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Issues and R&D needs for commercial fusion energy

An interim report of the ARIES technical working groups

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Center for Energy Research
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La Jolla, CA 92093-0417

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M. S. Tillack[1], D. Steiner[2], L. M. Waganer[3], S. Malang[4],
F, Najmabadi[1], L. C. Cadwallader[5], L. A. El-Guebaly[6], R. J. Peipert Jr[7],
A. R. Raffray[1], J. P. Sharpe[5], A. D. Turnbull[8], T. L. Weaver[7],
and the ARIES Team*

[1] UC San Diego
[2] Rensselaer Polytechnic Institute
[3] Consultant for The Boeing Company
[4] FNT Consulting
[5] Idaho National Laboratory
[6] UW-Madison
[7] The Boeing Company
[8] General Atomics

* Institutions involved in the ARIES Team include University of California San Diego, The Boeing Company, Georgia Institute of Technology, General Atomics, Idaho National Engineering Laboratory, Massachusetts Institute of Technology, Princeton Plasma Physics Laboratory, Rensselaer Polytechnic Institute, and the University of Wisconsin, Madison.

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1. Introduction

The ARIES Team currently is engaged in a study of pathways to commercial fusion energy, including characterization of facilities and R&D needs from the present time to a demonstration power plant. The goal of this activity is to provide guidance to the fusion energy sciences community based on industry requirements for the development of a new energy technology, including a methodology for evaluating the benefits of specific R&D proposals. The intended audience of this document includes decision makers from government and the fusion community, as well as scientists and designers engaged in the more detailed aspects of R&D definition and execution. It is not our purpose to advocate specific design concepts or R&D proposals, but rather to characterize the challenges ahead of us on the pathway to practical fusion energy and to establish a rigorous methodology for evaluating progress toward that goal.

We created three "Technical Working Groups" to provide a sound technical basis for the evaluation of issues and R&D needs. The groups are loosely based on the criteria for practical fusion energy defined by the ARIES Utility Advisory Committee and EPRI Fusion Working Group in 1994 [1]. These criteria are listed in Table 1. 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. The three groups have investigated: (a) Power management for economic fusion energy, (b) Safety and environmental attractiveness of a fusion power plant, and (c) Reliability, availability and stability of plant operation. The scope of each working group is not uniquely defined, as there exists some overlap between the criteria; our intent is to be comprehensive in addressing these criteria at the risk of some duplication.

Table 1. Criteria for practical fusion power systems

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

Our approach toward 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 different 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 is to evaluate the "mainline" tokamak research program, under the assumption that ITER will be constructed and will play a major role in the development path for fusion.

This interim report contains sections for each working group. Within each section, there are subsections to describe the issues and metrics for evaluating progress toward the ultimate goal, an evaluation of the current state of knowledge in each task area, discussion of the R&D needs to fill the gaps to commercialization, and an evaluation of the role of various facilities and programs toward resolving the issues.

The approach taken in the ARIES study uses the formalism of "technology readiness levels" (TRL's), which have been applied during recent years to major government-subsidized programs such as GNEP, NASA space missions and Department of Defense procurements. Section 2 describes the general methodology and our approach to applying it to fusion energy.

Sections 3–5 contain the detailed discussion of issues and R&D needs. For each "issue", readiness levels are described in terms of the unique features and requirements for a fusion energy source. These levels provide a quantitative methodology for evaluation. In order to apply the methodology we need to specify the end goal. The current US fusion program lacks a single design for an end product. We use recent ARIES designs in order to define example cases for the evaluation, and then apply the methodology to evaluate the current state of R&D and the gaps to advance each technology to a level of maturity needed to commercialize fusion. Following the discussion of gaps, various facilities and pathways are evaluated to determine their effectiveness in advancing fusion technology.

ITER plays a critical role in the development of fusion energy, and contributes valuable information on many of the elements of a burning fusion facility. However, ITER is not designed as a power-producing plant, and lacks essential features of an attractive power plant. Even the test modules, which themselves are designed to be prototypical of a commercial power plant, will be operated only for very short periods of time under conditions and constraints that prevent the thorough testing of nuclear components and systems.

There exists a general international consensus that in order to build and license a demonstration power plant, one or more facilities in addition to ITER will be needed – either in parallel or sequential with ITER. It is not necessary to wait for the completion of ITER operations in order to proceed with the design and construction of these additional facilities. The timescale for testing in ITER is long, and the decision to move ahead with fusion energy R&D depends on national needs, priorities and funding.

A recent FESAC subpanel produced a report entitled: "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy" [2]. We have evaluated the issues described in that report in order to ensure consistency between FESAC and ARIES activities. Due to the significantly different approach and ground rules used, we did not attempt to match issues one-to-one. Section 6 addresses the similarities and differences between the two approaches.

2. Evaluation Methodology

2.1 Technology readiness

We have developed a methodology for evaluating progress toward achieving practical fusion energy, and for quantifying the value of specific facility and R&D proposals in advancing toward that goal. The methodology adopts a limited number of broadly defined issues for fusion energy development with the intent to encompass the criteria for an attractive fusion power plant as defined by our 1994 Utility Advisory Committee. Our issues are divided into three categories, and are listed in Table 2. The technical substance of the issues is described in Sections 3–5 of this report, where metrics for evaluating progress are defined.

Table 2. 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 AND 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 method for evaluating progress utilizes "Technology Readiness Levels" (TRLs), which provide a systematic and objective measure of the maturity of a particular technology [3]. They were developed originally by NASA in the 1980's [4], but with minor modification, they can be used to express the readiness level of just about any technology project.

In a 1999 report [5], the General Accounting Office (GAO) concluded that failure to properly mature new technologies in the science and technology (S&T), or "laboratory" environment almost invariably leads to cost and schedule over-runs in acquisition weapons system programs. In their report, the GAO found that separating technology development from product development is an industry best practice. 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." This statement says that you must be certain that a technology is mature before including it as part of a product or weapon system.

> *"GAO recommends that the Secretary of Defense adopt a disciplined and knowledge-based approach of assessing technology maturity, such as TRLs, DOD-wide, and establish the point at which a match is achieved between key technologies and weapon system requirements as the proper point for committing to the development and production of a weapon system."*

The Department of Defense adopted this metric 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.

Table 3 shows an example of the definition of technology readiness levels appropriate for defense acquisitions. The initial step simply defines the basic scientific and technological principles involved in producing the final product, and the final 9th step represents a fully-functional final product. In our case, this would be a fully-functioning fusion power plant or "demonstration power plant" (Demo) in the language commonly used in the US.

More recently, the GAO recommended to the Department of Energy the adoption of a consistent approach for assessing technology readiness [6]. Subsequently, the GNEP (Global Nuclear Energy Partnership) program produced a Technology Development Plan using this technique [7]. Their assessment considered five key issues requiring intensive research and development:

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

As an example, Table 4 lists the issue-specific technology readiness levels they developed for the issue of LWR spent fuel processing.

In some applications of TRL's, the nine levels are further grouped into categories as follows:

Concept development

1. Basic principles observed and reported.
2. Technology concept and/or application formulated.
3. Analytical and experimental critical function and/or characteristic proof of concept.

Proof of principle

4. Component and/or breadboard validation in laboratory environment.
5. Component and/or breadboard validation in relevant environment.
6. System/subsystem model or prototype demonstration in a relevant environment.

Proof of performance

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.

Table 3. Defense acquisition definition of TRL's

	Technology Readiness Level	Detailed Description
1.	Basic principles observed and reported.	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 such as an aircraft, vehicle, or space. Examples include testing the 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.

Table 4. GNEP TRL definitions for LWR spent fuel processing [7]

TRL	Issue-Specific Description
1.	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.	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.	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.

Progress is characterized by increasing levels of system integration as well as increasing fidelity of the simulation environment. The concept development phase can be performed under laboratory conditions in individual system elements. The proof of principle phase increases both the relevance of the environment as well as the level of system integration. The proof of performance 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 up through TRL’s requiring increasing levels of system integration.

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 should be articulated in the explanation of TRL’s for each issue.

We have undertaken an exercise to formulate a set of technology readiness levels for fusion in order to determine the merits of this methodology to assist the Department of Energy and various stakeholders in the US fusion energy sciences program. The details of that exercise are presented below.

2.2 Reference concepts

Worldwide, there have always been important interactions between fusion power plant studies, experimental results from operating fusion devices, and R&D programs for the development of suitable materials and power core components. In general, the mission of power plant studies is a realistic extrapolation of the knowledge base obtained from the operation of experimental devices and the R&D work in key areas towards commercial fusion power plants attractive for utilities. "Realistic extrapolation" means here a compromise between the anticipated advances, the funding required for the R&D, and the risks that the development may not be successful in the anticipated time frame.

The present ARIES study takes a different approach. The mission is to define a "pathway" from the present position to a first fusion Demo plant, and this plant must – according to the US definition – employ the same technologies, concepts, and materials as anticipated for a following commercial plant. Clearly, such a pathway depends on the anticipated power plant concept. Different development steps will be required, for example, if breeding blankets based on ceramic breeder materials are used, or if liquid breeder blankets are employed. The focus of this study is therefore on the path to reaching a final product rather than on the final product itself.

A fairly detailed description of the current state of technology in view of future fusion power plants is therefore not possible in general terms but requires the definition of a complete set of components and their interactions in a power plant. Worldwide, there have been a considerable number of serious fusion power plant studies, and there are extensive programs underway for the development of the nuclear components, required materials and technologies needed for the fabrication of the power core.

In spite of all these efforts, it is very difficult to select now **one** power plant concept because such a selection requires a complicated trade-off between the conflicting requirements of "an attractive power plant" and the "necessary development program and the associated risks that this development could fail".

The TRL method as described in the previous sections is a very promising tool for such a quantitative evaluation of the development risks and the required R&D programs associated with each individual concept, provided sufficient details are considered.

The TRL process is designed to evaluate the readiness of specific technological components. This requires some modification in the case of fusion where there are several competing technologies available as potential solutions to the general issues that have to be solved. For example, as a general issue, one can pose the problem: "How are the plasma performance and heat loads balanced and controlled in a commercial tokamak power plant", or "How are the power fluxes extracted in a commercial tokamak power plant to yield useable energy?" To apply the TRL method, one needs to select a more specific technological or physics solution first. On the other hand, the aim of the present study is not to presuppose specific solutions but rather to evaluate them. To perform a TRL analysis on all possible physics and technological solution options is, however, prohibitive. Thus, in order to proceed, we have adopted a compromise solution. For each general issue, a set of TRL tables has been formulated with descriptions of what is needed to satisfy each TRL value in as general form as possible. For the Power Management issues, these are presented in Section 3.1. However, implicit in each are assumptions of the general form the solution is expected to take. For example, regarding the physics assumptions, in selecting the Technology Readiness Levels for control of plasma power distribution, it is assumed that the plasma power flux is distributed in several pieces: in volume radiation to the wall, in particle and heat flux to a localized surface (divertor) and a possible high energy "runaway" electron component distributed locally but not predictably. This presupposes a diverted high confinement mode tokamak burning plasma.

2.2.1 Reference concepts for energy capture and conversion

For the application of the TRL method, promising plant concepts were selected as example cases for the evaluation of the current technology readiness levels. The selection is influenced by the desired point of time a first fusion DEMO plant should go into operation, and the time scale anticipated for the development of a following commercial power plant. Basically, there are insufficient results of the R&D programs to make a final selection now. Therefore, it has been suggested to select as a first example ("a moderately aggressive reference concept") a kind of strawman characterized by the following combination:

- Helium cooled FW and blanket structure,
- Lead lithium cooled breeding zone (Dual Coolant Lead lithium (DCLL) blanket),
- FW and entire blanket structure made of Reduced Activation Ferritic Steel (RAFS),
- SiC flow channel inserts decoupling the flowing liquid metal from the steel walls, serving as electrical and thermal insulator,
- 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 strawmen, especially a plant concept based on Self Cooled Lead Lithium (SCLL) blankets of the ARIES-AT type, can be assessed later. Such an advanced plant concept offers higher performance with lower COE, but requires a substantially larger extrapolation of the present technology. This alternative, more attractive advanced concept is characterized by:

- Lead lithium cooled FW and breeding zone (Self Cooled Lead lithium (SCLL)blanket),
- FW and blanket structure made of SiC-composite,
- Permeator tritium extraction system from PbLi,
- Helium cooled divertors based on W-alloys, or, as an alternative Lead Lithium cooled divertors with SiC structure,
- Brayton cycle power conversion system.

Why do we suggest the DCLL blanket for this first strawman? There are two main reasons.

A) Credibility

In the past, we proposed in our studies a large variety of concepts based on austenitic steels, ferritic/martensitic steels, SiC-composites, and tungsten alloys as structural materials. However, there is a general agreement in the material community that the class of Reduced Activation Ferritic Steel (RAFS) is the only feasible structural material for a commercial power plant if this plant has to go into operation by the middle of the 21st century. There are doubts whether SiC-composites or tungsten alloys can be qualified as a FW material in this time frame.

World-wide it is agreed that the DCLL blanket concept is a good compromise between attractiveness and required extrapolation of technology because it is based on a well known structural material, has the smallest requirement on SiC-composites (insulator only, no structural function), allows liquid metal exit temperatures up to ~800˚C (sufficient for power plant efficiencies up to 50% as well as for hydrogen production), and, most important of all, it is on the pathway to a really attractive power plant with SCLL blankets with exit temperatures up to 1100˚C and power conversion efficiencies up to 60%.

It is generally acknowledged that the DCLL concept can be developed and tested in the time frame of ITER with further qualifying tests (reliability growth) in a CTF.

Some people judge the feasibility of HCLL and HCCB blanket concepts in a DEMO plant as slightly higher than the DCLL blanket, but there is general agreement that these two concepts would be less attractive in a commercial power plant (coolant exit temperatures <500˚C, large internal cooling surfaces ~ 20,000 m^2, leading to reliability concerns).

B) Time-line for the development of commercial power plants

During the ISFNT-8 in Heidelberg, there were many discussions on the "Broader Approach for the development of DEMO", "Fast track" and "Ultra fast Track" to commercial use of fusion, and the risk and benefits of the different approaches. There were talks about Apollo-like crash programs, and there was a general understanding that a fast employment of fusion for energy production is more important than the development of really advanced concepts from the beginning.

If we would address the development of concepts based on SiC-composites as structural material in a first power plant without a step between, we will be criticized for taking too high a risk and for delaying the construction of a first power plant. Blankets based on this structural material will require a large material development and qualification program, they cannot be tested in the time frame of ITER, and they would delay blanket tests in a CTF. What would be the situation if this development fails? Going back to concepts based on RAFS would cause a big delay in building a first power plant!

For these reasons we suggest to use a power plant system based on DCLL blankets as a moderately aggressive reference concept and an advanced power plant system based on SCLL blankets as a more attractive advanced concept. It will be very interesting to compare the TRL ratings for the reference case with the ratings for the advanced case. This comparison should allow a judgment of the necessary additional developments necessary for a transition from a more near term solution with limited extrapolation of the current technologies to a more advanced power plant with a potential for higher performance but larger development costs and risks.

2.2.2 Reference concepts for the remainder of the power core

The systems described in this section are those other systems necessary to help create, sustain, analyze, and control the fusion plasma as well as support, maintain, and provide power and cooling to the power core components. Corresponding to the definitions in the prior section, there will be reference sets of systems that will be defined for a level of performance sufficient to achieve a commercial fusion power plant that has all the positive attributes outlined in Table 2, namely, efficient and economic power management, attractive safety and environmentally features, and reliable and stable plant operations.

The plasma containment system of magnetic coils for the "moderately aggressive" reference concept (circa 2050-2060) will likely be either NbTi or Nb_3Sn superconducting coils with conventional fabrication methods, but incorporating innovative design and fabrication approaches to significantly lower the production costs and to achieve high operational reliability. The more attractive "advanced concept" (circa 2070-2080) will likely incorporate higher temperature superconductors to offer higher magnetic field strengths with much lower cryogenic load, easier fabrication (e.g., direct deposition of conductors), lower costs and improved operational reliability.

The Plasma Formation and Sustainment system of heating, current drive, and fueling subsystems for both the reference and advanced concepts will likely be the same types as on current experiments and ITER. No new advanced HCD&F subsystems are presently envisioned. However, the level of subsystem efficiency, power level, and cost will be significantly advanced from ITER to the moderately aggressive concept to the advanced concept.

The other Power Core support systems of the Power Core Vacuum, Primary Structure and Support, Power Supplies, Main Heat Transport, Cryogenic Cooling (Magnets), Fuel Handling and Storage, and Instrumentation and Control will be similar in nature to ITER and other large DT experimental facilities subsystems. However, they will have to be commercialized to increase the scale, efficiency and economics necessary for commercial success, with advancements between existing technology, the moderately aggressive concept and the advanced concept. There will also have to be adaptations and modifications in other systems, such as the Main Heat Transfer and Transport system, to handle much higher temperature heat transfer media in the advanced concept. The reference vacuum vessel approach will likely use ferritic steels with advanced low-cost fabrication techniques and a different design approach to enable high maintainability of the interior power core components. The modest I&C concept will need to be a very advanced state of the art systems or be highly adaptable to maintain efficiency throughout the plant lifetime. The advanced I&C systems would be even more so and can hardly be envisioned what might be employed (certainly health monitoring and perhaps fully automated control). The changes in these subsystems are largely evolutionary rather than revolutionary. Innovation will be enabled in the design concepts, materials, and fabrication to accommodate the more severe radiation environment and more aggressive cost, availability, safety, and environmental goals at each development stage.

One of the factors in determining the cost of electricity is the fixed charge rate (FCR). The actual value of the FCR is dependent on the economic lifetime of the plant over which the borrowed capital is repaid. Conceptual designs of future power plants, especially fusion power plants, tend to adopt the lifetime guidelines of other contemporary power plants. Fission plants generally had a 30-year plant lifetime, however as those fission plants in operation are approaching their lifetime limits, they have applied for license extensions of 20 or 30 years. The new GenIV fission guideline is nominally a 40-year lifetime but may be extended by the user. So the obvious benefits of a longer plant life are being recognized and pursued by fission. Fusion should also explore plant lifetimes of 40 to 80 years. All components and systems that would be very expensive and/or hard to replace (such as shield, vacuum vessel and magnets) should be designed with the maximum lifetime in mind. Easy to replace components and subsystems could be replaced incrementally. The downside of long plant lifetimes is technology obsolescence.

The technology of all subsystems will significantly advance during the 30-80 year plant lifetime. Value judgments will have to be made to shut down the plant for upgrades or continue to produce electricity less efficiently. But certainly, the lower technology portion of the plant should be designed with the longer lifetimes in mind. Higher technology subsystems should be designed to accommodate system upgrades.

Aggressive cost, availability, safety, and environmental goals will also require innovative revolutionary changes in the way the fusion power core is designed, repaired, and maintained. Designs and maintenance of 500 modules per the ITER approach is not acceptable in a commercial power plant where sector maintenance is highly recommended to enhance availability. All power plant components, especially the life-limited internal power core components, must be highly reliable and highly maintainable. Thus new designs and maintenance approaches must be validated via modeling and simulation and hardware mockups. Even the moderately aggressive design must achieve > 90% (long term) plant availability on the first commercial power plant and the advanced design will need to achieve >95% (likely goal by 2060 or beyond). Some maintenance innovations might be fuzzy logic, knowledge management, autonomous operation, internal in-situ repair, nanobots, *etc*.

A new framework has been developed worldwide to manage the continual stream of fusion-activated materials generated during power plant operation and after decommissioning. Recycling and clearance (avoiding geological disposal - the preferred option for ITER) offer the most environmentally attractive solution for fusion energy. Means to keep the volume of fusion radioactive materials to a minimum have been be developed through clever ARIES designs and smart choice of low-activation materials. At present, the US industrial experience with recycling and clearance is limited, but will be augmented significantly in 50-100 y by advances in fission spent fuel reprocessing (in support of the GNEP, MOX fuel, and Partitioning and Transmutation activities), fission reactor dismantling in 20-30 y, and bioshield clearing before fusion is committed to commercialization in the 21st century and beyond.

Table 5 summarizes the main characteristics of the “moderately aggressive” and “more attractive advanced” design concepts.

Table 5. Summary of reference design concepts

“Moderately Aggressive”	**“More 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
FPC radwaste volume 25% less than ITER; 95% of radwaste are recyclable/clearable	FPC radwaste volume 40% less than ITER; All radwaste potentially recycled and/or cleared
Human operators, A=90%	Autonomous operation, A=95%

3. Power management for economic fusion energy

3.1 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, 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.

The challenge of fusion power management is exacerbated by the absence of test facilities that can reproduce conditions that are prototypical of a fusion power reactor. Therefore, an R&D program must be designed carefully and executed in a manner that provides a high degree of confidence in the operation and survival of nuclear components in future fusion devices. The ability to license fusion facilities will depend on our ability to ensure safe and predictable performance of all of the systems involved in power generation. The economics of a fusion power plant will depend on low capital and operating cost coupled with high thermal conversion efficiency and a high degree of maintainability of long-lived, reliable power core components.

The challenge of power management has been subdivided into five major topical areas:

1. Plasma power distribution. The emission of fusion energy from a burning plasma is highly complex, involving multiple channels of energy release (neutrons, radiation, energetic particles) that are absorbed both volumetrically and on surfaces throughout all of the components located within the fusion power core. An attractive power plant will require that these energy release pathways are controlled adequately so that power levels, peaking factors and safety factors allow for efficient extraction of energy.
2. Heat and particle flux handling (PFC's). Even if we are able to perfectly control the release of energy from the plasma, still the heat and particle loadings on components will push the limits of materials and components. Most difficult is the challenge of surface heat flux removal in plasma-facing components. Constraints on efficient power conversion further exacerbate this problem, due to the requirement of high-temperature operation.
3. High temperature operation and power conversion. The economics of fusion will depend to a large extent on efficient conversion to electricity of all of the emissions from the plasma. Recirculating power within the plant, such as that required for current drive, places additional demands on conversion efficiency. System studies suggest that water cooling, similar to BWR and PWR designs of the past, will not lead to a competitive end product. In order to achieve efficiencies of 45% or higher, advanced cooling system materials and innovative power conversion schemes must be developed.
4. Power core fabrication. Fusion power cores contain complex, high technology components and systems. These systems serve a variety of functions within a very harsh, high-temperature nuclear environment. The use of conventional manufacturing techniques is expected to lead to very expensive and unreliable fusion power plants. Modern fabrication techniques, including bottoms-up engineering design of materials are needed.

5. Long term behavior of the power core. The behavior of fusion power core components in the operating environment of a burning fusion plasma represents a new frontier for materials and components. Component lifetime impacts plant availability due to scheduled and unscheduled outages, and affects operating costs due to component replacement, refurbishment and waste management. Damage caused by neutrons and energetic particles are a special concern, due to the lack of existing data, the extensive need for new data and the difficulty obtaining data. Innovative methods of accelerated testing and the use of modeling are needed.

This functional division of the issues tracks power as it is produced, absorbed in the surrounding structures, and finally transported as high-grade heat into the power conversion system that produces electricity. The two overarching subjects of power core fabrication and lifetime are treated as separate issues. The issues and metrics for evaluating progress in these 5 topical areas are discussed further in the following section.

3.2 Issues, Metrics and R&D needs

3.2.1 Plasma power distribution

An attractive fusion power plant will require that the energy release pathways from multiple channels through neutrons, radiation, and energetic particles are controlled adequately so that power levels, peaking factors and safety factors, both volumetrically and on surfaces, allow for efficient extraction of energy. The plasma power flux is distributed in volume radiation to the wall, in particle and heat flux to a localized surface (divertor) and a possible high-energy "runaway" electron component distributed locally but not predictably. The TRL requirements in Table 6 reflect the need to control all of these energy release pathways.

Current state of knowledge

Assuming a diverted high confinement mode tokamak burning plasma as discussed in Section 3.3.1, 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 parameter window (in power flux to the plasma edge) suggest it may become 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.

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 uncertain. Present 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 DEMO. The resultant, highly directed, high intensity electron beams exiting the plasma can then cause serious damage to the vessel and surrounding structures.

Table 6. Technology readiness levels for control of plasma power distribution

TRL	Issue-Specific Definition	Facility Needs
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 experiments. 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 experiment between current devices and ITER, or an upgrade. Detached divertor may or may not scale up.
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 the integrated power handling system in a steady state burning plasma configuration for lifetime conditions.	Demo

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 ELMs and 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 true 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 would warrant a TRL value of 4 with the current state of knowledge.

3.2.2 Heat and particle flux handling (PFC's)

Even in the event we are able to completely control the release of energy from the plasma, still the heat and particle loadings on components will push the limits of materials and components. A key challenge is the surface heat flux removal in plasma-facing components. Constraints on efficient power conversion further exacerbate this problem, due to the requirement of high-temperature operation. In addition, plasma-material interactions can lead to armor erosion and tritium retention, impacting the PFC lifetime (see Section 3.2.5 on power core lifetime) and plant safety (described in Section 4).

Table 7 summarizes the technology readiness levels for heat and particle flux handling. The definitions of these TRL levels are intended to be as technically detailed as possible to allow for an accurate assessment and to minimize any subjectivity, but yet applicable to all subsystems in this issue category (including first wall, baffle, limiter, and divertor PFC's as well as heating and current drive PFC's).

<u>TRL 1.</u> The basic principles guiding the heat and particle flux handling in a fusion power plant are formulated. The magnitude, time scale and footprint of the anticipated fluxes are characterized and bounded, through system studies. The likely effects on the PFC behavior, including heat and mass transfer mechanisms, are hypothesized and their relative importance estimated through system studies.

<u>TRL 2.</u> Possible PFC concepts that could handle the anticipated heat and particle flux conditions are explored, including armor, structural material and coolant choices and possible integrated configurations. The critical properties and constraints affecting the design are characterized.

<u>TRL 3.</u> Experimental data from coupon-scale heat flux and particle flux experiments are obtained for candidate armor materials to demonstrate their potential ability to accommodate the anticipated plasma facing conditions. Models are developed to characterize and understand the governing heat transfer and mass transfer processes and to help in extrapolating the small-scale test results to prototypical conditions.

<u>TRL 4.</u> Bench-scale submodule testing of PFC concept is performed in a laboratory environment simulating heat fluxes or particle fluxes at prototypical levels over long times (the heat and particle fluxes need not be integrated). The submodule should represent a unit cell of the PFC concept including armor, structural material and coolant. The testing time should be of the order

of the expected operating lifetime. The operating conditions (temperature, pressure, flow rates,..) should cover the expected prototypical conditions

Table 7. Technology readiness levels for heat and particle flux handling (PFC's)

TRL	Issue-Specific Definition	Facility Needs
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, and 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 flux and particle flux experiments; modeling of governing heat transfer 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 (if a prototypic PFC system is used), 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

TRL 5. Integrated module testing of the PFC concept is performed in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times. The module should include the integration of a number of unit cells of the PFC concept. The testing time should be of the order of the expected operating lifetime. The operating conditions (temperature, pressure, flow rates, ...) should cover the expected prototypical conditions.

TRL 6. Integrated testing of PFC concept subsystem is performed in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times. The subsystem should include an integrated unit of modules in a prototypical arrangement, including the integration of the subsystem to any cooled structural support. The testing time should be of the order of the expected operating lifetime. The operating conditions (temperature, pressure, flow rates, ...) should cover the expected prototypical conditions.

TRL 7. The PFC system is tested in a fusion machine and its operation demonstrated under prototypical conditions. The test unit should represent the complete PFC system as expected in a power plant.

TRL 8. The PFC system is tested in a fusion machine and its operation demonstrated under prototypical conditions over long operating times. The test unit should represent the complete PFC system as expected in a power plant. The testing time should be of the order of the expected operating lifetime. Complementary qualification testing of the system in a fusion-like environment through a series of post end-of-life tests is performed to qualify the component.

TRL 9. The PFC system is fully incorporated in a Demonstration fusion reactor and its performance demonstrated to end-of-life under fully prototypical conditions in a fully integrated mode with all system interfaces.

3.2.3 High temperature operation and power conversion

All of the credible near-term concepts for converting fusion energy to electricity involve thermodynamic cycles of one kind or another. Efficient thermodynamic conversion of fusion-generated heat to electricity requires high coolant temperature. Successive ARIES power plant studies have documented the importance of high conversion efficiency on the bottom-line cost of electricity and on the easing of constraints on other parts of the system [8,9]. Combining low conversion efficiency with high capital cost and, in some cases, high recirculating power, has been shown to lead to economically unattractive power plants.

High temperature pushes technology in several ways. First, the use of unconventional materials (like PbLi coolant) at elevated temperature can result in chemical interactions, materials degradation and mass transport. Second, if the coolant temperature is high, then the temperature of solid structures is also high. High-temperature properties, such as strength, are important in determining the maximum allowable power density and other performance characteristics. These also play a role in limiting the lifetime of components. Third, thermal management requires predictable control of fluid dynamics and heat transfer within critical in-vessel structures. Thermofluid studies can be especially complicated in a fusion environment due to the use of relatively exotic coolants and the possible impact of environmental conditions such as strong magnetic fields and neutrons. Finally, high coolant temperature and the drive for higher efficiency places additional challenges on the power conversion system outside the power core itself.

Due to the penetrating nature of neutrons, energy from a burning plasma is captured throughout all of the elements of the power core. Ideally, in order to convert all of this energy to electricity, every part of the power core would operate at high temperature. In ARIES studies, the boundary between the high and low temperature parts of the power core is usually defined by the requirement to capture 99% of the neutron energy. The low temperature shield and radiation-sensitive components are located behind this boundary. Some specialized items, such as radiation-hardened diagnostics, control coils or heating and current drive systems may be excluded from the requirement of high-temperature operation, depending on the net result on the energy balance. In cases where a substantial amount of energy is captured in one of these elements (such as a large rf antenna), high-temperature operation and power conversion may be necessary.

In Table 8 we define levels of technology readiness for the collective set of issues surrounding high temperature operation and power conversion.

3.2.4 Power core fabrication

The prior sections discussed some of the issues and technology developments necessary to achieve economic fusion energy, specifically power distribution within the power core, handling of heat and particle flux, achievement of high temperature operation, and efficient power conversion. In order to achieve the goal of economic fusion energy, all of those concepts must be developed, designed, fabricated, and validated to stringent standards that will assure economic, stable and reliable power production. This section will discuss the approaches and technologies necessary to achieve those power-oriented goals.

However, there are other aspects to achieve economic power. The envisioned fusion power plant is a base loaded system that operates under steady state, full power conditions for extended periods of time with high reliability. Magnetically confined fusion plasmas operate at very high temperature with a harsh environment of high-energy neutrons and alpha particles inside the power core, but also require a high vacuum condition with very controlled fuel and impurity mix. So there is a multitude of very stringent requirements on the design and fabrication of the power core. Due to the competitive arena of current and future electrical power plants, the needed plant availability should be greater than 90% for a competitive power plant. This requirement mandates both high maintainability and reliability for all plant systems. Both capital and operating costs must be (controlled, mandated, established) to very affordable values to assure competitive power production.

These sets of requirements on power core elements stress high performance, high efficiency, low cost, high reliability, and easy/quick maintainability. If only one or a few plants are envisioned, an economic power plant would not be possible as the development costs would be prohibitively expensive, the low production quantities would inflate the capital costs, and non-standard maintenance would yield low plant availability. Therefore it is imperative to develop a standardized design for future power plants, perhaps consisting of dozens or more identical plants. Only then would the economics of quantity development, production and operation pay off.

Each of these influencing topics will be addressed separately.

Table 8. Technology readiness levels for high temperature operation and power conversion

TRL	Issue-Specific Definition	Facility Needs
1	System studies define tradeoffs and requirements on temperature, effects of temperature defined. Power sources described. Blanket, coolant loop and power conversion materials and concepts defined.	
2	Coolants, power core materials, cooling systems and power conversion options explored, critical properties and compatibilities described.	
3	Scoping data in static capsule tests and convection loops, modeling of transport phenomena, mechanical property measurements, fluid flow studies, nuclear heating data, detailed power cycle analysis. Materials irradiation specimen tests.	Small single-effects test facilities, including fission reactors.
4	Thermomechanical analysis and tests on FW/blanket elements. Long-term compatibility tests with prototypical materials. Thermofluid tests and analysis for both in-vessel and ex-vessel components.	Multiple-effects facilities for submodule testing, high-temperature, off-normal, etc. Fission reactor module tests.
5	Forced convection loop with prototypical materials, temperatures and gradients for long exposures. Power conversion system tests. Blanket module mockups.	Non-nuclear engineering test facilities.
6	Forced convection loop with prototypical materials, temperatures and gradients for long exposures integrating power conversion system elements.	Partially integrated test facility: prototypical surface and volumetric heating, magnetic fields if needed.
7	Prototype blanket (sector) and power conversion system demonstration with fusion heat source over long periods of time.	Fusion machine ITER, CTF
8	Full blanket and power conversion system demonstration with fusion heat source over long periods of time.	CTF
9	Full blanket and power conversion systems operated to end-of-life in fusion reactor with prototypical conditions and subsystems.	Demo

High performance and high efficiency are closely related topics. The power handling systems of the power core were addressed in the prior Section 3. Performance and efficiency is also very important to all the other power core systems. Included are the Plasma Confinement, Plasma Formation and Sustainment, Primary Structures, Vacuum, Power Supplies, Main Heat Transfer and Transport, Cryogenic, Cryogenic Cooling, Radioactive Materials Treatment and Transport, Fuel Handling and Storage, Maintenance, and I&C. Each of the systems must be high performance and highly efficient to yield the best integrated system performance and efficiency. These systems must be designed and built to be competitive for their entire life of 40 plus years. Either low temperature or high temperature superconductor magnets will be significantly advanced in the years before the Demo is designed and built. The RF and NB plasma heating and current drive systems will be significantly matured based on ITER and following burning plasma experimental facilities. The remaining power core subsystems will benefit from other fusion and non-fusion developmental advancements. If there is a deficiency in a particular subsystem, it may be necessary to implement a fusion specific development program to advance the development of that subsystem. As the design decision point for Demo approaches, all of the power core subsystems need to assess their technical readiness levels to minimize technical risk to proceed into the design phases.

The second major factor is the economics of the subsystems. An MCF power plant has often been determined to be a capital-intensive facility. Fusion fuel is cheap, but the capital costs are high. This may be the Achilles Heel of economic fusion power. The capital costs must be lowered by significant amounts – an order of magnitude of cost reduction would be highly desirable but probably not attainable. Traditional cost cutting efforts offer marginal improvements and will not be sufficiently effective. Innovative approaches that promise orders of magnitude cost reductions on major items must be aggressively pursued. There are many other subsystem elements that cannot be reduced significantly, so the innovative approaches must carry the day. Innovative fabrication processes, nanotechnology, and additive fabrication, free-form fabrication, and solid state compaction of metal powders are a few of the new fabrication and production technologies that may be commercialized by the time fusion must be demonstrated. Some will falter and fail but others will blossom and provide the solution needed. These innovative materials and component developments are the least known and offer the greatest opportunity, but also have the greatest risk. Currently these are viewed as being highly speculative, but many new technologies have blossomed in less than 30-40 years.

The life-of-plant (LOP) power core components need to be designed and built to be as low a cost as possible, but their long lifetime allows a longer amortization period. But due to the effect of interest and return on investment, these LOP components and subsystems must be as low a cost as possible. The most emphasis is placed on the limited life components of the power core, namely the first wall, blanket, divertor, replaceable shield and some heating and current drive components. Not only must these components deliver high performance in the harsh, high temperature environment, they must be highly reliable (no leaks?), demonstrate predictable lifetimes, quick and easy to replace, easy to repair in-situ (if leaks occur), and be relatively inexpensive. These attributes will also help reduce the annual scheduled component replacement costs.

The power core components must also have a proven track record of high reliability. The ability to achieve high reliability begins with the design process by providing sufficient design margin, using fail-safe design concepts, and rigorous life and reliability testing. The use of standardized designs will also help increase the system reliability. NASA and DoD have urgent needs to deliver products with high reliability so they have set up programs with stringent quality standards and standard parts with documented databases/histories. High system reliability is essential to achieve the necessary high plant availability. New in-situ monitoring technologies now being applied as in-vehicle health monitoring will help achieve higher levels of reliability and availability by predicting incipient wear out and failure conditions before they occur.

Achieving high maintainability is the second factor to achieve high plant availability. The high-energy neutron power core environment induces high levels of radioactivity in all the interior power core components. This mandates fully remote maintenance of the power core as well as handling of these components outside the power core and maintenance/replacement of these components in the hot cell. The currently envisioned lifetime of the interior power core components is around 4 full power years. So the entire interior of the power core must be removed every 4.5 years or so. Existing DT MCF experiments also require remote maintenance, but availability is not a high priority issue. These experimental facilities, including ITER, usually replace individual blanket (shielding) and divertor modules through maintenance ports. Shutdown durations are usually 6 months or longer, which are not acceptable for a power plant. Most conceptual fusion power plants are designed to remove complete modular segments that include the first wall, blanket, shield, divertor, and some heating and current drive elements. Replacement of complete sectors (1/12 or 1/16th of the power core keeps all the plumbing connections intact in the sector with connections being made outside the power core. The replaceable sections of the sector will be removed and replaced in the hot cell. The sector is very massive, but moving approaches are feasible. Advanced autonomous remote maintenance will be simulated and validated in special remote maintenance test facilities. To this point, conceptual designs have developed feasible designs and future studies will optimize the maintenance approach.

Therefore fabricating a low cost power core is not the only answer. All the power core elements must work together as an integrated system. Certainly the power must be affordable, but it also must be high performance and efficient to extract the maximum energy from the fusion process, it must be reliable to assure a stable and long lived power source and it must be highly maintainable to assure high plant availability.

In Table 9 we define levels of technology readiness and facility needs for power core fabrication.

Table 9. Technology readiness levels for development and fabrication of low cost, high efficiency, and long-lived power core components

TRL	Issue-Specific Definition	Facility Needs
1	Top-level requirements defined including cost targets, performance parameters, physical design approach, expected lifetime, maintenance concept. Basic scientific principals observed.	None.
2	Nuclear and operational environments defined, technology concepts defined, performance estimates determined, validating experiments identified, risks identified.	None.
3	Analytical studies substantiate hypothesis. Preliminary design of components incorporating technology advancements completed. Early modeling and simulation conducted. Small, non-fusion, environment experiments support technology claims. Risk areas identified and mitigation plans created.	Some new small-scale prototype production and testing facilities may be required to demonstrate critical function or proof of concept. Proof of concept for long-lived and highly reliable materials will likely require a dedicated high-fluence materials test facility.
4	Some higher quality bench-scale experiments fabricated and operational in lab environment Component designs in work for use in relevant environment. Select preferred technology approach and build prototype component.	Some new bench-scale prototype production and testing facilities may be required to validate prototypical component in an applicable laboratory environment. Existing fusion experimental facilities may be useful.
5	Detailed component designs completed. Pre-production hardware built and assembled into test setup for installation into relevant fusion test facility for long term testing (post ITER). Individual components validated for functionality and performance. Key manufacturing processes verified. Final reliability and lifetime targets established.	Preproduction components will be tested in a relevant environment (perhaps ITER or component test facility). Key to applicability is long-term lifetime and reliability criteria/requirements. Validation of long-lived and highly reliable materials will likely require a dedicated high fluence materials test facility.
6	Quality and reliability levels established. M&S determined system performance. Higher fidelity system tested long term in relevant fusion test facility (pre-CTF). Critical manufacturing processes prototyped. Processes and tools are mature. Most pre-production hardware available.	Preproduction components are integrated into subsystems and tested long term in relevant environment (ITER or component test facility, depending on operational criteria).

7	Materials and manufacturing processes demonstrated. M&S modeled the few unavailable subsystem elements. Prototype subsystem built with "soft tooling". Subsystem and system tests in a relevant fusion nuclear environment with meaningful fluence. Testing also includes higher stress conditions with anomalous conditions. Maintainability, reliability, and supportability database above 60% level. Initial manufacturing sigma levels established. Scaling is complete. Limited quantity preproduction hardware is available. Ready for Low Rate Initial Production. Complete prototype system tested long term in a operational environment, such as a Demo.	Production prototype subsystems are tested long term in operational environment, such as Demo. CTF probably cannot handle entire and multiple subsystems and systems.
8	Components and subsystems are form, fit, and functionally compatible with operational subsystem (and system). Cost estimates are < 125% of goals. Machines and tooling demonstrated in production environment. Software thoroughly debugged. All materials are in production and readily available. Components operated to end-of-life in a relevant fusion environment with prototypical conditions and subsystems (excepting those life of plant components and subsystems that must be validated with extrapolations using M&S). Subsystems meet all specifications and qualified for plant operation (validation complete). Ready for full rate production. Actual system tested long term in Demo.	Production subsystems and systems are tested long term in operational environment, such as Demo.
9	Operational concept successfully implemented. Cost estimates < 110% of production cost goals. Design stable. System installed and operational. Training and supportability plans implemented. All manufacturing processes controlled to 6 sigma. Testing of life-of-plant components continue to be tested in fusion reactor environment with prototypical conditions and subsystems. Testing of power core components and subsystems with anomalous, fault, over-stressed conditions to improve performance and predictive capabilities. Actual system operational in Demo or first operational power plant.	Production subsystems and systems are operated long term in operational environment, such as Demo or the first operational power plant.

3.2.5 Power core lifetime

The operating lifetime of in-vessel components is highly uncertain, and plays a leading role in determining the feasibility and economics of fusion as an energy source. Lifetime is limited by materials degradation in the operating environment of a burning plasma, which primarily results from particle flux to surfaces and neutron-induced damage. Over time, damage accumulates in materials, ultimately leading to loss of function. Damage occurs for a variety of reasons, including atomic displacement, burn-up, transmutations, erosion, and defect generation. The function at risk may relate to structural integrity, hermeticity, breeding potential, thermal conductivity, or any other critical component function. The high operating temperature and chemical environment often contribute to and exacerbate concerns over lifetime. Off-normal events and thermal cycling of any kind will also impact component lifetime.

The choices of materials in a fusion power core are limited due to safety and environmental concerns. Notably, low-activation materials are believed to be essential in order to achieve public acceptance of fusion as an energy source. The lack of suitable existing candidate materials has led to rather large materials development efforts specific to fusion. Some narrowing of options has occurred as a result of these development and testing efforts, but still there are alternate material candidates that exist at varying stages of technology readiness.

Table 10 spells out technology readiness levels for power core operating lifetime.

Table 10. Technology readiness levels for power core lifetime

TRL	Issue-Specific Definition	Facility Needs
1	Lifetime requirements determined from system studies, life-limiting mechanisms defined.	
2	Materials systems proposed, operating environment characterized.	
3	Corrosion tests establish operating limits, low-fluence radiation damage coupon measurements & modeling, early failures determined in component tests.	Corrosion chemistry labs, fission reactors, 14-MeV neutron sources.
4	Reliability measured in component tests, supporting numerical simulations performed. High-fluence neutron irradiations.	Thermomechanical test facilities, fission reactors and 14-MeV neutron sources.
5	Early failures determined in a fusion-relevant environment, component reliability tested in a fusion-relevant environment.	14-MeV neutron sources, ITER
6	Integrated power core systems testing in a fusion-relevant environment.	ITER, CTF?
7	Component tests in a fusion nuclear environment with meaningful fluence, specimen tests approaching end-of-life fluences.	CTF
8	Components operated to end-of-life in fusion environment with prototypical conditions and subsystems	Demo
9	Components operated to end-of-life in fusion reactor with prototypical conditions and subsystems.	Demo

4. Safety and environmental attractiveness

4.1 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 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]. Therefore, an important goal of fusion R&D will be to demonstrate that these anticipated attractive features can be realized in practice.

Power plant studies indicate that the tritium inventory will be significant, ~5 kg, with the majority being in the blanket, the reprocessing system, and the fuel storage system. Confinement of the tritium 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/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 a target 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. The R&D program must demonstrate that such a release 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 – i.e., breeder, coolant, structure), it is clear that the activation levels will be substantial, in the vicinity of billions of Curies. During normal operation, power plant studies have noted that activation product release can occur as a result of leakage from the coolant system. Although such leakages could present a local maintenance issue, there do not appear to be any public health issues associated with such leakages. Therefore, the studies have emphasized confinement of the activation products during off-normal events. In this context, the 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 acceptable costs.

Based on the results of power plant studies [12], it appears that the management of radioactive wastes from fusion power would present new issues that are not already being addressed in the fission power industry [13]. 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 may lend themselves to recycling and clearance after reasonable cooling times [13]. The avoidance of wastes higher than Class C and the possibility of material recycling and clearance must be demonstrated by the R&D program.

Finally, there is substantial relevant experience gained through decommissioning activities in the commercial nuclear power industry and through nuclear weapons programs regarding the control, handling and confinement of tritium and activation products, and also in the small-scale recycling of radioactive wastes at INL, ANL, SRNL, and ORNL.

4.2 Issues, metrics and R&D needs

4.2.1 Tritium control and confinement

In assessing the environmental and safety implications of tritium handling in fusion power plants, three issues must be considered: (1) anticipated tritium inventories in key systems, (2) potential pathways for tritium release during normal operation, and (3) the potential for and the consequences of accidental releases of tritium. Technology readiness levels for tritium control and confinement were developed to indicate focus areas for these considerations; TRL definitions are outlined in Table 11. The levels progress from a basic understanding of tritium behavior in materials, demonstrating tritium handling at intermediate levels, then conclude with operating a tritium process and recovery system deployed in fusion power plants.

Based on power plant studies the following observations are noted regarding tritium inventories.

1. The total anticipated tritium inventory ranges between 5 – 10 kg.
2. The major inventories are associated with the blanket, reprocessing and storage systems.
3. The tritium inventory in the plasma is only of the order of 1 g.

During normal operation tritium could enter the environment by leakage and permeation through system piping and valves. Under such conditions tritium could enter the reactor cell and pose an occupational health hazard. In order to accommodate possible entry of tritium, power plant studies have generally adopted a design goal of limiting tritium levels in the reactor cell to a small fraction of the maximum permissible concentration [14] or derived air concentration [15], which is 2×10^{-5} Ci HTO/m^3 of air. The protective level usually adopted is ~ 5×10^{-6} Ci/m^3 of air volume. In order to achieve the desired tritium levels, the reactor design will include a tritium clean-up system. It is noted that special “suits” have been developed to allow workers to carry out operations in a tritiated environment [16]. These plastic suits supply fresh breathing air and are constructed so as to prevent penetration of the low-energy β-emitted by tritium decay and to prevent tritium permeation to the skin. Such suits allow entry into areas with airborne tritium up to levels of 10’s of mCi/m^3.

Leakage and permeation of tritium into the atmosphere or cooling water could pose a public health hazard. In power plant studies the design goal generally adopted is to limit waterborne tritium releases to ~10 Ci/day. The basis for this release rate derives from estimates of health effects associated with tritium release from light water reactor experience. In order to achieve a tritium release rate of 10 Ci/day, the tritium loss per day must be kept down to ~10^{-6} – 10^{-7} of the total inventory. Although the technology exists for maintaining the necessary degree for confinement [17], a major goal of the fusion R&D program must be to demonstrate that this degree of tritium confinement can be achieved within acceptable costs for the required high tritium throughput of a power plant.

In the event of an accident, one must consider the possibility that portions of the reactor and tritium handling systems might be breached, resulting in tritium release. The amount of tritium released under such accident conditions is difficult to predict. Estimates based on current power plant designs suggest that about 10 g of tritium might be released to the air during certain accident situations. The health effects associated with a 10 g accidental release of tritium is estimated to be minimal, a very small increase in latent cancer fatalities, resulting from latent effects. Clearly, the R&D program must validate that tritium release during off-normal events can be limited to the level noted above.

Current state of knowledge

Fusion researchers have worked with tritium for many years. The Tritium Systems Test Assembly, operated at Los Alamos National Laboratory from 1984-2001, was a test bed for components and a demonstration that tritium could be purified and handled safely. However, the TSTA only handled up to 100 grams of tritium. Both TFTR and JET safely utilized small tritium amounts (10's of grams) for DT plasma tests, using processing systems scaled to handle tokamak exhaust effluent. Facilities related to the military have handled larger amounts of tritium, for example the Savannah River Tritium Extraction Facility, operated since 2005, is a DOE hazard category 2 facility, licensed for up to 7 kg tritium. The Savannah Replacement Tritium Facility, operated since 1995, is also a kg-scale facility. The experiences in handling large quantities of tritium, combined with ITER experience, are necessary but not sufficient for the design and safe operation of tritium facilities at future reactors.

R&D needs

The experiences from previous fusion facilities and national defense facilities need to be studied and understood; then lessons can be taken from them to apply to future fusion power plant designs. However, due to the nature of the task, military facility experiences are not openly discussed. A substantial issue specific to fusion is the retrieval of tritium from the breeder material. If breeding blankets are used to generate tritium, that tritium must be retrieved from the blanket, purified, and stored for future use. Tritium permeation and retrieval from breeder materials is under study. Until the complete tritium processing cycle, including components required for tritium handling from breeder material, the TRL for tritium control and confinement is inherently limited to the developmental stages. Facilities are needed to study fundamental tritium behavior in breeder materials, then integrated systems can be tested at the intermediate level. Some activities in this area are underway within the ITER Test Blanket Module development program. The facilities needs for complete tritium fuel cycle handling are given in Table 11.

4.2.2 Activation product control and confinement

In the context of activation product control and confinement two issues must be considered: (1) release mechanisms during normal operation, and (2) accidental release mechanisms during off-normal events.

Table 11. Technology readiness levels for tritium control and confinement

TRL	Issue-Specific Definition	Facility Needs
1	Principles and data must be available regarding the solubility, permeation and transport of tritium in materials.	Laboratories needed to measure thermal physical/chemical properties of breeding 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.	Integrated test facility for processing breeder blanket tritium production.
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.	ITER/ITER-TBM
8	Successful tritium confinement must be demonstrated at the required fusion scale size.	Component Testing Facility (fusion-relevant nuclear environment)
9	Successful tritium confinement must be demonstrated at the required scale size and during fusion mission operations.	DEMO

During normal operation, activation products can enter coolant loops through corrosion processes and through neutron sputtering. The coolant stream can exhibit small leaks during normal operation and also as a result of routine maintenance operations. Such leakage would cause local contamination of components and the work area. This would complicate maintenance procedures but would not present a public health hazard. Activated dusts in the vacuum vessel, perhaps tens of kg, and in the vacuum system also complicate maintenance and detritiation. A vacuum vessel breach would release activated dust from the breach location. Thus, accidental releases are the major concern with regard to public health hazards.

Release of significant amounts of activated structure would require an energy source of sufficient strength delivered on a time scale short enough to heat, melt and vaporize a substantial fraction of the structure. The possible sources of energy release in a fusion power plant in the event of an accident include:

- Kinetic energy of plasma
- Plasma reaction potential
- Nuclear afterheat
- Magnetic energy
- Chemical energy in the first wall and blanket

Of these, chemical energy in the blanket poses a key concern. Since the blanket must contain lithium in some form, we must consider the possibility of chemical energy release since lithium and its compounds are reactive with H_2O and air (O_2 and N_2). The problem would be most severe if liquid lithium were used. If there were a breach of the blanket or if lithium feed lines broke, there would be a pathway for lithium to react with oxygen and this would present a potential mechanism for volatilizing substantial amounts of structure. Therefore, in the engineering design of fusion power plants we must incorporate features that mitigate the likelihood for such events (e.g., dual-walled pipes, use of guard pipes, operate the building in an inert atmosphere). Moreover, there are lithium compounds that are far less reactive than liquid lithium and these compounds are being considered for blanket applications. For a given selection of blanket coolant and breeder, the R&D program must demonstrate the safety goal of no requirement for an evacuation plan. Some lithium compounds, LiH, Li_2O, etc., have chemical exposure limits and these must be assessed as well as the radioactive exposures.

Technology Readiness Level definitions for activation product control and confinement are presented in Table 12. A number of issues for evaluation depend strongly on the materials chosen for cooling components and breeding tritium. The similar nature of activation product transport to tritium confinement yields TRL definitions that are similar, although the fundamental physical behavior can be very different.

Current state of knowledge

There are several areas of concern with activation products. First is neutron activated structural materials and plasma facing component materials. Small scale testing of coin-sized samples has been performed to characterize air and steam oxidation of many candidate materials (steels, inconel, tungsten, titanium, etc.) at elevated temperatures [18,19]. With surface oxidation known, mobilization of activated oxide particles can be accurately estimated.

Neutron activated crud deposits in the cooling systems are also a public safety concern due to their mobility in a loss of coolant accident event. Presently, fission reactor operating experience and computer codes are used to estimate the type and amount of activated corrosion products in fusion coolants. This appears to be adequate since this is not a major source term in accident analyses. The most well understood systems are water coolant in steel piping.

Table 12. Technology Readiness Levels for activation product control and confinement

TRL	Issue-Specific Definition	Facility Needs
1	Principals and data must be available regarding the solubility, permeation, and transport of activation product.	
2	Models must be developed to estimate activation product release during operation (normal and off-normal).	
3	Concepts and models must be successfully benchmarked against radiological release data, and measure against environmental release limits.	
4	Bench-scale tests must be conducted to validate the activation product confinement predictions.	Test facility for dust mobilization and explosion characterization
5	Large-scale tests must be conducted to validate activation product confinement predictions.	Integrated test facility for examining synergistic effects of activation product interaction.
6	Full-scale tests must be conducted to validate activation product confinement predictions.	
7	Prototype systems must demonstrate activation product confinement in a fusion environment.	ITER
8	Successful activation product confinement must be demonstrated at the required fusion scale size	Component Testing Facility (fusion-relevant nuclear environment)
9	Successful activation product confinement must be demonstrated at scale size and during fusion operations.	DEMO

Neutron activated dust inside the vacuum vessel is an important concern for many reasons. The erosion dust tends to be chemically toxic even before irradiation, the dust tends to adsorb tritium atoms, and the dust is typically small size so it is not only respirable by unprotected personnel but also easily mobile in the case of a loss of vacuum event. Dust in the vessel causes problems with heating antennas, diagnostic devices, vacuum valves, and vacuum pumps. The

INL has conducted a program to collect and characterize tokamak dust elemental composition and particle size distribution from existing machines [20]. Tokamak dust materials (Be, W, Fe, Cr, etc.), particle sizes (~1-10 micron), and kg inventory masses are easily in the metal dust explosive range for deflagration combustion. Millijoule electrostatic spark energies, or high radiant heat fluxes, can ignite these dusts if lifted into air. ITER estimated hundreds of kg dust in the vacuum vessel between cleanings, which poses a significant hazard. Also, dust motion in normal and accident situations is important to understand, and work is in progress to model dust lift-off in turbulent air inflow [21].

R&D needs

It is possible that some new materials that have not been tested for oxidation could be specified for fusion use. In that case, new test series would have to be performed. It is also possible that regulators could ask for larger size tests of material oxidation. The small-scale tests mentioned above were used to support the ITER safety assessment. Thus far, the Autorite Surete Nucleaire in France has not requested larger scale tests to verify effects of size (e.g., ITER in-vessel wall area is over 600 m^2), chimney effects, or any other size/configuration issues for in-vessel air or steam events.

Activated corrosion products in coolants are understood for water coolant in steel systems based on several decades of experience with fission reactors. However, there is much less experience with other proposed fusion coolants. The liquid metal coolants, such as liquid lead or liquid lithium, are similar in principle to liquid sodium used in fission, but there are differences in the chemistry. Thus, the experience base for fusion liquid metal coolants is not as strong as with water cooling systems. The lead-bismuth cooled fission reactors that have operated should be reviewed for corrosion products, as well as liquid sodium fission reactor experiences. Helium coolant is also proposed for fusion. Helium cooling in fission high temperature gas-cooled reactors has shown that while helium is benign even at very high temperatures, any impurities in the helium (air, steam, etc) are detrimental, especially at high temperatures of 800-900 C. Helium coolant purity is extremely important. The activated corrosion product issue would require further study for the exotic coolants to be able to characterize that source term.

There are many issues regarding tokamak dust that must be resolved. Accurate monitoring to estimate the mass of dust produced by plasma operation, dust motion in the vacuum vessel and vacuum system, dust effects on plasma heating antennas and plasma diagnostic devices, dust cleanup methods. Dust disposal is also an important concern; means to separate tritium from the radioactive dust to allow the many kilograms of dust mass to be disposed of as non-tritiated waste must be investigated.

Facilities needs for developing activation product control and confinement are indicated in Table 12. The level of validation for confinement approaches will vary with various regulatory bodies and depends to some degree on the nature of passive safety systems that are implemented.

4.2.3 Radioactive waste management

Because of the neutron-induced activation and the tritium inventory, fusion reactors will have associated with them radioactive wastes (radwaste). In comparing fusion radwastes with fission radwastes the following points are noted: (1) fusion has no radwaste generation associated with fuel ore tailings; (2) since fuel processing is an integral part of the fusion power plant, there is no radwaste generation in off-site fuel processing with fusion; (3) the volumes of radwaste generation associated with coolant contamination and plant decommissioning are presently much larger for fusion than for fission [13], but fusion does not generate any greater than Class C waste while fission generates spent fuel high-level waste. As a final point it is noted that certain classes of structural material may allow recycling and clearance after reasonable cooling and reprocessing [12]. The limitation of wastes to no higher than Class C and the possibility of material recycle must be demonstrated by the R&D program.

We acknowledge the importance of addressing the radioactive waste management issue, promoting recycling and clearance, and avoiding disposal [12,13]. The following quote from page 70 of the 2007 FESAC report [2] supports our position and summarizes the current status and R&D needs: "Beyond the need to avoid the production of high-level waste, there is a need to establish a more complete waste management strategy that examines all the types of waste anticipated for Demo and the anticipated more restricted regulatory environment for disposal of radioactive material. Demo designs should consider recycle and reuse as much as possible. Development of suitable waste reduction recycling, and clearance strategies is required for the expected quantities of power plant relevant materials. Of particular concern over the longer term could also be the need to detritiate some of the waste prior to disposal to prevent tritium from eventually reaching underground water sources. This may require special facilities for the large anticipated fusion components. The fission industry will be developing recycling techniques for the Global Nuclear Energy Partnership (GNEP) and the US Nuclear Regulatory Commission (NRC) is developing guidelines for the release of clearable materials from fission reactor wastes both of which may be of value to fusion."

Table 13 outlines the Technology Readiness Levels for radioactive waste management.

Current state of radwaste disposal knowledge

The US has successfully decontaminated and decommissioned the experimental Tokamak Fusion Test Reactor. However, TFTR D&D waste disposal followed all of the rules and protocols developed for the nuclear fission industry. This is expected since the fission industry pushes for progress in radioactive waste management in the US. Fission research in radwaste disposal has produced very safe shipping casks, several low-level waste disposal sites, and several workable waste volume reduction methods. Waste disposal is contentious and expensive, and it is expected to remain so for the foreseeable future. Many nuclear facilities are currently storing their low- and high-level wastes onsite because of the limited and expensive offsite disposal options. The political difficulty of constructing new repositories suggests reshaping all aspects of radwaste management, promoting recycling and clearance. Fission is currently working on clearance (also known as free release) of slightly activated materials.

R&D needs

A goal for fusion is that with good choices of low activation materials in fusion design and recycling within the nuclear industry, it should be possible to eventually reach a level of zero radwaste to be disposed of during facility operation and decommissioning [22]. At present we lack experience with clearance and have only small-mass, fission-related experience with recycling at national labs (INL, ORNL, and SRNL). Both recycling and clearance need further R&D. Adaptation to fusion needs (size, radiation type and level, T containing materials, etc.) is needed. The relevant R&D issues include [12,13]:

Table 13. Technology readiness levels for radioactive waste management

TRL	Issue-Specific Definition	Facility Needs
1	Define waste disposal rating and recycling/clearance potential for low-activation materials (ferritic steel, vanadium alloy, and SiC/SiC composites) using activation analysis. Determine the cooling periods that allow recycling and clearance of materials in < 100 years from plant decommissioning. Identify the alloying elements and impurities that violate the Class C disposal requirement, exceed the recycling dose limit, and delay the clearance of sizable components. Provide guidance on modifying the composition by altering the alloying elements and controlling the undesirable impurities.	
2	Reexamine modified alloys and calculate their activation responses in realistic fusion environment to assure satisfying recycling/clearance requirements. Validate activation cross-sections for fusion relevant materials.	Neutron-producing fusion experiments (*e.g.* JET or JT-60) for cross section validation
3	Experimentally validate predictions of analytical activation models.	Integral experiments on mockups with 14-MeV neutrons, *e.g.* FNS (in Japan) and FNG (in Italy). New facility to be built in US. IFMIF (small mockups < 6 liters).
4	Small-scale tests on irradiated mockups to demonstrate segregation of various materials, crushing, melting, and refabrication of components and to verify that slag from melting collects majority of radionuclides. Identify waste classification of slag. Bench scale tests to validate efficiency of detritiation system. Laboratory-scale tests of chemical handling processed for fusion materials recycling.	Fission nuclear facilities at INL and Oak Ridge, Tennessee. Recycling and detritiation facilities at Savannah River National Laboratory.
5	Large-scale tests conducted to validate predictions of activity and doses over longer irradiation periods in prototypical environment (neutron, heating, etc) for both highly irradiated and slightly irradiated components. Development of radiation-hardened remote handling equipment that can withstand high fusion doses > 10,000 Sv/h. NRC to develop clearance standard for fusion-specific radioisotopes.	Integral experiments with intense 14 MeV neutron source
6	Full scale test to validate activation and dose calculations at prototypical neutron flux and fluence. Reevaluate clearance index for clearable components using newly developed NRC fusion-specific clearance standards. Develop recycling infrastructure.	Integral experiments with multiple, intense 14 MeV neutron sources

7	Prototype tests of full size components conducted in D-T fusion machines to demonstrate the successful recycling of fusion radioactive materials within the nuclear industry. Develop clearance infrastructure and establish clearance market.	Component Testing Facility (fusion-relevant nuclear environment). Change out of components will generate recyclable materials.
8	Successful operation over long time of components made of recyclable materials in fusion machine. Recycling and clearance must be demonstrated for all components after facility decommissioning	Component Testing Facility (fusion-relevant nuclear environment)
9	Successful activation product containment must be demonstrated at scale size and during fusion operations.	DEMO

Recycling:

- Development of radiation-hardened remote handling equipment (> 10,000 Sv/h) for fusion use
- Large and low-cost interim storage facility with heat removal capacity
- Dismantling and separation of different materials from complex components
- Energy demand and cost of recycling process
- Cost of recycled materials
- Treatment and complex remote re-fabrication of radioactive materials
- Radiochemical or isotopic separation processes for some materials, if needed
- Efficiency of detritiation system
- Management of secondary waste. Any materials for disposal? Volume? Waste level?
- Properties of recycled materials? Reuse as filler? Structural role?
- Aspects of radioisotope and radiotoxicity buildup by subsequent reuse
- Recycling plant capacity and support ratio
- Acceptability of nuclear industry to recycled materials
- Recycling infrastructure

Clearance:

- Discrepancies between developed clearance standards
- Impact on Clearance Index prediction of missing radioisotopes (such as ^{10}Be, ^{26}Al, ^{32}Si, ^{91,92}Nb, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, ^{157,158}Tb, ^{163,166m}Ho, ^{178n}Hf, ^{186m,187}Re, ^{193}Pt, ^{208,210m,212}Bi, and ^{209}Po)
- Need for official fusion-specific clearance limits issued by legal authorities
- Large and low-cost interim storage facility
- Clearance infrastructure
- Availability of clearance market.

Facilities needed to progress the TRL for radioactive waste management are outlined in Table 13. The concept development phase (TRL=1,2) relies heavily on calculational assessments with known physical properties (*i.e.* reaction and activation cross-sections and chemical treatment procedures). Substantial facility needs arise when testing these models in the proof-of-principle phase (TRL > 3). These facilities are required to bridge the gap to deployment in fusion power plant systems.

4.3 Evaluation of facilities

The role of ITER. ITER will be a large-scale fusion plasma experiment, operating at 500 MW thermal power and with a significant tritium inventory of several kilograms of tritium. Many S&E issues can be benchmarked and evaluated by ITER, including plasma effects to first wall and divertor, magnet performance and reliability, a large-scale fusion tritium plant, operational safety, routine environmental releases from an operating facility, hands-on and remote maintenance, occupational radiation exposure, radwaste processing, and equipment reliability. ITER, however, remains a few steps away from process scaling representative of a fusion power plant.

The role of CTF. From a safety perspective, a CTF would give important data and support in two ways. Direct support would be realized in testing reactor-scale components, closed cycle tritium breeding and recovery, and other plasma-materials erosion issues such as dust removal. Indirect support would be realized in the study of fusion facility operations – studying the coolant system activated corrosion products, in-vessel and ex-vessel equipment reliability, and other operating experiences. Experience in licensing a CTF is invaluable for licensing fusion power plants because the framework developed for licensing ITER (e.g. the DOE Fusion Safety Standard [10]) would be extended and refined for CTF, providing pedigree to both the process and the regulatory agency in the unique aspects of fusion nuclear safety. Another key function of CTF is to provide a source of fusion-generated neutrons with the energy spectra (but not necessarily the high fluence) of a fusion power plant. Investigating the relationship of materials and safety analysis must eventually be performed in with a fusion nuclear test facility.

The role of non-nuclear testing. The different types and combinations of energy and radioactive materials inventories expected in fusion power plants comprise the potential threats to public safety. Many of the physical phenomena arising in accident scenarios are studied utilizing single effects testing or integrated effects analysis that are benchmarked against experiments [19]. Non-nuclear testing will continue playing an important role as fusion power plant designs mature. Non-nuclear safety-related studies should include coolant corrosion, oxidation reaction kinetics, dust explosions, hydrogen production, and other aspects of activation product transport investigated using surrogate materials. Some impact on the results is expected, however, when similar evaluations are performed on neutron-irradiated materials.

The role of accelerator and fission reactor testing. An acknowledged gap exists in understanding and evaluating the effects of high-energy neutron irradiation on structural and armor materials for fusion reactors. Safety analyses are impacted, for example, by differences in tritium permeation and retention behavior as materials receive increasing neutron dose from fusion reactions. While very few neutron sources exist with the capability of exposing material to neutron energy spectra expected for first-wall materials, many sources are available for lower-energy exposures, including thermal fission reactors and accelerator-based neutron sources. Such sources provide low fluences and softer energy spectra, however the fundamental materials response would adequately reflect a number of phenomena affecting materials microstructure. Much greater use could be made of existing neutron-irradiation facilities, advancing materials technology and improving safety analysis until fusion neutron sources are available (such as CTF). An additional important benefit of testing in existing irradiation facilities includes nuclear materials qualifications for licensing a next step fusion nuclear facility, as regulatory bodies will expect demonstration of materials behavior at conditions approaching those of the experiment facility.

5. Reliable, Available, and Stable Plant Operations

5.1 Introduction

Fusion energy potentially offers an abundant, safe and environmentally attractive source of energy for all of mankind. However, it must be demonstrated that a fusion power facility can controllably harness that power with a high degree of reliability at an affordable operational cost. All the key features of an advanced electrical power plant must be demonstrated as well as those unique features applicable to magnetic fusion energy. Handling of the radioactive tritium fuel is one of the key technologies to be demonstrated as well as the unique challenges of power handling involving high-energy neutrons, alpha particles and very high heat fluxes. This section focuses on the unique plant operations associated with a magnetic fusion energy electrical generation power plant, probably in excess of 1 GWe net to be competitive with other electrical generating plant in the time period considered.

ITER will play a critical role in the development of fusion energy, and will contribute valuable information on most of the elements of a burning plasma fusion facility. Physically, ITER is similar in scale to a fusion power plant being considered. However, ITER is not designed as a power-producing plant, and lacks many essential features of an attractive fusion power plant, such as steady-state operation, power conversion, power-plant relevant materials and conditions in the power core components (such as the divertor and blanket). ITER also lacks other key demonstrations that include high-temperature capability (for acceptable thermal efficiency), long-life and low-activation materials, highly efficient maintenance of life-limited components, sophisticated health management systems, advanced control systems to eliminate disruptive plasma behavior, use of commercial power plant systems, and validated plant operations and maintenance equipment/procedures. Even the ITER blanket test modules, which are intended to be prototypical of a commercial fusion power plant, will be operated only for very short periods of time under conditions and constraints that prevent thorough testing of long-lived nuclear components and subsystems.

The challenge of demonstration of commercial fusion hardware systems is exacerbated by the current absence of test facilities that can reproduce conditions that are prototypical of a fusion power plant facility. Therefore, an R&D program must be designed carefully and executed in a manner that provides a high degree of confidence (aka, low risk) in the operation, lifetime, and reliability of nuclear components and systems in future fusion devices. The licenseability of fusion facilities will depend on our ability to ensure safe and predictable performance of all of the systems involved in power generation.

The long developmental time scale for fusion introduces other factors that will influence (either positively or negatively) the development and introduction of fusion energy into the commercial market place. These factors will include: innovation in materials, advanced fabrication processes, enhanced components and subsystems, demanding environmental initiatives, imposition of carbon dioxide control/abatement programs, increased energy demand, advanced simulation and modeling, advanced control approaches for the interactions of systems that are themselves complex, and integration of other new technologies emerging over the next 30 years. Integrated system health and component lifetime prediction will be a major factor in plant operations.

Advanced simulation and modeling will help predict and refine how the plant can be operated and maintained. More automation and use of expert systems is anticipated in plant operations.

High-Level Goals and Objectives

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 the 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 [23] with well-performing plants achieving over 93%. Schultz [24] 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 [25]. 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.

The FESAC subpanel, "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy" [2] suggested that the demo "*ultimately achieve an availability > 50% and (be able to) extrapolate to commercially desired levels*". This would mandate that the Demo incorporate and demonstrate all the subsystems envisioned for the first commercial fusion power plant. The panel further states, "*Demonstrate the productive capacity of fusion power and validate economic assumptions about plant operations by rivaling other electrical energy production technologies.*"

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.

These goals will be reflected by the expectations of the general public and translated into governmental control agencies. It is expected that the functions of the US Environmental Protection Agency (EPA) will continue for the foreseeable future. The EPA has national emission standards for hazardous air pollutants (NESHAPs) and limits of routine radionuclide emissions in air and water are also controlled. While the annual allowable release limits may continue to decrease as time goes on, there will still be a limit to meet in the 2050-2070 timeframe. The US Nuclear Regulatory Commission (NRC) oversees nuclear power plants and will likely oversee the future fusion power plants just like fission plants. The NRC has radiation exposure limits for plants as outlined in 40 CFR and 10 CFR control documents.

Since 40CFR and 10CFR contradict each other for power plants (the entire uranium fuel cycle must be below 25 mrem/y, but an NRC licensee power plant must be below 100 mrem/y). To be sure that all regulations are satisfied, using the 25 mrem/year limit is a conservative course of action for a fusion power plant that does not have a uranium fuel cycle or reprocessing. The CFR has a section for DOE facilities (40CFR61.92) that states that such facilities must meet 10 mrem/year dose to the public. Therefore it is reasonable to expect that the other standards will trend downward toward 10 mrem/year over the next ~50 years.

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.

Electrical power generating plants have been around for over a century with many generations of plant operation capability and history. In hydroelectric power generation, the oldest was completed in 1870 in Cragside, Rothbury, England. The very first commercial central electrical generating stations were in New York and London, in 1882 using reciprocating steam engines. Many changes have implemented in these plants as they become larger, more efficient, more reliable, and provide more stable power to larger power grids. These trends will continue for all future power plants. Below are listed some areas that will be affected.

All electrical power generating plants including fission plants have previously used analog instrumentation and control (I&C) technology systems, which are considered to be mature technologies. However, analog I&C systems are now converting over to digital systems for modern control technologies to achieve more accuracy, reliability, and depth of data analysis. New I&C, data storage, and data analysis and mining technologies are maturing at an amazing pace. Fusion power systems will be the most data intensive power generation system envisioned.

Another trend is that automation will continue to displace manual control of power plants. The evolution of dials and gauges monitored by a large staff of operators has been steadily replaced by more sophisticated instrumentation and data analysis systems monitored by fewer and fewer experts. While people cannot be replaced for critical decisions, more and more control decisions will be predetermined or analyzed by computers, expanded knowledge databases, and fuzzy logic to actively control the very complex fusion plant.

DT fusion processes create a high-level neutron environment that necessitates complete remote maintenance of the power core. This will be highly automated to assure that all operations will be accomplished with speed and precision. In the future, these remote automated operations will continue to be more autonomous with more decisions and procedures being developed and executed with machine knowledge and learning.

5.2. Issues, Metrics, and R&D Needs

5.2.1. Plasma control and operations

Control of the fusion plasma is an inherent and necessary part of all prior and current experimental facilities. Knowledge of how to efficiently control the plasma is an evolving database of theory and experimental results. Much of the operating space for experimental interest is near or at the unstable operating plasma boundaries. But the commercial fusion plant will likely operate further from the unstable boundaries to minimize disruptive behavior, or active controls will be developed to allow operation closer to the unstable boundaries to improve plasma performance. There are two separate plasma control characteristics or goals that will be required for the future fusion power plant.

1. <u>Control of plasma to virtually eliminate all plasma disruptions and anomalous detrimental behaviors.</u> Plasma control is anticipated to be autonomous and automatic, and based on instrumentation and sensors and control algorithms derived and updated from prior operations, and from experience in control of complex and autonomous systems in related industries, such as process control and aerospace.

   Current plasma physics experiments have developed extensive capability to monitor some types of incipient plasma disruptions and make adjustments to a small number of inputs to prevent growth of the disruptions. However, the current capability is not sufficient to prevent disruptions to the degree that will be required for a commercial power plant. Achieving the required capability will require maturation of plasma control in two areas. First, a more complete understanding of the behavior of the plasma is necessary so that control system designers can specify what needs to be done to suppress or eliminate the growth of the various types of disruptions. Second, control laws and control hardware must be developed that can, in real time, accept sensor inputs of various levels of trustability and generate control commands to be issued to a variety of disparate effectors with different response times so as to suppress plasma instabilities. Maturation of plasma control can proceed individually for each area; however, the maturation can be accelerated if the work in the two areas is combined. Concepts such as a virtual laboratory made by linking plasma physics research facilities and physicists with aerospace control laboratories and engineers could greatly enhance development of stability control for plasmas.

2. <u>Control plasma at power levels of 1%, 10%, and 50% to 100% and control of heat fluxes to plasma facing surfaces</u>. Results from ITER will contribute to this body of knowledge. The same control system maturation for plasma control and disruption prevention must be applied to control of the plasma at system power levels between 0% and 100%, and during special modes of operation, such as start-up. An issue that is related to control at partial power levels is the existence of self-consistent plasma solutions (i.e. do profile and shape combinations exist) consistent with partial power operation. This needs to be addressed by a design process that incorporates solutions at all desired power levels. This is, however, outside the scope of the present study.

> Note: It is absolutely necessary for both of these prior goals to be attained even though they were discussed separately. However in the discussion below on *current state,* these two goals will be addressed as a fully integrated and cohesive requirement. In the following discussion, "sufficient control" means both control of the plasma parameters during full power operation as well as control during startup, shutdown, and partial power operation for sustained periods.

Current state of knowledge

Control of plasma shape and profiles essentially requires measuring a quantity and modifying it. This process can be divided into four steps: (i) Identification of the required parameter value and acceptable range. This is generally defined by the reactor design process and performance requirements. (ii) Diagnosis of the current state. This requires a diagnostic measurement of the parameters. Generally the measurement involves a set of diagnostics from which the parameters of interest can be derived. (iii) An actuator to modify the profile. Typically this involves controlling several kinds of input to the plasma that can be related to the parameter needing to be controlled. (iv) An algorithm to translate the required change in the profile to the actuator or actuators controlling the input to the plasma.

A general Technology Readiness Level (TRL) table can be constructed covering the issue of control of the plasma. This is shown in Table 14.

The plasma parameters requiring diagnostics and control are strongly interrelated but can be broken down into seven categories where the parameters are more closely related within each category. Using the TRL definitions in Table 14, individual TRL values can then be assigned to each category. These categories are: global parameters; plasma shape; plasma current density profile; plasma rotation profile; plasma composition profiles; and power handling control. Of these, the last is discussed elsewhere and separate TRL definitions have been constructed so will not be discussed further here. However, it should be kept in mind that the ultimate goal of the remaining plasma control issues is essentially to enable control of the power output from the fusion reactor.

The following paragraphs are devoted to discussing each of these categories in turn. Within each category, there are then several specific parameters requiring control. These will be detailed in each case. A brief description of the current status in terms of the four steps required for adequate control is then provided, leading to an evaluation of the present TRL level that should be assigned to each category. In this, the requirement under TRL of 5 for self-consistent integrated control is interpreted as requiring only integrated control of the parameters in that category. Integration of control for all categories is considered implicit in level 6.

Ultimately, the diagnostic and actuator technologies need to survive in a BPX environment. This is a serious requirement and it is important to gauge the confidence level that the current state of research can be extrapolated to a final reactor. Since most of the TRL values assigned are limited to below level 5 or 6 simply by the lack of appropriate facilities available, as described in the notes to Table 14, it is appropriate to estimate the level of confidence that the remaining TRL stages can be reached using the diagnostic and actuator techniques available now or with reasonable extrapolations. Consequently, an indication of this confidence level is also provided in the following paragraphs.

Table 14. Technology readiness levels for plasma control

TRL	Issue-Specific Definition	Facility Needs
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.	This can be performed in either a dedicated laboratory plasma physics experiment or one of the current national facilities.
4	Demonstration of controlled plasma shape and profiles within approximate limits in closed loop in a current high temperature plasma confinement experiment.	This should be performed in one of the current national facilities.
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.	This should be performed in one of the current national facilities
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.	This step should be performed in a dedicated planned experiment such as KSTAR.
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.	This step can be performed in KSTAR or in ITER running in high power mode.
8	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration.	ITER might be able to satisfactorily complete this step but it may require a burning plasma experiment. This may be a dedicated experiment or DEMO.
9	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration for lifetime conditions.	Demo.

The specific global parameters that are required to be controlled are fusion power, plasma beta, confinement quality, and heat and radiation loads. Overall, control of these global parameters is well understood. The required values and range set by fusion power requirements and POPCON calculations. Measurements of these values are routinely performed in current experiments using diamagnetic loop measurements, and neutron rates and power flows to material surfaces coupled with equilibrium reconstructions. The parameters can be modified by adjusting fueling, adjusting D-T ratios, and through control of transport barriers by various operational means – especially current ramp rates, and timing of auxiliary heating. Development of the required translation algorithms for converting the desired change in the global parameters to a change in the input fueling or operational details is generally through simple trial and error but more sophisticated time dependent 1½-D transport calculations can be used to provide more precise control. Overall, we can conclude that control of global parameters is unlikely to be an obstacle. Under either the modest extrapolation scenario or the advanced concept scenario, the current TRL can be rated as 5, limited only by the lack of facilities needed to test the scale up to fusion conditions. In addition, one can assign a very high confidence that the diagnostic, actuator, and algorithm techniques currently available will scale if applied in a BPX.

Control of the plasma shape includes control of plasma elongation, triangularity, and higher order shaping, especially squareness and divertor balance. As with global parameters, the status of control of plasma shape is also well advanced. The required values and range are set by the design process and are largely based on the ARIES-AT design. Plasma shape is relatively easily diagnosed in current experiments by measurements using external magnetic loop measurements coupled with equilibrium reconstructions. These parameters can be modified as needed through control of the external poloidal field coils and the translation algorithms required for this are well established since they are routinely applied and automated in all major tokamaks. Elongations up to 3 to 1 and triangularity ~ 1 have been obtained in those machines with the poloidal field coils equipped to reach these extremes. Attainment of the values specified in the ARIES-AT design is routine. Overall, control of plasma shape rates a moderate TRL. For the modest extrapolation scenario, the current TRL can be assigned a value of 5. For the advanced concept scenario, where optimization of the plasma shape is more crucial, the current TRL is naturally lower at a value of 4. There is high confidence that the techniques currently available will scale to a BPX. However, there is a concern that the stringent divertor requirements may limit the higher triangularities needed for the most advanced scenarios. However, this is a design issue, not really a technology readiness issue.

Plasma kinetic profiles include the electron and ion pressure, density, and temperature profiles. Control of these profiles is a key feature of all advanced scenarios. The required profiles and ranges are set by the design process and are largely based on the ARIES-AT design with $T_i \sim T_e$ and n_e set from fusion cross section requirements and the ranges determined from sensitivity calculations. The profiles are currently measured using Thomson scattering and Charge Exchange Recombination (CER) diagnostics and can be modified by pellet injection, gas puffing, and Neutral Beam input, as well as Radio-Frequency (RF) wave heating and divertor pumping. However, there is some level of profile consistency or resilience that presently limits how much these techniques can control the profiles. This will be more true when significant alpha heating is present. Translation of the desired profiles to fueling input typically requires deposition calculations for pellets, RF, beams, and gas. These need to be coupled to equilibrium reconstructions and transport simulations. In addition, for fusion relevant plasmas, alpha particle slowing down and heating calculations will be required but the tools needed to calculate these already exist. At present, control of kinetic profiles is still an active area of current research being one of the foci of the Advanced Scenario. For the modest extrapolation scenario where active control of the profiles is not a key element, the current TRL is assigned at a value of 4. For the Advanced concept scenario, where profile control is crucial, the current TRL = 3. Direct application of the diagnostic techniques to a BPX is not expected to be an issue. However, extrapolation of the actuator techniques to a BPX is limited to the extent that alpha heating will then dominate the temperature profile evolution.

Control of the current density profile, or equivalently, the safety factor, is a key element in the Advanced Scenario. Current profile control techniques are fairly well developed and present experiments are moving to closed loop. The required current profile and allowable range are set by the design process. For the advanced extrapolation scenario, these are largely based on set by ARIES-AT design and sensitivity calculations. The current profile in present devices is usually measured using the Motional Stark Effect (MSE) to find the magnetic field pitch angle and which requires at least a diagnostic Neutral Beam. The local current density is then found from the magnetic field pitch angle using an equilibrium reconstruction. Polarimetry has also been used to diagnose the current density but has generally not been particularly successful. Modification of the current profile is achieved by noninductive current drive from various waves but the efficiencies attainable are generally low. These include electron cyclotron current drive (ECCD), Lower Hybrid, and ion cyclotron radio frequency (ICRF) waves. The Advanced Scenarios typically compensate by attempting to maintain a large fraction of the current using the bootstrap current generated from the pressure gradient profile so that only a small part of the current is driven by the waves. However this provides additional strong constraints on the stable profiles that are allowed and that are typically not easily reconciled. The algorithm to translate the desired current profile to input current drive requires ray tracing and current drive deposition calculations, which are well known. Present research is actively focused on current profile control and for the modest extrapolation scenario, the TRL is currently assessed at 4 and for the Advanced concept scenario at TRL = 3. With respect to the extrapolation prospects, the MSE diagnostic scales well to the higher fields expected but current drive techniques have some scaling issues. In particular there are density limitations to each of the current drive schemes. While the efficiency generally scales with temperature, which is favorable, the required driven current also increases. There are also issues that MSE may not be viable even with MeV beams due to the expected signal noise ratio. These issues need to be resolved. However, they will already be issues in ITER and it should answer those questions. Nevertheless, there are other ways of obtaining the same data with better signal to noise ratios being considered. ITER is also expected to answer whether the efficiencies are adequate.

Plasma rotation profile control is a key issue for advanced but not for modest extrapolation scenarios. In the advanced scenario case, the required rotation values and profile are set by resistive wall mode (RWM) stability and possibly confinement requirements. The minimum generally needs to be satisfied only, but with low momentum input a reactor is unlikely to rotate too fast. The key physics involves the main ion rotation but this is not well diagnosed. Impurity rotation profile measurements are typically done using CER and the main ion rotation is inferred from it. The main ion rotation profile can be modified by momentum input from Neutral Beams.

This is the main actuator in current experiments. Drag from non-axisymmetric error fields can also slow the edge rotation but this introduces undesirable effects. Translation of the desired rotation to beam input requires beam deposition, angular momentum transport, particle loss, and magnetic drag calculations. Of these, the physics of angular momentum transport and magnetic drag is an ongoing area of research but significant progress has been made in the past few years. For the modest extrapolation scenario with limited need for rotation control, the current TRL = 4. For the Advanced concept scenario, however, the current TRL should be assigned a value 2 or lower, limited mostly by the lack of actuators that can control the profile details in a predictable way. In a BPX, while the rotation profile can be diagnosed, few methods to modify it appear to exist without large high voltage neutral beam input. It may also be possible to modify the edge rotation using external rotating nonaxisymmetric fields and this is an active area of research. The detailed profile is likely not necessary, just knowing the rotation is sufficient in some fairly global sense may be sufficient. But this basic physics is not yet well understood.

The category of plasma composition profiles consists of two main elements: D-T ratios and impurity fractions. These need to be considered somewhat separately, since the D-T ratio is critical for a fusion reactor. The D-T ratio is relatively easily controlled by fueling and the required values are set by fusion yield calculations with the allowable range adjustable during operation. Diagnostics for the D-T mix are obtained from global measurements of neutron rates and fusion power, which are easily diagnosed. D-T ratio profile measurements can also be obtained as was done in TFTR. The global mix and profile are fairly easily modified by a combination of Tritium neutral beam input, pellet fuelling and some additional control can be obtained through controlling the isotopic differential transport rates. Translation of the desired D-T ratios to fueling input requires deposition calculations for beams and alpha particle slowing down and heating calculations. One can expect to be able to empirically determine needed adjustments in D-T fueling. For both the modest extrapolation and advanced concept scenarios a current TRL value of 4 can be assigned. There is a high confidence that present techniques will scale to BPX conditions.

In contrast, impurity and alpha ash are not easily controlled. This requires control over the relative particle and heat transport rates. The values and allowable range are set by the desired fusion yield. The impurity profile density and temperature can be diagnosed using CER. The profile can be modified by altering the balance between the particle and energy confinement. MHD fluctuations from sawteeth and edge localized modes (ELMs) appear to be the main tool that can be used to control ash accumulation in particular. Translation of the desired ash and impurity concentration to MHD fluctuation size and frequencies requires somewhat detailed impurity transport calculations as well as some advances in the physics understanding of these processes. ELM and sawtooth frequency and size control will also be needed. These are currently active areas of research. Some techniques such as temperature and density transport barriers exist for selectively transporting impurities but are not yet reactor relevant. Some ELM-free regimes hold some promise. Current TRL values assigned for the modest extrapolation scenario and advanced concept scenario are 3 and 2 respectively. It is not clear how any of the control techniques will scale to a BPX. In particular, even moderate sawteeth and ELMs are problematical in a large fusion experiment; there are big questions on how this can be done and whether ELMs and sawteeth will provide real control while remaining at a tolerable level. ITER is intended to answer this and it is currently, this is the biggest question facing ITER. Given that, if it is marginal in ITER then it will be an issue that will restrict the TRL since the extrapolation to DEMO will remain problematic. There seem to be few other tools available for modifying the particle and energy confinement balance.

In summary, the key issue for control of the plasma in the modest extrapolation scenario is the problem of impurity accumulation. For the advanced scenario, the key issues are scale up of rotation control and impurity control technologies. This is summarized in Table 15 below.

Table 15. Summary of current state of key issues for plasma control

Issue	Modest Extrapolation Scenario TRL	Advanced Extrapolation Scenario TRL	Scale up Confidence Level
Global parameters	5	5	Very High
Plasma Shape	5	4	High
Kinetic Profiles	4	3	Moderate
Current Profile	4	3	Moderate
Plasma Rotation	4	2	Low
D-T Ratio	4	4	High
Impurities	3	2	Low-moderate

While ITER is expected to address many of the plasma control issues, there are three big issues that are not really resolved by ITER; two related to the difference between long pulse and steady state and one to the more commercial aspect of DEMO. The two related to steady state are robustness and the fluence. The third is the issue of limited diagnostic access available.

(i) The techniques used in ITER for the diagnostics and actuators may be insufficiently robust for DEMO. This remains to be seen but we have 10 years or so to make progress on improving the robustness of the current plasma control systems. The improvement over the past 10 years has been quite considerable, if not dramatic.

    A key difference between ITER and DEMO related to the issue of robustness is that in DEMO the concern is that there should be no windows having a direct line of sight between the main plasma volume and the outside world. This means diagnostics relying on collecting or emitting photons (or other particles or radiation) cannot have a direct line of sight to their target but must rely on reflections. This is not an insurmountable problem unless the diagnostic relies on measuring the polarization. But it does need work.

    The total suite of diagnostics needed – or the rate at which they can be reduced as fusion reactors become viable – also depends strongly on the robustness of the equilibrium solution targeted. Some targets such as ARIES AT require fairly detailed control keeping q in a specific range. Others might be more robust, requiring only control of the minimum q (lower aspect ratio and stronger shape). The so-called hybrid scenario is another example. For most AT solutions the key issue limiting robustness operationally is the possible formation of steep internal transport barriers leading to runaway pressure peaking and fusion rate and a disruption. This is a bifurcation event so in the neighborhood of this parameter choice the system is inherently non-robust. ITBs can apparently be avoided if the minimum of q is far enough out but the physics is still not that well understood so it is not fully clear if this is just due to the operational constraints needed to keep the minimum of q far enough out.

(ii) While the flux in DEMO is not much different from ITER but there this is a big difference in the total fluence in DEMO and this is the key problem DEMO must face. In the plasma control context, the effect of high fluence on diagnostics is a problem. There are some ideas around now but it is not being addressed in any systematic way. This is apparently tentatively planned to be addressed in ITER Phase II but it is not the priority for ITER.

(iii) Regarding limited access in DEMO – essentially a simple space limitation, ITER should reveal how much of its diagnostic capability is really necessary. This can also be done using the other machines expected to be available before ITER, namely KSTAR and EAST. But the real answer probably won't be fully known even after ITER unless ITER itself designates real time to looking at it.

Metrics

Plasma control metrics have not been established yet, but it probably will be the number of potential plasma disruptions avoided (or not avoided).

R&D needs

These are expected to be provided by the facilities listed in the notes to Table 14.

An overarching R&D need is to develop highly radiation resistant instrumentation that is very compact, preferably with a lifetime similar to the blanket and divertor modules.

5.2.2. Integrated Plant Control and Operations

The previous section discussed the present technical maturity status for the control of the tokamak fusion plasma and the R&D needs to provide a control capability consistent with an advanced power plant. It was mentioned that for some of those plasma control categories, interconnected control among parameters within a category has matured to TRL 5. However, to reach TRL 6 and above, control among the categories will be necessary. In addition to control of the fusion plasma, there remain a myriad of other power core and plant systems that must operate efficiently in a completely integrated manner to optimize the entire operation of the plant over its lifetime.

All the plant systems will be involved in this plant integrated control. In the past, many large process plants have distributed controls with a minimal top level control (aka, federated control). This control architecture is easy to separately design, test, and validate, but difficult to control during operation to achieve an optimized plant design and operation. More modern design philosophies suggest optimizing the entire plant, with the individual subsystems operating at a slightly sub-optimal design point and all plant systems under a complete plant integrated control (integrated control). Certain control functions are still under local control, especially those with fast acting time constraints and intensive data handling and transfer.

Control among the plasma control categories and the remainder of the power core and plant systems will be necessary for several reasons. First, it will increase the efficiency of the power plant. Second, it will increase the reliability of the power plant. Third, it will reduce the cost. These benefits come from maturing the control system from its present federated form to an integrated form.

First, the benefits of improved efficiency, comes directly from integration of control among the parameter categories. Control federation makes optimization of each subsystem within a larger system relatively simple. However, optimization of all the individual subsystems does not necessarily optimize the operation of the system. Plasma control and operation appears to be one of those areas in which optimization at the system level will require interactions among parameters in different categories, even if that interaction causes what may appear to be suboptimal operation within some categories.

Second, the benefits of increased reliability, comes from the ability of an integrated system to sense departure of a parameter from its normal range, and make compensating changes in parameters that may be in other categories to either bring the first parameter back into its normal range, or to maintain the plasma in a new stable state with the first parameter out of its normal range. It is also quite likely that the elimination of plasma instabilities, which will be necessary for fusion power plants to reach >90% availability, will only be possible with integrated control.

Third, the benefits of reduced cost, is both an indirect benefit that accrues from the first two benefits, and a direct benefit that comes from the ability of an integrated control system to be highly automated, and to interpret the signals from many disparate sensors to make predictions about maintenance requirements.

The two direct impacts of integrated plasma control on cost are worth examining further. Integrated control across the plasma parameter categories allows and supports two significant cost saving features that will be necessary if fusion power plants are to be economically competitive with other energy sources.

1. Highly autonomous control requiring a minimal number of control room operators for normal operations as well as maintenance operations. Cognitive modeling of the plant will incorporate prior plant operating experience to respond to present operating conditions and prescribed rules.
2. Incorporation of system health monitoring and predictive capabilities to determine the state of health of all plant systems and predict when maintenance or replacement actions are required.

During the introduction of early fission power plants, control room personnel included engineers, physicists, and operators for reactors like the first PWR (Shippingport atomic power station). As these fission plants became commonplace and the operations became more standardized, the staff was reduced to only trained operators. After the TMI-2 accident occurred, federal regulations then stipulated the number of operators on each shift to properly respond in accident situations. One of the new rules established that a degreed nuclear engineer should serve as a Shift Technical Advisor to deciphering unusual plant conditions and advise the operators of the correct action. The code of federal regulations (10CFR50.54) currently states the number of and certification level of operators on duty in a nuclear (fission) plant control room. Typically one power unit requires 2 senior operators and 2 operators plus a Shift Technical Advisor. The post-TMI rules have lived for ~25 years in the CFR, however, this may not continue in the future and may be different for fusion plants. In particular, if it can be demonstrated that by means of control automation a higher level of safety, availability, and reliability can be achieved than with many human operators, operational staff can be reduced, with a considerable cost savings.

In the fusion introductory period (Demo and the initial power plant), there will be, no doubt, numerous personnel required on-site at the fusion plant. However, after the initial operational periods and several plants operated, the data base of plant behavior would be large, which would greatly support autonomous operation of many of the systems, and the on-site staff would be reduced to only a few human operators overseeing the computers, which will do the bulk of the analysis and control.

Reliability, availability, and automatic supervision of technical processes and their control systems are important consideration in overall system design and operation. An integral element of a highly reliable, fault tolerant system is an efficient fault detection and identification technique that can detect and isolate the sensors, actuators, or system component failures so that remedies can be undertaken. A failure is defined to be any deviation of a system from its normal or intended behavior; diagnosis is the process of detecting an abnormality in the system behavior and isolating the cause or the source of this abnormality. Built in test (BIT) will help diagnose healthy systems, systems that are degrading or nearing failure, and those that have failed.

Integrated System Health Management (ISHM) in an ideal implementation reduces costs directly by predicting failures and thereby converting all unscheduled maintenance actions into scheduled maintenance actions. In addition, ISHM is capable of reducing costs by improving plant availability. At present, the most advanced control systems in industry, particularly aerospace, are capable of implementing what is called Reconfigurable Control. That means that when a failure occurs, the control system is capable of detecting the failure, determining what to do with the parameters it still controls and are functional so as to achieve continued operation of the system, and, finally, is capable of acting on that determination. ISHM takes this process one step further, in that the system is now capable of monitoring trends in performance of the system, and predicting failures before they occur. With that knowledge, the ISHM system is capable of taking actions ahead of time to prevent the failure from occurring, or mitigate its impact when it does occur, with minimal or no impact on the regular operation of the system. To give an example from aerospace, the IVHM (Integrated Vehicle Health Management) system is capable of monitoring switching speed and leakage through a hydraulic valve, and predicting if the valve will fail before the completion of the flight. If it is predicted the valve will fail under normal conditions before the end of the flight, the IVHM system will construct a new state of reduced load on the related flight surface. This will allow the valve, and the flight surface, to function in a degraded mode until the end of the flight. If the IVHM system finds such a state, it will determine what combination of commands are necessary for the other flight control actuators that will correctly unload and compensate for the weak valve and flight surface response while providing an acceptable level of flight control and vehicle performance.

In that last step lies one of the critical issues with ISHM. Again using the example of an aircraft, a flight control system uses sensors, computers, and software that are highly trusted. IVHM is a new system without years or decades of use history behind it. IVHM also may make use of new sensors that are more sophisticated, but potentially less reliable, than the simple sensors in the flight control system. It may also make use of inferences drawn from existing sensors using software that is also more sophisticated, but potentially less reliable, than the simple, scheduled, and intensely tested software of the flight control system. Finally, the IVHM system uses the new real and new inferred sensors to supply inputs to new software that develops complicated conclusions from the inputs. Given all the new components and the complexity of the IVHM system, it is no wonder that aircraft control system designers will not allow the flight control system to simply do whatever the IVHM system suggests to it. Instead, a vast effort is going into studies and experiments to determine how to reliably and safely make a flight control system and an IVHM system work together despite different levels of trustability of the physical components and software. The fusion energy community will probably never have the resources available to spend on ISHM that aerospace spends on IVHM. Fortunately, the issues in the two industries are so similar that if the fusion community works with the aerospace community on this technology, it is quite likely that the fusion community will be able to achieve the benefits of ISHM while only paying the cost of adapting working IVHM from aerospace applications to fusion.

Thus, methods for integrated control, including control automation and ISHM, are currently embryonic within the fusion energy community. These will need to be matured for use by future fusion power plants. Such methods are much more mature in other industries, especially aerospace, so there is a strong possibility that the integrated control methods that will be needed in the future by fusion power plants will not have to be wholly developed from first principles, but can be adapted from control systems in the other industries.

Metrics

Integrated plant control metrics have not been established yet, but it probably will be the number of operational hours per year, the number of outages and number of potential maintenance outages avoided (or not avoided).

R&D needs

Future development of plant integrated controls probably may not require dedicated facilities. Rather it will evolve based on advances in other contemporary large facility control systems. These advances will be adapted for use in the fusion plant control system. Plant control laws will be developed, tested, and validated with advanced simulation facilities.

Table 16. Technology readiness levels for reliable and stable plant integrated control (system interaction, control autonomy, knowledge based control, regulatory interaction, power grid interaction)

TRL	Issue-Specific Definition	Facility Needs
1	Conceptual definition of system control requirements determined from system studies, Control mechanisms identified	
2	Conceptual definition of system components and characterization of operating environment. Formulate control approach.	
3	Preliminary design of control approach and logic diagrams. Early system simulation and modeling to define operational environment and demonstrate proof of concept.	Some new small scale prototype production and testing facilities many be required to demonstrated critical function or proof of concept for operations
4	Firm requirements document and system architecture published. Preliminary control design completed. Modeling and simulation of hardware and software components and subsystems in a laboratory environment begun to help quantify key issues. Laboratory (breadboard or pre-production) components tested for functionality, reliability, failure modes, and response to failure metrics. Available components assembled into subsystem breadboard for testing, perhaps at subscale. Technology availability dates established	Some new bench-scale prototype testing facilities may be required to validate prototypical operations hardware or process in an applicable laboratory environment. Existing fusion experimental facilities may be useful to test new operations hardware and processes.
5	Detailed design completed. Pre-production software and hardware at brass-board level tested and validated in relevant environment to identify problems and confirm key metrics. Key processes identified. High fidelity lab integration of subsystem completed, ready for realistic/simulated environments. Final reliability and lifetime target levels not final yet.	Preproduction components and processes will be tested in a relevant environment (perhaps ITER or component test facility). Key to applicability is operational efficiency and reliability of decisions.
6	Firm operating environment established. M&S used to determine system performance in operational environment. Final test and evaluation plan approved. Model or prototype subsystem tested in relevant fusion environment. Critical manufacturing and software production processes prototyped. Most pre-production hardware and software available. Integration demonstrations have been completed. Processes and tools are mature. Requirements document formally approved.	Preproduction components and processes are integrated into operations subsystems and tested long term in relevant environment (ITER or component test facility, depending on operations criteria).

7	Materials and manufacturing processes demonstrated. M&S models the few unavailable subsystem elements. Prototype subsystem built with "soft tooling". Component tests in a relevant fusion nuclear environment with meaningful fluence. Specimen tests approaching end-of-life fluences for life limiting components (~4 y). Testing continues for longer life components. Testing also includes higher stress conditions with anomalous conditions. Maintainability, reliability, and supportability database above 60% level. Initial manufacturing sigma levels established. Scaling is complete. Limited quantity preproduction hardware is available. Ready for Low Rate Initial Production	Production prototype operations subsystems are tested long term in operational environment, such as Demo. CTF might accommodate new operations hardware and processes.
8	Components (and subsystems) are form, fit, and functionally compatible with operational subsystem (and system). Cost estimates are < 125% of goals. Machines and tooling demonstrated in production environment. Software thoroughly debugged. All materials are in production and readily available. Components operated to end-of-life in a relevant fusion environment with prototypical conditions and subsystems (excepting those life of plant components and subsystems that must be validated with extrapolations using M&S). Subsystems meet all specifications and qualified for plant operation (validation complete). Ready for full rate production.	Production operations hardware and processes are tested long term in operational environment, such as Demo.
9	Operational concept successfully implemented. Cost estimates < 110% of production cost goals. Design stable. System installed and operational. Training and supportability plans implemented. All manufacturing processes controlled to 6 sigma. Testing of life-of-plant components continue to be tested in fusion reactor environment with prototypical conditions and subsystems. Testing of life-limited components and subsystems with anomalous, fault, over-stressed conditions to improve performance and predictive capabilities.	Production operations hardware and processes are operated long term in operational environment, such as Demo or the first operational power plant.

5.2.3. Fuel cycle control and operations

The fuel for a deuterium tritium (DT) power plant consists of a naturally occurring isotope of hydrogen (deuterium) and another isotope that must be created using neutrons from fusion reactions (tritium). The natural abundance of deuterium, ~154 ppm [in water?], assures a nearly limitless supply, and extraction from water is not difficult. Tritium on the other hand can be bred in lithium-bearing blankets *via* nuclear reactions that utilize the neutrons generated in the plasma. The ability to breed sufficient tritium without overbreeding (creating an inventory problem), extract tritium from the breeder, process and track the tritium inventory, and clean tritium from the heat transport system and buildings are all essential for meeting regulatory requirements and for assuring that the fusion reaction can be sustained. Leakage and permeation are important additional issues, which were treated as safety concerns in section 4.2.1.

Technologies for handling tritium have been developed in the fission industry (especially CANDU plants) and weapons programs. In addition, ITER will handle a significant amount of tritium. Some of the processing and cleanup systems are similar to those anticipated for implementation in a fusion power plant, but significant differences exist.

- Although ITER is expected to breed some tritium in test blanket modules, the amount is very small compared with a power plant.
- The amount of tritium burned in the ITER plasma will be much less than a power plant due to plant duty cycle and fusion power levels.
- The availability requirements on a power plant are much higher than ITER, requiring a significantly higher degree of reliability and control in fuel systems.
- A substantial amount of tritium, of the order of 5-10 kg, will be needed to start up a power plant. For a commercial plant, this source of tritium is expected to come from other power plants or from nuclear test and production facilities. This must be considered in the startup and operational plan.

In 1983, EPRI sponsored McDonnell Douglas Corporation (MDC) to conduct a technical risk assessment of an MFE fuel system [26]. MDC teamed with Ontario Hydro because they had enormous experience processing and handling tritium. The Tritium Systems Test Assembly (TSTA) team also was fully involved and provided much technical guidance. The primary purpose was to identify at least two leading fuel subsystem candidates, evaluate their current (1982) capability and forecast their technical progress into the future (up to 2010). These data were gathered by interviewing all the US and Canadian fuel subsystem experts. These forecast data were input into a fuel system simulation, which estimated the likelihood of meeting future facility fuel needs and requirements. Supportive R&D activities were planned to achieve the necessary fuel system maturity.

With many similarities and many differences between a fusion power plant and other tritium-related technologies, it is difficult to assess the level of current progress toward a practical fusion power plant. In the application of TRL's the relevance of the environment and importance of scale suggest that large extrapolations will remain even after successful operation of ITER. Table 17 summarizes the current state of advancement for the 6 major sub-issues involved in the tritium fuel cycle for both the moderate extrapolation and advanced concepts. The difference between the reference concepts is fairly minor for this topic; the main differences occur as a result of the lesser database for SiC composites used in the advanced fusion power core. The issues and current state of knowledge are discussed in more detail below.

1. Control of breeding in the blanket requires an understanding of basic nuclear data for all materials involved in the neutronic behavior of in-vessel components and benchmarked integral models that predict the effect of various design and operational changes. At present, the vast majority of the required basic nuclear cross-section data is available. Sophisticated 3D numerical models of neutron transport have been developed, and some subscale integral benchmarking data exist. ITER will provide a great opportunity to further refine the models and provide direct data for tritium breeding. Some further refinements may be required for blankets that provide marginal tritium breeding (such as some ceramic breeder blankets), but ample breeding is possible in properly-designed liquid breeder blankets. In fact, a small excess of breeding in the blanket can result in a large buildup of tritium inventory, thus active control of breeding is likely to be necessary in a power plant. This might be relatively easy in liquid breeders and difficult in solid breeders. The technologies for active control still require formulation, prototyping and demonstration. Overall, the technology readiness in this area is judged to be at a current level of 3-4, and ITER could advance this to level 6 with a proper blanket module test program.

2. Recovery of tritium must be accomplished from the blanket and in-vessel components in an efficient and timely manner to reduce the inventory of tritium and reduce the demands on breeding. Tritium trapped in the breeder or other in-vessel materials is wasteful due to beta decay and contributes to accident hazards. For most breeding blanket concepts, techniques for extracting tritium have been identified, and for some concepts, proof-of-principle chemistry tests have been completed. In general, tritium recovery has advanced to level 3. ITER could advance this to level 6 assuming a proper blanket module test program.

3. Processing of tritium is required in order to close the fuel cycle and control the plant inventory. Feed streams for the tritium processing system include the plasma exhaust, blanket tritium extraction system, and cleanup systems from the buildings, hot cells, waste processing, and ancillary systems. Individual processes involved in tritium processing include isotope separation, fuel purification, recovery of tritium from water and other impurities, tritium storage, gaseous effluent processing, and tritium migration and cleanup.

The Tritium Systems Test Assembly (TSTA) was a facility that began operations in 1984 and contained all of the systems required to process DT fusion fuel [27]. These systems were sized at full-scale, and they were fully integrated for a complete tritium processing “loop”. However, the controlled “glove-box” environment is considerably different than the complex environment of a power plant. The level of control, reliability, and throughput will be higher in a power plant. Experiments such as JET and TFTR also contributed valuable operating experience in a more prototypic system configuration, albeit with very small quantities of tritium involved and lower duty cycles. Overall, tritium processing has advanced to TRL level 4, and should approach level 6 following successful operation of ITER.

Table 17. Technology readiness levels for fuel cycle control

TRL	Issue-Specific Definition	Facility Needs
1	Define requirements for breeding, fuel processing and inventory control; formulate scientific quesitons involving neutronics, tritium chemistry, permeation.	
2	Conceptual studies of breeding blankets, extraction and processing systems.	
3	Nuclear data, nuclear analysis methods, tritium handling and measurement techniques, specimen tests.	14-MeV neutron experiments, extraction chemistry, permeation measurements
4	Explore and demonstrate integrated behavior of tritium (or surrogate hydrogen isotope) in elements of the fuel cycle, including blanket mockups, individual processing systems, etc.	Integral breeding experiments, extraction from modules, fuel processing demo (TSTA), tritium handling in tokamaks
5	Fuel cycle component research and performance demonstration in a relevant neutron environment.	ITER test module operation, ITER tritium processing
6	Closed fuel cycle in a neutron environment. System inventory control demonstration.	Integrated fuel cycle prototype in ITER.
7	Fuel cycle demonstration in a continuously operating, high duty-cycle, high-throughput test reactor. Demonstration of tritium over-breeding and provision for large startup inventory.	Integrated fuel cycle prototype testing in a test reactor.
8	Operations completed successfully in a full-scale tritium fuel system servicing a high duty-cycle, high-throughput test reactor. Demonstrated ability to provide startup fuel and to overbreed.	Integrated fuel cycle prototype demonstration in a test reactor
9	Operation of a complete tritium fuel cycle in a demonstration power plant.	Demo

4. <u>Tritium cleanup</u> will be required from buildings, process loops and waste streams in order to meet safety and regulatory requirements. Affected buildings requiring atmospheric recovery include the power core building, the hot cell building, and the fuel handling and processing building. Heat transport loops (primary coolant, secondary coolant if used, and heat rejection systems) will be undoubtedly contaminated even with the use of tritium transport barriers and other mitigation schemes. Any pathway for solids, liquids or gases to escape the plant is a potential source of tritium loss. Therefore, cleanup systems must be developed and demonstrated for managing tritium throughout the power plant.

Many of the cleanup processes have been demonstrated already in TSTA and other facilities, as mentioned above. The same level of technology readiness is applied as with basic tritium processing techniques.

5. <u>Accountability and monitoring</u> of tritium is a serious issue as a result of the high mobility of tritium, the large anticipated inventory, and the fact that tritium is a controlled radiological substance. To put things into perspective, ITER is expected to contain ~10 kg of tritium on site in both in-vessel and ex-vessel locations. Commonly adopted safety goals for fusion power plants allow only 10 g of tritium to be released in an accident scenario (0.1%), and 1 mg per day (10 Ci/day) released under normal operations. Yet tritium atoms penetrate easily through solid metal, especially at elevated temperature, and easily leak through small cracks and joints. It is likely to be pervasive throughout the plant in small quantities. Technology is needed to detect and control tritium transport and to monitor and clean up tritium.

6. An <u>initial tritium inventory</u> is required to prime the fuel system and establish a nominal fuel mixture to the plasma. Before the fuel processing system can reach peak performance, all the fuel handling and processing components that contain tritium must reach tritium equilibrium. Then the plasma can be properly fueled and the fuel cycle, including the blankets, can begin to produce tritium. After tritium is being produced in the blankets, the entire fuel system and the entire power core will slowly reach tritium equilibrium. Estimates of the amount of startup tritium required for a power plant range as high as 5-10 kg. This is a very large amount that would be extremely expensive. One possible way to obtain the needed tritium is to design nuclear test facilities to breed excess tritium. Another approach is for the Demo or prototype power plants to be designed to operate with a very small startup inventory and to produce a large over-supply through specially designed blankets. Each facility would provide just enough tritium to supply the next power plant in line. Whatever the final solution, this topic has received little attention, and is still in the early stages of concept development.

Table 18 summarizes the current state of progress on fuel cycle control issues.

5.2.4. Maintenance control and operations

Designing the fusion power plant with efficient maintenance in mind is absolutely necessary to achieve a high level of availability. Unfortunately, there are no fusion experiments or facilities, present or planned, to validate some of the proposed high-availability maintenance approaches or concepts. ITER is a good experimental facility to explore burning plasmas, with high-energy neutron environment that requires complete remote maintenance. However ITER will not be a good example of how to efficiently and quickly maintain a fusion power plant.

Table 18. Evaluation of progress on fuel cycle control issues

Technology Area	**TRL**								
	1	2	3	4	5	6	7	8	9
Fuel cycle management									
Breeding	■	■	■	▨					
Recovery	■	■	▨						
Processing	■	■	■	■					
Cleanup	■	■	■	■					
Accountability	■	■	▨						
Initial inventory	▨								
AVERAGE	■	■	▨						

Conceptual fusion power plant designs by the US, EU and Japan have proposed many high-availability maintenance approaches for tokamak plants. There are two schools of thought on how to replace the inner power core components. Certainly, the inner power core components will be designed as replaceable modules. The first maintenance approach is to remove/replace individual modules with articulated arms and/or guide rails through a number of maintenance ports. The other maintenance approach is to remove/replace entire sectors with a number of replaceable modules attached to the sector, which is removed through a much larger port for each sector. Each approach has its merits but the current thinking is that the sector approach will be much faster to accomplish and will achieve a higher level of plant availability.

These operations are focused on the removal, inspection, and replacement of a portion or all of the life-limited power core components on a regularly scheduled basis. The power core will be shut down for a significant time to complete this core refurbishment. All removal and refurbishment activities will probably be directed from the main control room but there might be a dedicated area for control of the maintenance action or, alternatively, the control screens will be reconfigured for power core maintenance. These major maintenance campaign periods will allow refurbishment of all other plant systems at the same time, thus enhancing plant availability. Refurbishment of the removed power core segments and processing of the removed components will be accomplished in the separate hot cell building under a dedicated hot cell control system.

There are two main goals related to major plant maintenance to periodically replace the inner power core components, listed below.

1. Efficient and speedy refurbishment and maintenance of power core – This goal is the enabler for achieving the high level plant availability goal. This can be accomplished by employing power core component design for remote/autonomous operations, specialized maintenance tools, equipment, and facilities, development and training maintenance facilities, highly developed coordinate mapping and guidance systems, expert systems to handle maintenance systems, fuzzy logic algorithms to handle unanticipated maintenance situations, and optimization routines to continually improve maintenance operations.

2. Maintenance equipment, facilities, and operations must maintain plant safety assurance and environmental compliance. This goal supports the main plant goal #2, Safety and Environmental Compliance.

In addition to the replacement of the inner power core components, there are other scheduled maintenance operations that relate to routine maintenance of plant systems and subsystems that require the plant to cease power production. The power core will be shut down during these operational periods as there would be no ability create and maintain the plasma or to dissipate the generated thermal power from the power core. The goal for this category of maintenance operations is enable and support the plant availability goal. This can be accomplished by using extremely high reliability components, parallel subsystem architecture (at least one subsystem operational while failed components are being replaced), fault-tolerant designs, integrated health management systems employed, and other availability enhancing capabilities.

There is another significant class of unscheduled maintenance activities. These unscheduled maintenance operations of plant systems and subsystems will require the plant to cease power production at any time. The scope of the maintenance action might be very limited, such as repairing a small divertor coolant leak, or very extensive, such as replacing a malfunctioning blanket module that would require complete removal of an entire power core sector. This category of actions is similar to the scheduled actions for life-limited power core components previously discussed. But the maintenance action also might relate to a failure of a life of plant component, such as a leak in the vacuum vessel that would require a significant disassembly of the power core. This latter category is thought to be a very unlikely event, but still it is possible and must be considered and planned for as these maintenance outages could adversely affect the plant availability. The utilization of the Integrated Vehicle Health Management system would be invaluable in helping to predict, schedule and perhaps eliminate lost downtime for the plant.

Metrics

Maintainability has a whole cadre of metrics. They are reliability (mean time between failures) of components and subsystems, mean time to replace (modules and components), mean time to repair (in situ), and time to execute replacement campaigns.

R&D needs

Existing and currently planned fusion facilities probably would not help validate these maintenance concepts, equipment, and procedures. Instead, validation must be accomplished either with advanced modeling and simulation and/or scaled or full-sized maintenance facilities. Great strides have been made and will continue to be made in the modeling and simulation of complex structures and organizations. Already, dimensional validation of complex structures is routinely accomplished with CAD programs. Simulated crash testing of automobiles quickly and accurately models the mass properties and dynamics of complex highly-loaded and deflected structures. Modeling and simulation of maintenance concepts and equipment will significantly shorten the design time and help optimize the equipment and procedures. The final validation proof will probably will require some hardware equipment and facilities. This may either be a dedicated facility or a part of a future fusion prototype or demonstration facility.

Since the maintenance equipment must operate in a radioactive environment, it must be suitably hardened to radiation effects. Validation of radiation hardened equipment can be tested and validated in the component test facility.

Table 19. Technology readiness levels for reliable and efficient maintenance

TRL	Issue-Specific Definition	Facility Needs
1	Conceptual definition of commercial maintenance system requirements determined from system studies	
2	Conceptual definition of component and characterization of operating environment. Formulate maintenance approach.	
3	Preliminary design of maintenance elements. Early system modeling to define operational environment and maintenance approach. Early system simulation and modeling to define operational environment and demonstrate proof of concept.	Some new small-scale prototype maintenance and testing facilities many be required to demonstrate critical function or proof of concept.
4	Firm requirements document and system architecture published. Preliminary design completed. Modeling and simulation of components and subsystems in a simulated environment begun to help quantify key issues. Laboratory (breadboard or pre-production) components tested for functionality, reliability, failure modes, and response to failure metrics in a laboratory environment. Scalable prototypes will be used to verify functionality. Preliminary FMEA and risk waterfall analysis performed. Technology availability dates established.	Preliminary simulation would be necessary to reduce risk. Testing and validation of a prototypical maintenance component or subsystem in a applicable laboratory environment is needed. Existing maintenance or prototyping facilities or simulations may be used in this stage.
5	Detailed design completed. Pre-production hardware at brass-board level tested and validated in relevant environment (high heat or neutron flux) to identify early failures and confirm failure metrics. Key manufacturing processes identified. High fidelity lab integration of subsystem completed, ready for realistic/simulated environments. Final reliability and lifetime target levels not final yet. FMEA completed.	Preliminary simulation would be necessary to reduce risk. Preproduction maintenance components or subsystems will be tested in a relevant environment with simulated or actual geometry and mass properties of power core. This may require a full sized or subscale testing environment facility.
6	Quality and reliability levels established. Firm operating environment established. M&S used to determine system performance in operational environment. Final test and evaluation plan approved. Model or prototype subsystem tested in relevant fusion environment. Critical manufacturing processes prototyped. Most pre-production hardware and software available. Integration demonstrations have been completed. Processes and tools are mature. Requirements document formally approved.	Preliminary simulation would be necessary to reduce risk. Preproduction components are integrated into subsystems and tested long term in relevant environment. This may have to be a dedicated facility because of the need to correctly simulate the power core with the maintenance subsystem or system model or prototype.

7	Materials and manufacturing processes demonstrated. M&S models the few unavailable subsystem elements. Prototype subsystem built with "soft tooling". Component tests in a relevant fusion nuclear environment with meaningful fluence. Specimen tests approaching end-of-life fluences for life limiting components (~4 y). Testing continues for longer life components. Testing also includes higher stress conditions with anomalous conditions. Maintainability, reliability, and supportability database above 60% level. Initial manufacturing sigma levels established. Scaling is complete. Limited quantity preproduction hardware is available. Ready for Low Rate Initial Production	Production prototype maintenance systems are tested long term in operational environment, such as Demo for geometric and mass similitude. Key results are confirming system reliability and power core availability.
8	Components (and subsystems) are form, fit, and functionally compatible with operational subsystem (and system). Cost estimates are < 125% of goals. Machines and tooling demonstrated in production environment. Software thoroughly debugged. All materials are in production and readily available. Components operated to end-of-life in a relevant fusion environment with prototypical conditions and subsystems (excepting those life of plant components and subsystems that must be validated with extrapolations using M&S). Subsystems meet all specifications and qualified for plant operation (validation complete). Ready for full rate production.	Production maintenance systems are tested long term in operational environment, such as Demo for geometric and mass similitude. Key results are confirming system reliability and power core availability.
9	Operational concept successfully implemented. Cost estimates < 110% of production cost goals. Design stable. System installed and operational. Training and supportability plans implemented. All manufacturing processes controlled to 6 sigma. Testing of life-of-plant components continue to be tested in fusion reactor environment with prototypical conditions and subsystems. Testing of life-limited components and subsystems with anomalous, fault, over-stressed conditions to improve performance and predictive capabilities.	Production maintenance subsystems and systems are operated long term in operational environment, such as Demo or the first operational power plant.

All the current maintenance procedures are based on current technology solutions for equipment adapted from other uses. Autonomously removing and replacing blanket and divertor modules must be simplified and accomplished quickly with fail-safe components and procedures. The development and validation of a remotely operable leak-free plumbing connectors in the high radiation environment for helium and liquid metal heat transfer fluids would be invaluable for faster and more reliable replacement of blanket and divertor modules. Likewise, a remotely operated, highly radiation-tolerant structural fastener would be of great value in speeding maintenance operations.

6. Summary and conclusions

In the previous sections, technology readiness levels were described for the 12 issues derived from our utility criteria for practical fusion energy. Details were provided on the issue-specific meanings and associated facilities of the TRL levels, and an explanation was given for the assignment of a current TRL value. 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 uncertainty in the assignment of TRL's. In this exercise we attempted to proceed through a complete evaluation within the ARIES Team, taking into account the relatively broad expertise of the Team. However, it is clear to us 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.

Table 20 summarizes our evaluation of the current level of readiness for both the "modest extrapolation" and "advanced concept" power plant embodiments. 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 fusion energy 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 3. Maintenance, which is a critical requirement for a power plant, is the least advanced.

The TRL of the "advanced concept" is typically about one TRL level lower than the "modest extrapolation" case. The chart does not appear to show a large difference between these two cases because both are at relatively low levels of technology readiness.

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 robust test module program would be carried out including all of the essential ancillary systems, albeit at modest neutron flux and substantially reduced operating time and neutron fluence. The results of this evaluation showed that the primary beneficiary of ITER would be plasma control and plasma power management. Many of the technologies used in ITER are not reactor relevant, and therefore cannot be expected to advance technology readiness for a power plant. Notable exceptions are the fuel cycle, which shares many common elements with a power plant, and power conversion, which is expected to benefit from R&D related to blanket test modules. ITER intends to dispose its radwaste in geological repositories, and thus will not contribute to the technology of recycling and clearance – the preferred radwaste management approach for advanced fusion power plants. The assessment for heat and particle flux handling assumes non-prototypic divertor operation in ITER (*i.e.,* only low temperature water-cooled divertor with copper). However, PMI aspects would rank higher (perhaps 6 or 7) if a W divertor is used in ITER.

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 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? 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 ITER, in order to achieve TRL6 for each issue. This information is summarized in Table 21, and can also be found in the TRL tables themselves. Since the key feasibility questions for plasma-related issues are expected to be largely answered by ITER, the remaining credibility questions for fusion are found primarily in the power core, plant systems and radwaste management.

One of the most important questions to address is whether or not a nuclear test facility (a "CTF") is required in order to advance to TRL6. The answer is different for different issues, and depends on the interpretation of the definition of TRL6:

> *"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 a simulated operational environment."*

The importance of neutrons, high neutron flux and high neutron fluence is key to this determination. For many of the 12 issues, CTF is a key facility for the completion of TRL7 rather than TRL6. One notable exception is the issue of power core lifetime, which is highly dependent on substantial test volume and neutron fluence. Without a relevant and substantial neutron environment, TRL6 probably can not be achieved. Power core lifetime is likely to lag the other issues and represents a risk when the program shifts from proof-of-principle to proof of performance phases.

The design, construction and operation of a nuclear test facility will require a great deal of fundamental and applied research in several areas that are not currently supported in the US fusion energy sciences program. In order to proceed to a CTF with acceptable risk and to extract value from the facility, the technology readiness in most of the issues must advance to level 6.

We are aware of the recent activities performed within the US Fusion Energy Sciences Advisory Committee, FESAC, in which issues and R&D needs were documented using a different methodology [2]. The FESAC "themes" and issues are listed in Table 22. Although the purpose of our study and that of the FESAC panel on "Priorities, Gaps and Opportunities" are different, there exists much overlap at the technical level. Clearly, some of their issues are targeted specifically at the “science” mission of OFES (see for example their issues 1 and 13) whereas our issues are consistently focused on the ultimate goal of fusion energy. In the nomenclature of TRL’s, science plays a larger role in the early stages and a lesser role in the latter stages of any issue resolution. “Science” *per se* is not considered a separate issue in the application of TRL’s.

It is possible to adapt the TRL methodology to alternative descriptions of the critical issues for fusion energy. The ARIES Team is currently exploring some of these alternatives.

As we move forward toward the ultimate goal of practical fusion energy, an objective methodology for evaluating and demonstrating progress could be a great benefit for 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.

Table 20. Summary of evaluation of readiness for reference power plant concepts

Case 1: Modest extrapolation					**TRL**				
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	🟩	🟩	🟩	🟦	🟨	🟨	🟨		
Heat and particle flux handling	🟩	🟩	🟦						
Power conversion	🟩	🟩	🟦	🟨					
Power core fabrication	🟩	🟩	🟦						
Power core lifetime	🟩	🟩	🟦						
Safety and environment									
Tritium control and confinement	🟩	🟩	🟩	🟦	🟨	🟨			
Activation product control	🟩	🟩	🟩	🟩	🟨	🟨			
Radioactive waste management	🟩	🟩	🟩	🟩	🟩	🟨	🟨		
Reliable/stable plant operations									
Plasma control	🟩	🟩	🟩	🟩	🟨	🟨	🟨		
Plant integrated control	🟩	🟩	🟦						
Fuel cycle control	🟩	🟩	🟦	🟨	🟨				
Maintenance	🟩								

Case 2: Advanced concept					**TRL**				
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	🟩	🟩	🟩	🟨	🟨	🟨	🟨		
Heat and particle flux handling	🟩	🟦							
Power conversion	🟩	🟦							
Power core fabrication	🟩	🟦							
Power core lifetime	🟩	🟩							
Safety and environment									
Tritium control and confinement	🟩	🟩	🟩	🟦	🟨	🟨			
Activation product control	🟩	🟩	🟩	🟨	🟨				
Radioactive waste management	🟩	🟩	🟩	🟩	🟨	🟨			
Reliable/stable plant operations									
Plasma control	🟩	🟩	🟦	🟨	🟨	🟨	🟨		
Plant integrated control	🟩								
Fuel cycle control	🟩	🟩	🟦	🟨	🟨				
Maintenance	🟩								

Legend	
completed	🟩
in progress	🟦
with ITER	🟨

Table 21. Minimum needs for achieving TRL6 in the modest extrapolation case

1. Plasma power distribution	*none*
2. Heat and particle flux handling (PFC's)	Submodule facilities Integrated large facility: Prototypical plasma particle flux+heat flux
3. High temperature operation & power conversion	Non-nuclear engineering test facilities. Partially integrated test facility.
4. Power core fabrication	prototype production and testing facilities. high fluence materials test facility.
5. Power core lifetime	Thermomechanical test facilities, fission reactors, 14-MeV neutron sources.
6. Tritium control and containment	*none*
7. Activation product control and containment	*none*
8. Radioactive waste management	Integral experiments with 14-MeV neutron source
9. Plasma control	*none*
10. Plant integrated control	*TBD*
11. Fuel cycle control	*none*
12. Maintenance	Prototype facility Full sized or subscale test environment facility.

Table 22. FESAC themes and issues

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
Taming the Plasma Material Interface
8 Plasma-wall interactions
9 Plasma facing components
10 RF antennas, launching structures & other internal components
Harnessing fusion power
11 Fusion fuel cycle
12 Power extraction
13 Materials science in the fusion environment
14 Safety
15 Reliability, availability, maintainability, inspectability

References

1. 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.
2. M. Greenwald et al., “Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy,” A Report to the Fusion Energy Sciences Advisory Committee, October 2007.
3. http://en.wikipedia.org/wiki/Technology_Readiness_Level
4. John C. Mankins, “Technology Readiness Levels, A White Paper,” Advanced Concepts Office, Office of Space Access and Technology, NASA, April 6, 1995.
5. “Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes,” GAO/NSIAD-99-162, United States General Accounting Office, July 30, 1999.
6. “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.
7. “Global Nuclear Energy Partnership Technology Development Plan,” Global Nuclear Energy Partnership Technical Integration Office Report, GNEP-TECH-TR-PP-2007-00020, July 25, 2007.
8. F. Najmabadi and the ARIES team, “Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study,” *Fusion Engineering & Design* 38, 3-25 (December 1997).
9. F. Najmabadi and the ARIES Team, “The ARIES-AT Advanced Tokamak Advanced Technology fusion Power Plant,” *Fusion Engineering & Design* **80**, 3-23 (January 2006).
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. L. El-Guebaly, V. Massaut, M. Zucchetti, K. Tobita, and L. Cadwallader, “Goals, Challenges, and Successes of Managing Fusion Activated Materials,” to be published in *Fusion Engineering and Design*.
14. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure, Handbook 69, US National Bureau of Standards, 1969.

15. US Code of Federal Regulations, Title 10, Energy, Part 20, Standards for Protection Against Radiation, Appendix B, "Annual Limits on Intake (ALIs) and Derived Air Concentrations (DACs) of Radionuclides for Occupational Exposure, Effluent Concentrations; Concentrations for Release to Sewerage," US Government Printing Office, Washington, DC (2008).
16. B. Patel, D. C. Campling, P. Macheta, K. Sandland, P. A. Schofield, "Health physics aspects of tritium operation at JET," Fusion Engineering and Design, **47** (1999) 267-283.
17. R. V. Carlson, "Tritium handling safety and operating experience at the Tritium Systems Test Assembly," *Proceedings of the IEEE 13th Symposium on Fusion Engineering*, Knoxville, TN, October 2-6, 1989, volume 1, IEEE (1989) 620-625.
18. D. A. Petti, S. Reyes, L. C. Cadwallader, and J. F. Latkowski, "Status of Safety and Environmental Activities in the U.S. Fusion Program," *Fusion Science and Technology*, **47** (2005) 949-958.
19. D. A. Petti, B. J. Merrill, J. P. Sharpe, L. C. Cadwallader, L. El-Guebaly, and S. Reyes, "Recent accomplishments and future directions in the US Fusion Safety and Environmental Program," *Nuclear Fusion*, **47** (2007) S427-S435.
20. J. P. Sharpe, D. A. Petti, and H.-W. Bartels, "A review of dust in fusion devices: Implications for safety and operational performance," Fusion Engineering and Design, **63-64** (2002) 153-163.
21. J. P. Sharpe and P. W. Humrickhouse, "Dust mobilization studies in the DMX facility," Fusion Engineering and Design, **81** (2006) 1409-1415.
22. L. El-Guebaly, L. C. Cadwallader, "Future Trend Toward the Goal of Radwaste-Free Fusion: US Strategy and Regulations," to be presented at the 18th Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, September 28-October 2, 2008.
23. E. M. Blake, "U.S. capacity factors: Leveling off at last," *Nuclear News* **49** (May 2006) 26-31.
24. T. L. Schultz, "Westinghouse AP1000 advanced passive plant" *Nuclear Engineering and Design*, **236** (2006) 1547-1557.
25. *Advanced Light Water Reactor Utility Requirements Document*, EPRI NP-6780 Volume 1, Electric Power Research Institute, Palo Alto, CA (1990).
26. D. A. DeFreece, L. M. Waganer, and D. S. Zuckerman, "Assessment of Technical Risks and R&D requirements for a Magnetically Confinement Fusion Fuel System", EPRI AP-3283, Final Report, Nov 1983.
27. http://fusionenergy.lanl.gov/Technology/TSTA.htm

List of Tables