Engine Design for LIFE

Presentation to

National Academy of Science

National Academy of Engineering

January 29, 2011

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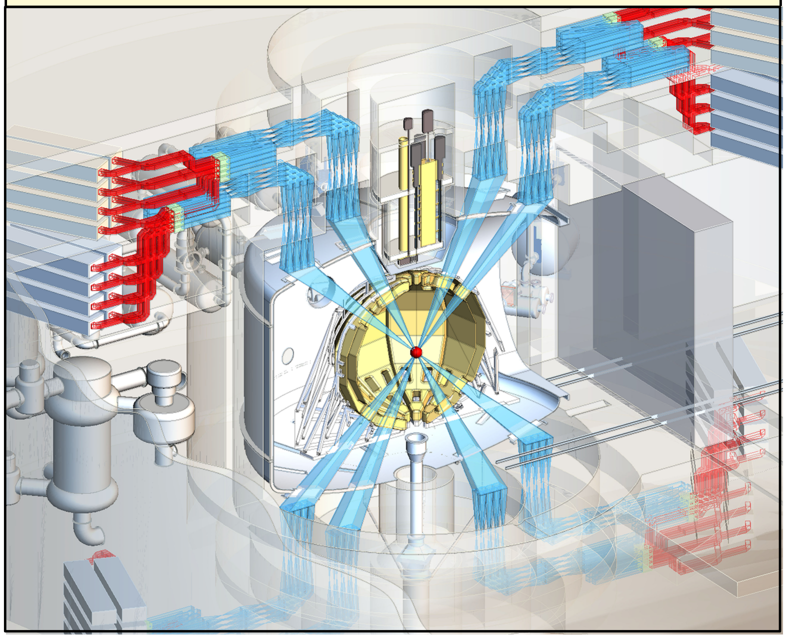
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

LIFE makes maximum use of available technologies, industrial capabilities and simplicity in design

Chamber designed to be modular and easily replaceable



Gas-protected first wall enables use of steels

Coolant selection and large chamber coverage provide ample tritium breeding margin and high blanket gain

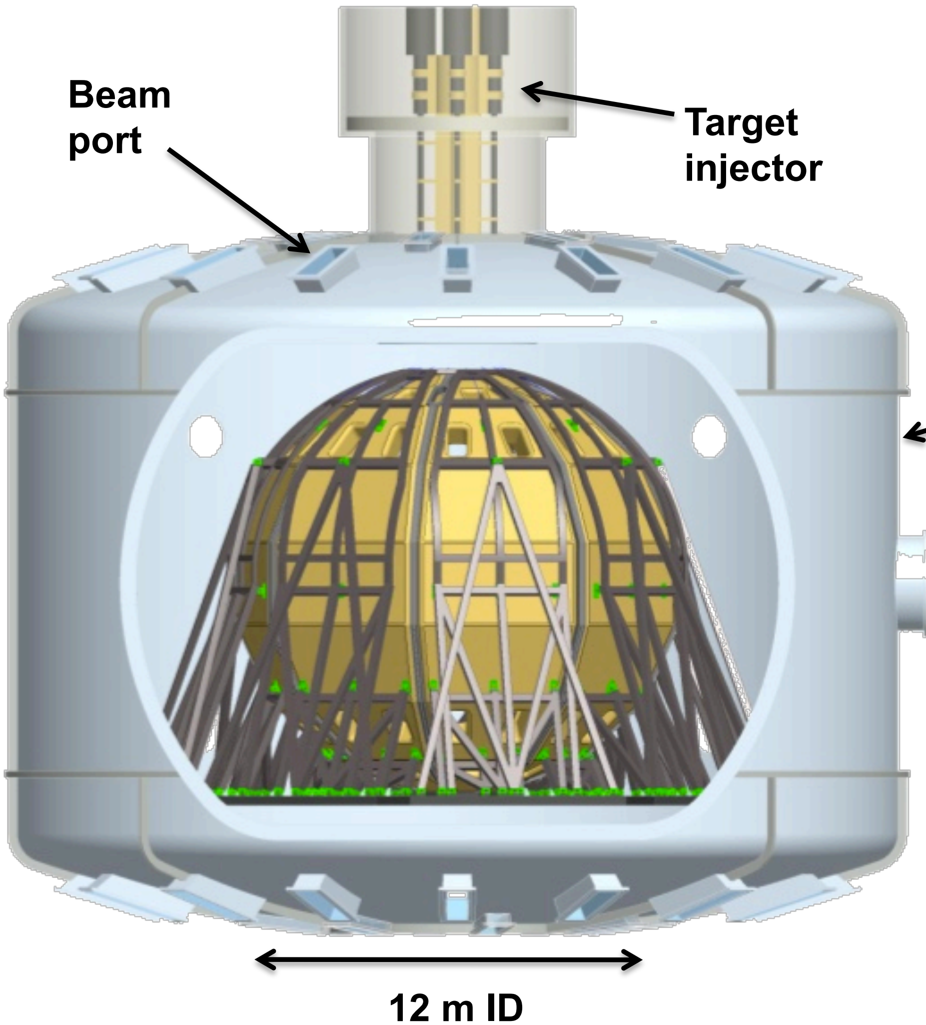
Coolant selection greatly reduces tritium permeation and reduces site inventory

Target material selection eliminates need for chamber clearing

Commercially available power cycle provides high (and improving) efficiency

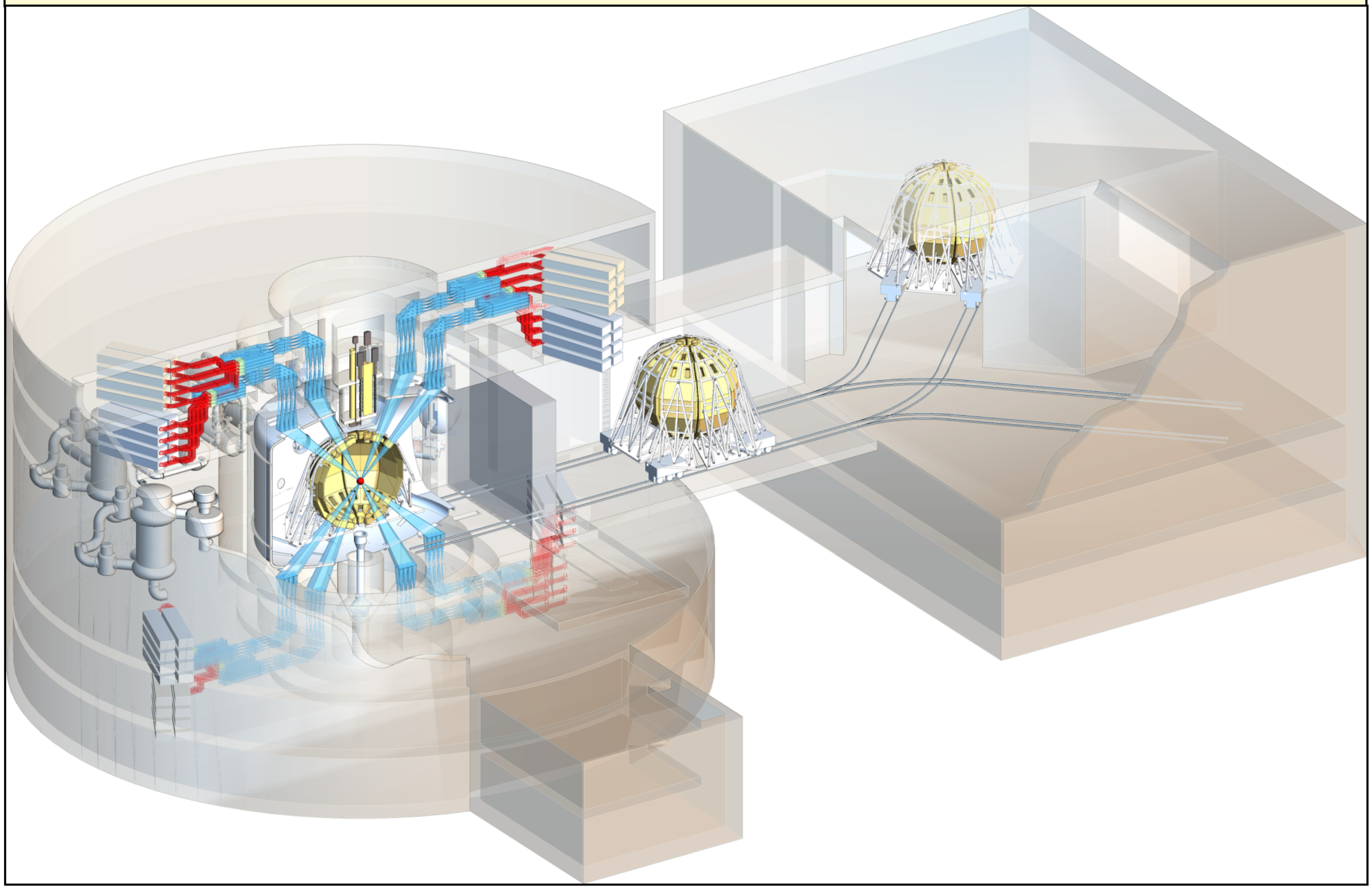
Radiation-tested final optic solution is available

The LIFE "chamber" is an unsealed, segmented array sitting within a low pressure gas environment

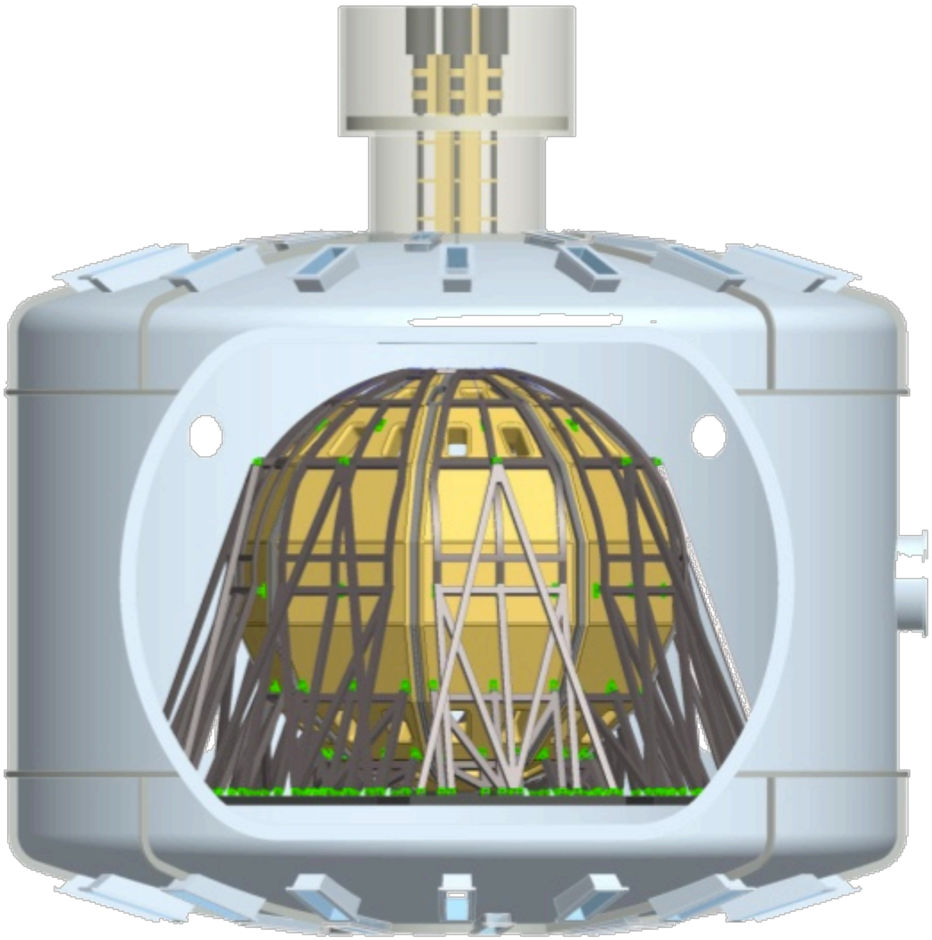


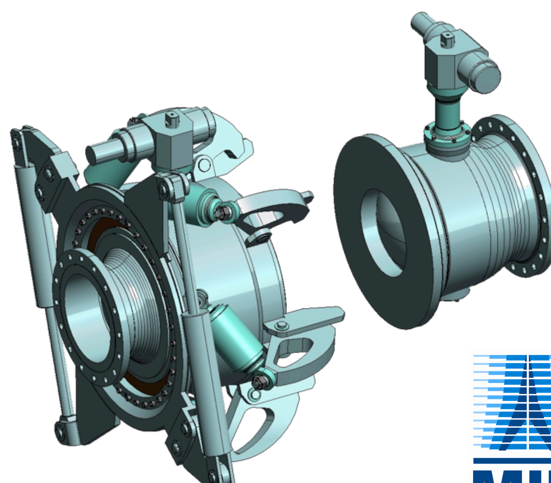
The chamber system can be transported for maintenance or replacement

Unsealed chamber, separate from the vacuum and optical systems



Once moved to the engine bay, cooling connections are made with hydraulic couplers from industry





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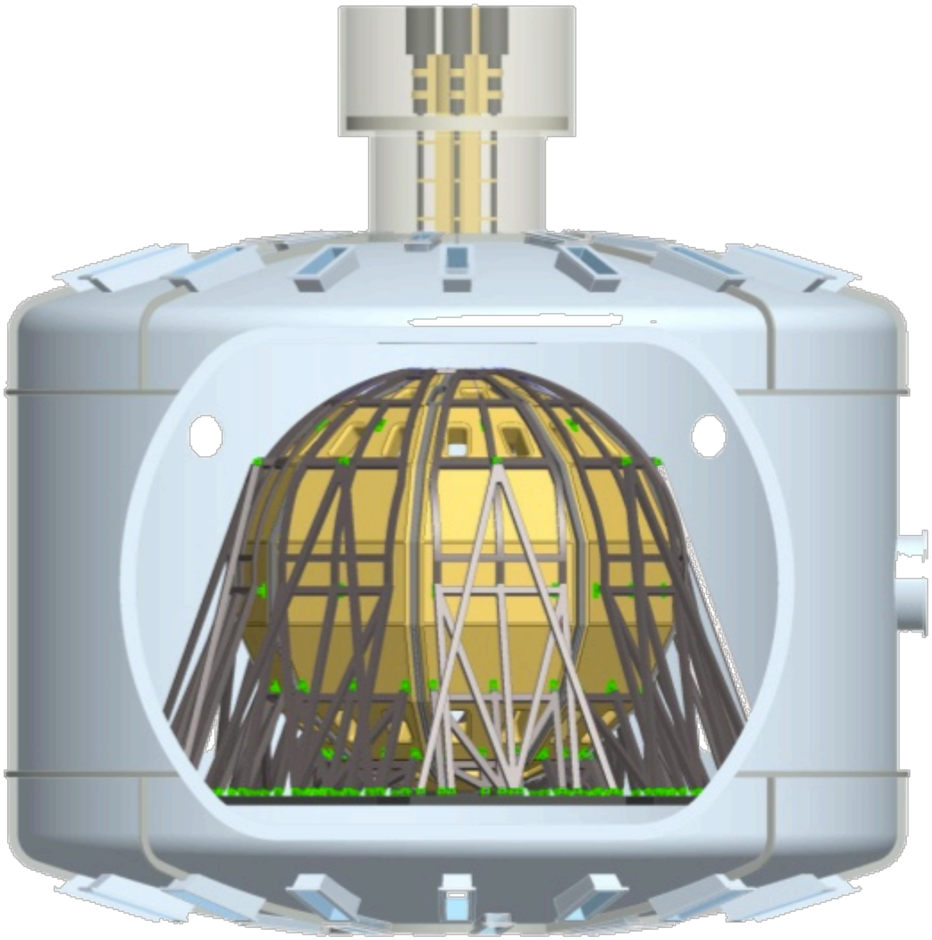
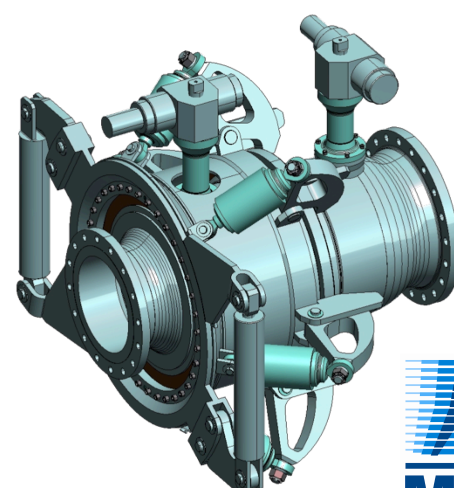
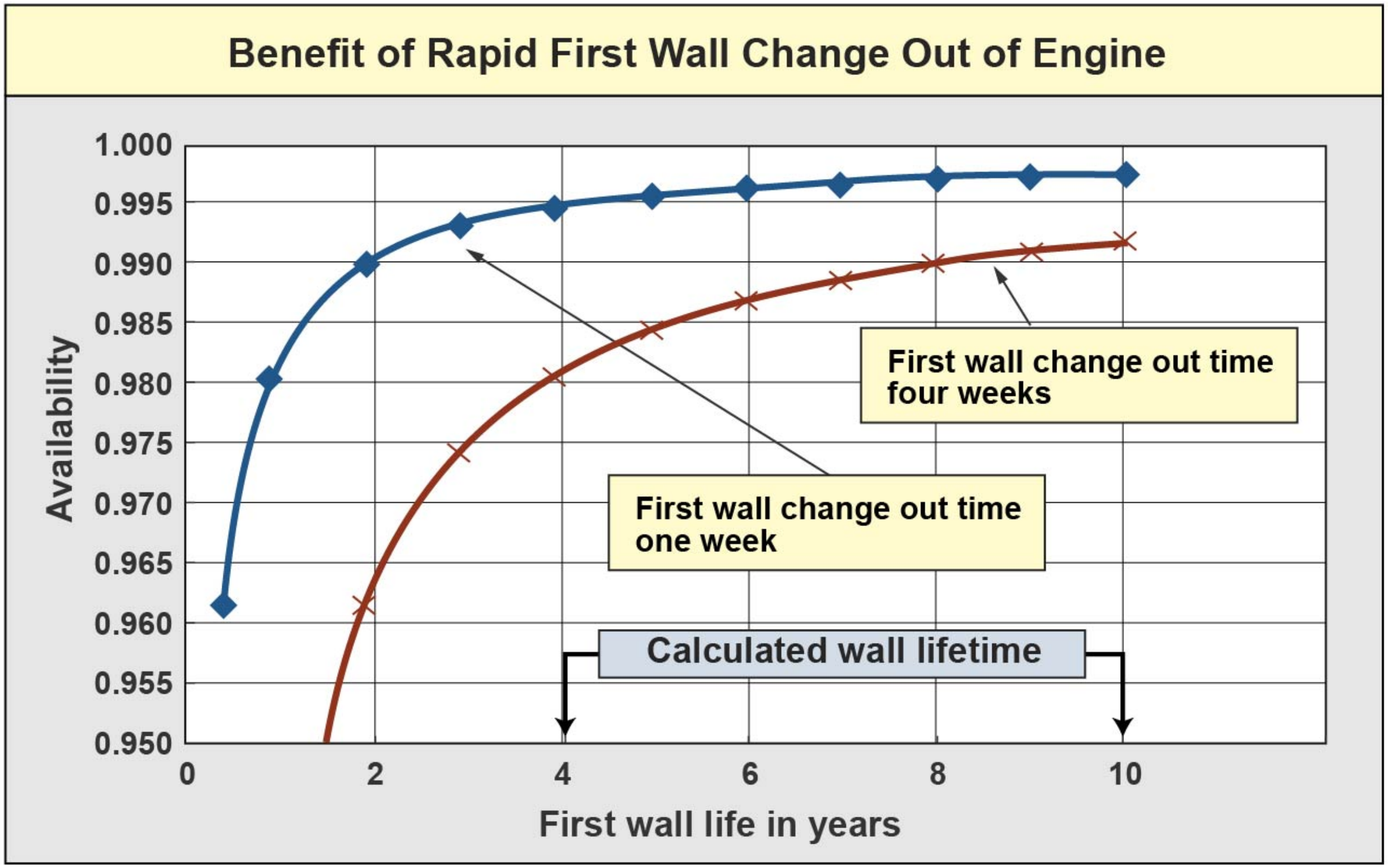


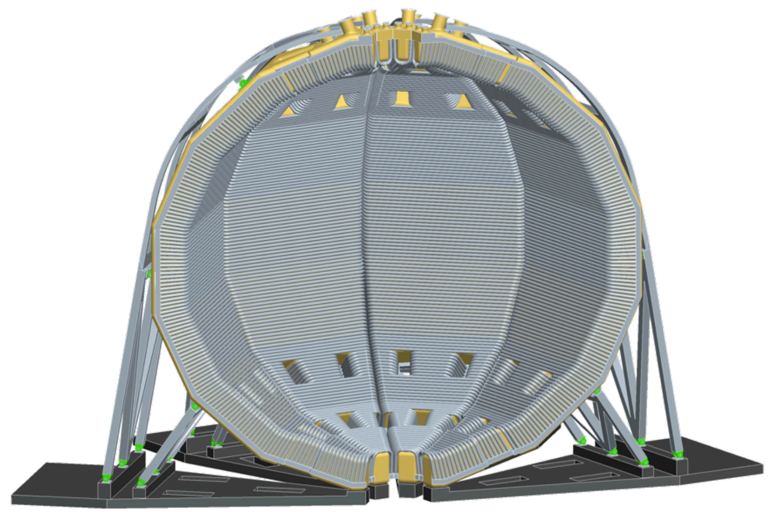


Chamber modularity results in high plant availability



First wall is comprised of U-shaped steel tubes with high strength-to-weight ratio

- 6 m radius chamber lined with 10 cm diameter, 1 mm thick tubes
- Chamber is *NOT* the vacuum barrier
- Tubes provide excellent strength and superior cooling
- Tubes can be manufactured today via extrusion and flow forming

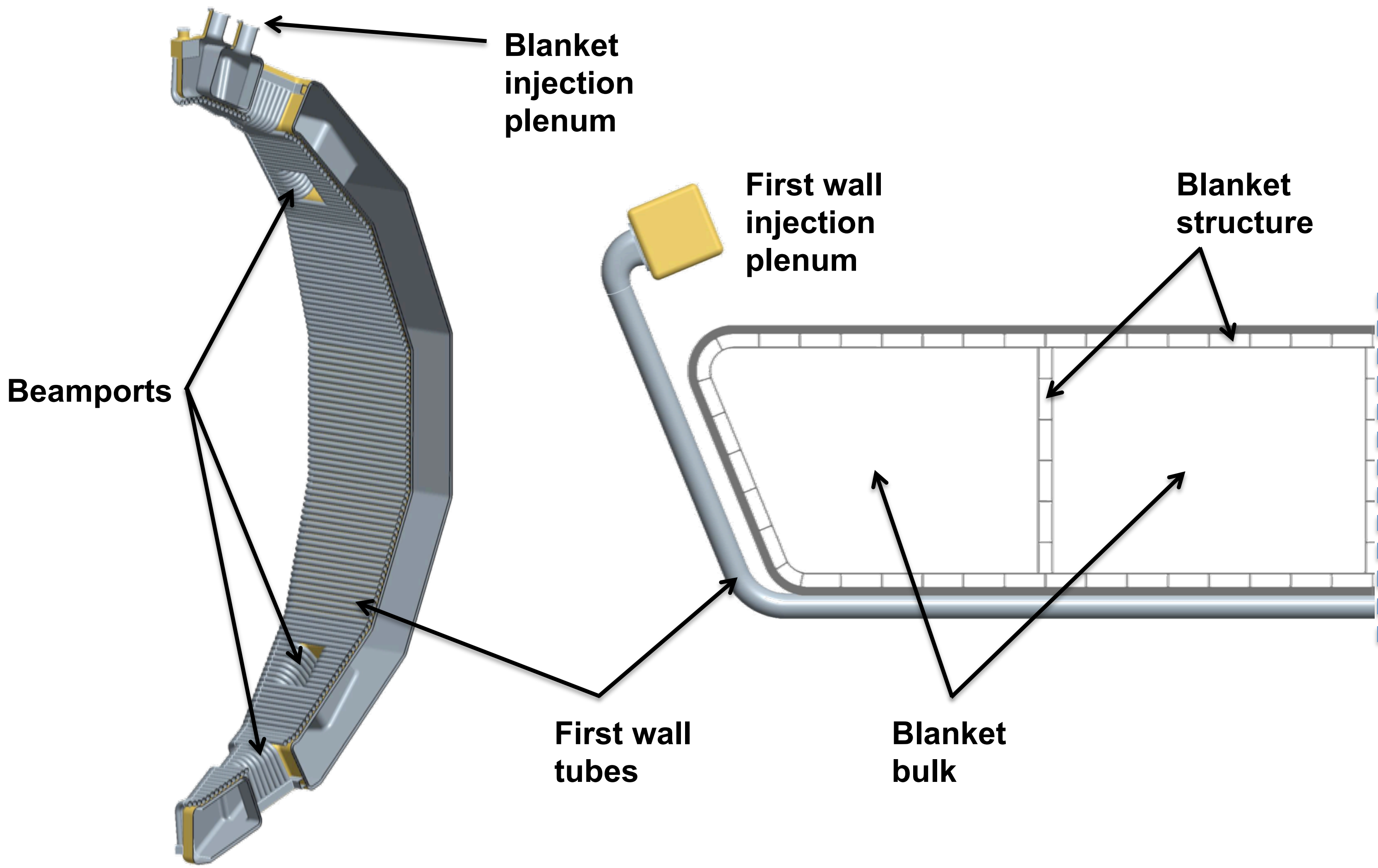


Low-impurity, modified HT-9 and ODS samples have been manufactured for LIFE

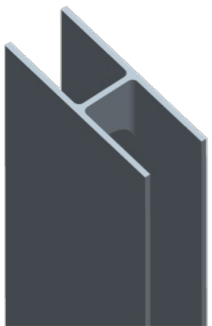
Extruded and flow formed ODS tubing (6")

* Courtesy Lew Shoemaker, Special Metals Corporation

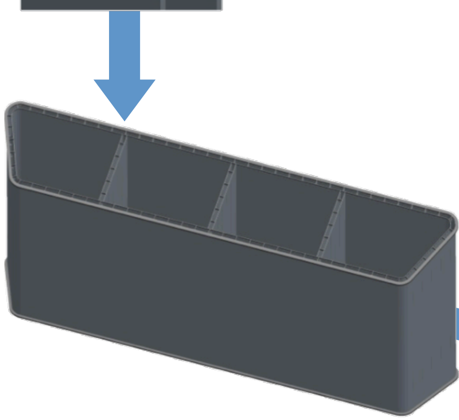
Blanket design utilizes skin cooling to provide best mechanical performance



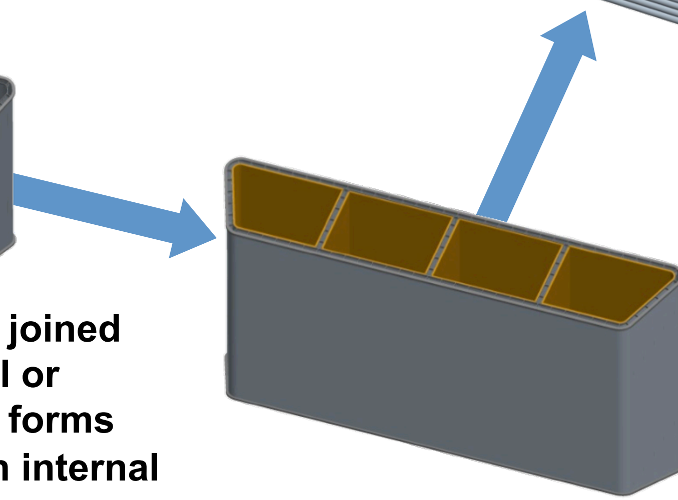
First wall and blanket can be fabricated using currently available technologies



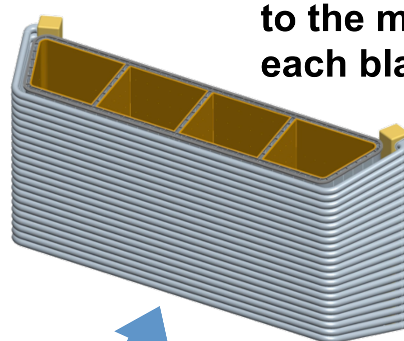
The LIFE blanket is fabricated from oxide dispersion-strengthened ferritic steel. Such extrusions can be produced today.



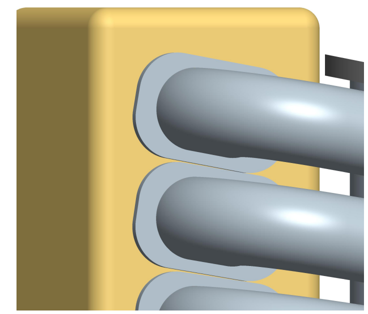
Extruded I-beams can be joined using either linear inertial or friction stir welding. This forms the blanket structure with internal cooling channels.



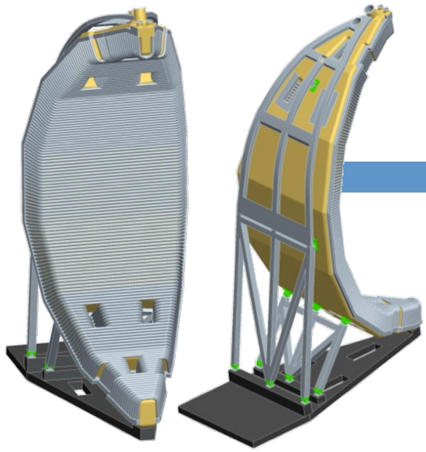
Tungsten inserts provide a thermal/corrosion barrier between Li and steel structure.

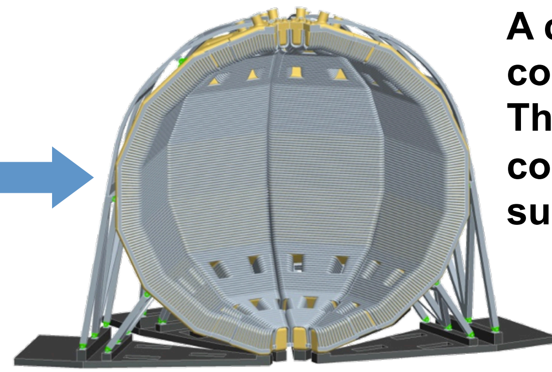


First wall tubes are connected to the manifold at the back of each blanket module.

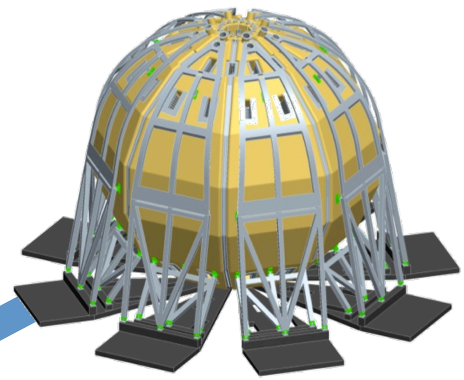


First wall and blanket can be fabricated using currently available technologies, (Cont'd.)

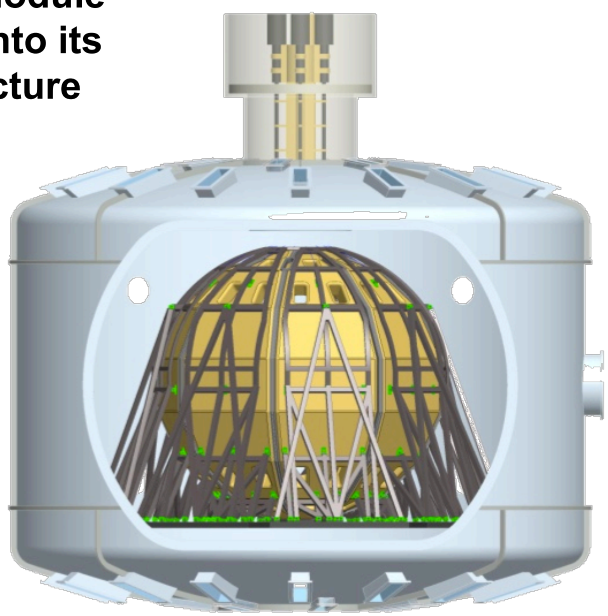




A completed LIFE chamber consists of eight modules. The modules are not physically connected other than via the support structures.



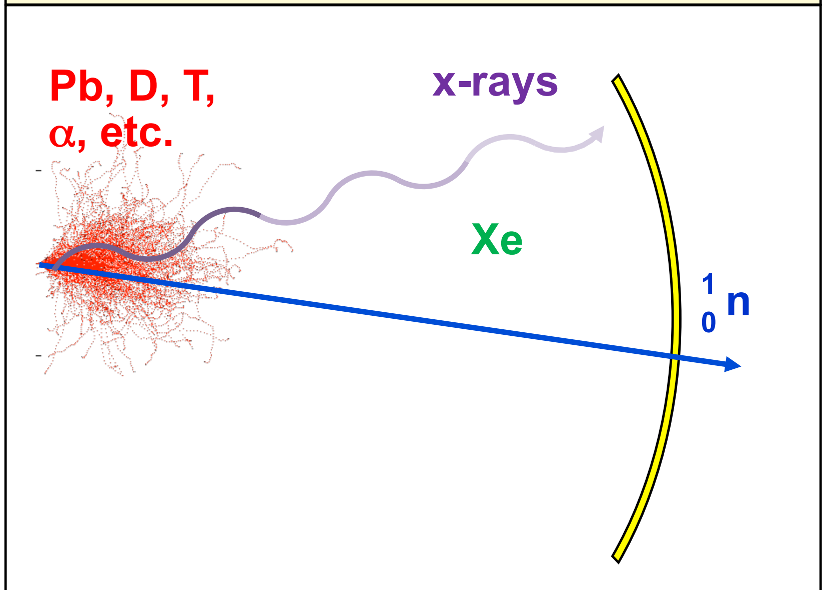
A chamber module is mounted into its support structure for transport.



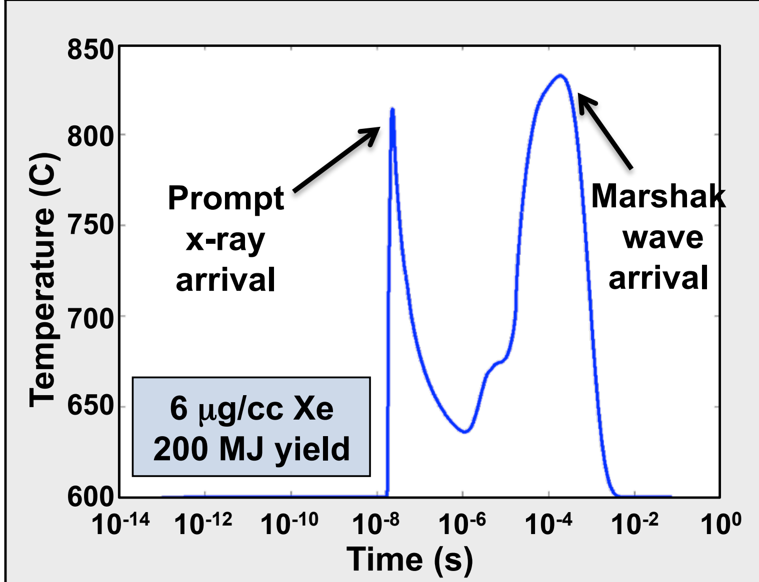
Once transported to the vacuum vessel, cooling lines are connected to the LIFE chamber. No beamline connections are necessary.

Chamber gas mitigates the threat to the first wall – allowing a NIF-sized, steel chamber to be used

Ions are stopped in ~ 10s of cm of xenon gas and x-rays are mostly absorbed



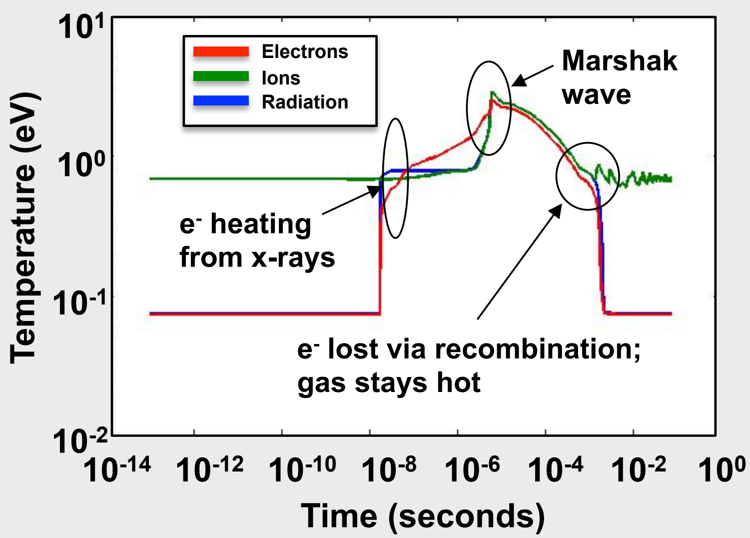
First wall heating is low enough to eliminate the need for tungsten coating



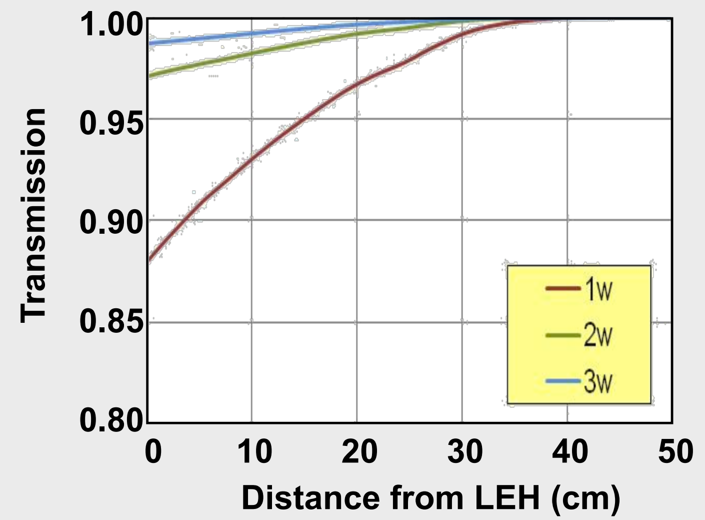
Wall is protected from ion and x-ray target output

Since the beam can propagate through lead vapor, "chamber clearing" is not actually required

Electrons lost ~ 0.5 eV; xenon stays hot from one shot to the next



Laser beam propagation through hot gas is acceptable

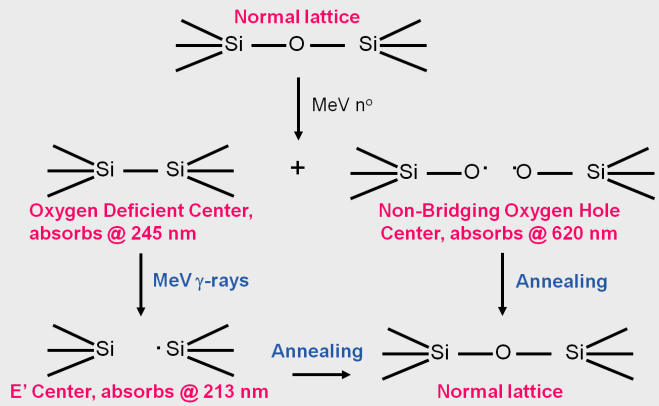


- Electronic Stimulated Raman Scattering (ESRS) has been observed in Pb
- Analysis shows metastable states saturate with investment of 20 kJ for 10^{15}/cc Pb

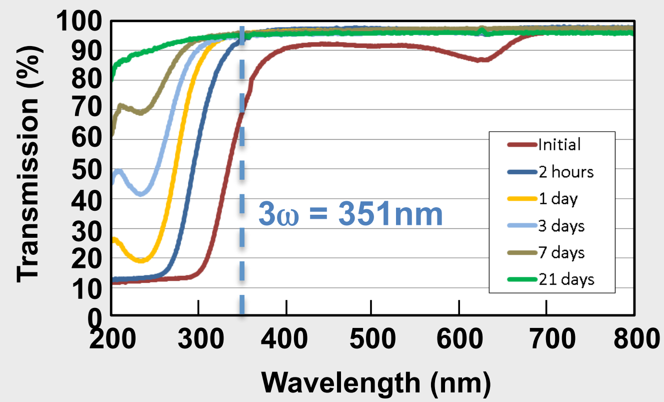
Chamber clearing of 0.5% is sufficient for a 1.5 g Pb target

Fused silica Fresnels are a robust option for the final optic that has already been tested to relevant doses

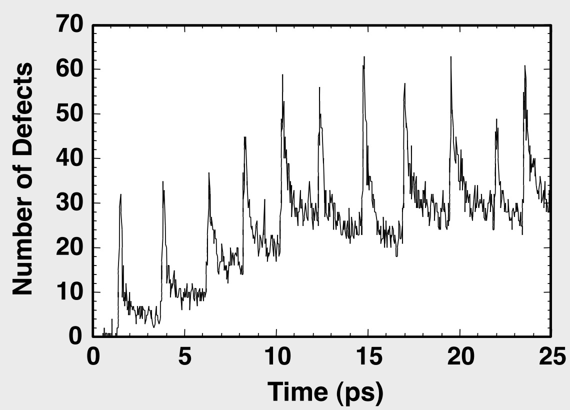
Neutrons and neutron-induced gamma-rays generate defects in the SiO_2



Neutrons generate color centers, but they can be annealed at 500°C

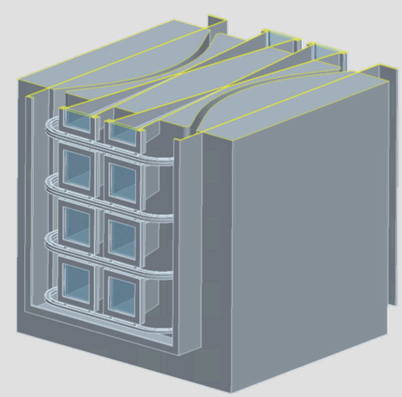


Defect concentration saturates at fairly low doses ("radiation annealing")



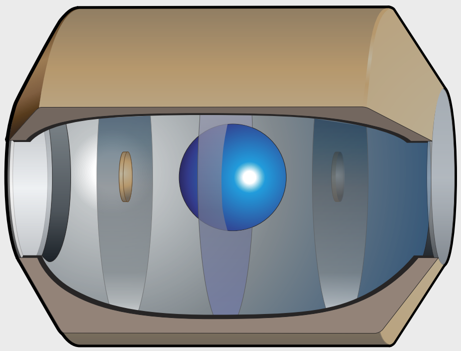
On-line replacement of the final optic is completed through the use of a labyrinth

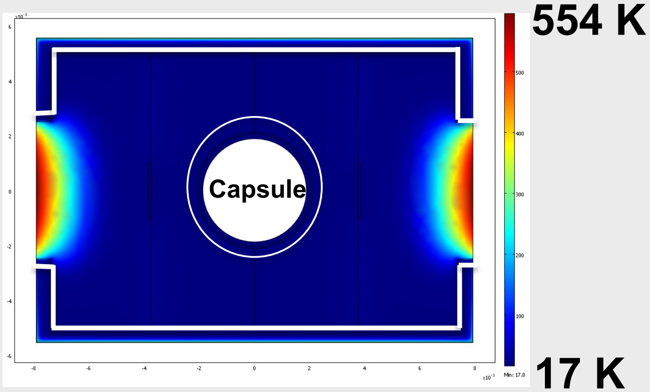
- Beam groups consist of 2×4 array of beams
- Each beam has its own neutron pinhole
- Optics move along rail system enabling on-line replacement



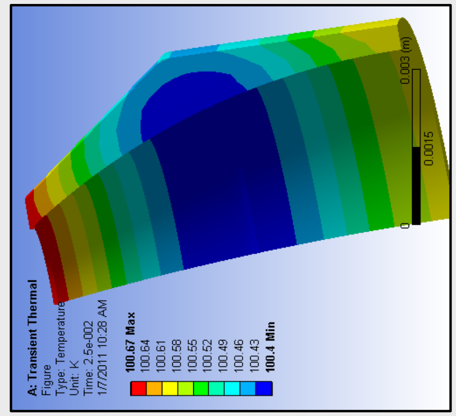
Target is robust against heating during injection

Hohlraum thermally protects capsule, permitting high density chamber gas

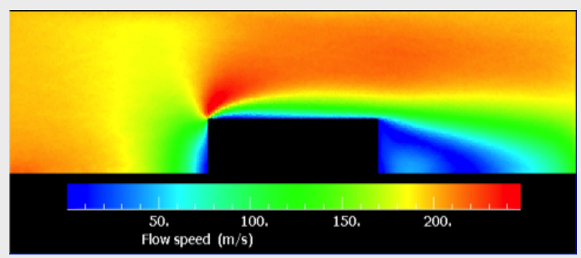




Inner gas cavities channel heat to hohlraum wall heat sink



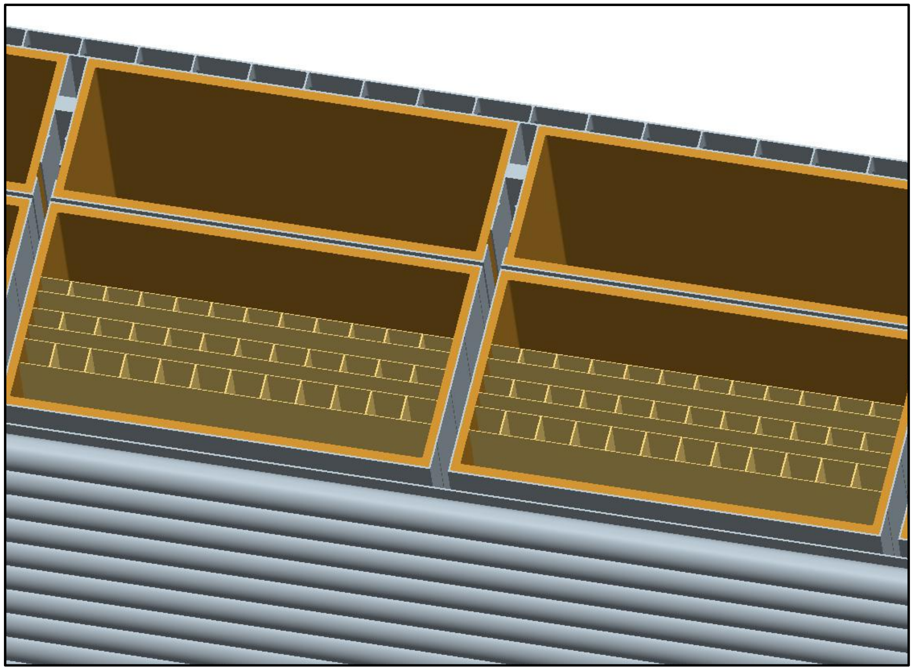
Multiple CFD models of the dynamic response confirm thermal survival



Design trade-offs with de-tritiation system, first wall chemistry, and thermo-mechanical response demand a fully integrated approach

We have developed a concept for a high-gain, highly tunable blanket

- Tritium breeding ratio and blanket gain can be dynamically tuned through use of internal tanks
- Provides ability to load-follow, and offset any uncertainties in breeding performance
- Blanket design balances thermal, structural and neutronic response



Operating Mode	TBR	G_{blk}
High-breeding mode	1.48	1.12
High-gain mode	1.02	1.32

Liquid lithium has been selected as the LIFE primary coolant

- Advantages:
  - — Low density provides low hydrostatic pressures and stresses
  - — Excellent tritium breeding capability:
    - – Obviates need for Be multiplier
    - – Enables large open solid angle for beamports and/or damage testing modules
  - — Good heat transfer properties (k, ρ, c_p)
  - — Very low tritium permeation due to high solubility
  - — Superior corrosion performance vs. molten salts and LiPb
  - — Low neutron activation

- Challenges:
  - — Need to control fire hazards
  - — Need to *re*-demonstrate efficient tritium extraction to ensure low inventory

Controls associated with handling of lithium are quite similar to those for uranium and sodium

LLNL has multi-decade experience in liquid metal technology from Atomic Vapor Laser Isotope Separation Program

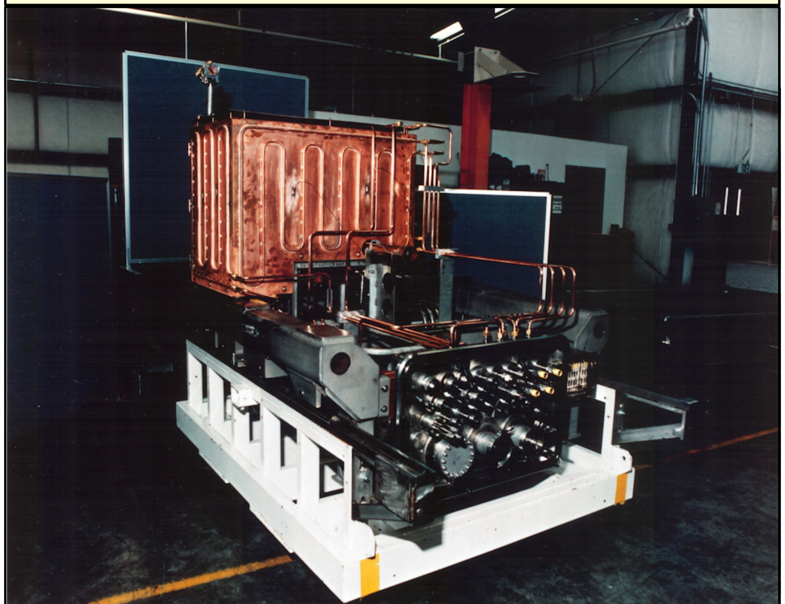


Photo: Plant scale uranium metal evaporator. Systems of this type were operated at metric ton levels of throughput. Program spanned roughly two decades.

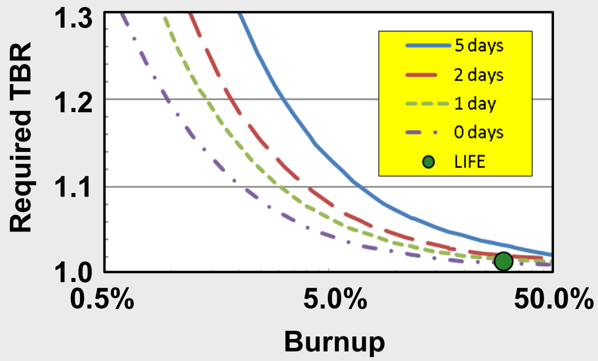
EBR-II sodium-cooled reactor operated for 30 years at Idaho National Laboratory

- Generated over two billion kW-hr of electricity
- Sodium-to-steam generator performance was exceptional. No tube leaks occurred
- EBR-II objective was achieved: sodium and water never came in contact during plant lifetime

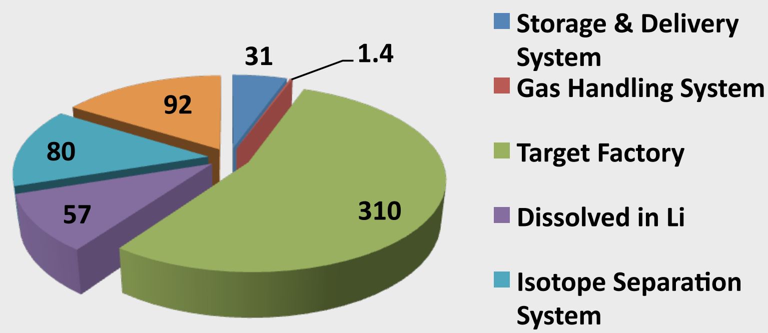
LIFE tritium systems are compact and able to maintain the site inventory at < 600 grams

LIFE

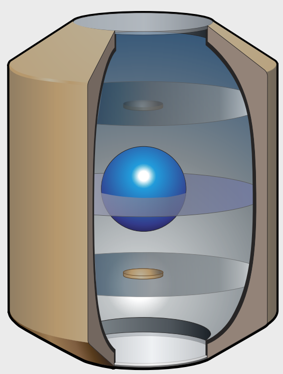
High burnup results in low TBR requirement for reasonable storage times (Abdou 1986)



More than 50% of the plant's T inventory resides in the target factory

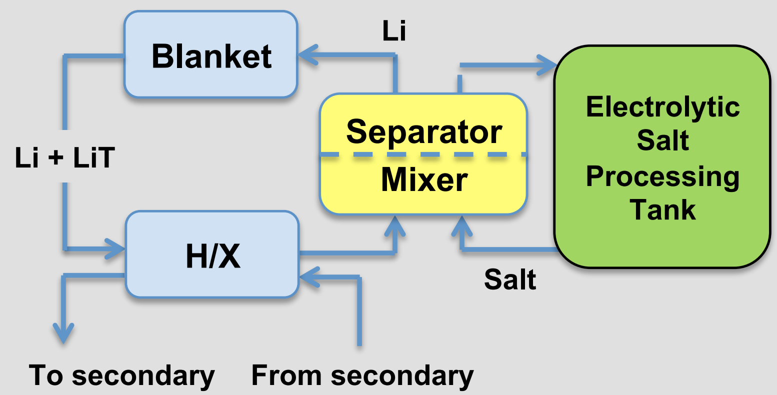


LIFE targets each contain only ~ 0.7 mg of tritium



- Tritium throughput is ~ 1 kg/day
- 300 g/day is burned
- 300-400 g/day can be bred in the blanket
- A new plant can be supplied with T inventory every week

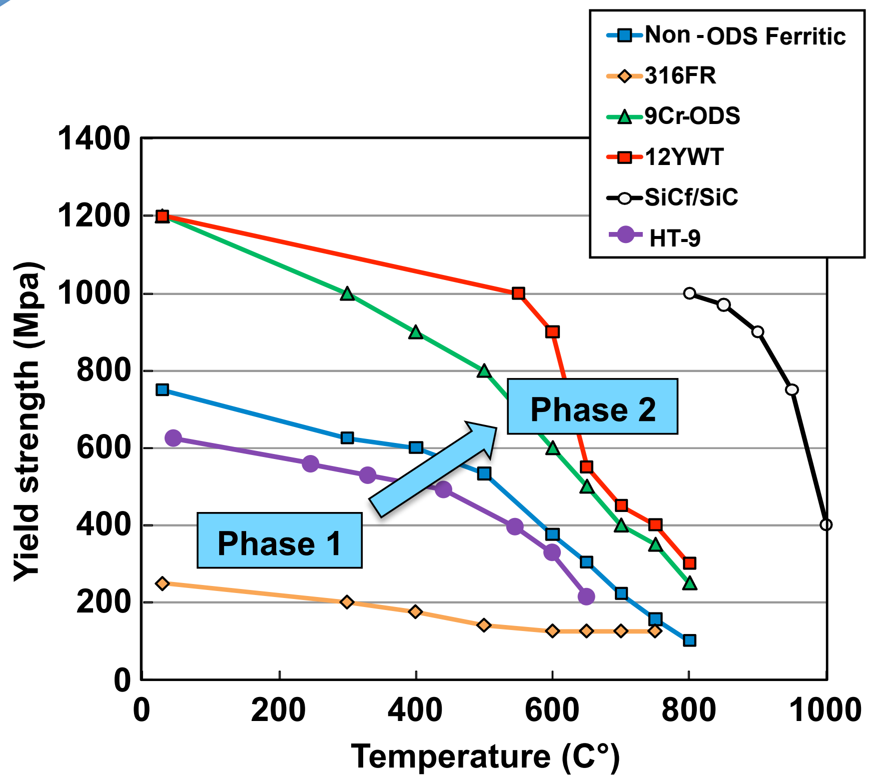
Compact system for T recovery from lithium demonstrated by Maroni in 1974



An HT-9 chamber could be utilized at full scale with reduced fusion power

- First wall design is balance between temperature (η_{th}), size and thermal stress
- We are using ASME piping code factors of safety:
  - — 3 on ultimate tensile strength
  - — 1.5 on yield strength
  - — 1.5 on creep rupture strength
  - — < 1% creep in 10^5 hours
- Initially, LIFE would use HT-9 and accept short chamber lifetime
- Facility will enable materials testing and a move to oxide-dispersion strengthened ferritic steel

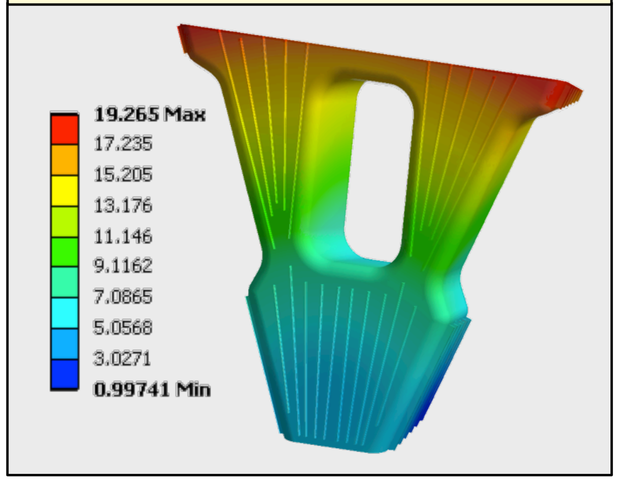
We increase these factors of safety by 2× to mitigate against material degradation under irradiation



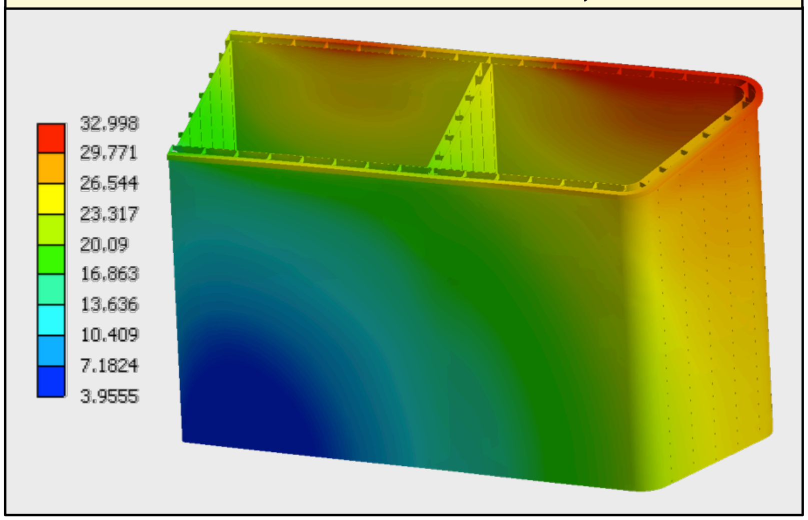
Blanket design provides efficient heat transfer while maintaining acceptable stresses

- Over 70% of the thermal power is absorbed volumetrically within the blanket
- Reduced thermal gradients and induced stresses enable higher fluid temperatures than in the first wall (750 vs. 515°C):
  - — Higher conversion efficiency
  - — Support structure is designed to accommodate greater thermal expansion

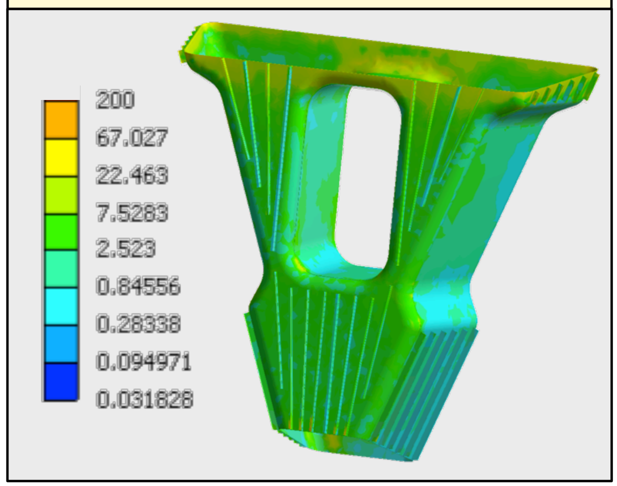
End section deformation, mm



Mid section deformation, mm



End section stress, MPa



LIFE can ride the wave of industrial improvements in the ultra-supercritical steam Rankine cycle

- There are nearly 400 power plants using supercritical steam technology; available today: 600-620°C, 45-47%
- AD700/COMTES700 projects aim to demonstrate ultra-supercritical technology at 700-720°C, 52-55%
- Industry leaders are saying 50%+, as early as 2014

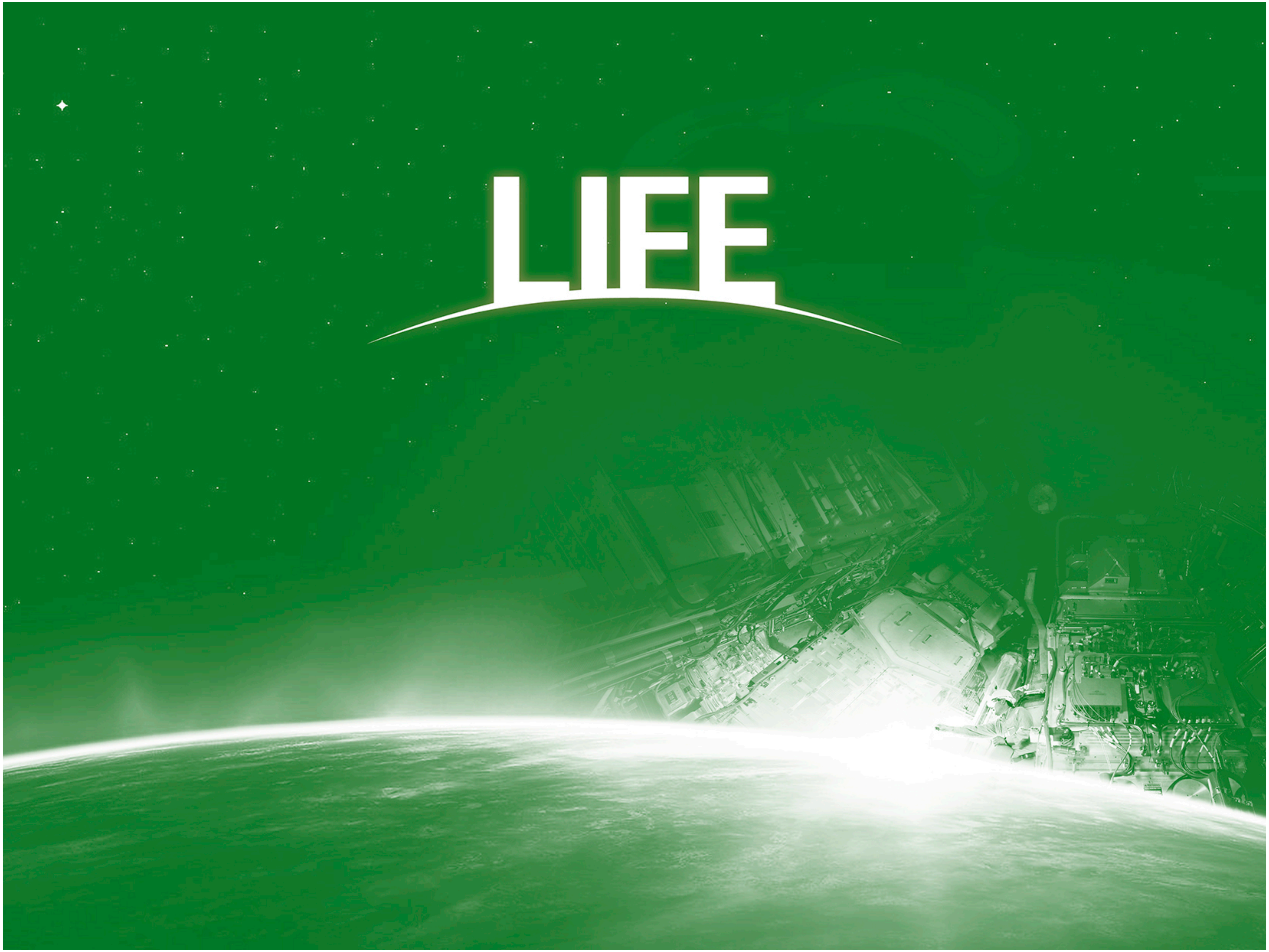
Industry is developing and demonstrating high-efficiency Rankine cycles without our help

Genesee Phase 3, Canada's first supercritical steam plant. Completed 2005.

Conclusions

- Chamber fill gas protects the first wall and enables a compact system while allowing both laser propagation and target injection
- "Chamber clearing," as traditionally thought of, is not required
- Modular, factory-built first wall/blanket modules can be constructed from near-term materials and rapidly replaced as needed
- Lithium provides superior tritium breeding in a highly tunable blanket design
- High tritium solubility greatly reduces tritium permeation and helps limit site inventory to < 600 grams
- Ultra supercritical steam Rankine cycle provides 46% thermal efficiency today and possibility of 50%+ by 2015-2020
- A fused silica diffractive optic offers radiation-tested performance

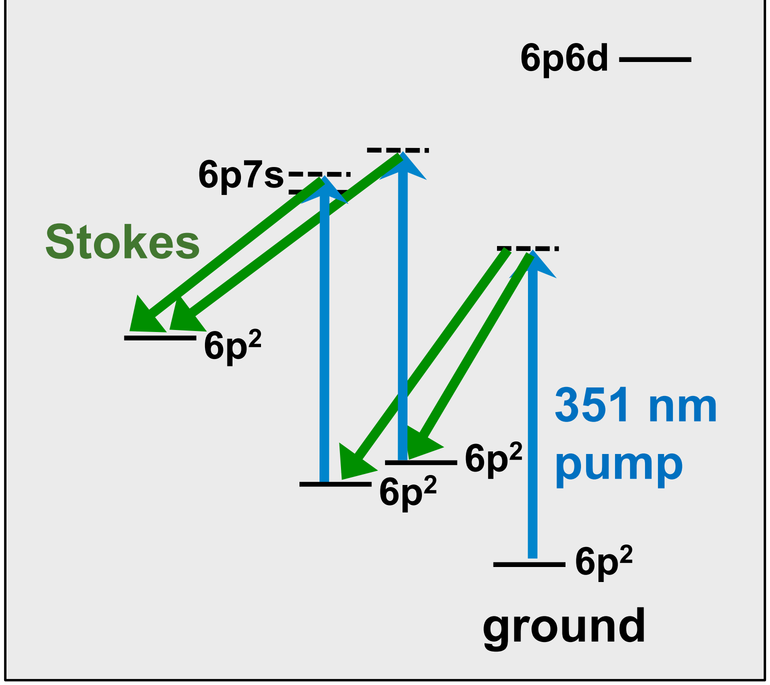
Rapid development, construction and maintenance are all enabled by separability and modular (LRU-like) design


LIFE

Since the beam can propagate through lead vapor, "chamber clearing" is not actually required

- Electronic Stimulated Raman Scattering (ESRS) has been observed in Pb vapor[1]
- Excited states are metastable (~ 10^{-6} s)
- Higher states and ionization are inaccessible with 351 nm photons
- Lasing will not occur as there is no population inversion (nor Anti-Stokes)
- Saturation is observed for alkali vapors at low pressures[2]
- ~ 1 photon per Pb atom is needed for saturation
- For 10^{15}/cc Pb vapor, energy cost to saturate all Pb in beam path is ~ 20 kJ

Pb has three accessible metastable excited states with 351 nm light[3]



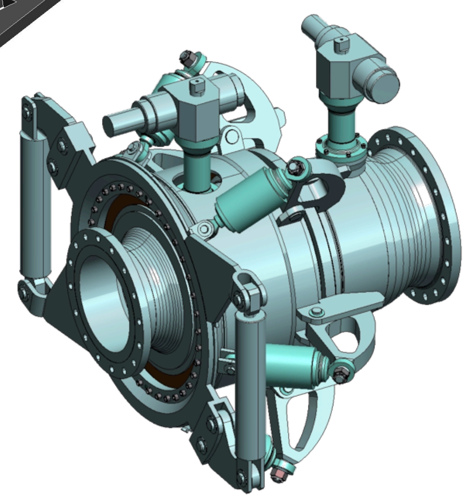
[1] Marshall & Piper, IEEE JQE 26, 1990
[2] Carlsten & Dunn, Optics Comm. 14, 1975
[3] Anderson et al., IEEE J. Quant. Elec. 12, 1976

Chamber clearing of 0.5% is sufficient for a 1.5 g Pb target

LIFE maintenance philosophy is based upon NIF's use of line replaceable units (LRUs)

- **LIFE plant would receive 8 factory-built chamber modules:**
  - **Modules will be connected in maintenance bay to form transportable unit**
  - **Sections share two sets of common coolant injection and extraction manifolds (first wall and blanket)**
  - **Sections are not attached to each other**

- **Quick connects made in the engine bay using hydraulically operated couplers (technology used for oil supertankers)**



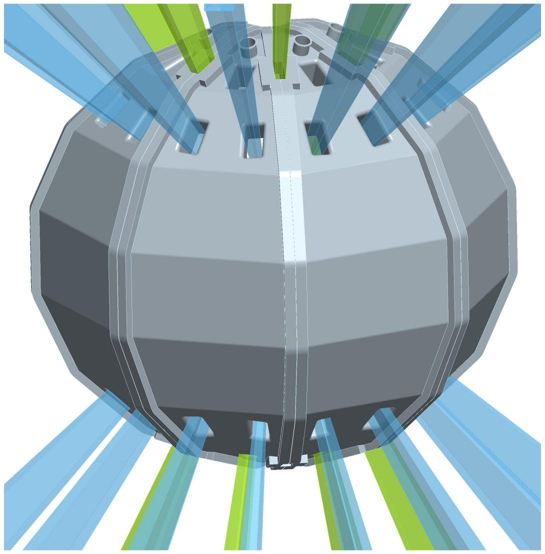
The LIFE chamber design must satisfy a number of requirements

Fabricate from an available material
(commercially available & weldable)

Capture and transmit thermal power to balance of plant
(handle 0.5-1.5 MW/m^2)

Operate at high temperature for high thermal efficiency
($T_{wall} \geq 600°C$ for $\eta_{th} \geq 46\%$)

Collect and process target debris through exhaust port
(Material recovery ≥ 99%)



Produce tritium to replace that burned in previous targets
(Tritium breeding ratio ≥ 1.02)

Enable successful propagation of target and laser beams
(Propagation efficiency ≥ 95%)

Reset for the next shot
(Support pulse rate of 16 Hz)

Maintain with high availability
(support ≥ 92%; flowdown TBD)

Meeting this complex set of requirements necessitates an integrated, systems approach

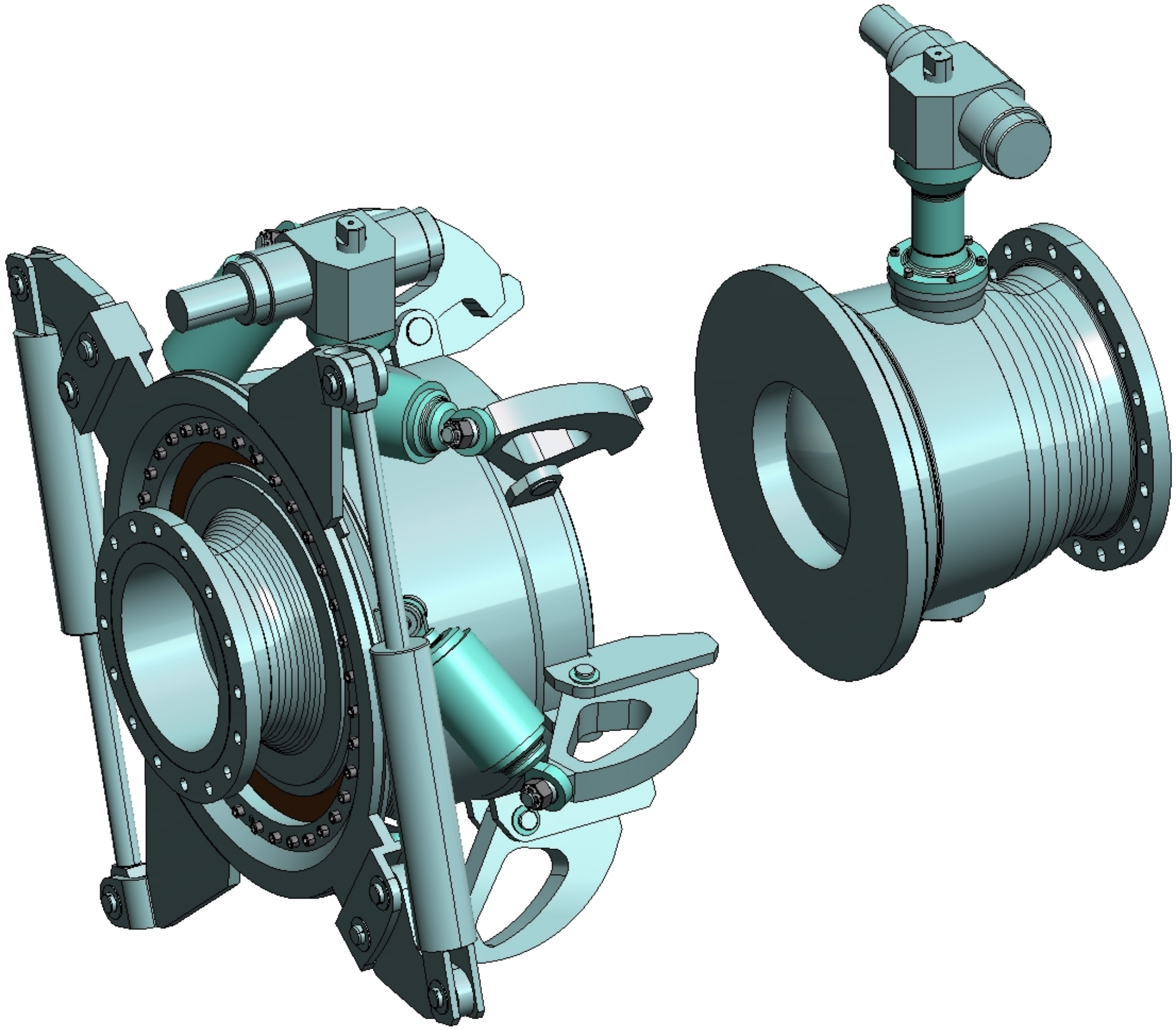
An HT-9 chamber could be utilized at full scale with reduced fusion power

- Modified HT-9 for low-activation (no Mo)[1]
- Fusion power of 1000 MW
- Li inlet at 450°C, outlet 492°C; flow speed of 4 m/s
- Factors of safety are 4.1 with respect to creep and 8.4 for ultimate tensile strength; these exceed the goals of 3 and 6, respectively
- Assuming a lifetime of 10 dpa, lasts 1 year at 88% availability

Lithium corrosion, fire safety and tritium recovery

- We have found a mixed collection of information about Li corrosion.
- None of the information is bad news but some might not be terribly relevant (e.g., static conditions)
- Widespread view is that corrosion is only slightly worse than that for Li and that it is 100-1000x better than LiPb or molten salt at similar flow rates
- Controlling impurities such as nitrogen is critical (>500 ppm will be very corrosive):
  - This probably rules out using nitrogen in the chamber to getter the carbon from the ablator (as if tritiated cyanide didn't already do so)
- BCSS study (Abdou et al.) specifies Li @ 1.5 m/s & HT-9 temperature limit of 550C for 5 μm/y or 580C if 20 μm/y is tolerable; comparable numbers are only 415/450C for LiPb or 430/470C for Li & PCA

Cooling connections are made using hydraulic couplers, which are available commercially*



* Currently available product can be used in cryogenic, room temperature or slightly elevated systems. MIB believes that they will be able to fabricate using TZM (Molybdenum alloy) for high-temperature applications.

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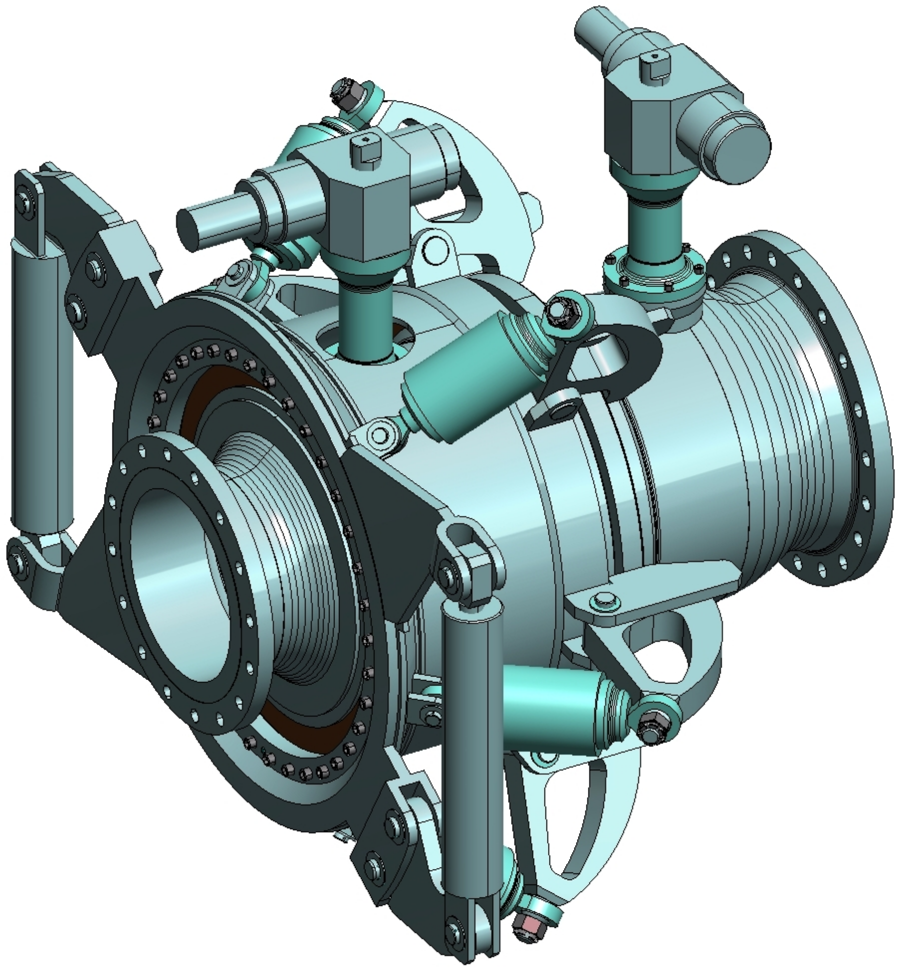

* Currently available product can be used in cryogenic, room temperature or slightly elevated systems. MIB believes that they will be able to fabricate using TZM (Molybdenum alloy) for high-temperature applications.

History of lithium corrosion work (Selle and Olson)

- Iron and iron-based alloys could be used to contain Li for short duration to T>800C
- Presence of carbides in low alloy steels could be a source of intergranular corrosion and penetration
- Dissimilar metals would transfer when immersed together in Li
- Higher Ni stainless steels were less resistant to general corrosion
- Radiation did not appear to influence the corrosion of iron
- Thermal gradient mass transfer is an issue

LIFE plant will be used for accelerated damage testing of both structural materials and fission fuels

- **Goal is to provide a 10× acceleration relative to expected LIFE.2 damage rates:**
  - — **Provide damage rate of 230 dpa/fpy**
  - — **Samples sit ~ 60 cm from chamber center**
  - — **Superior TBR of LIFE blanket enables large testing volume**

- **Design requirements:**
  - — **Accommodate rapid replacement of structures**
  - — **Provide temperature controlled sample environment**
  - — **High degree of neutron isochoric heating**
  - — **Thermal load of 12 MW/m^2**

- **Testing would be conducted in parallel phases:**
  - — **Coupons, welds, and sub-scale components at 1, 3 and 10× acceleration**
  - — **Full-scale modules at 0.4×**
  - — **FY26-30 offer ~2 FPY of LIFE.1 operation**

Separability of IFE enables accelerated testing without distorting the plasma