

## An Integrated Design for Demo-FPP to Achieve RAMI Goals

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**Scope:** This white paper discusses the need to establish a credible, detailed, and integrated design for the US Demo and the future Fusion Power Plant (FPP). This design would certainly be evolutionary, but it would provide the basis to select mainline and alternate subsystems that would be developed and matured for implementation into the Demo and ultimately into the FPP. With this baseline established and candidate subsystems and technologies identified, detailed technical roadmaps can be defined. These roadmaps will help to efficiently develop and mature the necessary capabilities and help eliminate extraneous developmental activities.

Much emphasis has been placed on controlling the magnetically confined plasma, the understanding the plasma/material interfaces, handling the power and particle flows, and converting the nuclear energy into fuel and thermal heat. These are essential scientific investigations that must be accomplished before fusion can be successful. However, the end goal is convert the fusion energy into useful, reliable, and stable electrical power. The advancement of Reliability, Availability, Maintainability, and Inspectability (RAMI) is an essential ingredient to achieve our end goal of a commercially viable fusion power plant. All the components and subsystems within the plant must meet stringent RAMI goals to assure the plant will operate as envisioned. Alternate subsystem options should be pursued to help mitigate programmatic risk. At some future point, all the baseline design choices must be completely validated as reliable and maintainable elements of an integrated design.

**Rationale:** Competitive electrical power production is the end goal for fusion energy. If the Demo does not substantially convince the decision makers and financiers of the viability of economically competitively electricity production, fusion will fail to be an energy source. The primary metric for competitive power production is the cost of electricity as defined by the equation shown below.

$$\text{COE} = [C_{AC} + (C_{O\&M} + C_{SCR} + C_f) * (1 + y)^Y / (8760 * P_E * P_f) + C_{D\&D}]$$

The COE is defined by the annualized plant and operating costs divided by the annual power production, which is the net electrical power production times the plant availability. It is very important to produce the power, but it is equally important to keep the power flowing to the grid as much of the time as possible (i.e., plant availability).

Plant availability is a multiplicative function of the availabilities of all the elements of the plant. If any one element cannot sustain a high level of availability, the entire plant falls to the level of the lowest element. The general equation for availability is defined below.

$$\text{Availability} = \frac{\text{Operational Time}}{\text{Operational Time} + \text{Scheduled Down Time} + \text{Unscheduled Down Time}}$$

Operational time is the power production time over a set period of time, typically a year. The scheduled down time is the sum of regularly scheduled maintenance actions for the entire plant,

including the power core, other reactor plant equipment, and the balance of the plant equipment. The scheduled down time is related to the component lifetimes, the replacement schedules and mean time to repair (MTTR). The unscheduled down time is the summation of the maintenance times to repair unscheduled operational failures that cause the plant to cease power production. These failures are characterized by the mean time to repair divided by the mean time between failures (MTTR/MTBF) for all the critical components.

Availability is intrinsically dependent on three elements: 1) reliability, 2) maintainability, and 3) inspectability. The inherent reliability of all the power core and plant component parts must be very high, usually greater than 0.99 for each major system. The more mature systems such as many of the BOP systems are operating at these levels currently. It will be very difficult to qualify the power core and the fusion-specific systems to these levels of reliability.

Maintainability is the ability to rapidly and reliably maintain all the plant parts, especially the remote maintenance for the power core. The power core maintenance approach may be highly automated and will likely be completely autonomous in 50 years. Inspectability is the examination of the plant components to determine if there are any indications that components might fail in service as well as any reduction or increase in performance and/or service lifetime. This implies extensive pre- and post-operational examinations, along with an embedded, real-time monitoring of all operational components as a part of an integrated system health management (ISHM) system that will predict and schedule preventative maintenance actions. This ISHM system represents a new technology that is currently being developed in the aerospace field.

Fission power plants are the most comparable power technology to our proposed fusion power plants. The availability of the first generation fission power plants in the late 1950s and 1960s were in the range of 50-60%, which was roughly comparable to competitive fossil generating plants in that time period. The Shippingport fission power plant had an initial availability goal of 70%<sup>1</sup>. Operational availability in the first few break-in years fell short of that goal, however within a few years, Shippingport did reach their availability goal. Since that time, fission and fossil plants have steadily improved their plant availabilities. All new and reasonably new electrical generating plants are now operating with availabilities in the 85-90% range, but that has required three or four decades of operating experience. In the next 25-40 years, the state-of-the-art power plant availabilities will be much greater than 90%. To compete, the first generation fusion power plants must demonstrate that they can achieve that high level of plant availabilities. Demo must be a convincing stepping stone that will provide that level of assurance.

**Approach:** The neutron activation of the internal power core elements limit the useful life of these components and requires remote maintenance of these internal components. Efficient power production suggests a compact power core pushing the surface and volumetric heat and particle limits for the materials, which tends toward shorter component lifetimes. The compactness of the core also complicates removal and reassembly of the removed blanket and divertor modules. Another complication is that any fluid leak of any size internal to the vacuum vessel will likely preclude plasma generation and control. Therefore, all fluid piping, connections, and seals must be highly reliable. So there are many engineering challenges to make fusion power safe, reliable and economical.

After fusion has been proven to work (e.g., successful operation of ITER), it must be proven that it can work efficiently and reliably. To do that, there has to be an integrated design of Fusion

Power Plant (FPP). This will enable the design and development of an integrated power core, maintenance system, health management system, maintenance system, hot cell, fuel processing facility, and balance of plant systems. All of these components and subsystems have to be designed, prototyped, produced, and tested in relevant and operational environments to qualify them for integration into a demonstration power plant, a Demo. The purpose of the Demo is to demonstrate that these integrated systems can be reasonably extrapolated to the Fusion Power Plant with an acceptable level of risk.

The ARIES designs from ARIES-I<sup>2</sup> to ARIES-AT<sup>3</sup> have provided the genesis for an integrated fusion power plant design. However, these designs are only starting points that suggest some approaches. The ARIES designs have been instrumental in assessing the merits and detriments of new technologies and suggesting areas of future research and development. However, they lack the level of detail necessary to initiate specific research and development initiatives. A more detailed preliminary design of the FPP (and Demo) is needed to establish the primary baseline and alternate subsystems to be developed. Alternate subsystems approaches are necessary to reduce the programmatic risk if the primary approach fails to achieve the necessary goals. In order to make sure the plant has the necessary level of availability, this definition has to include not only the power core elements, but also the maintenance equipment, hot cells, buildings and all other ancillary equipment that is implicit in a truly integrated plant design. Only then the job of maturing those components and subsystems can commence.

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