Implementing TRL's in the fusion program

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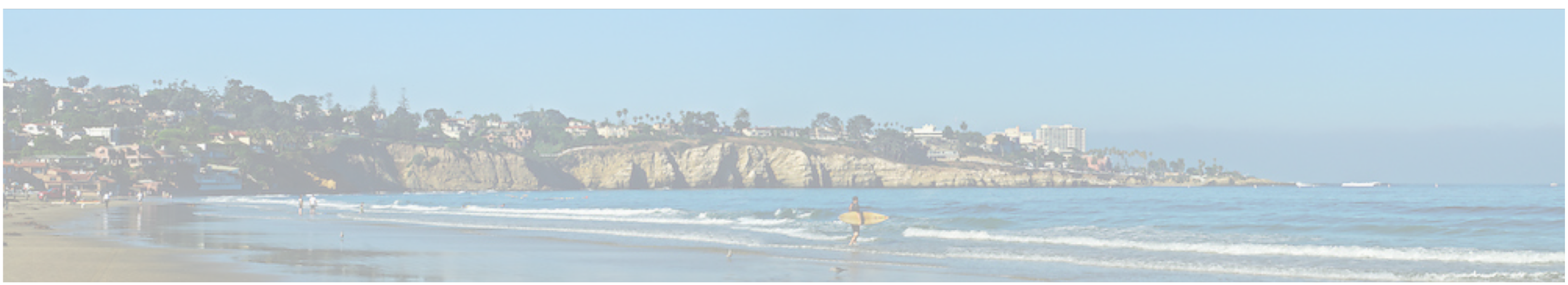


A brief history of my involvement with TRL's

- 2008 ARIES Pathways started, including facility considerations.
- Pathways was overtaken by ReNeW, redirected into ARIES-ACT study.
- During Pathways study, Waganer (Boeing) suggested TRL approach, believing DOE was likely to require it for next step facility approval.
- TRL's applied to ARIES power plants (led by Tillack), published in 2009.
- DOE interest led to FESAC briefing by Tillack & Whelan (Boeing) 2009.
- Applied to fusion materials and presented at ICFRM 2011.
- Occasional interest (and use of the language) since 2011, but no obvious follow-through (OFES program seems "*not ready*" for it).

What TRL's Are

- A common language for understanding technology maturity
- A common input for evaluating technology risk
- A common framework for understanding risk

What TRL’s Are Not

- **Product spec’s**
- **A complete program management system**
- **A complete progress tracking system**

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.

TRL's express increasing levels of *integration* and *environmental relevance*, terms which must be defined for any given technology 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.

More detailed guidance on TRL evaluation is available

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.

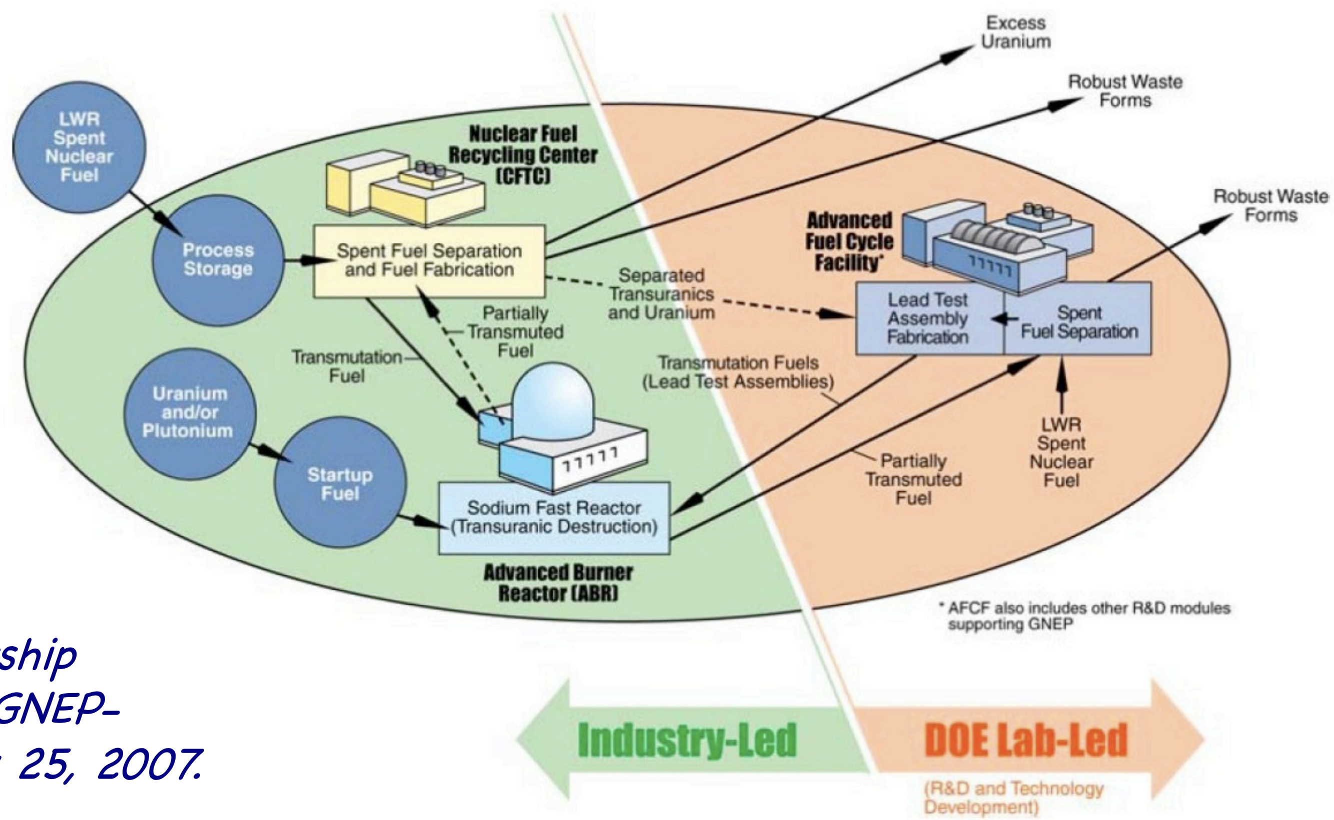
In ARIES, we used a 5-step approach to apply the TRL methodology to power plant R&D

1. Identify customer needs: *we adopted criteria from our advisory committee to express technology issues.*
2. Relate market criteria to fusion-specific, *design independent* issues and R&D needs.
3. Define attributes of the "Readiness Levels" for the key issues and R&D needs.
4. Define the end goal (a facility or demonstration) in sufficient detail to evaluate progress toward that goal.
5. Evaluate status, gaps, R&D facilities and pathways.

GNEP adopted TRL's and 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.*

Criteria for practical fusion suggest three categories of technology readiness

12 high-level issues

A. Power and particle 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: #2 Heat & particle flux handling

	Programmatic "metrics" for evaluating progress	Program Elements
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 parameters characterized.	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 simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.	Integrated large test facility with prototypical plasma particle and heat flux
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

The status of R&D was evaluated (in 2008)

- **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

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

The ITER program contributes in some areas, much less in others

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

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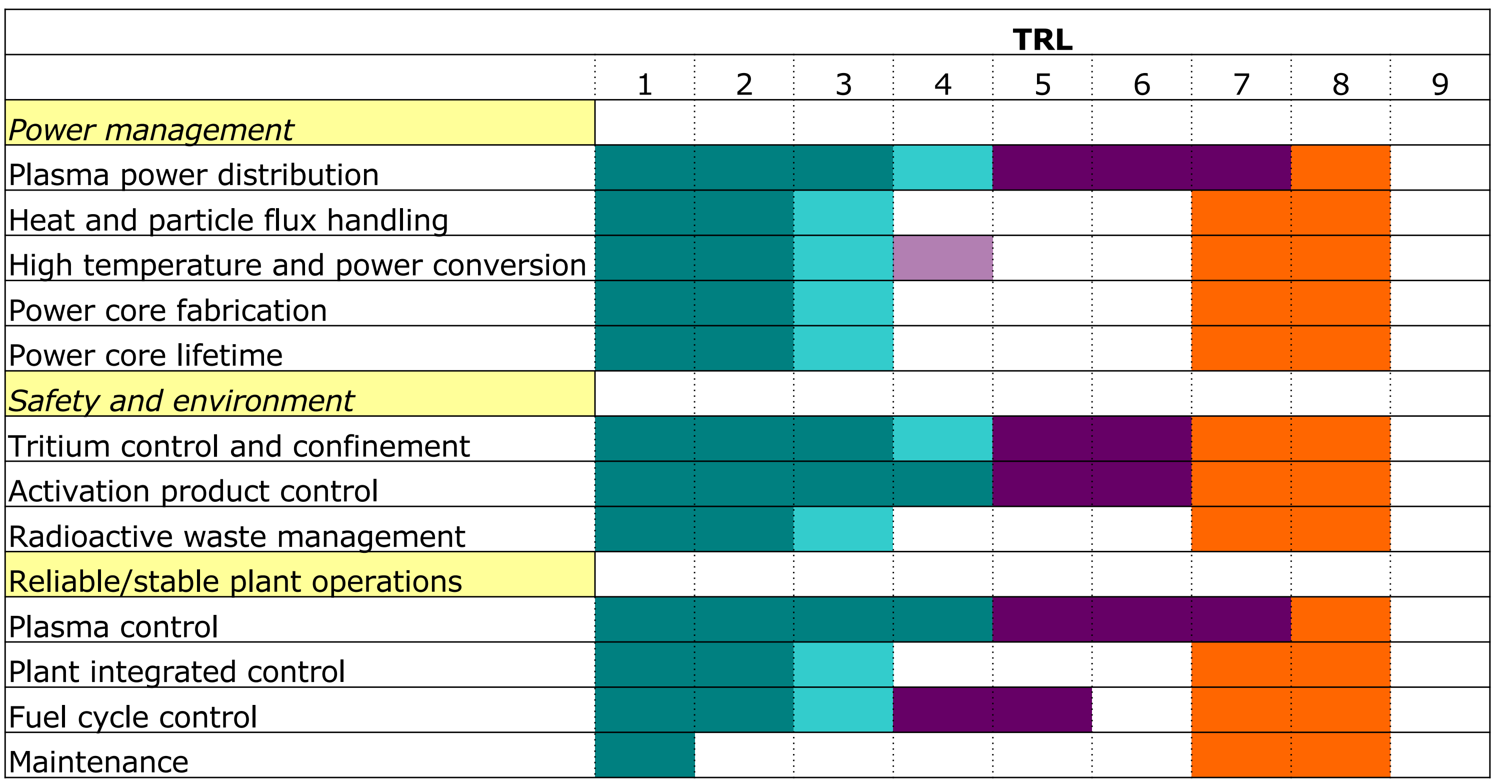
Plant integrated control									
Fuel cycle control									
Maintenance									

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



Technology readiness applied to materials for fusion applications

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with contributions from

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15th International Conference on Fusion Reactor Materials, Charleston SC October 16-21, 2011

Materials issues and R&D needs were used to help define metrics for evaluating progress

A. Fabrication and characterization of materials

- base material production in samples
- property measurements in samples (with and without neutrons)
- base material production in large heats and in semi-finished products
- joining and assembly of components
- NDE and inspection methods

B. Short-term responses to the operating environment

- temperature and stress fields, including transients for at least one operational cycle
- coolant chemistry
- tritium transport
- normal and off-normal responses
- responses to fully integrated environment

C. Long-term behavior of components

- creep, fatigue, fracture mechanics and their interaction
- characterization of radiation damage to materials
- characterization of long-term environmental effects on materials
- effects of radiation damage and environment on components and systems
- component reliability, failure modes and rates

D. Licensing

- development of codes and standards
- code qualification of components
- plant licensing

Attributes associated with TRL levels were posed in the form of questions, to assist in polling

TRL1	Has applied research on these materials begun?
TRL2	Have conceptual studies of the application been performed? Are the full ranges of environmental/operating conditions and material requirements known? Have coupon-scale samples been fabricated and characterized?
TRL3	Are basic thermophysical and mechanical properties of the material known over the required temperature range of operation? Do data exist on irradiation effects in single-material specimens? Have basic material-coolant compatibility tests been performed? Have joining techniques been demonstrated? Have cyclic heat flux tests at prototypic conditions been performed? Do models exist for predicting materials behavior? Do adequate data exist to validate the models?

Elaboration of the attributes (TRL3 example)

Are basic thermophysical and mechanical properties of the material known over the required temperature range of operation?	Minimum set of properties include density, thermal conductivity, specific heat, thermal expansion coefficient, magnetic susceptibility, tensile, fracture toughness, and fatigue from room temperature up to the maximum operating temperature, thermal creep at the operating temperatures and neutronic properties.
Do data exist on irradiation effects in single-material specimens?	"Full data" is defined as fission reactor studies that have investigated microstructure stability, tensile, irradiation creep, fracture toughness, etc. up to 50% of proposed design doses. Scoping studies using dual ion beams, spallation neutrons, or other simulation tests to investigate H, He effects should also be underway.
Have basic material-coolant compatibility tests been performed?	Minimum of static capsule tests at the proposed operating temperatures for >1000 h; loop tests for >10,000 h preferred.
Have joining techniques been demonstrated?	Coupon tests that demonstrate tensile strengths >50% of base material strength.
Have cyclic heat flux tests at prototypic conditions been performed?	Coupon tests on as-fabricated material at fusion-relevant heat fluxes.
Do models exist for predicting materials behavior?	
Do adequate data exist to validate the models?	Single-effects data at fusion-relevant conditions (cyclic heat flux, fission reactor and other irradiation sources).

My advice on "process"

1. Identify ultimate objectives (e.g. customer requirements).
2. Relate objectives to fusion-specific, *design independent* issues and R&D needs.
3. Define the end product, including technology options, in enough detail to evaluate progress toward that goal.
4. Define "Readiness Levels" for the key issues and R&D needs, in sufficient detail to allow evaluation.
5. Agree on an approach to evaluate status, gaps, R&D facilities and pathways.