AN EVALUATION OF FUSION ENERGY R&D GAPS USING TECHNOLOGY READINESS LEVELS

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The ARIES Team currently is engaged in an effort called the "ARIES Pathways Study". The goals of this study are to evaluate remaining R&D needs toward practical fusion energy and to identify and evaluate possible "next step" devices to bridge the gap between ITER and an attractive power plant. In order to evaluate our current state of readiness and remaining R&D needs, we adopted a methodology called "Technology Readiness Levels". We defined a quantitative set of readiness levels that encompass the major technology challenges for fusion energy development, and have applied them to evaluate our current level of advancement and R&D needs for an advanced tokamak power plant concept based on recent ARIES designs. Results of the evaluation and recommendations for future R&D are presented.

I. INTRODUCTION

As the ITER burning plasma experiment proceeds into its construction and operation phases, magnetic fusion energy research is expected to enter a new era. The physics feasibility of fusion is likely to be demonstrated in ITER, forcing the question "what else is needed to demonstrate the credibility of fusion as an energy source?" Most countries involved in fusion research around the world are struggling with this question and are undertaking a variety of planning activities.

In order to evaluate our current state of readiness and remaining R&D needs, we have adopted a methodology called "Technology Readiness Levels" (TRL's). This methodology has become increasingly utilized in large government-sponsored R&D programs in NASA, DOE and DOD. TRL's provide an objective, integrated, self-consistent and design-independent procedure that can be understood and used by the full range of stakeholders in fusion, including governments, R&D providers and private sector developers and end-users.

We have defined a detailed set of readiness levels that encompass the major technology challenges for fusion energy development, and have applied them to evaluate our current level of advancement and R&D needs for a tokamak power plant concept based on recent ARIES designs. Selected results of the evaluation are presented and recommendations given for future R&D.

II. EVALUATION METHODOLOGY

II.A. The Technology Readiness Level Method

Technology Readiness Levels provide a systematic and objective measure of the maturity of a particular technology. They were developed originally by NASA in the 1980's.[1] With minor modification, they can be used to express the readiness level of other technology projects.

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 science and technology, or "*laboratory*" environment almost invariably leads to cost and schedule over-runs in acquisition weapons system programs. 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 in July 2001 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.

The defense acquisition definition of TRL's includes nine stages; the initial stage simply defines the basic scientific and technological principles involved in producing the final product, and the final 9th stage represents a fully functioning final product:[1]

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 at this stage. 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 into a subsystem or representative of final products.
4. Component and/or breadboard validation in laboratory environment. Basic 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. Basic technology 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. This 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 such as an aircraft, vehicle, or space. Examples include testing a prototype in a test bed aircraft.
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 weapon system 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.

Progress along the TRL pathway is characterized by increasing levels of technology development and system integration, as well as increasing fidelity of the simulation or testing environment. The early phases can be performed under laboratory conditions in individual system elements. The intermediate phases increase both the relevance of the environment as well as the level of system integration. The final phase requires actual system demonstration in an operational environment. Note, "system integration" is not considered a separate issue in this formalism; rather, each and every technology issue must progress through TRL's requiring increasing levels of system integration. In the case of fusion energy, the final goal represented by a TRL of 9 is interpreted to be a fully-functioning demonstration power plant.

Clearly, the definition of key terms such as "laboratory environment", "relevant environment", "operational environment", "component" and "system" must be defined in order for this methodology to be applied sensibly. These terms must be articulated in the explanation of TRL's for each issue.

In March 2007 the GAO recommended to the Department of Energy the adoption of a consistent approach for assessing technology readiness.[3] Subsequently, the GNEP (Global Nuclear Energy Partnership) program produced a Technology Development Plan using this technique.[4] Their assessment considered five key issues requiring focused research and development:

- LWR spent fuel processing
- Waste form development
- Fast reactor spent fuel processing
- Fuel fabrication
- Fuel performance

The use of TRL's is expected to continue for large DOE-funded programs such as fusion energy. Therefore, we have adopted them as the basis for our evaluation.

II.B. Description of Fusion Energy Issues

There are many possible ways to describe the technical issues for fusion energy. We chose to derive our issues based on the criteria for practical fusion energy developed by the ARIES Utility Advisory Committee and EPRI Fusion Working Group in 1994 (see Table I).[5] In order to succeed, fusion must be economically competitive, gain public acceptance, and operate in a reliable and stable manner comparable to existing nuclear and non-nuclear sources of electricity. By using these criteria as a starting point, we believe fusion will maximize the probability that the technologies developed will lead to commercialization of a viable energy source.

Table I. Criteria for practical fusion power systems[5]

1.	**Have an economically competitive life-cycle cost of electricity**
2.	**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
3.	**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

From these top-level goals, we derived technical issues (listed in Table II) that correlate to specific features of a fusion energy source. Economic competitiveness relates to the ability to produce, control and extract energy from fusion reactions, including affordable component fabrication and adequate operating lifetime of the power core. Safety and environmental attractiveness is subdivided into tritium, activation products and waste management. Plant operation is divided into the issues of controlling the plasma, operating the plant, managing the tritium fuel cycle and maintaining the plant.

Table II. Issues for Commercial Fusion Energy

POWER MANAGEMENT FOR ECONOMIC FUSION ENERGY	
1.	Plasma power distribution
2.	Heat and particle flux handling (PFC's)
3.	High temperature operation and power conversion
4.	Power core fabrication
5.	Power core lifetime
SAFETY & ENVIRONMENTAL ATTRACTIVENESS	
6.	Tritium control and confinement
7.	Activation product control and confinement
8.	Radioactive waste management
RELIABLE AND STABLE PLANT OPERATIONS	
9.	Plasma control
10.	Plant integrated control
11.	Fuel cycle control
12.	Maintenance

Our approach to defining the issues and the methodology for evaluating progress seeks to be independent of specific design concepts, to the extent that is possible. Different design concepts approach the challenges of economic fusion energy production in varying ways, and therefore will exhibit different levels of maturity and different degrees of dependence on future progress. Our near-term intent in undertaking this exercise was to evaluate the "mainline" tokamak research program, under the assumption that ITER will be constructed, will operate and play a major role in the development path for fusion.

II.C. Reference concept

The application of the TRL methodology requires the specification of a particular set of technologies intended to be used in the final product. The US fusion program has not down-selected a single reference concept of a power plant; each design must be evaluated individually. More conservative approaches are likely to score higher in their technology readiness, whereas advanced, more speculative concepts are likely to score lower (less developed). TRL's do not attempt to evaluate the attractiveness of the final product, but only the level of advancement towards operational readiness.

To illustrate the usefulness of TRL's, we considered promising plant concepts from previous ARIES design studies, such as ARIES-RS,[6] ARIES-ST[7] and ARIES-AT.[8] The selection is influenced by the desired point of time a first fusion demonstration plant should go into operation, and the time scale anticipated for the development of a following commercial power plant. We chose to examine a "moderately aggressive reference concept" that appears to be sufficiently attractive to become a power plant without excessive extrapolation and R&D uncertainty. The reference concept for energy capture and conversion components uses the following:

- Helium cooled first wall and blanket structure,
- Dual coolant (lead lithium and helium) blanket,
- First wall and blanket structure fabricated with reduced activation ferritic steel,
- SiC flow channel inserts,
- Permeator tritium extraction system from PbLi,
- Helium cooled divertors based on W-alloys,
- Brayton cycle power conversion system with helium temperatures up to 800˚C.

Other aspects of the power core were defined, but are not described here due to space limitations. Additional details can be found in Ref. 9.

III. EVALUATION

Each of the issues in Table II represents a broad function of a fusion power plant, involving multiple components and interfaces. This grouping of issues naturally accounts for important system interactions. Below we describe in more detail the scope of three selected issues, define the goals for each technology readiness level, and attempt an evaluation of the current level of readiness taking into account the complete range of R&D programs throughout the world. Space limitations prevent us from presenting this evaluation for every issue in Table II. We selected as examples one issue from each of the three themes.

III.A. Power Management

III.A.1. Introduction

In order to realize the promise of fusion energy, we must learn to harness the energy from burning plasma in a reliable and affordable way. Power management includes all of the processes and systems involved from the release of energy by fusion reactions up to the delivery of electric power to the grid. It involves controlling the distribution of plasma emissions to in-vessel components, developing and maturing a variety of nuclear components that can reliably and safely withstand the severe environment created by a burning plasma for long operational lifetime, and integrating plant systems that operate at high efficiency, hence high temperature, using materials that in many cases do not have an established industrial basis for reliable operation in this environment.

For each issue, we have developed a preliminary set of readiness levels. Due to space limitations, we are unable to present all of the tables here. For the sake of illustration, Table III illustrates one of our TRL level descriptions for plasma power distribution. The full set of tables can be found in Ref. 9.

III.A.2. TRL's and Current State of Knowledge for Plasma Power Distribution

Assuming a diverted high confinement mode tokamak burning plasma, a solution for controlling the ratio of volume radiation versus localized heat and particle fluxes exists for present tokamak experiments in the "radiative detached divertor" configuration. Implicit in formulating the TRL table, it is recognized that the scaling of this configuration to ITER and then DEMO is highly problematical. There are three major sources to this uncertainty. Projections of the power flux to the plasma edge suggest the operating window may be too small or non-existent for obtaining proper detachment of the radiative region. The volume needed for the detached region to dissipate sufficient power in volume radiation may be so large that it destroys the core plasma performance.

Second, some of the power flux out of the plasma consists of so-called "runaway electrons" accelerated by local electric fields in the plasma and amplified by plasma processes. The scaling of the amplification factor in the number of accelerated electrons is presently uncertain. Current experiments generate relatively small runaway electron fluxes, but projections obtained by scaling between smaller and larger tokamaks suggest much larger amplification factors for ITER and even more so for a Demo. The resultant, highly directed, high intensity electron beams exiting the plasma can then cause serious damage to the vessel and surrounding structures.

A third source of uncertainty in extrapolating the present technology for controlling the power flux is the existence of fluctuations in the power flux from edge localized modes and internal sawtooth events in the core plasma. Current projections from present experiments suggest ITER may have little tolerance for fluctuations above the steady state power flux. This will be even more important for Demo. Experimental techniques aimed at controlling the level of fluctuations have some success but their scaling and application to ITER and Demo is also questionable. For example, the most promising technique at present is to use nonaxisymmetric coils inside the vacuum vessel. On this basis, the "radiative detached divertor" configuration warrants a TRL value of 4 with the current state of knowledge (see Table III).

Table III. TRL's for plasma power distribution

	Issue-Specific Definition
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, 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 particle 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.
5	Scale-up of techniques and technologies to realistic fusion conditions and improvements in modeling to enable a more realistic estimate of the uncertainties.
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.
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.
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.
9	Demonstration of the integrated power handling system in a steady state burning plasma configuration for lifetime conditions.

III.B. Safety and Environmental Attractiveness

III.B.1. Introduction

A major driver for developing commercial fusion power is the expectation that it will exhibit attractive safety and environmental characteristics. Although fusion power will require the handling of substantial amounts of tritium and the generation of significant quantities of radioactive by-products, power plant studies suggest that during normal operation the environmental impact associated with releases from the tritium and activation product inventories can be minimized by system design and by choice of low-activation materials. Moreover, the energy sources that might result in the release of these radioactive inventories during off-normal events can also be substantially mitigated by design and material choice. Three of the high-level criteria for attractive fusion power relate directly to safety and environmental features: (1) no need for an evacuation plan; (2) no generation of high-level waste; and (3) ease of licensing. The rationale for these criteria is described in the Fusion Safety Standard.[10]

Power plant studies indicate that the plant tritium inventory will be significant, ~5 kg, with the majority being in the blanket, reprocessing system, and fuel storage system. Confinement during normal operation and off-normal events has received emphasis in these studies. Cadwallader and Petti[11] calculated that elevated airborne releases of up to 8 g-HTO/year will meet EPA routine release limits; however, the EPA limits tritium in liquid effluent releases to 0.02 microCuries per liter. The general approach by ITER and other design studies has been to limit water-borne tritium releases to about 10 Ci/day to meet the EPA water quality limit. The R&D program must demonstrate that such an operational requirement can be achieved at acceptable cost. During off-normal events, the goal of the power plant studies has been to limit airborne tritium release to ~10 g, which will satisfy public exposure limits. R&D must demonstrate that such a release level is achievable at reasonable cost.

While power plant studies differ with regard to the details of the activation products produced (depending on the choice of materials), it is clear that activation levels will be substantial, in the billions of Curies. Although leakage during normal operation could present a local maintenance issue, there do not appear to be any associated public health issues. Therefore, studies have emphasized confinement of activation products during off-normal events. Our studies have focused on minimizing energy sources that could mobilize and release significant amounts of radioactive material. The R&D program must demonstrate that the environmental and safety goals associated with the activation products can be achieved at economically acceptable costs.

Based on the results of power plant studies, management of radioactive wastes from a fusion power presents new issues that are not already being addressed in the fission power industry.[12] These issues include sizable components, tritium containing radwaste, high recycling doses, fusion-specific radioisotopes, and large volume of radwaste. Moreover, fusion studies suggest that all wastes can be limited to Class A and C wastes (avoiding high-level wastes) and that all materials lend themselves to recycling and clearance after reasonable cooling times.[12] The avoidance of wastes higher than Class C and the possibility of material recycle and clearance must be demonstrated by the R&D program.

III.B.2. TRL's and Current State of Knowledge for Tritium Control and Containment

For the sake of illustration, Table IV shows our TRL level descriptions for tritium control and confinement. Relevant experience exists from the fission industry and weapons programs. In addition, the Tritium Systems Test Assembly (TSTA) at LANL demonstrated that tritium could be purified and handled safely. In spite of the significant progress on tritium control, two factors led us to evaluate the current achieved TRL as 3 (with ongoing efforts at TRL4). First, the quantity of tritium handled to date in fusion experiments is rather limited. Second, until components required for tritium handling from breeder materials are included in the complete tritium processing cycle, the TRL for tritium control and confinement is inherently limited to the developmental stages.

Table IV. TRL's for tritium control and confinement

	Issue-Specific Definition
1	Principles and data must be available regarding the solubility, permeation and transport of tritium in materials.
2	Models must be developed to estimate tritium release during operation (normal and off-normal).
3	Concepts and models must be successfully benchmarked against radiological release data, and measured against environmental release limits.
4	Bench-scale tests must be conducted to validate the tritium confinement predictions.
5	Large scale tests must be conducted to validate the tritium confinement predictions.
6	Full scale tests must be conducted to validate the tritium confinement predictions.
7	Prototype systems must demonstrate tritium confinement in a fusion operational environment.
8	Successful tritium confinement must be demonstrated at the required fusion scale size.
9	Successful tritium confinement must be demonstrated at the required scale size and during fusion mission operations.

III.C. Reliable, Available and Stable Plant Operations

III.C.1. Introduction

In order to properly assess the issues, metrics, and R&D needs for reliable, available, and stable plant operations, the overall goals and objectives for the future commercial electrical power plant must be established. This plant has to be competitive with our projections of what future power plants must do and it must be compatible with projected environmental and safety standards.

Three high level goals and objectives have been defined to be applicable to the entire plant, and most directly applicable to the plant operations. Indeed all components, subsystems, and systems must be designed, developed and tested to specifications that will ensure these overall goals can be met. But achieving these goals each day and year is the responsibility of plant operations.

1) The plant availability must exceed 90% for a mature fusion electricity generating power plant (probably in the 2050-2070 timeframe). Presently, the existing "Generation II" fleet of nuclear fission power plants have been increasing their average on-line time from the 60% range in the 1970's to the 90% range in the mid-2000's[13] with well-performing plants achieving over 93%. Schultz[14] stated that with proven components, design simplifications, good design margins, and lessons learned from the present fleet of reactors, the AP600/AP1000 "Generation III" advanced fission plants are expected to exceed 93% availability. More advanced reactors, such as the Global Nuclear Energy Partnership "Generation IV" plant designs, are expected to exceed 90% availability. The Electric Power Research Institute published a requirements document for advanced reactors that called for 87% availability over the plant's 60-year lifetime.[15] Therefore the fusion plant availability goal of ≥ 90% is not so much a step forward as it is maintaining the status quo so that fusion can equitably compete with other technologies for base-load electrical power generation.

2) It is recommended that the commercial fusion power plant **exceed all current safety and environmental standards.** One of the basic precepts for the development of fusion is that it has the potential to be extremely safe and have high environmental standards. Thus the expectation is that a high level of safety and environmental performance is an intrinsic fusion goal.

3) To be successful, a new fusion power plant must build upon evolutionary and revolutionary control technologies to **establish and maintain a future state of the art control system** that will be viable, effective, and easily adaptable for its operational lifetime. Due to an anticipated rapidly changing state of the art in control system technologies, the underlying control system architecture must be flexible to accommodate future updates and improvements. This adaptability would extend to all aspects of the control system including the instrumentation sets, control architecture, control algorithms, and diagnostic and executing software and hardware.

III.C.2. TRL's and Current State of Knowledge for Plasma Power Distribution

Table V shows our TRL level descriptions for plasma control. Control of plasma shape and profiles essentially requires measuring a plasma parameter or profile and appropriately modifying it. This process can be divided into four steps: (i) Identification of the required parameter value and acceptable range as defined by the reactor design process and performance requirements. (ii) Diagnosis of the current plasma state. This requires a real-time diagnostic measurement of the plasma parameters, involving a set of robust and unobtrusive instrumentation. (iii) An actuator to modify the plasma parameters and profiles. Typically this involves controlling several kinds

Table V. TRL's for plasma control

	Issue-Specific Definition
1	Development of basic concepts for diagnostics and actuators for controlling plasma shape and profiles.
2	Design of systems and hardware to diagnose profiles and systems to modify profiles in open loop in a moderate β plasma. Development of robust algorithms for translating diagnostic measurements to actuator signals.
3	Demonstration of techniques for controlled plasma shape and profiles within approximate limits in closed loop in a moderate β laboratory plasma.
4	Demonstration of controlled plasma shape and profiles within approximate limits in closed loop in a current high temperature plasma confinement experiment.
5	Self-consistent integration of multiple techniques to control each of the required plasma parameters in closed loop in a current high temperature plasma confinement experiment.
6	Scale-up of diagnostic and actuator technologies to realistic fusion conditions. Demonstration that excursions from transient phenomena can be kept to a tolerable level.
7	Demonstration of the integrated plasma shape and profile control system with control of excursions from transient phenomena in a high performance reactor grade plasma in long pulse, essentially steady state operation.
8	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration.
9	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration for lifetime conditions.

of input to the plasma to attain the desired plasma condition. (iv) An algorithm to translate the required change in the plasma profile and parameters to the actuator or actuators controlling the input to the plasma.

An assessment of the current state of knowledge was performed by subdividing the issue of plasma control into several classes of parameters to be controlled, including global parameters, plasma shape, kinetic profiles, plasma rotation, D-T ratio and impurities. The average level of current readiness in this issue was judged to be 4.

III.D. Summary

In this exercise we attempted to progress through a complete evaluation of our current state of readiness and remaining R&D needs for three of the issues identified for commercial fusion energy. We described a set of readiness levels, the requirements for achieving each level, and the current status. However, it is clear that our work represents only a starting point, and that additional effort will be required to evolve this methodology and to evaluate readiness through broader community participation. The assignment of TRL levels requires an interpretation of the precise meaning of the language in the definition of TRL's, as well as a judgment on the relevance of existing facilities and R&D programs throughout the world. As a result, there is an element of subjectivity in the assignment of TRL's.

Table VI summarizes our evaluation of the current level of readiness for the reference concept for all of our issue categories. In some cases, we provided a further breakdown on the TRL level that has been already completed and the TRL level that is underway. In general, most of the issues for commercial fusion energy applications remain in the "concept development" phase in levels 1–3. Perhaps surprisingly, even the issues of plasma power management and plasma control have achieved only TRL level of 3-4. Highly automated and very short maintenance time capability (high availability), which is a critical requirement for a power plant, is the least advanced.

In addition to our evaluation of the present-day status, we examined the expected contribution of ITER to advance each issue. 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 the primary beneficiaries of ITER are plasma control and plasma power management. The ITER fuel cycle shares many common elements with a power plant, and high-temperature operation is expected to benefit somewhat from R&D related to blanket test modules (although ITER has no power conversion system, and the coolant exit temperatures from the test blankets may be considerably lower than needed in a power plant). However, many of the technologies used in ITER are not reactor relevant, and therefore cannot be expected to advance technology readiness for a power plant. The evaluation for heat and particle flux handling assumes non-prototypic divertor operation in ITER (*i.e.* only a low temperature water-cooled divertor with copper). PMI aspects would be advanced by ITER (to perhaps 6 or 7) if a W divertor was used.

One of the topics of current interest in the US fusion energy sciences program is the determination of R&D needed to fulfill the science mission of the program. In

Table VI. Summary of evaluation of current readiness for the reference power plant concept

Technical Issue									
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	completed	completed	completed	in progress	with ITER	with ITER	with ITER		
Heat and particle flux handling	completed	completed	in progress						
High temperature & power conversion	completed	completed	in progress	with ITER					
Power core fabrication	completed	completed	in progress						
Power core lifetime	completed	completed	in progress						
Safety and environment									
Tritium control and containment	completed	completed	completed	in progress	with ITER	with ITER			
Activation product control	completed	completed	completed	completed	with ITER	with ITER			
Radioactive waste management	completed	completed	in progress						
Reliable/stable plant operations									
Plasma control	completed	completed	completed	completed	with ITER	with ITER	with ITER		
Plant integrated control	completed	completed	in progress						
Fuel cycle control	completed	completed	in progress	with ITER	with ITER				
Maintenance	completed								

Legend	
completed	(dark teal)
in progress	(light cyan)
with ITER	(hatched)

other words, what is the minimum amount of R&D needed to establish the credibility of fusion as an energy source, and to transition from a science program into an energy development program? Which new facilities will be needed for this goal? The TRL methodology provides a possible framework for quantifying this question. In a general sense, TRL6 represents a transition point from a science-based "proof of principle" program to a technology-driven development program.

Under this assumption, we asked ourselves what would it take, in addition to an assumed successful ITER, in order to achieve TRL6 for each issue. Since we expect the key feasibility questions for plasma-related issues to be largely answered by ITER, the remaining credibility questions for fusion are found primarily in the power core and plant systems.

Beyond TRL6, it is clear that additional major facilities will be needed to bridge the gap to a demonstration power plant. These facilities must advance the level of integration and prototypicality of materials and environmental conditions. The TRL methodology provides a framework for evaluating the utility of proposed facilities.

IV. CONCLUSIONS

As we move forward toward our ultimate goal of practical fusion energy, an objective methodology for evaluating and demonstrating progress could serve an important role in the US fusion energy sciences program. We believe the methodology of Technology Readiness Levels can fulfill this role. Our first attempt at developing TRL's and applying them to assess the current status of fusion energy research and future R&D needs has shown that the methodology is sufficiently adaptable to be used in the fusion program through its various stages of development, from a science-based program to a more energy-directed development program.

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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. "Global Nuclear Energy Partnership Technology Development Plan," Global Nuclear Energy Partnership Technical Integration Office Report, GNEP-TECH-TR-PP-2007-00020, July 25, 2007.
5. J. KASLOW, M. BROWN, R. HIRSCH, R. IZZO, J. MCCANN, D. MCCLOUD, B. MUSTON, A. PETERSON, Jr., S. ROSEN, T. SCHNEIDER, P. SKRGIC, and B. SNOW, "Criteria for Practical Fusion Power Systems: Report from the EPRI Fusion Panel," *Journal of Fusion Energy* **13** (2/3) 1994.
6. F. NAJMABADI and the ARIES Team, "Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study," Fusion Eng. & Des. 38 (1997) 3-25.
7. F. NAJMABADI and the ARIES Team, "Overview of the ARIES-ST Spherical Torus Power Plant Study," Fusion Engineering & Design 65, 143-164, 2003.
8. F. NAJMABADI and the ARIES Team, "The ARIES-AT advanced tokamak, advanced technology fusion power plant," Fusion Engineering and Design 80 (2006) 3–23.
9. 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.
10. "Safety of Magnetic Fusion Facilities: Requirements," DOE-STD-6002-96, US Department of Energy, Washington, DC (1996).
11. L. C. CADWALLADER and D. A. PETTI, "Safety in the Design of Three Burning Plasma Experiments," *Fusion Science and Technology*, **44** (2003) 388-392.
12. L. EL-GUEBALY, "Evaluation of Disposal, Recycling, and Clearance Scenarios for Managing ARIES Radwaste after Plant Decommissioning," *Nuclear Fusion* **47** (2007) 485-488.
13. E. M. BLAKE, "U.S. capacity factors: Leveling off at last," *Nuclear News* **49** (May 2006) 26-31.
14. T. L. SCHULTZ, "Westinghouse AP1000 advanced passive plant" *Nuclear Engineering and Design*, **236** (2006) 1547-1557.
15. *Advanced Light Water Reactor Utility Requirements Document*, EPRI NP-6780 Volume 1, Electric Power Research Institute, Palo Alto, CA (1990).