reactor Study." Fusion Science and Technology 19.3P2A (1991): 783-790.

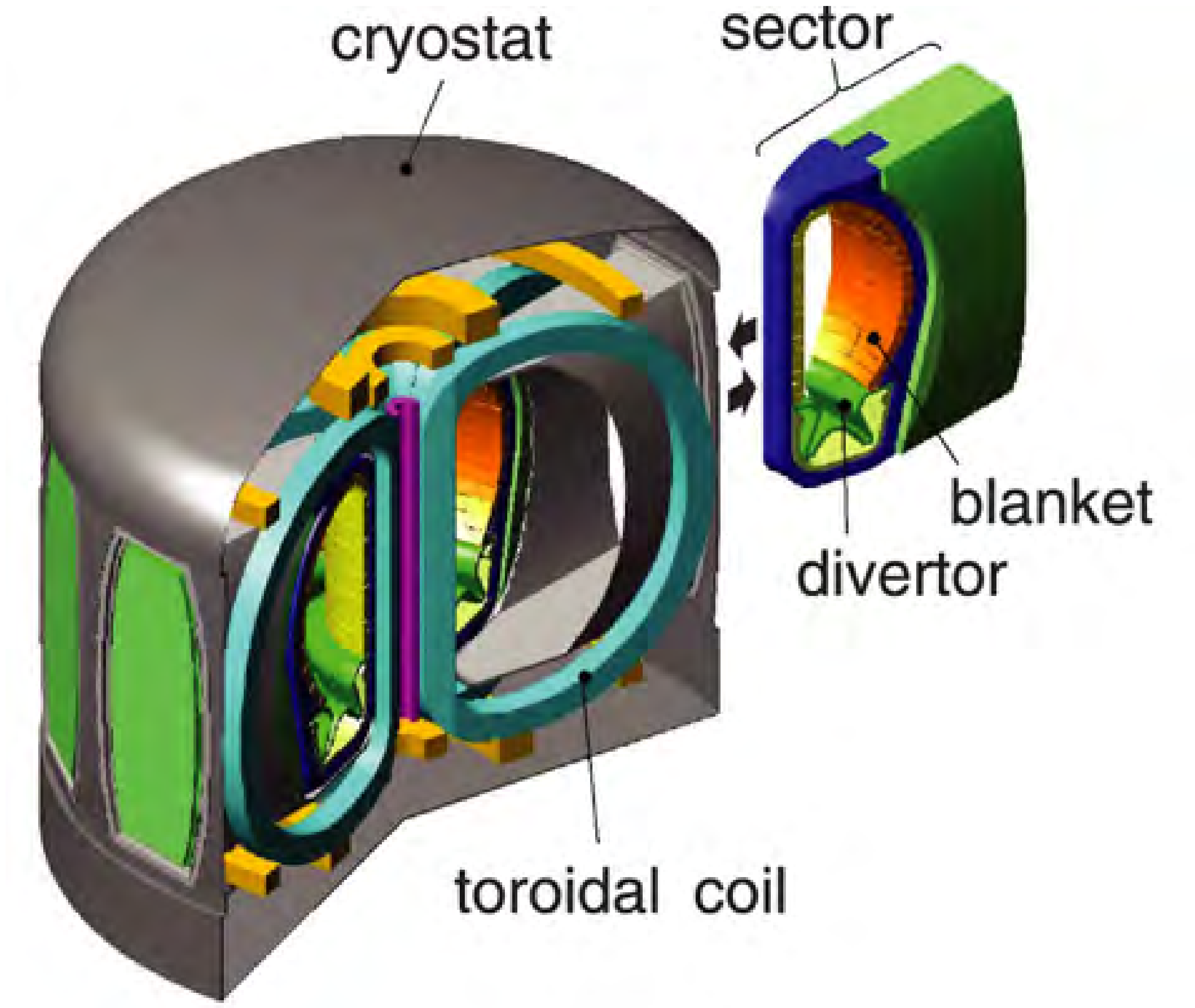
Giancarli, L., et al. "Breeding blanket modules testing in ITER: an international program on the way to DEMO." Fusion Engineering and Design 81.1 (2006): 393-405.

Solid blankets are complicated



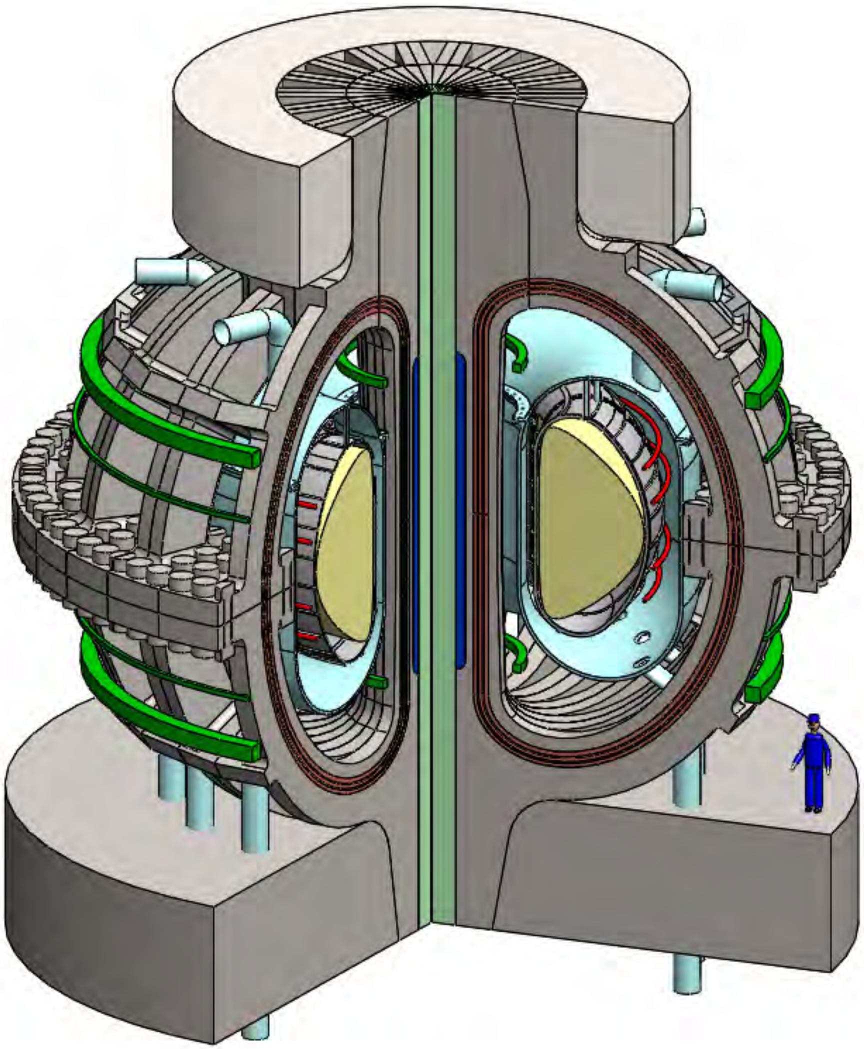
https://www.iter.org/newsline/-/2207

Sector maintenance is not ideal



http://jolisfukyu.tokai-sc.jaea.go.jp/fukyu/mirai-en/2008/3_10.html

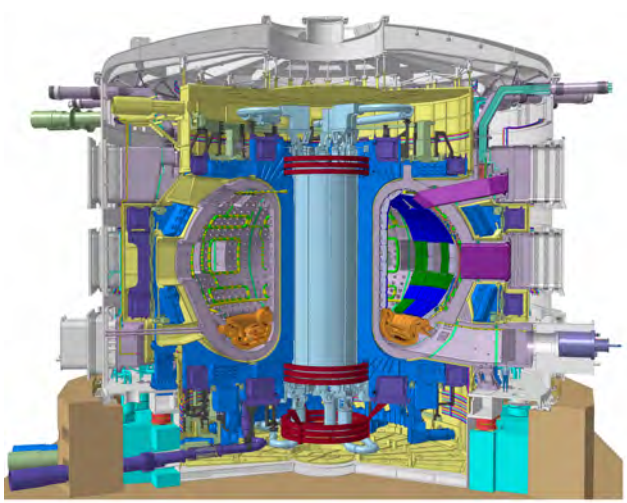
The ARC reactor is a high-field conceptual pilot plant design



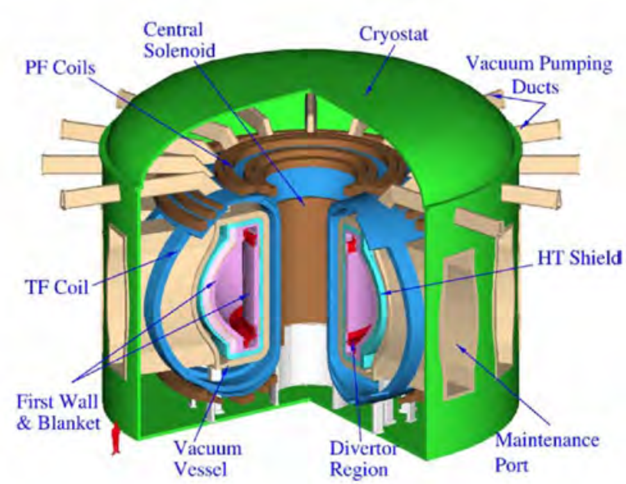
Key Design Parameter	Value
Fusion Power	525 MW
Total Thermal Power	708 MW
Net Electric Power	190 MW
Plasma/Electric Gain	13/3
Major Radius	3.3 m
Minor Radius	1.1 m
Toroidal Magnetic Field	9.2 T
Plasma Current	7.8 MA
Average Temperature	13.9 keV
Average Density	1.75×10^{20} m^{-3}
Tritium Breeding Ratio	1.10

What makes ARC different from other reactor designs?

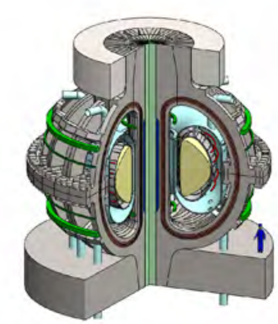
- ARC is compact and has a high magnetic field through the use of high-temperature superconductors
- ARC's magnets are demountable (no sector maintenance)
- **ARC has an all liquid, molten salt blanket**



ITER[2]

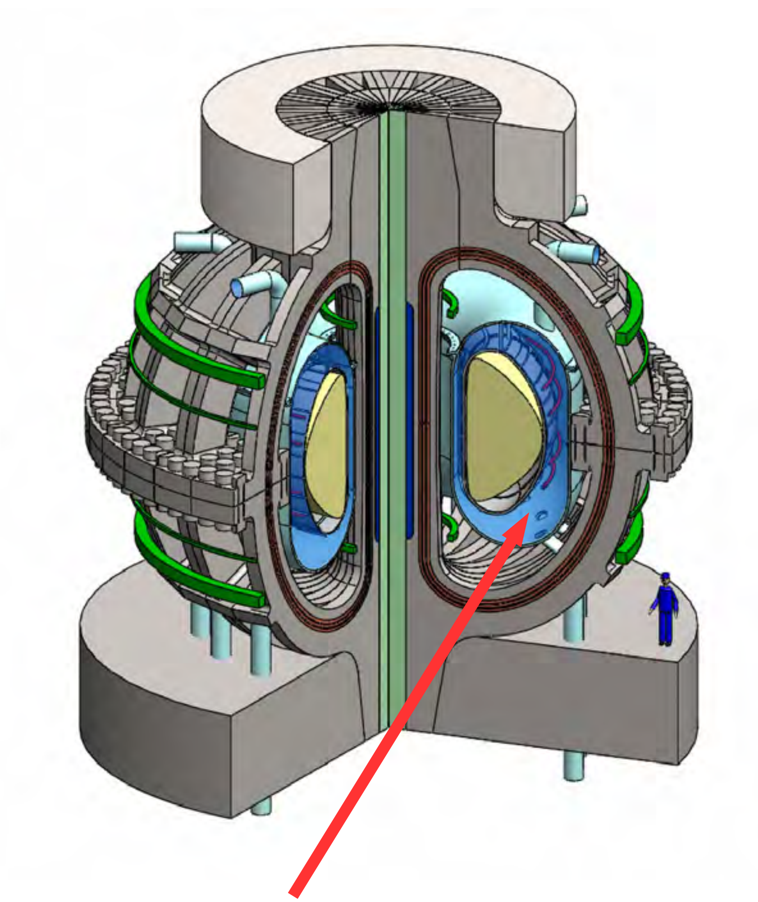


ARIES-AT[3]

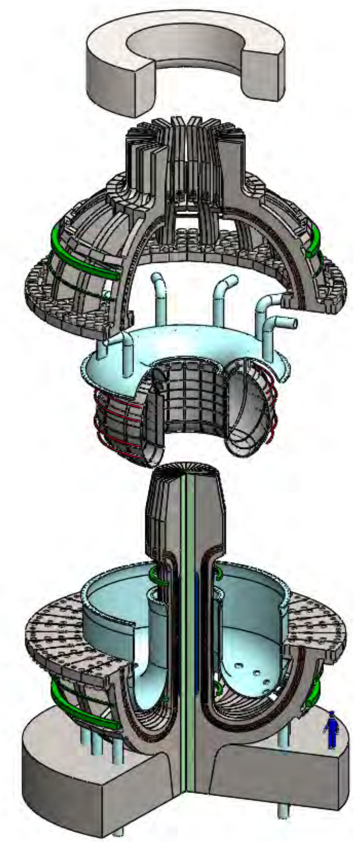


ARC

Liquid immersion blanket fully surrounds the vacuum vessel

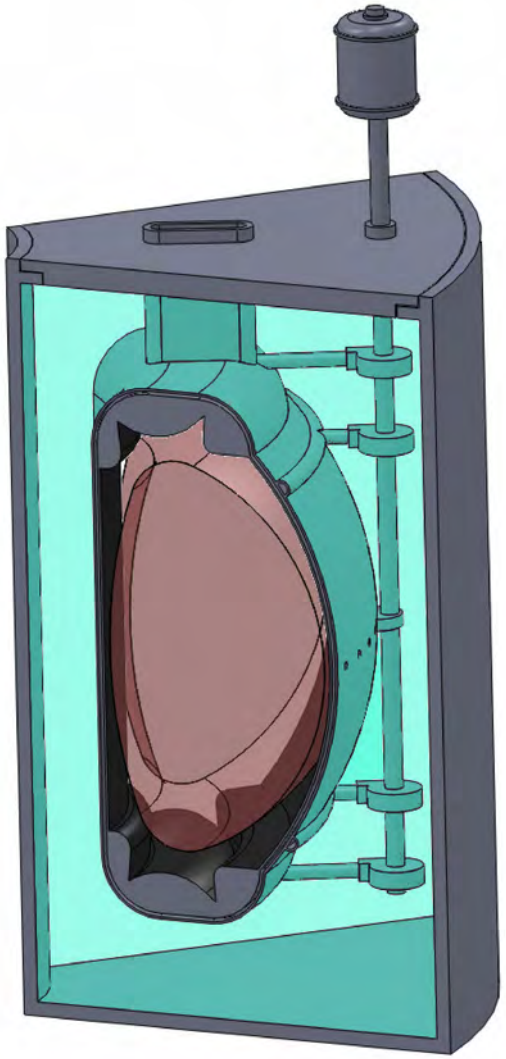


Liquid Blanket
(represented as blue liquid)



Liquid blanket not required for vertical maintenance scheme, but simplifies things considerably

Outline



- What functions do a fusion blanket have to perform?
- Traditional blankets vs. the liquid blanket
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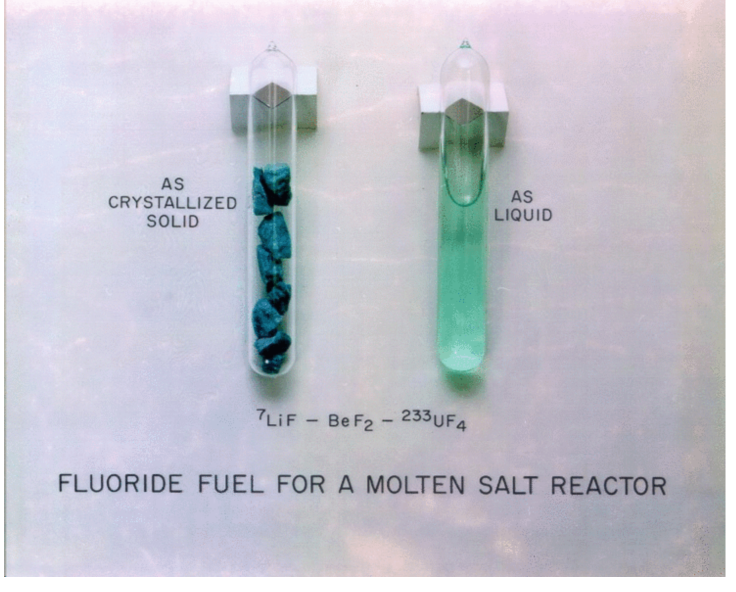
Many liquid blanket candidates have been investigated by the fission community

- For fusion, tritium breeding sets first requirement—the liquid must have some element that can breed tritium
- As mentioned before, lithium is only practical tritium breeding material, so whatever liquid is chosen must contain lithium



- An (incomplete) list of liquid blanket materials
  - **LiF-BeF_2 (FLiBe)**
  - **LiF-NaF-KF (FLiNaK)**
  - Kf-ZrF_4
  - Kcl-$MgCl_2$
  - $NaNO_3$-$NaNO_2$-KNO_3
  - NaF-ZrF4
  - **PbLi**
  - **Liquid lithium**

How does a liquid blanket stack up? – Thermohydraulics

- FLiBe and FLiNaK have the closest heat transfer properties to water
- All liquid blankets look roughly as easy to pump as water...but what about MHD?

Property[2]	FLiBe	FLiNaK	Liquid Li	PbLi	Water
Melting Point (K)	732	727	453	507	273
Density (kg/m^3)	1940	2020	475	8940	1000
Specific Heat (kJ/kg K)	2.4	1.93	4.15	0.19	4.2
Thermal Conductivity (W/m K)	1	0.88	57.7	19.5	0.58
Viscosity (mPa s)	6	4.11	0.280	0.89	1
Reynolds Number[1] normalized to water	**0.32**	**0.49**	**1.7**	**1**	**1**
Prandtl Number normalized to water	**2.4**	**1.26**	**0.002**	**0.001**	**1**

1. Assumed characteristic length of 1m and flow velocity of 0.2 m/s

2. Zinkle, S. J. "Summary of Physical Properties for Lithium, Pb-17Li, and (LiF) n. BeF2 Coolants." APEX Study Meeting, Sandia National Lab. 1998.

MHD effects on liquid metals lead to large pumping power requirement but molten salts are less affected

- We have a liquid moving through an extremely high magnetic field—if the liquid is conductive, this leads to MHD effects!
- Simple flow through a conducting pipe, transverse to a magnetic field leads to the relationship:

$$P_p \propto \sigma_f B_\perp^2$$

- Actual pumping power required is highly dependent on geometry and magnetic field structure, but calculations[1] for simple cooling systems indicate that pumping power for liquid Li is ~10% of the thermal power of fusion device
- **FLiBe and FLiNaK are both orders of magnitude less conductive and would have very small MHD effects**

Property[2]	FLiBe	FLiNaK	Liquid Li	PbLi
Electrical Conductivity, σ_f (S/m)	241	230	2.3×10^6	7.0×10^7

1. Kammash, Terry. "Fusion reactor physics: principles and technology." (1975).
2. Zinkle, S. J. "Summary of Physical Properties for Lithium, Pb-17Li, and (LiF) n. BeF2 Coolants." APEX Study Meeting, Sandia National Lab. 1998.

COMSOL turbulent flow simulation suggests minimal inlet velocity required to exhaust neutron heating

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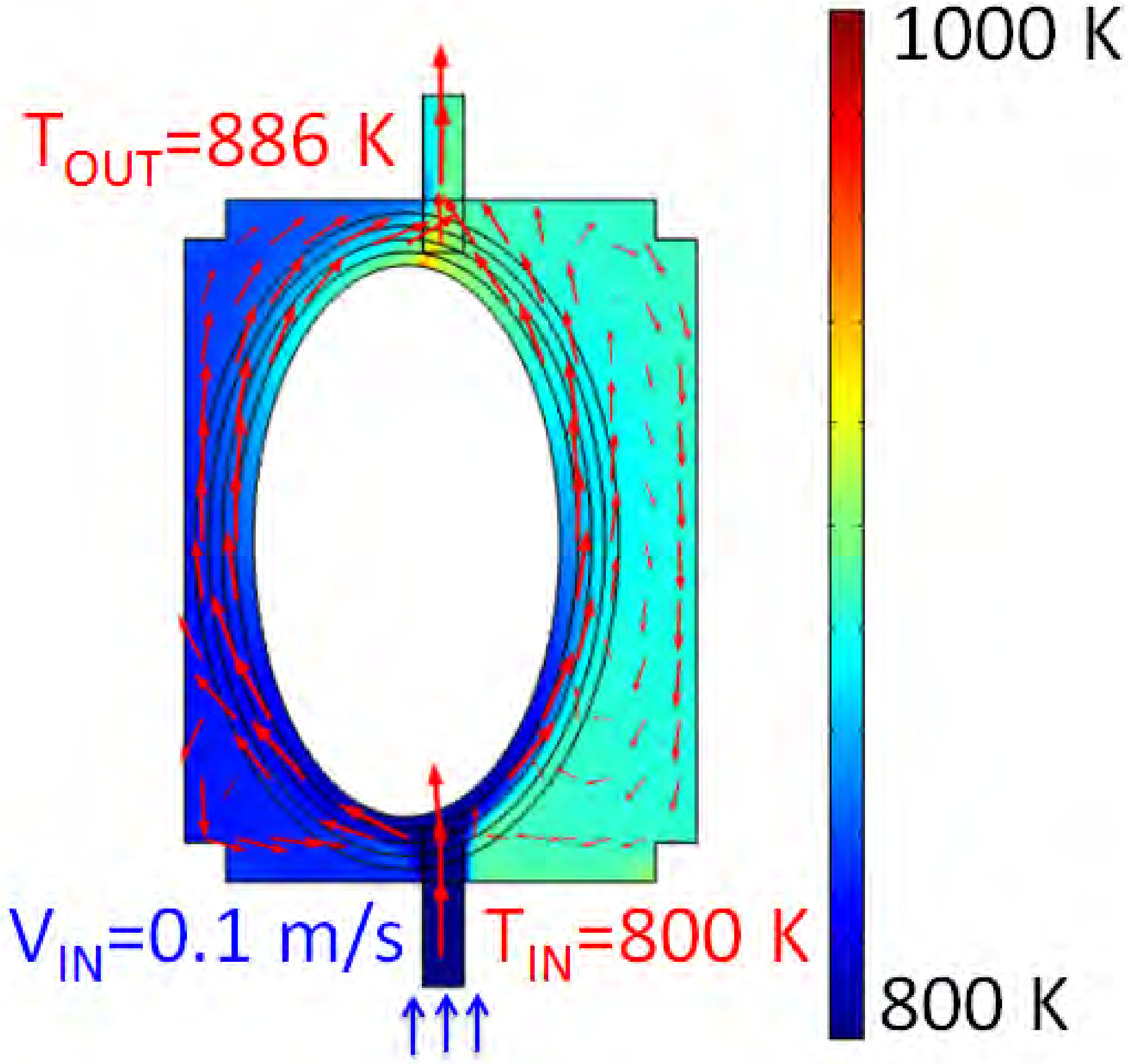
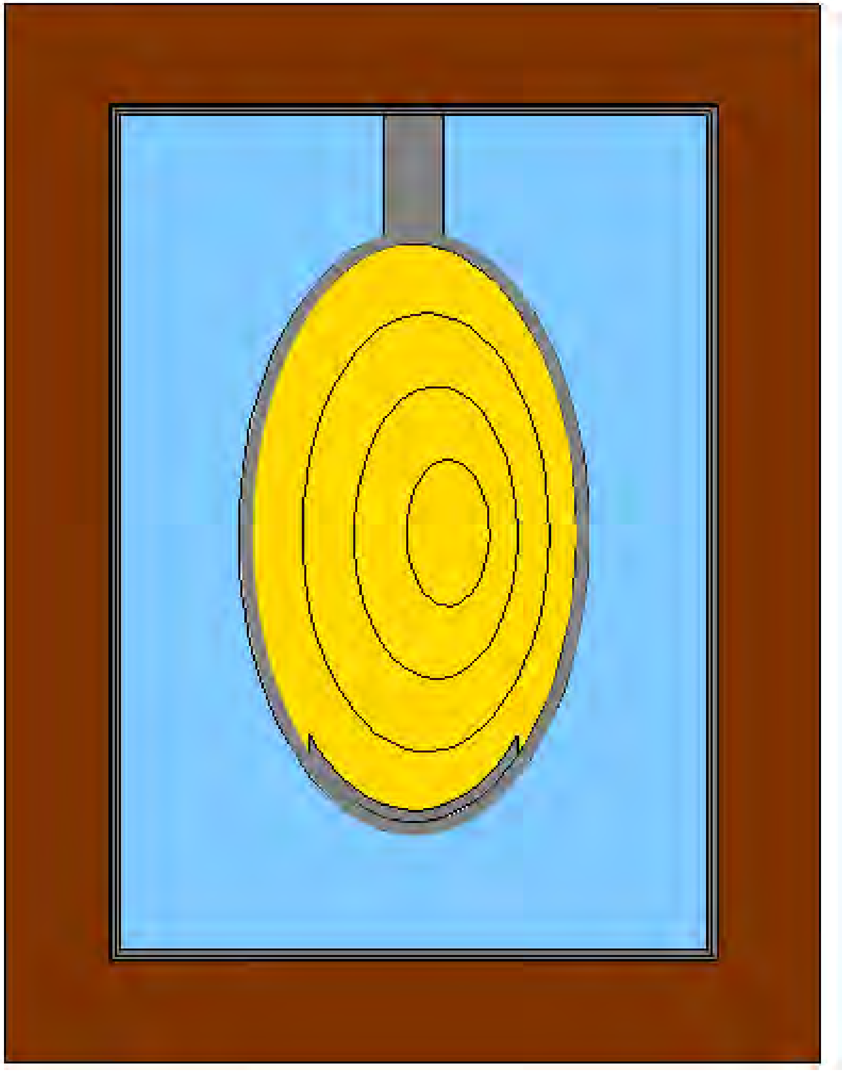
- FLiBe used as molten salt for COMSOL simulation, temperature-dependent properties (e.g. specific heat, thermal conductivity) manually input from literature
- MHD effects considered negligible for FLiBe and are not modeled
- Heating inputs are modeled as conduction through vacuum vessel from plasma heating and volumetric neutron heating assessed using MCNP
- Goal for ARC outlet temperature is approximately 900 K

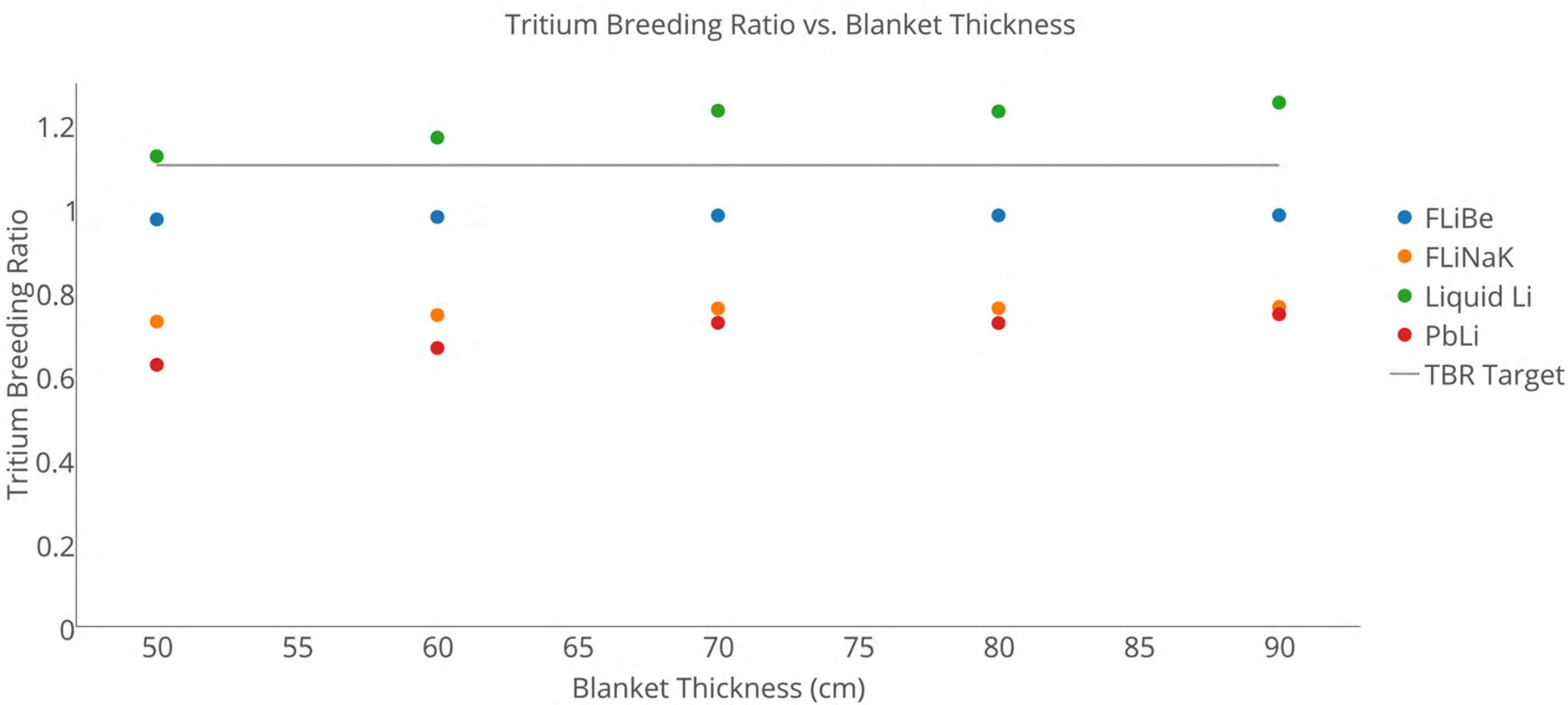


How does a liquid blanket stack up? – Tritium Breeding

- Unlike fission, we actually *want* to breed as much tritium as possible!
- For this assessment, I have used a simple MCNP model of the ARC reactor to compare our four candidates
- Neutron source is a four-volume approximation based on fusion plasma profiles, with most neutron production coming from core (also note that core shifted out due to plasma effects)
- Structural material in model is Inconel 617, a nickel-based alloy
- Vacuum vessel has internal cooling channel to model first wall cooling scheme



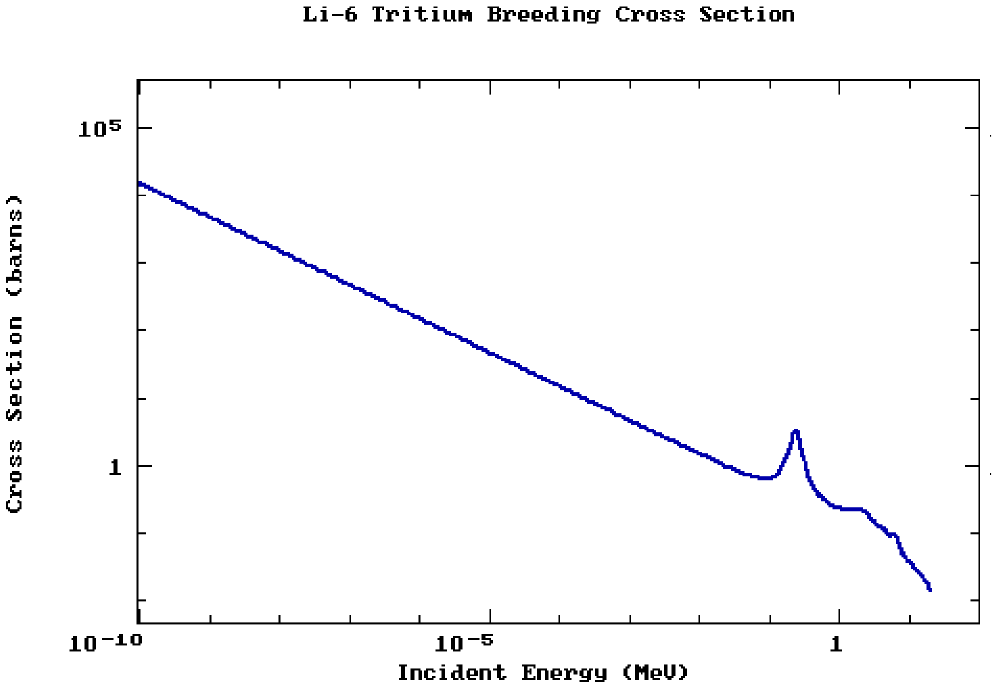
Natural abundance Li liquid blankets struggle to breed enough tritium

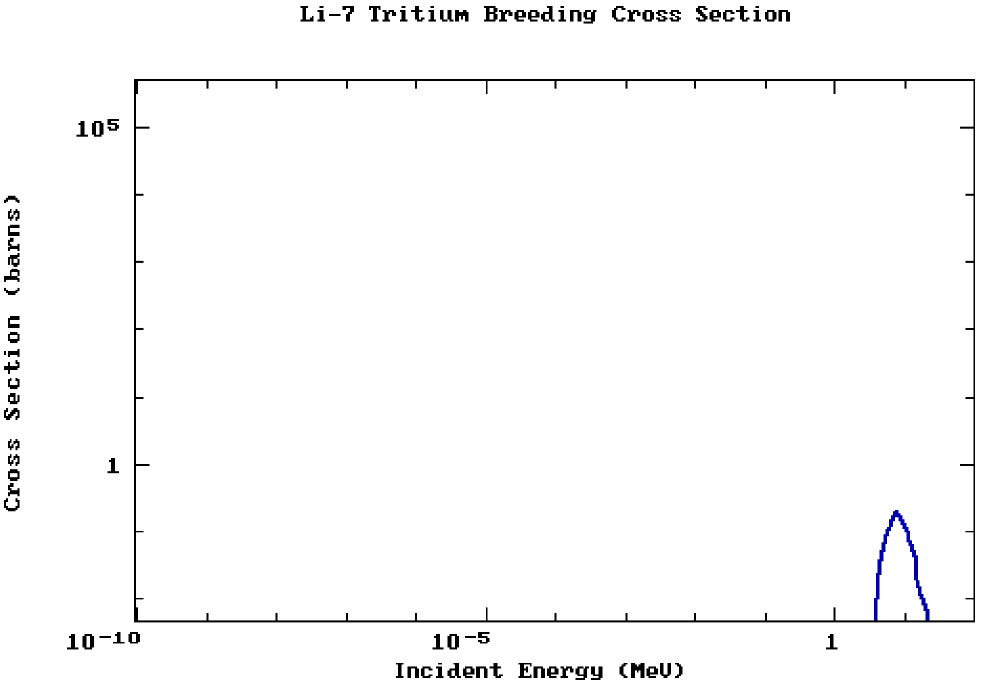


- Liquid lithium is the only blanket material which achieves TBR > 1.1
- Possible to boost breeding capacity by changing isotopic lithium fractions

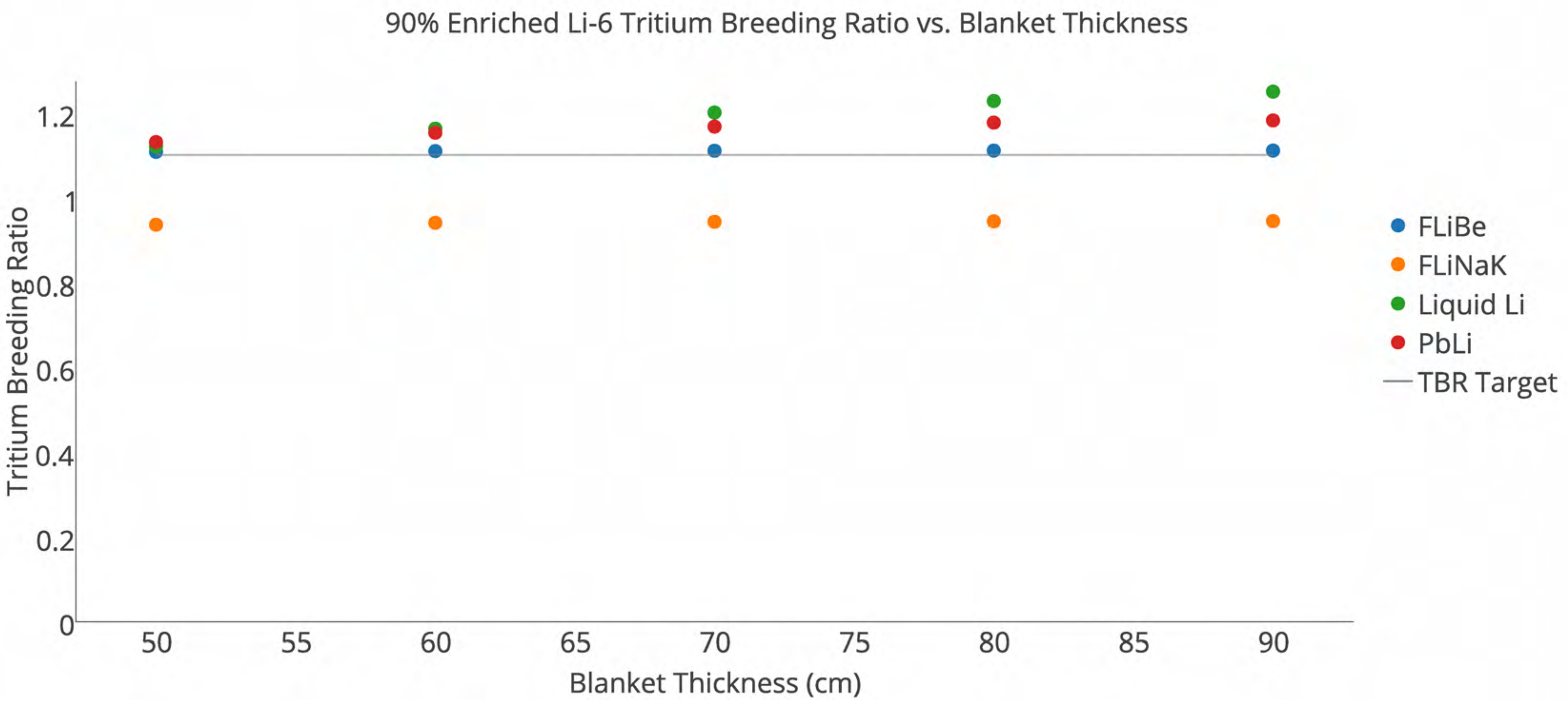
Lithium must be enriched to provide adequate tritium breeding

- Li-6 has an enormously higher breeding cross section than Li-7, extending down to thermal energies
- Natural abundance is 7.5% Li-6 and 92.5% Li-7
- Enriching blanket with Li-6 will increase tritium breeding performance





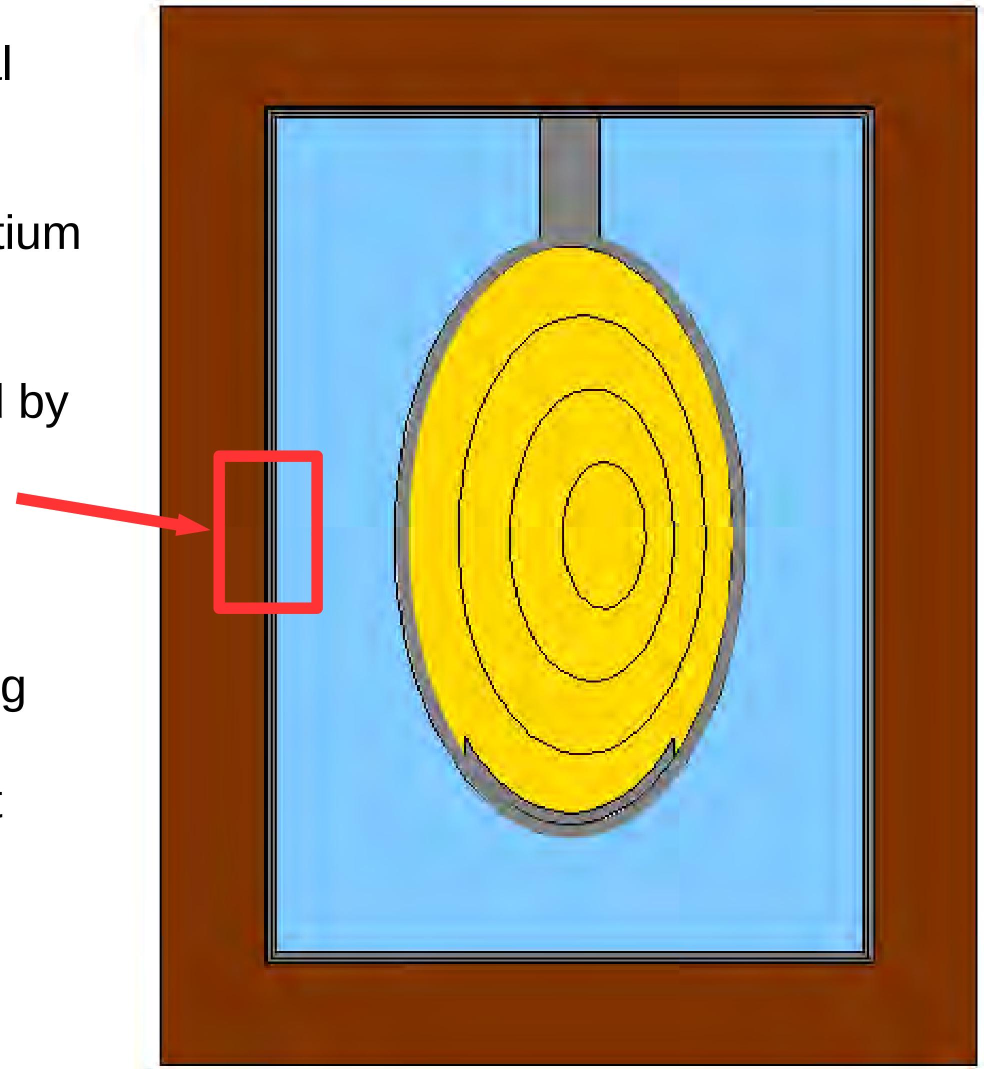
Enriching to 90% Li-6 significantly improves breeding performance



- Enriching to 90% Li-6 allows FLiBe and PbLi to be used as tritium breeders
- Blanket thickness has much less of an effect on breeding for enriched blankets (this will be important later...)

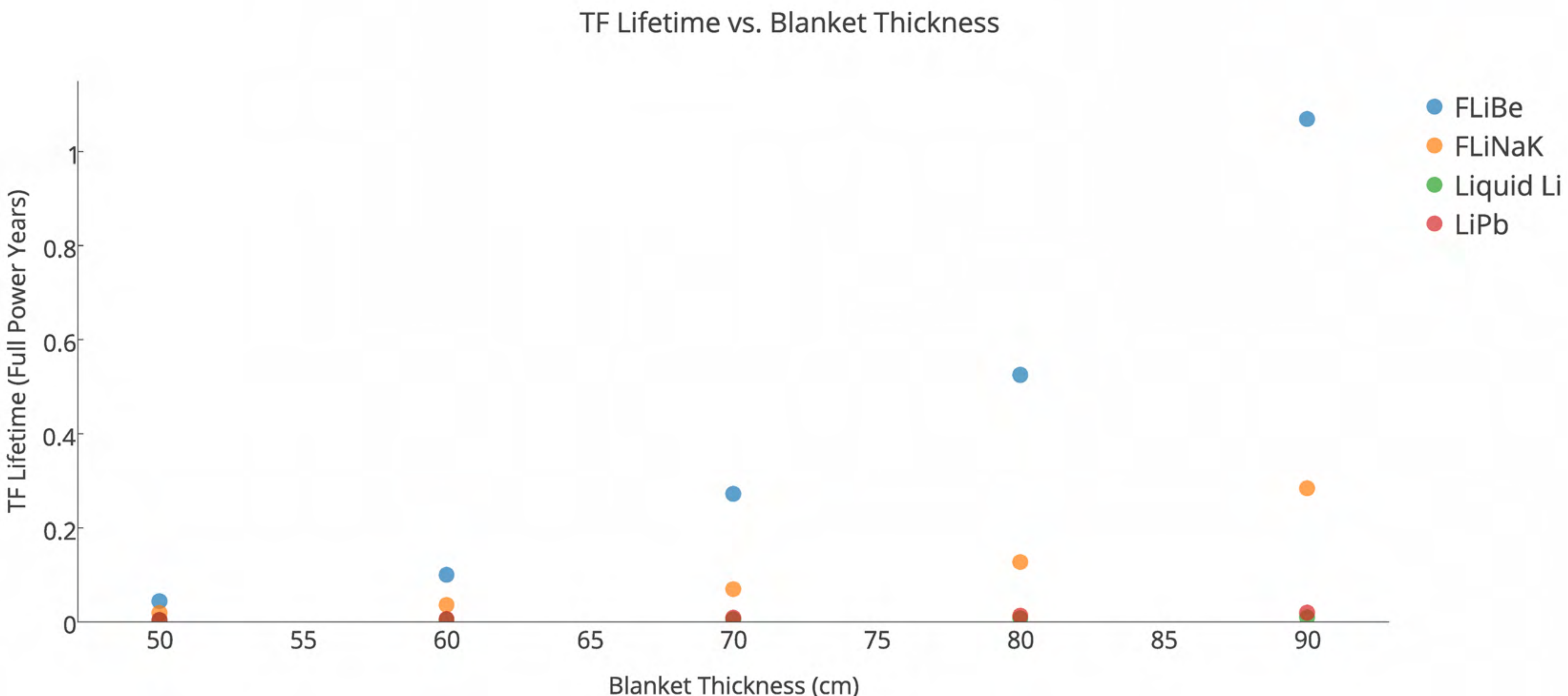
How does a liquid blanket stack up? – TF Shielding

- Also highly dependent on material and geometry
- Use same MCNP model as for tritium breeding calculations
- "Worst case" scenario considered by assessing neutron flux at inner midplane, where space is most limited
- TF lifetime calculated by assuming ARC power (525 MW) and using conservative neutron fluence limit from Nb_3Sn



Liquid blankets are abysmal neutron shields

- Would require a lot of blanket to effectively shield TF, even with the best candidate material
- This requires us to use a secondary shielding material
- Hydrides work well (this was the solution for ARC)



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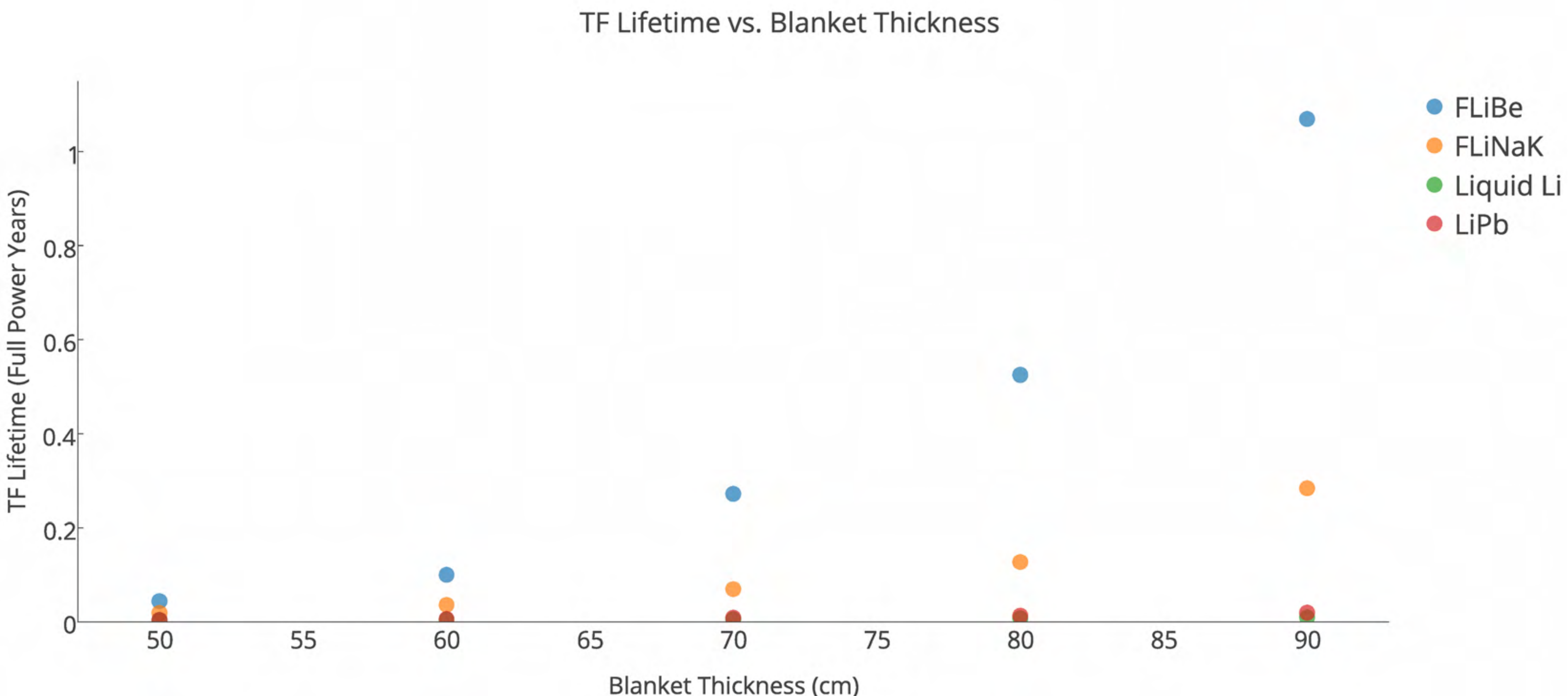
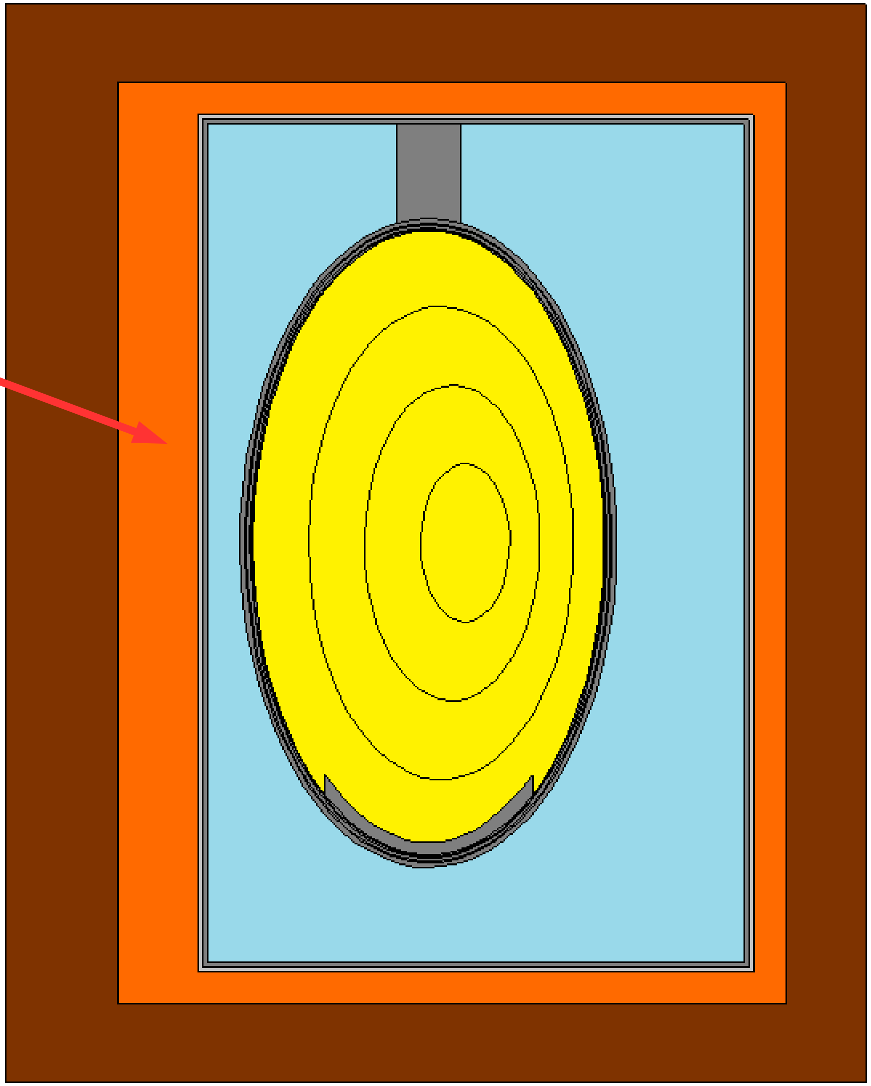


Solid shields on inboard side improve lifetime tremendously

- Solution to TF lifetime problem in ARC was to replace inboard blanket volume with TiH_2 shielding (represented in orange)
- For ARC, replacing 50cm of 70cm blanket with hydride shielding raised TF lifetime to 10 FPY (up from 0.4 FPY for pure FLiBe)
- Since most tritium breeding was found to occur within the first 30-40 cm of blanket, TBR was largely unaffected (1.095 from 1.110)



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Other observations about liquid blankets...

- Less high-Z solid material in blanket means less activated waste and liquid is constantly circulating so less overall neutron exposure to blanket
- Exothermic nuclear reactions in blanket can have a large effect on power balance (ARC blanket reactions contribute ~100 MW on top of the 500 MW of fusion power)

Are we happy or sad about using liquid blankets in fusion?

- Energy conversion? – Happy, liquid blankets have favorable thermohydraulic properties
- Tritium breeding? – Happy, achieve TBR > 1.1
- Shielding? – Mostly happy, can supplement liquid blanket with additional shielding material
- Conclusion: Liquid immersion blankets are an attractive concept, worth pursuing in fusion reactor designs.

References

1. B. Sorbom et al. “ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets,” Submitted to Fusion Engineering and Design (2014)

2. Iter.org, http://www.iter.org/album/media/7%20-%20technical#2044

3. F. Najmabadi et al. "The ARIES-AT advanced tokamak, advanced technology fusion power plant." Fusion Engineering and Design 80.1 (2006): 3-23.

4. Zinkle, S. J. "Summary of Physical Properties for Lithium, Pb-17Li, and (LiF) n. BeF2 Coolants." APEX Study Meeting, Sandia National Lab. 1998.

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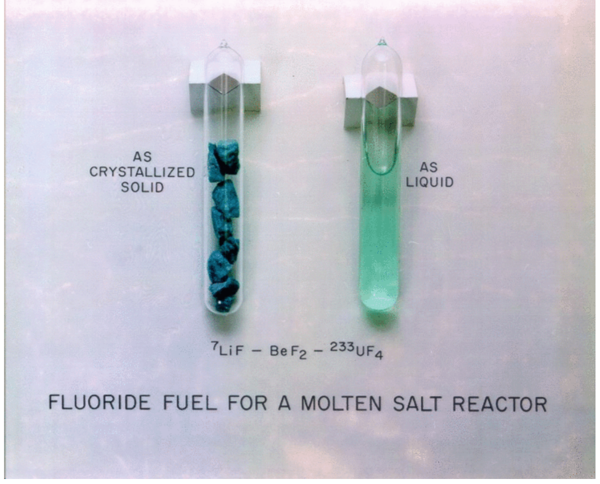
Backup Slides

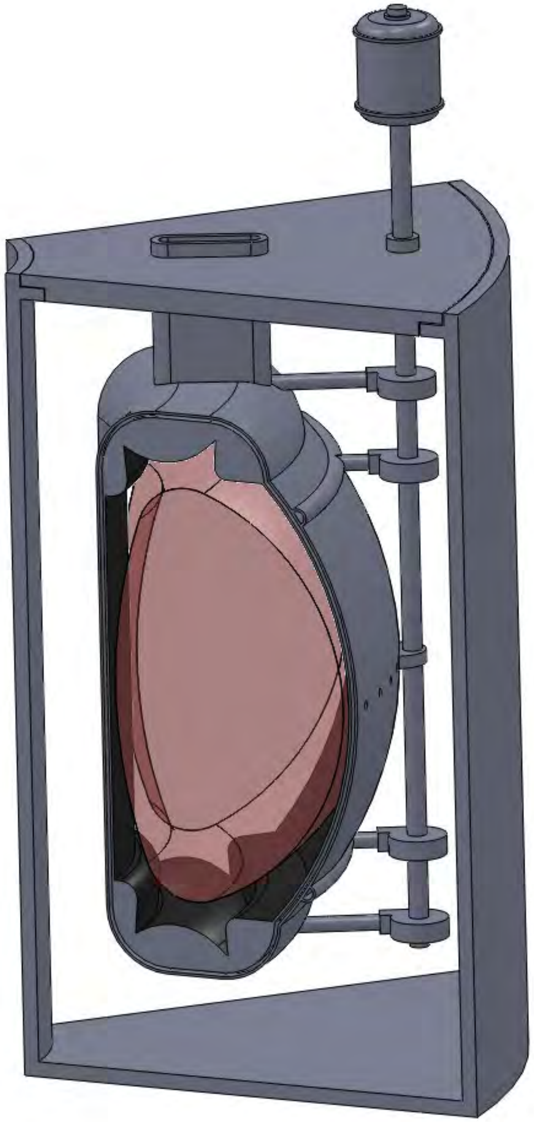
An all-liquid FLiBe blanket provides magnet shielding, tritium breeding, and is a working fluid



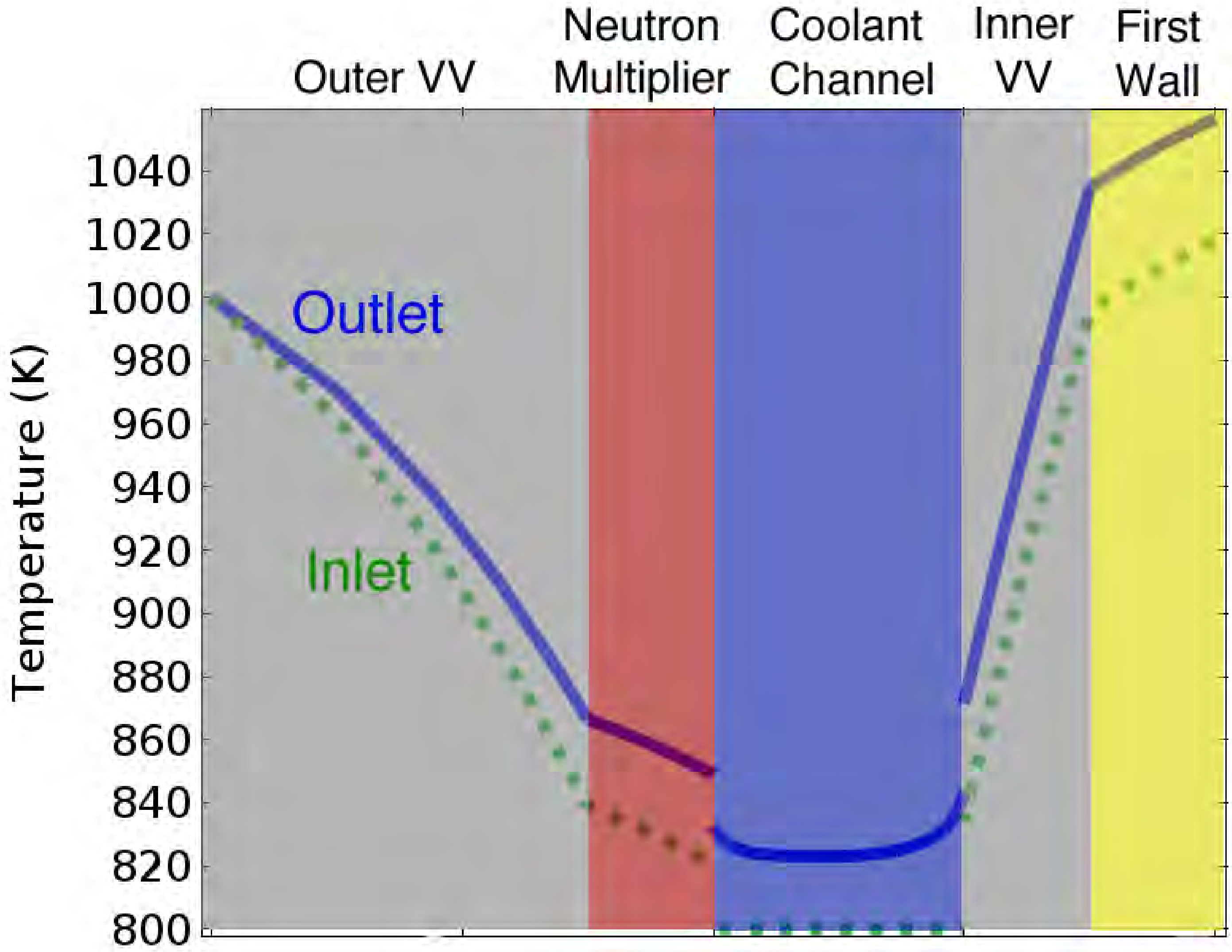
- Molten salt use in reactors is well-studied within fission community
- Fluorine Lithium Beryllium (FLiBe) molten salt has similar thermohydraulic properties to water—but at higher temperature (and operating window)

Property	FLiBe	Water
Melting Point (K)	732	273
Boiling Point (K)	1703	373
Density (kg/m^3)	1940	1000
Specific Heat (kJ/kg K)	2.4	4.2
Thermal Conductivity (W/m K)	1	0.58
Viscosity (mPa s)	6	1

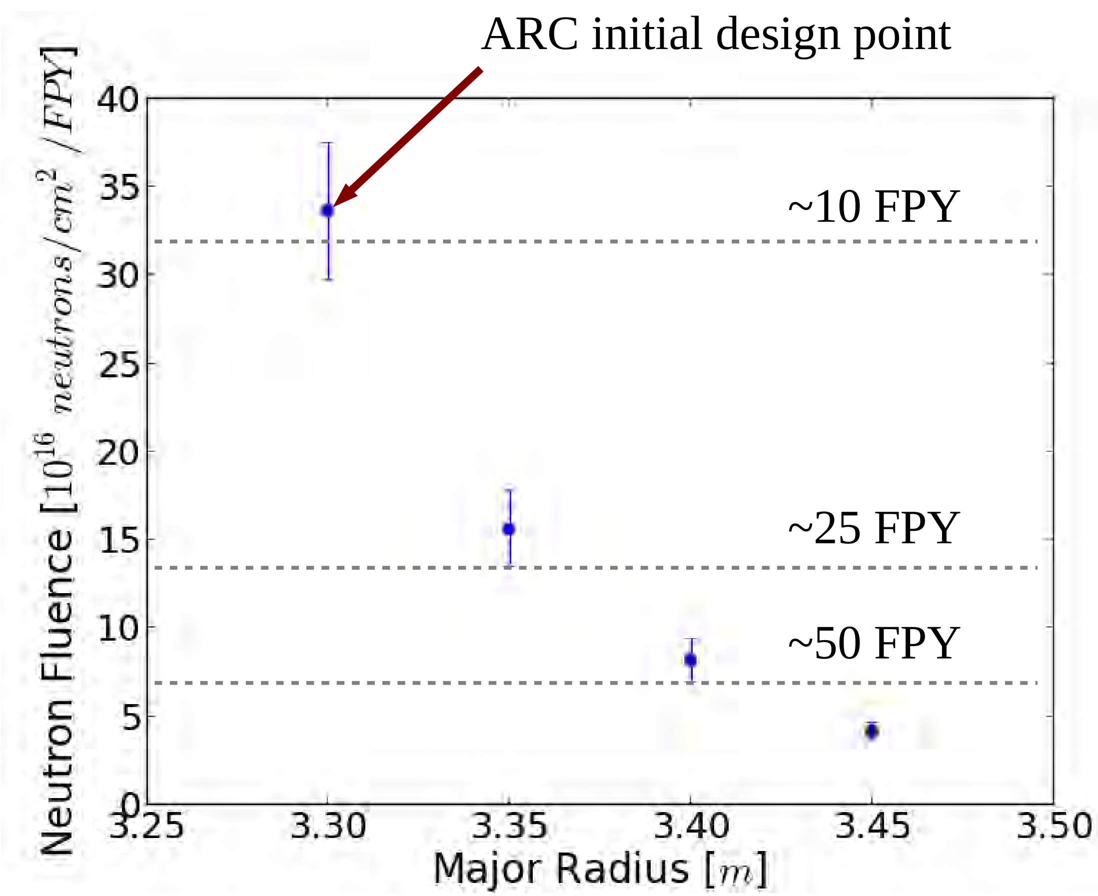
Double-walled Vacuum Vessel



Vacuum vessel has a cooling channel, with higher velocity FLiBe used as coolant

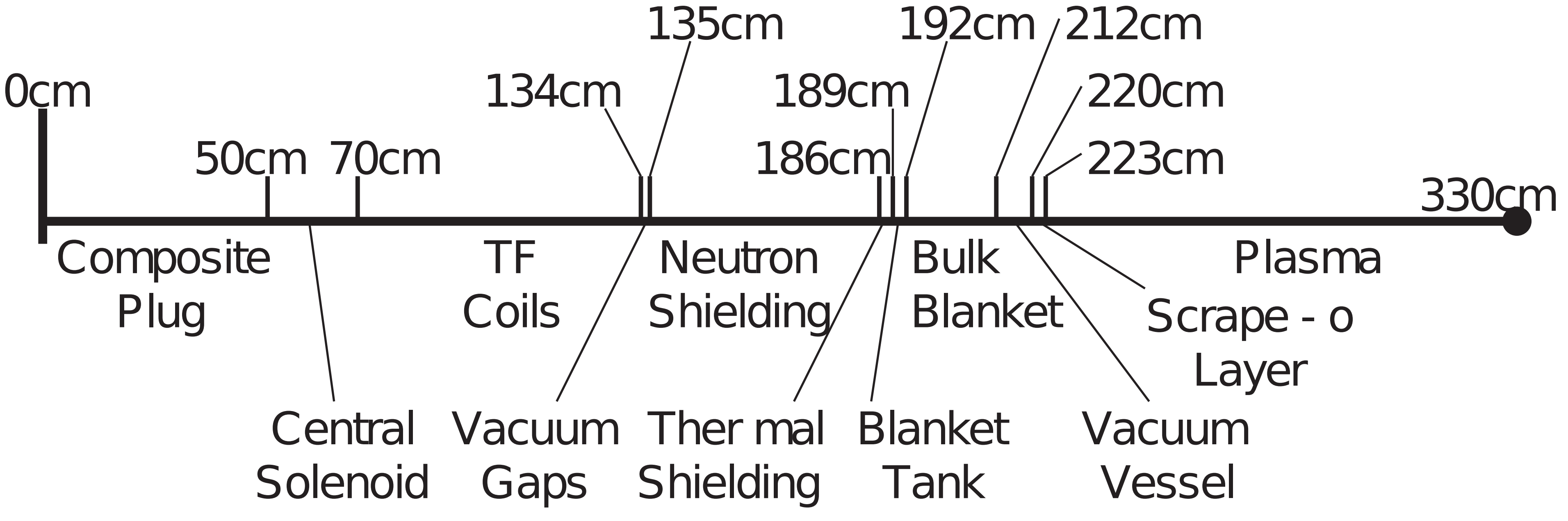


3% increase in R improves coil lifetime by a factor of 5

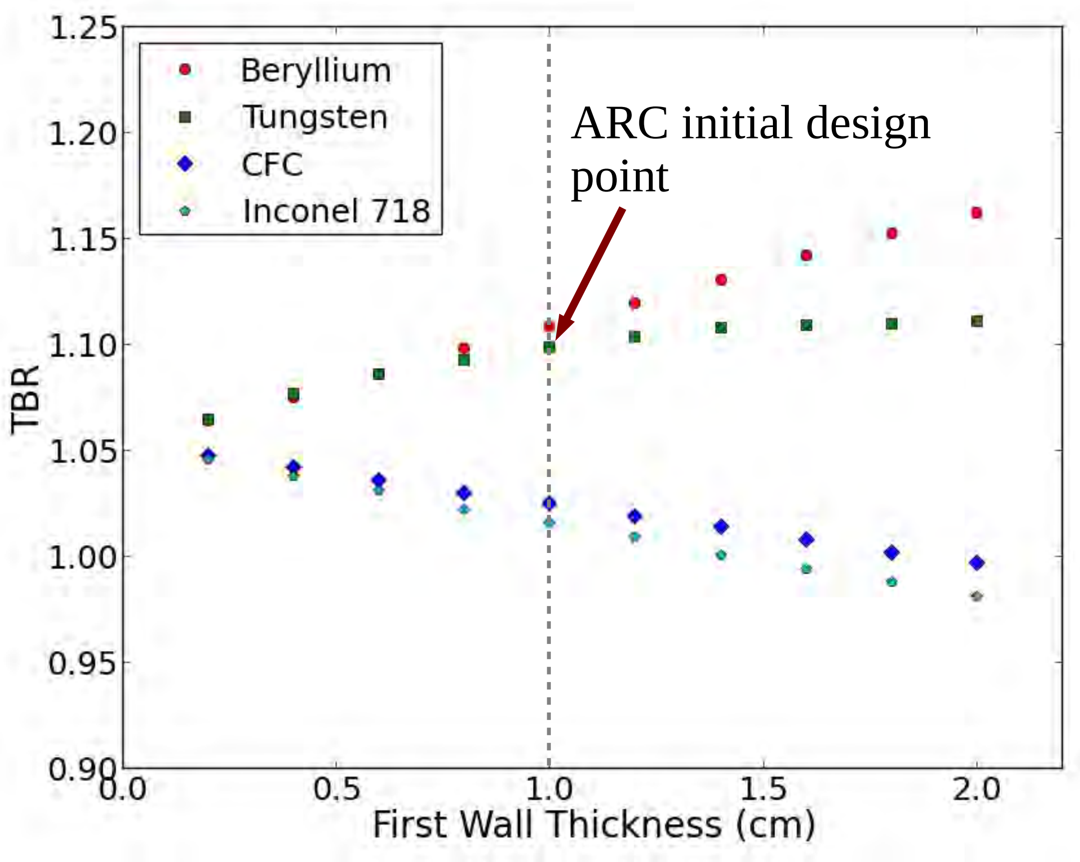


- Reactor lifetime limited by neutron fluence to superconducting coils
- ARC was optimized to provide the most compact reactor, so ~10 full-power year operation is acceptable
- Scaling up reactor size a small amount would allow for much longer lifetime, appropriate for a commercial power plant

ARC Inboard Radial Build



Neutronics simulations indicate range of possible first wall choices



- Tritium breeding ratio (TBR) must be above 1 to breed enough fuel to run reactor
- First wall material and thickness has a large effect on TBR
- ARC will allow multiple vacuum vessel/first wall configurations to be tested without building an entirely new device

Tritium Recovery System

- Full analysis beyond the scope of this conceptual design
- Through a literature search, found recent[1] Japanese studies on T extraction from FLiBe using "counter-current extraction tower"
- Basic concept:
  - Saturate FLiBe with Be to maintain TF concentration in FLiBe
  - Pass saturated FLiBe down through series of filters with He pumped up in opposite direction
  - TF diffuses in He, and T2 is pumped out with He and separated
  - According to study, achieves T recovery > 99.9%

1.) S. Fukada, A design for recovery of tritium from Flibe loop in FFHR-2 (2007)

TBR Uncertainty in Cross Sections for MCNP Calculation

- UCLA study found 2-6% uncertainty in TBR for various materials based on uncertainties in nuclear databases[1]
- Closest material combination to ours (FLiBe/He/FS/Be) had TBR predicted overestimate of ~4.3%
- Total uncertainty subtracted from our TBR still gives a TBR of 1.07

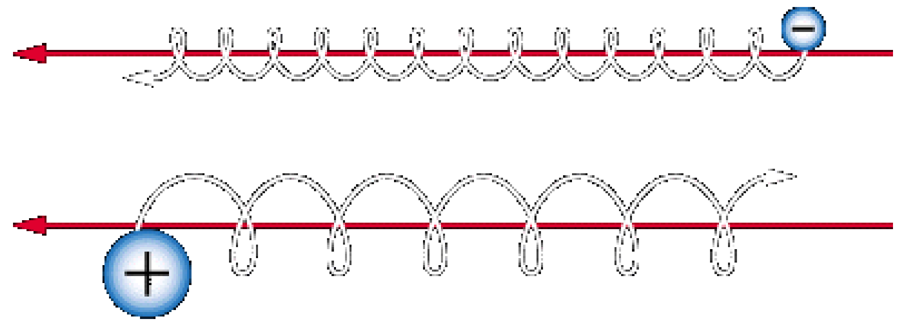
1.) Uncertainties in Prediction of Tritium Breeding in Candidate Blanket Designs Due to Present Uncertainties in Nuclear Data Base, M.Z. Youssef et al, (1986)

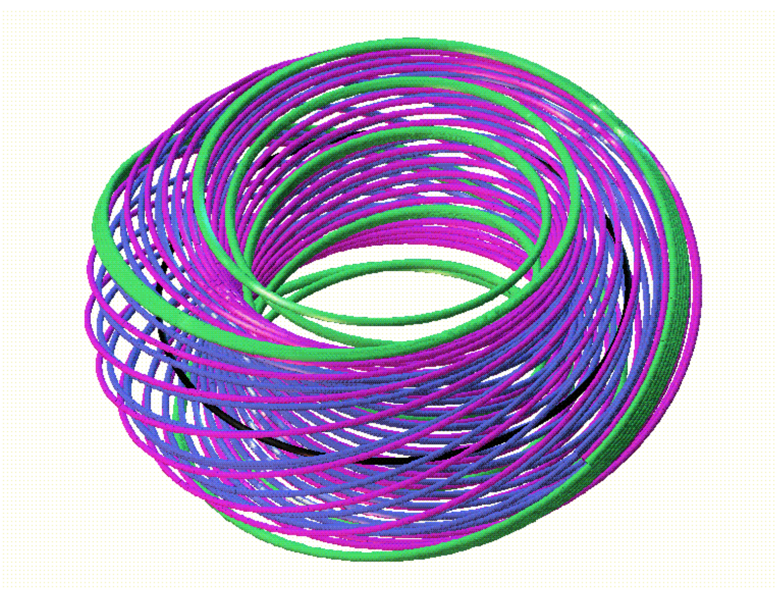
MCNP Validations

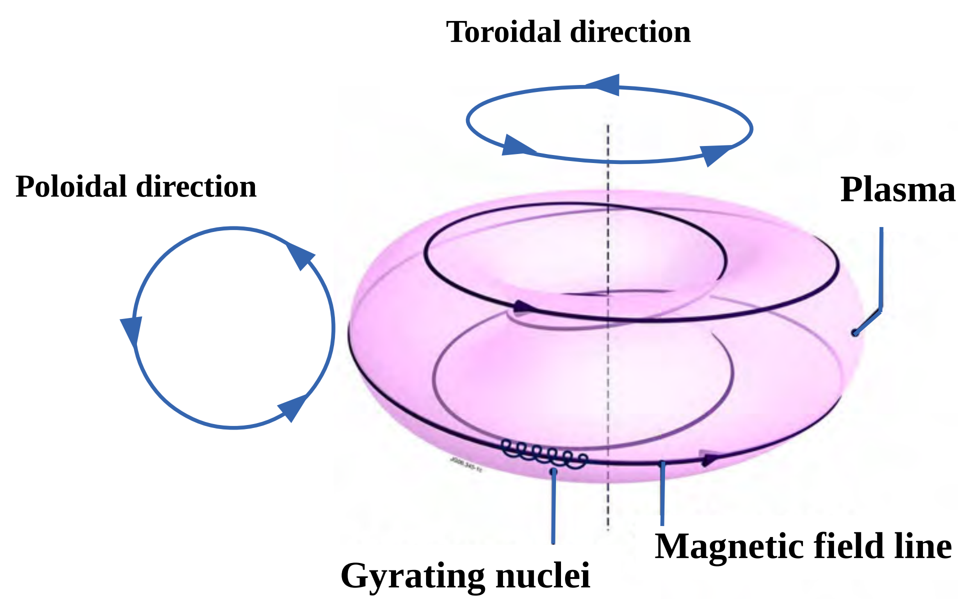
- Simple fluence validation – changed all cells to vacuum and made sure that all source neutrons accounted for
- TBR validated using simple toroidal model and comparing to UW results

Mainstream fusion community has accepted toroidal magnetic confinement as best candidate for fusion energy

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

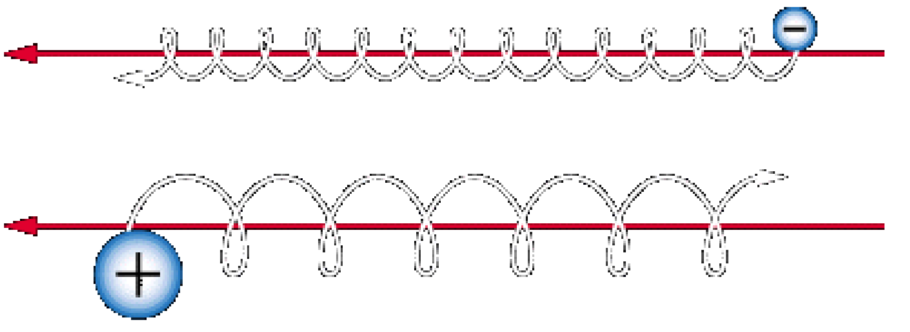




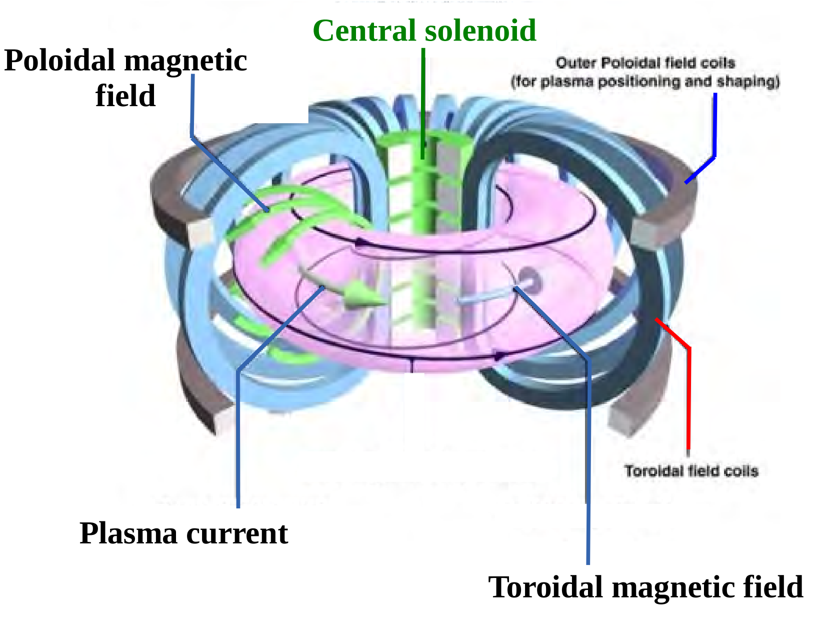


Mainstream fusion community has accepted tokamak magnetic confinement as best candidate for fusion energy

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



- Wrap linear device around into a donut (torus)
- Add a central solenoid to inductively drive current in the plasma and give field lines a helical twist—now you have a tokamak!



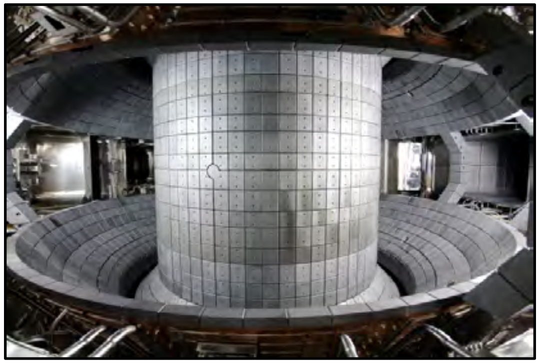
DEPARTMENT OF
NUCLEAR SCIENCE
& ENGINEERING

Fusion research is a serious, multinational effort, specifically tokamak research

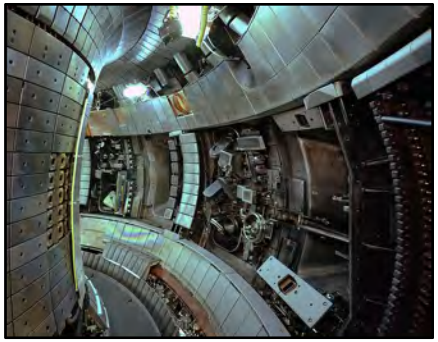
Alcator C-Mod
Cambridge, MA, USA

EAST (HT-7)
Hefei, Anhui, China

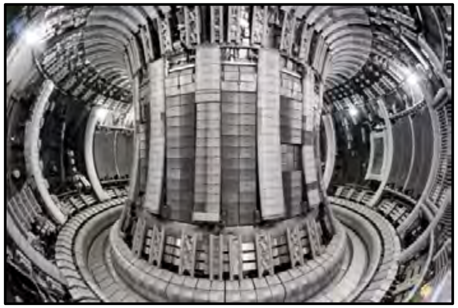
KSTAR, *Daejeon, Republic of Korea*



ASDEX Upgade
Garching, Germany



Joint European Torus (JET)
Culham, Oxfordshire, UK

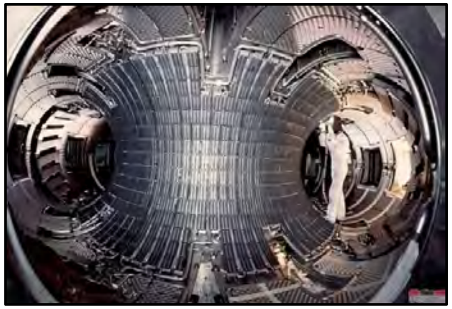


SST-1, *Gandhinagar, Gujarat, India*

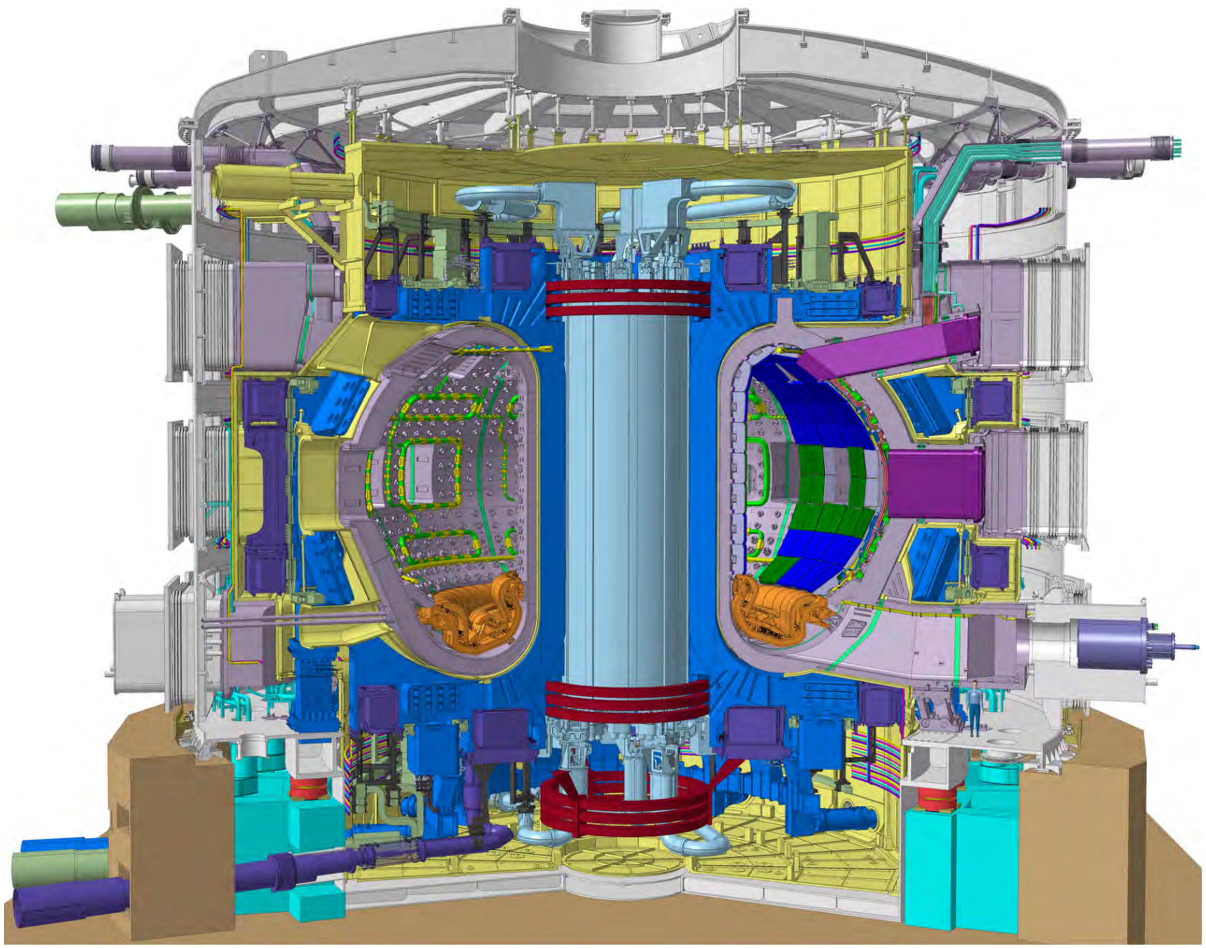
DIII-D, *San Diego, CA, USA*

JT-60SA (under construction)
Naka, Japan

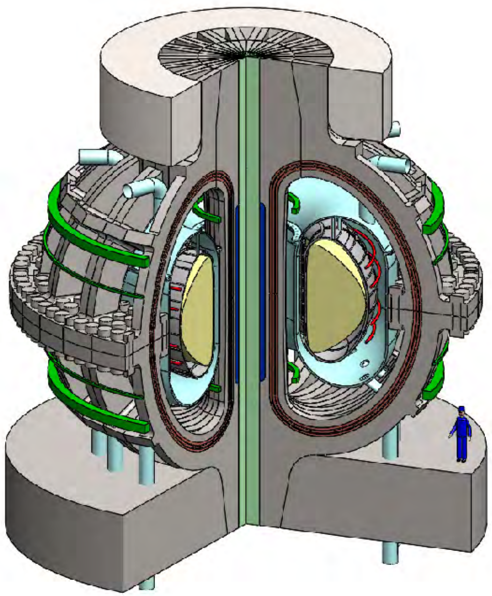
Tore Supra, *Cadarache, France*



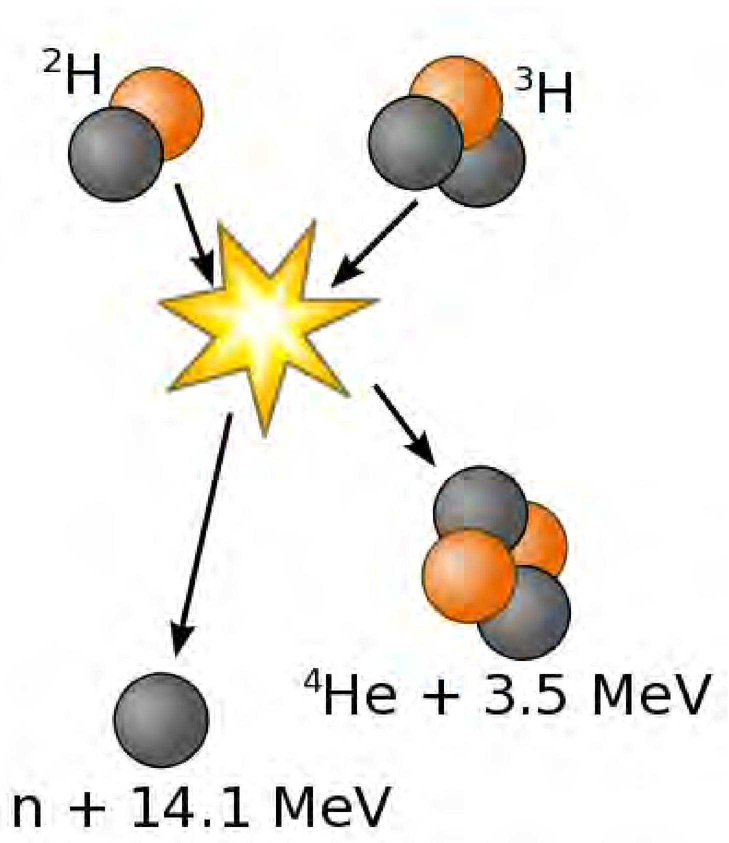
ARC is significantly smaller than ITER with the same fusion power



- Both machines produce ~ 500 MW of fusion power
- Engineering drawings are same scale



The DT reaction is most favorable for a fusion reactor

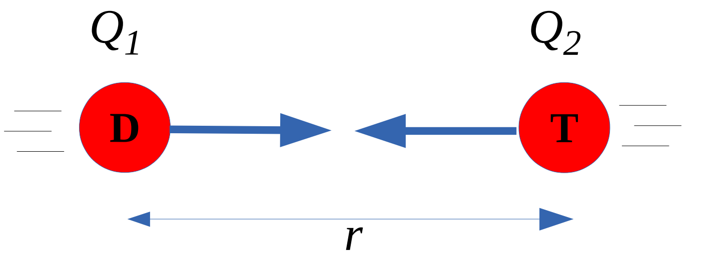


- Fusion reactions which release energy are possible for many light nuclei
- The most promising reaction is the reaction between deuterium and tritium (abbreviated DT), two isotopes of hydrogen
- The sun uses pure hydrogen fusion (really inefficient but the sun is big enough)

Nuclei must overcome Coulomb repulsion in order to fuse

- Potential energy between two charged particles is given by:

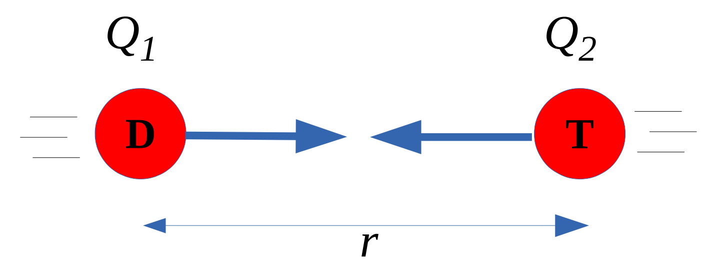
$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$



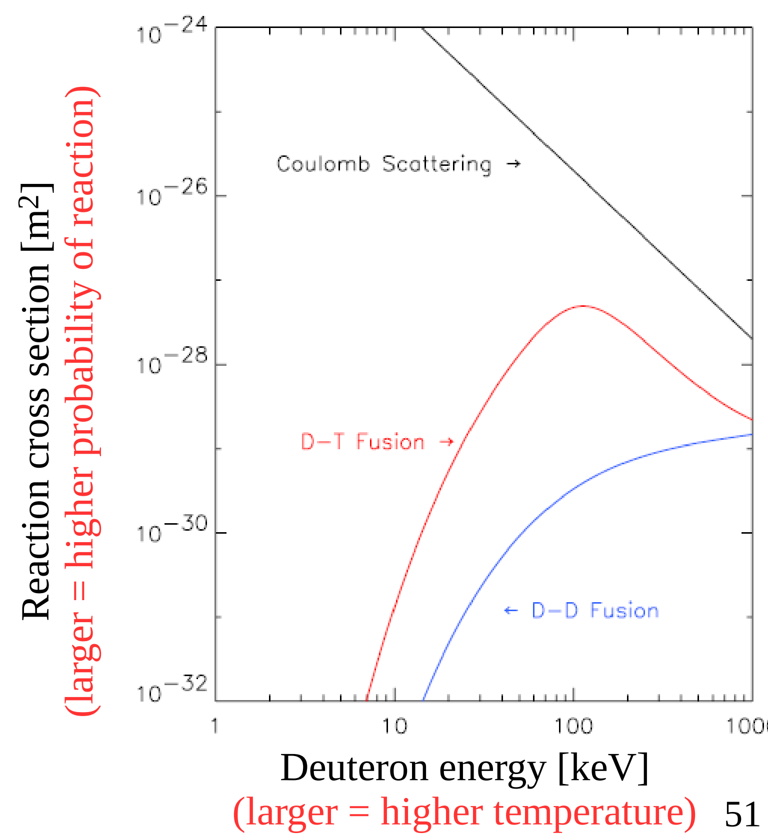
This requires particles to be moving really, really fast!

- Potential energy between two charged particles is given by:

$$U = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r}$$



- As particles get close enough to fuse, potential energy "barrier" increases
  - Particles need to move fast → i.e. need high energy → i.e. need high heat
  - For D-T, minimum energy for fusion is 10 keV, roughly 100 million Kelvin*



* or Celsius, it doesn't really matter at this high of a temperature...

Temperatures required for fusion necessitates confinement of plasma

- Matter at thermonuclear fusion temperatures only exists in a plasma state
- Plasma is the "fourth" state of matter where electrons are ripped off of nuclei and gas becomes ionized
- So how do you confine a superheated, charged gas?