

Evaluating gaps in fusion energy research using Technology Readiness Levels,

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In order to evaluate our current state of readiness and remaining R&D needs on the path toward practical fusion energy, the ARIES Team adopted a methodology called “Technology Readiness Levels”, or “TRL’s”. Technology Readiness Levels are commonly used in industry, especially those receiving federal support. They provide a systematic and objective measure of the maturity of a particular technology. NASA developed TRL’s originally in the 1980’s [1]; with minor modification, they can be used to express the readiness level of almost any goal-oriented project.

In a 1999 report [2], the General Accounting Office (GAO) encouraged the use of TRL’s and concluded that failure to properly mature new technologies in the “laboratory” environment almost invariably leads to cost and schedule overruns. The report puts it this way: “Maturing new technology before it is included on a product is perhaps the most important determinant of the success of the eventual product.” The Department of Defense adopted this methodology as a best practice to evaluate the readiness levels of new technologies and to guide their development toward the state where they can be considered “operationally ready”, thus helping to ensure that new technologies can be included in new programs with a lower degree of risk.

TRL’s encompass 9 levels of achievement, or hurdles, that must be passed in order to progress toward a final product. These levels include:

1. Basic principles observed and reported. This is the 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. Technology concept and/or application formulated. 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. Analytical and experimental critical function and/or characteristic proof of concept. 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. Component and/or breadboard validation in laboratory environment. 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. Component and/or breadboard validation in relevant environment. 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. System/subsystem model or prototype demonstration in a relevant environment. 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. System prototype demonstration in an operational environment. 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. Examples include exposing a prototype to the true operational environment on a surrogate platform, demonstrator, or test bed.

8. Actual system completed and qualified through test and demonstration. 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 final form to determine if it meets design specifications.
9. Actual system proven through successful mission operations. 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.

Compelling reasons for adopting this methodology were highlighted by the GAO [3]. TRL's:

- *“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.”*

These features clearly express the current needs of the fusion research program.

To encourage the US fusion program to adopt TRL's and to further demonstrate their utility, we applied TRL's to a fusion-specific example. We defined a comprehensive set of issues for fusion energy and then created tables describing fusion-specific readiness levels to be used in evaluations [4]. One such table is presented here as Table I for plasma-facing components.

In order to use this table and evaluate readiness and gaps, the technology features of the ultimate goal at level 9 must be defined at some level of detail. We considered two possibilities for plasma-facing components: 1. high-temperature, high-performance commercial fusion power plant PFC's, and 2. ITER-like PFC's. Our reference concept for the power plant uses helium coolant, reduced activation ferritic steel structure for the blanket/FW, W-alloy structure for the divertor and W for the plasma-facing surface. The divertor operation is assumed to be detached, with significant impurity radiation from the core and mantle. The resulting surface heat flux is approximately 0.5 MW/m^2 on the first wall and 10 MW/m^2 on the divertor surfaces. The coolant is coupled to a Brayton power conversion system.

With a power plant as the final goal, we evaluated our current readiness level for PFC's. We concluded that TRL 2 has been achieved, and that research at the level of TRL 3 has begun. The design concept and principal challenges have been defined, and current research concentrates on modeling and coupon-scale testing. Much more effort is required at this TRL level before passing the TRL 3 hurdle.

With ITER-relevant technology as the end goal, our level of readiness is obviously much higher. We estimated the current level of readiness at 6. ITER will provide the environment needed to demonstrate low-temperature PFC's to a TRL of 7 and beyond.

We also sought to evaluate the expected contribution of ITER (and other facilities) to advance each issue toward the ultimate goal of practical fusion energy. We assumed that ITER would be successful at meeting all of its goals, and that a test module program would be carried out including all of the essential ancillary systems, albeit at rather low neutron flux and substantially reduced operating time and neutron fluence. The results of our evaluation showed that ITER provides little benefit to the advancement of power-plant relevant PFC's. The reason is that the materials choices and design features of the ITER first wall and divertor bear little resemblance to the US vision for an attractive power plant. ITER alone will not push the TRL level of power plant PFC's beyond 3.

Table I. TRL's for plasma facing components

TRL	Issue-Specific Definition
1	System studies to define parameters, tradeoffs and requirements on heat & particle flux level, effects on PFC's.
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized. PMI and edge plasma modeling.
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.
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.
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.
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.
7	Prototypic PFC system demonstration in a fusion machine.
8	Actual PFC system demonstration and qualification in a fusion energy device over long operating times.
9	Actual PFC system operation to end-of-life in a fusion reactor with prototypical conditions and all interfacing subsystems.

References:

[1] J. C. Mankins, "Technology Readiness Levels, A White Paper," Advanced Concepts Office, Office of Space Access and Technology, NASA, April 6, 1995.

[2] "Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes," GAO/NSIAD-99-162, United States General Accounting Office, July 30, 1999.

[3] "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.

[4] M. S. TILLACK, *et al.*, "Issues and R&D needs for commercial fusion energy: An interim report of the ARIES technical working groups," UCSD-CER-08-01, July 2008.