Architectural development of an ST fusion device*

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Abstract

A recent U.S. National Academy study recommended the development of a next step Sustained High Power Density (SHPD) facility within the U.S. as an intermediate step in designing and building a Pilot Plant device [1]. Several papers have been written describing the physics [2], design [3] and engineering scoping analysis performed in developing this machine design. This paper places emphasis on the continued evolution of the architectural development of past activities to meet the requirements of an ST fusion pilot plant and power plant. The current effort centers on meeting basic physics and component requirements in a machine design that improves the chance of achieving fission level availability (95 %) within an arrangement that promotes design simplicity, offsite construction with on-site modular assembly. As a prelude to both the SHPD and Pilot Plant, a scoping design of a 500MWe Spherical Tokamak Advanced Reactor (STAR) has been defined to investigate design options and physics scenarios that can successfully meet physics performance, engineering requirements and economic conditions of an ST power plant. Following a successful physics/engineering assessment, the STAR Power Plant design will be downsized to meet the specifications established in the design of a near term ST Pilot Plant

Keywords: Sustained High-Power Density, high-temperature superconducting magnets, liquid metal (LM), Economies of Scale

1. INTRODUCTION

Fusion experimental devices have evolved in efforts to understand plasma operating conditions, through the ITER project to make a long-awaited transition from experimental studies to physics conditions of a burning plasma. And thanks to the private sector, increased fusion research and development has become available to augment the building of full-scale electricity-producing fusion pilot plants. The ITER tokamak design was an outgrowth of the EU JET physics device and not a machine design that promotes a viable maintenance strategy needed in a power plant design. A scoping design of a 500MWe Spherical Tokamak Advanced Reactor (STAR) device has been developed as a prelude to a Sustained High-Power Density (SHPD) facility or a larger pilot plant to help define the attributes that offer a good chance in meeting all power plant requirements. Four STAR design objectives were promoted:

1. Meeting physics requirements,
2. within established engineering design allowables,
3. in a design configuration that leads to fission level operating availability values, while
4. offering the best chance of meeting economic cost conditions

ST physics requirements and engineering allowables have been established. The challenge rest in defining a machine architect that enables fission level high availability that can meet energy completive cost objectives. The tenets that underpin the machine architect include:

1. Promoting design simplifying features,
2. Maximizing off site construction,
3. Pursuing size reducing options that lowers costs and fosters offsite construction,
4. Pursuing LM blanket options that foster design simplicity and lighter weights when drained,
5. Pursuing design options and techniques that reduces the assembly time to install and remove blanket/shield components to/from the maintenance facility, and
6. Having faith that current high-cost compact components used in reducing the device size will decrease in price through technology improvements over time.

Another important premise established was not to specifically design to the lowest possible device size but rather achieve an amicable balance between all design requirements, recognizing that a larger size device operating at higher power levels can be an important aspect in reducing energy costs through economies of scale (EOS) considerations.

2. BACKGROUND

As defined in this paper’s title and stated in the abstract, the details presented herein represents a design configuration made of concepts intended to balance physics, engineering, operating availability with capital cost considerations to arrive at a machine design that “may” lead to an economically viable fusion power plant. Any economical fusion device will be difficult to achieve, all innovative ideas need to be pursued.

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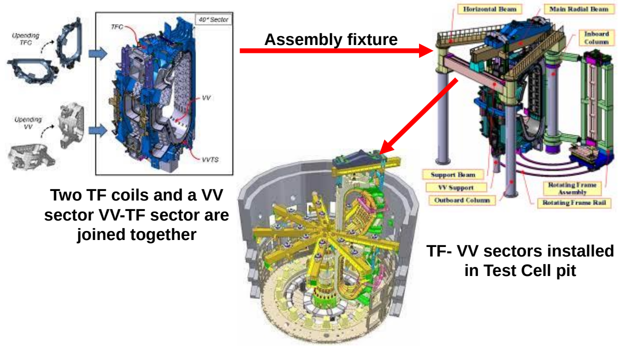
The level of engineering activity supporting this early concept design doesn't come to the level of design and analysis support that's behind ITER and EU-DEOM designs. The principal author of this study fully recognizes the thoroughness, quality and documentation rigor generated in these projects and where appropriate have incorporated some of their features.

To fully appreciate the machine architecture presented and the scope of the changes made, some comparisons between this new design and features presented in ITER and the EU-DEMO design is informative. Given this introduction, section 3 presents a selective overview of the ITER and EU-DEMO design to act as a backdrop to the changes being proposed in developing the STAR deign. Section 4 will give an overview of the STAR power plant device. Section 5 will follow with basic comparison of RM and facility elements between the STAR design and EU-DEMO, section 6 will provide early PROCESS code results followed by concluding remarks in Section 7.

3. ITER AND EU-DEMO BACKDROP

ITER has made a major contribution to the advancement of magnetic fusion even before the start of first plasma operation through engineering development and technology advancement. This project has set a foundation of some major components from which to design a next step DEMO device.

The EU-DEMO follows ITER in many respects. It incorporates a vertical maintenance scheme with a single divertor at the bottom and 16 TF coils (in lieu of ITER's 18 coils). The ITER tokamak is assembled in 9 sectors, each with a toroidal angle of 40°, comprising a vacuum vessel sector, two toroidal field (TF) coils, the associated vacuum vessel (VV) thermal shield, a pair of intermediate outer intercoil structure friction joints, which connect the outboard regions of the two TF coils. Once assembled the TF-VV assemblies are installed in the reactor pit as illustrated in Figure 3-1. A major issue in the assembly of a tokamak core is the tight installation tolerances required for the major components, especially components installed with limited access.



Two TF coils and a VV sector VV-TF sector are joined together

TF- VV sectors installed in Test Cell pit

Fig. 3-1: ITER VV-TF sector, its assembly fixture and the installation within the test cell pit

Maximizing offsite assembly has been emphasized in the PPPL STAR power plant design to reduce construction cost. The ITER TF coil was constructed off site and shipped to the ITER facility therefore the ITER shipping container envelope and the coil itself was used as a sizing metric in determining the maximize size of the STAR TF coil, or any other component within the STAR design. Figure 3-2 shows a layout of the ITER shipping container with the TF coil inside. Also shown in the figure is the container with a collection of ITER, STAR and an estimated sizing of the EU-DEMO TF coil and one shown with a large STAR vacuum vessel sector inside. As indicated by the shipping container with three TF coils inside, the expanded STAR TF coil easily fits whereas the EU-DEMO TF coil extends outside the container envelope. The STAR designed TF coil has been expanded beyond the dimensions established within the ITER or EU-DEMO designs to allow greater space to extract a reduced number of larger blanket-shield sectors in a 12 TF coil arrangement. The four circular diameter outer ring coils remains to be of a size that will require it be built on site, albeit with a coil geometry easier to fabricate.

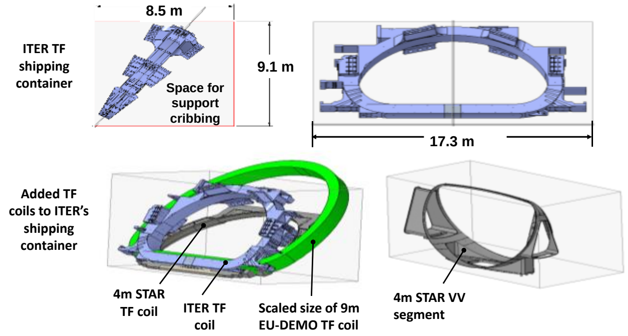
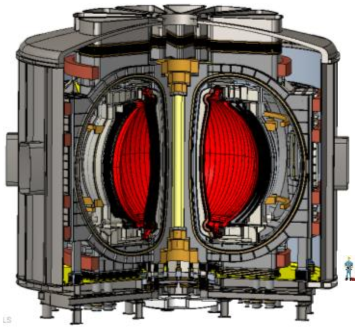


Fig. 3-2: ITER shipping container used in setting the STAR component size limit where possible

Magnet systems, buildings and site facilities are dominate cost components in a fusion device and any approach that will reduce this cost is welcomed. To reduce the size of the STAR power plant design, higher performance High Temperature Superconductors (HTS) were used.

4. OVERVIEW OF THE STAR POWER PLANT DEVICE

The 4.0m STAR power plant shown in Figure 4-1 identifies the general arrangement and lists basic physics parameters. Several design assumptions were made to enhance the ability to meet availability and cost goals on this project:



STAR Power Plant design

- **4.0m R0, A=2.0, 2.5 elongation**
- **12 TF coils**
- **5.1 T B0, 20.2 T Bmax**
- **HTS winding, 20 K temperature**
- **Vapor Box, Double null divertor**
- **Liquid metal FW**

Fig. 4-1 Cutaway view of the concept defined STAR design

1. To minimize the device inner build space, it was assumed that the presence of an external cryostat will allow a thinner, single wall VV to be constructed with a pressure disk connection to the cryostat in case of loss of vacuum and a disruption load support system with an impulse

connected support off the inboard semi-permanent shield; a support system that minimizes the movement of the VV wall,

2. Interconnected, inboard-outboard blanket sectors attached to the machine base (with radial movement) will have sufficient stiffness to support disruption loads,
3. A successful vapor box divertor will be defined by physics that eventually offers blanket level operating lifetime, and
4. An intermediate RM chamber above the reactor pit allows passage of in-vessel components to an adjacent maintenance facility without an intermediary cask system.

A STAR design can be developed outside these parameters but with a larger device with availability performance and cost consequences.

ITER style inner TF compression rings were replaced with a radial coil-to-coil bolting scheme and semi-permanent shield segments installed on the VV inboard section to stop streaming and fortify the inboard VV shell. As stated earlier, the TF coil outboard legs have been expanded to increase the internal space to allow a fewer number of larger in-vessel (IV) blanket-shield sectors to be removed through much larger vertical ports. It's recognized that the cost of the TF HTS winding will be higher than a Low Temperature Superconducting (LTS) winding, but it's expected that the simplification of the IV sector design, improvement in RM features and prospects for higher availability will offset the TF conductor cost. Also, with time, technology and manufacturing improvements, HTS windings will reduce in cost.

A cross section of the STAR TF coil is shown in Figure 4-2 with respect to the ITER coil. The 12 TF enlarged coils was sized for 0.3% ripple. Upon further optimization the position of the back leg can be reshaped and moved in approximately 1m with the inclusion of an ITER style ferromagnetic insert. In lieu of the ITER style inner TF compression rings and corner shear pins, an inboard corner coil-to-coil bolting scheme has been defined but not yet analyzed in detail. FEA analysis has been performed on a reference TF set with 316 SS case material and a second analysis with a higher strength Nitronic 33 forging (894 MPa at 20 K allowable) in the nose region to provide increased strength to support a higher operating field. Acceptable preliminary results were achieved to allow the higher strength design to move forward.

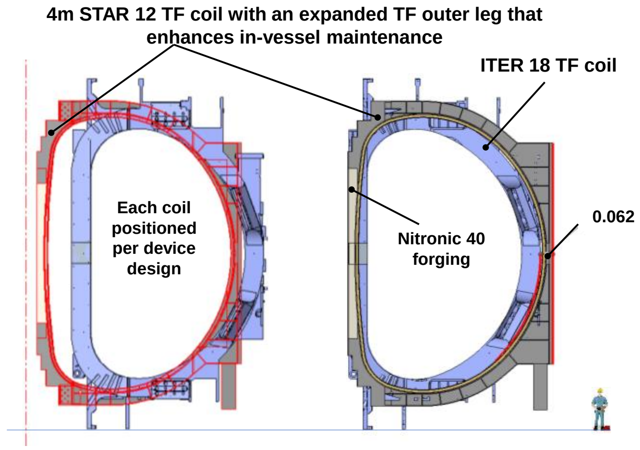


Fig. 4-2: STAR expanded TF coil shown with respect to the ITER TF in defined and overlay

The TF coils are supported off a cryostat base structure that is reinforced to support the entire device with local supports connected to the reactor hall floor. Enlarged lower ports are sized to accommodate blanket pipe feeds emanating from below the device, not through the upper vertical ports. Figure 4-3 shows two lower sections with cuts between TF coils and one through the TF coil that calls out some of design details.

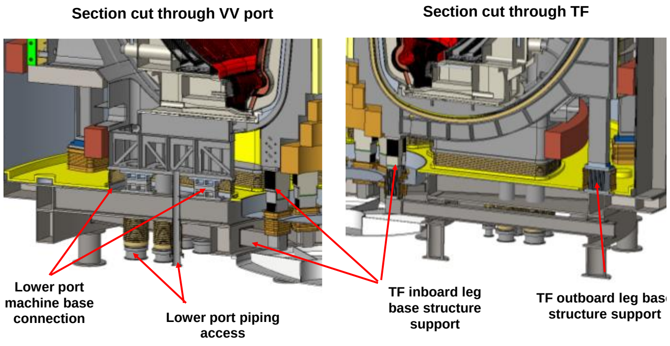


Fig. 4-3: Local details showing the base structural with blanket lines passing through lower ports

Rather than a multi-TF coil and included vacuum vessel sector installation as used in ITER, the STAR design involves assembling individual components in an onion skin design following a staged assembly where:

- Individual TF coils are installed first on a cryostat base,
- followed by the insulation of the thermal shield system, then
- VV segments installed to form the full vacuum vessel

Figure 4-4 is shown to depict the assembly stage of individual TF coils, thermal insulation (TI) and vacuum vessel segments. After all coils are optically aligned and secured a continuous TI system is installed around the TF inboard leg and local VV segments (TI attached) positioned within the bore of the TF and temporarily supported. Larger VV mid-sections that include the vertical ports are installed at the last stage; all TI interfaces joined and the VV system is then welded and leak checked. Space is needed between the TF back leg and the outer VV surface to vertically install the larger VV mid-section sector. Local details are shown in Figure 4-5.

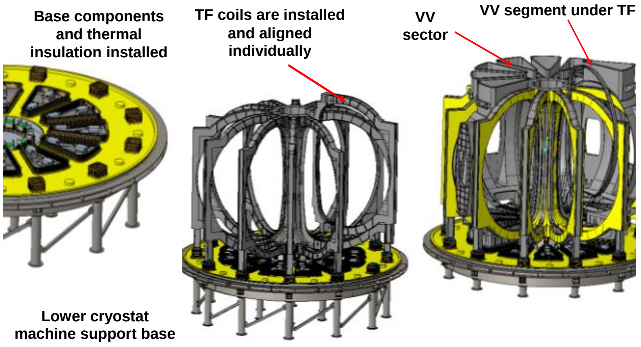


Fig 4-4: The STAR design provides sequential assembly

The STAR base structure (shown in Figure 4-6) supports the entire blanket-shield system and incorporates a drain scheme that will collect the lithium that flows on the FW. Included in the floor plate structure is an embedded roller track system used to guide a Hilman roller plate structure with guide pins that receive retracted blanket-shield sectors. Vertical support structural connections are provided along the inboard perimeter of the base plate and at the outside permitter to act as a blanket-shield tie-downs against possible vertical disruption loads.

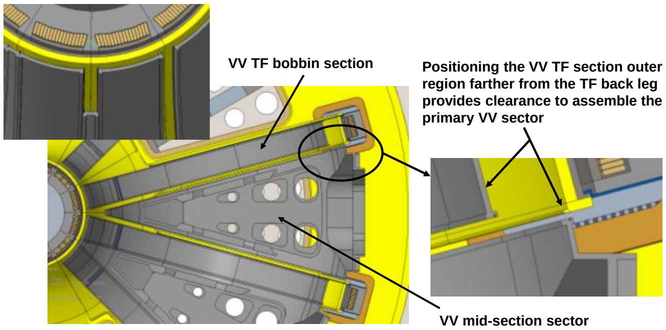


Fig. 4-5: Local view of VV mid-section installation

Other design features that play a role that affects the device cost, and its operating availability are VV space within the TF bore, the blanket-shield segmentation approach and the concept defined for maintenance. The expanded TF arrangement provides the geometry to increase the size of the vertical ports and internal space to extract fewer numbers of larger blanket-shield sectors. Employing a liquid blanket system as in DCLL blankets improves design simplicity and allows draining the Li-Pb content to reduce weight, aiding RM handling. The Li-Pb fluid itself can be stored, topped off and reused after the installation of a new blanket system. A retracted inboard-outboard shield sector (IOSS) illustrated in Figures 4-7 has been defined in the STAR conceptual design. The inboard and outboard blanket/shield sectors are connected at the bottom and top with a sliding beam system guiding the inboard sector into a defined cavity formed by the structure of the outboard blanket back wall shield. All blanket/shield joined sectors located under the vertical ports require a small horizontal movement before lifting the unit straight up through a vertical port. Once the sectors under the ports are removed, vertical lifts from two ports can access the banket sector sitting under a TF coil to allow a roller base support system to be installed beneath the sector. Guides cuts in the base support system operated from a vertical port can be used to move the sector under a vertical port. While the sector is in motion temporary segmented circular beams can be installed with a roller system to stabilize the sector movement if needed to control movement under a vertical port (see Fig. 4-6) with motorized rollers or hydraulic or cable driven system used depending on the radiation level. When drained the LM retracted blanket sector to be handled/lifted through the vertical port weighs 52 t. Figure 4-8 shows a midplane cut to illustrate more of the design features. The inboard blanket-shield is shown moving out, a staggard inboard semi-permanent shield arrangement surrounding the VV, the TF inboard leg showing the HTS region and space allocated for a 25 v-s supplied OH solenoid. The blanket-shield system is designed to be dismantled, followed by removing and discarding the plasma facing section (discussed later).

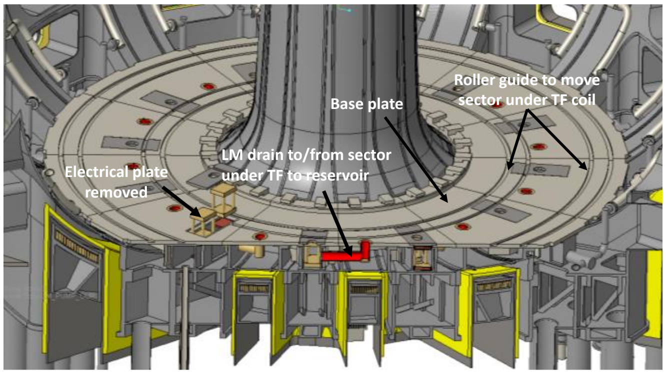


Fig. 4-6: STAR base support and lithium drain system

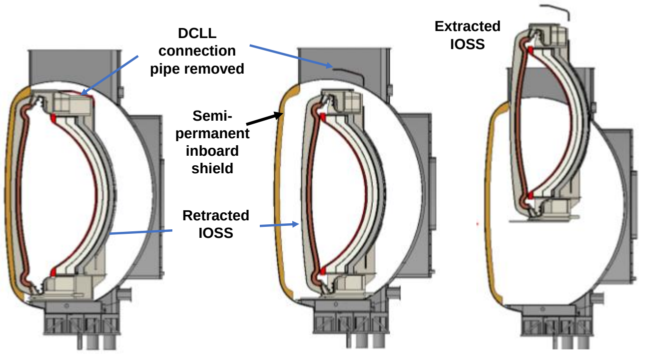


Fig. 4-7: In-vessel joined segment removal sequence

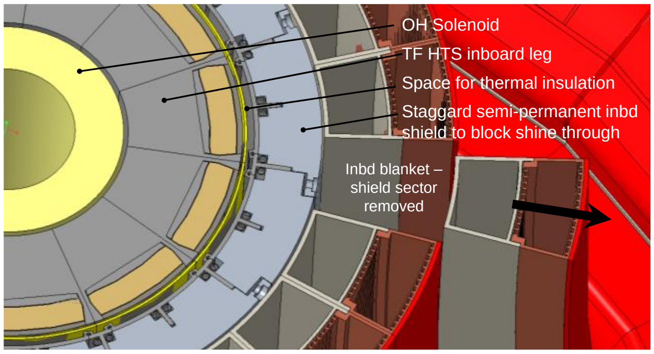


Fig. 4-8: Midplane cut of STAR inboard region depicting component design features

The central approach in reducing the blanket maintenance time is in defining a design that allows the inboard blanket to move into the space once occupied by the plasma, joining the outboard blanket in a compact unit. An interlock system is required for support against disruption loads when in operation and mechanisms are needed to move the sectors. The VV chamber itself must be of sufficient size to allow the number of joined blanket sectors to be equal to twice the number of TF coils, one joined sector under the TF and one under a large vertical port. Figure 4-9 illustrates some of the features defined for movement of the retractable blanket sectors. Shown are

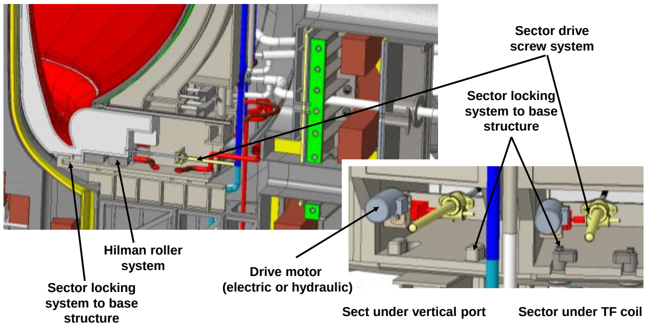
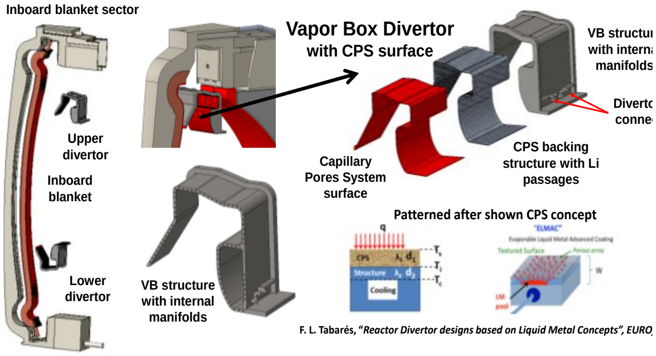


Fig. 4-9: Views showing IV sector drive systems and sector attachment to base structure

inboard blanket radially constrained support system, screw drives, drive motors and a Hilman roller system at the base of individual sectors. Hilman rollers provides reliability in a durable system that can handle tremendous weight in a compact design. Outside RM access to all mechanized areas is also available through lower ports located between TF coils if needed.

Further design features are shown in Figure 4-10 illustrating the Inboard blanket-shield sector assembly and the vapor box divertor concept. A small DCLL blanket is shown pulled away from its attachment to a backing shield and units of the upper and lower vapor box moved away from their position in the upper/lower section of the inboard shield structure. The vapor box divertors can be replaced individually but to meet high availability values their lifetimes need to be extended to be the same as the blanket system, allowing all IOSS units to be replaced at one time.



F. L. Tabarés, *"Reactor Divertor designs based on Liquid Metal Concepts", EURO*

Fig. 4-10: Inboard blanket-shied sector detailing assembly features and vapor box divertor concept design

In conjunction with the lithium vapor box divertor, a LM capillary pores system [4] is planned for the remaining FW surface. Both lithium, Tin and other options will be considered in conjunction with helium cooling. This will reduce (or eliminate) dust build-up from Tungsten divertors and minimize (or eliminate) tritiated water conditions. Also, the inert nature of helium should allow the storage and process of helium to be operated outside the reactor hall (RH), reducing the RH size. An early concept design of the Li FW system is shown in Figure 4-11 showing FW and outboard blanket features. The DCLL blanket has a plasma side channel with an inlet at the bottom and a return at the top to bring the Pb-Li back down, connecting to the outlet pipe. The blanket itself is attached to an outboard shield shell structure which can be detached (discussed later). Although not fully designed, a FW system is being defined with an attachment to the blanket with an intermediate temperature standoff to control its lower operating temperature. The surface geometry has been patterned off the EU-DEMO contoured plasma side wall shape [5] which offers improved alignment characteristics.

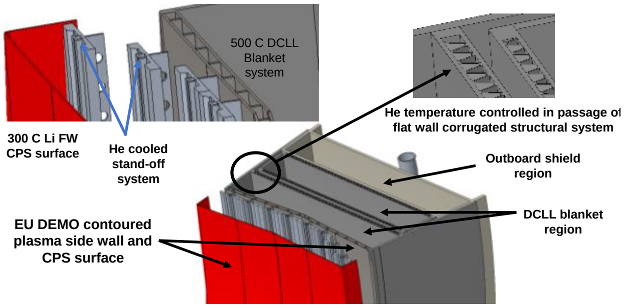


Fig. 4-11: Local FW and blanket details of the outboard blanket

5. ARCHITECTURAL DEFINITION OF THE STAR MAINTANCE FACILITY

One significant item that contributes to operational availability and the overall project cost is the handling, storage and maintenance operation of the fusion components and the size and complexity of the maintenance/storage facility itself. To date there is no underlining design approach that's being followed since there are variations in next step fusion concepts proposed and the maintenance approaches and facilities that supports these activities.

Within the architectural definition of the STAR design, the maintenance approach and the maintenance facility that supports this activity is yet another approach to be considered. The STAR system design, maintenance approach and maintenance facility were defined holistically, striving to define a system that has the potential of meeting acceptable physics and engineering standards while being commercially viable.

As an economic benchmark, the cost of the new Westinghouse AP1000 fission power plant has been used as an acceptance test – with cost and size based on the four AP1000 plants constructed in China. It's expected that a fusion power plant will cost more than an equivalent powered fission plant but hoped that the much-improved safety and activation features will offset this cost differential…. a possibility if a fusion plant capital cost is a reasonable offset of a fission power plant cost.

Again, to fully understand the nuances of the STAR design its best to compare it to alternates. The EU-DEMO design is the most developed with substantial physics and engineering support. This project therefore garners a high level of confidence one can assume with reasonable probability that the operational performance of the device can be achieve… but operating at high level of availability and its economic viability can be brought into question.

Figures 5-1 and 5-2 provides some general details of the EU-DEMO design depicting the significant thought-provoking details in the facility layout of the reactor hall and the active

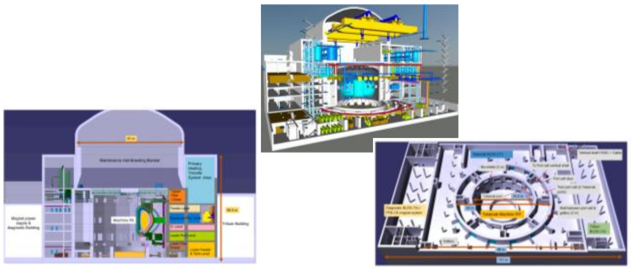
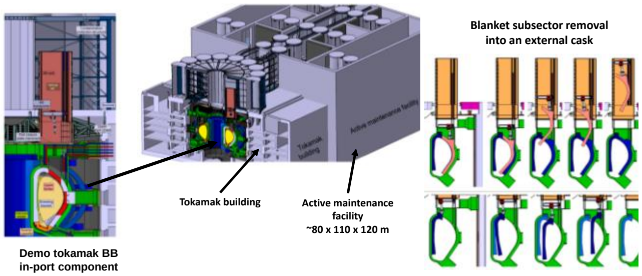

Figures from EU DEMO paper "Containment structures and port configurations"

Fig: 5-1: EU-DEMO data depicting the Reactor Hall details of the 9m device design are shown



Conceptual study of the remote maintenance of the DEMO breeding blanket, C. Bachmann, et al.

Fig.5-2: EU-DEMO maintenance facility in relation to planned tokamak core machine design

maintenance facility which are not yet present in the architectural layout of the STAR design. A side-by-side elevation view of the 9m EU-DEMO design and the 4m STAR device is illustrated in Figure 5-3. The STAR reactor hall follows a somewhat different arrangement to improve operating availability and increase the chance of meeting cost objectives. The following assumptions were made in developing the reactor hall and the joining maintenance facility:

1. In-vessel components are allowed to pass directly through vertical ports into a metal surfaced, tritium-controlled RM staging area above the reactor pit where blanket-shield units can pass without enclosed in a cask system,
2. The RM staging area houses a circular bridge crane with the capacity to concurrently remove/install six in-vessel retracted blanket-shield sectors,
3. Once removed from the reactor pit, in-vessel components are moved to the adjacent Maintenance Facility (MF) through a defined passageway,

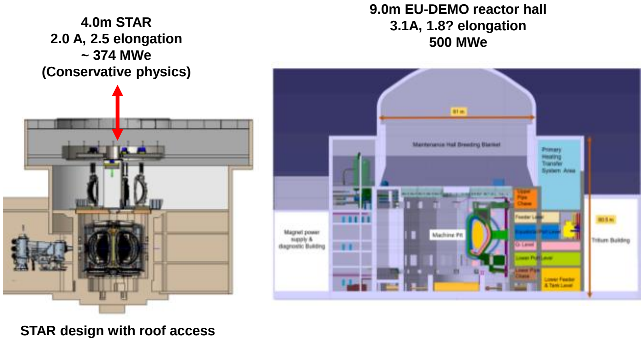


Fig. 5-3: Front view comparison of the STAR concept design and EU-DEMO

4. The MF contain both radiation controlled (glove box systems) and uncontrolled zones with room air tritium removal/monitoring systems,
5. Plasma facing blanket segments are remotely removed from their sector unit, crushed and stored until cooled for shipping to an offsite long-term storage site.

Figure 5-4 Provides a close-up view of the circular bridge crane used to install/remove in-vessel components from the reactor pit and the tracked system to move the components to the maintenance facility opening shown in the included facility side view. A very early concept definition of the STAR maintenance facility is shown in Figure 5-5 which has been sized to operate concurrently in dismantling six retracted in-vessel BS sectors. In keeping with the spirit of high availability and lowering cost each blanket segment was designed to be dismantled, disconnecting the plasma facing front section from the shield supporting structure with the intent of discarding the plasma side components as depicted in the concept details of Figure 5-6.

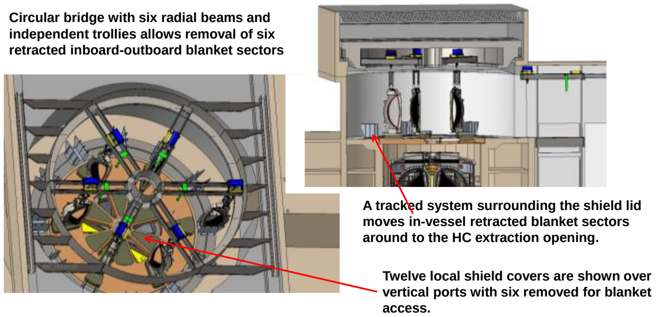


Fig. 5-4: An intermediate hot cell above the reactor pit incorporates a circular bridge crane to install/remove in-vessel

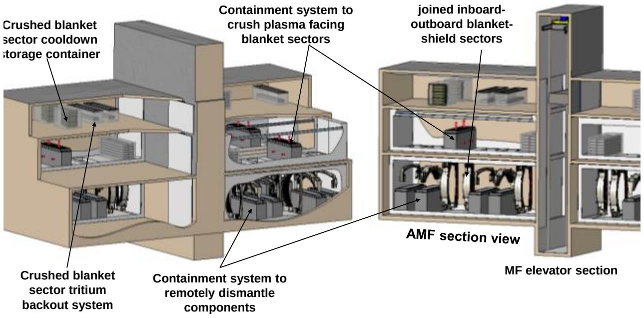


Fig. 5-5: Early concept design of the STAR maintenance facility defined to concurrently process six retracted inboard-outboard blanket shield sectors

After a retracted inboard-outboard blanket shield sector is disengaged, the individual blanket-shield segment is placed shield side up in a shielded containment unit where the blanket-shield sector is dismantled remotely with non-dexterous remote handling tools capable of high temperature operating conditions. The highly activated plasma side segment will be crushed to reduce its size, baked to remove tritium and placed in a cooldown unit until shipped to a long-term storage site.

The direct interface to a RM staging area from the reactor pit will substantially reduce the transfer time and the risk of failure involving removing blanket sector modules using a cask extraction system. The enlarged TF with extended vertical ports enables a retracted IOSS to move straight up (or down) through the vertical port once the Li-Pb and helium services are disconnected at the base with the aid of local RM services acting through lower base ports. Figure 5-7 illustrates the retracted IOSS lowered straight down onto an earlier positioned roller support plate system with floor mounted guides set into grooves in the base support structure. If radiation levels permit, a motor driven system can be included, otherwise an external drive system would be used operating through lower access ports. Space within the vertical ports allow a three-point support using a vertical crane rigging system, operating over the CG of the retracted IOSS to accurately position the unit.

6. VERY EARLY PROCESS CODE RESULTS

The STAR power plant concept is in the early stage of design with more supporting design and analysis needed to underpin the concepts under development. The PROCESS code has been an important early tool to determine physics and engineering performance conditions and act as a benchmark against some of early FEA analysis. Most of the spherical tokamak operating parameters and performance conditions have been updated in the PROCESS code though some important elements need to be included. Most importantly, the advanced divertor models in PROCESS are not available for a spherical tokamak nor is the inboard blanket considered in the neutron flux and fluence calculation. The results are also highly sensitive to the bootstrap fraction model. A higher-fidelity model including self-consistent bootstrap current must be run to confirm results. Table 6-1 provides some early physics operating results considering field on axis, device size, kappa, and level of physics performance (conservative vs aggressive). Although not comprehensive in nature performance consideration included bootstrap scaling (71.9% using the Wilson conservative model [6] and 82.2% for the more aggressive Sauter model) [7]. A conservative value for normalized beta was based on Menard scaling [8] (3.5 %mT/MA) and an aggressive value for this aspect ratio of (4.2 %mT/MA). For permissible core radiation fraction the conservative value assumed 72,5% leaking out of the core whereas the aggressive value was set at 80%. Finely, within the PROCESS code [9, 10] divertor Psep/R value was set at 20 MW/m for the conservative case and 30 MW/m for an aggressive case. The plasma elongation plays a role in extending the net power at a same major radius and as the physics operating parameters becomes more aggressive higher net power levels are achieved.

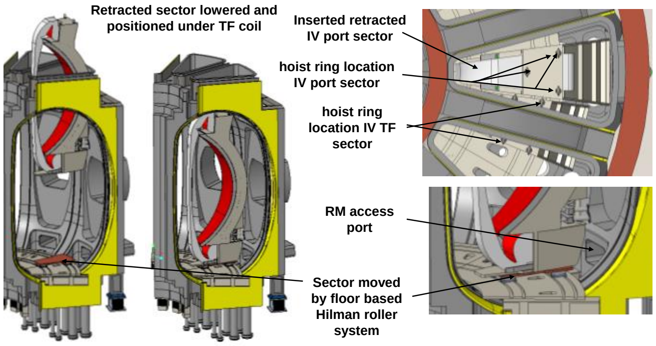


Fig. 5-7: installation method of retractable IOSS under the TF coil

Table 6-1: STAR physics performance data

R0 (m)	B0 (T)	k	Pfus (MW)	Pnet (MW)	Plasma Physics
4.00	4.77	2.5	1,085	347	Conservative
4.00	4.77	2.5	2,529	1107	Aggressive
4.22	5.24	2.5	1,300	500	Conservative
4.35	4.11	2.5	1,484	554	Aggressive

The motivation in developing the STAR power plant design was to investigate at a very conceptual level, design concepts with simplifying design features, technologies and physics options that could be combined to set the path of an economically violable fusion power plant. The AP1000 fusion power plant was used as a benchmark in comparing the size of a couple of facility buildings, shown pictorially in Figure 6-1. Although not a representative method used in making a cost comparison, the size difference between the reactor hall of STAR, EU-DEMO and a AP1000 containment/shield building, and fusion remote maintenance facilities is constructive. Figure 6-1 pictorially compares with a line chart the cubic meters of the different facilities, with comments given in the conclusion section.

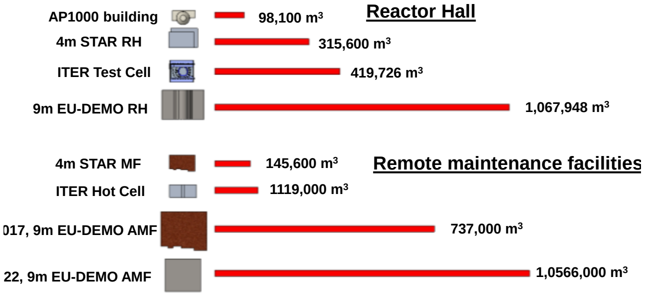


Fig. 6-1 Comparison of Reactor Hall and RM buildings volumes of relevant facilities

7. CONCLUSION

Decades have passed where numerous studies have been performed, experimental devices built and operated in the pursuit of developing a viable fusion device. Due to the scientific complexity, science has dominated the effort in defining confinement schemes that will hold, control, and reach reactor-like operating conditions. Physics performance breakthroughs and understanding over the past decades have dramatically improved but defining a fusion design that is both physics-wise feasible and technically possible while also economically viable has been elusive.

Early machine configuration and remote maintenance concepts, buildings, hot cell layouts and balance of plant systems studies [11 – 21] laid the groundwork in defining the EU-DEMO conventional tokamak. My activities in developing the TPX SC tokamak design (finished by NFRI with a K-STAR name change), the design and “partial” construction of the NCSX stellarator experimental device followed by the design of K-DEMO, years working with Jon Menard developing next step stellarator designs and the review of related studies [22 – 36] …led to a recognition that remote maintenance and cost would play a pivotal role in developing a successful fusion design. To achieve an economically viable fusion device required the implementation of progressive physics and engineering features, as defined in this paper, to reduce the device size, maximize off site construction and simplify maintenance operations. The physics of fusion is important but no more important than defining a balanced design that achieves the necessary performance and economic conditions to operate in a commercial energy environment.

The device presented here is an early scoping study with the goal of defining an integration of design components, features and assembly operations that collectively will reduce the cost of an ST fusion device while meeting physics and engineering requirements. Knowing a large CAD model would evolve, it was expected that all physics and engineering requirements would not be met, but rather than upgrading this design we would rely on the PROCESS code or equivalate, specifically tailored to the design presented, to tweak the device and/or component local sizes as needed to establish a new starting design point.

The EU-DEMO device that emanated from physics experiments is based on very sound physics and engineering principles. This device has a high chance of success in achieving the missions 500 MWe operating goal but given its complexity will have a lower chance in reaching fission level high availability conditions and at ~11 times the size of an AP1000 containment/shield building it’s difficult to see this evolving into an economically viable fusion power plant; especially considering an AP1000 net power is 1,100 MW compared to the 500 MW EU-DEMO implying an even larger device size is needed.

As it currently stands the 4m STAR power plant offers a higher potential for increased availability and depending on physics conditions can provide near AP1000 level net performance. Moving up in size would produce the AP1000 performance with conservative physics performance but at a higher cost. At the 4m size it’s about three times the size of a AP1000 containment/shield building implying further improvements are needed.

The STAR reactor hall was sized with two JT60SA NNBI’s with extra sources added to provide 15 MW each. Operating with higher field provides opportunities to consider a smaller profile H&CD system with improved efficiencies that can lower the size of reactor hall. Using chemically inert helium as the coolant may allow helium storage to be placed outside of the reactor hall unlike the water-cooled system of ITER, further reducing the reactor hall size. A reduced regulation environment of fusion will result in lower regulation costs and lower activation will lower waste disposal cost…. but further improvements are needed to enhance the economic viability of the STAR design. An organized review of all components, design solutions and physics parameters are needed to further reduce the device cost. Increasing the fusion device size to increase power output can bring down the cost per kilowatt-hour based on EOS bases, but there will be a capital cost ceiling where financing will be difficult to secure. The Physics of fusion has been extremely important in developing and operating fusion experimental devices, but of equal importance going forward is the economic condition in which it operates. Fusion has matured to the point that the economics of fusion should be at the forefront of future fusion design activities.

One could never criticize the EU-DEMO program, as too much valuable physics and engineering data has been generated which has benefited all organizations striving to move fusion along. Difficulties however do result when the technology and physics followed cannot evolve to be commercially competitive and the device size itself makes it unacceptably expensive to build; so, following a "low risk" design path may need to be reevaluated to consider solutions with some increase in risk and design concepts which proports lower cost.

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