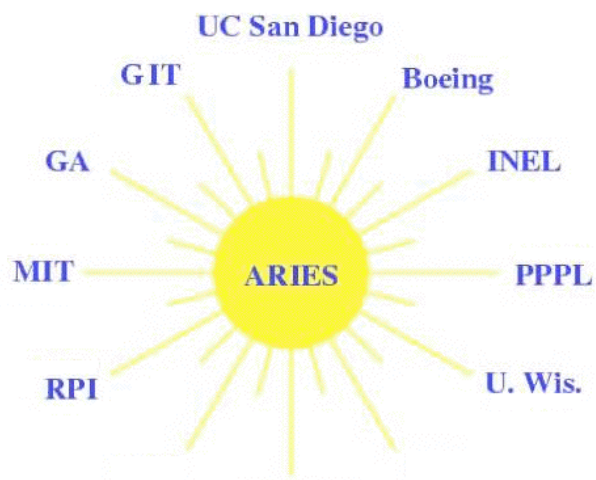
An evaluation of fusion energy R&D gaps using Technology Readiness Levels

M. S. Tillack and the ARIES Team



Fusion Power Associates Annual Meeting
Livermore, CA
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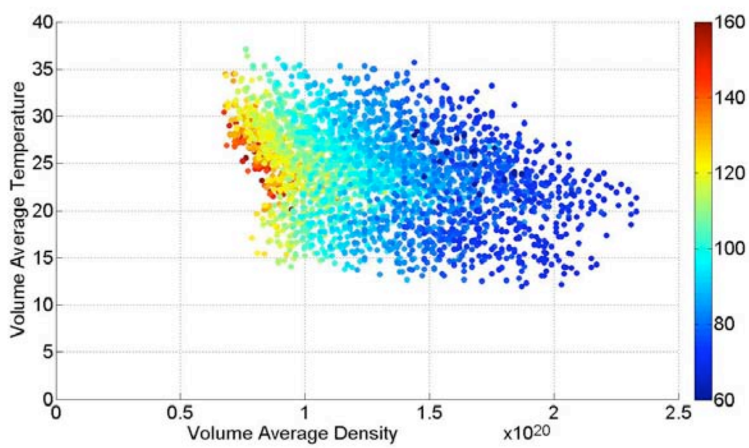
The "ARIES Pathways" study is developing quantitative measures to evaluate fusion development options



- A new systems-based approach to establish the importance of various power plant parameters and define metrics for prioritization.

- R&D metrics to evaluate the status of the field and progress along the development path.

	Readiness level								
	1	2	3	4	5	6	7	8	9
Issues, components or systems encompassing the key challenges									
Item 1									
Item 2									
Item 3									
Etc.									

The topic of fusion energy <u>R&D gaps</u> is receiving increased attention

- *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 develop a long-range strategic plan defining "priorities, gaps and opportunities"
- 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 and utilized **outside** of the fusion community.
  - Initial efforts to develop and apply this technology assessment approach to fusion energy are reported here.

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

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.

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

Detailed guidance on application of TRL's is available

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

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.

Readiness levels can identify R&D gaps between the present status and any level of achievement

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Etc.									

Fusion proof of principle

Demo

Power plant

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

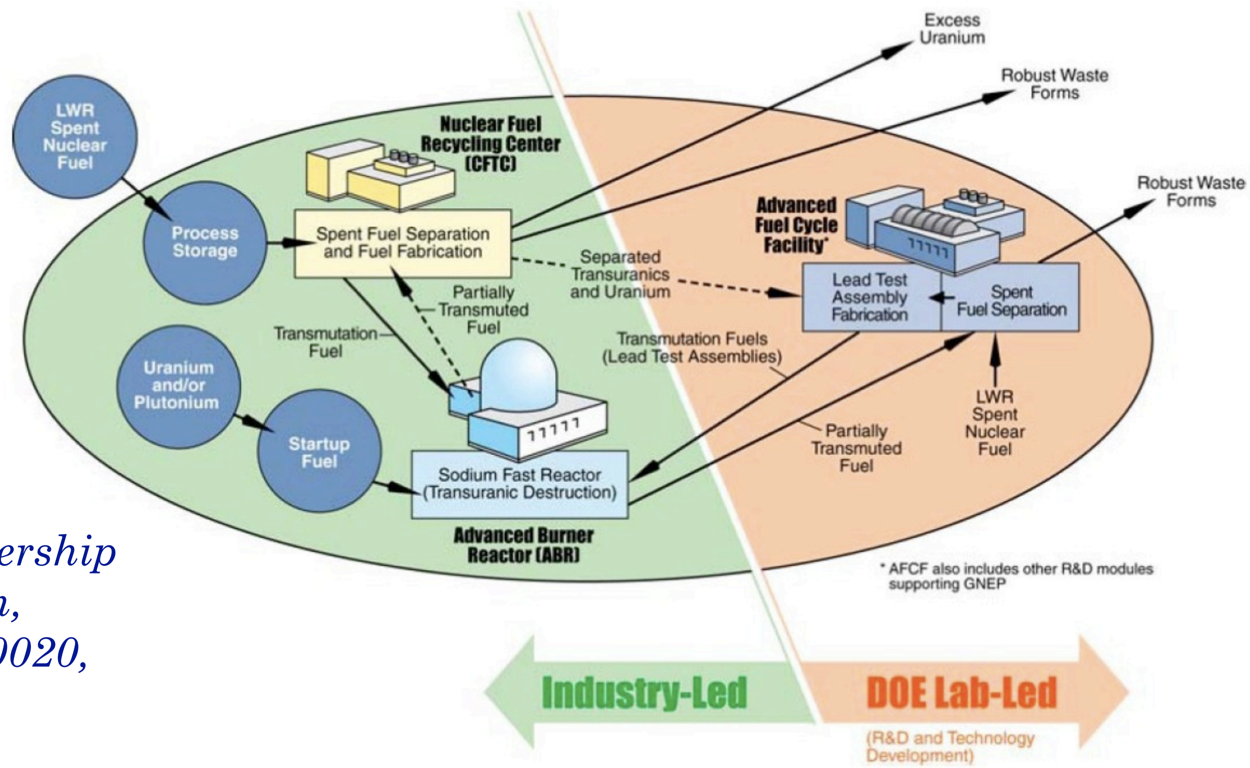
- ***"Provide a common language*** *among the technology developers, engineers who will adopt/use the technology, and other stakeholders;*
- ***Improve stakeholder communication*** *regarding technology development – a by-product of the discussion among stakeholders that is needed to negotiate a TRL 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"*

DOD, NASA, and other agencies use TRL's

*e.g., GNEP 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	Concept Development	Calculated mass-balance flowsheet developed; scoping experiments on process options completed successfully with simulated LWR spent fuel; preliminary selection of process equipment.
3	Concept Development	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	Proof of Principle	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	Proof of Principle	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	Proof of Performance	Demonstration of integrated system with full-scale equipment and actual LWR spent fuel completed successfully; short (~1 month) periods of sustained operation.
9	Proof of Performance	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.**

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

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

Example TRL table: Heat & particle flux handling

	Issue-Specific Description	Program Elements
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical parameters characterized.	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: *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 test facility with prototypical plasma particle and 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

The level of readiness depends on the design concept

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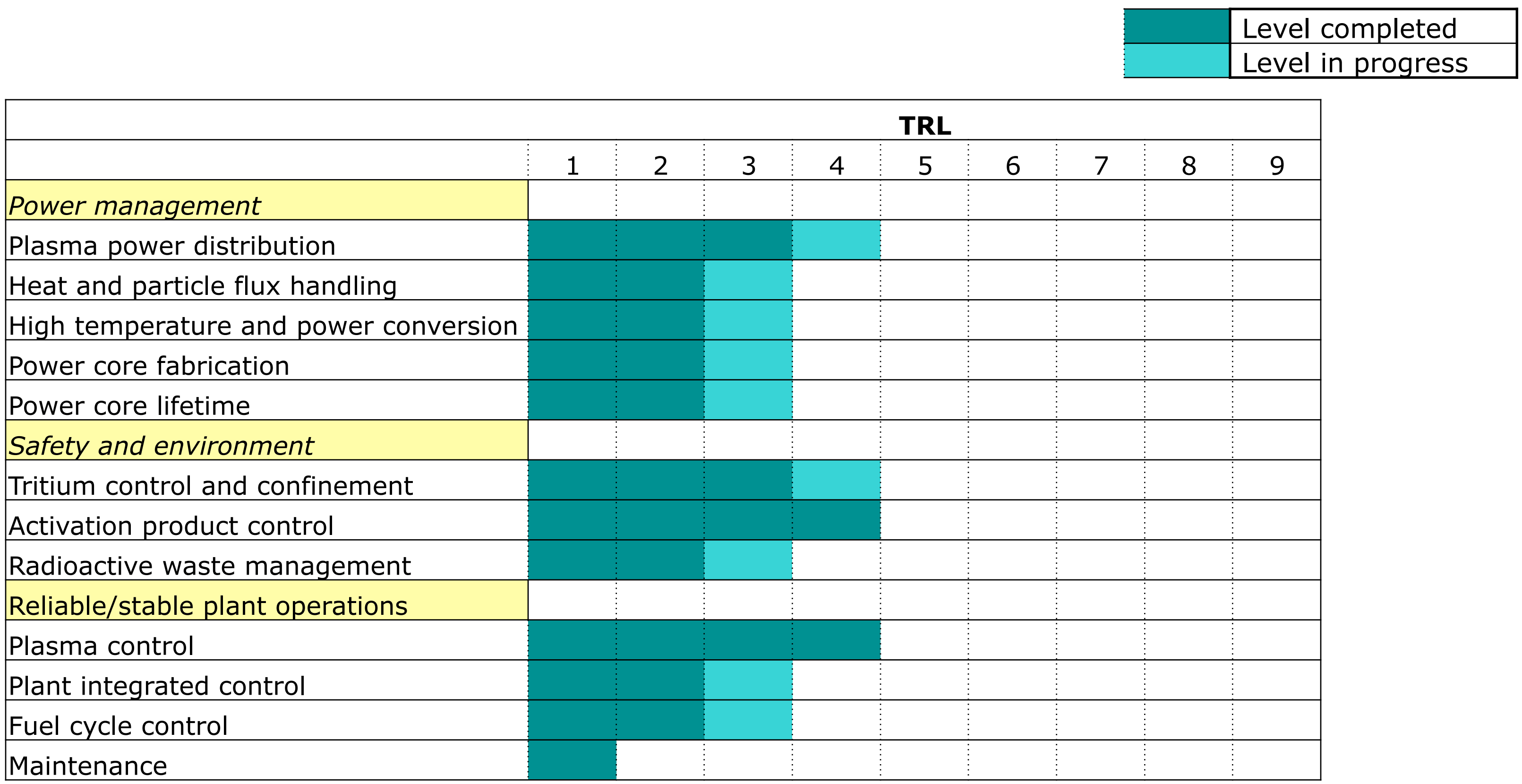
Power plant relevant high-temperature gas-cooled PFC's

Low-temperature water-cooled PFC's

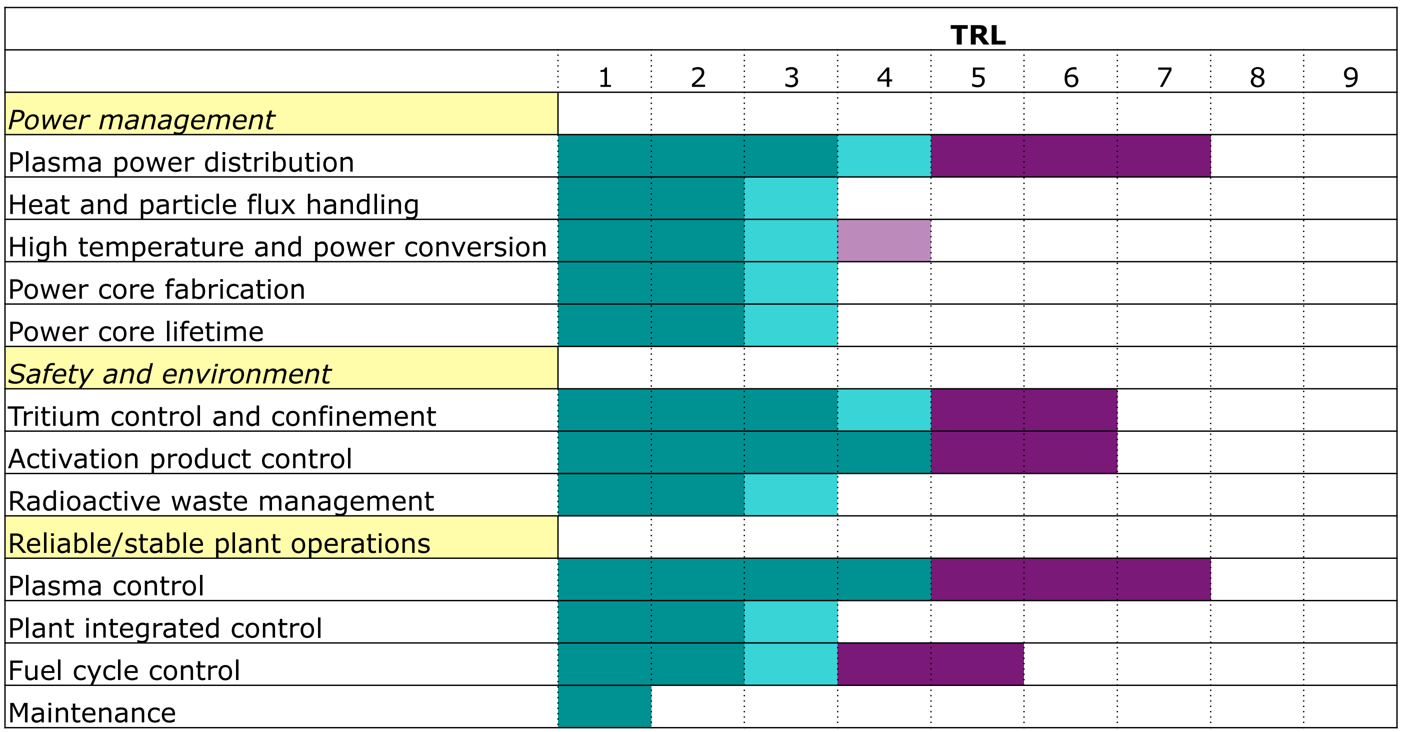
The current status was evaluated for a reference ARIES power plant

- **For the sake of illustration, we considered a Demo based on the ARIES 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



The ITER program contributes in some areas, very little in others

- **ITER promotes to level 6 issues related to plasma and safety**
- **ITER helps incrementally with some issues, such as blankets, PMI, fuel cycle**
- **The absence of reactor-relevant technologies severely limits its contribution in several areas**



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**

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Activation product control									
Radioactive waste management									
Reliable/stable plant operations									
Plasma control									
Plant integrated control									
Fuel cycle control									
Maintenance									

ICOPS/SOFE 2009

36th International Conference on Plasma Science and 23rd Symposium on Fusion Engineering

May 31 – June 5, 2009
Omni Hotel, San Diego, California USA

ICOPS 2009 SOFE
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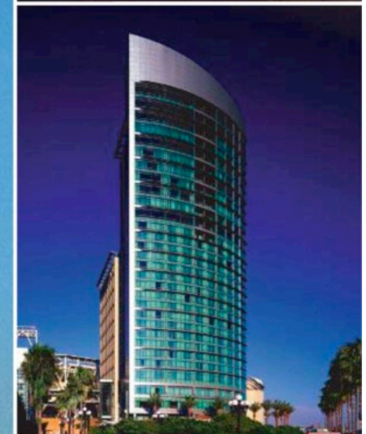

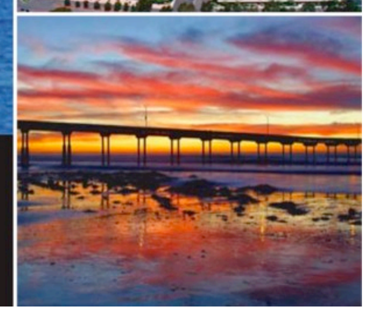

Abstract Submission	January 9, 2009
Student Travel Grant Applications	February 27, 2009
Notice of Abstract Acceptance	March 13, 2009
Hotel Booking	March 27, 2009
Advanced Registration (Reduced Fee)	May 1, 2009
Mini-Course Registration	May 1, 2009

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