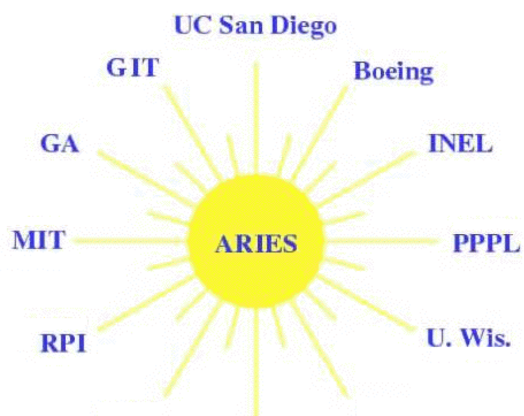
The Application of Technology Readiness Levels in Planning the Fusion Energy Sciences Program



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UC San Diego

ARIES Project Meeting

4–5 September2008

Center for Energy Research

Topics

- **Status and plans**
  - ✓ Oral and printed publication of our results
- **TOFE Presentation**
  - ✓ Dry run, solicit recommendations for improvement
  - ✓ Possible adjustments for broader (FESAC) consumption (later)
- **Discussion of TRL evaluation results, pathway analysis**
  - ✓ Current readiness, value of ITER, role of CTF
- **Discussion**
  - ✓ Revisions, action items to complete this exercise

Review of progress

Jun 07	TWG's created, tasked to define R&D status & needs, plans & options Advisory committee meeting
Sep 07	Idea of using TRL's floated
Dec 07	Agreed to adopt TRL's Defined issues and assigned individuals to create/describe TRL's Methodology defined, based on utility requirements
Mar 08	Draft TRL tables produced, report outline created
May 08	Reference concepts defined, first evaluation performed Report details filled in
Aug 08	Scenarios examined Publications 95% complete

Plans to present TRL methodology to the broader community

(see http://aries.ucsd.edu/ARIES/WDOCS/ARIES07/TWG/)

- **Printed matter**
  1. TWG "Interim Report" UCSD-CER-08-01 (posted on web site ASAP)
  2. Proceedings of TOFE (preprint to be distributed at TOFE)
  3. ANS Newsletter, December 2008

- **Oral presentations**
  4. TOFE invited talk, 9/30/08
  5. ARIES HHFC workshop, 12/10/08
  6. FESAC meeting, if rescheduled

University of California, San Diego

UCSD-CER-08-01

Issues and R&D needs for commercial fusion energy

An interim report of the ARIES technical working groups

M. S. Tillack, D. Steiner, L. M. Waganer, S. Malang,
F, Najmabadi, L. C. Cadwallader, L. A. El-Guebaly, R. J. Peipert Jr,
A. R. Raffray, J. P. Sharpe, A. D. Turnbull, T. L. Weaver,
and the ARIES Team

July 2008

Current Status

UCSD-CER-08-01	~70 pages, 95% complete, under final review *evaluation of current TRL, with ITER, role of CTF*
TOFE paper	8 pages, 95% complete, same as interim report *selected tables presented due to space limitation* **1. plasma power flows, 2. tritium control, 3. plasma control**
ANS Newsletter	Due November 1
TOFE talk	Complete draft, to be shown today
ARIES HHFC	Same as TOFE, except more emphasis on HHFC
FESAC talk	Partial draft, to be integrated with Raffray's work? *May require some revisions, depending on the prevailing state of affairs.* *No date.*

An evaluation of fusion energy R&D gaps using technology readiness levels

M. S. Tillack, A. D. Turnbull, L. M. Waganer, S. Malang,
D. Steiner, J. P. Sharpe, L. C. Cadwallader, L. El-Guebaly, A. R. Raffray,
F. Najmabadi, R. J. Peipert Jr, T. L. Weaver and the ARIES Team

18th Topical Meeting on the Technology of Fusion Energy San Francisco, CA
September 28 – October 2, 2008

The topic of fusion energy R&D gaps is seeing increased attention in the US and worldwide

- In EU and Japan, the “broad approach” and “fast track” activities have placed additional attention on R&D **gaps**
- In the US, DOE and FESAC initiated a series of panels and workshops to respond to requests for a coherent program plan.
- The ARIES Pathways study began in 2007 to evaluate R&D needs and gaps for fusion from ITER to Demo.
- In this study we adopted and tested a methodology for evaluating R&D needs that is widely recognized **outside** of the fusion community.
- Initial efforts to develop and apply this technology assessment approach for fusion energy are reported here.

Development of TRL's is one element of the ARIES "Pathways" Program

- What are the remaining major R&D areas?
  - ✓ What is the data base needed to field a commercial power plant (including licensing, operations, reliability, *etc*.)?
  - ✓ Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (*i.e.*, fission reactors)?
  - ✓ What is the impact of each R&D item on the attractiveness of the final product (metrics for prioritization of R&D)?
- What other major facilities are needed?
  - ✓ What are the possible embodiments for CTF and what are the their cost/performance attributes?

➢ **The goal is to develop <u>quantitative</u> metrics in each area.**

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

TRL	Category	Generic Description
1	Concept Development	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	Proof of Principle	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	Proof of Performance	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.

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

More detailed guidance on TRL evaluation is available

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

TRL	Generic Description
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.

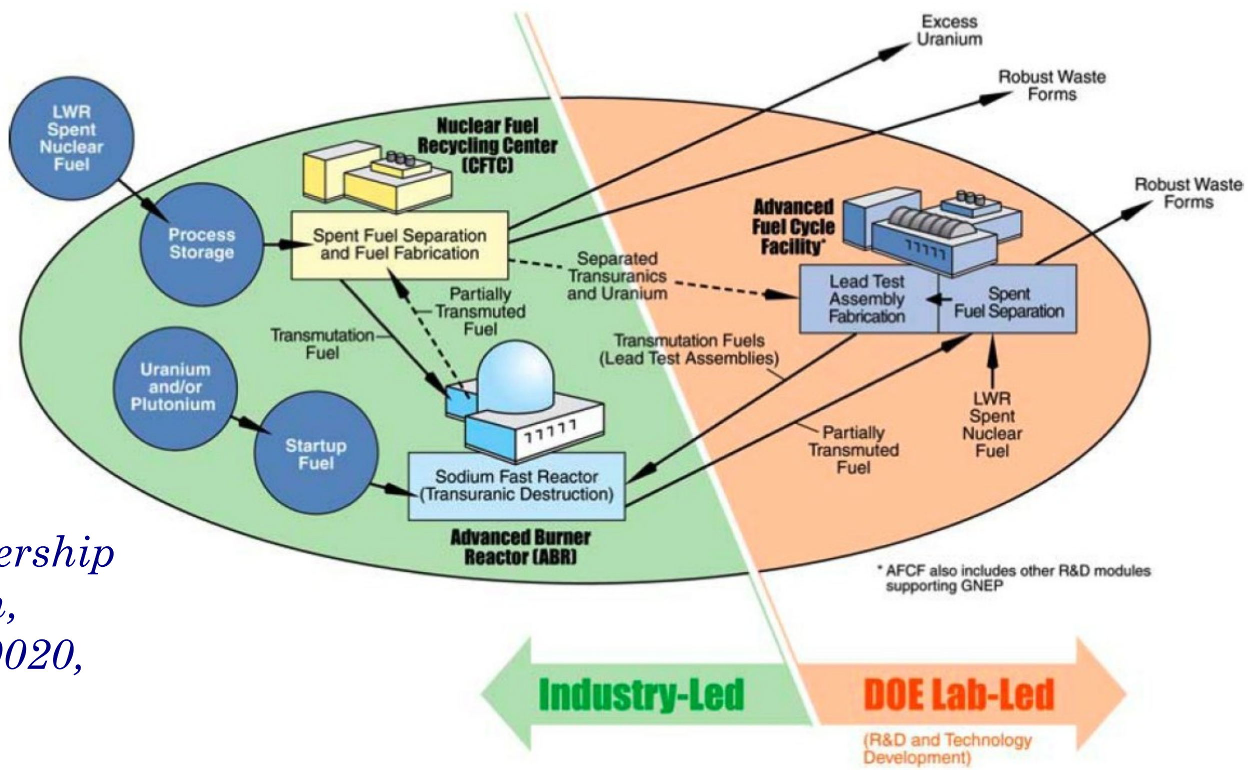
GAO encouraged DOE and other government agencies to use TRL's (*a direct quote*), to...

- ***"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"*

For example, 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.*

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 orange.*

We used a 5-step 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 (a facility or demonstration) in enough detail to evaluate progress toward that goal.**
5. **Evaluate status, gaps, R&D facilities and pathways.**

1) Utility Advisory Committee
"Criteria for practical fusion power systems"

J. 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

2) These criteria for practical fusion suggest three categories of technology 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

3) Example TRL table: Heat & particle flux

	Issue-Specific Description	Facilities
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized.	
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 facility: Prototypical plasma particle flux+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

3) 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

3) Example TRL table: #1 Plasma power (continued)

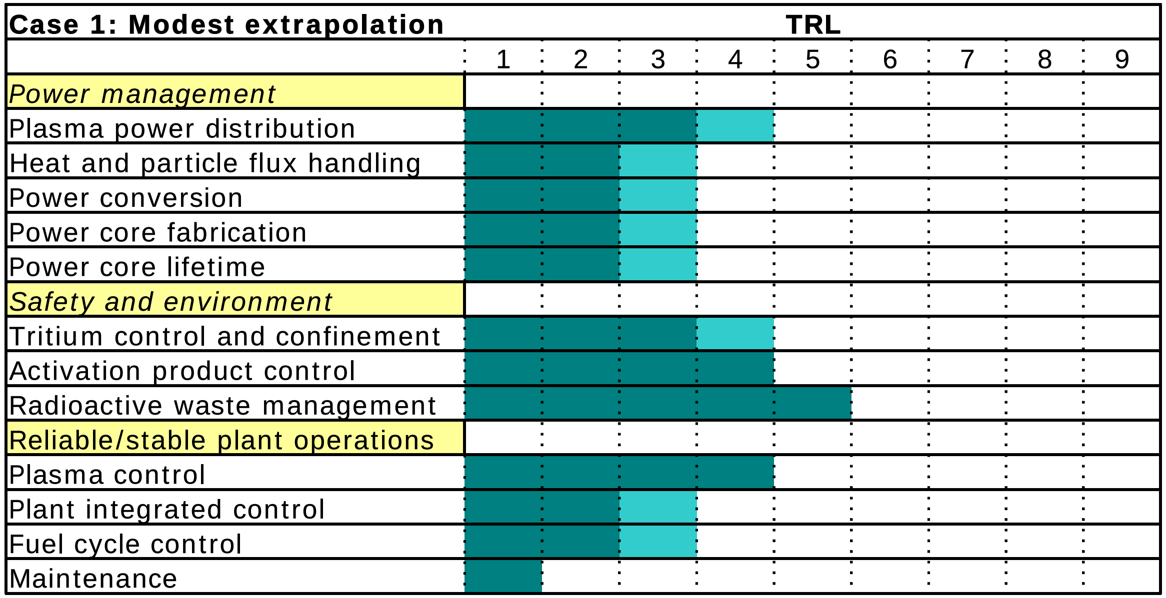
	Issue-Specific Description	Facilities
6	Integration of systems for control and handling of base level outward power flows in a high performance reactor grade plasma with schemes to moderate or ameliorate fluctuations and focused, highly energetic particle fluxes. Demonstration that fluctuations can be 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 performance 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.	

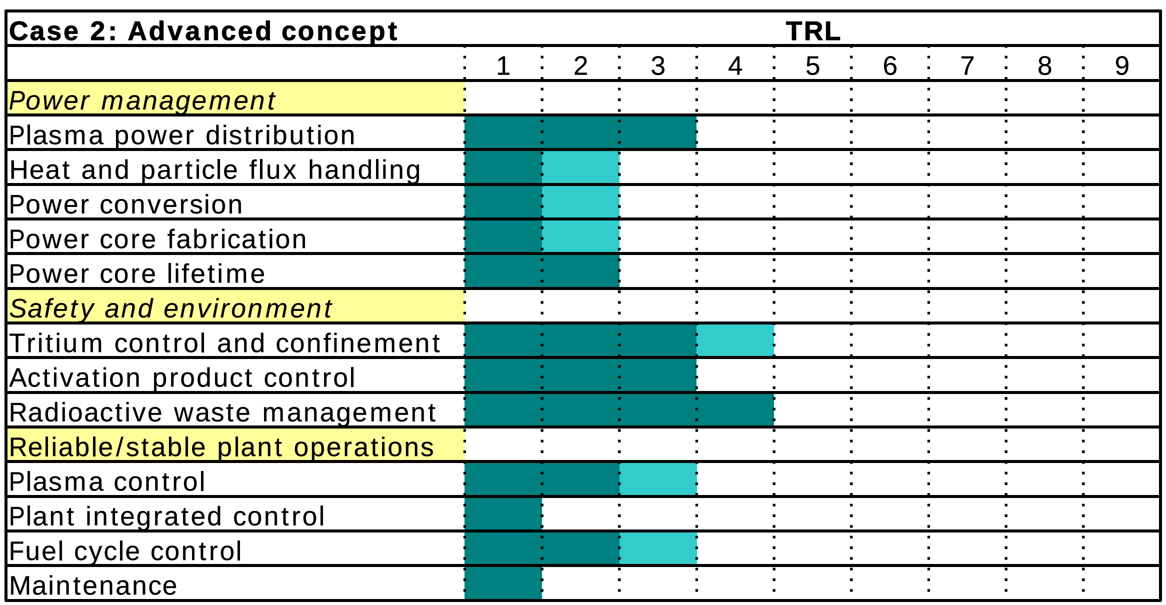
4) Evaluation of readiness requires identification of the end goal – "ready for what?"

- **For the sake of illustration, we considered two Demo's based on near-term and long-term ARIES power plant design concepts**

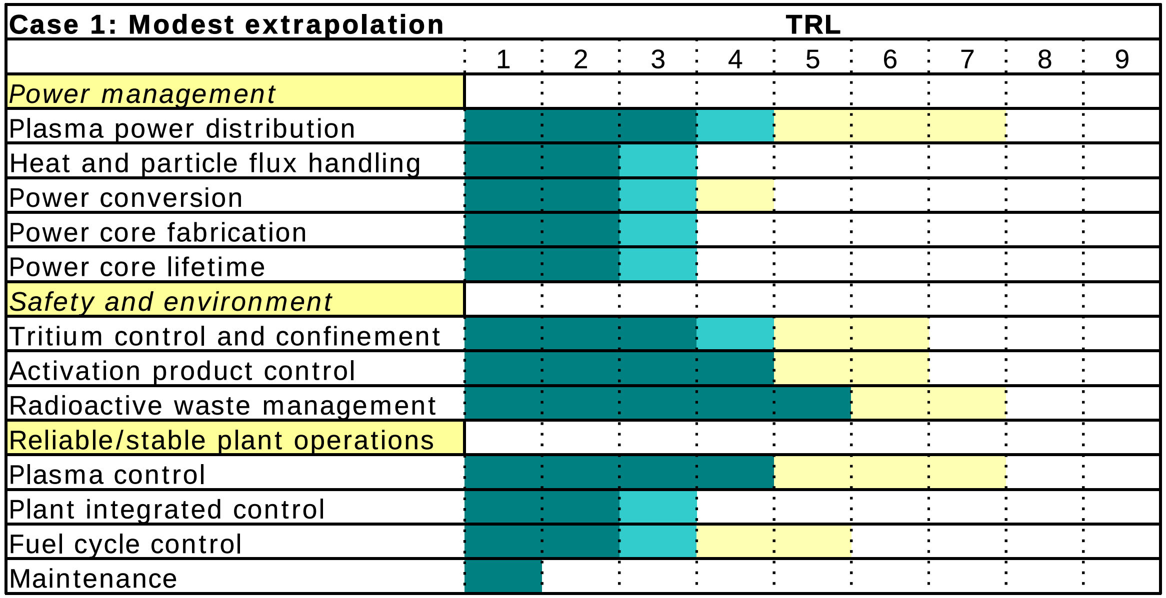
"Modest Extrapolation"	"Advanced Concept"
ARIES-RS type of plasma: β=5%, B_T=8, I_p=11, I_{bs}>90%, κ=1.7	ARIES-AT type of plasma: β=9%, B_T=5.6, I_p=13, I_{bs}=88%, κ=2.2
He-cooled W divertor	PbLi-cooled SiC_f/SiC divertor
Dual-cooled He/PbLi/FS blanket	PbLi-cooled SiC_f/SiC
700˚C coolant, Brayton cycle	1100˚C coolant, Brayton cycle
3-4 FPY in-vessel components	4-5 FPY in-vessel components
Low-temperature superconductors	High-temperature superconductors
Conventional automated fabrication	Advanced fabrication 4x cheaper
Waste 2x less than ITER	Waste 3x less than ITER
Human operators, A=70%	Autonomous operation, A=90%

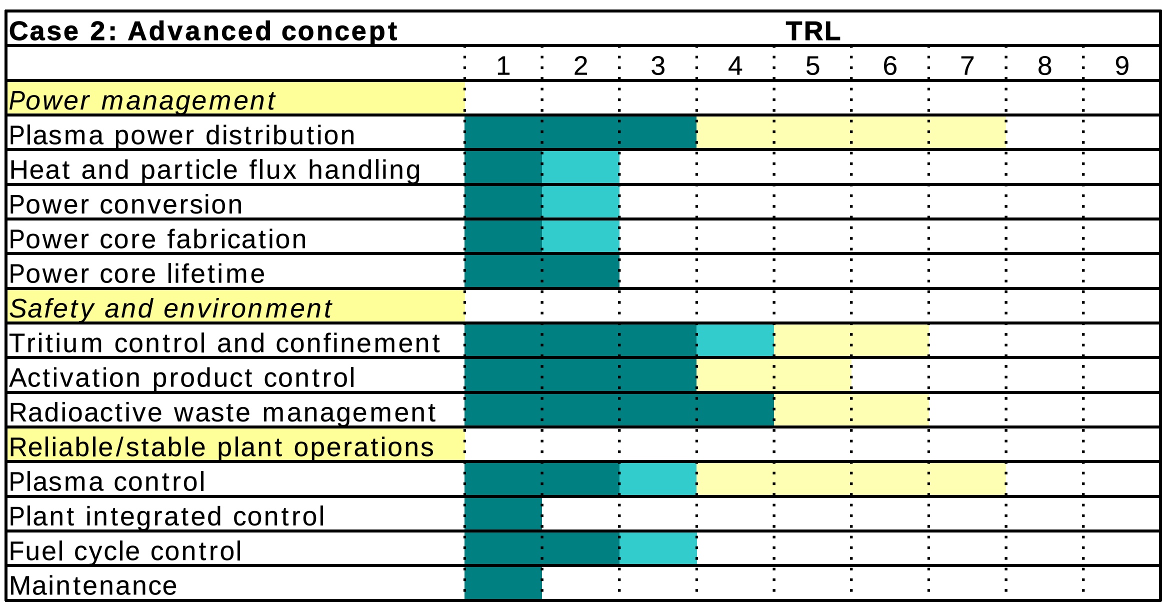
5) The current status was evaluated





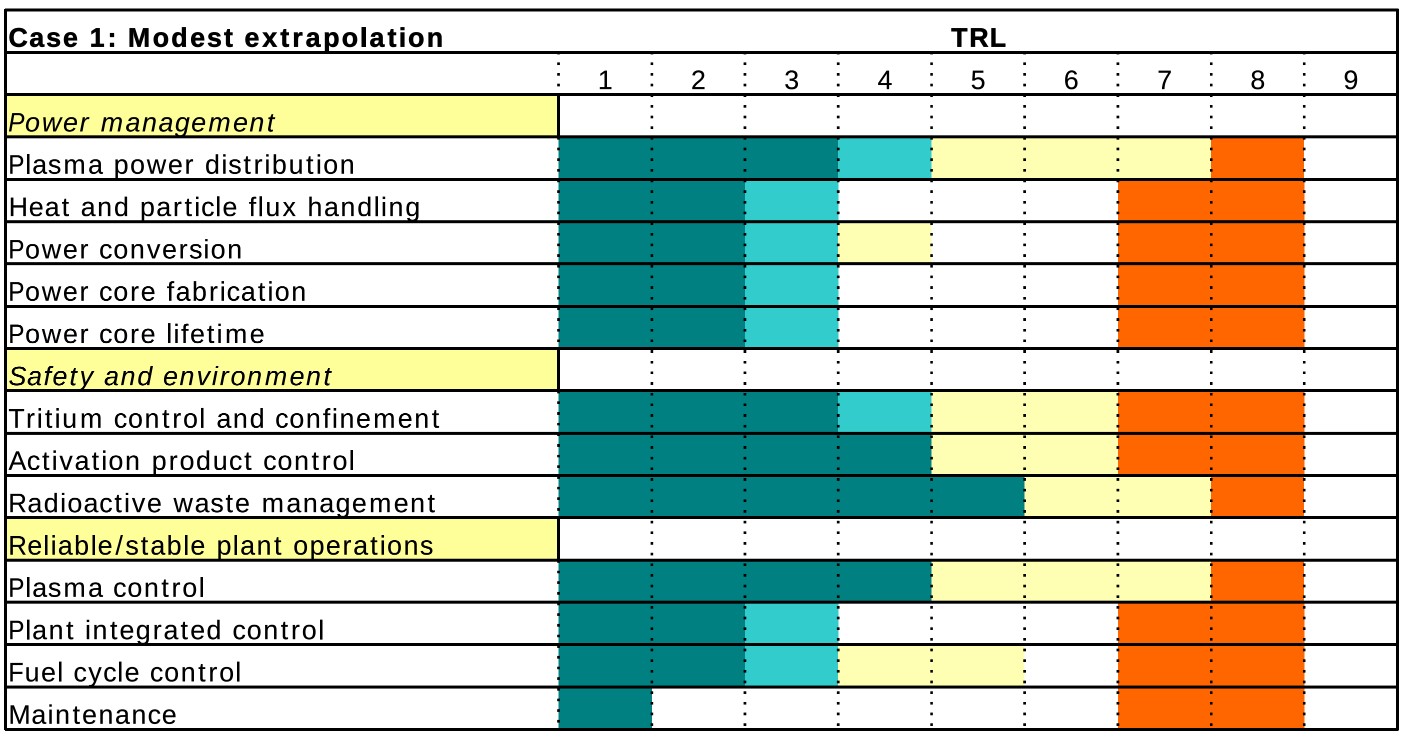
ITER contributes in some areas, not others





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

- **An engineering test facility such as CTF is required before a Demo can be considered**
- **A range of nuclear and non-nuclear facilities are required to advance from the current status to TRL6, prior to CTF**



Discussion and Action Items

1. …
2. …
3. …

Backup

Reasons for an issue-oriented approach

1. **Component issues and R&D were described in more detail previously. We aren't likely to do better.**
2. **It breaks through the unproductive division between plasma and non-plasma interest groups.**
3. **It avoids problems caused by the lack of US reference designs.**
4. **It maintains a strong connection to the end user and other stakeholders (who don't know or care about the fine design details).**