Evaluation of Technology Readiness for Physics-Oriented Issues

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The present White Paper is the second of three concerning the issue of plasma control, which is taken here to include control of the power flow in addition to the main plasma parameters and profiles. The first paper, "Control of the Plasma and the Power Flow in a Reactor", identifies the individual issues that need to be addressed. This second paper addresses the need for quantitative measures of the status of the issues, and the prospects for the presently available techniques to be useable in ITER and a demonstration fusion reactor. It describes these needs in general terms, considering the Technology Readiness Levels, (TRLs) as described in the Theme III White Paper, "Evaluating gaps in fusion energy research using Technology Readiness Levels", as an example. It then considers some of the general lessons that were learned in constructing the TRL Tables but that have an importance beyond the specific nature of TRLs. These are general issues that arise in identifying and quantifying the steps needed for maturing any control related technology for a specific application. The third paper, "Technology Readiness For Control of the Plasma and Power Flow in a Reactor", develops specific TRL tables and values for each of the control issues identified in the first White Paper. This is intended as an example to show how the TRL process can be applied to more physics oriented issues. The three companion White Papers are designated as WPI, WPII, and WPIII.

Technology Readiness Levels

Technology Readiness Levels, (TRLs) were described by Mark Tillack (see Theme III White Paper "Evaluating gaps in fusion energy research using Technology Readiness Levels") but can be summarized here. While originally intended for use in defense and aerospace, and therefore developed with a specific viewpoint appropriate to those areas, they can be adapted to fusion engineering and even to some of the more physics oriented issues in fusion. The TRL tables are a set of nine levels that any technology needs to go through before being considered sufficiently mature to be used in a complex operational system such as an aircraft or fusion reactor. Generic descriptions of the nine levels are set and from these, specific requirements for a specific technology are developed that describe precisely what needs to be demonstrated by the technology to reach each level. The trend is from conceptual ideas (TRL = 1) through laboratory demonstrations of the principles, breadboard demonstrations, prototypes, and up through more complex levels of integration in the intended operational environment (TRL = 9). As an example of this, a set of TRLs was constructed for the two issues of control of the plasma and control of the power flow. These are discussed in the accompanying White Paper (WPIII).

Using these tables, each specific issue can be given a TRL value for the status of the current proposed solution relative to the ultimate requirement. The ultimate requirement depends, however, on the type of reactor envisaged – specifically for control issues on whether it is expected to operate in a more conventional scenario with perhaps some level of control of the profiles, or as a true Advanced Tokamak, as envisaged in ARIES-AT. Thus, although the table descriptions were developed to apply unchanged to both ultimate targets, the values assigned will be different for the different scenarios.

In addition, one can make the assumption that ITER will be successful and assign a TRL value that would be reached under that assumption. For the final DEMO, it is considered here that this will correspond to a TRL of 9. If DEMO is envisaged as an actual commercial reactor, TRL = 9 will be required before it is built. If DEMO is considered as the penultimate step to a commercial reactor, DEMO itself can be the facility used to demonstrate level 9.

The process of constructing TRL Tables can be summarized as follows: In each case, one begins with a specific high level requirement that a proposed technology is intended to address. For example: the requirement might be "Economic Power Management. From this one derives one or more physics issues. For the requirement above, the key physics issue would for example be: "Control of the power flux distribution from the core plasma to maintain levels at which the power flux but can be handled by material surfaces but is sufficient to achieve the economic goals". One then constructs an issue-specific TRL Table in which descriptions of the requirements to reach each of the nine levels are given. These should be general enough to apply to any physics scenario and accompanying technology that could potentially provide a solution to the issue. Then one uses the descriptions to evaluate the present status of a given solution in terms of the level it is currently at. The evaluations for different solutions can then be directly compared.

A set of TRL values is therefore assigned for each of the individual issue categories described earlier in the first White paper (WPI). The following paragraphs describe some specific lessons learned and issues encountered that are general enough to transcend both the specific TRL prescription and the control-related issues, and apply to any attempt at elaborating the steps needed for maturing any control related technology for a specific application.

Technology Readiness is not a plan

No evaluation of technology readiness such as TRL tables is a substitute for a plan. A plan or roadmap is needed in addition to the technical evaluation process and an evaluation of technology readiness is only a tool that can be used as an aid to planning.

Need for a Well Defined And Agreed Target Application

The ultimate requirement depends on the type of reactor envisaged. There are two targets for what is generically called an Advanced Tokamak (AT) and for each target, there are also two different and not fully compatible views or philosophies of how the final product would operate. These are never properly elaborated.

First, the two different targets usually named AT are essentially embodied respectively in the ITER Advanced scenarios and the ARIES-AT design. The former takes a conventional tokamak and utilizes some active control of the profiles to partially optimize the performance. The final target is then something with q above unity, a moderate fraction of the current provided by bootstrap, and moderately improved performance over conventional operation. This can be referred to therefore as the 'modest extrapolation' scenario. In contrast, the ARIES-AT target envisages a highly optimized configuration operating in steady state, which generally requires a tailored q profile well above unity and a tailored pressure profile, along with active stabilization of instabilities. To distinguish it, we refer to this target option as either the advanced concept, or simply, ARIES-AT target.

Two different philosophical views can be applied to either target and the distinction is crucial. The first view takes the approach that there are two paths identified to achieve fusion: the conventional path that takes essentially an H-mode plasma with the profiles 'nature intended' (i.e. set up by the current ramp up) and accepts them; and an orthogonal AT path that uses active control to optimize the profiles and possibly also instabilities, depending on which target is considered, to find a viable solution that is sufficiently better in terms of fusion performance that the large increase in complexity is more than compensated. The conventional path machine is made big enough then to achieve the fusion yield desired. This is ARIES I. It is the simplest device that will yield fusion. For the Advanced Tokamak path, there are a number of different places this can end up, depending on how much complexity one is willing to live with or how one measures gain and pain. But basic picture in this philosophical view is one with dynamic - not just active, but responding to - control of both the plasma equilibrium and stability. This usually implies noninductive current drive, fueling, pumping, and resistive wall mode control either through rotation or active coils, and possibly ECCD/ECH suppression of islands. The key to this view is the need for both the actuators and diagnostics so the actuators actually respond as parameters evolve or drift.

In the alternative view, the AT is a different equilibrium solution – a tokamak with different profiles from the conventional path. The profiles need some additional external current drive and heating and stronger shaping but it is essentially a static view. The plasma state is assumed be that which was designed for and set by modeling. Hence, while all the actuators - the current drive and heating systems - are needed, there is no need or allowance made for sophisticated diagnostics or for the algorithms needed to link the diagnostics with the actuators in the design. The actuators are intended to be on all the time but are not intended to respond. This view is , in fact, embodied in the actual ARIES-AT design

The two views are also essentially the distinction between open versus closed loop control. The active view is closed loop but the alternative view is really an open loop system. Since both are in a sense active control, the two views can be distinguished by referring to them as *passive* and *dynamic* respectively.

In terms of evaluating technical readiness, the values assigned will be different for the different scenarios. For the two different conceptual AT targets, they will differ in the requirements for both the diagnostic and actuator requirements. For the two competing philosophical views, in general, the minimum number of diagnostics is a goal but the two views consider the minimum to be very different. In either case, the required diagnostics for DEMO or even the first several power plants will still be a sizeable subset of the ITER diagnostics since every new device has it's own distinct characteristics; plasma discharges are highly reproducible within a given device but not so well across devices and it can take days-weeks-or months to reproduce phenomena in a different experiment. In the passive view, it is assumed that identical reactors will be easier and as confidence is gained running DEMO and a couple of power plants, the number of diagnostics can be reduced. However, it is not entirely clear that the passive view is ultimately feasible – it is difficult to imagine that the plasma will behave in the way designed with no excursions that need to be measured. On the other hand, it may not be feasible to diagnose all the parameters and profiles envisioned in the dynamic view and some compromise will need to be reached that still maintains the overall high level goals for the reactor.

There is therefore a clear need to decide beforehand what the target configuration, including which philosophy –passive or dynamic - is before attempting to define precisely what the gaps are in reaching the final DEMO. Otherwise, confusion will persist beyond the point where it is too late.

Grouping of Technologies

An issue specific to the use of TRL tables, but somewhat more broadly applicable is that there is an ambiguity in any definition of what a 'single' technology means. The TRL tables are intended to have a common description that can be applied to any of the different conceivable technological and physics solutions intended to address that issue. This reveals two different but related issues that are a common source of confusion.

First, in general, a specified technology or physics solution to a high level issue also comprises several sub-technologies addressing different aspects of the solution. This should not be confused with different technologies addressing the same issue. However, where sub-technologies are similar enough, the same descriptions can also be used and hence a common TRL table. A set of TRL values should, in principal be assigned for each of the individual technologies, as well as for the technology directly addressing the high level issue. Then, the group should be assigned the value of the limiting individual sub-technology.

Second, a problem in evaluating TRL values beyond level 6 is that the TRL descriptions are written so that level 7 requires integration of the technology into a system that includes technologies designed to address other high level issues. Since the TRLs are independently written for each specific issue, this can only really be taken to mean integration of all the features involved in that issue, not integration of all the systems described by other TRLs. Otherwise the separate TRL tables would not have any value beyond level 7. Only the table for the overall issue – namely achieving an economically viable fusion reactor – would be relevant above TRL = 7. Thus for the issue of plasma control, TRL Level 7 would be taken as meaning integration of all the plasma control categories.

One could alternatively consider a process where the TRL tables get merged as several individual component technologies get combined and considered as a group as a single technology. In that case, the individual TRL tables for each component technology could be written with the goal of being utilized in the integrated system as level 9. Only the final merged table would have to reflect the operational environment of a DEMO reactor.

Though each has its drawbacks, one or the other process needs to be adopted and adhered to. Otherwise, confusion develops as to what state the individual component technologies are at. Here, we take the former approach and use the individual component TRL tables with the tacit assumption that TRL levels above 7 are taken to mean integration of all the plasma control categories even though separate tables are retained.

Relation Between TRL levels and Facilities

TRL levels do not necessarily coincide with facilities although they could. One could choose to skip facilities in the planning and use the next level facility (eg operational instead of relevant, or breadboard instead of laboratory bench) but at added risk. This must be decided as part of the overall plan.

Need For An Evaluation of Confidence Levels

Ultimately, the solution being pursued to address a given issue must be capable of reaching the level where it can be successfully used in the final integrated system – in the case of TRL tables, this means reaching TRL = 9. For example, for plasma control, the diagnostic and actuator technologies need to survive in a BPX environment. For control of the power flux, the proposed solution needs to handle the much larger power fluxes in a reactor. 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.

It is therefore appropriate to estimate the level of confidence that the remaining TRL stages can be reached using the diagnostic and actuator techniques being considered now or with reasonable extrapolations. An indication of this confidence level is always needed in addition to an evaluation of the current state of technological readiness, as expressed, for example, in a TRL table and value. As part of the overall plan or roadmap, the confidence level must also be continually re-evaluated.

Need For Additional Decision Points in the Planning Process

Given two competing solutions to a given issue, a mechanism must be in place to decide to replace a given technology by one at a lower level if the likelihood of it reaching maturity (level 9 in a TRL table for example) is lower than the alternative. This is a decision that must be made as part of the planning process. It is 'orthogonal' to the evaluation of the current status of the competing solutions.

As an example, given two competing diagnostics, one that has reached prototype status and the other perhaps as only a laboratory bench level development, the prototype level option may be deemed to be unviable in a high fluence neutron environment and be incapable of being realistically shielded. At some point, this realization must lead to a shifting of resources to develop the alternative solution. The question is clearly one of balancing resources but the TRL tables or equivalent, and confidence level estimates are intended as tools to inform the decisions.

Given this, however, it must also be recognized that some solutions, though not viable in the final operational environment, may be sufficient in the less demanding environment needed at intermediate levels of development (for example, the 'relevant environment in the TRL levels 5-6) and serve as substitute technologies, or essentially scaffolding, to enable other issues to be worked through, while the alternative solution is developed. Then these technologies should still be pursued. Thus, some solutions used in ITER may not be viable in DEMO but still should be pursued. In that case the TRL table goals should be modified to reflect the goal that it is intended for a different issue – namely to work in an integrated system, but now with low fluence or with low lifetime, for example. Again, this option should be part of the planning process.

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