Characteristics of an Economically Attractive Fusion Power Plant

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Fusion: Energy Source for the Future?
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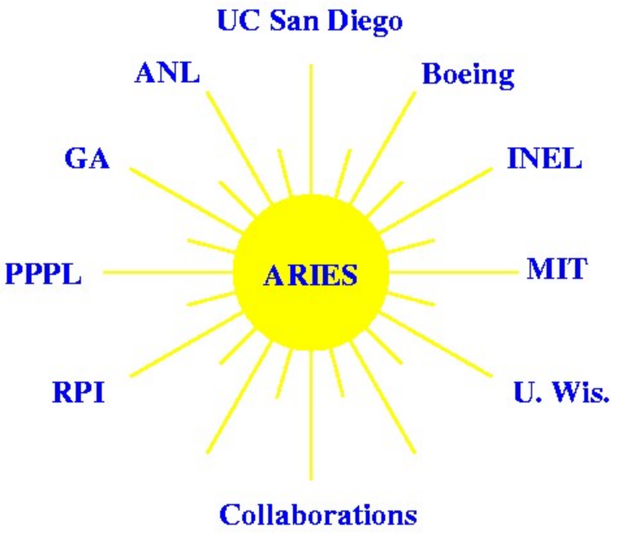
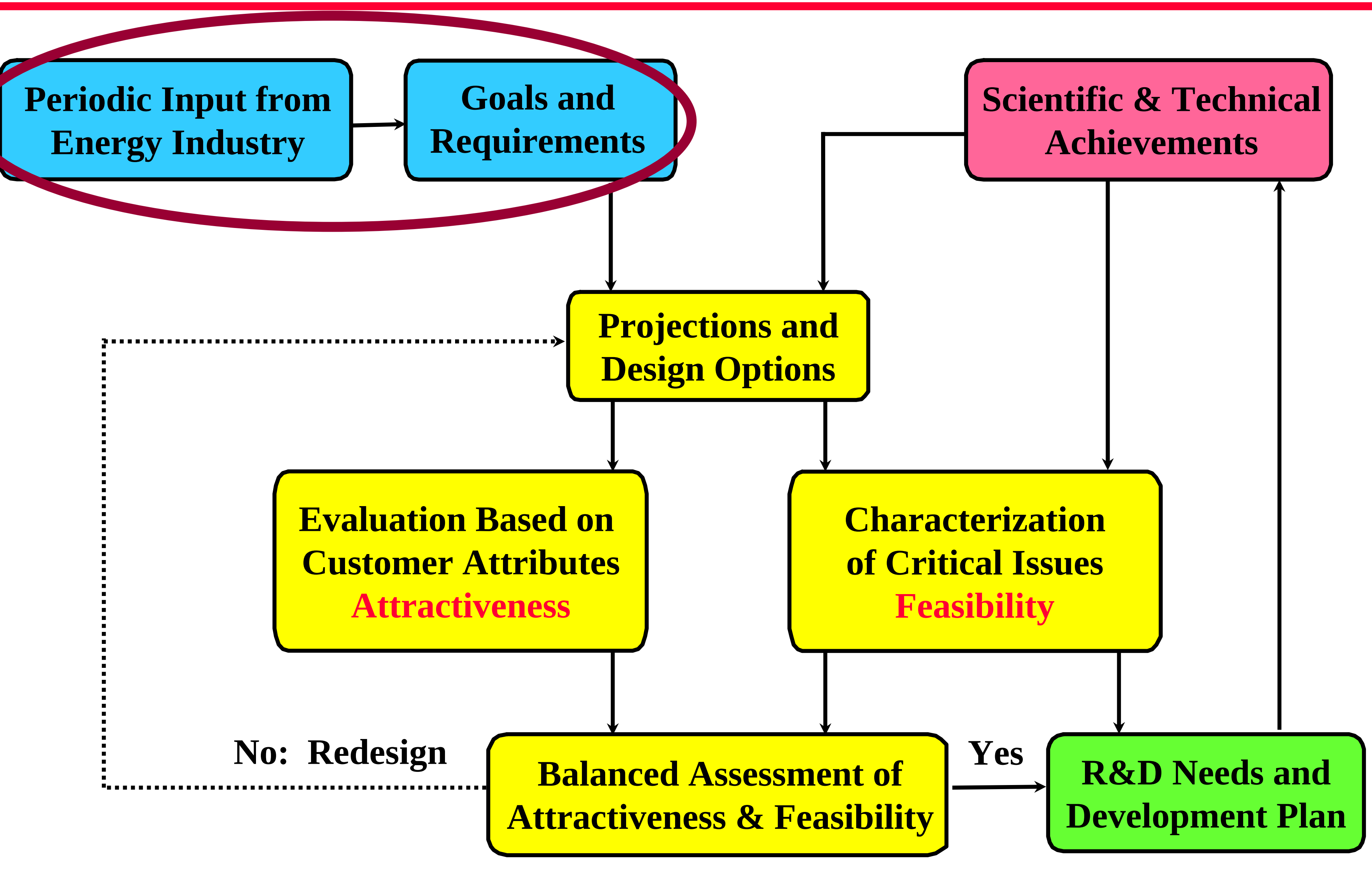


Framework:
Assessment Based on Attractiveness & Feasibility



Elements of the Case for Fusion Power Were Developed through Interaction with Representatives of U.S. Electric Utilities and Energy Industry

- **Have an economically competitive life-cycle cost of electricity**
- **Gain Public acceptance by having excellent safety and environmental characteristics**
  - ✓ No disturbance of public's day-to-day activities
  - ✓ No local or global atmospheric impact
  - ✓ No need for evacuation plan
  - ✓ No high-level waste
  - ✓ Ease of licensing

  Low-activation material
- **Reliable, available, and stable as an electrical power source**
  - ✓ Have operational reliability and high availability
  - ✓ Closed, on-site fuel cycle
  - ✓ High fuel availability
  - ✓ Capable of partial load operation
  - ✓ Available in a range of unit sizes

Fusion physics & technology

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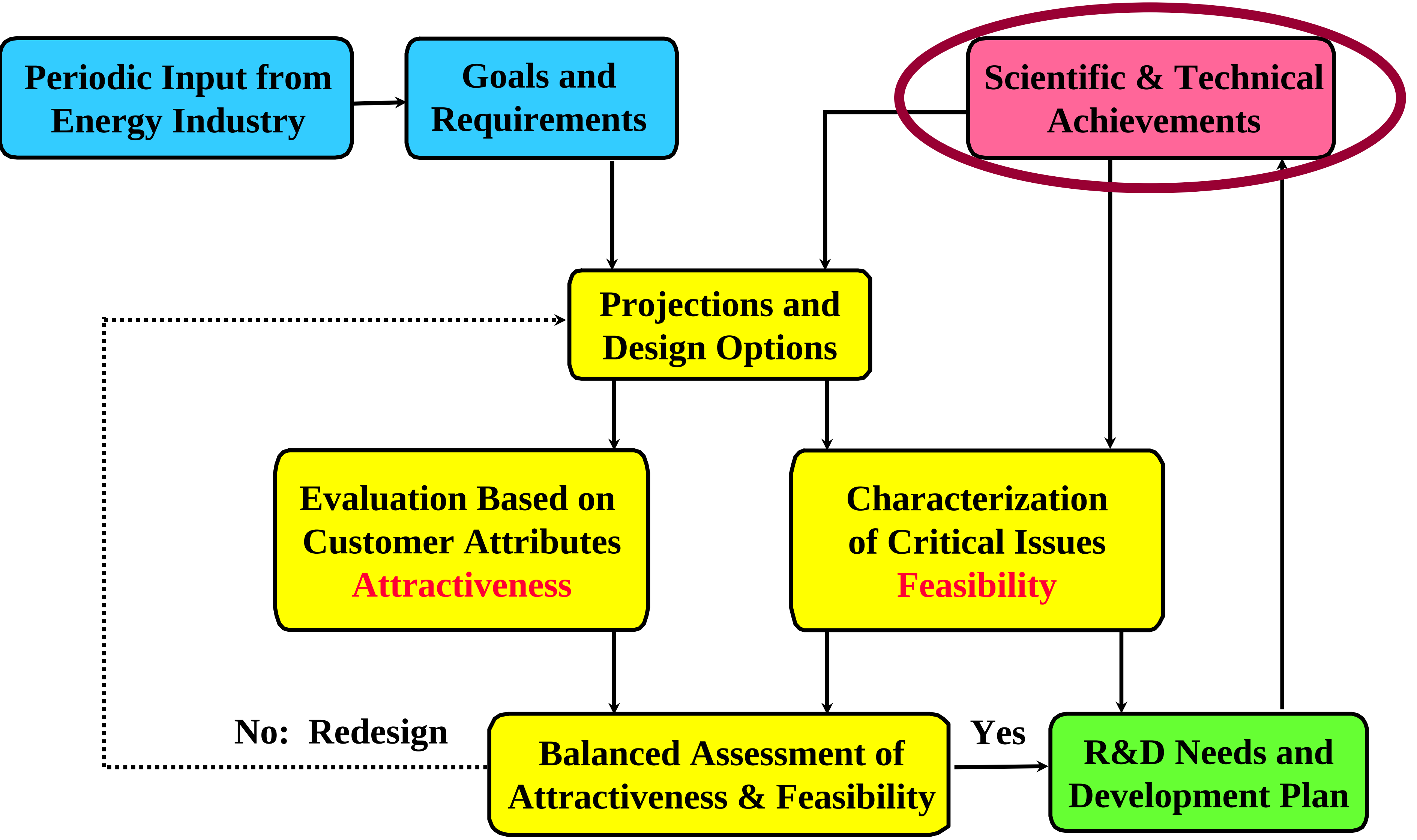
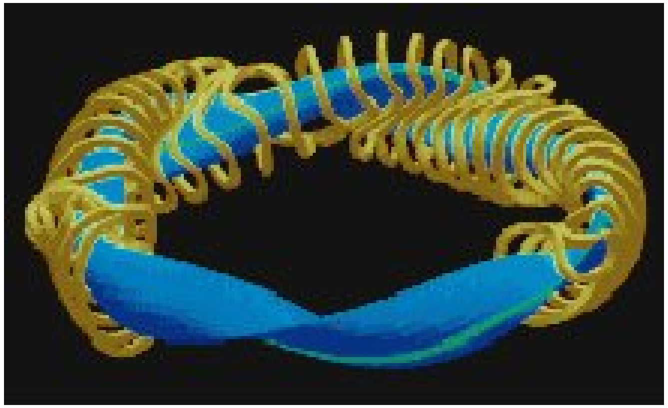
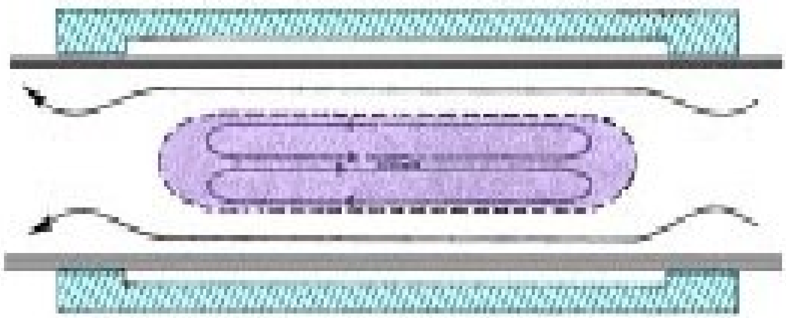


Portfolio of MFE Configurations

Externally Controlled ⟷ **Self Organized**





Example: Stellarator

Confinement field generated by mainly external coils

Toroidal field >> Poloidal field

Large aspect ratio

More stable, better confinement

Example: Field-reversed Configuration

Confinement field generated mainly by currents in the plasma

Poloidal field >> Toroidal field

Small aspect ratio

Simpler geometry, higher power density

Portfolio of IFE Configurations

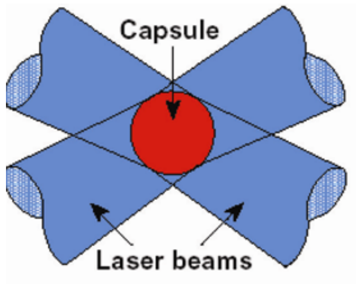
Driver:

Lasers
(η = 5%-10%)

Heavy-ions
(η = 15%-40%)

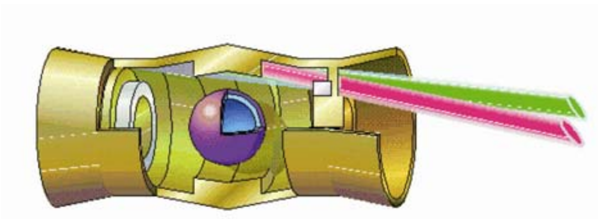
Z-pinch
(η ~ 15%)

Target:

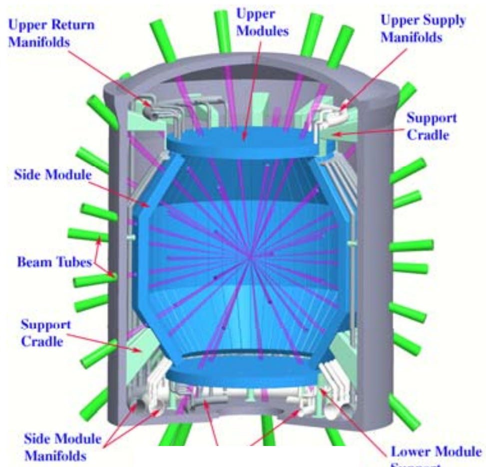


Direct drive

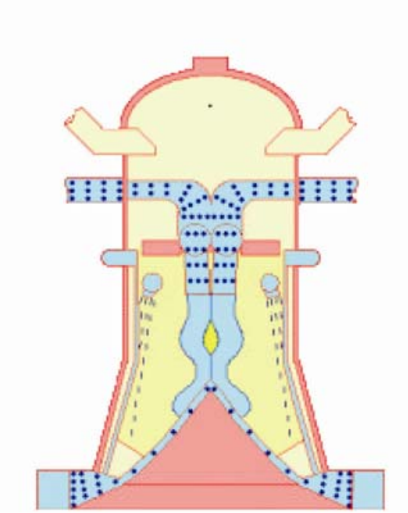
$\eta G > 10$
for energy


Indirect drive

Chamber:



Dry Walls


Liquid Walls: HYLIFE II

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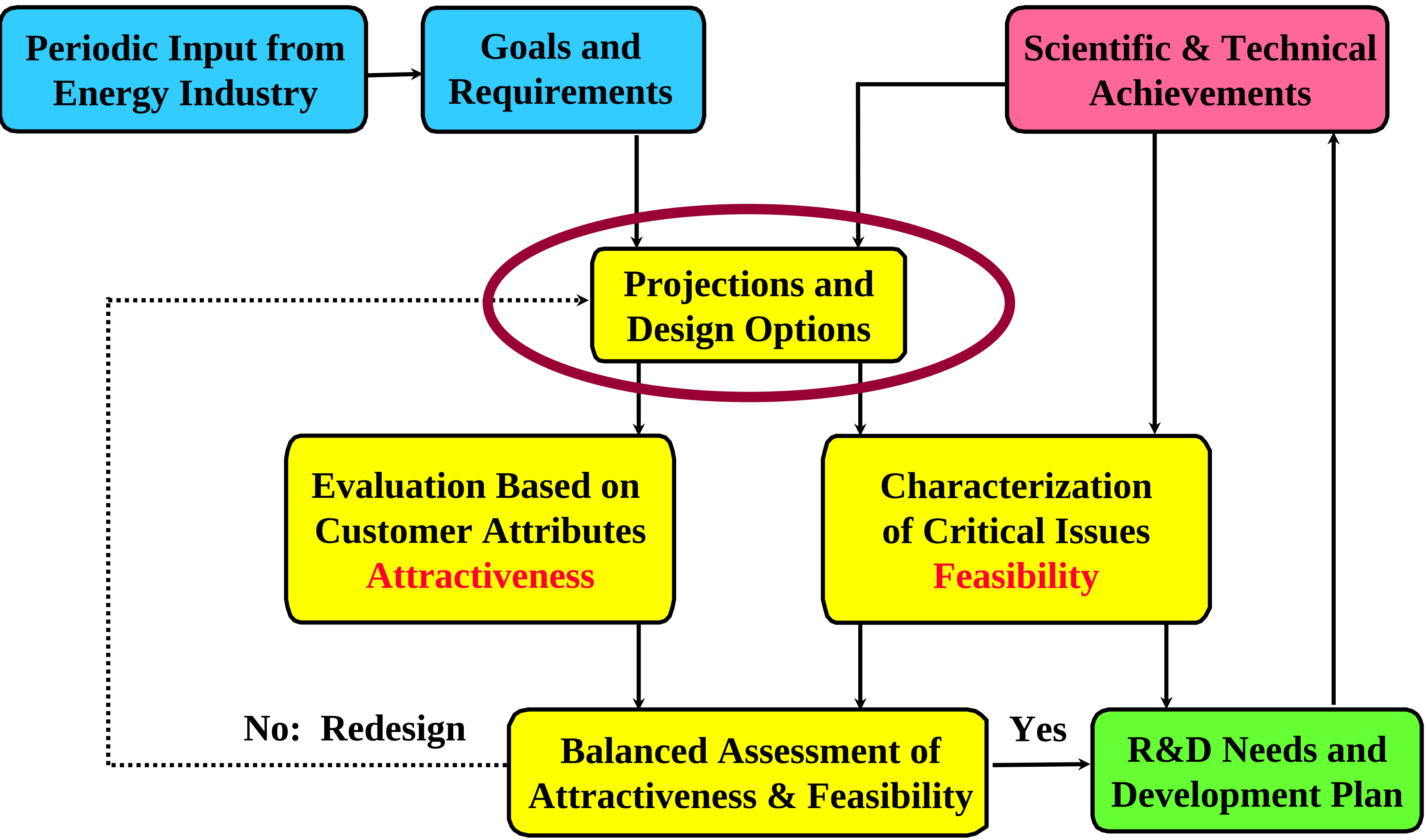
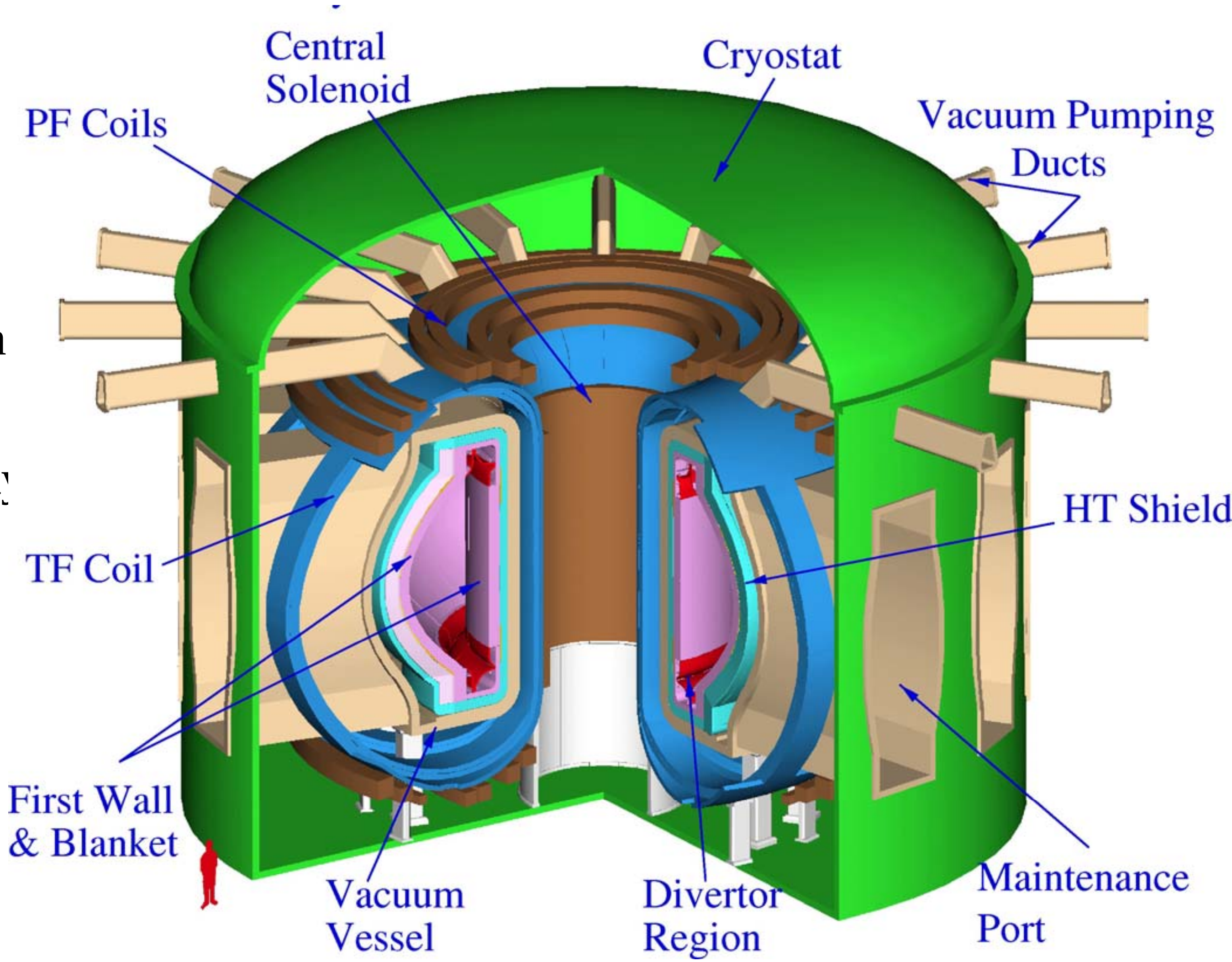


ARIES-AT is an attractive vision for fusion with a reasonable extrapolation in physics & technology

* Competitive cost of electricity (5c/kWh);
* Steady-state operation
* Low level waste;
* Public & worker safety
* High availability.



A high-performance plasma should have a high power density & a low recirculating power fraction

Requirement: Establish and maintain the magnetic bottle

- **External magnets:**
  - ✓ Superconducting: size and cost
  - ✓ Normal conducting (e.g., copper): power consumption
- **Maintenance of plasma profiles (mainly plasma current)**
  - ✓ Inductive (transformer action): non-stationary
  - ✓ Non-inductive through Neutral beams, microwave, …: Inefficient

- Key parameters:
  - ✓ **Plasma β** (ratio of plasma pressure to magnetic pressure)

    Non-dimensional parameter β_N is a measure of plasma performance
  - ✓ **Current-drive power P_{CD}**

A dramatic change occurred in 1990: Introduction of Advanced Tokamak

- Our vision of a fusion system in 1980s was a large pulsed device.
  - ✓ Non-inductive current drive is inefficient.
- Some important achievements in 1980s:
  - ✓ Experimental demonstration of bootstrap current;
  - ✓ Development of ideal MHD codes that agreed with experimental results.
  - ✓ Development of steady-state power plant concepts (ARIES-I and SSTR) based on the trade-off of bootstrap current fraction and plasma β

    ARIES-I: β_N= 2.9, β=2%, P_{cd}=230 MW

Reverse Shear Regime

- Excellent match between bootstrap & equilibrium current profile at high β.
- **ARIES-RS** (medium extrapolation): β_N= 4.8, β=5%, P_{cd}=81 MW (achieves ~5 MW/m^2 peak wall loading.)
- **ARIES-AT** (aggressive extrapolation): β_N= 5.4, β=9%, P_{cd}=36 MW (high β is used to reduce peak field at magnet)

DT Fusion requires a T breeding blanket

Requirement: Plasma should be surrounded by a blanket containing Li

$$\left.\begin{array}{l} D + T \rightarrow He + n \\ n + {}^{6}Li \rightarrow T + He \end{array}\right\} \quad D + {}^{6}Li \rightarrow He + He$$

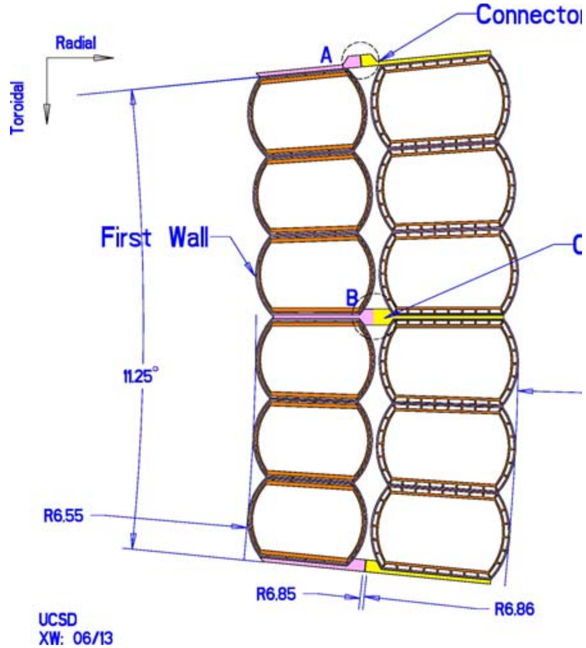
- **DT fusion turns its waste (neutrons) into fuel!**
- Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity
  - ✓ Rad-waste depends on the choice of material: Low-activation material
  - ✓ Rad-waste generated in DT fusion is similar to advanced fuels (D-^{3}He)
  - ✓ For liquid coolant/breeders (*e.g.*, Li, LiPb), most of fusion energy (carried by neutrons) is directly deposited in the coolant simplifying energy recovery
- **Issue: Large flux of neutrons through the first wall and blanket:**
  - ✓ Need to develop radiation-resistant, low-activation material:

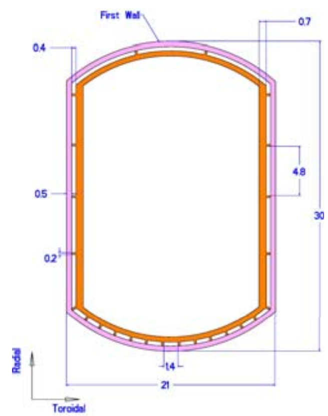
    Ferritic steels, Vanadium alloys, SiC composites

ARIES-AT: SiC Composite Blankets

Outboard blanket & first wall

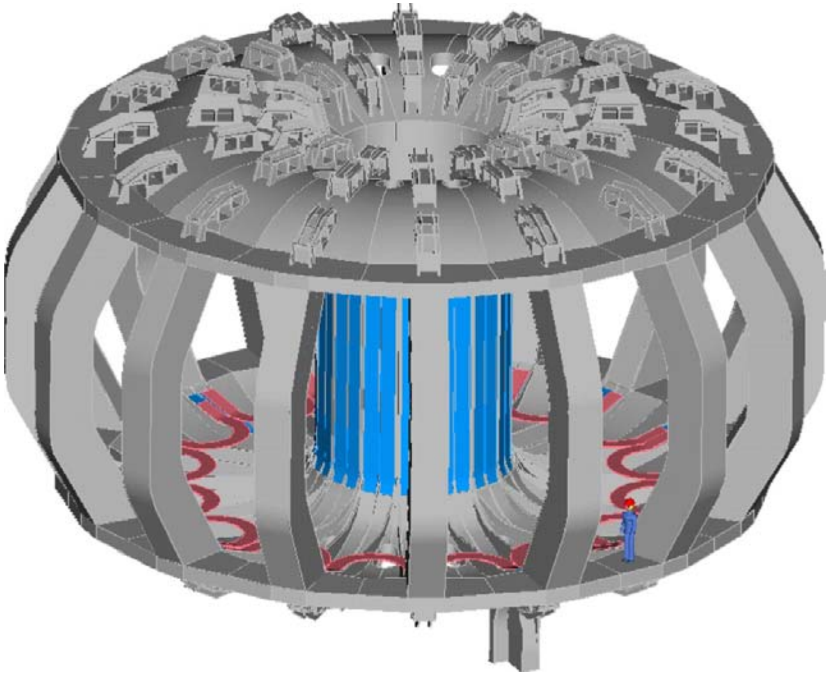
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1,100°C) while keeping SiC structure temperature below 1,000°C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.

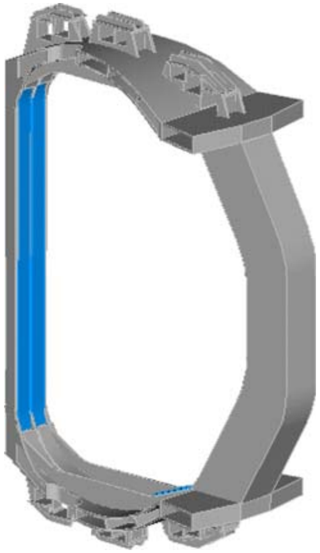




The ARIES-AT Utilizes An Efficient Superconducting Magnet Design

- On-axis toroidal field: 6 T
- Peak field at TF coil: 11.4 T
- TF Structure: Caps and straps support loads without inter-coil structure;



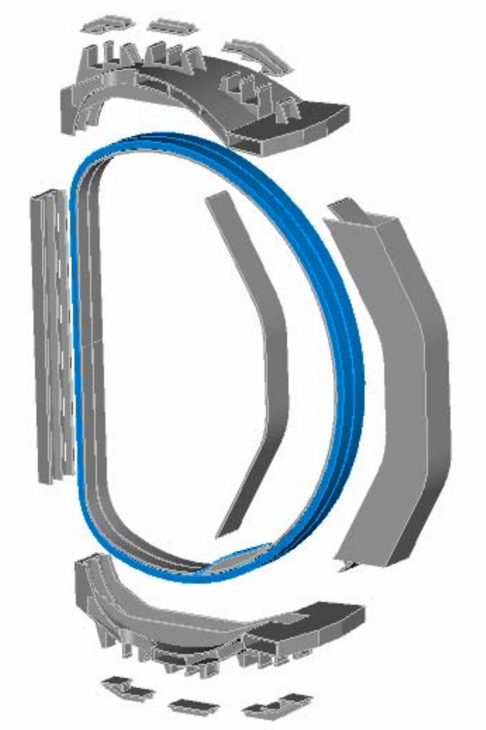


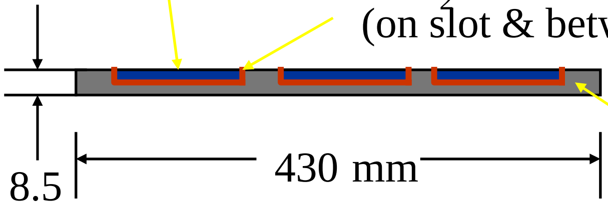
Superconducting Material

- Either LTC superconductor (Nb_3Sn and NbTi) or HTC
- Structural Plates with grooves for winding only the conductor.

Use of High-Temperature Superconductors Simplifies the Magnet Systems

- HTS does offer operational advantages:
  - ✓ Higher temperature operation (even 77K), or dry magnets
  - ✓ Wide tapes deposited directly on the structure (less chance of energy dissipating events)
  - ✓ Reduced magnet protection concerns

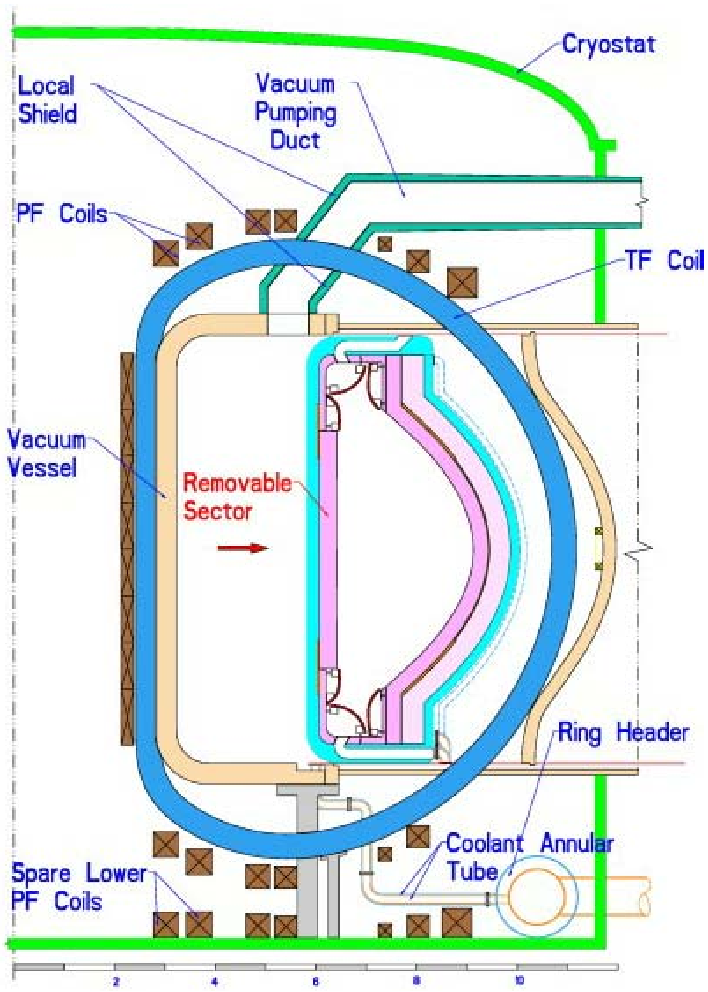




- **Epitaxial YBCO**

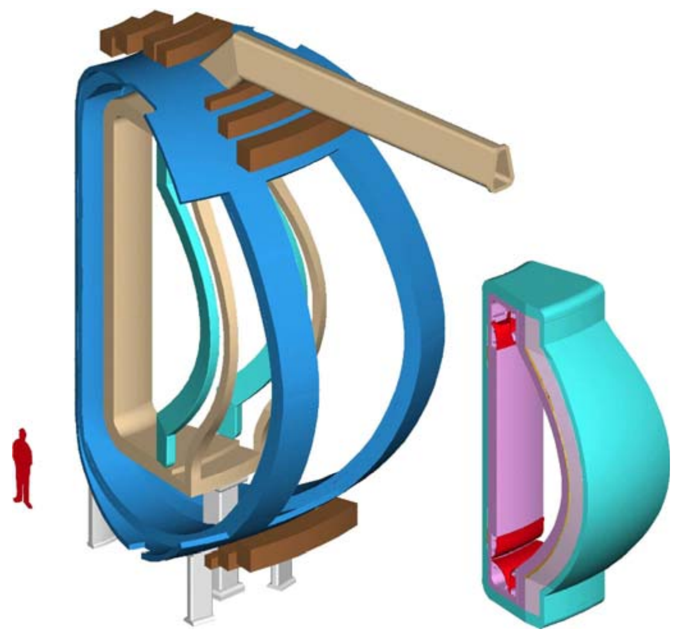
  Inexpensive manufacture would consist on layering HTS on structural shells with minimal winding!

Modular sector maintenance enables high availability



ARIES-AT elevation view

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks



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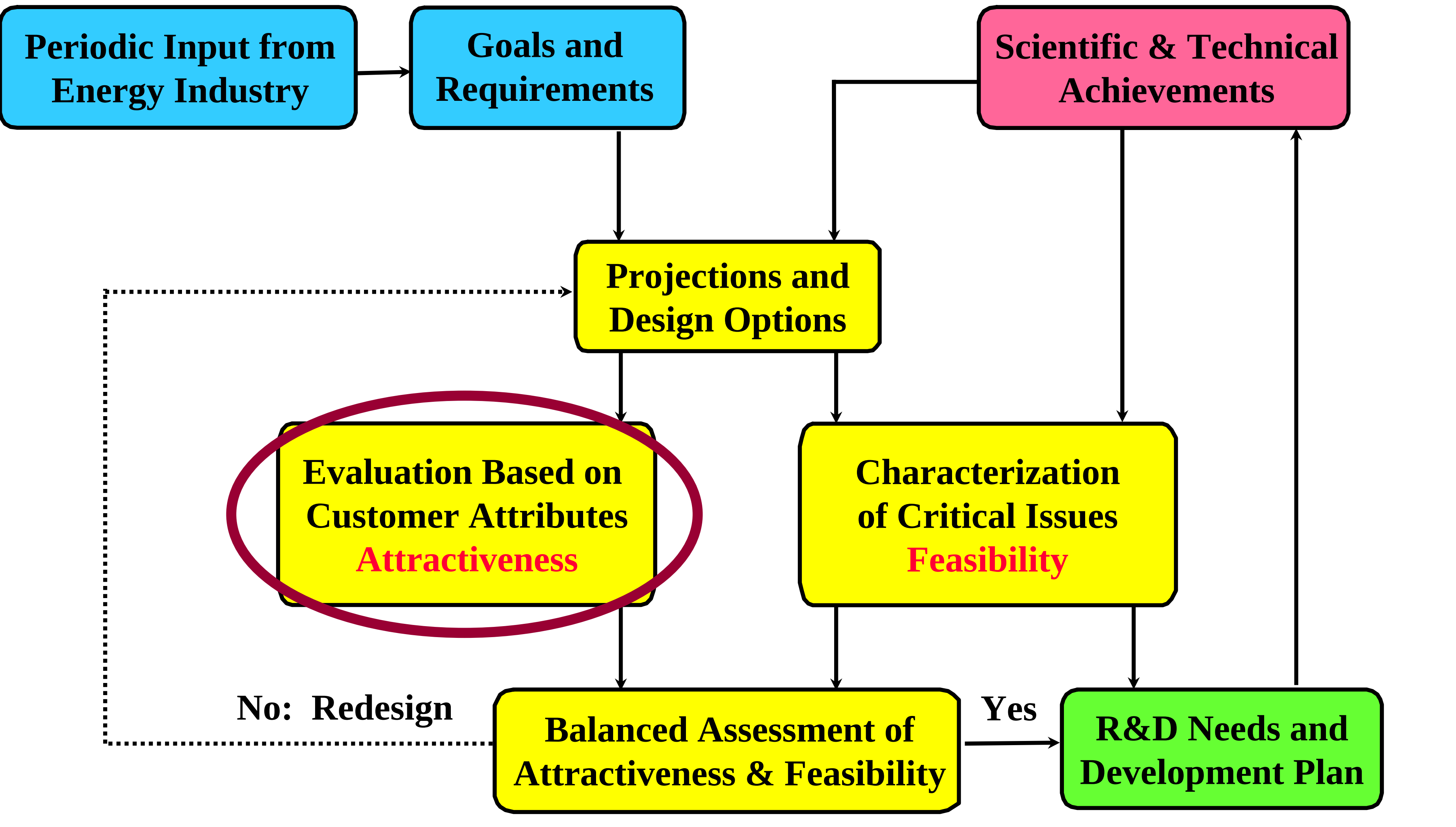
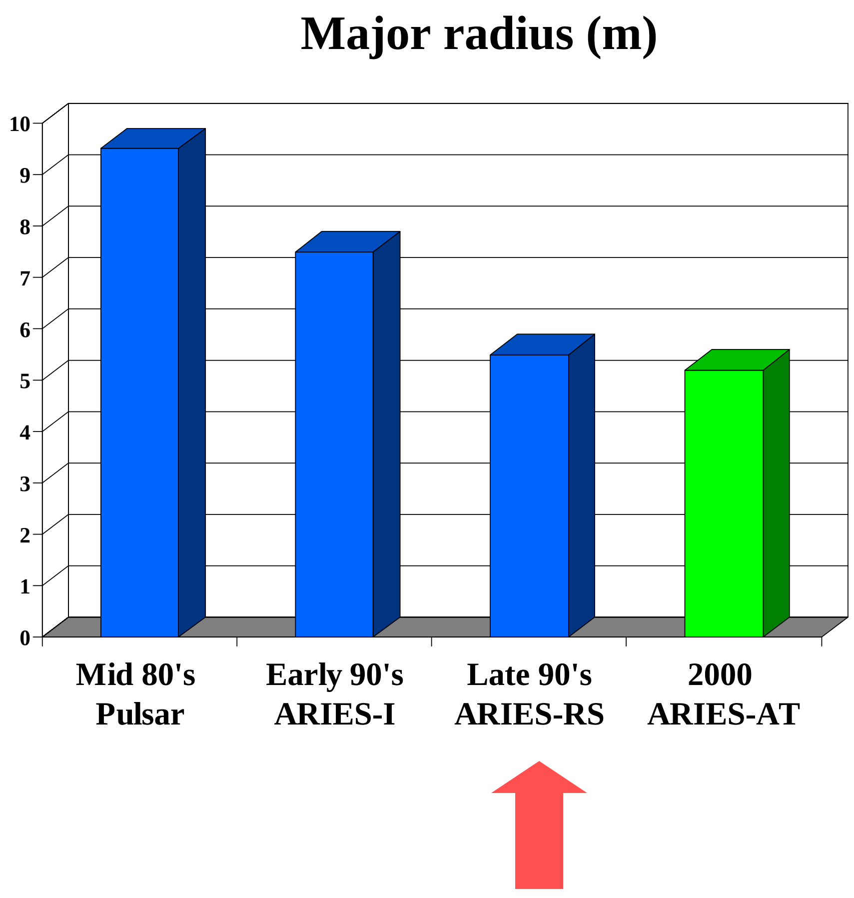
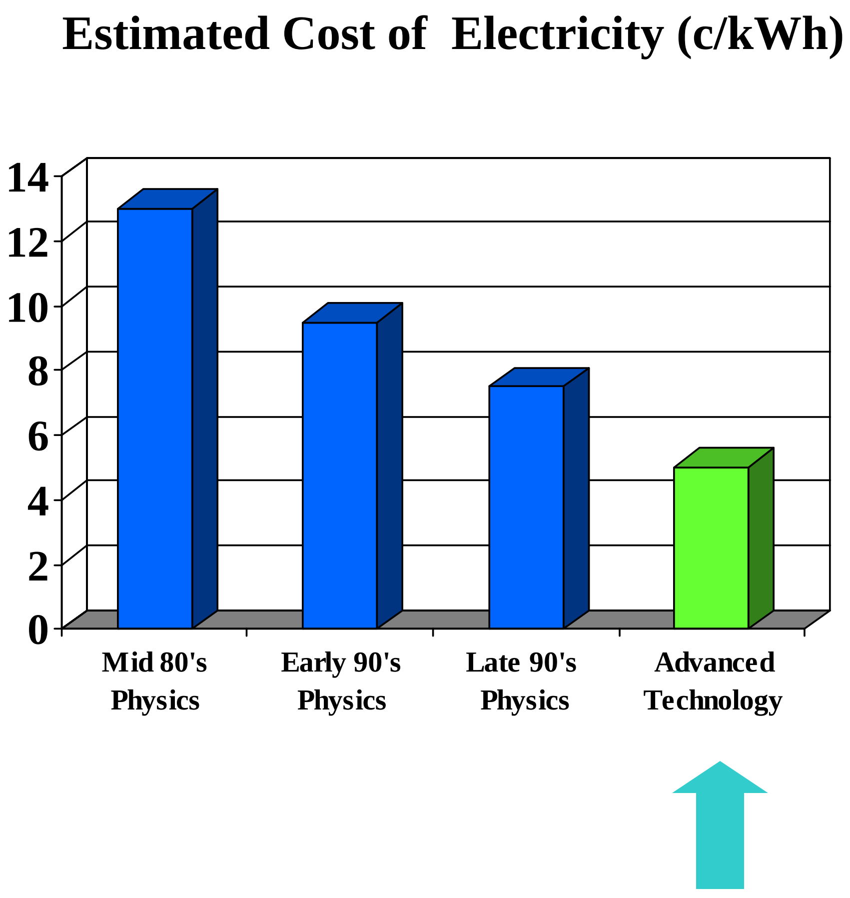


Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology



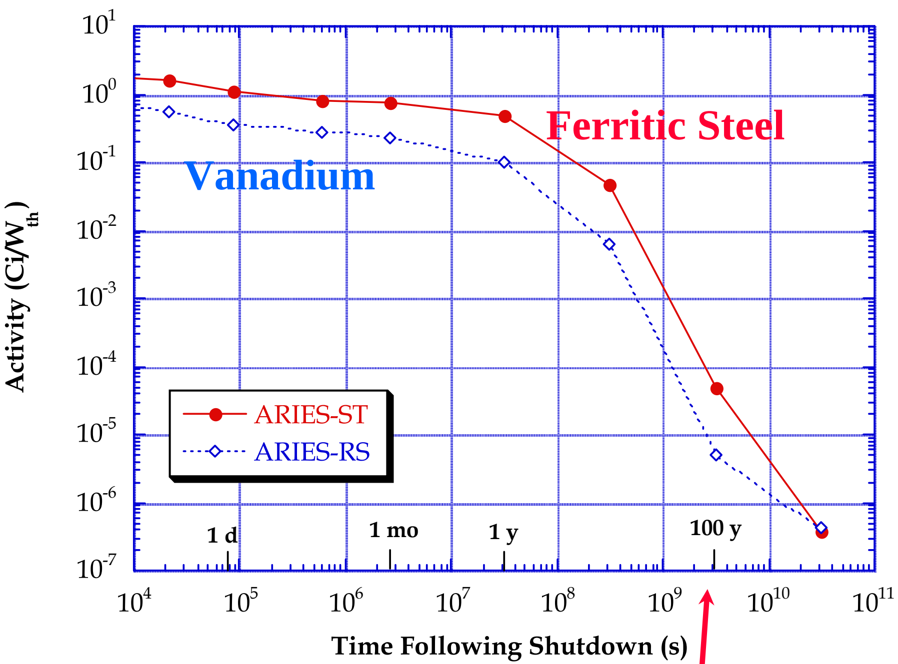


Approaching COE insensitive of power density

High Thermal Efficiency

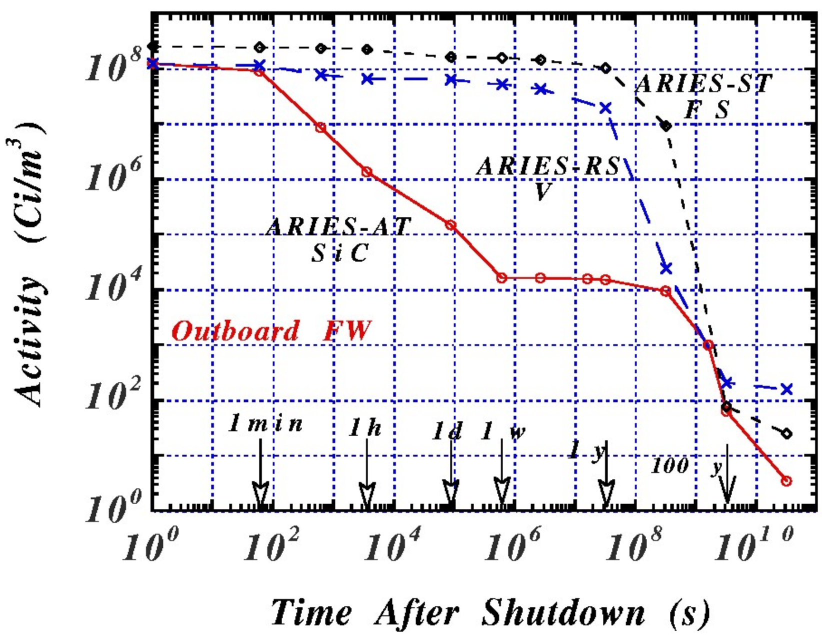
High β is used to lower magnetic field

Radioactivity Levels in Fusion Power Plants Are Very Low and Decay Rapidly after Shutdown

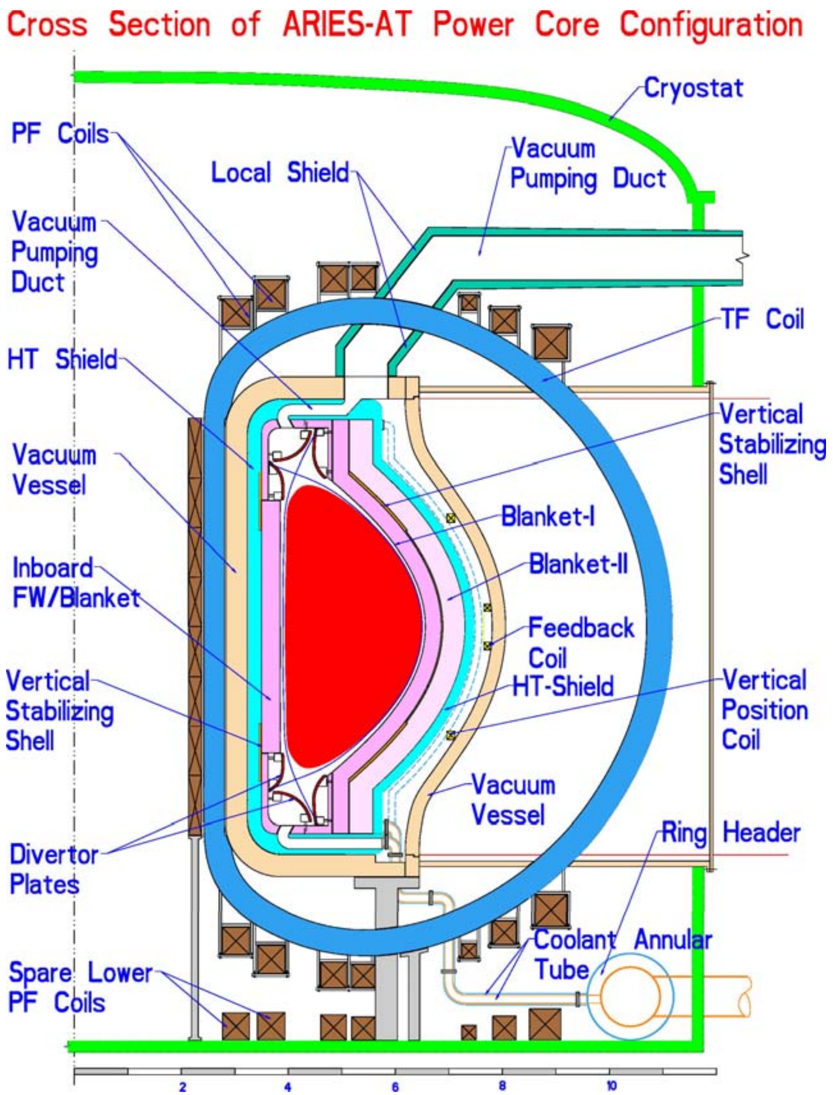


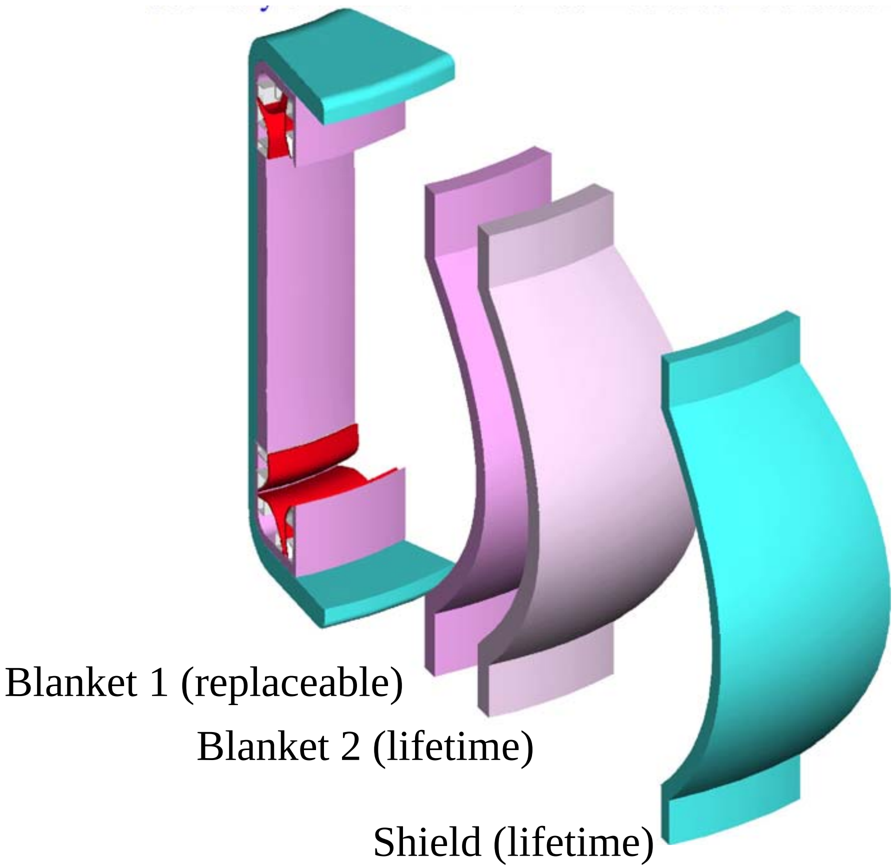
- SiC composites lead to a very low activation and afterheat.
- All components of ARIES-AT qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.

After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.



Fusion Core Is Segmented to Minimize the Rad-Waste

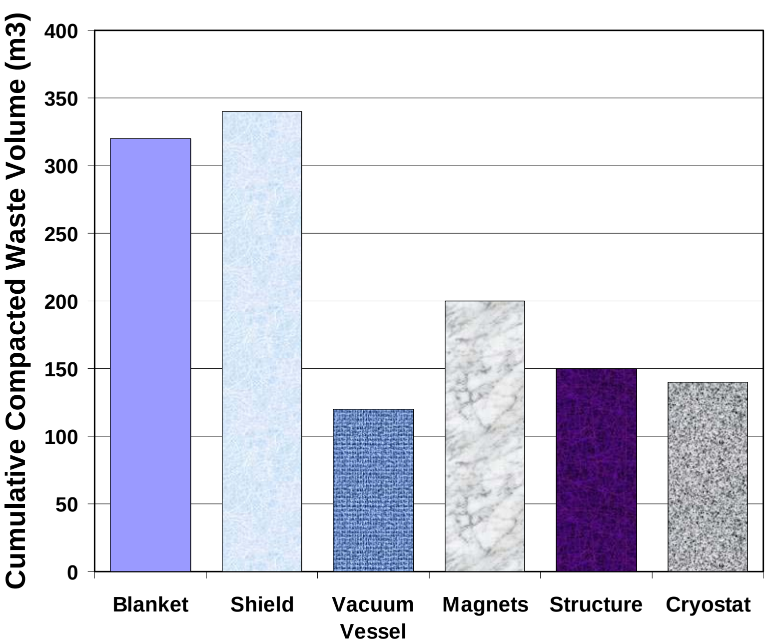


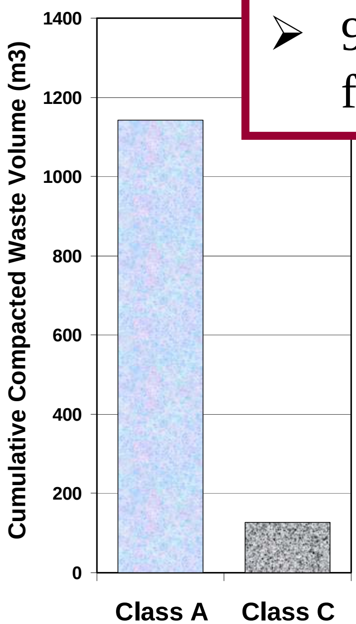


- Only "blanket-1" and divertors are replaced every 5 years

Generated radioactivity waste is reasonable

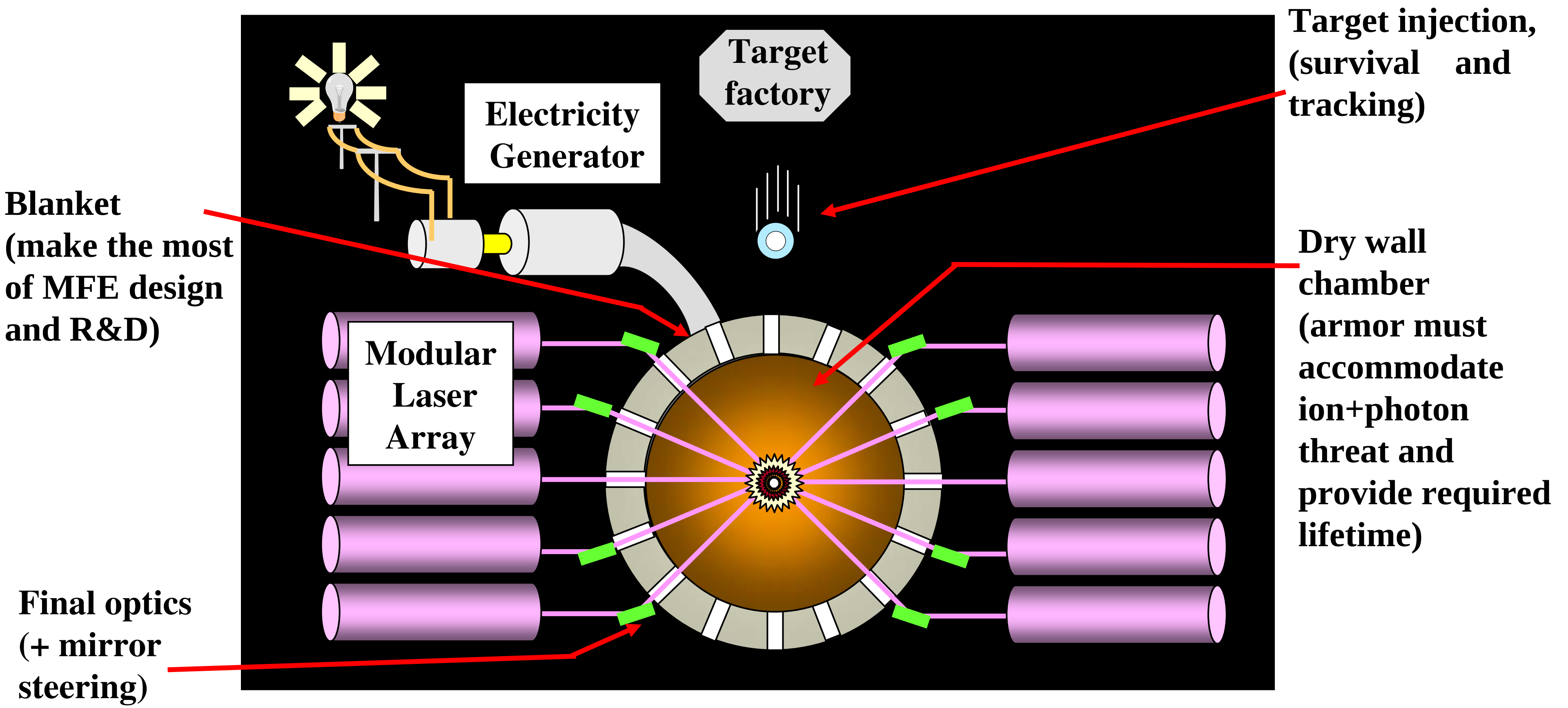
- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation (~50 years)
  - ✓ Coolant is reused in other power plants
  - ✓ 29 m³ every 4 years (component replacement)
  - ✓ 993 m³ at end of service
- Equivalent to ~ 30 m³ of waste per FPY
  - ✓ Effective annual waste can be reduced by increasing plant service life.





- 90% of waste qualifies for Class A disposal

IFE Power plant based on Lasers, Direct Drive Targets and Solid Wall Chambers



- ➢ Modular, separable parts: lowers cost of development AND improvements
- ➢ Conceptually simple: spherical targets, passive chambers
- ➢ Builds on significant progress in US Inertial Confinement Fusion Program

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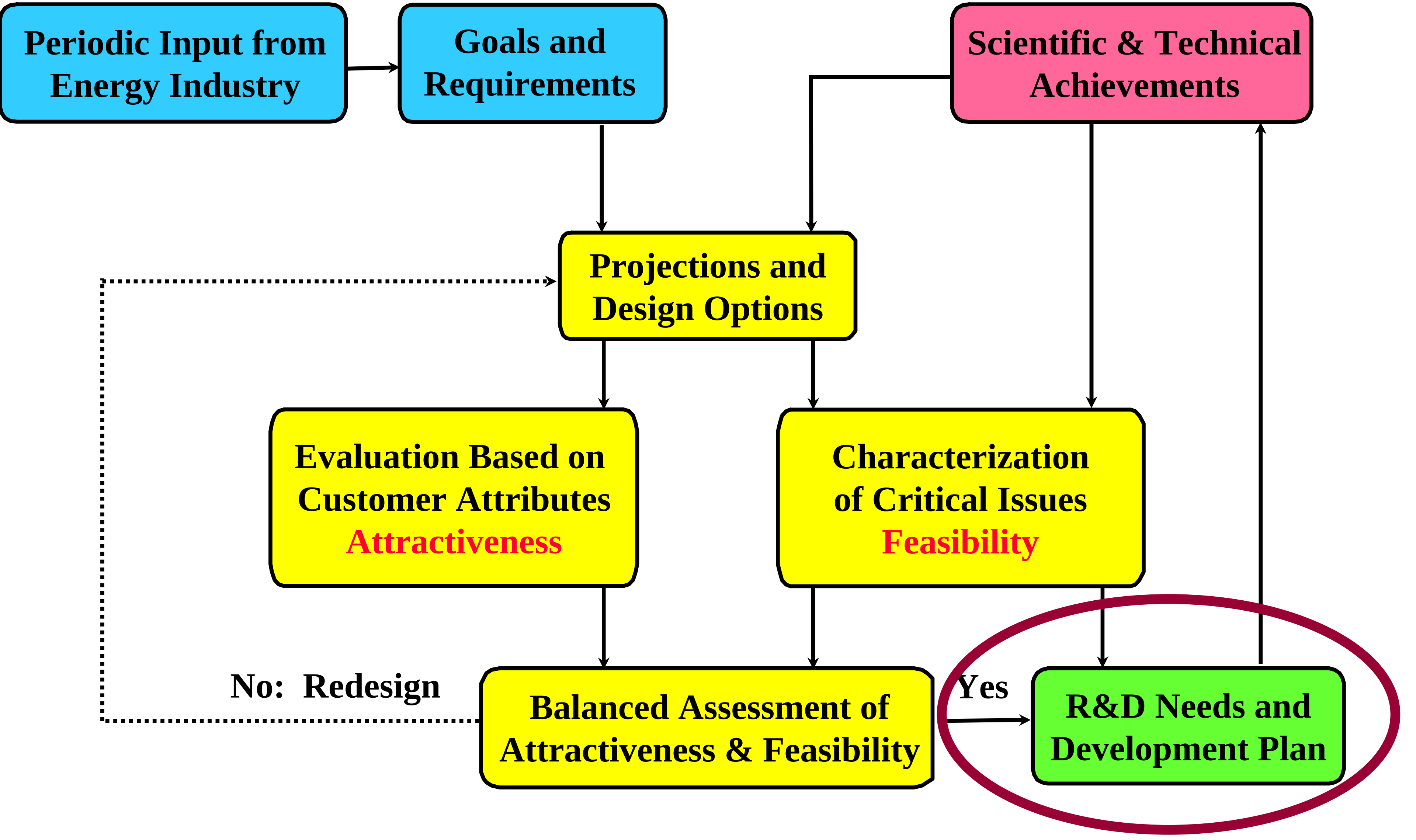

Advances in plasma physics has led to a dramatic improvement in our vision of fusion systems

- Attractive visions for tokamak exist.
- The main question is to what extent the advanced tokamak modes can be achieved in a burning plasma (e.g., ITER):
  - ✓ What is the achievable β_N (macroscopic stability)
  - ✓ Can the necessary pressure profiles realized in the presence of strong α heating (microturbulence & transport)
- Attractive visions for ST and stellarator configurations also exist

- Similarly, inertial fusion energy target physics has made tremendous progress:
  - ✓ NIF will test ignition and high gain
  - ✓ New opportunities, e.g., fast ignition

Fusion "technologies" are the pace setting element of fusion development

- Pace of "Technology" research has been considerably slower than progress in plasma physics.
- R&D in fusion power technologies (fusion engineering sciences) have been limited:
  - ✓ Experimental data is mainly from Europe (and Japan), but their program focus is different.
- Most of "technology" research has been focused on ITER (real technology).