The use of technical readiness levels in planning the fusion energy development

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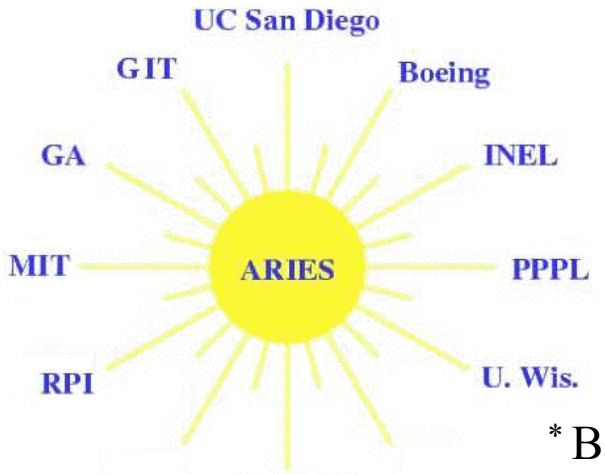
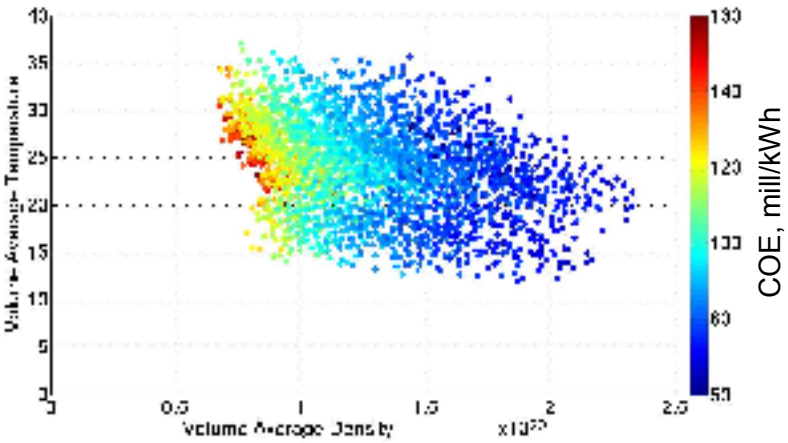


* Backup materials can be found at http://aries.ucsd.edu/ARIES/TRL/

The ARIES Pathways Study began in 2007 to evaluate R&D needs and gaps for fusion from ITER to Demo



- A new systems-based approach to establish the importance of various power plant parameters and define metrics for prioritization.

	Readiness level								
	1	2	3	4	5	6	7	8	9
Issues, components or systems encompassing the key challenges									
Item 1									
Item 2									
Item 3									
Etc.									

- R&D metrics to evaluate the status of the field and progress along the development path.
  - *In this study we examined a methodology for evaluating R&D needs and gaps that is widely recognized and utilized* ***outside*** *the fusion community.*
  - *We have actively communicated with and incorporated feedback from the community: OFES, TOFE, FPA, ANS news, IHHEC, ReNeW, and FESAC*

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady-state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Heating, current drive and fuelling	1	2		3	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Remote handling	1	2		R	R	R
Materials, Component performance & lifetime	Materials characterisation			3	R	R	R
	Plasma-facing surface	1	2		3	4	R
	FW/blanket/divertor materials		1	1	3	4	R
	FW/blanket/divertor components		1	1	2	3	R
	T self sufficiency		1		3	R	R
Final Goal	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Output:	
1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
4	Must resolve the issue

Input:	
r	Solution is desirable
R	Solution is a requirement

UKAEA September 2007 (revised/improved version of original table in UKAEA FUS 521, 2005).

We chose "readiness levels" as the basis for our R&D evaluation methodology

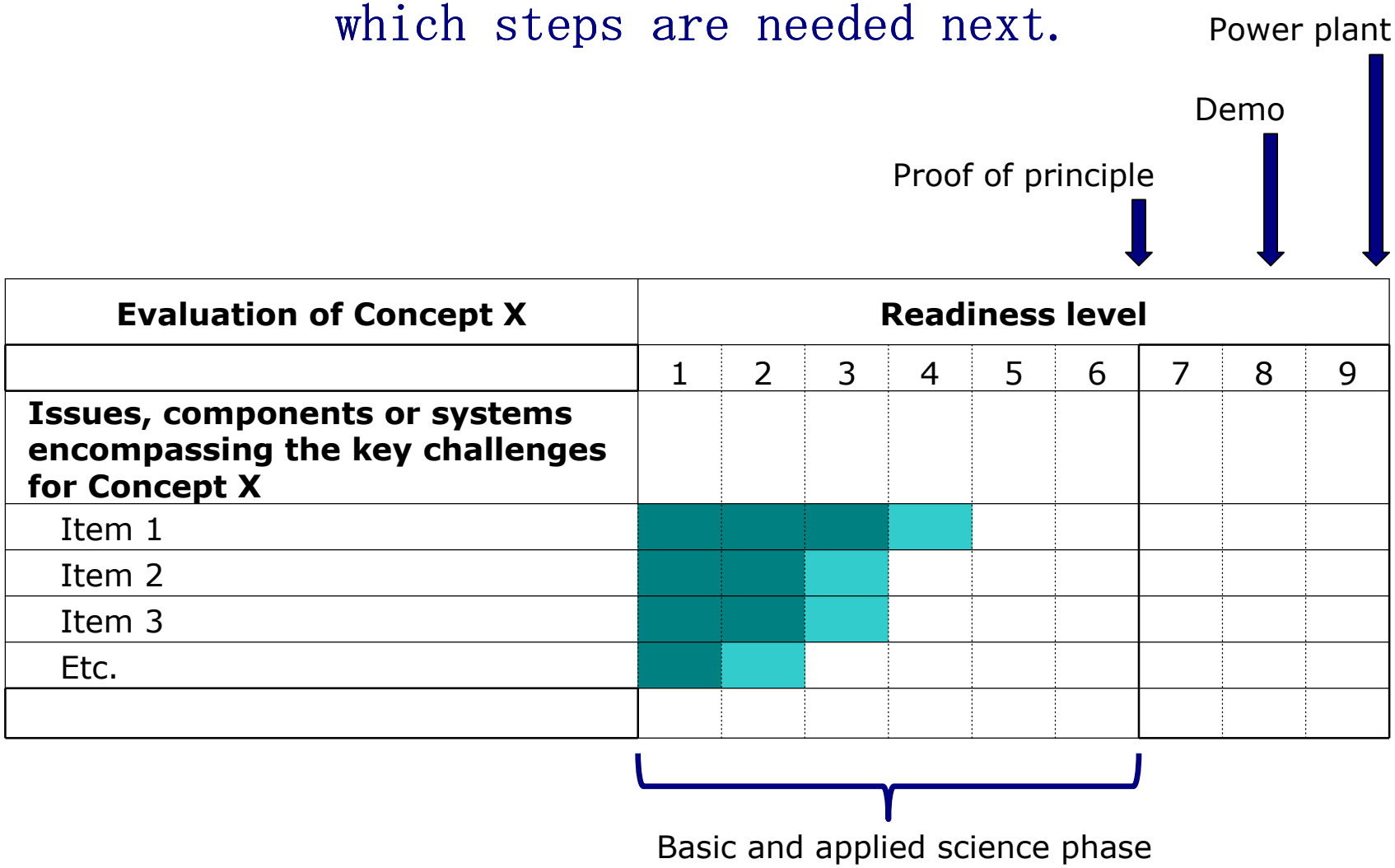
Other methods of identifying gaps have been used historically in fusion:

- *by listing the remaining "issues"*
- *by measuring one or more performance parameters*

TRL's express increasing levels of integration and environmental relevance, terms which must be defined for each application.

TRL	Generic Description *(defense acquisitions definitions)*
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.

Readiness levels identify R&D gaps between the present status and any level of achievement, for a particular concept. They help to identify which steps are needed next.



Detailed guidance on application of TRL's is available

e.g., a TRL calculator at https://acc.dau.mil/CommunityBrowser.aspx?id=25811

TRL	Description of TRL Levels
1	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

GAO encouraged DOE and other government agencies to use TRL's (*a direct quote**), to…

- *"Provide a **common language** among the technology developers, engineers who will adopt/use the technology, and other stakeholders;*
- ***Improve stakeholder communication** regarding technology development – a by-product of the discussion among stakeholders that is needed to negotiate a TRL value;*
- ***Reveal the gap** between a technology's current readiness level and the readiness level needed for successful inclusion in the intended product;*
- ***Identify at-risk technologies** that need increased management attention or additional resources for technology development to initiate risk-reduction measures; and*
- ***Increase transparency of critical decisions** by identifying key technologies that have been demonstrated to work or by highlighting still immature or unproven technologies that might result in high project risk."*

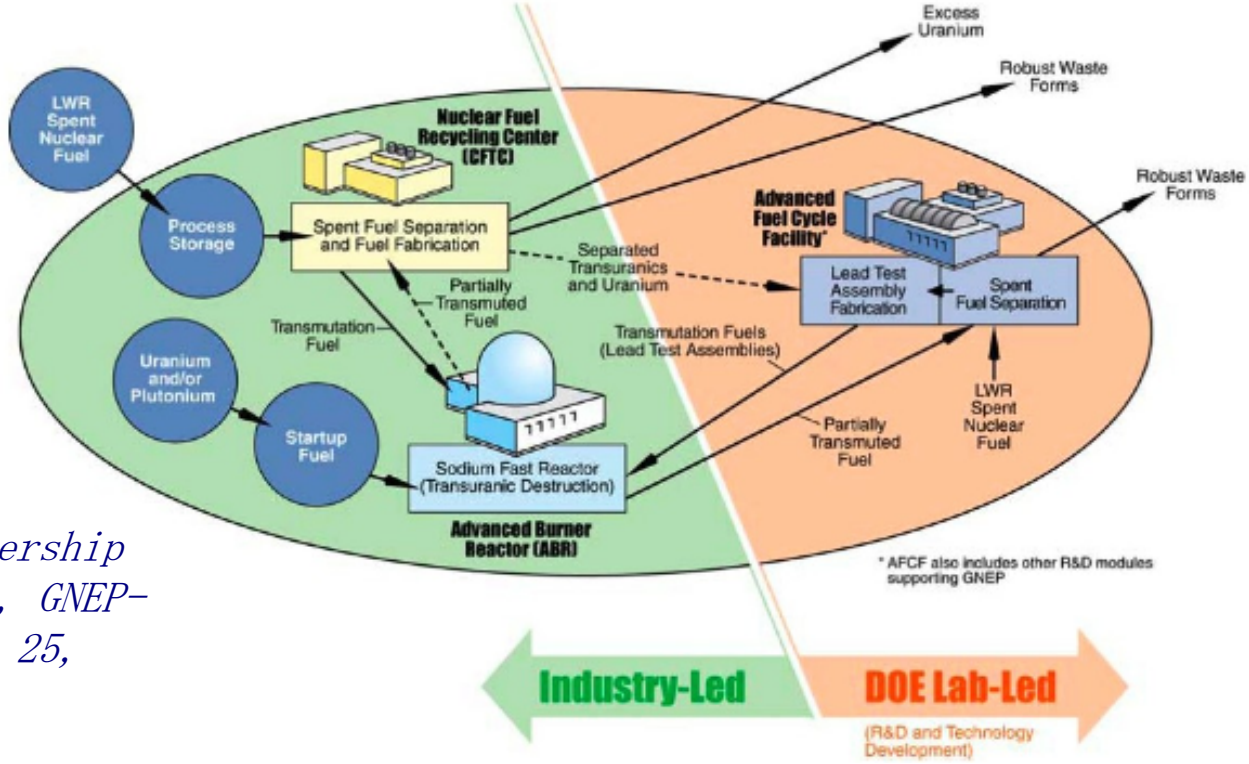
** "Department of Energy: Major construction projects need a consistent approach for assessing technology readiness to help avoid cost increases and delays," United States Government Accountability Office Report to the Subcommittee on Energy and Water Development, and Related Agencies, Committee on Appropriations, House of Representatives, GAO-07-336, March 2007.*

DOD, NASA, and other agencies use TRL's

*e.g., GNEP defined readiness in 5 technical areas**

- LWR spent fuel processing
- Waste form development
- Fast reactor spent fuel processing
- Fuel fabrication
- Fuel performance

GNEP facilities plan



** Global Nuclear Energy Partnership Technology Development Plan, GNEP-TECH-TR-PP-2007-00020, July 25, 2007.*

Technology Readiness Levels for LWR Spent Fuel Processing

TRL		Issue-Specific Description
1	Concept Development	Concept for separations process developed; process options (*e.g.,* contactor type, solvent extraction steps) identified; separations criteria established.
2		Calculated mass-balance flowsheet developed; scoping experiments on process options completed successfully with simulated LWR spent fuel; preliminary selection of process equipment.
3		Laboratory-scale batch testing with simulated LWR spent fuel completed successfully; process chemistry confirmed; reagents selected; preliminary testing of equipment design concepts done to identify development needs; complete system flowsheet established.
4	Proof of Principle	Unit operations testing at engineering scale for process validation with simulated LWR spent fuel consisting of unirradiated materials; materials balance flowsheet confirmed; separations chemistry models developed.
5		Unit operations testing completed at engineering scale with actual LWR spent fuel for process chemistry confirmation; reproducibility of process confirmed by repeated batch tests; simulation models validated.
6		Unit operations testing in existing hot cells w/full-scale equipment completed successfully, using actual LWR spent fuel; process monitoring and control system proven; process equipment design validated.
7	Proof of Performance	Integrated system cold shakedown testing completed successfully w/full-scale equipment (simulated fuel).
8		Demonstration of integrated system with full-scale equipment and actual LWR spent fuel completed successfully; short (~1 month) periods of sustained operation.
9		Full-scale demonstration with actual LWR spent fuel successfully completed at ≥100 metric tons per year rate; sustained operations for a minimum of three months.

* *The current TRL for this technology is highlighted in*

We used a 5-step systematic, bottoms-up approach to apply the TRL methodology to fusion energy

1. Identify customer needs: *use criteria from utility advisory committee to derive technical issues.*
2. Relate the utility criteria to fusion-specific, *design independent* issues and R&D needs.
3. Define "Readiness Levels" for the key issues and R&D needs.
4. Define the end goal in enough detail to evaluate progress toward that goal.
5. Evaluate status, gaps, R&D facilities and pathways.

Utility Advisory Committee

"Criteria for practical fusion power systems"

J. Kaslow et al, Journal of Fusion Energy ***13*** *(2/3) 1994.*

- 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
- Operate as a reliable, available, and stable 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

These criteria for practical fusion suggest three categories of technical readiness

12 top-level issues

A. Power management for economic fusion energy

1. Plasma power distribution
2. **Heat and particle flux management**
3. High temperature operation and power conversion
4. Power core fabrication
5. Power core lifetime

B. Safety and environmental attractiveness

6. Tritium control and confinement
7. Activation product control and confinement
8. Radioactive waste management

C. Reliable and stable plant operations

9. Plasma control
10. Plant integrated control
11. Fuel cycle control
12. Maintenance

Example TRL table: Heat & particle flux handling

	Issue-Specific Description	Program Elements
1	System studies to define parameters, tradeoffs and requirements on heat & particle flux level, effects on PFC's.	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized. PMI and edge plasma modeling.	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 through submodule testing in lab environment simulating heat or particle fluxes at prototypical levels over long times, mockups under representative neutron irradiation level/duration.	Larger-scale facilities for submodule testing, high-temperature + all expected conditions. Neutron irradiation (fission).
5	Integrated module testing of PFC concept in an environment simulating the integration of heat, particle, neutron fluxes at prototypical levels over long times. Coupon irradiation testing of PFC armor and structural material to end-of-life fluence.	Integrated large facility: Prototypical plasma particle + heat flux (*e.g.* an upgraded DIII-D/JET?) IFMIF?
6	Integrated testing of the PFC concept subsystem in an environment simulating the integration of heat & particle fluxes and neutron irradiation at prototypical levels over long times.	Integrated large test facility with prototypical plasma particle & heat flux, neutron irradiation.
7	Prototypic PFC system demonstration in a fusion machine.	Fusion machine, e.g. ITER (w/ prototypic divertor), CTF
8	Actual PFC system demonstration and qualification in a fusion energy device over long operating times.	CTF
9	Actual PFC system operation to end-of-life in a fusion reactor with prototypical conditions and all interfacing subsystems.	DEMO (1st of a kind power plant)

Example TRL table: Heat & particle flux handling

	Issue-Specific Description	Program Elements
1	System studies to define parameters, tradeoffs and requirements on heat & particle flux level, effects on PFC's.	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized. PMI and edge plasma modeling.	Code development, applied research
3	Power plant relevant high-temperature gas-cooled PFC's function of PFC concept.	lities: l plasma simulators
4	Bench-scale validation through submodule testing in lab environment simulating heat or particle fluxes at prototypical levels over long times, mockups under representative neutron irradiation level/duration.	Larger-scale facilities for submodule testing, high-temperature + all expected conditions. Neutron irradiation (fission).
5	Integrated module testing of PFC concept in an environment simulating the integration of heat, particle, neutron fluxes at prototypical levels over long times. Coupon irradiation testing of PFC armor and structural material to end-of-life fluence.	Integrated large facility: Prototypical plasma particle + heat flux (*e.g.* an upgraded DIII-D/JET?) IFMIF?
6	Integrated testing of the PFC concept subsystem in an environment simulating the integration of heat & particle fluxes and neutron Low-temperature water-cooled PFC's	Integrated large test facility with prototypical plasma particle & heat flux, neutron irradiation.
7	Prototypic PFC system demonstration in a fusion machine.	Fusion machine, e.g. ITER (w/ prototypic divertor), CTF
8	Actual PFC system demonstration and qualification in a fusion energy device over long operating times.	CTF
9	Actual PFC system operation to end-of-life in a fusion reactor with prototypical conditions and all interfacing subsystems.	DEMO (1st of a kind power plant)

Example TRL table: Plasma power control

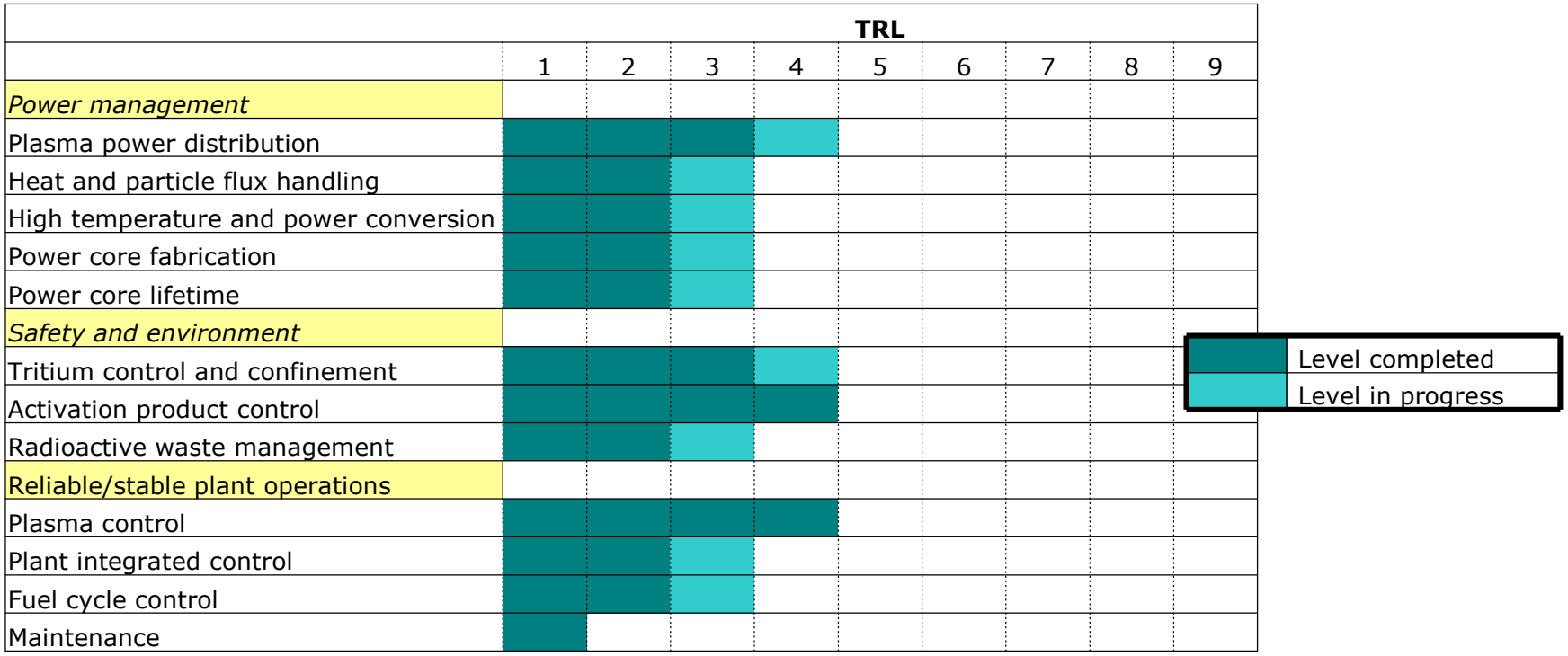
	Issue-Specific Description	Facilities
1	Development of basic concepts for extracting and handling outward power flows from a hot plasma (radiation, heat, and particle fluxes).	
2	Design of systems to handle radiation and energy and particle outflux from a moderate beta core plasma.	
3	Demonstration of a controlled plasma core at moderate beta, with outward radiation, heat, and particles power fluxes to walls and material surfaces, and technologies capable of handling those fluxes.	
4	Self-consistent integration of techniques to control outward power fluxes and technologies for handling those fluxes in a current high temperature plasma confinement experiment.	Can be performed in current expts. The detached radiative divertor is sufficient to satisfy this requirement.
5	Scale-up of techniques and technologies to realistic fusion conditions and improvements in modeling to enable a more realistic estimate of the uncertainties.	May require an intermediate expt between current devices and ITER, or an upgrade. Detached divertor may or may not scale up
6	Integration of systems for control and handling of base level outward power flows in a high performance reactor grade plasma with schemes to moderate or ameliorate fluctuations and focused, highly energetic particle fluxes. Demonstration that fluctuations can be kept to a tolerable level and that energetic particle fluxes, if not avoided, at least do not cause damage to external structures.	Envisaged to be performed in ITER running in basic experimental mode.
7	Demonstration of the integrated power handling techniques in a high perfor-mance reactor grade plasma in long pulse, essentially steady state operation with simultaneous control of the power fluctuations from transient phenomena.	Envisaged to be performed in ITER running in high power mode.
8	Demonstration of the integrated power handling system with simultaneous control of transient phenomena and the power fluctuations in a steady state burning plasma configuration.	Requires a burning plasma experiment.
9	Demonstration of integrated power handling system in a steady state burning plasma configuration for lifetime conditions.	

TRL's can be applied to components & subsystems

	Generic Definition	Blanket Subsystem-Specific Definition
1	Basic principles observed and formulated.	System studies define tradeoffs &requirements: heat loads, tritium breeding, magnetic effects (MHD, loads under off-normal operation scenarios), material constraints (temperature, stress, tritium inventory, radiation effects).
2	Technology concepts and/or applications formulated.	Blanket concepts including breeding material, structural material and cooling configuration explored. Critical parameters characterized.
3	Analytical and experimental demonstration of critical function and/or proof of concept.	Coupon-scale experiments on heat loads (and thermal-hydraulic), tritium generation and mass transfer; modeling of governing heat transfer, thermal-hydraulic (including MHD) and mass transfer processes (tritium behavior and possibly corrosion) as demonstration of function of blanket concept. Maintenance methods explored.
4	Component and/or bench-scale validation in a laboratory environment.	Bench-scale validation through submodule testing in lab environment simulating heat fluxes or magnetic field over long times, and of mockups under neutron irradiation at representative levels and durations. Maintenance methods tested at lab-scale.
5	Component and/or breadboard validation in a relevant environment.	Integrated module in: (1) an environment simulating the integration of heat loads and magnetic fields (if important for concept) at prototypical levels over long times; and (2) an environment simulating the integration of heat loads and neutron irradiation at prototypical levels over long times. Coupon irradiation testing of structural materials to end-of-life fluence. Lab-scale demo of selected maintenance scheme for blanket unit.
6	System/subsystem model or prototype demonstration in relevant environment.	Integrated subsystem testing in an environment simulating the integration of heat loads and neutron irradiation (and magnetic fields if important for concept) at prototypical levels over long times. Full-scale demonstration of maintenance scheme.
7	System prototype demonstration in an operational environment.	Prototypic blanket system demonstration in a fusion machine (for chosen confinement), including demonstration of maintenance scheme in an operational environment.
8	Actual system completed and qualified through test and demonstration	Actual blanket system demonstration and qualification in a fusion machine (for chosen confinement) over long operating times. Maintenance scheme demonstrated and qualified.
9	Actual system proven through successful mission operations	Actual blanket system operation to end-of-life in fusion power plant (DEMO) with operational conditions and all interfacing subsystems.

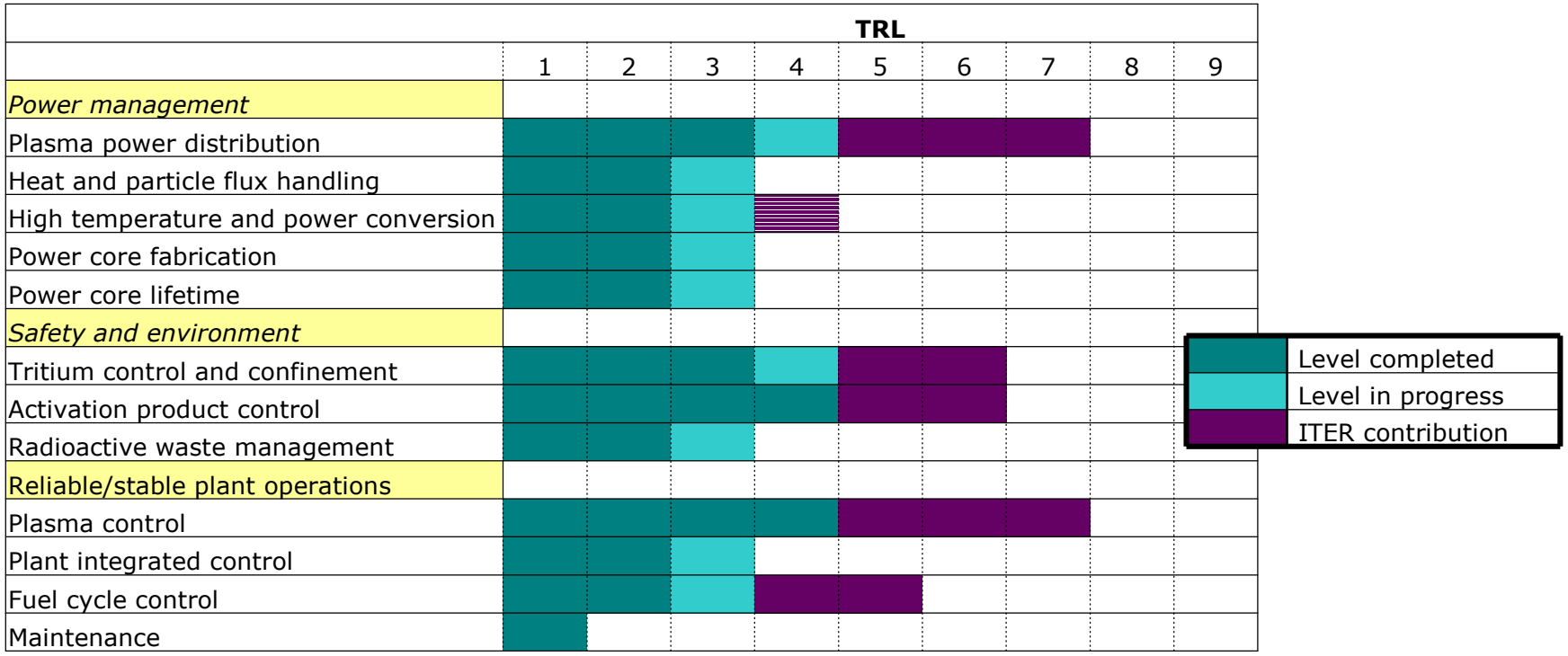
A preliminary evaluation was performed by the ARIES Team for a reference ARIES power plant

- For the sake of illustration, we considered a Demo based on the ARIES advanced tokamak DCLL power plant design concept.
- He-cooled W divertor, DCLL blanket @700°C, Brayton cycle, plant availability=70%, 3-4 FPY in-vessel, waste recycling or clearance.
- Other concepts would evaluate differently.



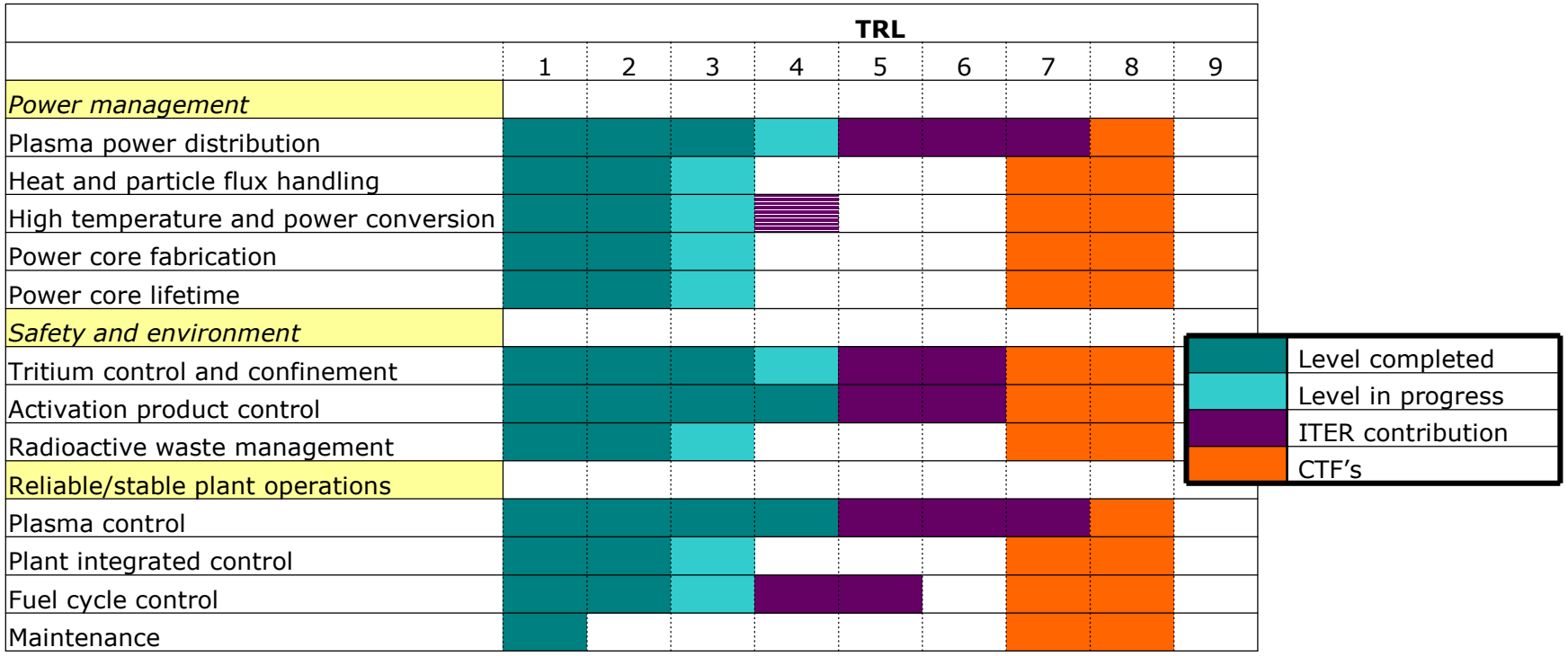
In this case, the ITER program contributes in some areas, but very little in others

- ITER promotes to level 6 issues related to plasma and safety
- ITER helps incrementally with some issues, such as blankets (depending on TBM progress), PMI, fuel cycle
- The absence of reactor-relevant technologies severely limits its contribution in several areas



Major gaps remain for several of the key issues for practical fusion energy

- A range of nuclear and non-nuclear facilities are required to advance from the current status to TRL6
- One or more test facilities such as CTF are required before Demo to verify performance in an operating environment



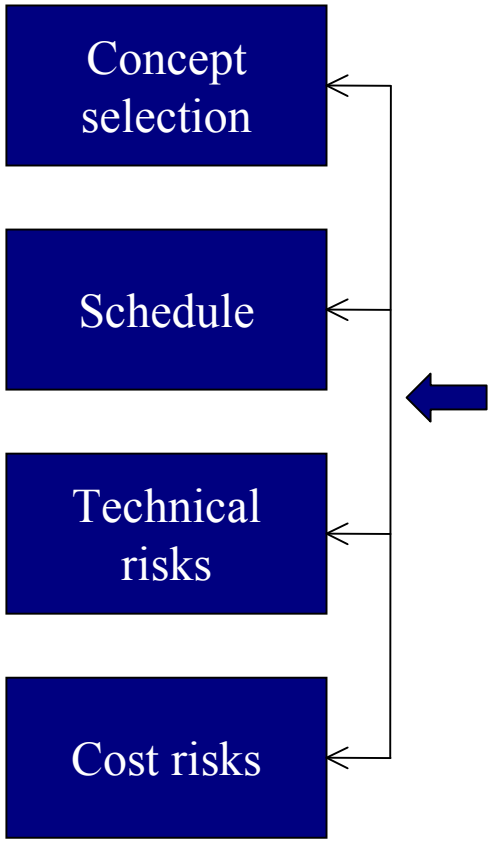
Conclusions

1. TRL's provide an objective, systematic, widely accepted tool for planning large application-oriented programs.

2. Fusion-relevant TRL tables were developed in ARIES and used to evaluate our readiness on the pathway to an advanced tokamak power plant.

3. TRL's are adaptable and can be used to help guide the ReNeW process.

TRL's are a *tool* for evaluating progress and risk and not a complete program management system



	Readiness level								
	1	2	3	4	5	6	7	8	9
Design options *(confinement concepts, components, etc)*									
Concept 1									
Concept 2									
Concept 3									
Etc.									