What Must Demo Do?

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ABSTRACT*

The U.S. fusion demonstration plant (Demo) must satisfy certain top level requirements so that energy producers will confidently invest in a commercial fusion version for their next generation power plant. To instill that level of confidence to both the investor and the public, Demo must achieve high standards in safety, low environmental impact, reliability, and economics. This is a most difficult set of goals to meet. The public is demanding ever more strict environmental rules and regulations. The hazards of radioactive and toxic waste and emissions are becoming better understood. The difficulties of establishing and maintaining long-lived repositories are enormous. Neighborhood action groups have an aversion to large power plants in their back yards. Utilities and independent power producers are reluctant to commit to a long-term financial arrangement for a new technology. To achieve these stringent goals, the competition is continuing to improve to meet these challenges. Only the best can adapt and survive.

Can fusion meet the challenge? Does it have enough advantages to offset the difficulties ahead? Fusion has many inherent advantages. Fusion can be environmentally safe. By tailoring the materials used, it can achieve low level waste standards. It can meet demanding public standards for safety. It does not have a melt-down scenario. Abnormal events can be tolerated with no major hazard potential. Redundancy and robust engineering can be designed into the system and testing can verify demanding reliability standards. Plant economics can be achieved if rigid cost standards are established and maintained.

The Demo plant is not expected to achieve all requirements demanded of the commercial power plant, but it must demonstrate values close enough to the commercial machine so that extrapolation to the commercial carries minimal risk in all key areas. Specifically, Demo must demonstrate all the major performance parameters in an integrated system similar to that of the commercial plant. It should be large enough so that all aspects of the Demo can be confidently scaled to that of the commercial plant, including the economics, reliability, availability, and operability.

The U.S. Starlite Demo project is establishing quantifiable top level requirements to assure that Demo will satisfy the aforementioned needs for the commercial plant. At the same time, it must be determined that Demo can be achieved by extrapolating today's current physics, engineering, and material databases.

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I. INTRODUCTION

The Starlite project is a comprehensive investigation of the Fusion Demo, its mission, requirements and goals, features, and R&D needs. One of the first actions of the Starlite project was to establish a Utility Advisory Group to help formulate a set of goals to help guide fusion to a more attractive power plant concept for both the utilities and the general public. Using the customer-based goals, the Starlite project formulated a mission statement and goals for the Demo Plant.

The Starlite project has adopted the following mission statement for the U.S. Demo Power Plant [1].

The Fusion Demo demonstrates that fusion power is a secure, safe, licensable, and environmentally attractive power source that is ready for commercialization at an economically superior cost.

This mission statement is supported by the demonstration of a set of qualitative attributes. These attributes include:

- Commercially-relevant Technology
- Integration and Scalability
- Economics
- Safety and Ease of Licensing
- Waste Disposal
- Decommissioning and Decontamination
- Reliability
- Maintainability
- Availability
- Operability
- Industrial Infrastructure
- Utility/User Interface

This list of attributes must be quantified in order to formulate a Demo program and eventually define a credible conceptual Demo design which would lead to a commercially acceptable, electric generation plant. This list of positive attributes must be restated as specific requirements that the Demo must meet or achieve in order to be successful. This paper explains the development and the application of these top level requirements.

II. TOP LEVEL REQUIREMENTS FOR DEMO

The prior section discussed the general goals or attributes needed for the demonstration plant, or for a commercial fusion power plant, to be accepted by the public and to commercially succeed. The Demo must "demonstrate" those attributes that would convince the utility or their investors and the public that this new technology, over long periods of time, is safe, economical, and does not harm the environment. The commercial power plant that would evolve from the Demo plant must be able to meet an increasingly demanding set of goals. The Demo need not meet 100% of all commercial power plant goal objectives, but the risk of eventually meeting those commercial goals should be acceptable. To quantify the goals or attributes supporting the Demo Mission Statement, the Starlite project defined a set of top level requirements for both the Demo and the commercial power plant, shown in Table 1. Each of these requirements will be discussed as to background and implications for meeting the requirements.

Table 1. U.S. Demo Top Level Requirements

Requirement	Demo	Commercial
1. Must use technologies to be employed in commercial plant	Yes	Yes
2. No evacuation plan required. Dose at site boundary	1 rem total	1 rem total
3. Generate no radioactive waste greater than:	Class C	Class C
4. Must demonstrate public's day-to-day activities not disturbed	Yes	Yes
5. Must not expose workers to a higher risk than other power plants	Yes	Yes
6. Demonstrate a closed tritium fuel cycle	Yes	Yes
7. Net electric output must be greater than:	75% of commercial	Not applicable
8. Must demonstrate operation at partial load conditions	50%	50%
9. Demonstration of robotic or remote maintenance of power core	Yes	Yes
10. Demonstrate routine operation with less than (x) unscheduled shutdowns per year including disruptions	1	1/10
11. Cost of electricity must be competitive (in 1995 mill/kWh)	80 (Goal) 90 (Reqmt)	65 (Goal) 80 (Reqmt)

1. *Commercially-relevant technologies:* The U.S. Demo must use and demonstrate the same technologies that will be incorporated in a fully-commercial power plant. This requirement is fundamental in determining the features of the Demo and may or may not be adopted by other countries in their definition of a "Demo". If the basic technologies are changed following the Demo, then another Demo must be built before the design and construction of the commercial plant. A private investor will not accept risk of failure or reduced performance due to unproven and undemonstrated technologies. Additionally, it may be impossible to insure and/or license such a plant.

This requirement allows for the performance levels to be reduced from a fully commercial plant as specified in the remaining Demo requirements. For example, a reduced level of thermal efficiency, availability and component lifetime in the Demo (owing to less competitive cost of electricity) allows the components to be designed slightly different and operate at lower temperatures and stresses. There is no requirement that specifies the component operating conditions must be exactly prototypical.

However, through operation of the Demo, a high level of confidence must be gained so that the first commercial plant is assured to meet the more stringent commercial power plant requirements. If performance levels are reduced from that of a full commercial plant, then the ability to extrapolate must be clearly demonstrated. The method to demonstrate this extrapolation has not been specified.

2. *No evacuation plan:* One of the most powerful advantages that fusion may possess is that the risk to the public may be low enough so as to not require an evacuation plan for the surrounding population. In discussions with the utilities, much time and effort are devoted to prepare for and obtain acceptance of the evacuation plans. If there were no need for an evacuation plan, the siting of the plant would be much eased and the licensing could be expedited.

Careful control of vulnerable tritium inventories should allow attainment of this goal of 1 rem total dose at the site boundary. Choice of power core materials and coolants will be tailored to eliminate or limit generation or transport of hazardous material to the site boundary. This will minimize the accident potential or consequence.

3. *No radioactive waste greater than Class C:* The requirement to generate no radioactive waste greater than Class C was levied on the Demo plant because there is a general public aversion to creating hazards that need protection for long periods of time. The governmental regulators are responding to the public concern by increasingly stiffening applicable legislation. Fusion power plants could be constructed and operated with a number of materials that could meet the physical design properties. However, it was anticipated that plants that generate high-level radioactive waste, even at small amounts, might result in an adverse public reaction. Power plants, both public and private, are highly visible by the general public and environmental groups. Thus to be prudent, Starlite adopted the requirement that all generated waste must meet the requirement to be Class C or better.

This stringent requirement requires that the in-vessel materials generally be low-activation materials. This would suggest vanadium, ferritic steel, or silicon carbide as the structural material. The composition of these materials would be tailored to eliminate or reduce offending trace elements that would contribute to high level radioactivity. There are still open questions as to the use of mixed waste, the degree of isotopic tailoring required, and the cost of meeting these requirements.

4. *Public's day-to-day activities not disturbed:* The requirement to 'demonstrate the public's day-to-day activities should not be disturbed' arose from the desire to have public acceptance of fusion. Utilities spend a great deal of time and money assuring the public that they will not be disturbed. There are many public hearings discussing the intrusion of electrical generating plants into their communities. Fusion

has long professed that it was a safe energy option and now it must demonstrate that indeed it is.

This requirement is foreseen to be a combination of many factors to assure the public that the fusion power plant will not intrude into their lives (except through the wall outlet). The requirement for no evacuation plan is an integral part of the plan. They can be assured that regardless of what happens at the plant, they will never have to be evacuated from their homes. The requirement for no high level radioactive waste assures that they will never worry about transportation of that waste through their highways, rivers, or rail lines. The on-site, closed fuel cycle minimizes the traffic of fuel suppliers.

5. *Not expose workers to a higher risk:* Protection of the plant worker is also a strong incentive to provide safeguards. A requirement was added to not expose workers to a higher risk than other power plants. All work environments entail additional risks over and above that for non-work environments. Fission plants have adopted design approaches and strong requirements to safeguard their employees from nuclear materials. Other forms of electrical power generation plants provide stringent worker safety related programs.

From the start, fusion should be mindful of the plant worker safety. It is a nuclear process with radioactive components. In all activities involving radioactive components or dangerous situations, robotic or remote maintenance should be incorporated. Particular attention is required for tritium handling and containment. High pressure or liquid metal coolants will require special hardware and procedures.

6. *Closed fuel cycle:* Tritium is not available naturally, therefore an important Demo requirement is to demonstrate that a power plant will never be at risk of running out of fuel. Since there are no secure external sources of tritium, loss of the on-site tritium inventory could lead to a serious crisis for the utility, making it impossible to operate the plant. During long down-times, on-site tritium will decay (12.4 y half-life). Thus, maintenance of adequate reserves to survive extended down-times is mandatory. In an economy with multiple fusion plants on-line, the guarantee for reserves is reduced somewhat, since an operating plant could provide start-up inventory for a plant coming on line.

The power level and availability goals of Demo are such that Demo itself could not operate without a closed fuel cycle. At 3000 MWe and 80% availability, 250 g of tritium would be consumed daily. The expected supply of tritium from external sources (such as CANDU reactors) for Demo will be only a few kilograms [2,3], and even this may be absorbed by test facilities such as ITER. In that case, the demonstration of a closed fuel cycle is mandatory if Demo itself meets its other requirements.

The utilities have not specified any requirements on Demo to overproduce tritium, although this may be an important goal in order to provide the initial start-up inventory needed for the first generation of commercial plants. In any case, even small excess tritium production rates in Demo will provide more than adequate start-up inventories (estimated at a few kilograms), such that this is not expected to create any additional design considerations.

Aside from the uniqueness of tritium, it is a powerful advantage for a utility to have the autonomy of possessing all the fuel on-site for the lifetime of the plant. There can be no pressure from suppliers or natural disasters to impede the availability of the fuel supply. This feature also allows the utility to determine up front the fuel cycle costs and not be subject to the whims of the external marketplace.

7. *Net electric output greater than 75% of commercial:* The requirement for the demonstration plant to generate electricity at a capacity near to that anticipated for the commercial plant is determined by economics and the perceived risk to scale to a full-sized plant. The premise is that Demo is to be built and operated by a utility. This plant is to be designed to be fully integrated into a power grid for the purpose of power generation. Thus it must of a size sufficient to contribute to the grid demands and be profitable. The present understanding of tokamak fusion power plants is that below a net capacity of several hundred megawatts, the plants have very unfavorable economics. Even with a moderate size and other less optimal performance parameters such as reduced availability, substantial financial subsidies will be required for a nominal rate of return for the Demo.

The second factor is technical risk to scale to a full-sized plant from a much smaller demonstration plant. If the demo is too small, it entails too high a risk for the investor. On the other hand, building the Demo too large puts a larger burden of risk on Demo, extrapolating from the database of the then existing experimental devices. ITER may have the proper size plasma, but other subsystems may not be of an adequate size to serve as the design basis for Demo.

Within the fusion community and the Utility Advisory Committee, the debate continues regarding the proper size for a commercial plant. One faction would prefer a small plant that could be sited anywhere there is a demand, basically in a distributed network. Another view is that large power parks should be used as bigger is better. The latter view is better suited to the nature of tokamak power plants, but it is not a convincing argument. In formulating its Demo requirements, Starlite is begging the question by recommending that the Demo be roughly 75% of the size of the commercial plant. This would provide adequate size for the economics to be viable and also have acceptable risk in scaling the relevant technologies. Ultimately the Starlite project will have to recommend a size for the commercial machine and also the size of the Demo.

8. *Operation at partial load conditions:* The operation of a power plant at partial load condition is a reasonable expectation for any plant that is to be integrated into a power grid with a minimum of difficulties. The only question is the lower level of operation at which it is expected to operate continuously. The Utility Advisory Group thought that 50% would be a reasonable value for a base-loaded plant. If it were to be load-following, which it is not, then it would have to operate at a much lower capacity. It is not foreseen that

tokamak reactors would have any inherent problems with operation at reduced capacity. As with any base-loaded plant, the economics are not favorable at reduced capacity operation.

9. *Maintainability:* It is not foreseen that a fusion power plant will allow hand-on maintenance following operation with DT fuel. Therefore, the ability to remotely remove and replace any component which can fail must be demonstrated, even if the component doesn't actually fail during operation. It is anticipated that the majority of fusion power plant maintenance will be done robotically, such that all robotic systems must be demonstrated during Demo operations. Further, robotic maintenance is meant to be predominantly computer controlled maintenance with minimal human intervention except for key actions or unique situations. This will allow faster and more reliable maintenance operations for known and repetitive operations.

It is likely that these maintenance demonstrations would be performed prior to the start of DT operation, such that any flaws or failures may be corrected prior to activation. A high degree of confidence in the repair time is necessary in order to meet the very high availability goal of Demo. The availability goal of Demo is stated in such a way that initial operations need not meet the full availability goal. This allows for some tolerance for extended down-times due to maintenance. However, given that Demo is expected to be constructed with some fraction of private investment, there will be very strong economic incentives to minimize downtime during any phase of operation.

Demonstration of maintenance actions encompassing plant operations to the end-of-life of in-vessel components also will be essential. Changes in material properties, permanent deformations, and chemical and physical interactions may complicate maintenance procedures. End-of-life maintenance demonstration will occur naturally because the total operating life of Demo is expected to exceed the lifetime of a set of in-vessel components. A utility will demand positive results from the demonstration and replacement of life-limited components prior to committing to the construction of the first commercial plant.

10. *Unscheduled shutdowns:* Unscheduled shutdowns are very undesirable for a power plant operator. Besides the obvious impact on availability resulting from down-time, a power plant cannot be brought back on-line immediately following an unplanned outage until the source of the problem is identified, any damage is repaired, and corrective actions are taken to prevent future occurrences.

A major plasma disruption is one such intolerable event. The requirement to avoid disruptions is difficult to achieve and may require performance trade-offs in order to operate the plasma far enough from any stability boundaries that the frequency of disruptions is reduced below one per year [4]. Note that the unscheduled shutdown requirement is one per year total for all systems and should include in-vessel component premature failure, power conversion systems, fueling systems, etc. Surprisingly, the consequences to the surrounding structures may become a secondary concern since these can be repaired and replaced relatively quickly, while the ability to determine the source of a disruption and correct the flaw may require substantially more time.

11. *Cost of Electricity:* The final requirement is that the cost of electricity (COE) for the Demo must establish the economic competitiveness of fusion [5]. An actual value for this requirement was difficult to quantify but the Starlite project felt the general fusion community needed guidance in this area. In response to that need, both a goal and an upper limit requirement were established for the Demo and the commercial power plant. While long-range electrical demand projections are uncertain and the target for a competitive COE is elusive, costs are an important design consideration. It was felt that if the COE of 65 mills/kWh were obtained, fusion energy would likely be seen as a formidable competitor. Realists sought some relief from the seemingly difficult demand to reach such a value. Thus the commercial goal was provisionally set at 65 mill/kWh and the upper limit requirement was established at 80 mill/kWh. Rollback to the Demo requirements resulted in adoption of a COE goal of 80 mill/kWh and a requirement of 90 mill/kWh.

To achieve the bottom line COE values, all the elements in the cost of electricity must be determined and controlled. Resolved into capital and operating cost components, the COE projection is driven by decisions regarding plant size (noting economies of scale), materials choices [6], thermal cycle efficiency, availability, and maintenance scheme as well as a host of other factors. There is a strong incentive to expedite the construction time to lower the finance costs. Plant availability is determined by the interplay between design margins and redundancy, which affect the forced outage rate. Access and sectorization of the power core influence the mean time to repair, scheduled outage durations, and capital cost. These subtier requirements will be initially allocated to arrive at an overall acceptable COE. As the design evolves, trade studies will continue to determine the best mix of risk, performance, and cost [7].

Since the Demo will still be on steep part of the performance and cost learning curve, it will not represent an optimal design for a commercial plant. Moreover, it would still have to carry the burden of some development costs, increased costs associated with first-of-a-kind production components, and higher contingency allowances. Thus Demo would not be expected to achieve the desired COE values without significant government or investor subsidy to artificially lower the capital and operating costs. Thus the owner/operator of this demonstration power plant must be able to operate this demo plant on the power grid for long periods of time and gain both operational experience and profit for the sale of electricity.

III. SUMMARY

This set of requirements constitutes the Starlite project's guiding principles to arrive at a commercially acceptable electric-generating power plant. This is the "market pull" portion of the equation. On the other side of the coin is the "technology push." The size and power level of tokamak plasmas are reaching the size necessary for commercial applications. The control and stability of the plasmas are sufficient for experiments, but need to be demonstrated for commercial usage. The current drive systems for long duration, steady-state plasma need to be applied to large tokamak plasmas. Low-activation materials for the power core structure and shielding need to be developed, validated, and applied in representative high heat and radiation environments. Much work remains to establish the solid technology and engineering foundations upon which the Demo can be designed, built, and operated. Hopefully, these top level requirements will provide insight for the program to help achieve a successful commercial venture.

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