Technology readiness applied to materials for fusion applications

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Introduction

- **"Technology readiness"** is a concept adopted by both government and industry in the US.
- It uses **metrics** as one element of program planning to evaluate progress, R&D gaps and risk.
- We defined technology readiness levels (TRL's) for materials to be used in **commercial fusion power core components**.
- Four classes of materials were evaluated: **RAF, ODSS, SiC, W**
- The results will be discussed, as well as the prospects of this methodology for fusion R&D planning.

TRL's express increasing levels of integration and environmental relevance

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.

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.

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".*

What TRL's Are

BOEING

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

DoE FESAC
13 January 2009

From "Technology Readiness Levels and Aerospace R&D Risk Management,"
Dr. David Whelan, Chief Scientist, Boeing Integrated Defense Systems

What TRL's Are Not

BOEING

- Product spec's
- A complete program management system
- A complete progress tracking system

From "Technology Readiness Levels and Aerospace R&D Risk Management,"
Dr. David Whelan, Chief Scientist, Boeing Integrated Defense Systems

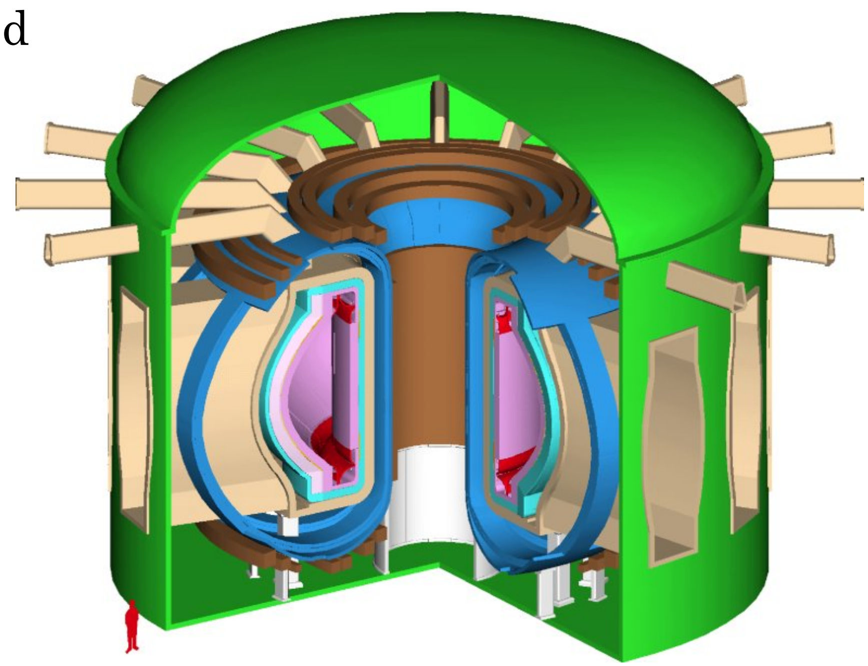
TRL's require specification of the end product (TRL9)

- The "readiness" in our assessment refers to applications of materials in commercial fusion power plant components.

- TRL9 means materials have been proven successful in an operating commercial fusion power plant.

- 4 material classes have been evaluated
  - RAF
  - 9(12)Cr and 15Cr ODSS steels
  - SiC composites
  - W alloys
    (both functional and structural alloys)

- More detailed product definition is needed to refine the process.



Materials development needs were used to help define metrics

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, in the form of a questionnaire

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).

Attributes associated with TRL levels, cont'd

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

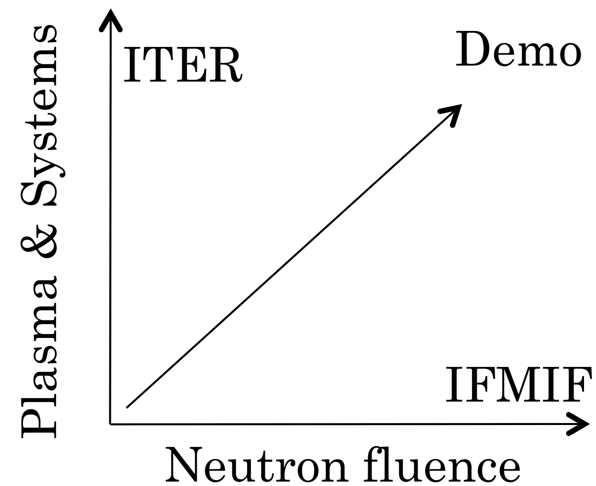
Attributes associated with TRL levels, cont'd

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 neutron problem

- In order to progress beyond TRL4, integrated (component) tests in a "relevant" neutron environment should be performed.
- We don't expect this until a nuclear test facility (with substantial fluence) is available, perhaps in 10-20 years.
- Fusion development around the world relies on decoupling high fluence exposure from integrated testing.
- The hope is that separate-effects testing with neutrons (IFMIF) combined with component tests in non-neutron facilities and ITER will suffice.
- This clearly adds risk.

TRL5 requires component validation in a relevant environment



Research Program Elements

TRL	Generic Description	Research Elements & Facilities
1	Basic principles observed and formulated.	Problem definition, paper studies.
2	Technology concepts and/or applications formulated.	Design studies, requirements, alloy development, modeling.
3	Analytical and experimental demonstration of critical function and/or proof of concept.	Property measurements, irradiation tests of coupons in fission and ion sources, compatibility, steady and unsteady conditions.
4	Component and/or bench-scale validation in a laboratory environment.	Single and multiple-effects tests on components (e.g., high temperature, high heat flux, PMI), supplemented by high-fluence specimen exposures in a multiple-effect (H,He, dpa)14-MeV fusion environment.

Research Program Elements, continued

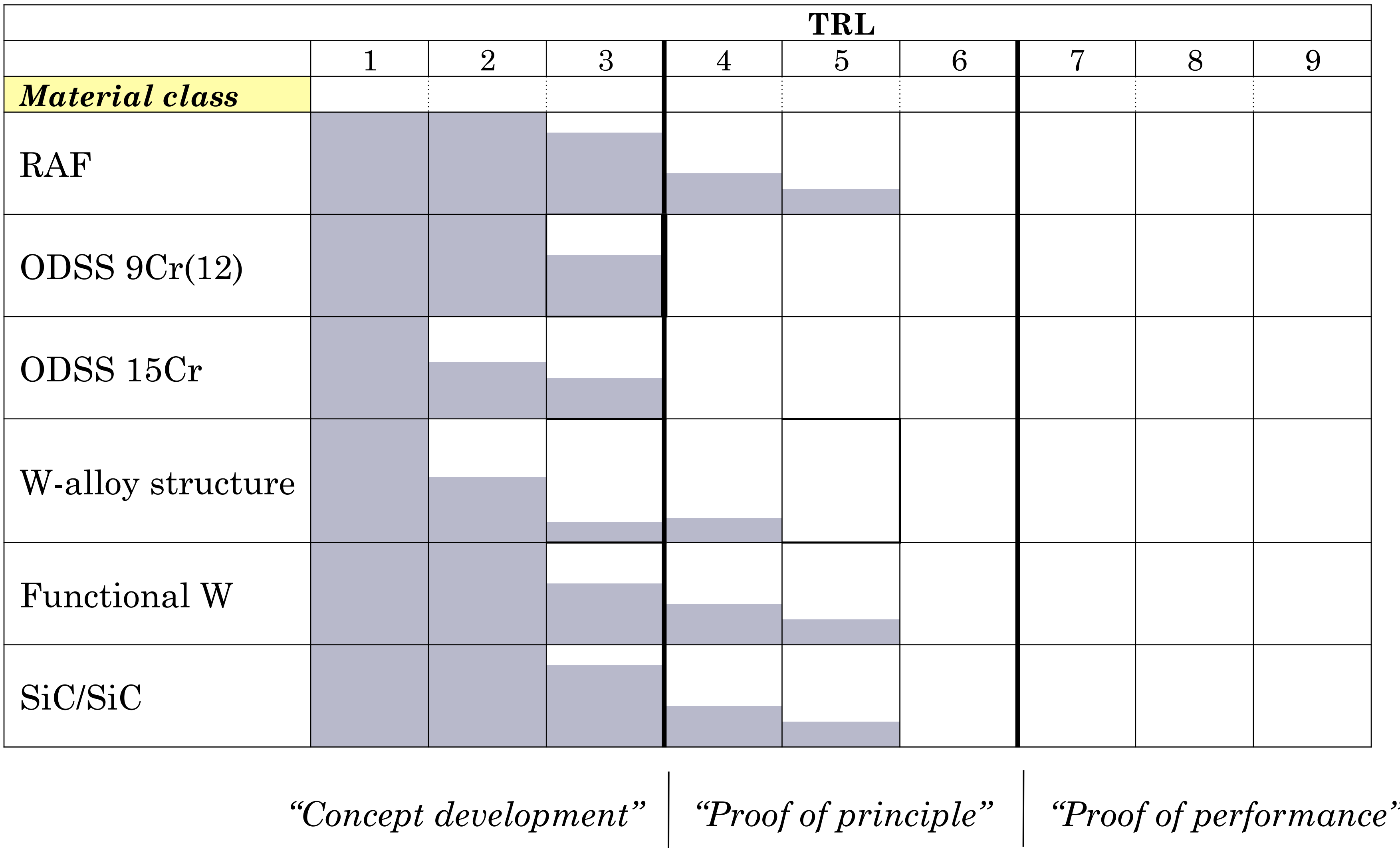
TRL	Generic Description	Research Elements & Facilities
5	Component and/or breadboard validation in a relevant environment.	Large-scale non-neutron tests of components, supplemented by high-fluence specimen exposures.
6	System/subsystem model or prototype demonstration in relevant environment.	ITER, large-scale non-neutron system tests in a relevant environment (temperature, heat flux, plasma flux, EM, transients), supplemented by high-fluence specimen exposures.
7	System prototype demonstration in an operational environment.	FNSF-like device, supplemented by high-fluence specimen exposures.
8	Actual system completed and qualified through test and demonstration.	Demonstration power plant.
9	Actual system proven through successful mission operations.	Commercially successful power plant.

Quantification of success and risk

- How much data is sufficient to advance to the next level?
- How do we plan for risk of failing at a future TRL?
- How critical is material data to the overall success of a concept (involving many other elements)?
- What are the consequences of "failure"? Is it reduced performance, or catastrophic failure?

- **TRL's don't really answer these questions. They only provide a framework for discussion.**

The current status was evaluated by experts
(the speakers in this session)



Conclusions

- Materials research has been, over decades, concerned primarily with research at TRL level 3.
- From the 10,000-ft level, only minor differences exist between materials classes in their level of readiness to be installed in a power plant.
  - TRL1-2 has been mostly completed on the basis of paper studies
  - Progress beyond TRL3 requires large investments in facilities
  - Most materials research has been, and continues to be performed at TRL3
- The scarcity of fusion neutron sources implies significant risk at higher TRL levels. This is an inherent problem with fusion energy development.
- The application of TRL's has led to productive discussions of the status and R&D needs for materials. Further refinement and use of TRL's in R&D programs will be beneficial.