



Technology readiness evaluations for fusion materials science & technology

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*FESAC Materials panel conference call
20 December 2011*

Introduction

- “**Technology readiness**” is a concept recently adopted by both government and industry (DOD, NASA, DOE) in the US.
- It uses quantitative **metrics** (TRL1-9) as one element of program planning, to evaluate progress, R&D gaps and risk.
- The metrics must be defined for each unique application
 - At ICFRM 2011, we defined technology readiness levels for materials to be used in commercial fusion PFC’s.
 - At TOFE 2008 (also FESAC 2009), we defined technology readiness levels for tokamak fusion power plants.
- Here I will explain the method, the applications to fusion and the issues for full implementation.

TRL's express increasing levels of integration and environmental relevance

TRL	Generic Description (<i>defense acquisitions definitions</i>)
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.

These terms must be defined for each technology application

More detailed guidance on TRL evaluations exists

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.

Materials development needs were used to help define metrics at ICFRM

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 framed in the form of a questionnaire

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

Requirements to fulfill the attributes (TRL3)

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).

Attributes associated with TRL levels, cont'd

TRL4	<p>Have joining techniques been demonstrated?</p> <p>Do data and modeling of coolant and other corrosive interactions exist?</p> <p>Are there models and experiments under heat flux demonstrating key mechanical behaviors under normal and off-normal conditions?</p> <p>Do data and models exist on irradiation effects in subcomponents?</p> <p>If data exists only in coupons, can that data with modeling adequately demonstrate subcomponent behavior?</p>
TRL5	<p>Have large, reproduceable quantities been produced (sufficient to build objects)?</p> <p>Have prototypes been built and operated in a simulated integrated environment (e.g., non-neutron test facilities)?</p> <p>Have methods for nondestructive evaluation of structures been matured?</p> <p>Are the relevant ASTM/ISO standards in existence to provide code-relevant data for nuclear applications?</p>
TRL6	<p>Have prototypes been operated in an integrated fusion environment (e.g., ITER)?</p> <p>Have all of the components been code qualified?</p>

Attributes associated with TRL levels, cont'd

TRL7	Is the database adequate for licensing of a demonstration reactor? Has the material been used in a component of a demonstration power plant?
TRL8	Have the operating characteristics in a commercial power plant been fully demonstrated? Have prototypes been operated to end of life? Are the end-of-life characteristics understood (failure modes and rates)?
TRL9	Has the material been used in an operating power plant?

The current status of materials development was evaluated by experts at ICFRM

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	TRL								
	1	2	3	4	5	6	7	8	9
Material class									
RAF	■	■	■	■	■				
ODSS 9Cr(12)	■	■	■						
ODSS 15Cr	■	■	■						
W-alloy structure	■	■	■	■					
Functional W	■	■	■	■	■				
SiC/SiC	■	■	■	■	■				

“Concept development”

“Proof of principle”

“Proof of performance”

“Criteria for practical fusion” were used in ARIES to define *system level* TRL’s

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: <i>e.g.</i> , 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 (<i>e.g.</i> 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, <i>e.g.</i> 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 (1 st of a kind power plant)

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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 (1 st of a kind power plant)

Power plant relevant high-temperature gas-cooled PFC's

Low-temperature water-cooled PFC's

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

- For the sake of illustration, we considered TRL9 as a **Demo** based on an 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.

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

	Level completed
	Level in progress

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

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

	Level completed
	Level in progress
	ITER contribution

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

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

Lessons learned regarding the application of TRL's for fusion

- TRL's are **not** a complete program planning tool.
- TRL's depend on the goal (the definition of TRL9).
- TRL's require judgment in their definition and application.
 - Need to decide what to measure: materials, components, systems
 - Need to define achievements corresponding to each level.
 - Need to evaluate whether the achievement has been met.
- The neutron problem for fusion: we will have difficulty passing true TRL4 without volumetric neutron sources. We may need to “decouple” neutrons.
- Considering we are “stuck” at TRL3, and will have difficulty passing TRL4, the granularity of this methodology may not suit our current programmatic needs.