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Methodology for Scaling Fusion Power Plant Availability

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Summary - Normally in the U.S. fusion power plant conceptual design studies, the development of the plant availability and the plant capital and operating costs makes the implicit assumption that the plant is a 10^{th} of a kind fusion power plant. This is in keeping with the DOE guidelines published in the 1970s, the PNL report[1], "Fusion Reactor Design Studies – Standard Accounts for Cost Estimates. This assumption specifically defines the level of the industry and technology maturity and eliminates the need to define the necessary research and development efforts and costs to construct a one of a kind or the first of a kind power plant. It also assumes all the "teething" problems have been solved and the plant can operate in the manner intended. The plant availability analysis assumes all maintenance actions have been refined and optimized by the operation of the prior nine or so plants. The actions are defined to be as quick and efficient as possible. This study will present a methodology to enable estimation of the availability of the one of a kind (one OAK) plant or first of a kind (1^{st} OAK) plant.

To clarify, one of the OAK facilities might be the pilot plant or the demo plant that is prototypical of the next generation power plant, but it is not a full-scale fusion power plant with all fully validated "mature" subsystems. The first OAK facility is truly the first commercial plant of a common design that represents the next generation plant design. However, its subsystems, maintenance equipment and procedures will continue to be refined to achieve the goals for the 10^{th} OAK power plant.

Methodology for mature power plant availability - The most technically correct method to estimate the expected plant availability for a future plant is to have a complete set of all relevant data. This would include detailed and verifiable reliability and lifetime data as well as maintenance procedures and timelines for all components, subsystems and systems. This is a desirable, but probably an unobtainable wish that never will be realized in any new product introduction. All the needed data are never available for an accurate availability prediction. Instead, the best that can be hoped for is to extrapolate from prior reliability and maintainability experience with some level of prototype testing and simulation/modeling. Fidelity of predicted results is a trade of time and money.

The past, and present, methodology to estimate the 10^{th} OAK fusion plant availability in the U.S. designs is to estimate the time to do the essential serial maintenance actions consistent with highly refined procedures using specialized automated maintenance equipment. The inherent assumption is that these equipment and procedures will be available and optimized in the distant future when this 10^{th} OAK fusion plant is operational. The downtime of the plant is the only free parameter in the determination of plant availability. It is assumed that the fusion power plant is a capital intensive facility and it will be operated as a baseload power plant that is operational at full power except in planned or unplanned shutdowns. The duration of the downtime depends on the scheduled plant maintenance time (determined by the component, subsystem or system operational lifetimes and the time to maintain, repair or replace those plant elements) and the unscheduled downtime (determined by the reliability or failure rate of the components, subsystems or systems and the time to repair or replace those plant elements). It is highly desirable that the 10^{th} OAK fusion plant can achieve a plant availability of 90% or better to be competitive with other capital intensive power sources. Initially, the ARIES-AT fusion power plant study[2] intended to achieve an overall plant availability of 90%, but more conservative assumptions resulted in an estimated overall plant availability of 87.6%.

The power core typically has the most technical interest and most fidelity in the pre-conceptual design phase. So the availability analysis of this study concentrated on the major power core elements. More specifically, the scheduled maintenance durations of the power core elements will be examined in some depth as the design definition of these elements allows insight into the scheduled maintenance actions required, maintenance equipment and the associated timeline durations. This allows the definition of a preliminary availability analysis of the scheduled maintenance for the major power core elements. The detailed assessment of the ARIES-AT[2] major power core maintenance yielded an averaged maintenance duration of 4.23 days/FPY based on a trade study of the number of maintenance sets operable and the portion of power core replaced at a time. (FPY is defined as a full power year).

At this point of pre-conceptual design, the remainder of the power plant design does not have sufficient definition to enable a detailed availability assessment. Instead, some preliminary guidelines are established to help scope the design requirements. The ARIES-AT maintenance and availability analysis[2] developed a methodology to establish availability (or maintenance days/FPY) guidelines to achieve the desired overall plant availability. To simplify that analysis, the facility was subdivided into major categories for analysis of maintenance actions:

- Scheduled maintenance for major power core elements
- Scheduled maintenance for minor power core elements
- Unscheduled maintenance for power core elements (both major and minor)
- Scheduled and unscheduled maintenance for the power core (support) plant equipment (cryogenic plant, fuel processing plant, main heat transfer and transport, turbine plant, electric plant, miscellaneous plant and others)
- Scheduled and unscheduled maintenance for the balance of plant (BOP) equipment

The data shown below are not from experience; rather these values represent the composite guidelines for mean time to replace/repair (MTTR). The availability equation used is:
Availability = FPY/(FPY + Maintenance Days/FPY) = 365.25/(365.25+ Maintenance Days/FPY)

Major power core elements, scheduled – For the availability analysis, the major power elements are generally divided into those that are routinely replaceable, such as the blankets, divertors, shields and hot structure and those that are considered to be nominally "life of plant", such as cold shields, vacuum vessels, TF/PF coils and support structures. The ARIES-AT availability assessment[2] analyzed the expected durations for the replaceable elements with their expected lifetimes to yield a value of 4.23 maintenance days per FPY or a system availability of 0.989. This ARIES-AT analysis assumed replacement of half the power core every 2 FPY based on an estimated life of 4 FPY for those replaceable components. Horizontal sector replacement was the baseline maintenance scheme. If a different confinement concept, design approach or maintenance scheme is adopted, a different value of maintenance days will be determined combined with another FPY replacement period. The non-replaceable elements were not included in the availability assessment as their likelihood of failure should be too low to be considered. However, the design of the maintenance equipment must be designed to replace all power core and power core equipment inside the bioshield.

Minor power core elements, scheduled - As stated earlier, the maintenance of the minor power core elements cannot be estimated analytically without more detailed definition of these elements. To achieve the desired ARIES-AT availability, the maintenance of the minor power core is estimated to take a factor of approximately 1.4 times as long as the scheduled maintenance of the major power core elements or 6.05 days/FPY. This is probably a conservative estimate for that portion of minor power core maintenance that would require the facility or plant to cease operation for repair or replacement. Much of the time, the minor power core elements can be replaced while the plant remains operational. It is recommended this same value of 6.05 days/FPY from the ARIES-AT analysis be adopted.

Power core, unscheduled – These unscheduled maintenance actions for both the major and minor power core elements arise from actual or incipient failures predicated on the mean time between failure (MTBF) data, which equates to 1/ (failure rate). There is practically no definitive data on the likely MTBF times for any of the high power level and long duration fusion components and subsystems needed for these new classes of fusion facilities or power plants. The ARIES-AT availability approach[2] established maintenance timeline guidance for the power core unscheduled maintenance timelines using a factor double the power core scheduled and unscheduled maintenance action durations (namely, 20.56 days/FPY). The ARIES-CS[3] power plant study chose to adopt the same methodology and maintenance duration values to retain similarity between then two studies and allow more direct comparisons of the power core and its scheduled maintenance approach. It would be appropriate to adopt the same power core unscheduled maintenance timeline of 20.56 days/FPY. This is felt to be a conservative estimate of the unscheduled maintenance of the power core.

Power core equipment, scheduled and unscheduled - The availability of the power core (support) equipment presently does not have a substantial database upon which to draw. Some of these systems are being used in current experiments, but these systems will be obsolete for the first generation fusion power plants. These systems are remote from the core and should be able to be largely maintained while the power core is operational. They could also have redundant subsystems and components to increase the availability as high as necessary. It is judged that the power core equipment would also need to have a combined availability (scheduled and unscheduled maintenance) of 97.5% (= 9.37 days/FPY).

BOP, scheduled and unscheduled - The availability of the BOP for large power plants of all types has steadily been improving and will likely be in the range of 97.5% in the time period of interest (approximately 2100 for the 10^{th} OAK), which equates to 9.37 days/FPY (scheduled and unscheduled maintenance).

Summary of maintenance action durations – Table 1 shows the average maintenance durations and availabilities by the major systems groups required to yield an overall plant availability of 87.6%. The scheduled power core maintenance will be specific to any particular conceptual design study, hence the TBD in the table. The remainder is derived from ARIES-AT data to be consistent with the comparisons of different plant types and configurations.

[Repeat of availability equation: Availability = FPY/(FPY + Maintenance Days/FPY) = 365.25/(365.25+ Maintenance Days/FPY)]

Table 1. System Maintenance Days/Full Power Year and Availabilities (Ref 2)

System Group Maintenance	Maintenance Days/FPY	System Availability
Power Core, Major, Scheduled	TBD (4.23 for ARIES-AT)	TBD (or 0.989
Power Core, Minor, Scheduled	6.05	0.984
Power Core, Unscheduled	20.56	0.947
Power Core Equipment, Scheduled and Unscheduled	9.37	0.975
BOP, Scheduled and Unscheduled	9.37	0.975
Total		TBD (or 0.876)

<u>Availability as related to plant maturity</u> – In comparison to the 10th OAK power plant availability shown in Table 1, the availability of the one OAK plant will only be a fraction of that for a highly developed plant. This is due to the exploratory nature of an initial or prototypical plant or facility. The one OAK plant might be representative of a pilot plant or a demonstration power plant. Power core or power core equipment generally has not been employed in this scale before; lifetimes, reliability and maintenance needs are unknown and maintenance procedures are being written and tried. Experience data from prior, smaller experimental facilities (even ITER) are largely not applicable as those experimental plants were not designed or intended to extend their availability experience database to a one OAK large fusion power plant, except for a few technologies and subsystems. Thus, it is felt that only an "educated judgment" factor can be used to scope the likely one OAK fusion plant availability. This factor can be used to scale the individual action timelines of the 10th OAK plant to the one OAK plant. These data can be used to estimate the necessary timelines and element reliabilities given the desired range of availability for the one OAK plant. It is hoped the one OAK fusion plant might achieve a plant availability on the order of 50% or better to lessen the risk to achieve competitive availabilities with other capital intensive power sources. This value of 50% is generally recognized by the community as a reasonable goal for the one OAK facility to minimize the technical and programmatic risk to build the first OAK facility. If more than one OAK plant is built, the learned experiences can benefit the second plant or facility.

The availability analysis of the first OAK plant of the new design generation is in the middle ground between the one OAK and the 10th OAK. In other words, the first OAK plant will adopt either the same or improved subsystems or maintenance procedures from the prior plants. These prior experience databases will certainly improve upon the operational plant availability, but it will not initially be up to the standards of other competitive power sources with more extensive learning experiences and more mature designs. These fusion plant subsystems and maintenance procedures need to be vetted for this new application. This design is intended to be the standard design and operation for a whole series or generation of fusion power plants. This is a different scenario from the situation observed in the development of fission plants where almost every fission plant was a unique design, with little in common for the differing fission plant designs (BWR vs. PWR; light water reactors vs. heavy water reactors). Even within these broad categories, there was little design commonality. The new fission Gen IV power plants are intending to use more common modular designs.

The plant availability of the first OAK plant will certainly benefit from the previous one OAK plant. It is hoped the initial plant availability of the first OAK fusion power plant would be in the range of 70-80% after the early design and operational problems are solved. During the lifetime of this plant, the plant availability will continue to improve if the subsystem designs are reliable and long-lived. On the other hand, if the teething problems in the subsystems continue to plague the plant, the availability will decrease to less than desired levels. The latter situation might suggest significant design changes might be needed before committing to future plants.

To scope the relative maintenance duration estimate differences between the 10th OAK, first OAK and one OAK plants, Table 2 proposes some guideline factors to estimate the maintenance durations on fusion power plants with differing maturities. These factors will be used in conjunction with the maintenance durations shown in Table 1. The values proposed in Table 1 are for scoping purposes only and do not have any basis in experience. However it is felt that the scheduled maintenance times for the 10th OAK plant could be halved with experience gained in the prior 9 plants, hence a factor of 2. Likewise there would be a similar learning experience in the scheduled maintenance times from the one OAK to the first OAK, therefore a factor of 4 relative to the 10th OAK maintenance durations. The unscheduled maintenance would likely have a pronounced learning curve with lots of unexpected failures and premature wear-out; therefore factors of 4 and 10 were applied. The scheduled and unscheduled maintenance durations for the power core equipment is a blend of wear-out and failure instances, but with less impact on the plant availability due to on-line replacement and parallel equipment approaches, therefore the factors are reduced to 3 and 6. The BOP maintenance durations are similar in that they are a mixture of scheduled and unscheduled, but the BOP includes much more mature technologies. Therefore their factors are suggested to be 1.5 and 3.0.

Table 2. Relative Maintenance Duration Factors Relating to Plant Maturity

System Group Maintenance	Relative Maintenance Duration Factors* 10th Of A Kind Plant	First Of A Kind Plant	One Of A Kind Plant
Power Core, Major, Scheduled	1.00	2.00	4.00
Power Core, Minor, Scheduled	1.00	2.00	4.00
Power Core, Unscheduled	1.00	4.00	10.00
Power Core Equipment, Scheduled and Unscheduled	1.00	3.00	6.00
BOP, Scheduled and Unscheduled	1.00	1.50	3.00

* These factors are assumed to apply after the procedures have evolved and the maintenance equipment matured and design flaws corrected

The values suggested in Table 2 were then applied to the maintenance durations from the ARIES-AT availability analysis[2] as shown in Table 3. This methodology suggests that if a 10th OAK plant might achieve a plant availability of 0.876, then a first OAK plant with similar equipment and maintenance procedures might achieve a plant availability of 0.69 and a similar first OAK plant (pilot plant or demonstration plant) would be expected to achieve an availability of 0.46. This analogy would probably not apply to plant designs that were not similar or prototypical, e.g., a component test facility. It should be pointed out that with this methodology and the values assigned, the unscheduled maintenance of the power core is responsible for the largest downtime, followed by the scheduled and unscheduled maintenance of the remainder of the power core equipment. This is based on the assumption that the known issues can be addressed ahead of time, but the unknown issues and failures will likely prove to be the hardest to solve in real-time.

Admittedly, this approach represents a lot of this approach uses a combination of supposition and educated or best-guess scenarios, but this methodology gives a reasonable progression of expectations regarding maintenance durations and plant availabilities as the fusion plant equipment and procedures mature.

Table 3. Relative Maintenance Duration Factors Relating to Plant Maturity

10th Of A Kind Plant			First Of A Kind Plant			One Of A Kind Plant		
System Group Maintenance	Maintenance Days/FPY	System Availability	Factor	Maintenance Days/FPY	System Availability	Factor	Maintenance Days/FPY	System Availability
Power Core, Major, Scheduled	TBD (4.23 for ARIES-AT)	TBD (or 0.989)	2.00	8.460	0.977	4.00	16.920	0.956
Power Core, Minor, Scheduled	6.05	0.984	2.00	12.100	0.968	4.00	24.200	0.938
Power Core, Unscheduled	20.56	0.947	4.00	82.240	0.816	10.00	205.600	0.640
Power Core Equipment, Scheduled and Unscheduled	9.37	0.975	3.00	28.110	0.929	6.00	56.220	0.867
BOP, Scheduled and Unscheduled	9.37	0.975	1.50	14.055	0.963	3.00	28.110	0.929
Total		TBD (or 0.876)			**0.69**			**0.46**

Conclusions – A methodology has been developed to help estimate a set of reasonable expectations of maintenance durations and availabilities for the major plant elements as the fusion plant designs evolve from a one of a kind, to the first of a kind and finally to the 10th of a kind fusion power plants. All these plants share a common design architecture and prototypical/identical components, subsystems, systems, equipment and procedures that have been validated in incremental stages of relevant environmental operations. It is hoped this methodology will help establish reasonable goals and requirements for future staged facilities leading to the desired commercial fusion power plant.

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