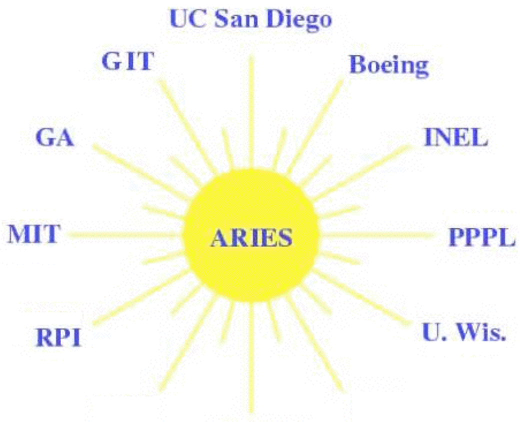
ARIES Issues and R&D Needs
– Technology Readiness for Fusion Energy –



M. S. Tillack

UC San Diego

ARIES Project Meeting

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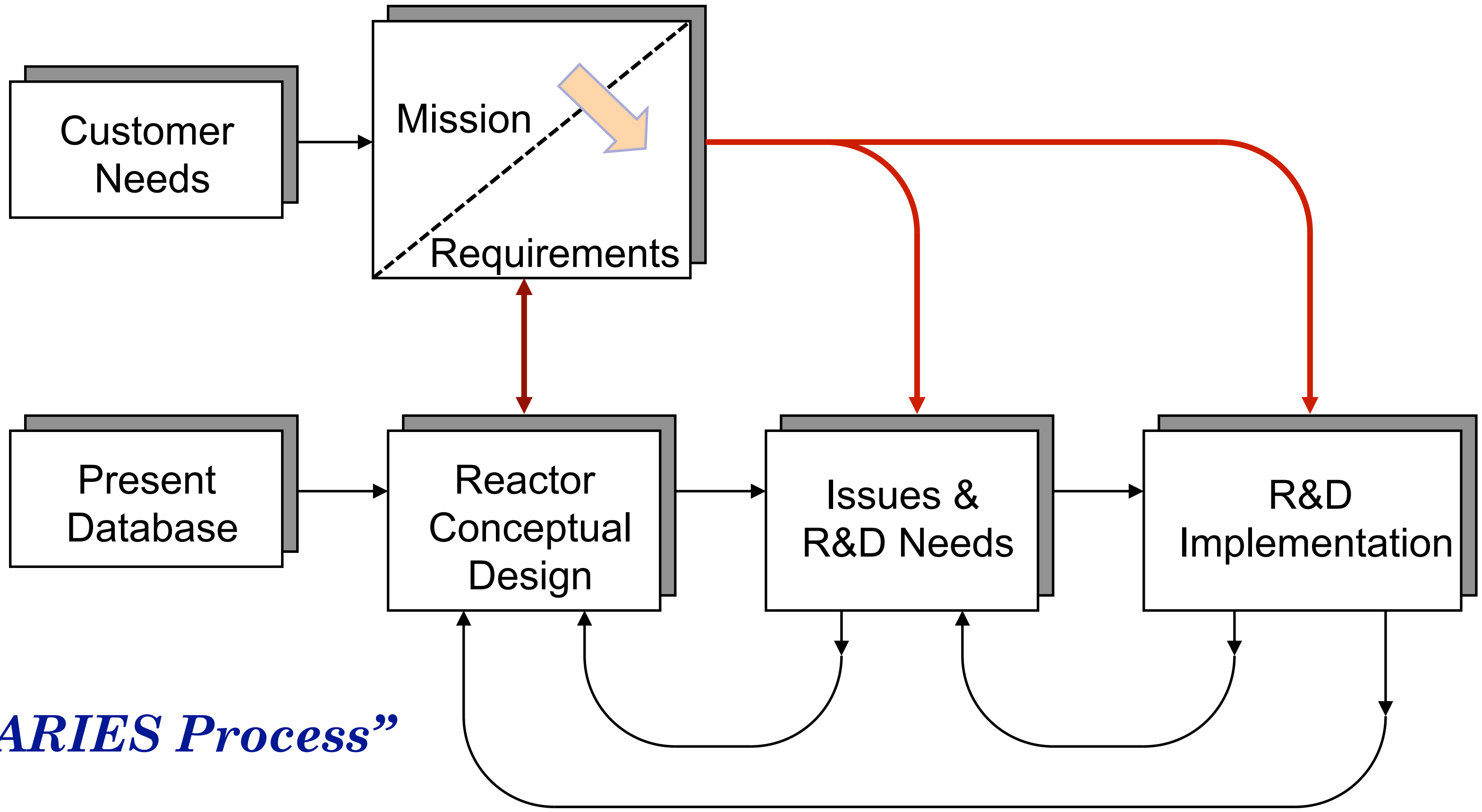
Center for Energy Research

The goal of the TWG's is to translate advisory committee recommendations into design requirements and an R&D plan (April/07)

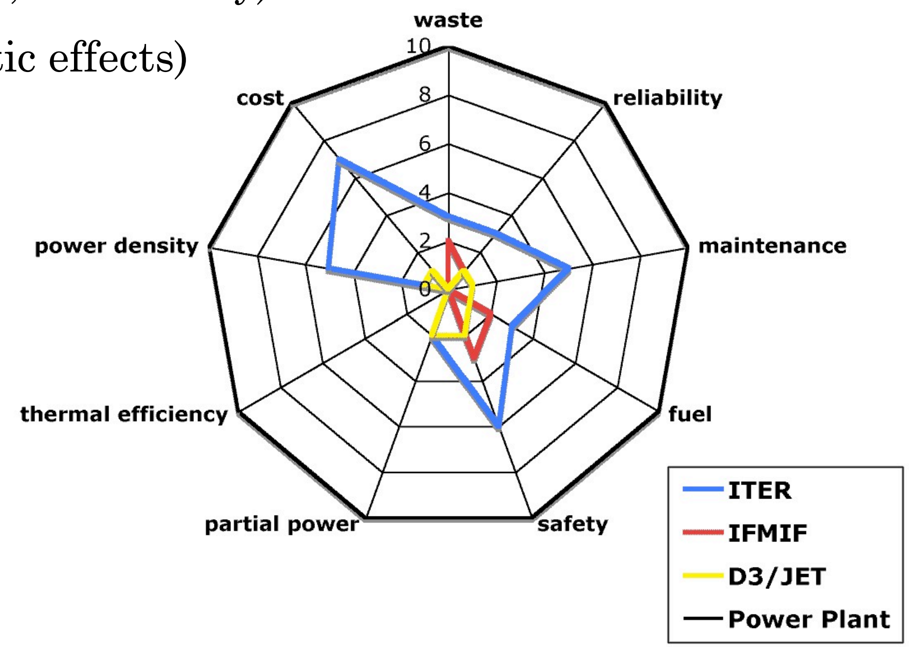


The "ARIES Process"

Metrics are a key element of R&D planning

A parameter-based approach was explored (June/07):

- ***For power conversion***
  - Operating temperature (relates to efficiency, ability to produce H_2)
  - Power flow control, uncertainty in power flows, peaking factors
  - Heat flux and total heat (prototypical gradients, scale)
  - Operating lifetime (relates to reliability, availability)
  - Degree of system integration (synergistic effects)
- ***For tritium***
  - Breeding ratio, uncertainty in TBR
  - Inventory, uncertainty in inventory
  - Leakage from plant under normal, off-normal conditions
- ***For operations***
  - Disruption frequency



Instead, we adopted “readiness levels” as the basis for our evaluation methodology (Dec/07)

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.

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"*

We defined a 5-step approach to apply the TRL methodology to fusion energy

1. Use criteria from utility advisory committee (*not components or program elements*) to derive 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.
4. Define the end goal (design or facility) 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 attractive 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 handling
3. High temperature operation and power conversion
4. Power core fabrication
5. Power core lifetime

B. Safety and environmental attractiveness

6. Tritium control and containment
7. Activation product control and containment
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: #1 Plasma power

	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.	

3) Example TRL table: #2 PMI

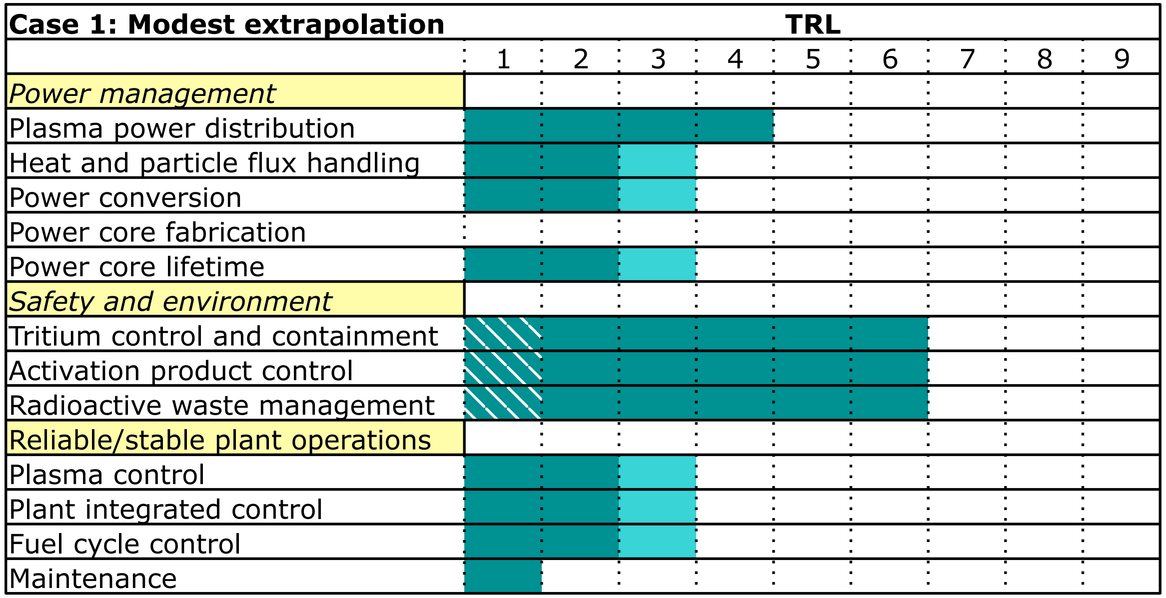
	Issue-Specific Description	Facilities
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized.	
3	Data from coupon-scale 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 PISCES-like
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, 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

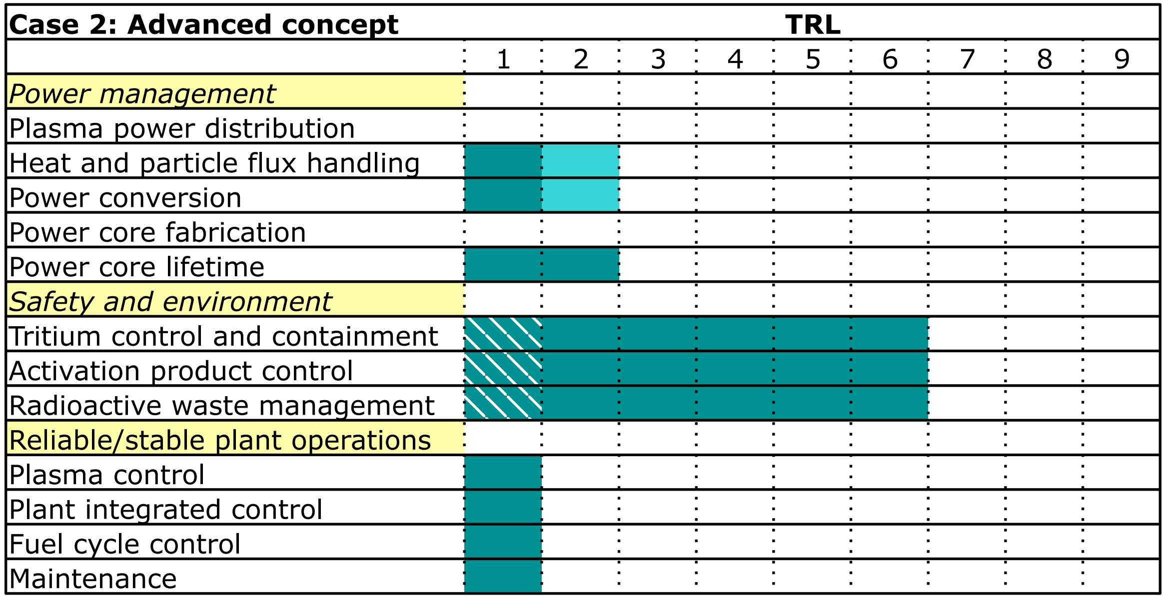
4) Evaluation of readiness requires identification of the end goal – "ready for what?"

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

"Conservative"	"Aggressive"
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 10x less than ITER	Waste 4x less than conservative
Human operators, A=70%	Autonomous operation, A=90%

5) An initial evaluation was performed





FESAC issues and themes are different from ARIES: problem or opportunity?

A. Creating predictable high-performance steady-state plasmas

1. Measurement ("for the scientific mission")
2. Integration of high-performance, steady-state, burning plasmas
3. Validated theory and predictive modeling
4. Control
5. Off-normal plasma events
6. Plasma modification by auxiliary systems
7. Magnets

B. Taming the Plasma Material Interface

8. Plasma-wall interactions
9. Plasma facing components
10. RF antennas, launching structures & other internal components

C. Harnessing fusion power

11. Fusion fuel cycle
12. Power extraction
13. Materials science in the fusion environment
14. Safety
15. Reliability, availability, maintainability, inspectability

FESAC issues can be correlated to ARIES

1. Measurement ("for the scientific mission")
2. Integration of burning plasmas
3. Validated theory and predictive modeling
4. Control
5. Off-normal plasma events
6. Plasma modification by auxiliary systems
7. Magnets

8. Plasma-wall interactions
9. Plasma facing components
10. RF antennas, launchers, *etc.*

14. Fusion fuel cycle
15. Power extraction
16. Materials science ?
17. Safety
18. RAMI

1. Plasma power distribution
2. Heat and particle flux handling
3. High temp. power conversion
4. Power core fabrication
5. Power core lifetime

6. Tritium control and containment
7. Activation products
8. Radioactive waste

9. Plasma control
10. Plant integrated control
11. Fuel cycle control
12. Maintenance

We can envision a direct pathway from the roll-forward to roll-back approaches

Conclusions

- Fusion energy issues were described using our “criteria for practical fusion power systems”.
- A methodology for evaluating progress, using TRL’s, was assessed and found to be a viable tool.
- Evaluations of technology readiness were made for modest and aggressive power plant demos.
- Facility and pathway assessments have not yet been accomplished
- Roll-forward and roll-back approaches were shown to be compatible

Science program

Roll forward “community” planning

this gap can be bridged

ARIES activities

Roll backward R&D planning

Visions for attractive power plants