Realization of Fusion Energy: Why, When, How?

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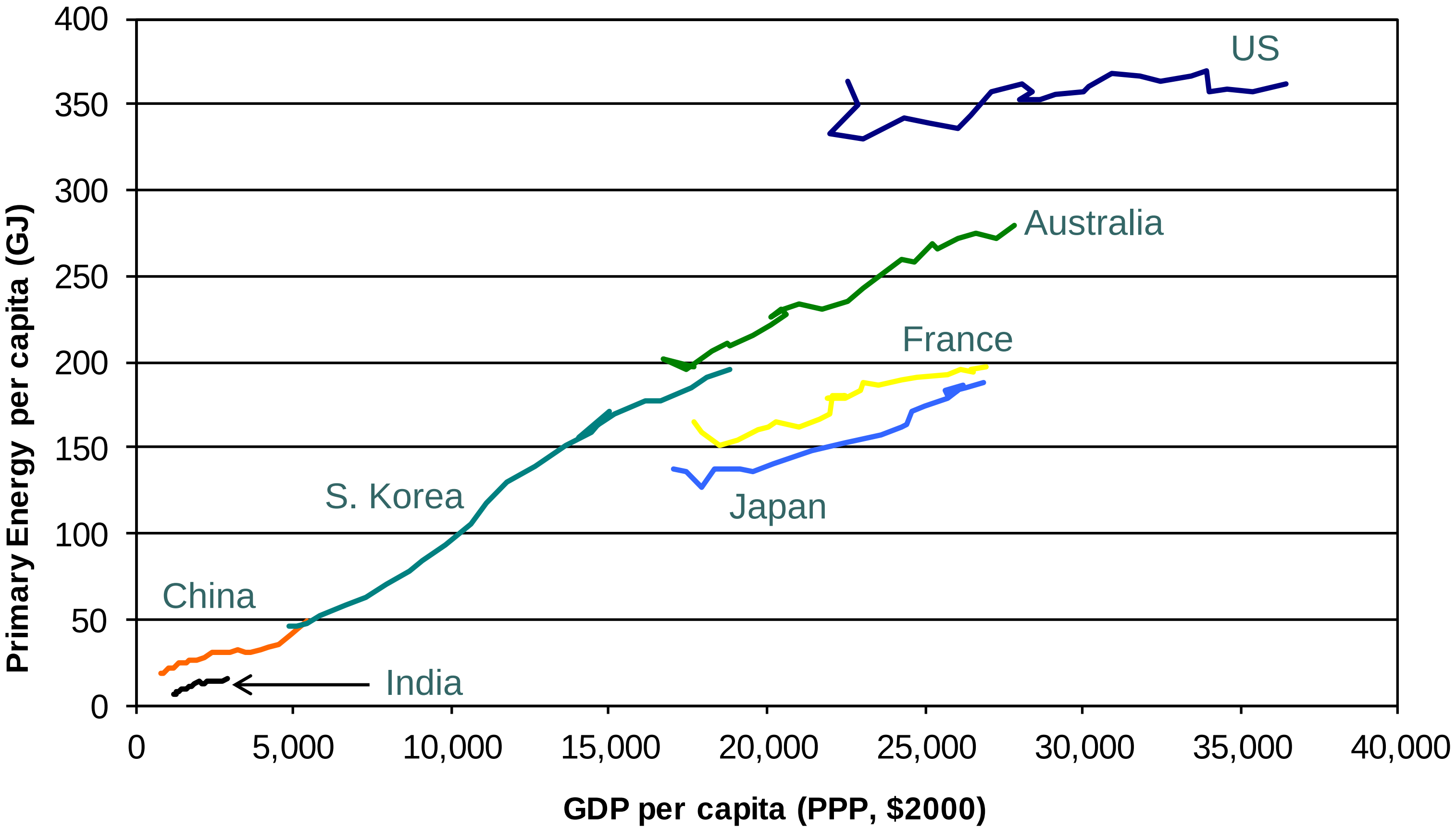
We are transitioning from the Era of Fusion Science to the Era of Fusion Power

- Large-scale fusion facilities beyond ITER and NIF can only be justified in the context of their contribution to world energy supply. We will have
  - Different Customers (e.g., Power Producers)
  - Different criteria for success (e.g., Commercial viability)
  - Timing (e.g., Is there a market need?)
  - **Fusion is NOT the only game in town!**
- Is the currently envisioned fusion development path allows us the flexibility to respond to this changing circumstances?
  - Developing alternative plans and small changes in R&D today can have profound difference a decade from now.

Is there a case for a “unified” international road-map for fusion?

“World” needs a lot of energy!



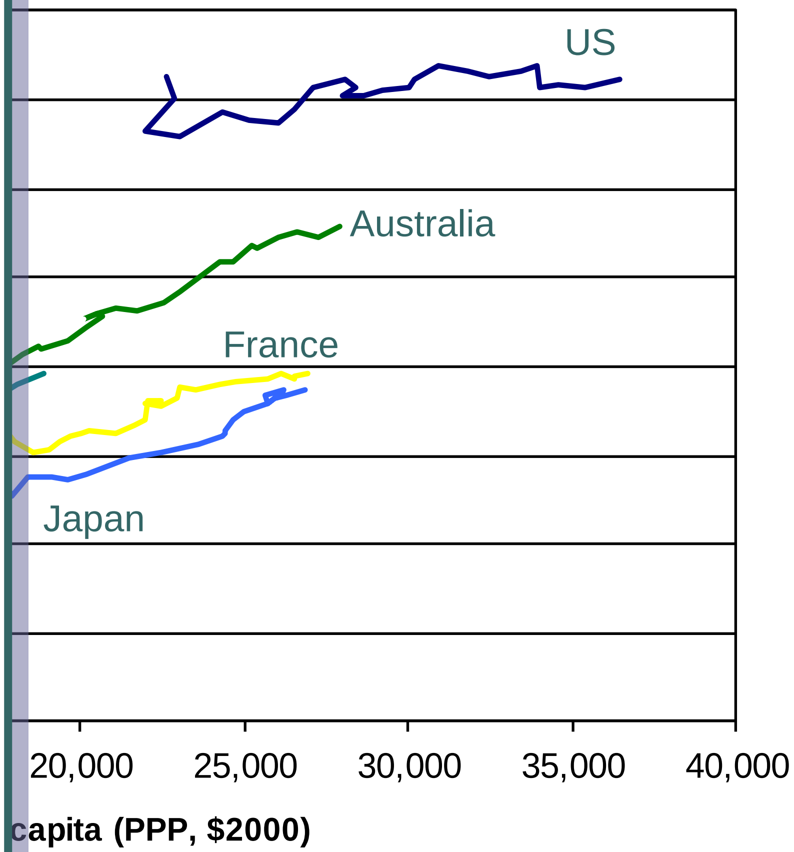
- With industrialization of emerging nations, energy use is expected to grow ~ 4 fold in this century (average 1.6% annual growth rate)

* Data from IEA 2006 annual energy outlook (1980-2004)

However, energy needs are different in different parts of the world:

US, EU, Japan (advanced fusion research):

- Electricity supply needs are mainly for the replacement of existing power plants.
- Government regulations have been driving the choice of energy supply.
- Different level of access to indigence fossil fuels for electricity production.
- Different socio-political atmospheres.



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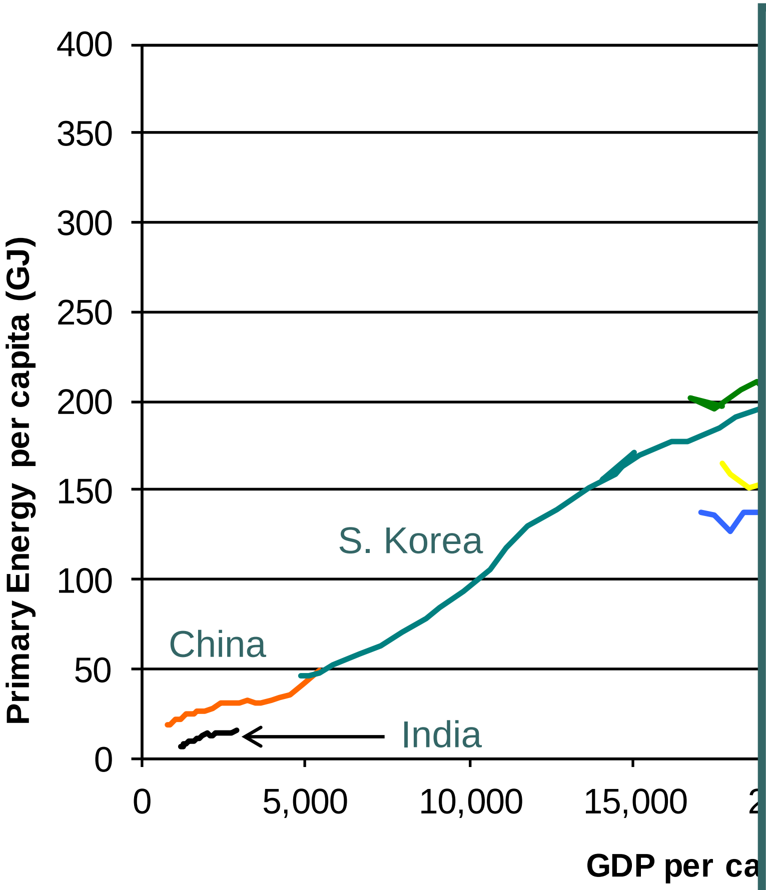


China, India, (S. Korea), ….
(“new” to fusion research)

- Large supplies of electricity is needed to maintain economic growth.
- Governments actively following policies to expand energy supply.
- Different level of access to indigence fossil fuels for electricity production
- Different socio-political atmospheres.

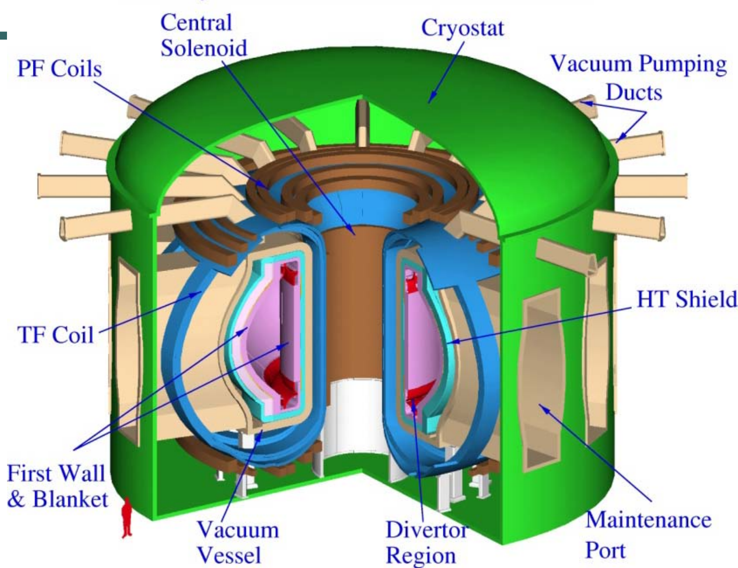
Rationale for fusion development varies substantially around the world.

- Fusion R&D expenditures are justified to government agencies who have different priorities and, therefore, respond to different “Roadmaps.”
  - Energy supply, growth of high-teach industry
  - “Grand Challenge” scientific undertaking
- Fusion plasma physics remains an international endeavor.
- Fusion engineering R&D is limited.
  - Most of the “relatively small” R&D is in EU and Japan but their program focus is different.
  - US has little influence on other countries because of
    1) absence any serious R&D 2) developing fusion energy is not our stated program goal.

When & How:
Power Plant Needs and State of Current Achievements

Fusion Energy awaits development of Fusion Nuclear Sciences

- Power plant studies indicate that attractive visions for tokamak exist (with a range of extrapolation from present physics data base).
  - ITER operation as well as Asian superconducting tokamaks will provide the plasma physics basis to move forward to a fusion nuclear device/Pilot Plant/Demo.
  - **However, fusion nuclear sciences are in their infancy.**



See ARIES Web site:
http://aries.ucsd.edu/ARIES

Technical Readiness Levels provides a basis for assessing the development strategy

Level	Generic Description
1	Basic principles observed and formulated.
2	Technology concepts and/or applications formulated.
3	Analytical and experimental demonstration of critical function and/or proof of concept.
4	Component and/or bench-scale validation in a laboratory environment.
5	Component and/or breadboard validation in a relevant environment.
6	System/subsystem model or prototype demonstration in relevant environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system proven through successful mission operations.

Increased integration

Increased Fidelity of environment

Basic & Applied Science Phase

Validation Phase

- Developed by NASA and are adopted by US DOD and DOE.
- TRLs are very helpful in defining R&D steps and facilities.

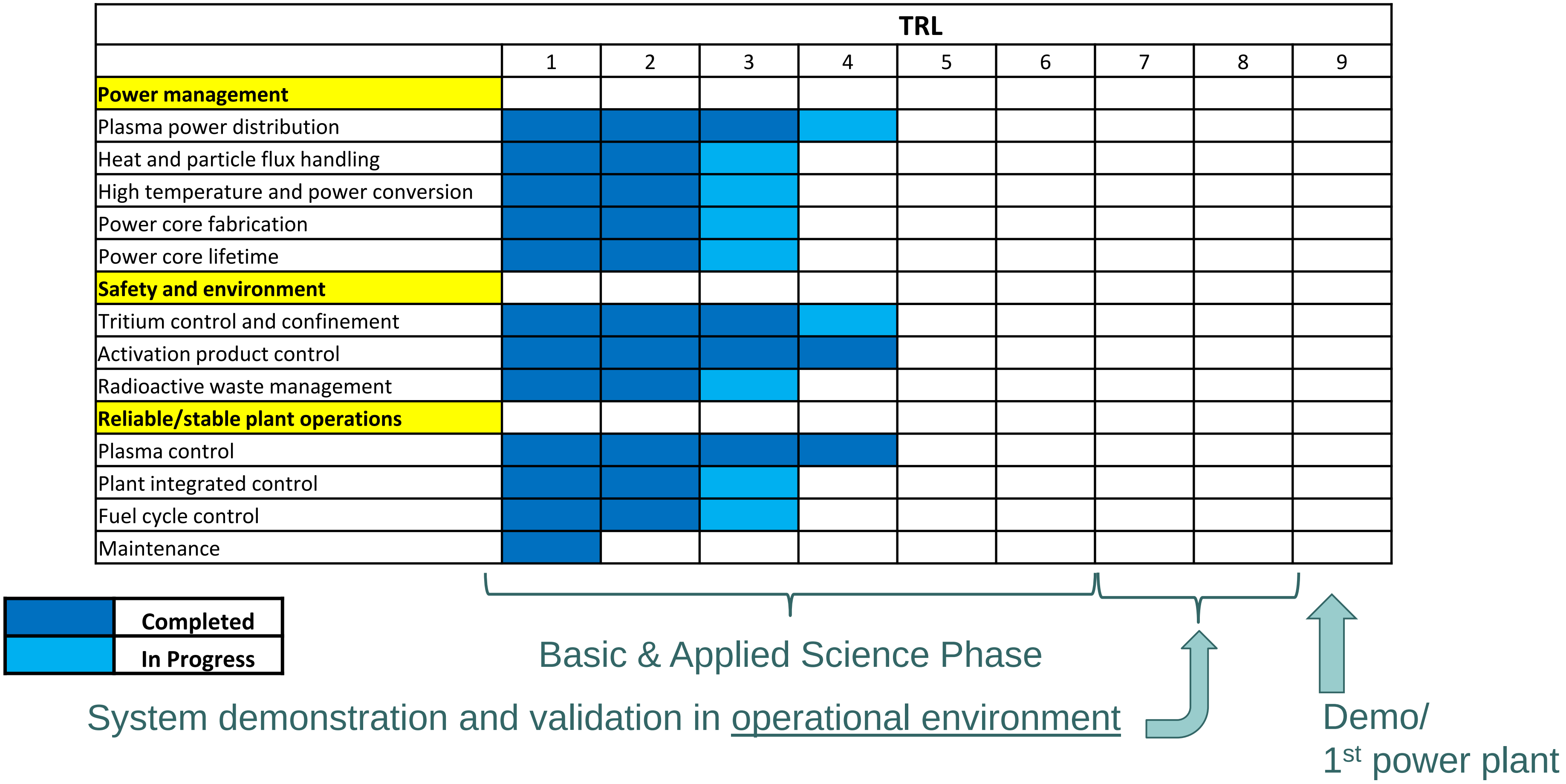
Example: TRLs for Plasma Facing Components

	Issue-Specific Description	Facilities
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical paramete	Code development, applied research
3	Data from coupon-scale heat and particle flux experiments; modeling of governing heat and mass transfer processes as demonstration of function of PFC concept.	Small-scale facilities: *e.g.*, e-beam and plasma simulators
4	Bench-scale validation of PFC concept through submodule testing in lab environment simulating heat fluxes or particle fluxes at prototypical levels over long times.	Larger-scale facilities for submodule testing, High-temperature + all expected range of conditions
5	Integrated module testing of the PFC concept in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.	Integrated large facility: Prototypical plasma particle flux+heat flux (*e.g.* an upgraded DIII-D/JET?)
6	Integrated testing of the PFC concept subsystem in an environment simulatin levels ov	Integrated large facility: Prototypical plasma
7	Prototypic PFC system demonstration in a fusion machine.	Fusion machine ITER (w/ prototypic divertor), CTF
8	Actual PFC system demonstration qualification in a fusion machine over long operating times.	CTF
9	Actual PFC system operation to end-of-life in fusion reactor with prototypical conditions and all interfacing subsystems.	DEMO

Power-plant relevant high-temperature gas-cooled PFC

Low-temperature water-cooled PFC

Application to power plant systems highlights early stage of fusion technology development



	TRL								
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	■	■	■	▨					
Heat and particle flux handling	■	■	▨						
High temperature and power conversion	■	■	▨						
Power core fabrication	■	■	▨						
Power core lifetime	■	■	▨						
Safety and environment									
Tritium control and confinement	■	■	■	▨					
Activation product control	■	■	■	■					
Radioactive waste management	■	■	▨						
Reliable/stable plant operations									
Plasma control	■	■	■	■					
Plant integrated control	■	■	▨						
Fuel cycle control	■	■	▨						
Maintenance	■								

■	**Completed**
▨	**In Progress**

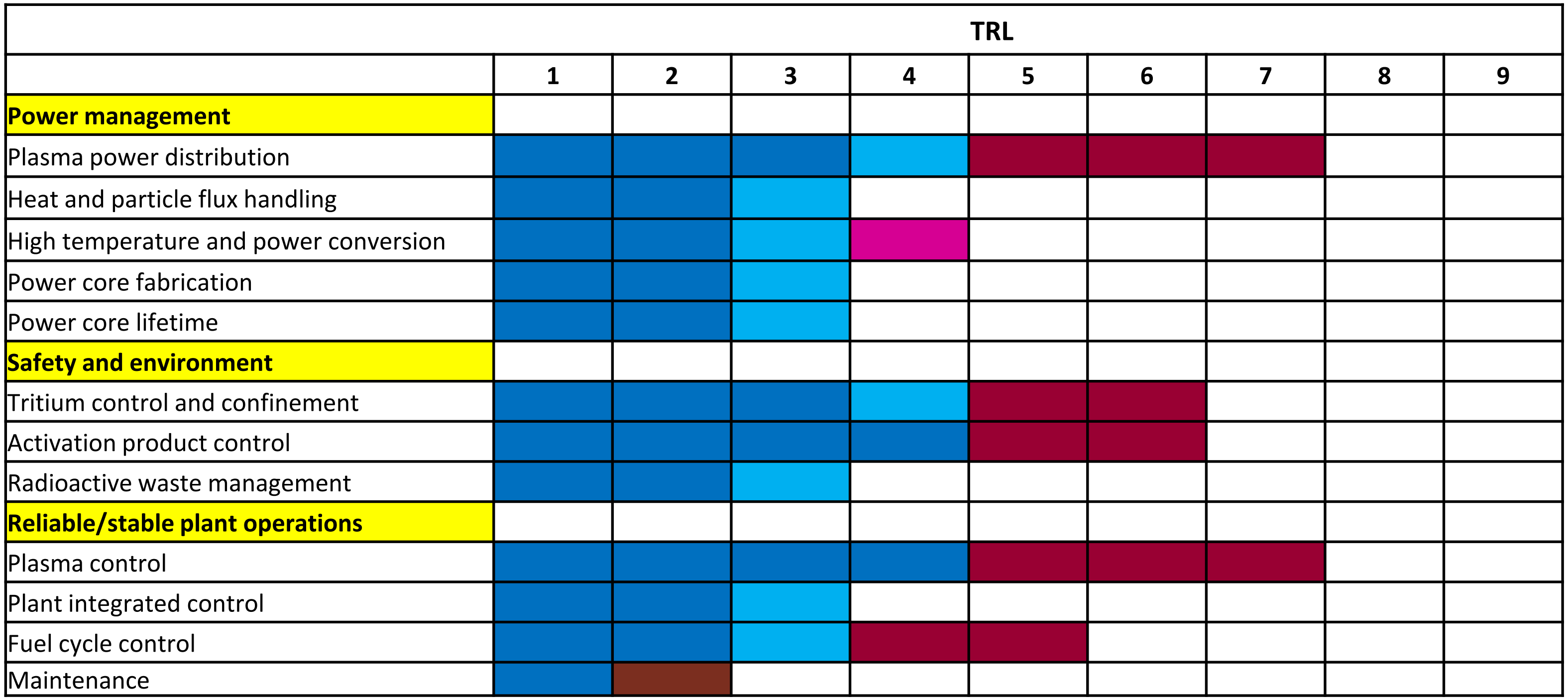
Basic & Applied Science Phase

System demonstration and validation in operational environment

Demo/
1st power plant

For Details See ARIES Web site: http://aries.ucsd.edu/ARIES/TRL

ITER will provide substantial progress in some areas (plasma, safety)



	TRL								
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	🟦	🟦	🟦	🔷	🟥	🟥	🟥		
Heat and particle flux handling	🟦	🟦	🔷						
High temperature and power conversion	🟦	🟦	🔷	🟪					
Power core fabrication	🟦	🟦	🔷						
Power core lifetime	🟦	🟦	🔷						
Safety and environment									
Tritium control and confinement	🟦	🟦	🟦	🔷	🟥	🟥			
Activation product control	🟦	🟦	🟦	🟦	🟥	🟥			
Radioactive waste management	🟦	🟦	🔷						
Reliable/stable plant operations									
Plasma control	🟦	🟦	🟦	🟦	🟥	🟥	🟥		
Plant integrated control	🟦	🟦	🔷						
Fuel cycle control	🟦	🟦	🔷	🟥	🟥				
Maintenance	🟦	🟫							

Fusion Nuclear Sciences remain at an early stage of development.

🟦	**Completed**
🔷	**In Progress**
🟥	**ITER**

Addressing
Fusion Engineering
“Grand Challenge”

Device-Driven program vs science-based engineering

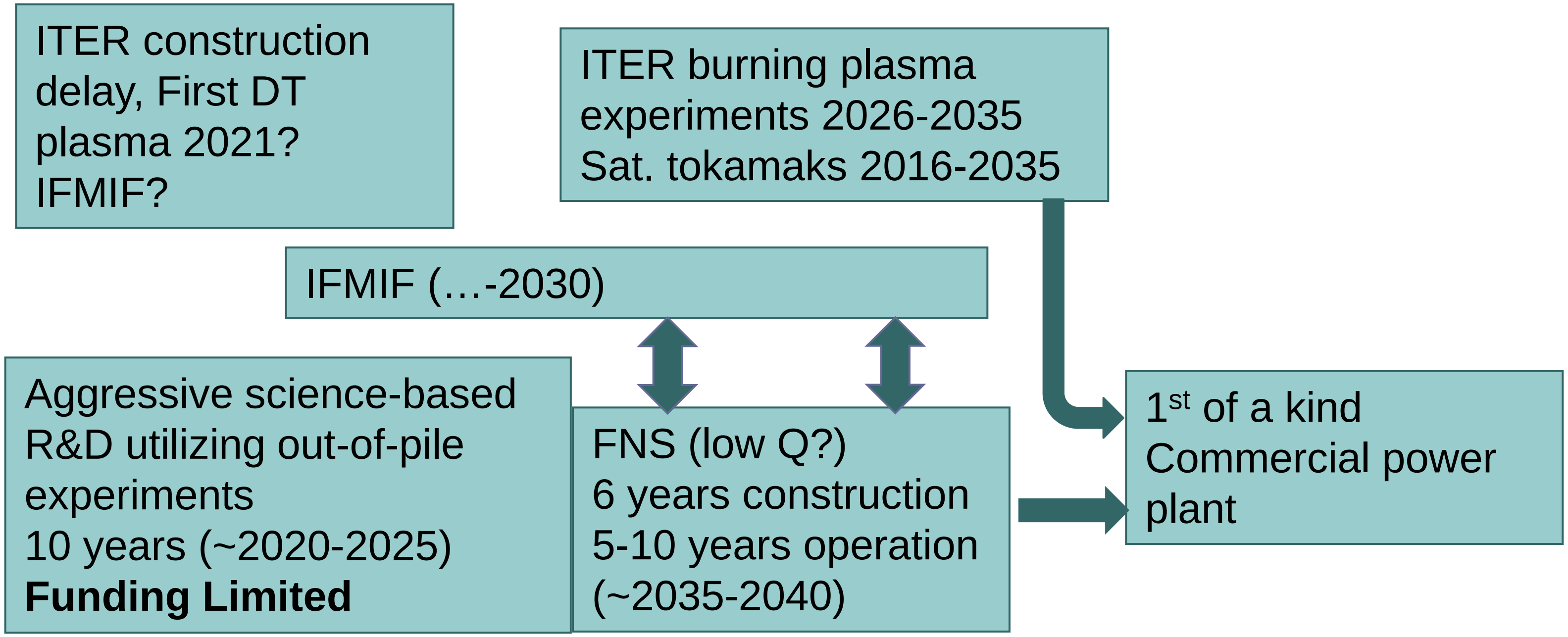
- Roadmaps which are driven by large devices have a high probability of leading to lengthier and costlier programs for commercial fusion.
  - Mission will be redefined to fit the “promised” time frame.
  - Cost, availability of material and technology will lead to further mission contraction, expanding the R&D needed after the next step and may also to un-necessary R&D.
  - Issue related to operation in a nuclear environment are often ignored.
- Recall ITER history (proposed in mid-80s, many revision of its mission, considerable expenditure, …).

This is in contrast with the normal development path of any product in which the status of R&D necessitates a facility for experimentation.

Utilize Modern Product Development

- Use modern approaches to “product development” (i.e., science-based engineering vs “cook and look”)
  - Extensive “out-of-pile” testing to understand fundamental processes
  - Extensive use of simulation techniques to explore many of synergetic effects and define new experiments.
  - Experiment planning such that it highlights multi-physics interaction (instead of the “old” approach of testing integrated systems to failure repeatedly).
  - Aiming for validation in a fully integrated system

Developing fusion energy requires a re-orientation of program goals & priorities.



ITER construction delay, First DT plasma 2021?
IFMIF?

ITER burning plasma experiments 2026-2035
Sat. tokamaks 2016-2035

IFMIF (…-2030)

Aggressive science-based R&D utilizing out-of-pile experiments
10 years (~2020-2025)
Funding Limited

FNS (low Q?)
6 years construction
5-10 years operation
(~2035-2040)

1st of a kind Commercial power plant

2035:
Decision to field 1st commercial plant

Key is aggressive science-based engineering up-front

Developing commercial fusion energy requires changes in our folklore:

- Fusion power technologies (fusion nuclear sciences) are in their early stages of development. We are NOT ready!

- Development of fusion nuclear sciences requires a large amount of resources.
  - We readily talk about multi-billion-$ plasma-based facilities but frown at $1B price tag of IFMIF.

- We need to utilize modern science-based engineering approach (cook and look approach is very expensive and time-consuming)
  - A large potion of R&D can and should be performed in simulated environments (non-nuclear and/or fission test).
  - Fusion nuclear testing is needed only to validate the predicted performance plus all synergetic effects that were not foreseen.
  - With this framework, It is possible to field a <u>commercial</u> fusion power plant before 2050, but we lay the ground work now!

Thank you!