Proof-of-Principle ICCs and Integrated Fusion Energy Development (E4)

Connections with a Tokamak BPX

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Context: Stated U.S. Fusion Policy and Plans

Policy Goals (FEAC-1996)

- Advance plasma science in pursuit of national S&T goals;
- Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; and
- Pursue fusion energy science and technology as a partner in the international effort.

Fusion Energy Science Plan (FESAC-1999, IPPA-2000), Goals 1-4 (of 6):

1. Advance plasma understanding ⇒ enhance predictive capability.
2. Advance ICC science ⇒ reduced-cost paths to more attractive fusion systems.
3. Advance the AT and participate in an international burning plasma experiment.
4. Develop technologies: enabling technologies to advance the science; technology and material innovations, system design to improve the vision; tests in realistic environments.

This is a good plan that can be built on.

Starting Point: How do the ICCs and a BPX fit into Integrated Fusion Energy Development?

Specifically:

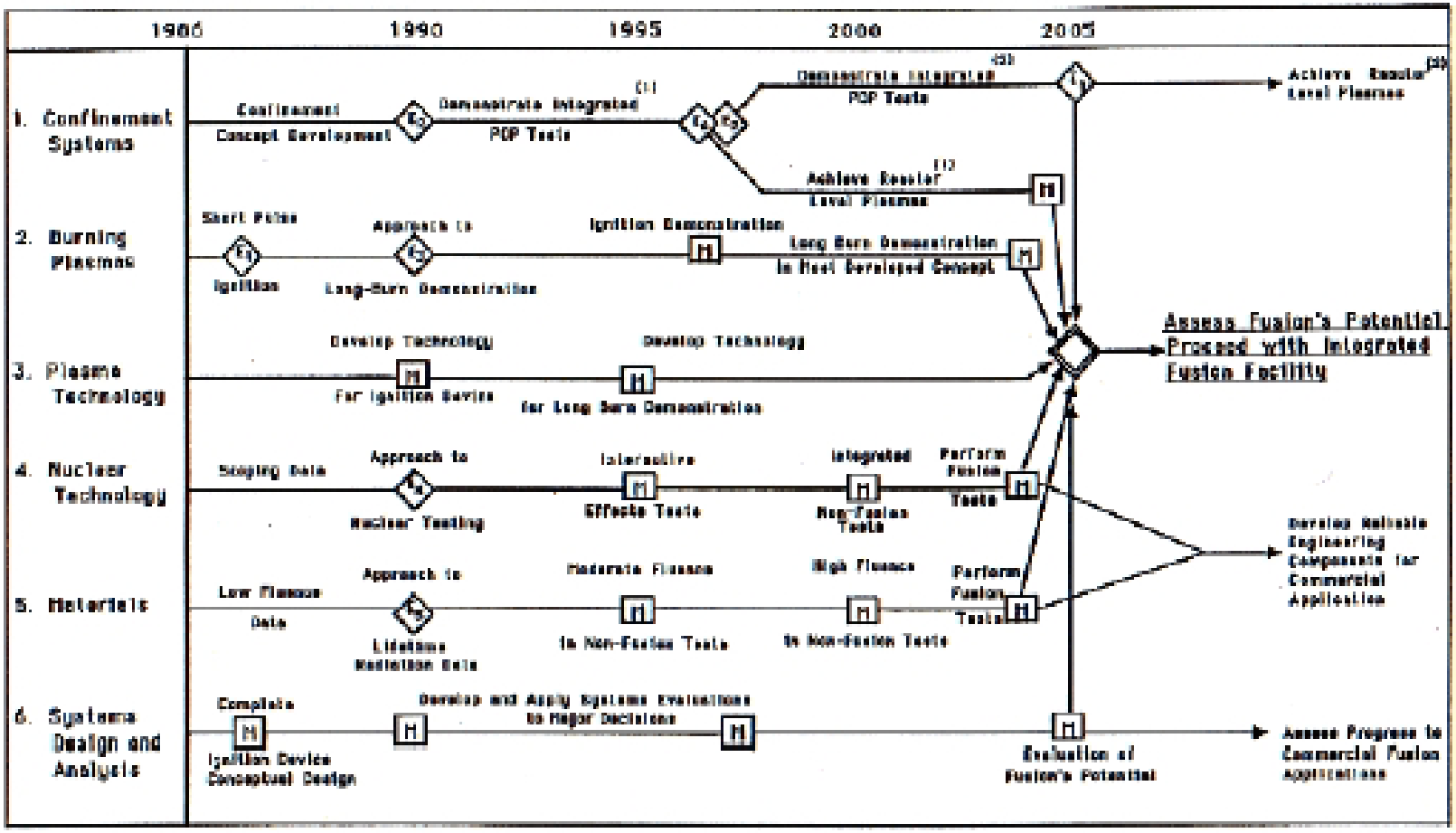
- *What will each approach contribute to the integrated development of fusion energy over the next 20 years?*
  - *Physics understanding*
  - *Reactor attractiveness*
  - *Technology/materials*

- *What are the requirements for a BPX to advance integrated fusion energy development in terms of :*
  - *Demonstrating fusion burn?*
  - *Advancing the science and technology of fusion common to the portfolio of concepts?*

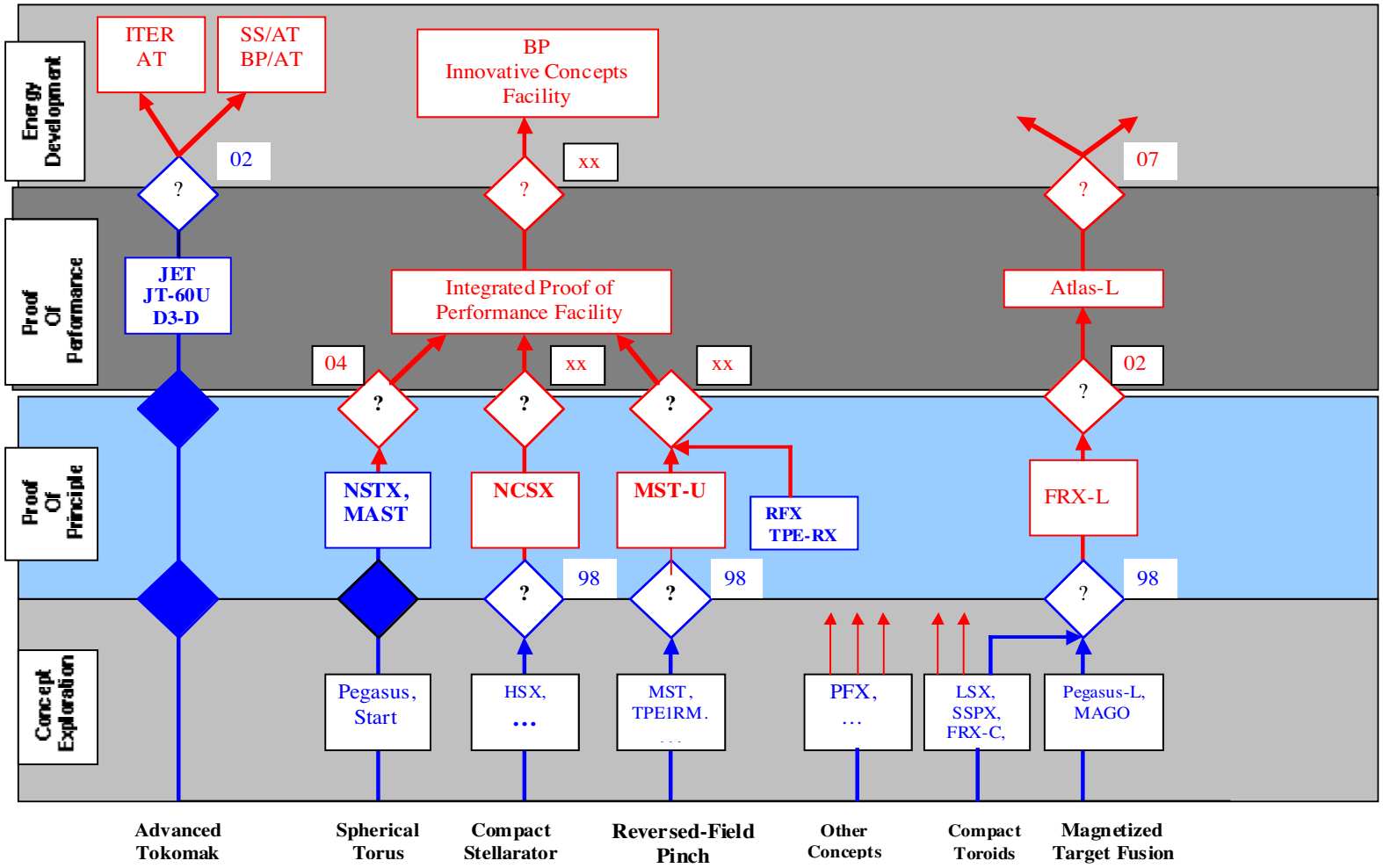
Magnetc Fusion Program Plan Technical Planning Activity 1987

(1) From class of present "moderately-developed" concepts

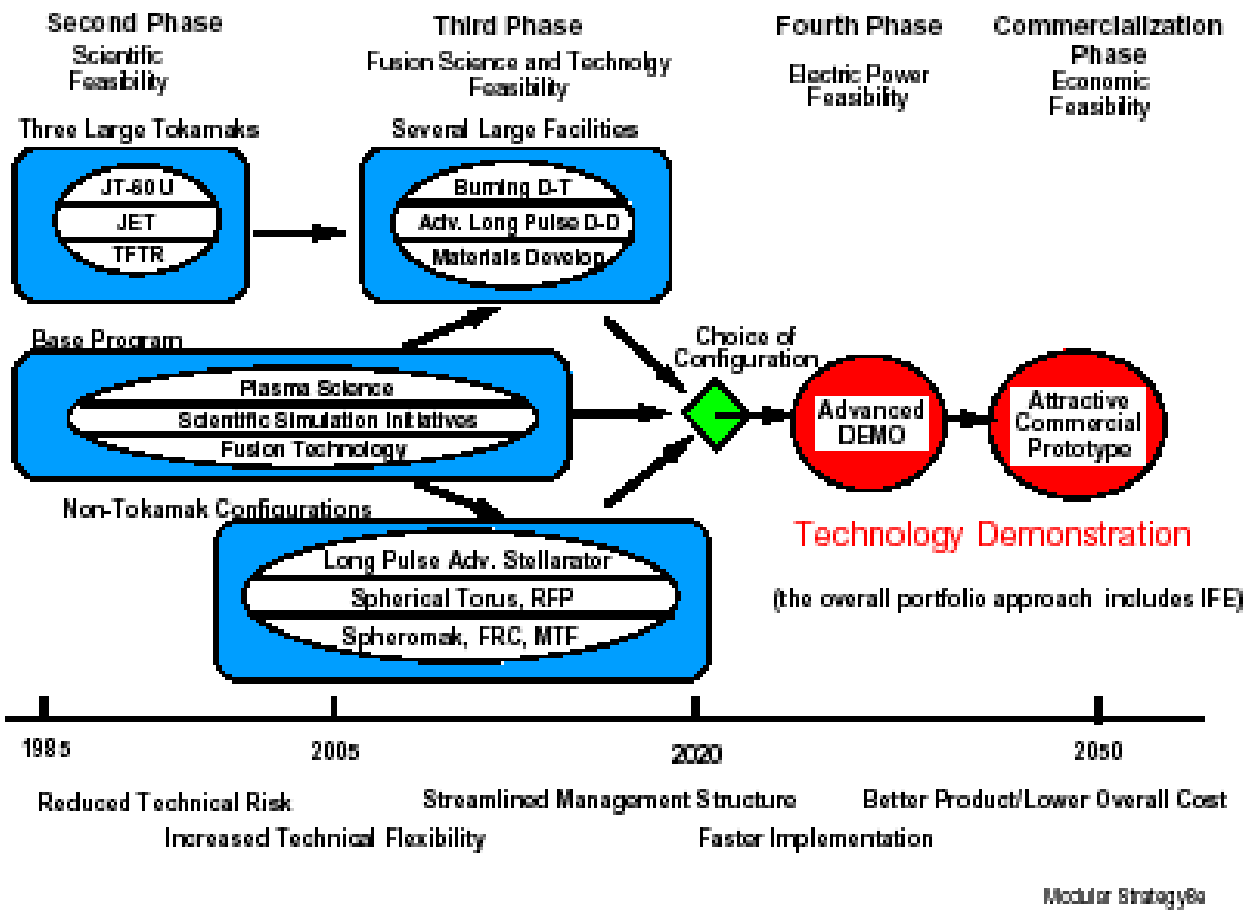
(2) From class of present "developing" concepts



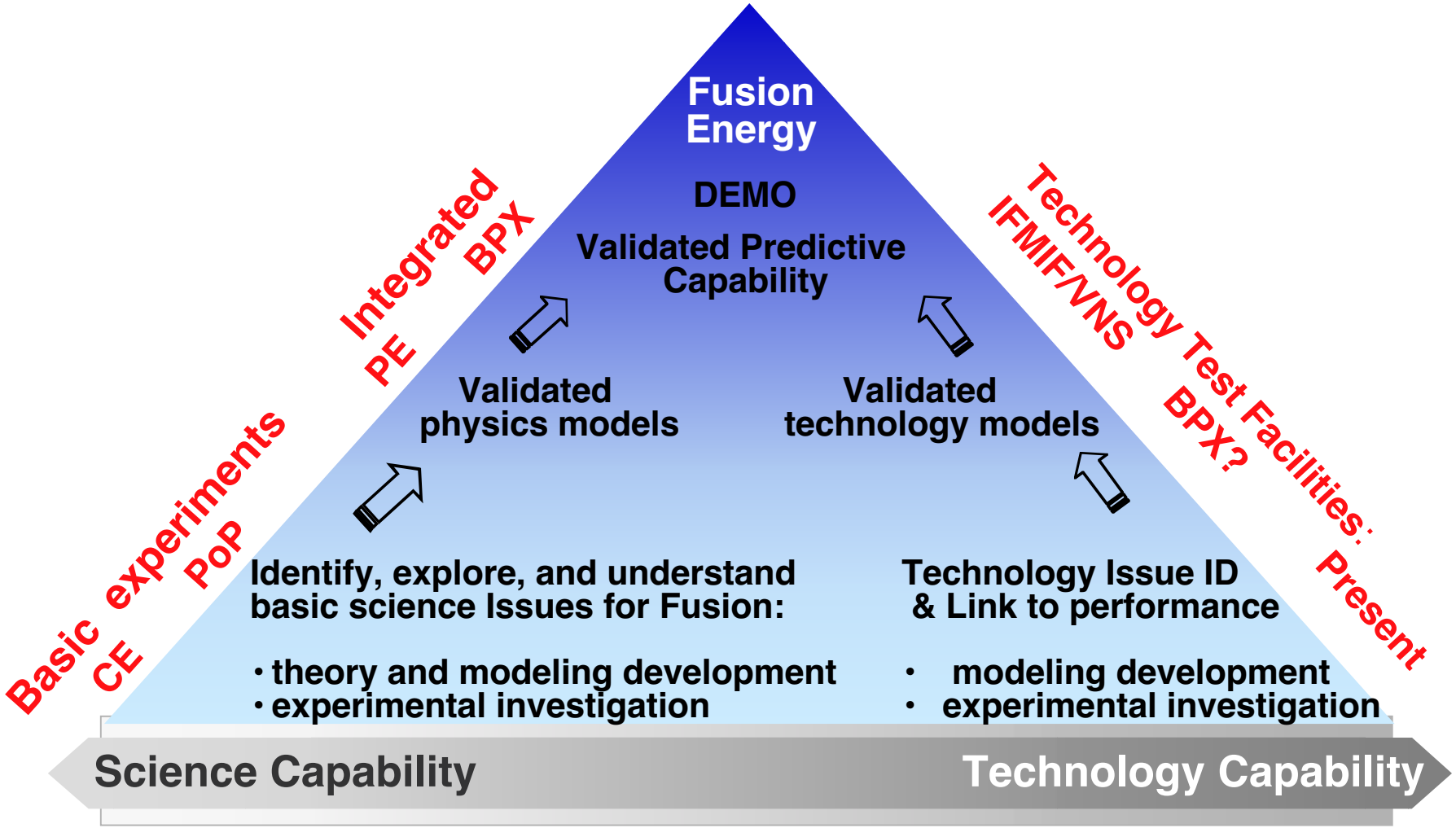
Program Development "Think" circa 1999 was Missing Coherent Integration



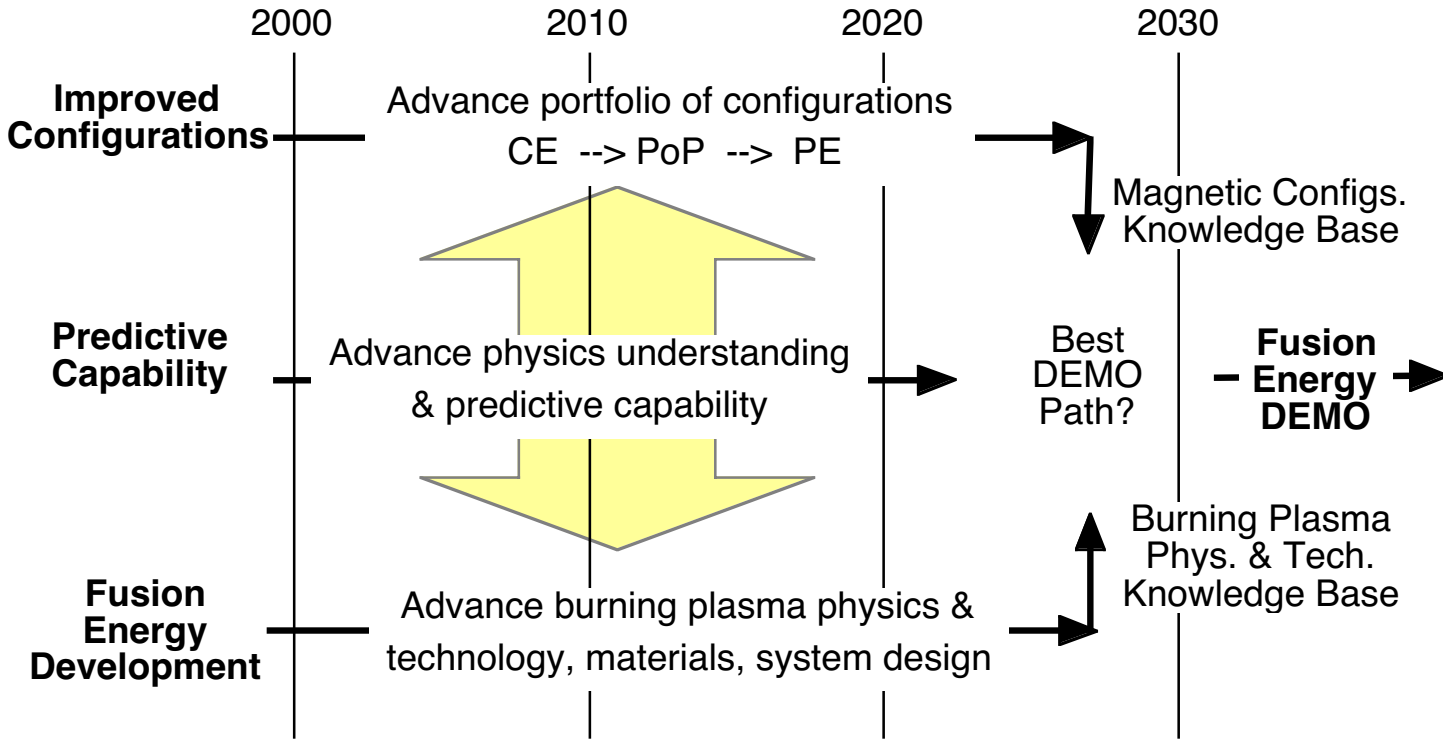
FIRE-based Development Path



Integration of Experiments, Theory, and Modeling Enables Fusion Energy Development



An Integrated Development Roadmap for Fusion Energy



An Integrated Development Path is the Keystone for Fusion Development

- A ***coherently integrated development path*** that encompasses ***"a diverse portfolio"*** of confinement concepts will ensure the continual advancement of the program's science and technology base.

- The portfolio must allow for a range of concepts advancing through the concept exploration, proof-of-principle (PoP) and performance extension (PE) stages (depending on merit).

- BPX, as an important element of the integrated development path, must deliver benefits that are generic to a range of MFE concepts.

Integration of ICC, AT, & BPX Experiments with Theory and Modeling will Develop the Predictive Capabilities Needed for Enabling Fusion Energy

Development Path: Criteria for Success

- Commercial Fusion is the goal of development path scenario
- Top-Level metrics and goals for fusion power are identified by various national programs (i.e., FESAC Panel on Priorities & Balances):

1) Safety & environmental goals: low-level waste and no evacuation
   a. Requires that fusion core is constructed entirely of low-activation material;
   b. Requires intense 14-MeV neutron source and development and testing of power technologies using low-activation material.
2) Operational goals: High capacity factor and ease of maintenance
   a. Requires early integration of integration of physics and technology in order to develop extensive reliability/maintainability data.
3) Economic Goals: 0.7-1.5 times of present costs of electricity
   a. Requires advanced tokamak mode (steady-state) operation;
   b. Requires advanced technologies, in particular, high-efficiency blankets.

- We have used relevant power plant studies, e.g., ARIES-RS, ARIES-AT, etc., or similar studies overseas, e.g., SSTR to derive physics and technology requirements.

Concept Innovation and Development

Attractive Reactor Attributes are Investigated with a Diverse Portfolio

smaller unit size → **high β**

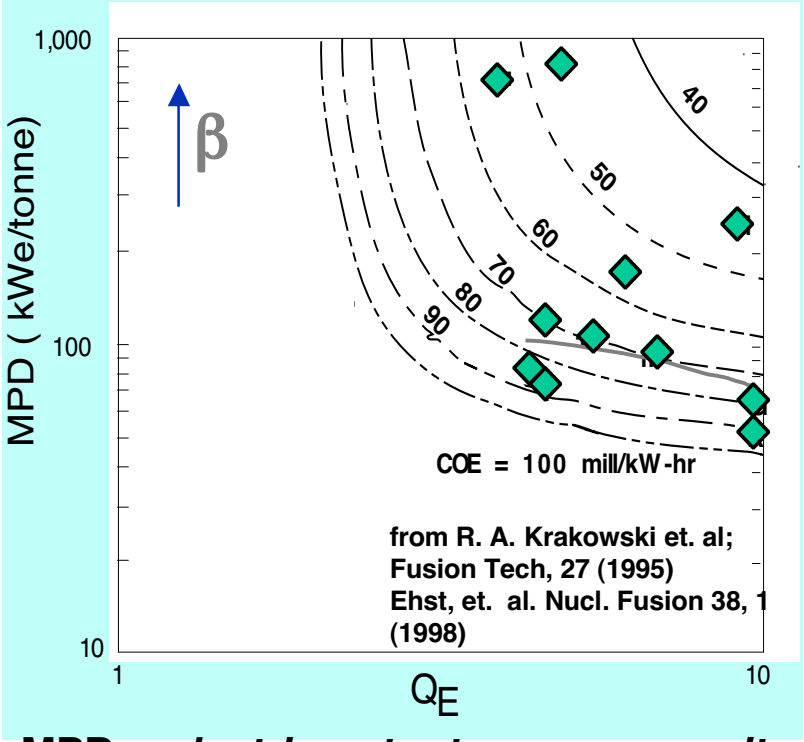
eased magnet requirements → **plasma self-organization**

reduced active control requirements → **3D shaping**

reduced materials requirements → ***confinement topology***

smaller unit size

Example of COE scaling



MPD = ***electric output power per unit mass of fusion power core***

Q_E = ***electric power/recirculated power***

Integration of Portfolio Science

	Stellarator	Spherical Torus	Reversed Field Pinch
Macrostability	• Beta limits • External transform effects on kinks, neoclassical tearing modes and disruptions	• Effects of large Alfven mach numbers on equilibrium & stability • Effects of large ion gyroradii	• Beta-limit in high-magnetic shear – bad curvature geometry • Active control of resistive wall modes
Transport and Turbulence	• Scaling in compact, QS systems • connection between Anomalous transport control in tokamaks and QS stellarators	• ST plasma feature effects on transport barriers • Effects of high beta and large magnetic well on neoclassical diffusivities	• Electrostatic transport in low q plasmas • Control magnetic fluctuation driven Transport
Wave-Particle Interactions	• Alfven eigenmode spectrum of QSS	• Effects of super-Alfvenic fast ions • Strong wave refraction	• RF heating and current drive in high dielectric, high beta plasma
Boundary physics	• 3D field characteristics and boundary physics	• Large mirror ratio and curvature effects	• toroidal divertors

Technology Cross-cuts Portfolio Requirements

- Magnetics - superconducting and normal coil technology
  - 3D shaping
- Heating and current drive - RF and helicity injection
- Materials
- Plasma facing components - high wall loading
- Fueling - gas puffing & pellet injection
  - CT injection
- Remote handling and Nuclear technologies -

Conclusion: Expectations for a BPX

Scientific Requirements:

- Define and achieve realistic goals of integrated fusion burn.
- Operational flexibility (physics phase space) - maximize the knowledge transfer to and from “the portfolio” with the goal of developing a predictive capability for designing the best fusion energy sources.
- Well diagnosed (and diagnosable) to achieve the flexible and integrated physics mission.
- Strong theory and modeling support coordinated with experiments to develop predictive capabilities.

Fusion Technology:

- Integration of fusion technologies in a realistic fusion environment
- Fusion technologies most likely will have significant transferability to other concepts