Fusion Safety, Environment, and Regulatory Issues: An Historical Perspective

David Petti

Fusion Safety Program

Idaho National Engineering and Environmental Laboratory

Outline

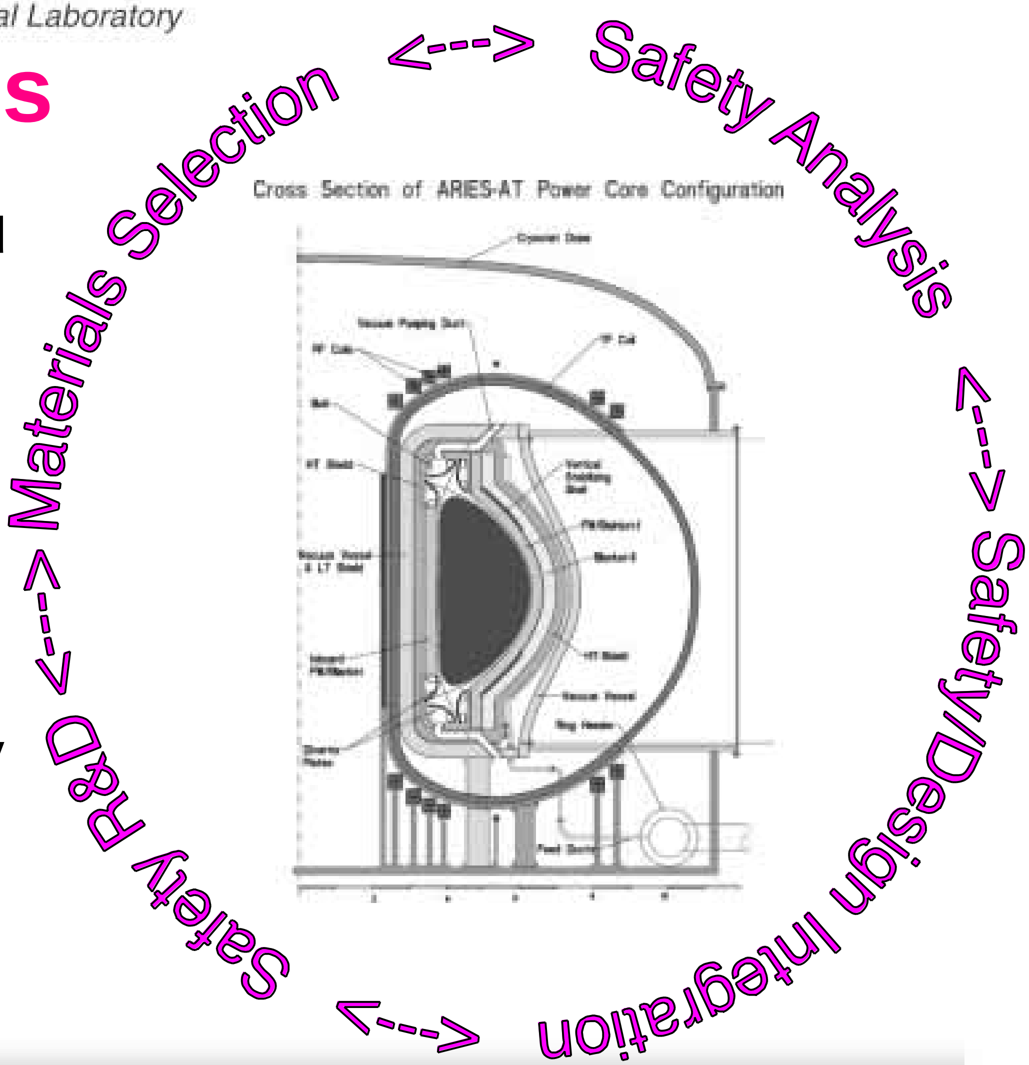
- Historical Background
- Overall Theme
- Design Philosophy
- Energy Source Analysis
- Source Term Analysis
- Safety Computer Code Analysis
- Waste and Environmental Considerations

Historical Background

- Since the earliest days of the fusion program, material choices have long been recognized as a way to minimize hazards and thus help demonstrate the safety and environmental potential of fusion power plants
  - Decay Heat and Radioactive Inventory
  - Chemical Energy Sources
  - Activation Product Mobilization
  - Tritium Permeation and Inventory
  - Waste Management Options
- Over the past decade, a realization that focusing solely on smart/prudent materials selection was not enough, in large part since regulations have gotten stricter. Safety/design integration and much improved safety analysis were needed to improve the safety and environmental picture for fusion while at the same time having the side benefit of removing unnecessary constraints on the system
  - Integral state of the art systems safety analysis
  - Passive safety implementation

Overall Themes

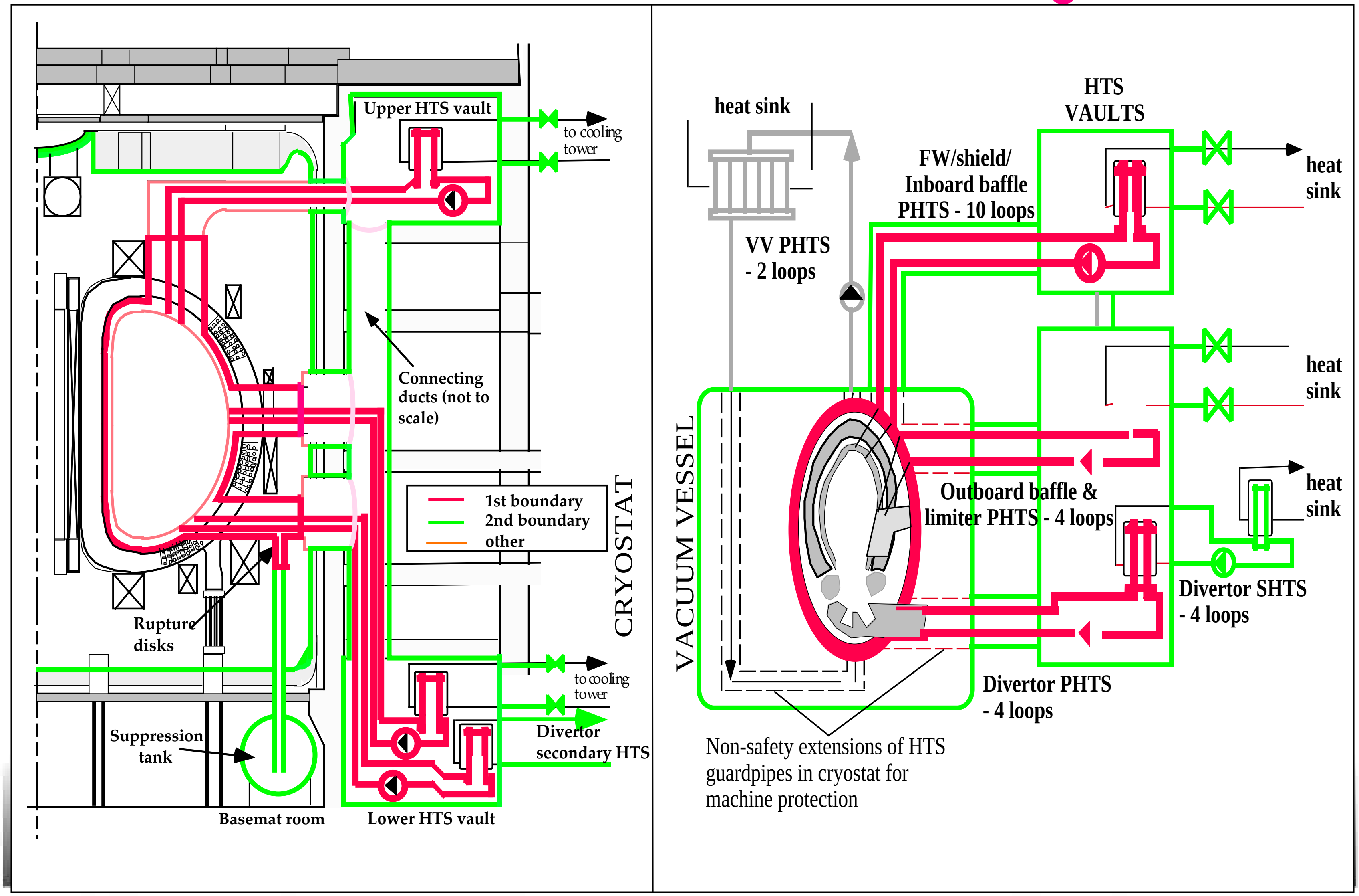
- **As the design of fusion power plants has improved and more details have become available,**
  - **the level and sophistication of the safety and environmental analysis has increased**
  - **the integration of safety and design has improved**
  - **R&D has been focused to solve problems**



Safety/Design Integration

- Early in the program safety/design integration was viewed as less important given all the constraints on the system. There was a lack of effective communication and understanding between safety and design.
- Safety and environmental considerations were key drivers in previous ARIES designs, especially in materials selection.
- In the last decade, the ITER project has shown that early implementation of safety in the design process is key to solving safety

Confinement in the ITER-EDA design



Energy Sources

- **Fusion has a number of energy sources that in an off-normal event could threaten to mobilize radiological or toxic material inventories**
  - **Decay heat**
  - **Chemical reactions**
  - **Magnets**
  - **Plasma**
- **How we address these issues has changed over the years**

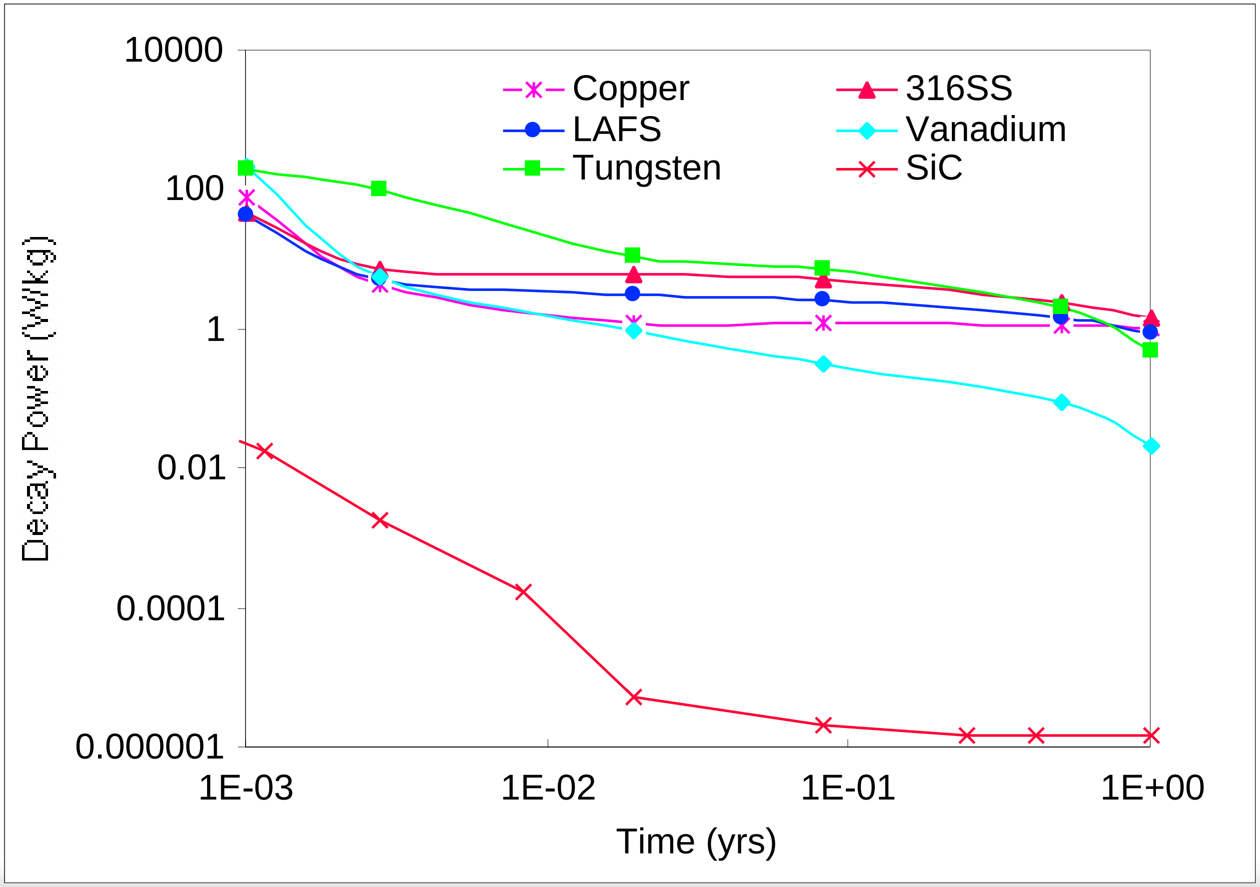
Decay heat and chemical reactivity evaluations

- Important safety issues for fusion that are strongly dependent on the specific coolant and materials in the design.
- Early in the program, simple adiabatic heat-up calculations and engineering judgement drove selection of optimal coolant and materials and evaluation of worst case accidents
  - For example, in ARIES-II --> complete LOCA of Li/V blanket with unlimited air ingress. Flame temperature from experiments of 1200°C + 100°C for decay heat. Temperature of 1300°C used for source term calculations
- Passive removal of such energy is an important way to demonstrate the safety advantages of fusion.

Decay heat and chemical reactivity evaluations

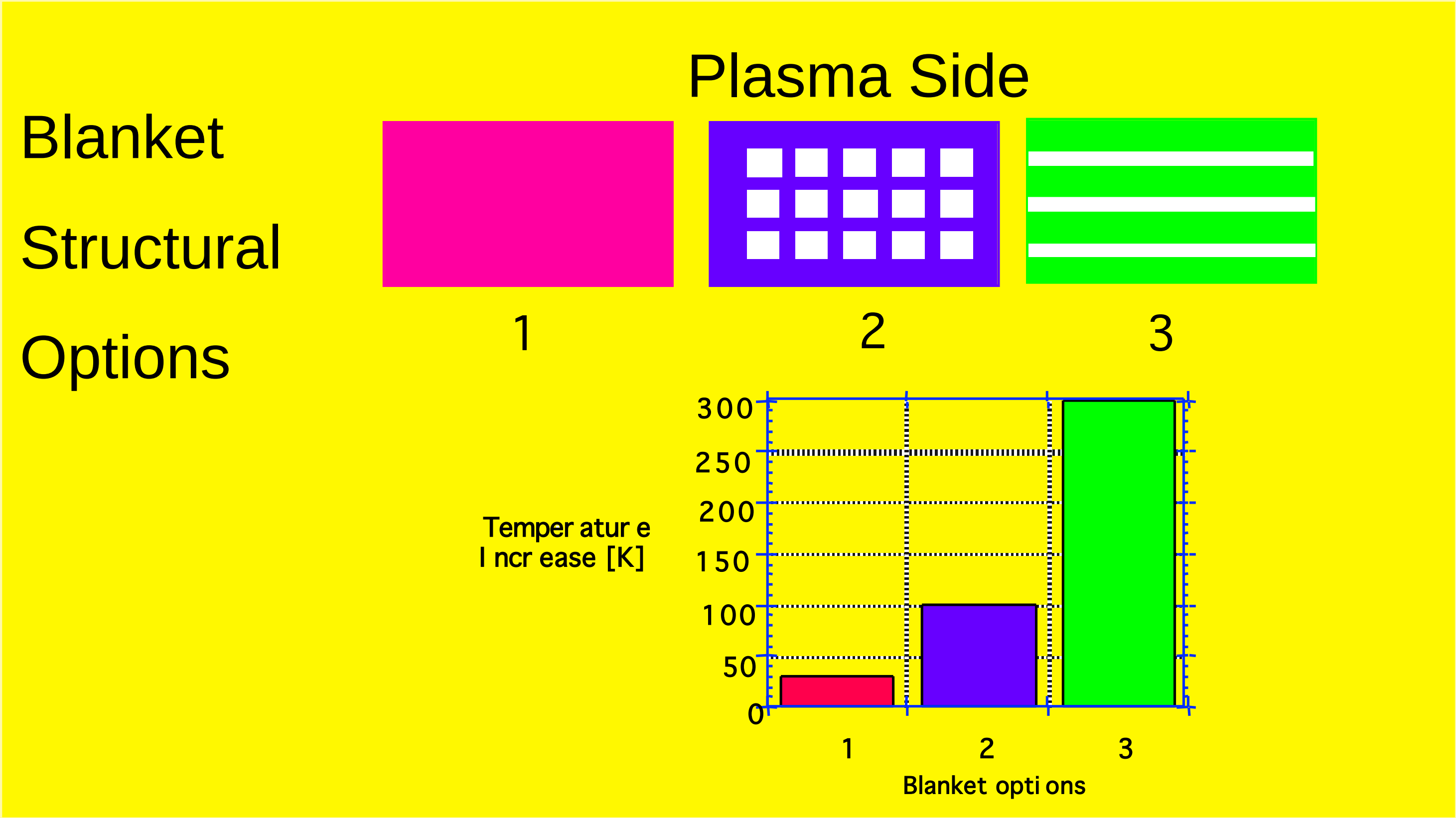
- We cannot evaluate whether a material is good or bad from a decay heat or chemical reactivity standpoint unless we understand the behavior of the in-vessel system (coolant, structures, design specifics) under off-normal conditions.
- Decay heat removal and chemical energy control are more of a system design issue, of which materials is only one facet.
- Metrics based on simple decay heat calculations or chemical reaction energies can be misleading.
- The evaluation of a material is best done in the context of a design and is best resolved by safety analysis that use actual kinetic data for reaction rates and actual design information for relevant heat transfer.
- Sometimes only modest design detail is needed for such assessments and design/safety iteration can improve the situation a lot.

Decay Heat Comparisons (1 MW/m^2 for 1 yr -- 1 MWyr/m^2)

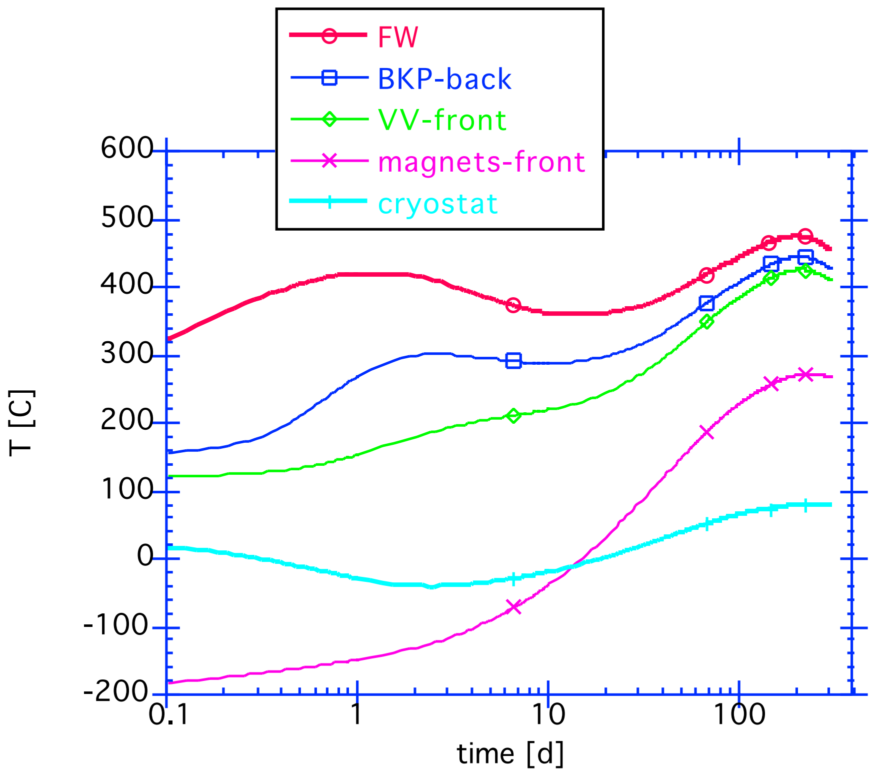


Passive decay heat removal during a LOCA is important to demonstrate the safety and environmental potential of fusion

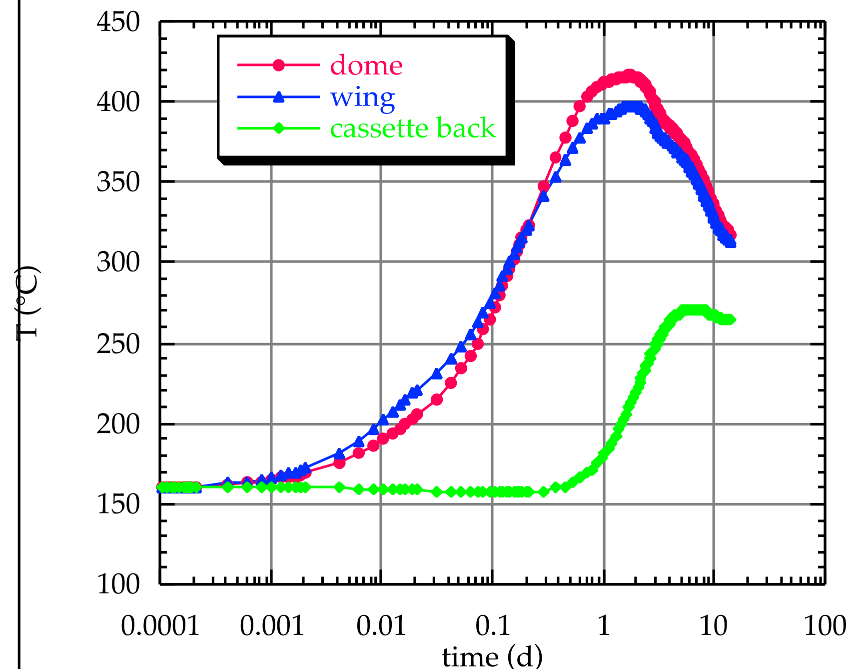
Blanket/shield design is critical to accomplishing this goal



In ITER-EDA, decay heat is removed by passive means. Peak temperatures are always below 500°C.

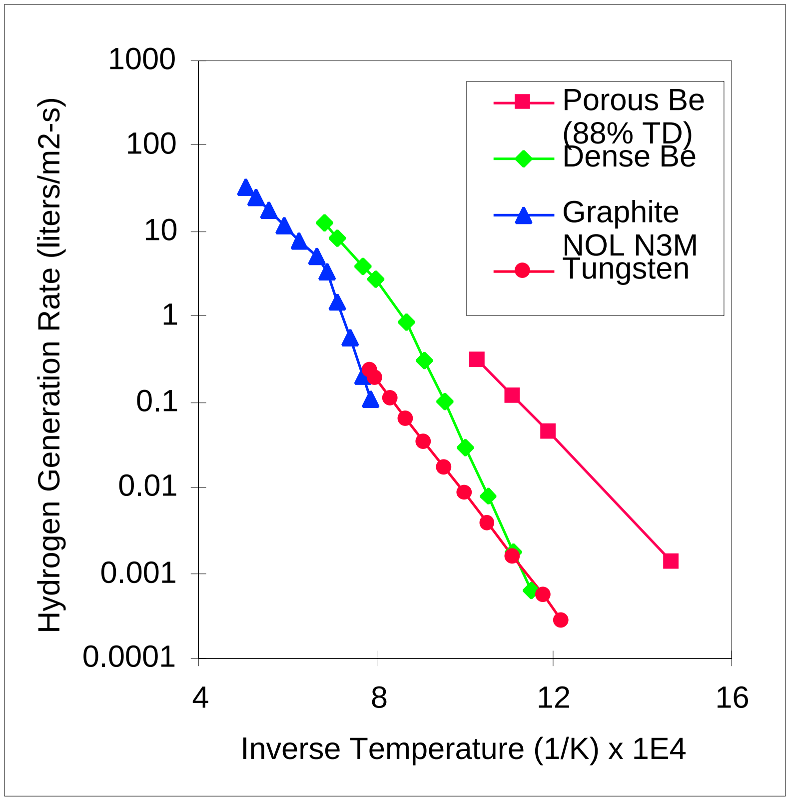


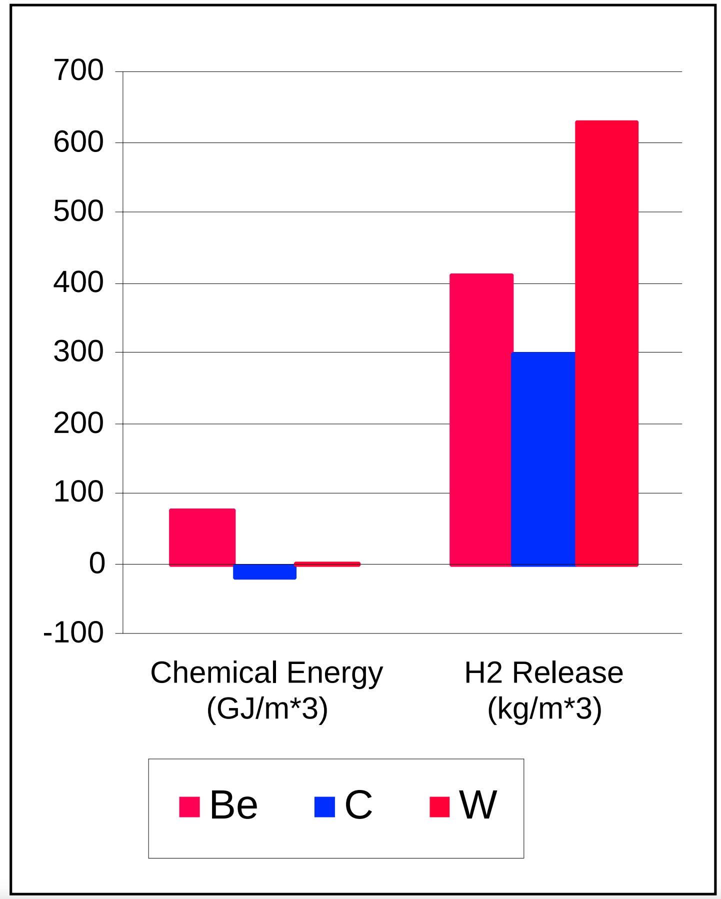
First Wall



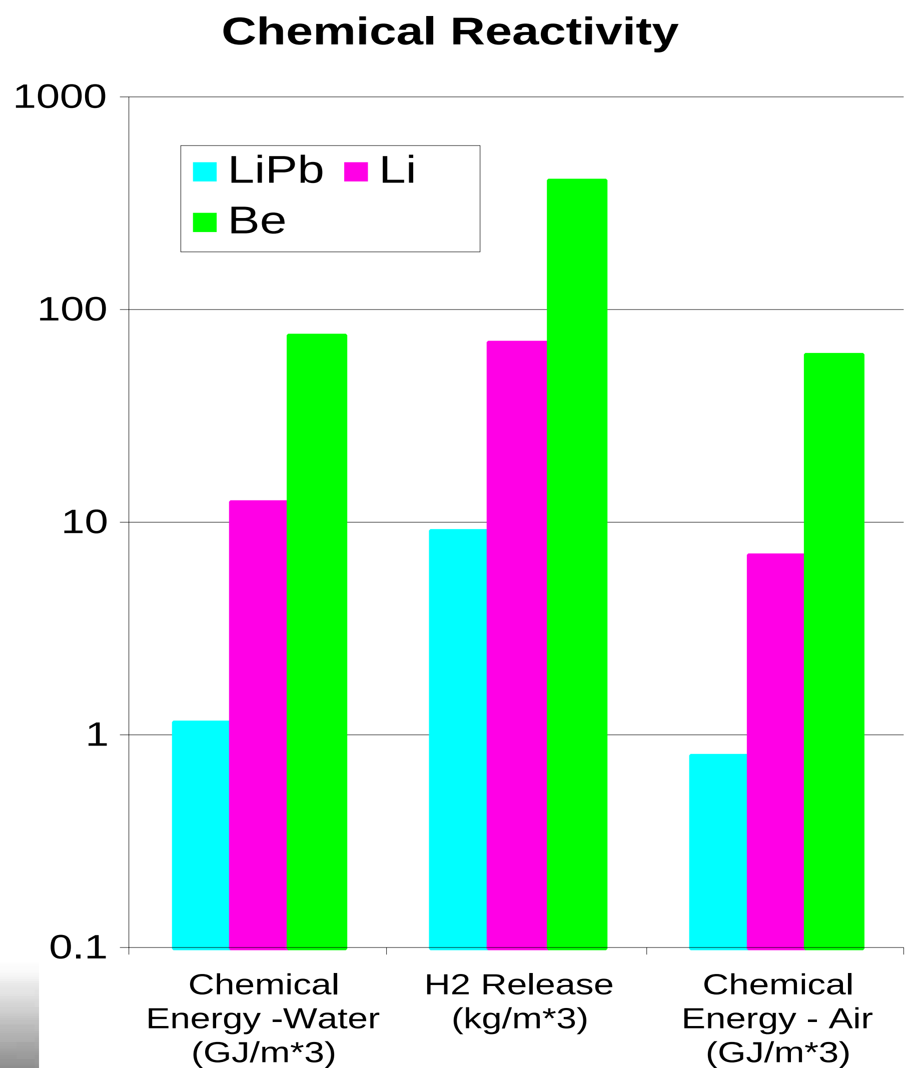
Divertor

Chemical Reactivity of PFCs



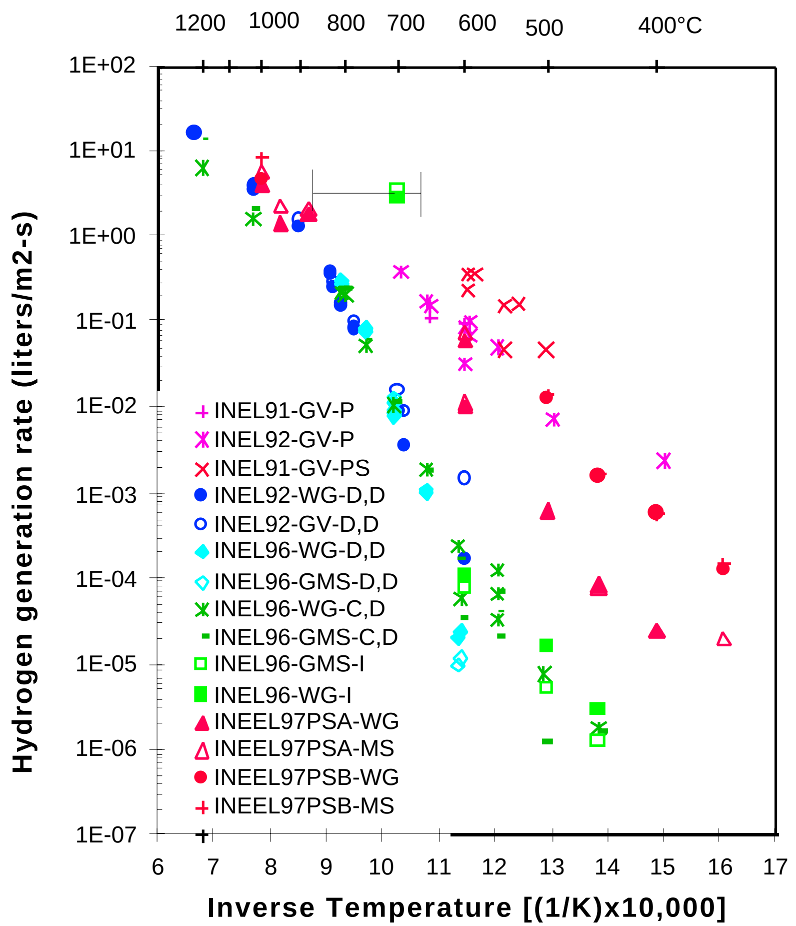


Breeder Safety Issues

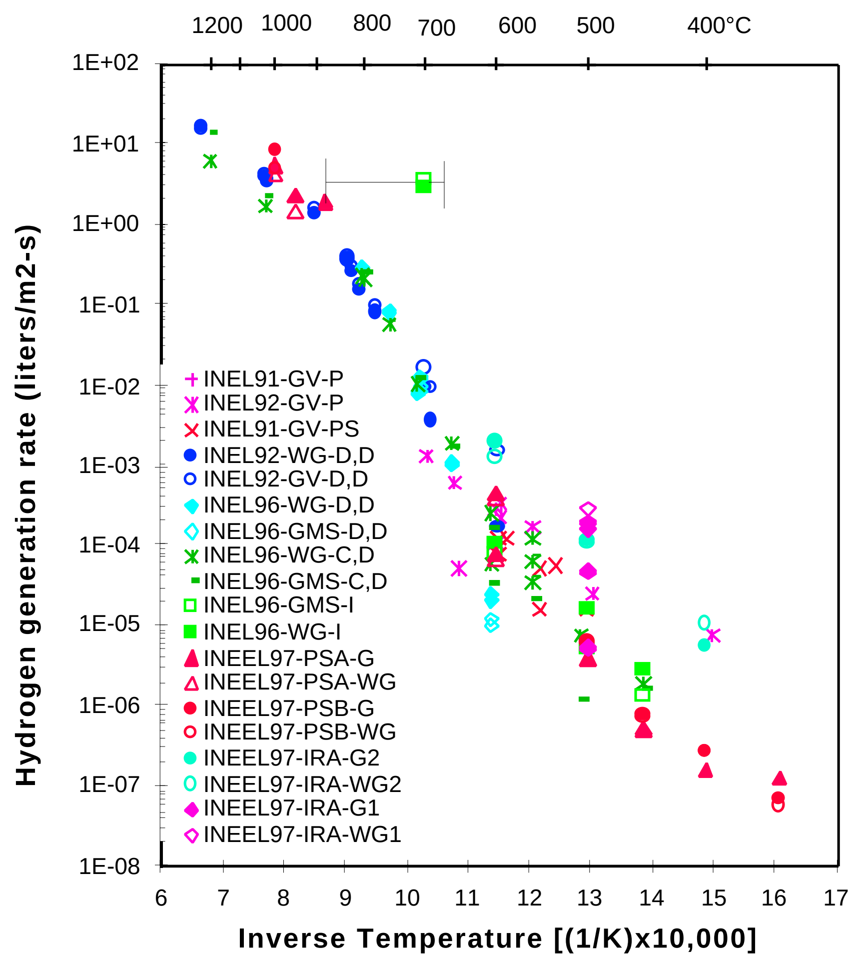


Be-steam chemical reactivity of a number of physical forms of Be indicate that reaction rates are a strong function of physical surface area

Geometrical surface area



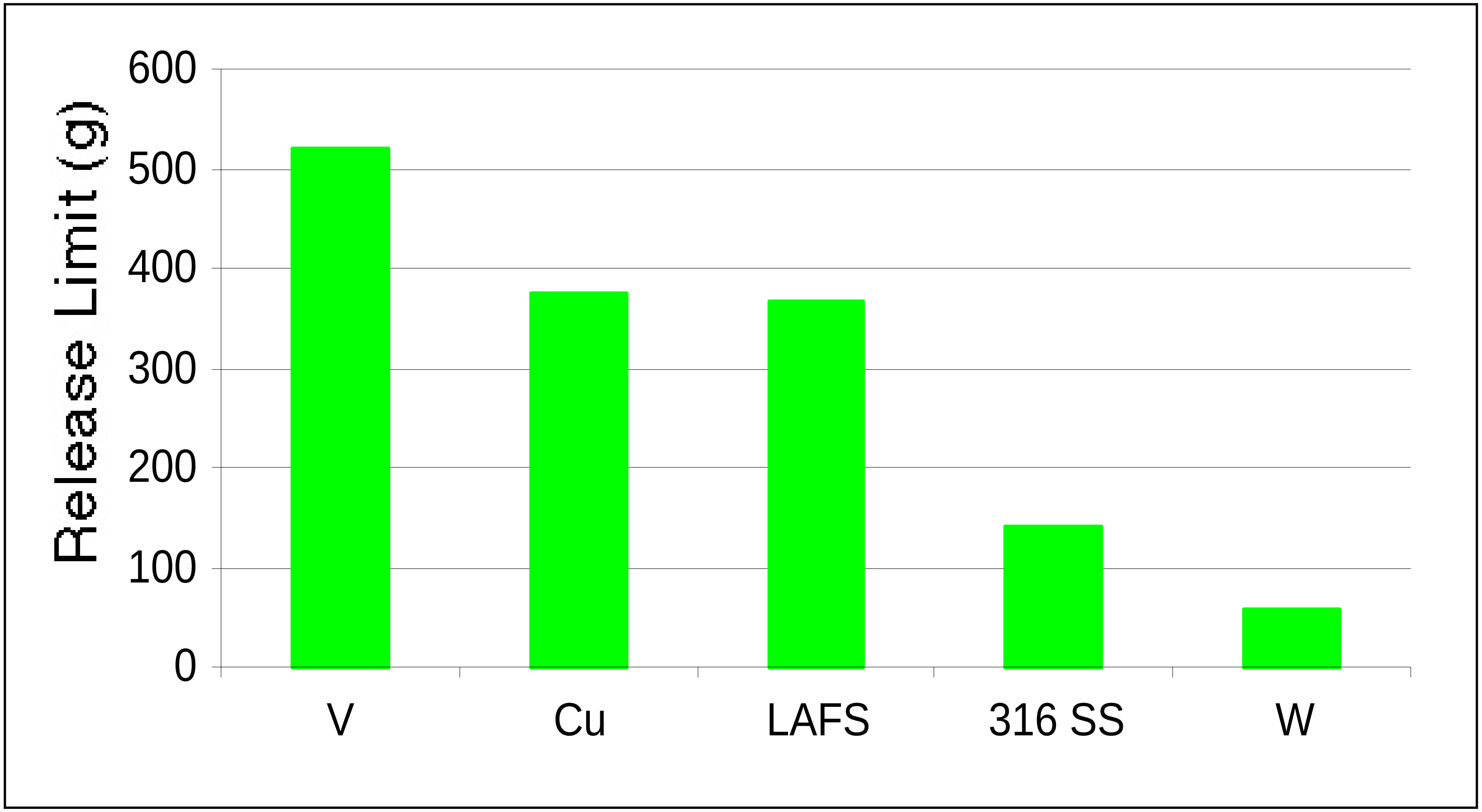
Physical (BET) surface area



Radiological Source Term

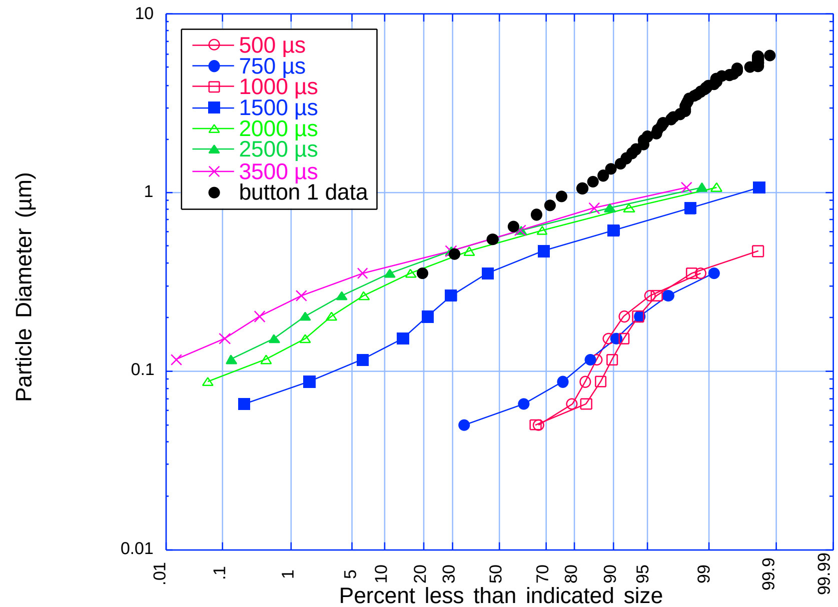
- Key component of fusion safety case
- In early days, inventory based release metrics were used.
- Although conceptually simple, these can be misleading in the context of a real design
- Now different components of the radiological source term are considered
  - Activated corrosion products
  - Tokamak dust
  - Oxidation driven mobilization (via air or steam reactions)
- Also holdup by confinement barriers in the facility during transport is now considered explicitly

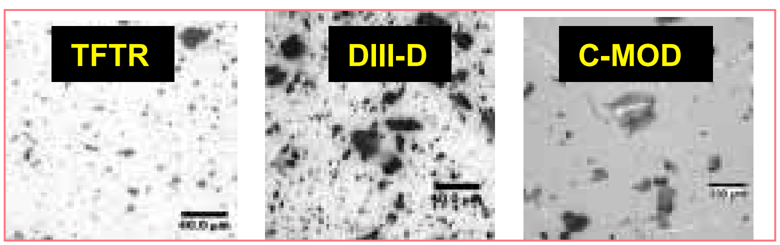
Inventory Based Activation Hazard

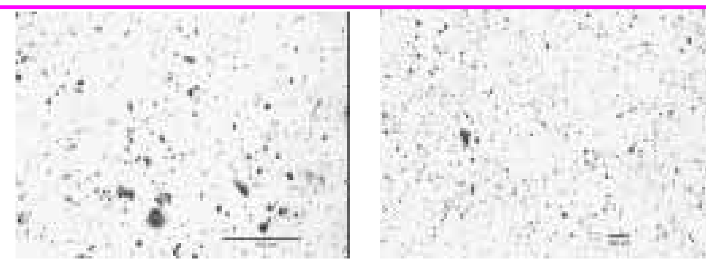


Dust Characterization Activities

Nova Debris from bottom of vessel (< 500 microns, ~ 1 g)

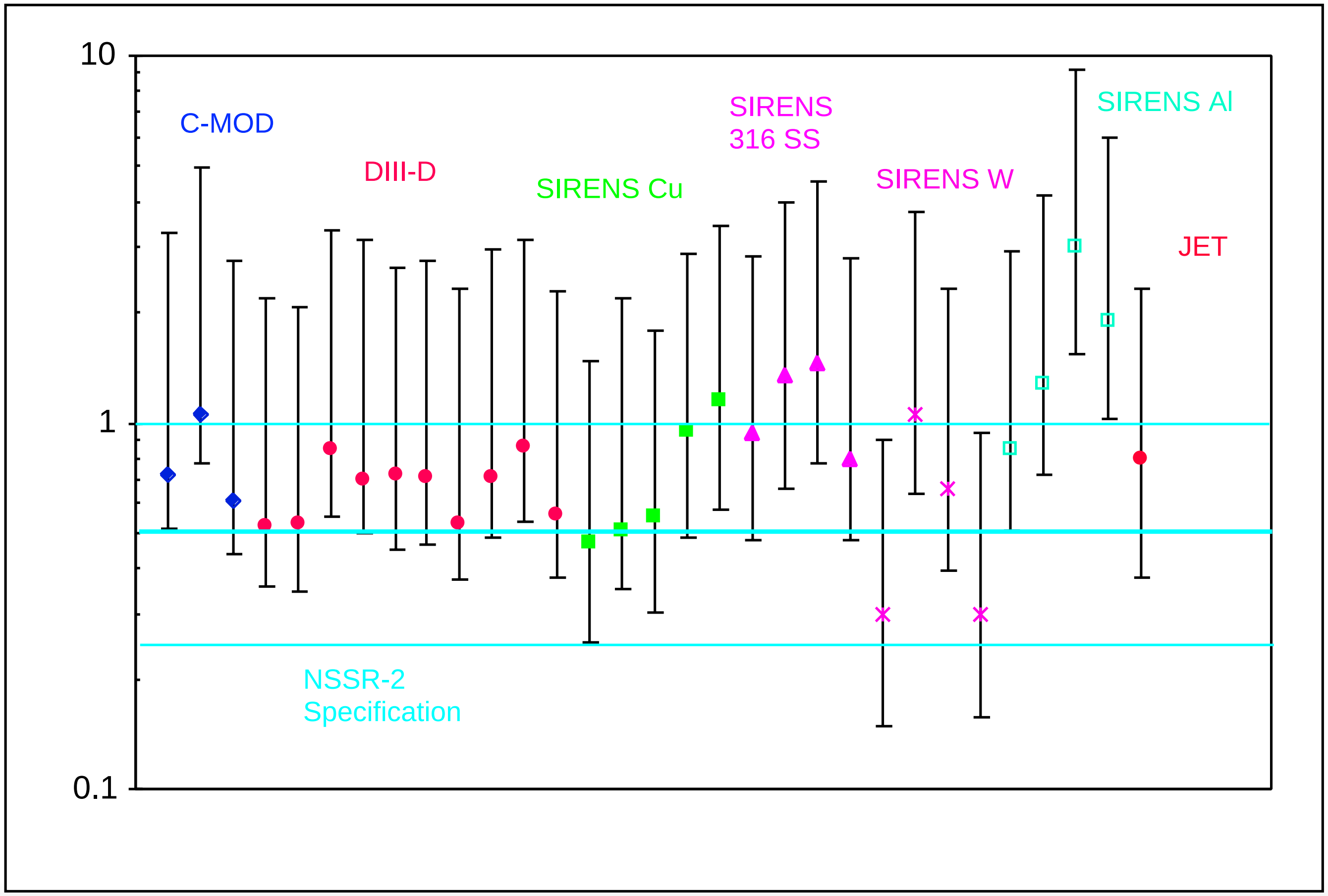






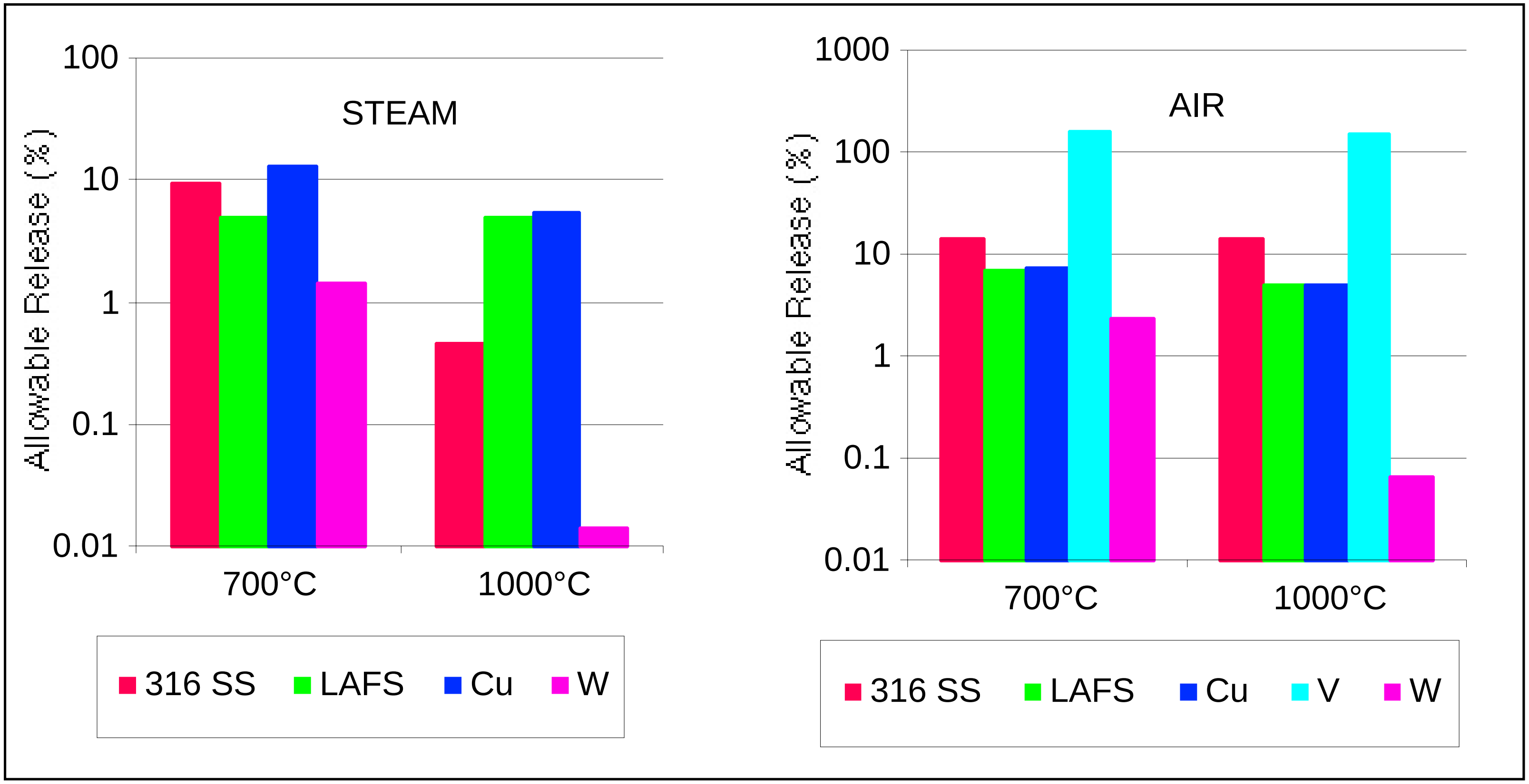
Tore Supra

Dust Data from Existing Tokamaks and Plasma Gun Experiments Were Used to Characterize ITER Dust Source Term

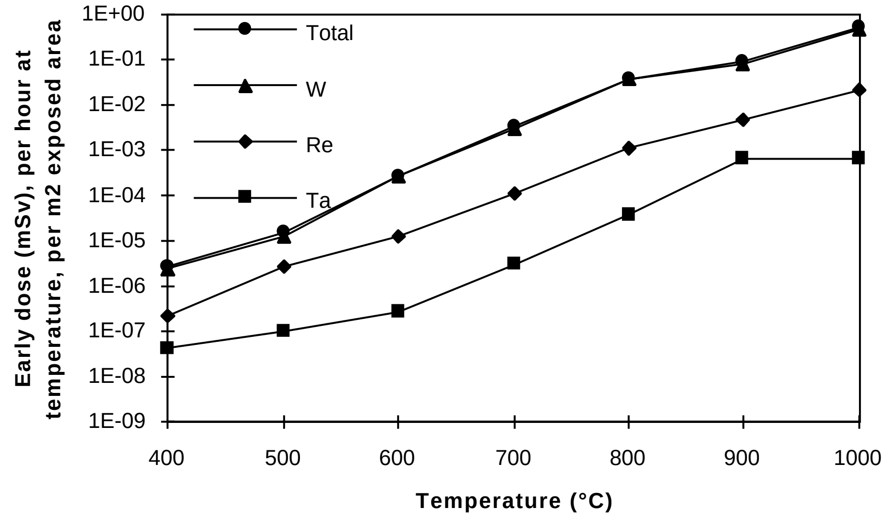


Allowable Release for Oxidation Driven Activation Product Mobilization

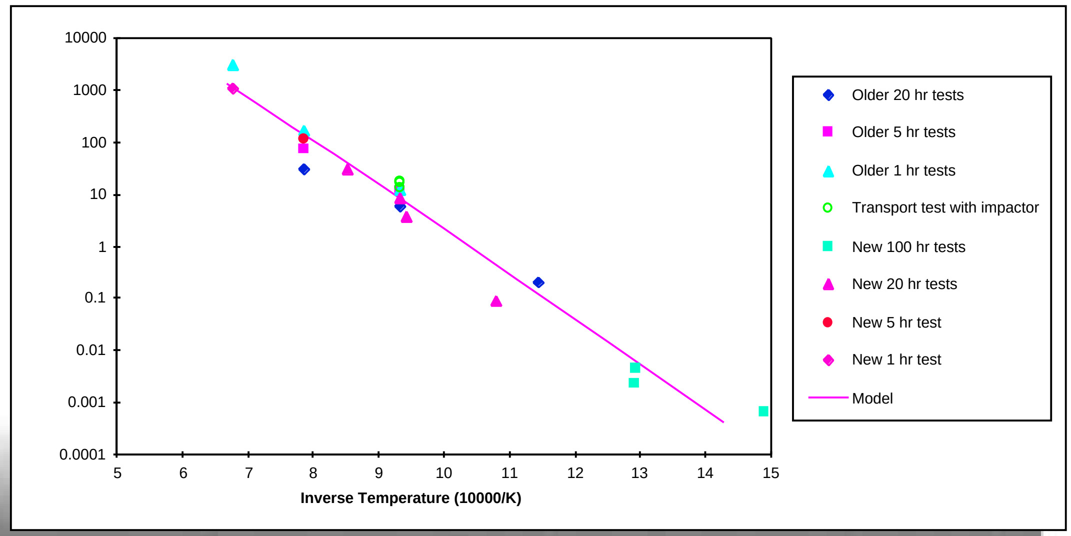
(no credit for confinement)



Measurements of tungsten mobilization in steam down to 400°C results in low site boundary doses.

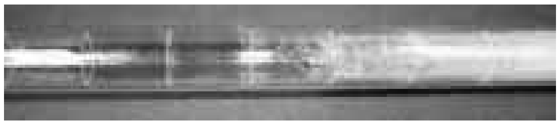


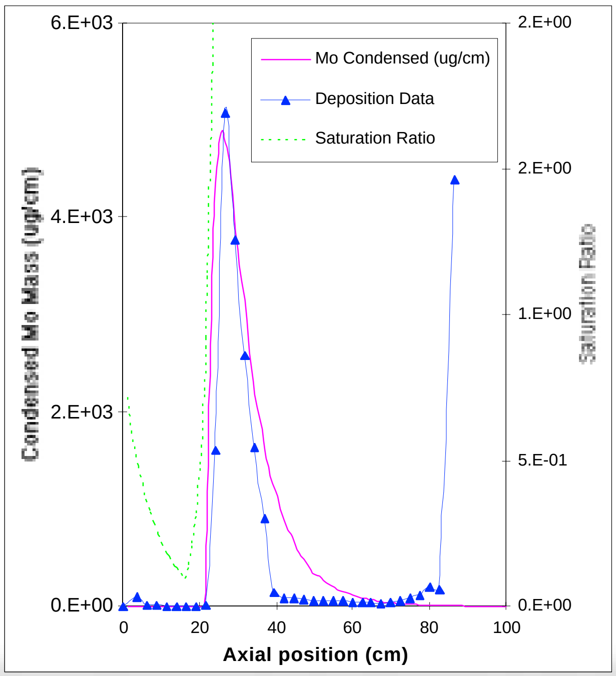
Modeling helped confirm our understanding of the mobilization process



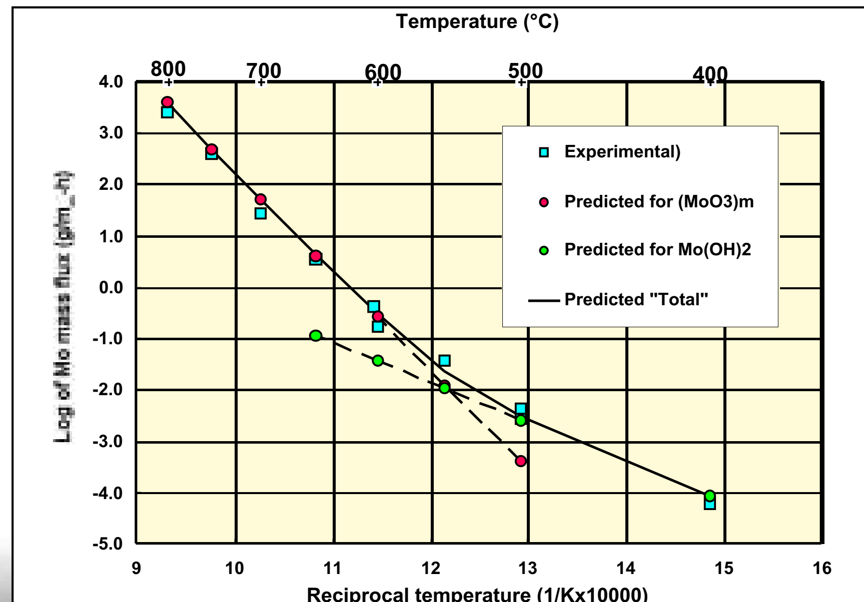
INEEL

Activation Product Mobilization and Transport

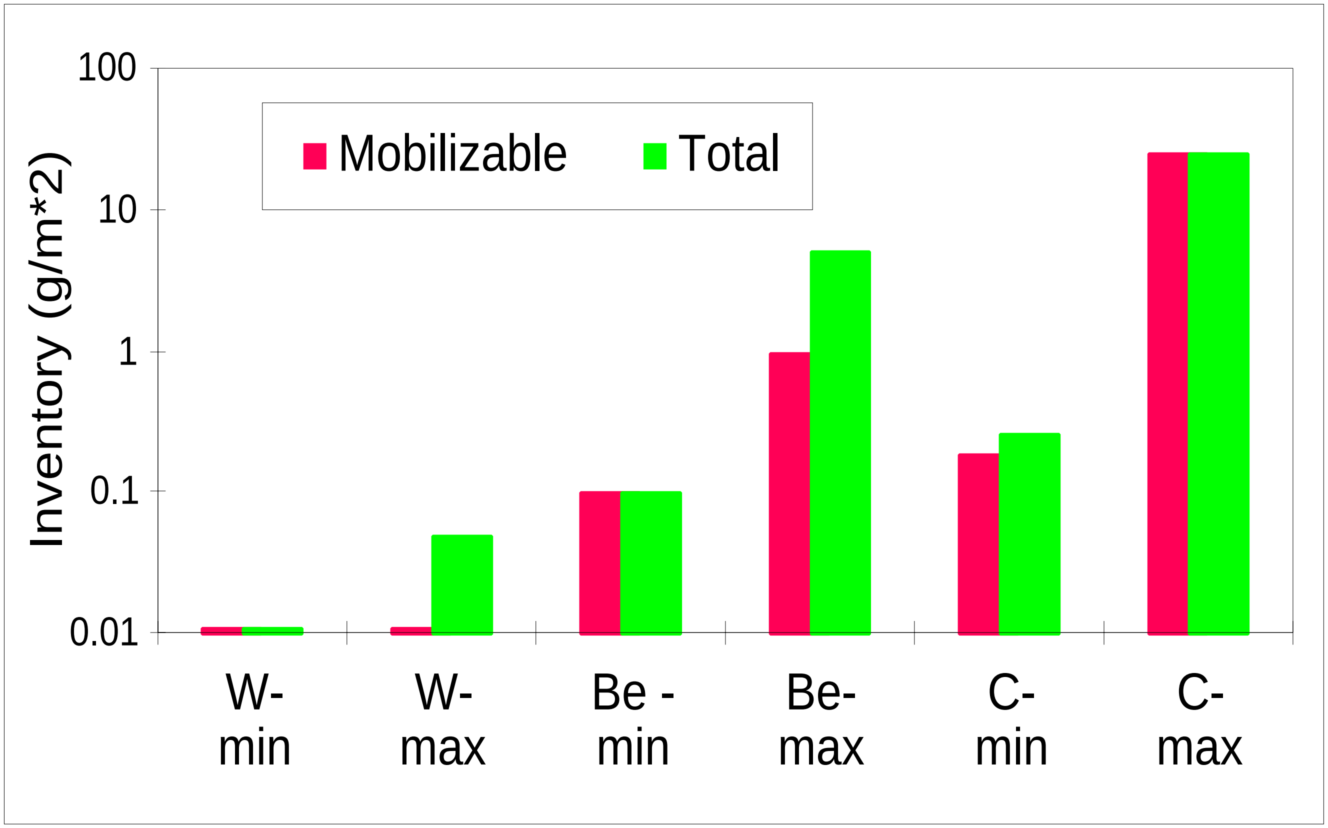




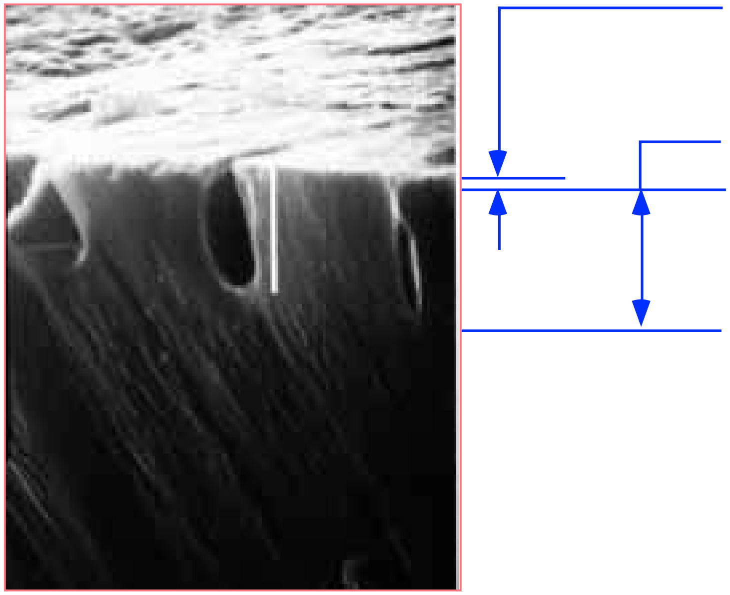
- Oxidation driven mobilization experiments on fusion materials (e.g , V. FS, SS, Cu, W, Nb, Mo, Ta) under air ingress
- Modeling of results
- Oxidation driven mobilization experiments on irradiated SiC (future)



Early Estimates of Tritium Inventory and Mobilization for PFCs



TRITIUM SATURATION EFFECT IN BE



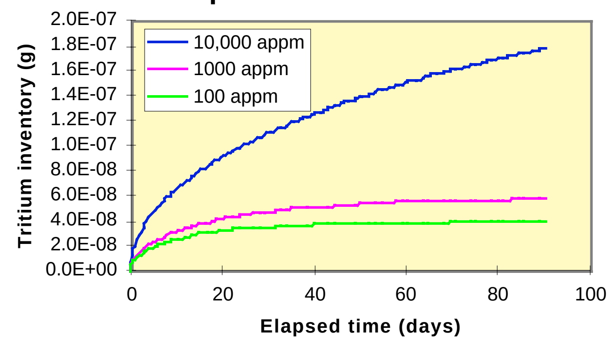
Implantation zone: ions are trapped in small bubbles and defects. Most of them recycle quickly to the surface.

Damage zone: traps are more numerous in this region than in the bulk beryllium. Cavities and channels built by diffusion and agglomeration of damage produced by the ions in the implantation zone.

Impact: inventory due to implantation in Be is much smaller than originally anticipated so Be has a much smaller tritium source term

Saturation of hydrogen isotopes at the surface limits the driving potential for diffusion to a low value related to the yield strength of the beryllium, the implantation depth, and the diffusivity of hydrogen in the implantation-zone beryllium.

First Wall Inventory for Different Trap Concentrations

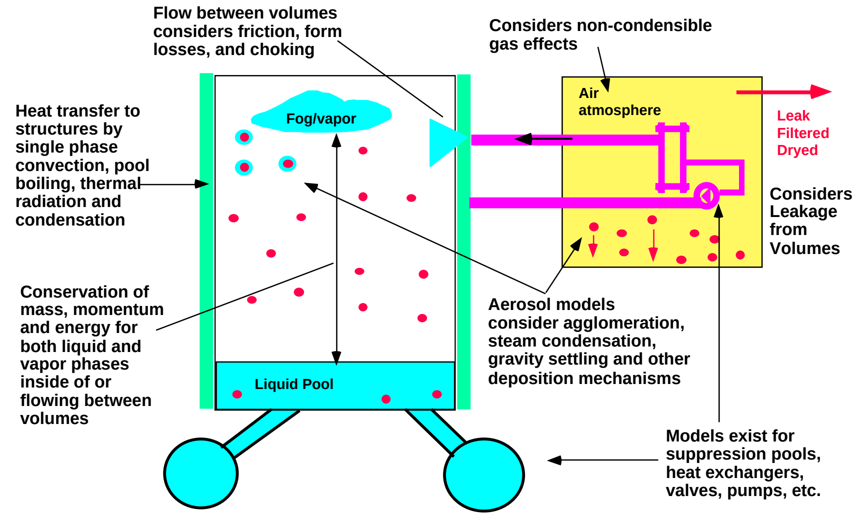


Safety Analysis

- Early safety evaluations of fusion design concepts focused on the importance of the selection of materials and coolant in minimizing the hazards of fusion
- In early studies, safety analysis tools were not very refined which often resulted in overly conservative safety analyses and safety-important design details were not available to incorporate into the safety assessment
- In the mid-80's and early 90's component level analysis was performed (blanket loss of coolant or loss of flow) but no integrated system-level analysis.
- Safety requirements got a stricter --> we needed to really sharpen the pencil.
- Existing fission state of the art systems safety codes were upgraded to deal with fusion specific issues (e.g., cryogenic conditions, chemical reactivity of fusion specific materials).
- These tools provided the first self-consistent analysis to understand the integrated behavior of a tokamak under accident conditions and allowed us to demonstrate that fusion designs could meet the no-evacuation objective (1 rem).

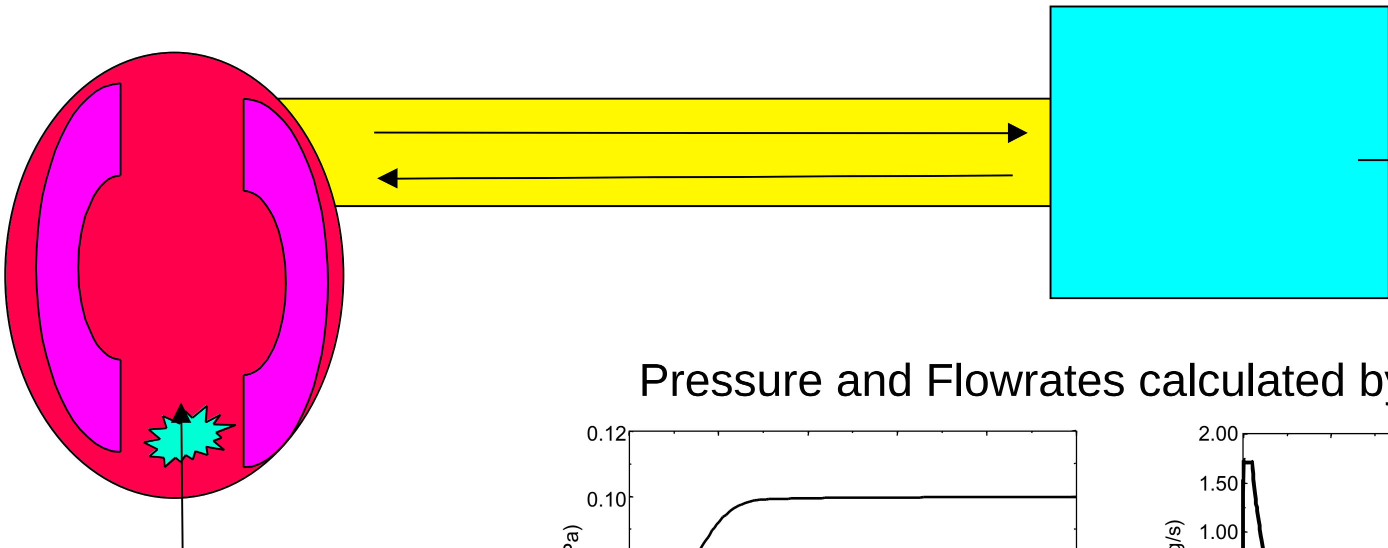
Fusion Safety Computer Codes

- MELCOR code developed by Sandia National Laboratory to analyses severe accidents in fission reactors
- MELCOR tracks the flow of two-phase water during these accidents as well as any aerosols that may exist in the phases
- The temperatures of heat structures is calculated from one-dimensional heat conduction equations



- Heat transfer to both phases is considered. External (walls) or internal (pipes) cooling configurations considered during force/natural/boiling/condensation heat transfer modes
- Modifications have been made to MELCOR for fusion specific analyses

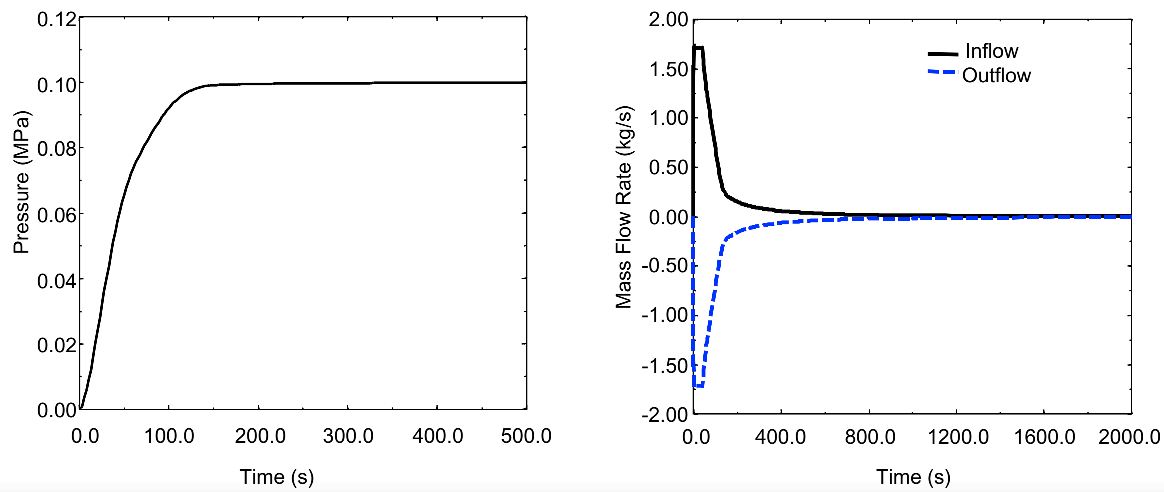
ARIES-AT LOVA Results



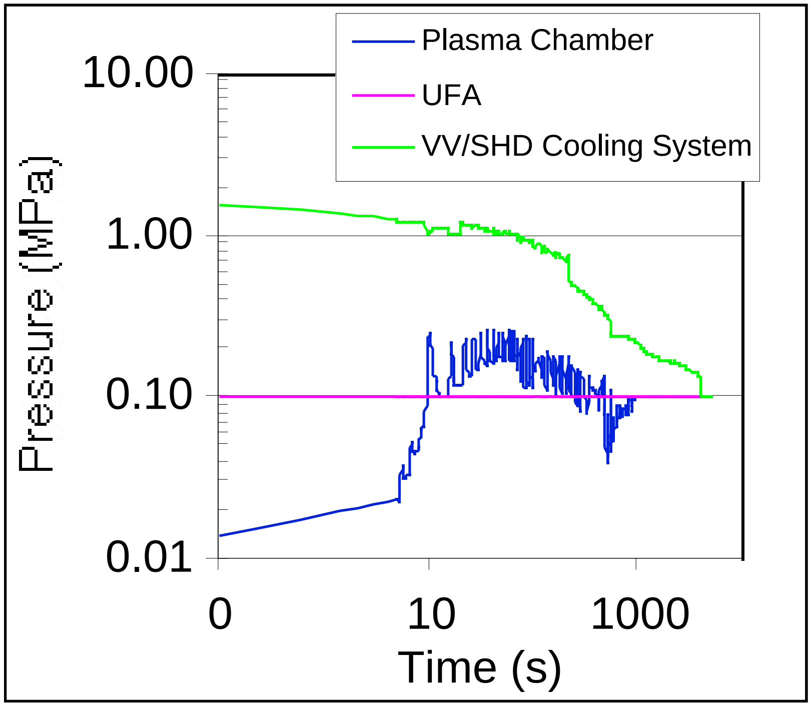
0.08 g of tritium and 0.04 g of dust is released

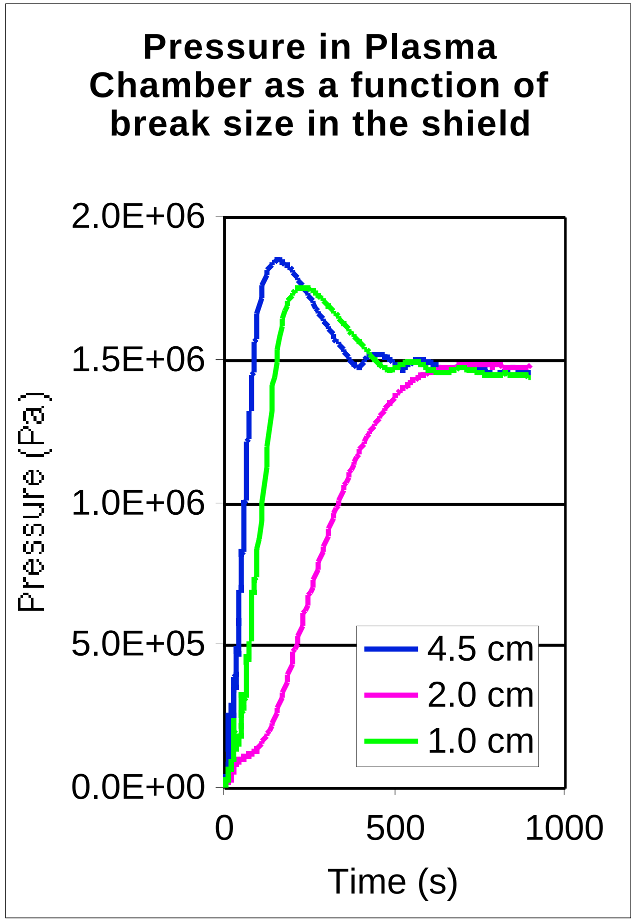
180 g of tritium and 10 kg of dust is mobilized

Pressure and Flowrates calculated by MELCOR



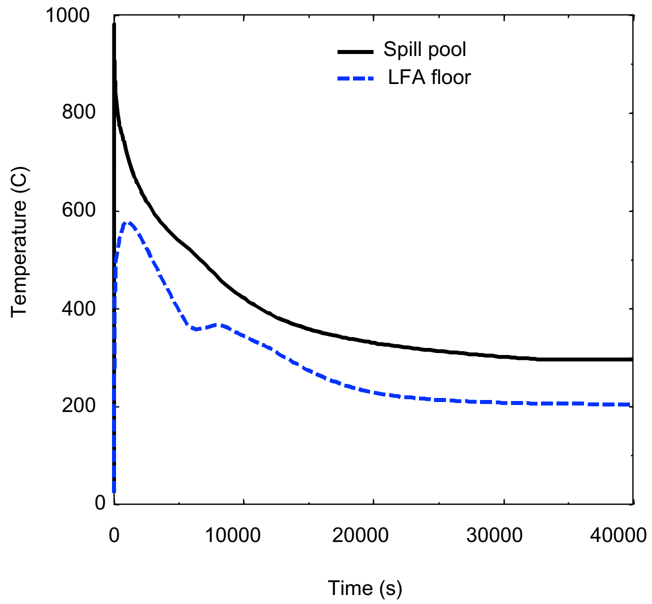
In-vessel Shield LOCA for ARIES-AT with and without suppression system





ARIES-AT Ex-Vessel LOCA

- An ex-vessel LOCA into the functional area below the maintenance corridor was analyzed.
- The MELCOR model included all of the in-vessel fluid components, plus the ring header and the primary cooling system. MHD pressure drop was included in the calculation.
- The total spill was about 150 m^3 from one of four loops. Pool surface area is 525 m^2 and pool depth is 0.24 m. Pool cools by transferring heat to floor. No drain tank in the analysis.
- The ventilation system provides one volume exchange per hour, which exhausts directly to the stack. The leak rate is 1 volume per day at an over pressure of 400 Pa.



- About 500 Ci of Po-210 and 250,000 Ci of Hg-203 are available for release

Mobilization of Po-210 and Hg-203 from LiPb pool

- Diffusional fractional release from the pool is given by:

$$FR = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp[-\frac{D(2n+1)^2\pi^2}{4L^2}]$$

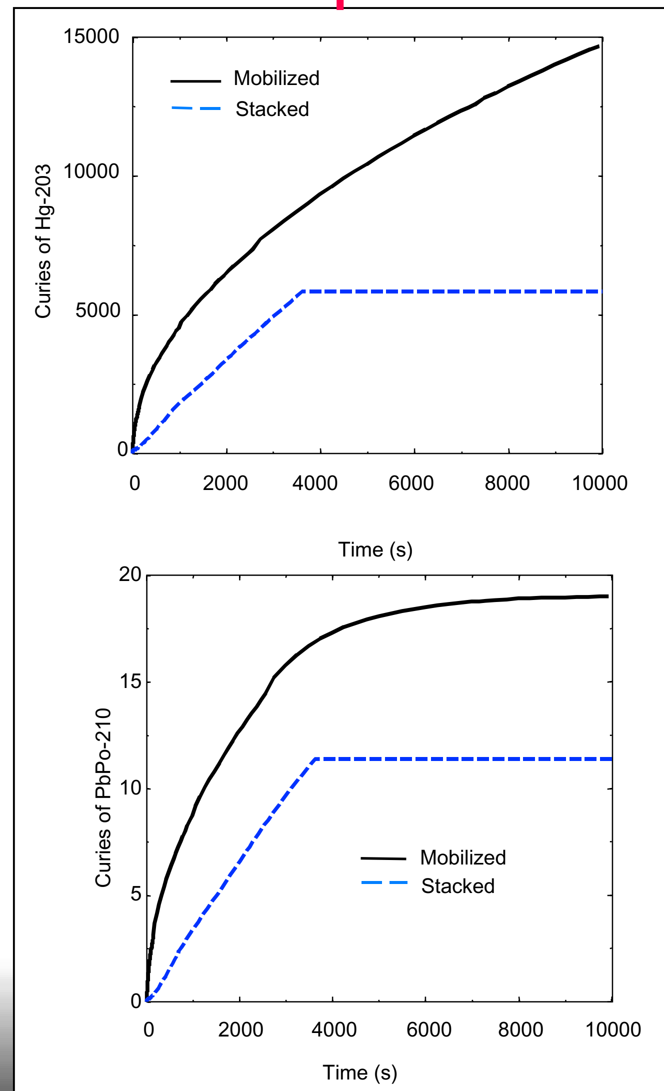
- Where L is the pool depth and D is given by:

  $D(cm^2/s) = 8.2E\text{-}10\ [1 + (3V_a/V_m)2/3]\ T/\ [\mu(V_m)^{1/3}]$

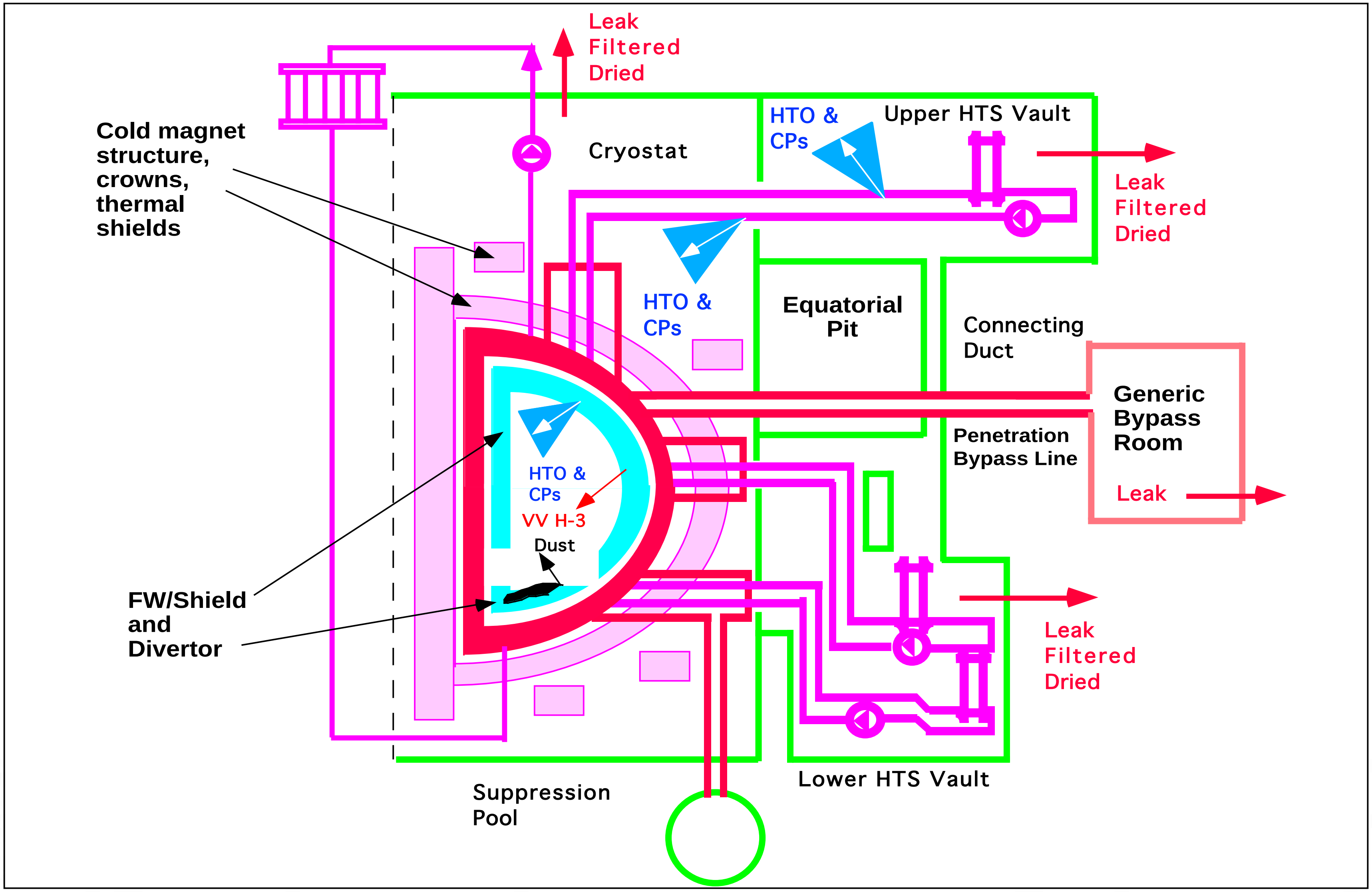
- Vaporization off of the surface for Po-210 is given by:

  $J\ (Ci/cm^2\text{-}hr) = 2.75 \times 10^{-5}\ P_{sat}(T)\ (1000/T)^{0.5}$

- Mobilization is given by the minimum of these two rates for Po-210. Complete vaporization of Hg is assumed since pool is above boiling point of Hg



Schematic MELCOR Model of ITER



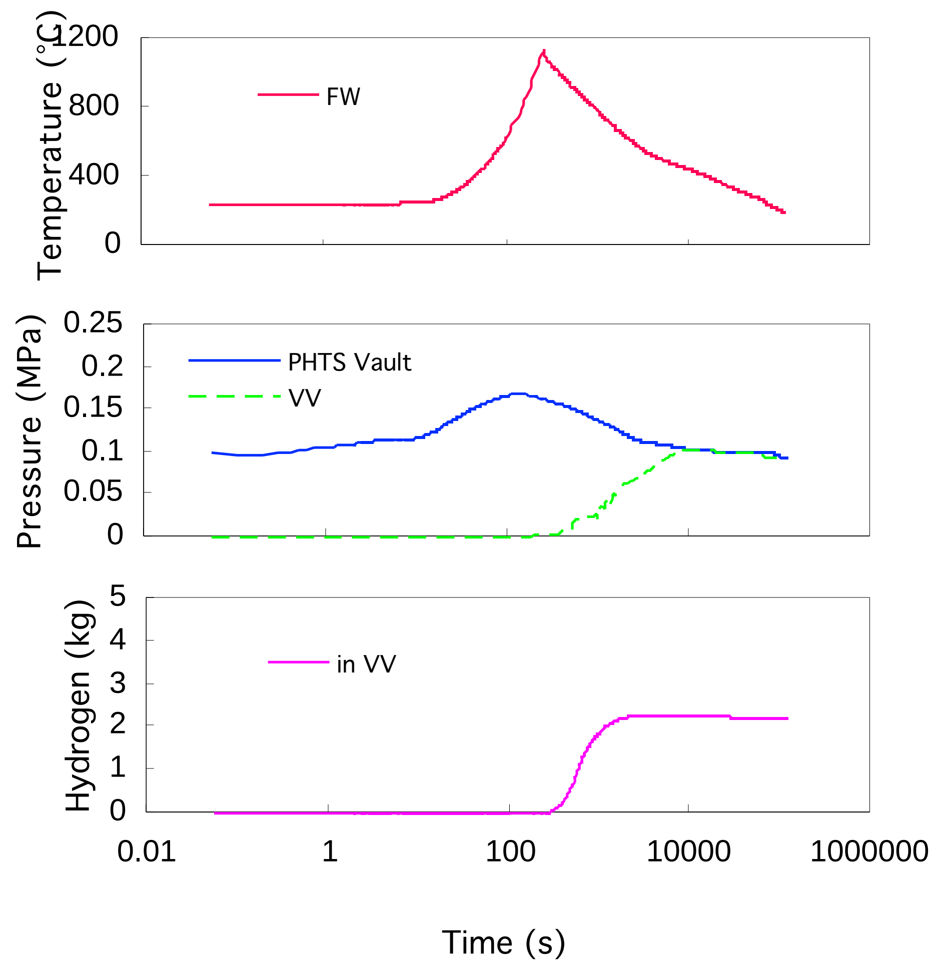
Ex-Vessel Loss of Coolant without Fusion Power Shutdown in ITER EDA

In case of on-going plasma burn temperature increase in affected components.

- failure of in-vessel components at elevated temperatures
- ingress of steam into VV
- Be/steam chemical reactions
- hazard of hydrogen formation
- Bypass primary confinement barrier

=> plasma burn will be terminated by fusion shutdown system

In worst case, if shutdown system fails, inherent passive shutdown of the plasma at 1150°C due to Be evaporation limits hydrogen production in an ex-vessel LOCA to below the deflagration limit (10 kg in VV)



Base Case Analysis

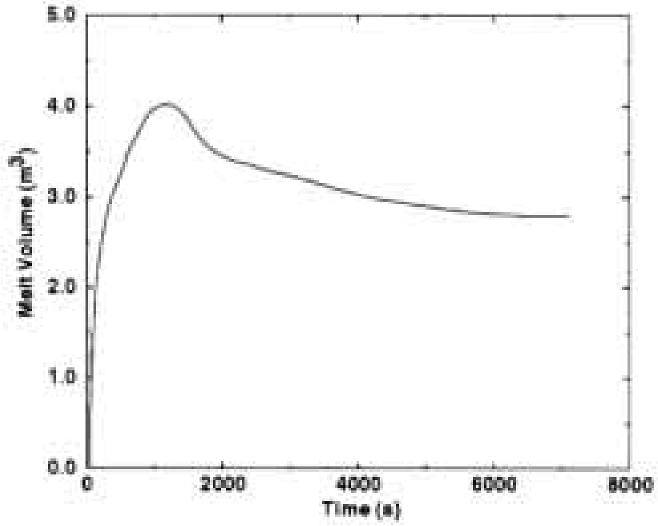
Unmitigated TF Quench

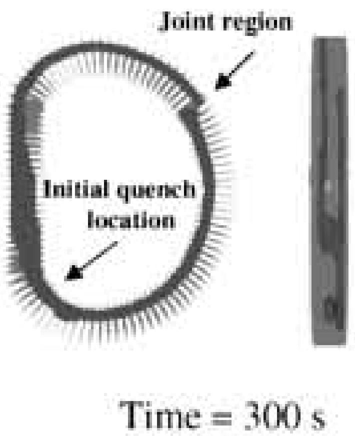
Model Capabilities and Benchmark

- Conduction - copper stabilizer, glass epoxy insulation, radial plates, and coil case
- Arcing, displaced currents, resistive heating, and material melting
- Helium convection and fluid flow
- Turn to turn heat flow benchmarks against other ITER models

Model Results

- Current decay by 300 s, with 98% resistive heating, 2% arc heating
- ~ 4 m^3 of melt at 1000 s. Case meltthrough at 7000 s.
- Radiological consequences bounded by VV LOCA with 1 m^2 hole in both VV and cryostat. Operation of VV pressure suppression system and cryopumping of magnets limits releases well below no-evacuation criterion

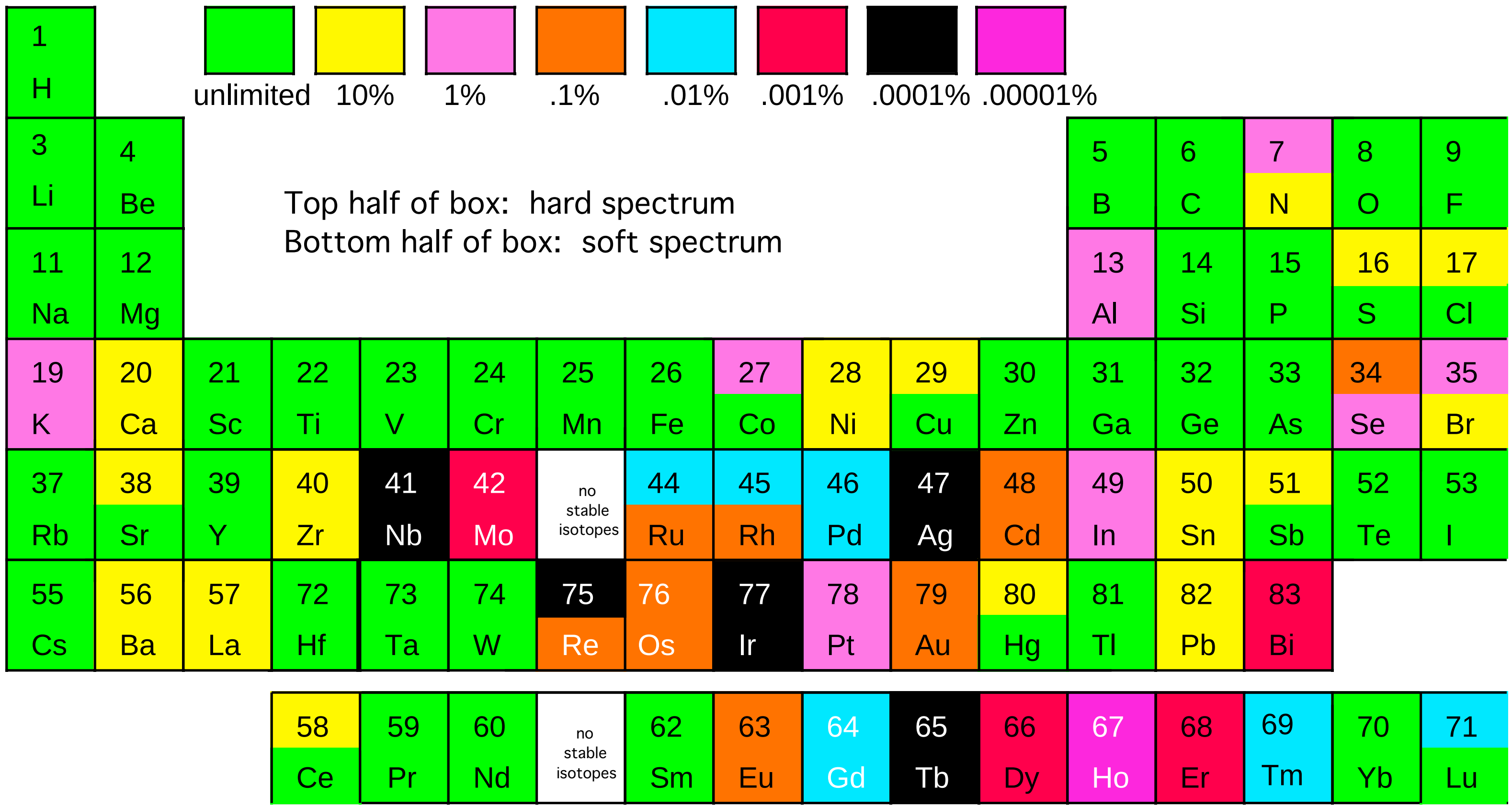




Environmental Considerations

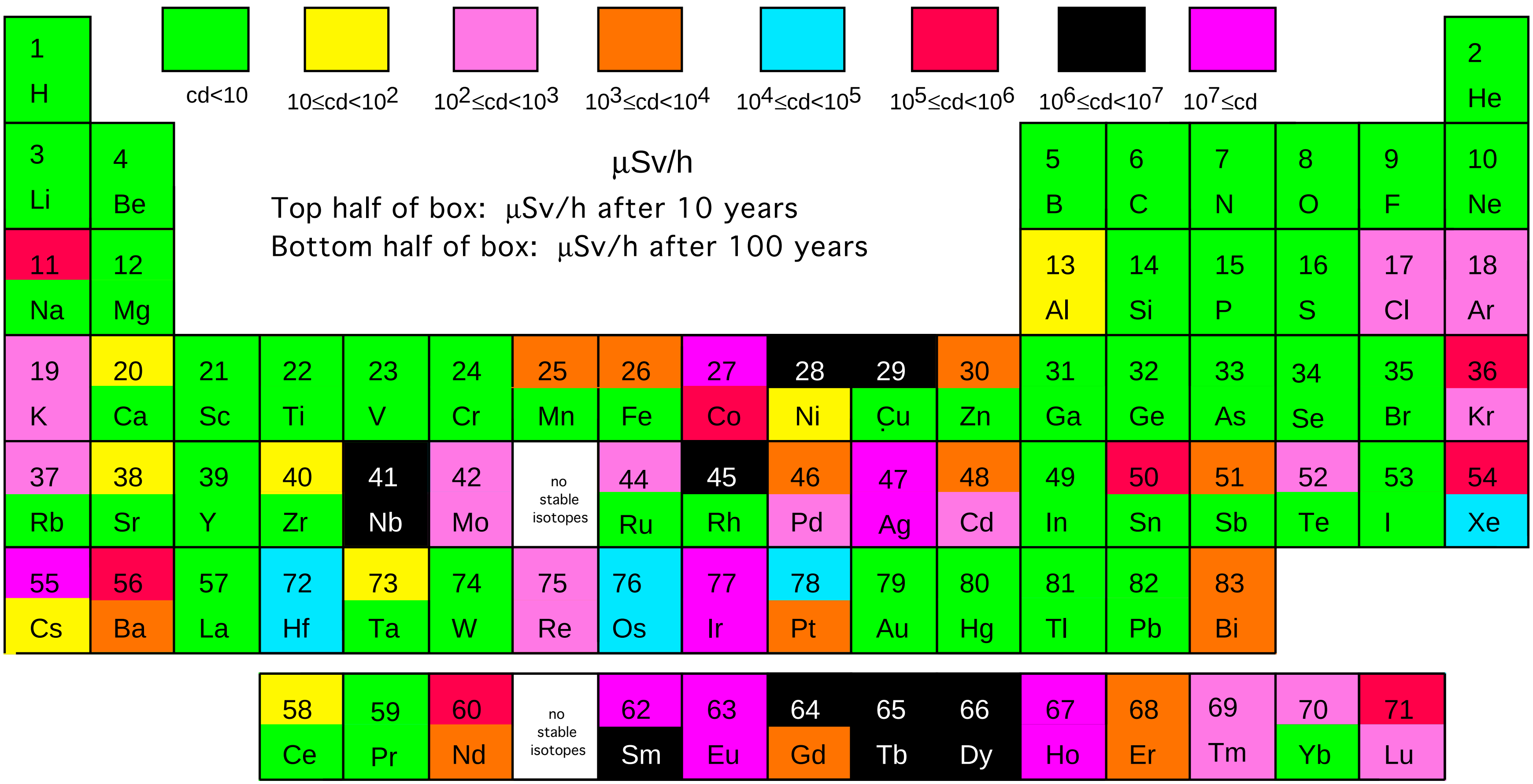
- Early in the program, the concept of biological hazard potential was used to evaluate long term hazard of fusion wastes
- 10CFR61 delineated the requirements for low level waste requirements
- Fusion expanded the list of fission isotopes to include fusion isotopes.
- Requiring that all waste from fusion meet low level waste requirements has been a hallmark of the ARIES program
- Comparison of waste from fusion and other energy technologies were developed
- More recently with the difficulty of disposing of anything radioactive, we have been examining
  - Recycling (both remote and hands-on) potential of fusion materials
  - Clearance of very low level radioactive material
  - Volume of fusion waste versus hazard

Limits on Elements for Class C Waste Qualification



From: Piet, et al., "Initial Integration of Accident Safety, Waste Management, Recycling, Effluent, and Maintenance Considerations for Low-Activation Materials", **Fusion Technology**, Vol. 19, Jan. 1991, pp. 146-161. Assumes 5 MW/m^2 for 4 years; and E. T. Cheng, "Concentration Limits of Natural Elements in Low Activation Materials", **presented at ICFRM-8, Sendai, Japan,October 1997**

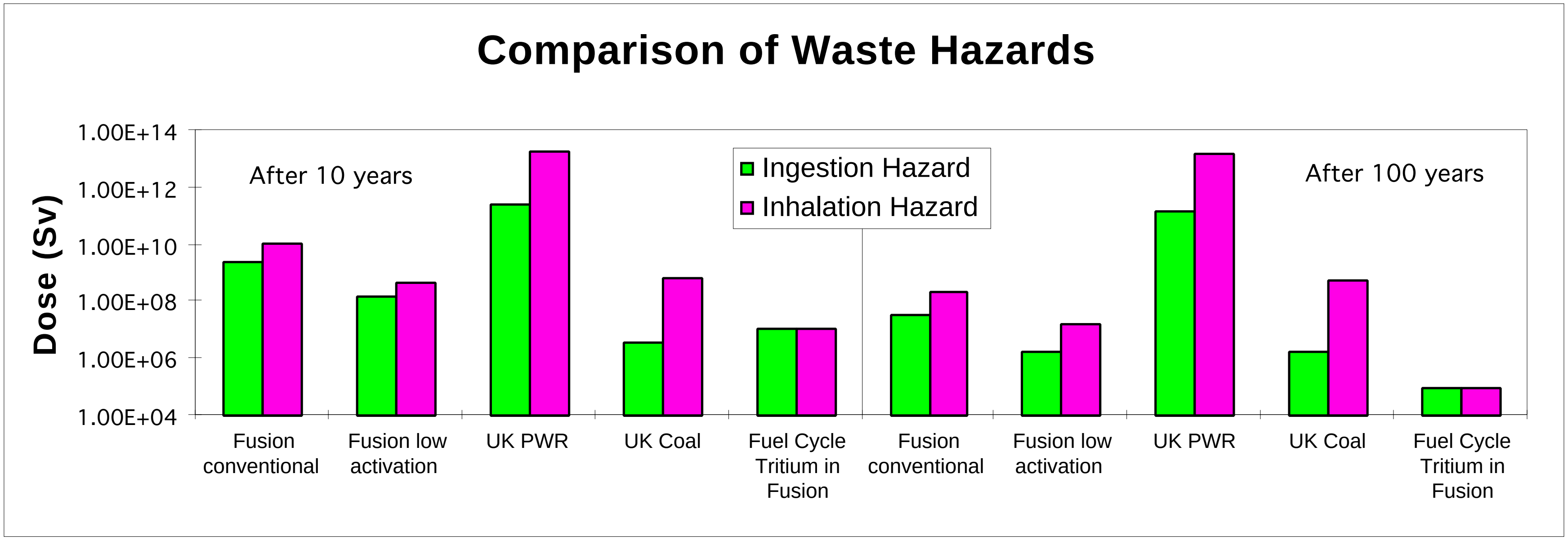
Contact Dose at Shield After 10 and 100 Years

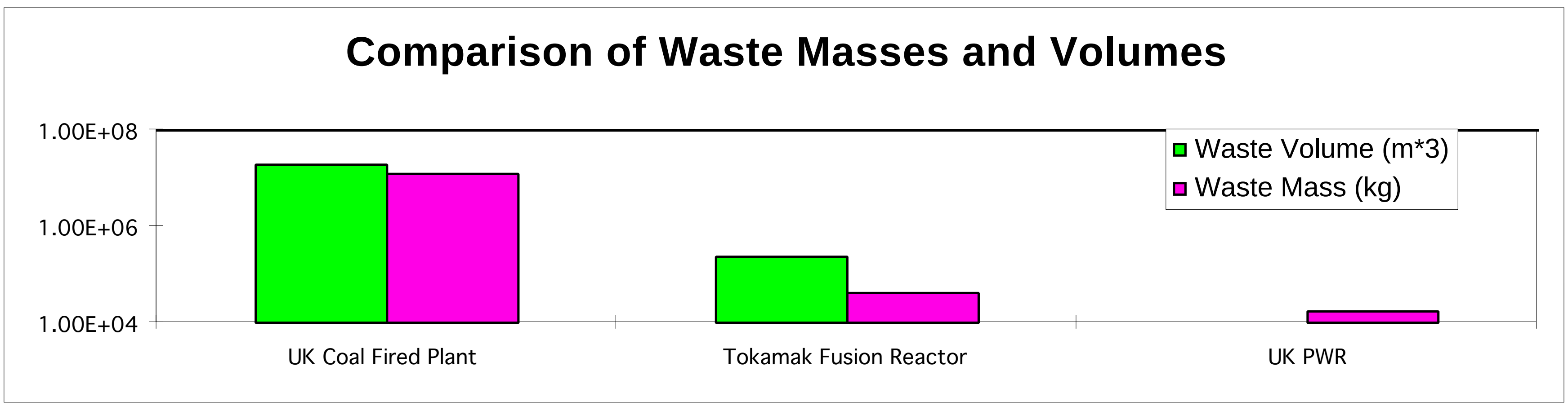


Based on C. B. A. Forty, et al., Handbook of Fusion Activation Data; Part 1. Elements Hydrogen to Zirconium, AEA FUS 180, May, 1992. Assumes 4.15 MW/m^2 for 25 years

Comparison of the Hazards of Fusion With Those From Fission and Coal Based on Radioactive Inventories in Fusion, Fission and Coal (e.g., Ra, U, Th, Po).

From “A Study of the Environmental Impact of Fusion” (AERE R 13708, 1990)





Summary

- Over the past 25 to 30 years, safety and environmental issues have played an ever increasing role in fusion power plant design
- As fusion power plant designs have matured, safety requirements have gotten more stringent.
- Materials selection, while important to minimizing the hazard from fusion facilities, was not enough to meet today's more stringent safety requirements
- Better safety/design integration, improved safety analysis tools, more complete safety analyses, and focused R&D are also needed along with materials selection to help demonstrate the safety and environmental potential of fusion