Physics and Technology Conditions for Attaining Tritium Self-Sufficiency for the D-T Fuel Cycle

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Abstract

There is no practical external source of tritium for fusion energy development beyond ITER and all subsequent fusion systems have to breed their own tritium. To ensure tritium self-sufficiency, the calculated achievable tritium breeding ratio (TBR) should be equal to or greater than the required TBR. The potential of achieving tritium self-sufficiency depends on many system physics and technology parameters. Interactive physics and technology R&D programs should be implemented to determine the potential of realizing those physics and technology options and parameters that have large effects on attaining a realistic "window" for tritium self-sufficiency. The ranges of plasma and technology conditions that need to be met, in order to ensure tritium self-sufficiency, are identified.

1. Introduction

Attaining tritium self-sufficiency is necessary for self-sustaining fusion plants operating on the D-T fuel cycle. There is no practical external source of tritium for fusion energy development beyond ITER. Tritium resources are not even adequate for a possible extended operation phase of ITER. All subsequent DT experimental devices and power plants have to breed their own tritium. The time window for the availability of tritium to supply the requirements for the DT physics devices and power plants is closing rapidly. It is therefore important to define and understand the conditions for attaining tritium self-sufficiency. To ensure tritium self-sufficiency, the calculated achievable tritium breeding ratio (TBR) must be equal to or greater than the minimum required TBR [1,2]. The tritium fuel cycle involves many subsystems whose physical and operational characteristics impact the success in achieving tritium self-sufficiency. Tritium self-sufficiency is affected by all aspects of the fusion system including the plasma configuration, operation modes and parameters, control systems for plasma stability, heating and exhaust systems embedded in the blanket, and the blanket and tritium processing systems. It is clear that tritium self-sufficiency in DT fusion power plants cannot be assured unless specific plasma and technology conditions are met. In this paper, we will address these conditions and shed light on possible plasma, nuclear, material, and technological conditions in which tritium self-sufficiency can be attained.

2. Tritium availability for DT fusion development

Tritium is consumed in DT fusion systems at a very large rate of 55.6 kg per full power year (FPY) of operation at 1 GW fusion power. The first generation of burning plasma experiments are designed without tritium breeding blankets and rely on existing tritium resources for fueling. However, these resources are decreasing due to radioactive decay and reduced production rate. The tritium bred in the CANDU reactors is the only practical source available for ITER and other DT fusion systems [3,4]. The tritium is removed from the heavy water moderator at the Darlington Tritium Removal Facility (DTRF). The tritium will be collected at a rate of ~1.7 kg/yr until 2025 when the rate will decrease rapidly due to reactors reaching their end-of-life. Tritium is sold to various applications at a rate of about 0.1 kg/yr in addition to the loss due to decay at a rate of 5.47%/yr. Based on these values the expected inventory of tritium available for DT fusion development peaks at about 27 kg in the late 2020s time frame with a rapid decrease thereafter. The total available inventory will drop as tritium is used in ITER. For the ITER-FEAT design [5] operation scenario, with 500 MW fusion power and expected start of construction in 2005, there will be insufficient tritium remaining for fueling follow-on DT fusion systems. If ITER were to run at 500 MW fusion power with 20% availability all tritium supply would be exhausted in less than 5 years of operation. Note that further delays in the ITER schedule will further complicate the tritium supply issue as available tritium continues to be lost by radioactive decay. The availability of an external tritium supply for continued DT fusion development is an issue and subsequent DT fusion test facilities and power plants must breed their own tritium.

3. The required TBR

The required TBR should exceed unity by a margin to: (a) compensate for losses and radioactive decay of tritium during the period between production and use, (b) supply inventory for startup of other reactors, and (c) provide a “holdup” or “reserve” storage inventory necessary for continued reactor operation under certain conditions. An example is the inventory kept in reserve to keep the power plant operating while there is a failure in a tritium processing line such as the plasma exhaust processing line. To accurately determine the required TBR, one has to consider the “dynamics” of the entire fuel cycle for the DT plant that involves many subsystems. Because tritium decays in a relatively short time (half life is 12.3 years), it is essential to accurately calculate the time-dependent tritium inventories and flow rates throughout the system. The main subsystems of the power plant with significant tritium inventories are plasma exhaust and vacuum pumping, first wall (FW), blanket, plasma-facing components (PFC), fuel cleanup, isotope separation, fuel management, storage, and fueling. Simulation of this cycle, including the dynamic behavior of tritium inventories and flow rates were investigated in detail in previous work [1,2]. Kuan and Abdou [2] developed detailed analytic dynamic models to describe various tritium processes and to quantify the characteristic parameters of the various elements of the tritium fuel cycle as a tool for evaluating the required TBR.

The required TBR depends on many system physics and technology parameters. For example, tritium fractional burnup in the plasma impacts the tritium fueling rate and associated tritium inventory. Operating the plasma in a high plasma edge-recycling mode increases the tritium fractional burnup and reduces the tritium fueling rate and inventory, and hence improves the potential for achieving tritium self-sufficiency. Technology parameters that affect the required TBR include the tritium inventories in the chamber components that depend on the tritium release and retention characteristics of materials used. The required TBR is also affected by the desired doubling time and the efficiency, capacity, and reliability of the tritium processing system. The uncertainties in the performance characteristics of the plasma and other subsystems of the fuel cycle contribute to the uncertainty in the required TBR.

3.1 Dynamic modeling of fuel cycle

The most recent model by Kuan and Abdou [2] utilizes a detailed, accurate, and efficient methodology based on an analytical scheme that makes use of different types of tritium inventories inside the fuel cycle as calculated from detailed numerical simulations. Short-term and long-term tritium inventories as well as tritium lost through waste material are differentiated. Maximum tritium inventory limits were also considered from safety and operational standpoints. Fig. 1 is a simplified schematic of key elements of the fuel cycle system.

The model allows studying the dependence of the required TBR on system operating conditions. The results show that tritium radioactive decay combined with potentially large requirements for time-dependent tritium inventories in various parts of the system can lead to large values of the required TBR. Among the key parameters whose values can have large effects on the required TBR are: 1) doubling time for fusion power plants, 2) tritium fractional burnup in the plasma, f_b, 3) "reserve time", i.e. days of tritium supply that must be kept in "reserve" storage to keep the plasma and plant operational in case of any malfunction in the tritium processing system, 4) time required for tritium processing of various tritium-containing streams (e.g. plasma exhaust, tritium-extraction fluids from the blanket), 5) parameters and conditions that lead to large "trapped" inventories in various reactor components (e.g. in divertor, FW, blanket), and 6) inefficiencies in various tritium processing schemes.

3.2 Required TBR dependence on key parameters

Examples of the dependence of the required TBR on various key parameters can be drawn from the work of Kuan and Abdou [2] and are shown in Figs. 2-3. The results given here assume a fusion power of 1.5 GW, long term inventory of 9 kg, short term inventory of 2 kg, and the other reference parameters given in Table VII of Ref. 2. Figure 2 shows the required TBR as a function of the tritium fractional burnup, f_b, for various values of the doubling time with the reserve time fixed at 5 days. Also shown in the figure (and also in Fig. 3) is a shaded area to indicate the most likely values for the "achievable" TBR based on present conceptual power plant studies and accounting for uncertainties in system definition, modeling and nuclear data as discussed in Sec. 4. The tritium self-sufficiency

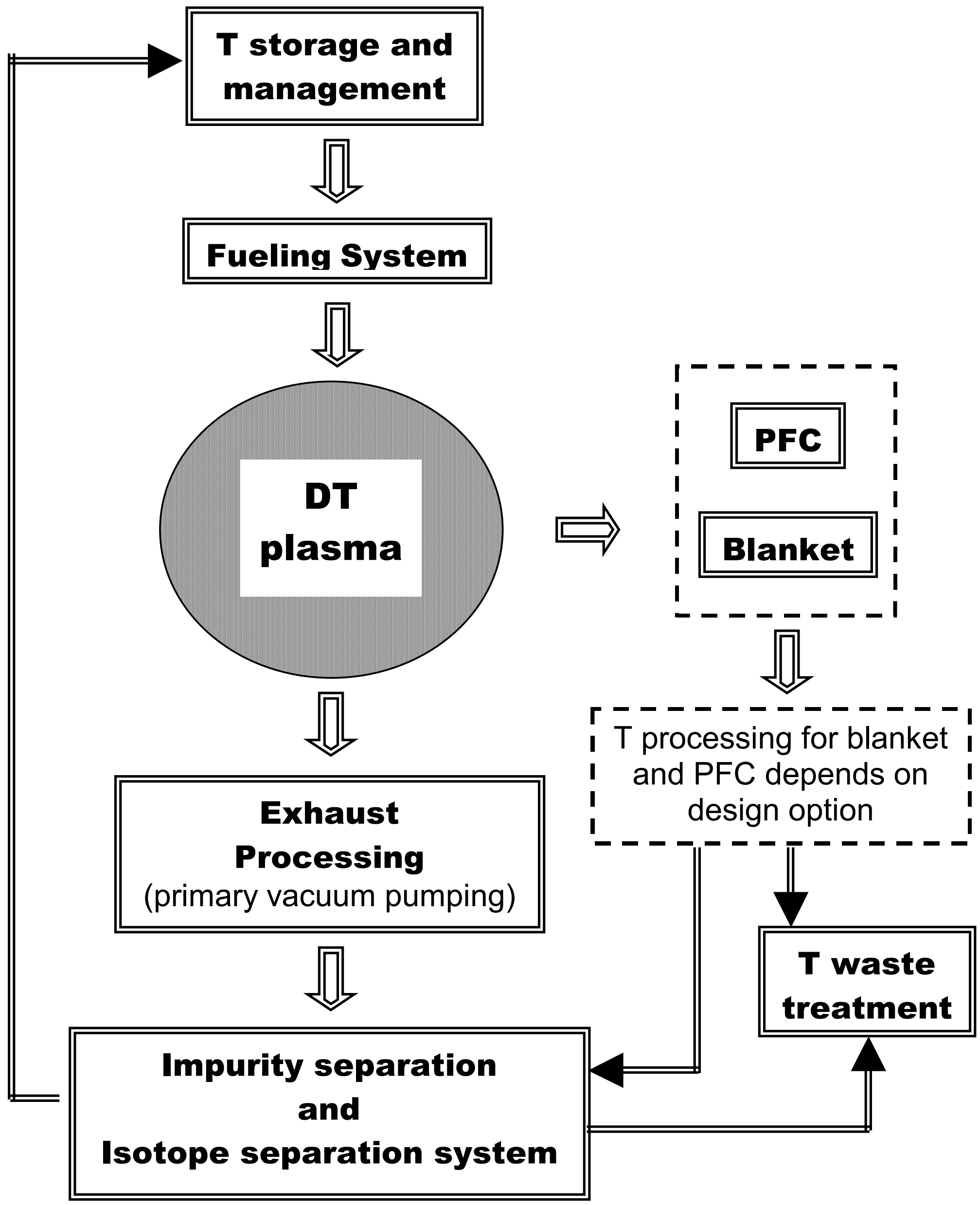

Fig. 1. Simplified schematic of the fuel cycle.

condition is met when the achievable TBR is equal to or greater than the required TBR, i.e. when the required TBR falls in the shaded area of Figs. 2-3.

From Fig. 2 it is noted that the required TBR increases as the fractional burnup, f_b, decreases. The increase is very rapid as f_b falls below about 2%. This is because the tritium fueling rate to the plasma is inversely proportional to f_b. The tritium fueling rate plays a major role in determining some of the most dominant inventories such as that in the plasma exhaust, and reserve storage inventory. For all values of f_b, the required TBR increases with decreasing the doubling time.

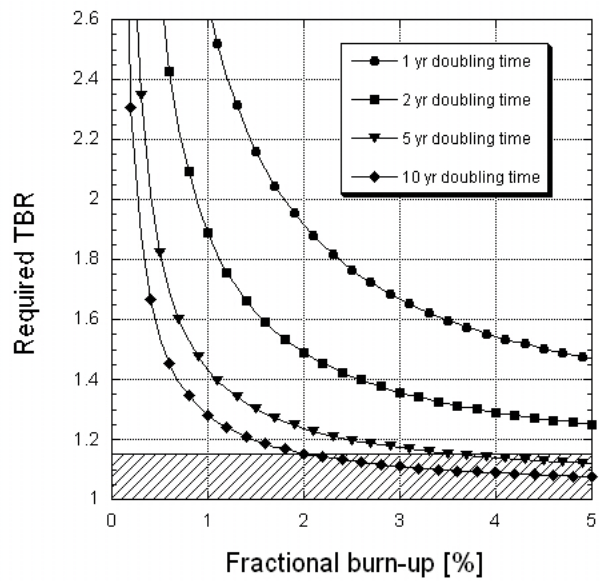

Fig. 2. Required TBR as a function of tritium fractional burnup for different doubling times and 5 days reserve time.

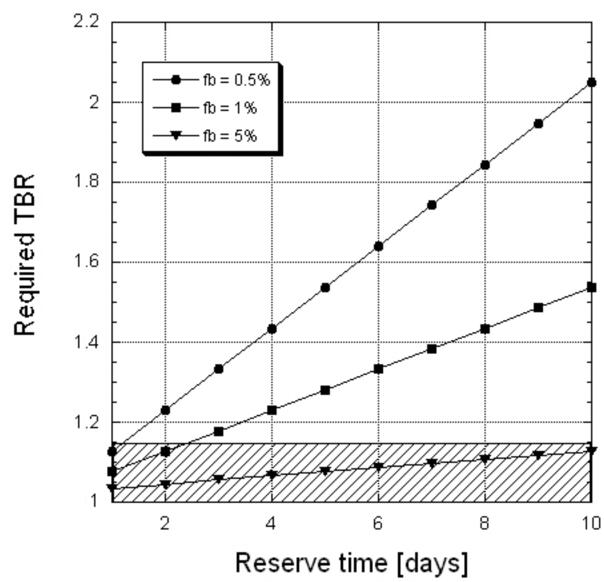

Fig. 3. Required TBR as a function of reserve time for different tritium burnup fractions and 10 years doubling time.

Figure 3 shows the dependence of the required TBR on the reserve time for different values of f_b with the doubling time fixed at 10. The required TBR increases rapidly as f_b is decreased, and this increase is dramatically larger for longer reserve time. The reason can be explained by the fact that the tritium inventory required in the “reserve” storage for a given reserve time is itself a function of the tritium fractional burnup. The latter determines the tritium fueling rate to the plasma, while the reserve inventory is the supply required to provide this fueling rate for a period equal to the reserve time. Thus, decreasing f_b and increasing the reserve time has the compound effect on increasing the required TBR. At a low f_b of 0.5%, the required TBR increases rapidly as the reserve time increases, reaching 1.65 at a reserve time of 6 days. At f_b of 5% or higher the increase in the required TBR with the reserve time is relatively small. The results indicate that the combination of low fractional burnup, long reserve time, and short doubling time has a compound and dramatic effect on increasing the required TBR to very large values.

3.3 "Window" for attaining self-sufficiency

Figures 2-3 show the dependence of the required TBR on various physics and technology parameters and characteristics with a shaded area representing the achievable TBR. The maximum achievable TBR depends on many design conditions as discussed in detail in Sec. 4. Present blanket designs in conceptual tokamak power plant studies have calculated TBR values ~1.15 and uncertainties in system definition, calculation procedure and nuclear data used in these studies can lead to lower achievable TBR values as discussed in Section 4. Hence, the achievable TBR is likely to be less than about 1.15. This is used here to define The "window" of parameters that can lead to satisfying the tritium self-sufficiency condition are those that lead to a required TBR of less than about 1.15. From the results in Figs. 2-3, a possible window of parameters is fractional burnup >5%, reserve time <5 days, and doubling time >4 years.

Based on the data in Figs. 2-3, the following observations can be made:

- It is crucial that the tritium fractional burnup in the plasma be kept high, at least above a minimum of 2% and most preferably above 5%. Thus, plasma edge physics modes that lead to higher tritium recycling are needed. The complexity here is that high tritium recycling may also lead to high alpha-particle recycling, which would reduce the sustainable DT particle density in the plasma for a given stability limit of beta, and hence would lower the achievable fusion power. Therefore, schemes that lead to preferential pumping of the alpha particles and preferential recycling of tritium into the plasma, need to be investigated.

- The tritium processing system, being an engineering system, will have some failures during operation. Therefore, a reserve tritium inventory to keep fueling the plasma and continue reactor operation during periods of malfunction of the tritium processing system is necessary. To keep the reserve inventory, and hence the required TBR, sufficiently low requires: a) tritium fractional burnup must be kept high as discussed above, b) the reliability/availability of the tritium processing system of a fusion reactor needs to be high, c) redundancy in some of the tritium processing system, especially the plasma exhaust processing line, can increase its "effective" availability and reduce the required reserve time and inventory.

- Doubling times much shorter than 5 years lead to higher required TBR and inability to attain tritium self-sufficiency. This is a serious issue for fusion power development and commercialization. For fusion to be a serious contender for energy production, shorter doubling times are needed. This situation is complicated further by the fact that there will be no other suitable sources of tritium beyond ITER. Therefore,

- Retention of large tritium inventories in reactor components such as the blanket, FW, and divertor can have a large impact on increasing the required TBR. The results in all the figures above are based on selected design and technology options that minimize these reactor inventories. Selection of other options can increase the required TBR.

- To make fusion based on the DT cycle practical, it is necessary that the world fusion research extensively explore the "phase-space" of plasma, nuclear, material, and technological conditions in

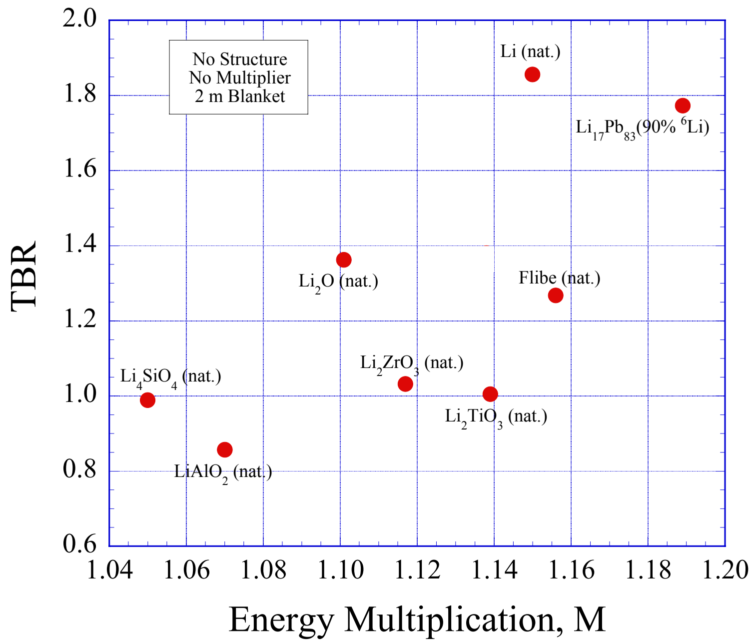

Fig. 4. Tritium breeding potential of candidate breeding materials without structure in a 2 m-thick blanket.

which tritium self-sufficiency can be attained. In addition to the many parameters and options discussed here, there are other areas that need to be explored further. An example is improvements in the tritium processing system to substantially shorten the time between production and use.

4. Achievable TBR

The achievable TBR is a function of technology, material and physics design and operating conditions. The concepts and materials used in chamber components (blanket, divertor, etc.) have significant impact on the achievable TBR. The presence of stabilizing shells and conducting coils for plasma control and attaining advanced plasma physics modes also affects the achievable TBR. The achievable TBR is also influenced by the size and materials used in plasma heating and current drive components and fueling and exhaust penetrations. The achievable TBR depends on the confinement scheme, primarily due to the impact on breeding blanket coverage and possible limitation on blanket thickness. Calculation of the achievable TBR should be based on detailed three-dimensional (3-D) models that account for all design details. Uncertainties in predicting the achievable TBR due to modeling, system definition, and nuclear data should be accounted for when assessing the potential for achieving tritium self-sufficiency.

4.1. Impact of FW/blanket design

4.1.1 Breeding material

The breeding potential varies substantially with FW/blanket concepts. The inherent breeding capacity of breeders considered in previous fusion designs is illustrated in Fig. 4 for thick breeder zones that do not include structural material or "external" neutron multiplier with full coverage of the plasma. Note, however, that some breeders have an "internal" multiplier as part of its composition; for example, lead in LiPb and beryllium in Flibe. In realistic designs, the structure, configuration, and penetrations will degrade the achievable overall TBR below the values shown. The breeders could be divided into three groups according to their breeding potential. The first group includes liquid Li and LiPb with the largest breeding potential. The second group contains Li_2O and Flibe with medium breeding potential. With these breeders, the structure content needs to be minimized and/or a moderate amount of neutron multiplier should be added. The third group includes several ceramic solid breeders, such as Li_2ZrO_3, Li_2TiO_3, Li_4SiO_4, and $LiAlO_2$, which have poor breeding potential and need a substantial amount of neutron multiplier to achieve adequate breeding. Enriching the lithium in the isotope ^6Li does not always help the breeding. Breeders with natural Li provide the highest TBR except for LiPb. The TBR could optimize at higher enrichment when structural materials and multipliers are included in the blanket.

4.1.2 Structural material

Using structural material in the FW/blanket results in degrading the achievable TBR. The amount of structure in the FW and front layer of the blanket has a much more severe impact on tritium breeding relative to the structural content in the bulk of the blanket. Consideration of elemental induced radioactivity along with the demanding structural requirements led to three candidate structural materials; reduced activation ferritic steels (FS), vanadium alloys, and SiC/SiC composites [6]. Among these materials, SiC/SiC composites can operate at the highest temperature followed by V alloys with FS alloys allowing the lowest operating temperature [7]. An extensive materials R&D program is underway to develop and qualify these structural materials for fusion applications and determine their performance limits in the severe fusion nuclear environment. We investigated the impact on TBR of using the FS alloy F82H, the V alloy V-4Cr-4Ti, and SiC/SiC composite structural materials with different volume fractions in blankets utilizing the Li, $Li_{17}Pb_{83}$, Flibe, and Li_4SiO_4 breeders. The results are shown in Fig. 5 with the structure content varied up to 20%. Depending on the breeding and structural materials, up to 30% degradation in TBR might result. In general, using V structure has the least impact on TBR. The largest impact of structural material occurs in blankets utilizing the liquid Li breeder. Many considerations influence the choice of structural material used in the breeding blanket. These include compatibility with other components and blanket thermal, mechanical, and safety performance requirements. The structure content should be adequate to ensure structural integrity of the blanket under both normal and abnormal load conditions. Concepts that rely on thick liquid breeder jets to protect the chamber metallic wall such as in the HYLIFE-II inertial fusion (IFE) chamber [8] and magnetic fusion (MFE) liquid wall concepts [9] have high breeding potential due to elimination of structural material from the front breeding zone.

4.1.3 FW thickness

Detailed ITER engineering design shows that the FW may have to be quite thick (~7 cm). Since such a thick neutron absorber is located between the plasma and the breeding blanket, it has a significant impact on the achievable TBR. We investigated the effect of FW thickness on TBR in two dual coolant blanket concepts that employ helium cooling for the ferritic steel FW and blanket structure. Two breeding options were considered; a LiPb breeder zone that uses SiC inserts as MHD and thermal insulator, and a low-melting point Flibe with Be multiplier [10]. The FW is 4 mm thick followed by 30 mm thick He-cooled channels (17% FS) and 4 mm thick second wall. The results in Fig. 6 also include the effect of FW thickness on TBR in a He-cooled solid breeder blanket. The results show that the TBR drops by up to ~16% if the FW thickness is increased to 4 cm. It is therefore necessary to carry out detailed structural-mechanical and thermal-hydraulics analyses for accurate determination of practical values for FW thickness and blanket structure content to be used when evaluating blanket options regarding their potential for achieving tritium-self-sufficiency.

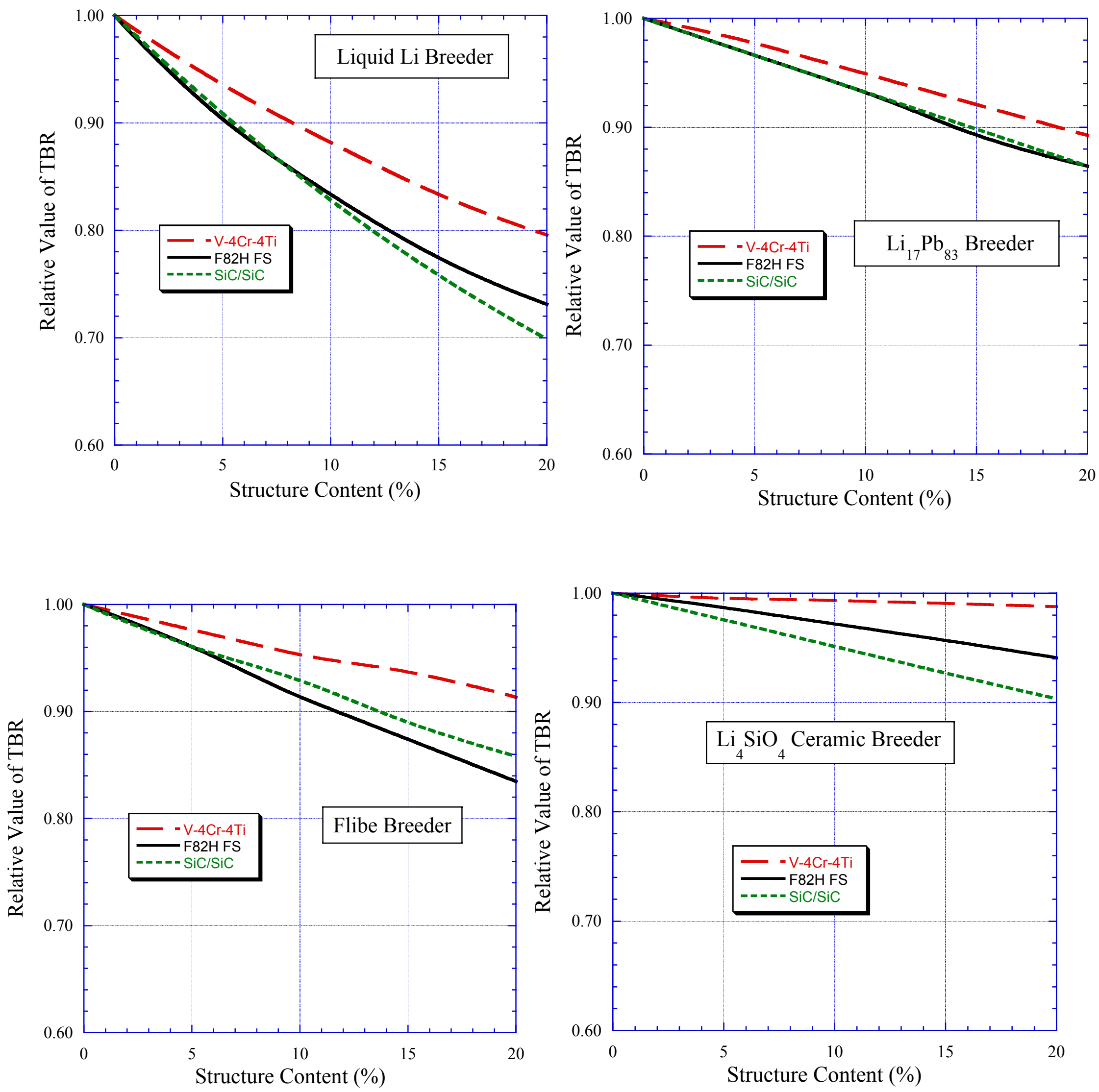

Fig. 5. Impact of structural material content in the blanket on achievable TBR.

4.1.4 Coolant

While the liquid breeder can serve as the coolant in a self-cooled concept, separate coolants could be utilized with solid and liquid breeders. Due to its low density, He gas has a negligible impact on the amount of neutrons available for tritium breeding. However, a thicker blanket is needed to compensate for the volume occupied by He. In addition, using high pressure He gas in the blanket requires larger structure content that has a negative impact on the achievable TBR. While the large neutron moderation in water helps enhance tritium breeding from ^{6}Li, the large absorption tends to decrease the total TBR. In typical liquid and solid breeder designs, using 20% water coolant in the FW/blanket system reduces the TBR by up to 7%.

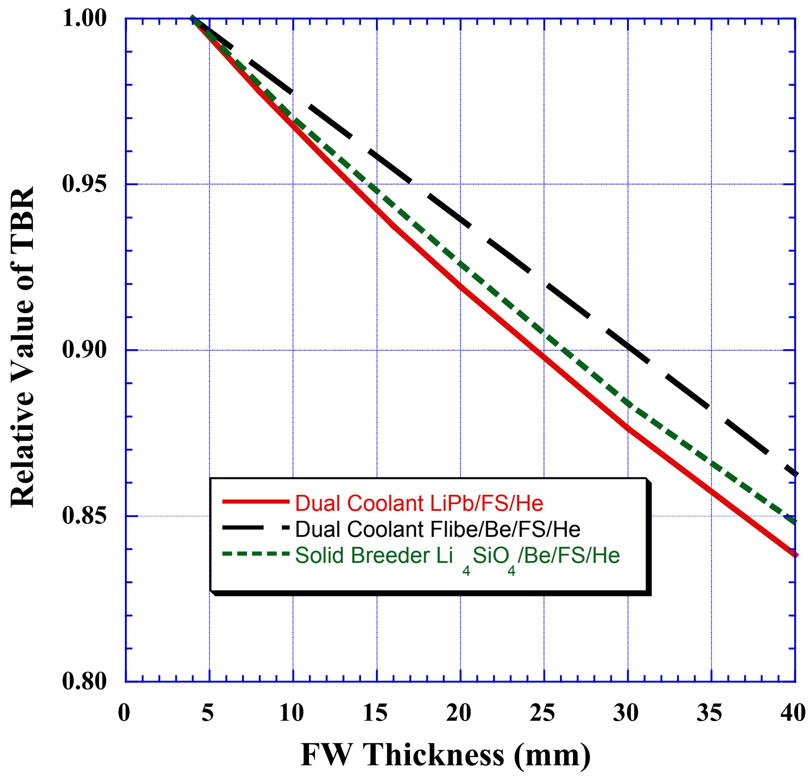

Fig. 6. Impact of FW thickness on TBR in dual coolant and solid breeder blanket concepts.

4.1.5 Neutron multiplier

Different neutron multipliers (Be and Pb) can be used to enhance the achievable TBR. Due to its much lower (n,2n) reaction threshold energy, Be yields better enhancement in TBR than with an equivalent amount of Pb. There are several issues with using both multipliers that need to be resolved. These are primarily compatibility issues in addition to tritium production and retention in Be, Be swelling, and polonium production in Pb. Note that cooling of the multiplier region is a serious consideration. Depending on the melting point and thermal conductivity, the thickness of the multiplier region is limited. Cooling requires structure that tends to have high absorption of the soft neutrons emerging from the multiplier. Using lead in solid form with high temperature cooling is impossible because of the low melting point of lead (about 327°C). The preferred form for beryllium is pebble bed that has a lower packing fraction and lower thermal conductivity than beryllium at 100% theoretical density. The benefits of using the neutron multiplier can be maximized by careful optimization of its configuration in the blanket.

4.1.6 Electric insulator

In magnetic confinement systems, blankets that utilize moving liquid metals such as Li and LiPb require MHD insulators. Several oxide and nitride coatings are under consideration for Li/V blankets [11]. These are very thin ~10-micron layers bonded to the V structure with minimal impact on TBR. However, for in-situ self-healing of the microcracks developed in the coating during operation, it is considered to add up to ~10 atom% Ca, Y, Al, or Er to the Li breeder. This was shown to degrade the

TBR by up to ~13% with Ca and ~27% with Er [12]. 5 mm thick SiC flow channel inserts are considered in the dual coolant blanket design with LiPb to provide MHD and thermal insulation. We determined that using these inserts degrades the achievable TBR by 8%. Hence, while blankets that utilize the high electric conductivity Li and LiPb breeders have the highest breeding potential, adding the required electrical insulators should be assessed regarding their negative impact on the achievable TBR.

4.2. Impact of chamber configuration and physics considerations

The achievable TBR depends on the 3-D geometrical configuration of the plasma chamber that differs with the confinement concept used. The confinement concept affects the breeding blanket coverage and could impose a limitation on blanket thickness. In addition, plasma physics considerations require introduction of components and penetrations in the chamber that could influence the achievable TBR.

4.2.1 Differences between IFE and MFE systems

There are several geometrical, spectral, and temporal differences between IFE and MFE systems that could impact the achievable TBR [13]. While the neutron source is volumetric in MFE systems, the target represents a point neutron source in IFE plants. As a result, source neutrons in IFE chambers impinge on the FW/blanket in a more perpendicular direction leading to a lower tritium production rate at the front with lower radial gradient. Fusion neutron interactions in the highly compressed target result in considerable softening of the neutron spectrum incident on the FW/blanket in IFE chambers. These neutrons can have average energies as low as 10 MeV. The combined geometrical and spectral effects result in slightly lower local TBR values in IFE chambers depending on the type and thickness of the FW/blanket. However, since the chamber size is decoupled from the size of the driver, thicker blankets are easier to accommodate in IFE chambers without impacting the high cost driver. In addition, lack of magnetic fields makes it easier to employ flowing thick liquid breeder concepts without structure. The difference in the temporal characteristics of the source neutrons in IFE and MFE systems does not affect the time integrated TBR.

4.2.2 Divertor requirement

Confinement schemes, such as tokamak, spherical torus (ST), and stellarators, in which the plasma is linked by TF coils, require a divertor system that faces the plasma. The overriding design consideration for the divertor will be for power exhaust (accommodating high surface heat fluxes continuously and reliably) and particle control (pumping fuel and helium ash out of the plasma chamber). Hence, tritium breeding will be compromised or absent in the divertor region. The coverage fraction of the divertors is 5-12% depending on whether a single or double null divertor configuration is employed. In general, a tokamak with a single null divertor will have about 5% higher breeding capability than a double null design that uses the same FW/blanket concept. The coverage fraction of the divertor in stellarators is relatively large. Confinement systems, like field reversed configuration (FRC) and spheromak, in which there are no TF coils linking the plasma, have a potential advantage in that power and particles can be diverted along field lines that leave the plasma chamber. Hence, the power and particle control systems do not compete with the tritium breeding systems for space facing the plasma in these confinement systems.

The PFC material used in the divertor is based on either tungsten or carbon. W, which is a strong neutron absorber, has a more negative effect on the achievable TBR. On the other hand, C results in increasing the tritium inventory and consequently increasing the minimum required TBR. We investigated the effect of divertor PFC material on overall TBR for a tokamak configuration that utilizes the dual coolant molten salt blanket [14]. Replacing the W by C in 1 cm divertor armor in the double null divertor resulted in a negligible <0.1% increase in the 3-D TBR. For the thin divertor armor, the Cu and steel used in the divertor heat sink and structure have the dominant effect on TBR. A breeding blanket can be installed behind the divertor system to enhance the achievable TBR. However, the contribution to the overall TBR is severely reduced due to the large attenuation of neutrons by the sizable divertor heat sink and structure needed to handle the severe radiation, thermal, and mechanical conditions and the difficulty of integrating a breeding blanket in the geometrically complex divertor configuration.

4.2.3 Chamber configuration

Due to space limitation in the inboard (IB) side of a tokamak, a thinner blanket is usually used in the IB region with a negative impact on the achievable overall TBR. In spherical tokamaks (ST) with very low aspect ratio, it is unlikely that a breeding blanket could be installed in the space-constrained IB side [15]. However, this is not expected to drastically affect the overall TBR since the low aspect ratio results in less than 10% IB coverage. On the other hand, the achievable TBR will be influenced by material choice for the center-post shield [15].

The external coils producing the rotational transform of the magnetic field in stellarators are required to be as close to the plasma as practicable imposing severe restrictions on the breeding blanket thickness. In ARIES-CS, the blanket is replaced by a highly efficient shield at locations where the external coils have to be close to the plasma [16]. On the other hand, absence of disruptions allows using thinner first walls than in tokamaks. In linear confinement concepts such as the FRC, elongating the cylindrical chamber can reduce the end losses and increase the blanket coverage.

4.2.4 Chamber penetrations

Penetrations are required in MFE chambers to accommodate heating and current drive systems, fueling, and diagnostics. Ion cyclotron (ICH) and electron cyclotron (ECH) heating systems employ antennas and launchers facing the plasma. Material choice for these components could affect the achievable TBR based on their ability to reflect neutrons into the chamber rather than absorb them. Careful choice of material and minimizing streaming path in these systems can help improve the potential for achieving tritium self-sufficiency. Neutral beam injector (NBI) ports are relatively larger with larger streaming path.

In recent conceptual MFE power plant designs [17,18], the area taken by the heating and current drive penetrations amounts to 1-3% of the FW area and the net effect on the overall TBR is about 2-4% reduction. However, this predicted small coverage fraction needs to be confirmed. Some diagnostics will be required for any confinement concept. They will be particularly important for concepts, like advanced tokamaks, STs, and compact stellarators, in which optimized performance is to be achieved through controlled plasma profiles. Fueling and diagnostic penetrations are much smaller than those for heating and current drive and do not have a dominant impact on the TBR.

No heating or current drive systems are needed in IFE power plants. Penetrations in an IFE chamber provided for the laser or ion beam fusion driver represent less than 0.5% of the FW area for direct drive concepts with up to ~100 beam ports [19]. For indirect drive concepts, the fraction taken by the beam ports is much lower [20]. Hence, the impact of chamber penetrations on the achievable overall TBR is minimal in IFE plants.

4.2.5 Plasma control requirements

In order to attain advanced plasma physics modes of operation with higher β and elongation, conducting shells need to be introduced in the blanket. The stabilization shells for both axisymmetric and resistive wall modes need to be located closer to the plasma to have favorable impact on plasma performance. In ARIES-AT [18], a kink stability shell is employed at a depth of 30 cm in the 75 cm thick blanket allowing for a larger plasma elongation and helping with the kink mode stabilization. Passive vertical stabilization shells are also utilized at the same radial location. El-Guebaly [21] investigated three candidate stabilizing shell materials. These are W, Cu, and Al. Al has the least impact with W resulting in the largest TBR degradation for the same shell thickness. The thickness of the shell depends on the conductor material, operating temperature, and time constant. In ARIES-AT, W was selected as the preferred material for the shells that operate hot and are passively cooled. The toroidally continuous 4 cm thick W vertical stabilizing shells and placed at the upper and lower extremities of the OB blanket result in ~4% reduction in the overall TBR. The 1 cm thick resistive wall mode shell located at the OB mid-plane dropped the TBR further by ~2%. It is, therefore, essential to determine from plasma control requirements the exact configuration and size of the stabilizing shells as they can influence the potential for achieving tritium self-sufficiency. In addition, the presence of conducting shells near the front of the blanket might add several safety concerns (decay heat and radwaste) that should be addressed.

4.3. Uncertainties in predicting achievable TBR

4.3.1 Uncertainties due to system definition

The achievable TBR depends on many system parameters and design considerations as explained in sections 4.1 and 4.2. Most of these system features are not yet well defined resulting in uncertainties in the achievable TBR. For example, uncertainties in defining the amount and configuration of structure required to ensure structural integrity of the blanket could lead to significant uncertainty (up to ~30%) in predicting the achievable TBR. In addition, failure to accurately determine the required FW thickness introduces large uncertainties in the achievable TBR. Other blanket design considerations that introduce uncertainties in the achievable TBR include using separate coolant and/or neutron multiplier, and the need for electric insulator in conducting liquid breeder flow channels. Introducing strong neutron absorbing materials in chamber components such as stabilizing shells, divertors, and plasma heating and current drive systems reduce the achievable TBR. In addition, divertors and chamber penetrations replace valuable breeding space. Hence, uncertainties in defining such chamber systems introduce additional uncertainties in the achievable TBR.

4.3.2 Uncertainties due to modeling and calculation methods

While accurate modeling of the FW/blanket is the dominant factor, all other chamber components will have an impact on the TBR as discussed in section 4.2. Therefore, detailed 3-D modeling is necessary for calculating the achievable TBR. This should accurately reflect the detailed chamber configuration including all components with detailed design and material distribution. Geometrical simplification of some components might be tolerable but the breeding blanket and FW as well as any components embedded in the blanket (e.g. stabilizing shells) have to be modeled accurately with the appropriate configuration and material heterogeneity. In addition, the accurate source profile should be modeled. Peaking at the magnetic axis at mid-plane of a toroidal facility will affect the distribution of tritium breeding in the IB and OB blankets.

To guide the design process, a series of parametric 1-D analyses is usually established at an early stage of the design. In the early stages of the design when several iterations are needed, the overall TBR is estimated by coupling the 1-D local TBR values obtained in the different regions surrounding the plasma with the appropriate coverage fraction. While many radial regions are used in the 1-D model to account for radial blanket configuration, material homogenization in each region is necessary.

We performed 3-D neutronics calculations for a dual coolant blanket concept with Flibe breeder in a tokamak power plant configuration [14]. The model explained in detail in Ref. 14 includes the detailed heterogeneous geometrical arrangement of the IB and OB blanket sectors. A water-cooled steel with 1 cm tungsten armor in the double null divertor region that has 12% coverage fraction was used. The calculated TBR was compared to that predicted from 1-D local TBR values coupled with blanket coverage fractions (72.6% OB, 15.4% IB) [22]. While material composition in each radial zone of the 1-D model was carefully determined to account for the toroidal and poloidal material arrangement, the TBR based on 1-D calculation is ~6.3% higher than the calculated 3-D value of 1.07. Therefore, the combined effects of blanket and source 3-D configurations and detailed blanket heterogeniety modeling could lead to more than ~6% lower TBR compared to 1-D estimates.

We investigated the effect of homogenization in the dual coolant Flibe blanket 3-D model. We performed a calculation for the blanket with the FW and multiplier zone homogenized. This resulted in a TBR of 1.09 which is ~2% overestimate compared to the heterogeneous model. On the other hand, using a single homogenized mixture in the blanket resulted in a TBR of 1.02 which is ~5% lower than that from the heterogeneous model. The underestimate is primarily due to distributing the Be multiplier uniformly over the blanket. We performed 1-D calculations for a dual coolant LiPb blanket concept [10] with detailed radial configuration (16 radial zones) and compared the results to the case when a single homogenized mixture is used in the FW/blanket. Full homogenization resulted in ~6% overestimate of the calculated TBR. These results indicate that modeling the detailed heterogeniety of the blanket is essential for accurate determination of the achievable TBR.

Due to the statistical nature of the Monte Carlo method, results of calculations have a statistical uncertainty. However, this uncertainty is very small for integrated values like the overall TBR. Using efficient variance reduction techniques and sampling from millions of source neutrons allow reducing the statistical uncertainty in the overall TBR to a negligible level of <0.01%. Deterministic methods such as the discrete ordinates method has a limitation on modeling complex 3-D geometries and the accuracy of the results is influenced by the discretization of the space, angle, and energy phase space and could be in the range 1-3%.

4.3.3 Uncertainties in nuclear data

The uncertainties in the achievable TBR associated with nuclear data are primarily due to uncertainties in the measured cross sections and energy and angle distributions of secondary neutrons. Another uncertainty arises from processing the cross sections into multi-group data libraries. However, this uncertainty can be greatly reduced by relying on continuous energy cross section data or using a fine energy group structure. Many cross section sensitivity/uncertainty analyses have been performed to provide an estimate of the uncertainty in the calculated TBR in different blanket concepts and values in the range of 2-6% were found [23]. Nuclear data for fusion applications have been under continuous improvement. Several fusion neutronics integral experiments have been performed in facilities that utilize 14 MeV neutron sources [24,25] where breeding blanket mock-ups are used to validate nuclear data and compare the calculated and measured tritium production rates (TPR). A series of integral experiments was performed recently in the FNS facility on one breeder

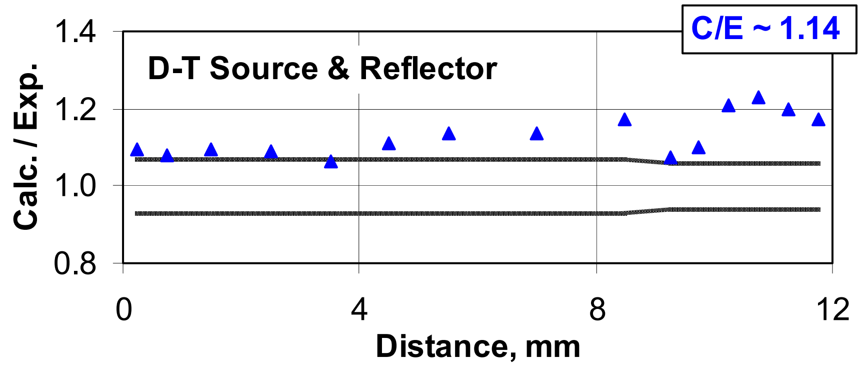

Fig. 7. Comparison between calculated and measured TPR in the 12 mm-thick Li_2TiO_3 layer (from Ref. 26).

layer blanket mock-ups containing F82H, Li_2TiO_3, and Be layers [25]. Direct measurements of the tritium production rate were performed using diagnostic pellets inserted into the breeder layer. A SS316 steel source reflector was utilized to simulate the fusion reactor environment. Analysis showed that calculation of the tritium production rate overestimated the experimental value by an average factor of ~1.14 as shown in Fig. 7 [26]. Integral experiments on a two-breeder layer blanket mock-up are being performed to further assess the large discrepancy between calculation and measurement [26]. While there is uncertainty of ~5% in measuring the TPR, the large overestimate from the calculation is alarming and implies that an intensive R&D program is needed to validate and upgrade nuclear data to improve our ability to accurately predict the achievable TBR.

5. Physics and technology R&D needs to assess the potential for achieving tritium self-sufficiency

It is clear from the above discussion that both the required and achievable TBR values depend on many system physics and technology parameters. Many of these parameters are not yet well defined. In addition, the rapidly decreasing tritium resources imply that the time window for the availability of tritium to supply fuel for the DT physics devices is closing rapidly. It is, therefore, necessary to establish without delay an extensive R&D program to determine the "phase-space" of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency can be attained. This requires parallel and highly interactive research in plasma physics, plasma control technologies, plasma chamber systems, materials science, safety, and systems analysis.

The R&D for subsystems that involve penetrations and the use of non-breeding materials around the plasma, e.g. impurity control/exhaust and plasma auxiliary heating, should focus on design options that result in minimum impact on the TBR. Design choices that necessitate the use of large neutron absorbing materials imbedded in the blanket region for plasma stabilization and attaining advanced plasma modes should be examined regarding their implication on tritium self-sufficiency. Plasma physics experimental and theoretical research is needed to assess the potential for operating in high plasma-edge recycling mode to attain high tritium fractional burnup in the plasma.

The ITER test blanket module (TBM) program will be the first integrated experimental verification of several principles necessary for assessing tritium self-sufficiency. Testing in ITER with the TBMs having their own integrated loops and systems for tritium breeding, tritium processing, and heat extraction will provide information (e.g., tritium mean residence time, tritium inventory, and reliability and efficiency of tritium processing system) that allows better determination of the minimum required TBR. In addition, testing in ITER will provide information that helps better define practical blanket design parameters (e.g., FW thickness, structure content, and coolant conditions). Conditions in ITER are different from those in a DEMO or commercial reactor and measuring tritium production in the TBM will not be adequate to conclude whether tritium self-sufficiency can be achieved. However, testing in ITER TBM, along with dedicated 14 MeV neutron integral experiments, will help validate the predictive capabilities (nuclear data and codes) used for calculating the achievable TBR. Research involving extensive modeling of materials and plasma chamber phenomena and experiments in various laboratory-scale testing facilities and fission reactors will be necessary to supplement ITER testing in providing the scientific and engineering capabilities for more comprehensive fusion tests in later facilities.

An experimentally verified, comprehensive fuel cycle dynamics model needs to be developed to predict tritium behavior, transport, and inventories in all system components such as plasma exhaust, plasma facing components, blankets, and tritium processing. Tritium retention and release in chamber components as a function of operating conditions need to be fully understood and material choice should take into consideration the need to minimize the tritium inventory. This fuel cycle dynamics model coupled with physics and engineering science modeling and experimental results should be used, in a systems studies approach, to provide critical feedback on which plasma configurations and operating modes, and plasma chamber concepts have good potential for attaining tritium self-sufficiency.

To increase the prospect of achieving tritium self-sufficiency, the R&D program should aim at reducing the uncertainties associated with the achievable and required TBR. This can be achieved by better definition of the system parameters. An aggressive effort is required to reduce the uncertainty due to nuclear data to <3%. This can be achieved by continued data improvement and validation in integral experiments using 14 MeV neutron sources. In order to eliminate uncertainties in predicting the TBR resulting from modeling approximations, the capability to use the detailed engineering CAD drawing files directly in the neutronics calculations needs to be developed.

6. Summary and conclusions

There is no practical external source of tritium for fusion energy development beyond ITER, and all subsequent fusion systems have to breed their own tritium. Tritium self-sufficiency in DT fusion systems cannot be assured unless specific plasma and technology conditions are met. We addressed these conditions and shed light on a possible “phase-space” of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency can be attained.

It is crucial that the tritium fractional burnup in the plasma be kept high, at least above a minimum of 2% and most preferably above 5%. Thus, plasma edge physics modes that lead to higher tritium recycling need to be explored. A reserve tritium inventory to keep fueling the plasma and continue reactor operation during periods of malfunction of the tritium processing system is necessary. To keep the reserve inventory, and hence the required TBR, sufficiently low requires high reliability/availability of the tritium processing system, and redundancy in some of the tritium processing system, especially the plasma exhaust processing line. Design options that minimize tritium inventories in reactor components such as the blanket, FW, and divertor are needed.

Up to 30% reduction in TBR could result from using 20% structure in the blanket. Hence, it is necessary to accurately determine the amount and configuration of structure required to ensure structural integrity of the blanket under normal and abnormal conditions. Practical FW thickness and blanket structure content based on detailed structural-mechanical and thermal-hydraulics analyses need to be well defined. Accurate definition of other blanket design considerations that introduce uncertainties in the TBR (e.g., using separate coolant and/or neutron multiplier, and the need for electric insulator) is necessary. Using stabilizing shells and conducting coils for plasma control and attaining advanced plasma physics modes should be examined carefully to minimize the impact on tritium breeding. The size and materials used in plasma heating and current drive components and fueling and exhaust penetrations impact the TBR. Use of strong neutron absorbers in these systems should be eliminated or minimized and design options that minimize streaming path should be considered. Calculation of the TBR should be based on detailed 3-D models that account for all design details. Neglecting heterogeneity effects results in errors up to ~10% in predicting the TBR. Integral experiments are needed to validate and improve nuclear data.

It is necessary to establish without delay an extensive parallel and highly interactive R&D program in plasma physics, plasma control technologies, plasma chamber systems, materials science, safety, and systems analysis to determine the "phase-space" of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency can be attained.

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