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Snowmass Hot Topic

Chamber Science and Technology

Key Question number 6

Potential for Achieving Tritium Self-Sufficiency

What is the potential of current plasma confinement and chamber technology concepts for attaining tritium self-sufficiency and what are the implications for requirements on plasma and technology R&D?

Is there a time window for the availability of tritium startup inventory? What are the implications of such time window on the schedule for tritium-producing Chamber technology?

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1. Introduction (Sawan)

Tritium is the main fuel ingredient in the plasma of MFE and IFE systems based on the D-T fuel cycle. Since tritium is not a naturally existing isotope, attaining tritium self-sufficiency is necessary for self-sustaining fusion plants operating on the D-T fuel cycle. Tritium is bred in a lithium-containing blanket surrounding the plasma. Once tritium is generated, it needs to be collected, processed, and redirected to the plasma. The tritium fuel cycle involves many subsystems whose physical and operational characteristics will dictate the success in achieving tritium self-sufficiency.

The achievable tritium breeding ratio (TBR) is predicted by performing neutronics calculations. It depends on the type of the breeding material as well as the coolant and structural materials used in the FW/blanket subsystem. The calculated achievable TBR should account for the 3-D geometrical configuration of the chamber including penetrations. Hence, in addition to the dependence on the blanket type, the achievable TBR could depend on the plasma confinement concept considered. Moreover, the geometrical and spectral differences of the neutron source in MFE and IFE chambers affect the achievable TBR. The calculated achievable TBR for a given FW/blanket concept is uncertain due to the uncertainty associated with the system definition and the prediction of the TBR. The latter includes the uncertainty associated with the geometrical modeling, calculational methods, and basic nuclear data.

The required TBR in a fusion system must exceed unity by a margin that accounts for the calculational uncertainties, tritium losses and radioactive decay during the period between production and use, tritium inventory in the plant components, and supplying inventory for startup of other fusion plants. To accurately determine the required TBR, one has to consider the entire fuel cycle for the D-T plant. The tritium fuel cycle involves many subsystems. The main subsystems are plasma exhaust and vacuum pumping, FW/blanket, plasma-facing components (PFC), fuel clean-up, isotope separation, fuel management, storage, and fueling. Simulation of this cycle, including the dynamic behaviour is required for accurate evaluation of tritium build-up and consumption/losses in this closed cycle.

The required tritium breeding margin depends on many system parameters. These include the desired doubling time, tritium inventory in the different components, and the tritium extraction and processing system utilized. In addition, tritium fractional burn-up in the plasma impacts the tritium inventory in some of the components, such as the plasma fueling system, and hence affects the required TBR. The required TBR, therefore, depends on the plasma confinement scheme, the breeding blanket concept, and the tritium extraction and processing system. The uncertainty in the performance characteristics of the plasma and other subsystems of the fuel cycle contributes to the uncertainty in the required TBR.

To attain tritium self-sufficiency, the calculated achievable TBR must exceed the required TBR. Uncertainties in predicting both the achievable and required TBR should be assessed. In this report, the potential of the plasma confinement concepts in both MFE and IFE and the breeding blanket concepts for attaining tritium self-sufficiency will be assessed. Possible plasma and technology R&D required to reduce the uncertainties and increase the potential for achieving tritium self-sufficiency will to be identified.

The first generation of fusion ignition machines are designed without tritium breeding blankets and rely on the existing tritium resources for fueling. These resources are decreasing due to radioactive decay and reduced production rate. An important issue, to be addressed in this report, is whether there is a time window for the availability of tritium to supply the tritium requirements for the ignition machines. This time window will impact the schedule for developing tritium producing chamber technologies.

2. Achievable TBR

What is the achievable TBR in different plasma confinement and breeding blanket concepts?

2.1 Impact of FW/blanket concept (El-Guebaly/Sawan)

How does TBR vary for different breeding blanket concepts?

The breeding potential varies substantially with FW/blanket concepts. The achievable local TBR depends on the Li bearing breeder type, Li enrichment, coolant, and structural material. Neutron multipliers, particularly beryllium, could enhance the tritium breeding potential of almost all breeders.

2.1.1 Effect of breeding material (El-Guebaly/Sawan)

The inherent breeding capacity of numerous breeders considered in previous fusion designs over the past 30 years is illustrated in Fig.1. A fairly thick breeding zone without structure or neutron multiplier is considered for each breeding material. Enriching the lithium in the isotope ^{6}Li does not always help the breeding. Breeders with natural Li provide the highest TBR except for LiPb and LiSn. The TBR could optimize at higher enrichment when structural materials and multipliers are included in the blanket. In realistic designs, the structure, configuration, and penetrations will degrade the achievable overall TBR below the values shown in Fig. 1.

The breeders could be divided into three groups according to their breeding potential. The first group includes liquid Li and LiPb which have the largest breeding potential with local (full coverage) TBR values greater than 1.7 without structure or multiplier. The second group contains Li_2O, Flibe, and LiSn. These breeders have medium breeding potential with local TBR values ranging between 1.2 and 1.4 without structure or multiplier. To achieve tritium self-sufficiency with these breeders, the structure content needs to be minimized and/or 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 substantial amount of neutron multiplier to achieve adequate breeding.

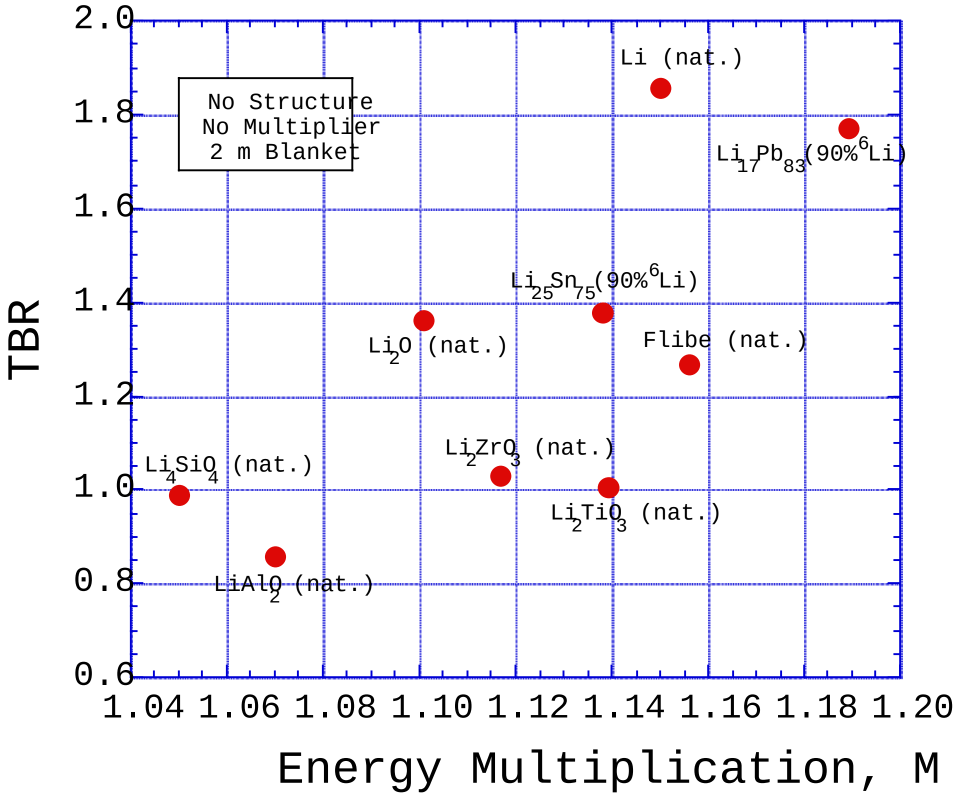

Fig. 1. Tritium breeding potential of candidate breeding materials.

2.1.2 Effect of structural material (El-Guebaly/Sawan)

Using structural material in the FW/blanket results in degrading the achievable TBR. The extent of degradation depends on the structural and breeding materials used. 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. Depending on the breeding material and structure type and content, up to 20% degradation in TBR might result. Candidate structural materials used in conceptual designs include austenitic steel, ferritic steel, vanadium alloys, SiC/SiC composites, and C/C composites. Because of their ability to handle high surface heat fluxes and operate at high temperatures, refractory alloys, such as W, Ta, Mo, and Nb alloys, have also been considered.

Vanadium and SiC structures have the least impact on tritium breeding of the Li and LiPb systems, respectively. W and V alloys yield the smallest degradation in TBR when used as structural material with Flibe or LiSn breeders. For solid breeders, the use of vanadium structure gives the least impact on tritium breeding. Except for LiPb and LiSn, which use highly enriched Li, some of the TBR degradation resulting from the structure can be recovered by enriching the Li in ^{6}Li. However, the net effect is still a lower TBR compared to the case without structure. Eliminating the structure completely as for IFE chambers and MFE liquid wall concepts will have an advantage regarding the tritium breeding capability. Although the choice of structural material and the amount used is design dependent and is usually driven by other considerations, an effort should be made to reduce the amount of structural material because of its negative impact on tritium breeding.

2.1.3 Effect of coolant (El-Guebaly/Sawan)

While the liquid breeder can serve also as the coolant in a self-cooled concept, separate coolants, such as water or helium gas, could be utilized with solid and liquid breeders. Due to its low density, He gas has negligible impact on tritium breeding. On the other hand, the large neutron moderation in water helps enhancing tritium breeding from 6Li. However, the large absorption tends to decrease tritium breeding. The net effect depends on the breeding and structural materials used. In typical liquid and solid breeder designs, using 20% water coolant in the FW/blanket system reduces the TBR by up to 7%.

2.1.4 Effect of neutron multiplier (El-Guebaly/Sawan)

Different neutron multipliers can be used to enhance the achievable TBR. The enhancement depends on the breeding and structural materials used. Beryllium is the best neutron multiplier followed by Pb, Be_2C, and BeO. No multiplier is needed in concepts utilizing Li or LiPb as a breeder. If Flibe and LiSn are used without structure, adequate breeding could be achievable without a multiplier. However, it seems to be necessary to add a neutron multiplier when Flibe, LiSn, or solid breeders are used in a FW/blanket concept with structure.

2.2 Differences between MFE and IFE systems (Sawan)

Is there significant difference between achievable TBR in MFE and IFE systems?

There are several geometrical, spectral, and temporal differences between the IFE and MFE systems that could impact the achievable TBR. While a cylindrical or toroidal chamber surrounds a volumetric distributed source in MFE systems, a nearly spherical chamber in IFE plants surrounds a point neutron source. As a result, source neutrons in IFE chambers impinge on the FW/blanket in a more perpendicular direction than in MFE chambers. This leads to lower tritium production rate at the front with lower radial gradient. The achievable TBR will be similar in the two systems if the blanket is quite thick. On the other hand, for relatively thin blankets utilizing the same materials, the local TBR is expected to be lower in IFE chambers. However, since the chamber size is decoupled from the size of the driver in IFE plants, thicker blankets are easier to accommodate in IFE chambers than in MFE chambers.

Fusion neutron interactions in the highly compressed target results 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 depending on the target fuel compression (ρR). This tends to decrease the achievable local TBR The combined geometrical and spectral effects result in local TBR values in IFE chambers that are lower than those in MFE chambers by up to 5% depending on the FW/blanket concept used.

While steady state or long pulse operation is envisioned for MFE plants, neutrons are born over 10-100 ps pulses in IFE plants. The neutrons emanating from the target traverse the chamber in 40-100 ns depending on the radius. The time of flight spread of source neutrons with the softened spectrum along with the neutron slowing down in the blanket results in tritium production being spread over several hundreds of nano seconds following each pulse. This temporal effect does not affect the time integrated local TBR. However, it could affect tritium permeation and extraction.

2.3 Impact of chamber configuration (El-Guebaly/Sawan/Nevins)

What is the impact of chamber configuration in different confinement concepts on achievable TBR?

The calculated achievable TBR should account for the 3-D geometrical effects. The plasma chamber configuration differs with the confinement concept and, therefore, impacts the blanket coverage and the achievable TBR. Confinement schemes, such as tokamaks, STs, and stellarators, in which the plasma is linked by TF coils, require a divertor (or limiter) system that faces the plasma. The overriding design consideration for the divertor will be power exhaust (accepting ~10 MW/m^2 of power 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. Confinement systems, like FRCs and spheromaks, 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 need not compete with the tritium breeding systems for space facing the plasma in these confinement systems. No divertors or limiters are needed in an IFE system.

Conventional tokamaks rely heavily on the inboard (IB) and outboard (OB) blankets to breed all the tritium needed for plasma operation. The contribution to the overall TBR from a blanket installed behind the divertor system is insignificant due to the large attenuation of neutrons by the sizable divertor structure. 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. Due to space limitation in the IB side of a tokamak, a thinner blanket is usually used in the IB region with a smaller local TBR than the thicker OB blanket. This tends to have a negative impact on the achievable overall TBR.

In spherical tokamaks, it is unlikely that a breeding blanket could be installed in the space-constrained IB side. Therefore, spherical tokamaks depend entirely on the OB blanket for tritium breeding. However, this is not expected to drastically affect the overall TBR since the low aspect ratio results in less than 10% IB coverage. As the aspect ratio of a ST increases, the OB blanket coverage fraction decreases and it becomes difficult for the OB blanket to provide the required tritium. Hence, STs with lower aspect ratios will have higher breeding capability.

In stellarators, the aspect ratio is high and a blanket with uniform thickness could surround the entire plasma. Although the coverage fraction of the divertor in stellarators is relatively large, thin divertor plates or baffles are used allowing for substantial breeding in the area behind the divertor system. Thick divertor plates or baffles may cause breeding problems for blankets with marginal breeding. To insure that the external coils producing the rotational transform of the magnetic field are as close to the plasma as practicable the tritium breeding blanket in stellarators might need to kept as thin as possible.

In linear confinement concepts such as the FRCs and tandem mirrors, elongating the cylindrical chamber can reduce the end losses. This increases the blanket coverage, which helps enhance the overall breeding potential. The linear confinement concepts also allow for using uniformly thick blankets. In IFE plants, the chamber geometrical configuration results in nearly full coverage with blankets that could be as thick as needed at all locations in the chamber. As a result, the achievable overall TBR is very close to the local value.

Based on the above discussion, we conclude that with respect to the chamber geometrical configuration impact on the achievable TBR, the IFE configuration has a clear advantage followed by the linear magnetic confinement concepts. It should be emphasized that, even though some MFE confinement concepts suffer from reduced blanket coverage due to their geometrical configuration, tritium self-sufficiency can still be achieved in such concepts with carefully designed blanket concepts that have high breeding potential.

2.4 Impact of chamber penetrations (Nevins/El-Guebaly/Sawan)

Is there significant difference in size of penetrations required in different confinement concepts and how does this impact the achievable TBR?

The impact of the chamber penetrations (including diagnostic ports, heating/current drive ports in MFE systems, and beam ports in IFE systems) on the TBR can be held to less than a 2% reduction in the TBR for MFE systems, and 0.5% for IFE systems. Hence, we do not believe that this will be a determining factor in the choice of confinement schemes.

Penetrations are required in MFE chambers to accommodate heating and current drive systems, and diagnostic systems. Heating and current drive systems will probably be required for fusion power plants based on any magnetic confinement scheme. Given our present limited knowledge regarding the heating and current drive requirements for the various alternate confinement schemes, it is not possible to reach any conclusion regarding the relative advantages in tritium breeding of any one magnetic confinement scheme over the others. In particular, the predicted lower non-inductive current drive requirements for STs relative to advanced tokamaks results mainly from the greater optimism of the proponents of STs regarding our ability to control the pressure profile and, thereby, the profile of the bootstrap current. This cannot reasonably be translated into a tritium breeding advantage for STs.

Stellarators will require heating systems, while compact stellarators (which carry a toroidal current) may also require non-inductive current drive for current profile control. What advantage stellarators may achieve in tritium breeding from reduced (or absent) current drive systems will probably be balanced by the need to keep the tritium breeding blanket as thin as possible to insure that the external coils producing the rotational transform of the magnetic field are as close to the plasma as practicable. FRCs with rotating magnetic field current drive would appear to require substantial antenna systems, which would compete with tritium breeding systems for space facing the plasma.

The penetrations for heating and current drive are normally placed in the OB side of the toroidal concepts. This is the region where the local TBR is the highest. As a result the impact on reducing the achievable overall TBR will be greater than predicted by the fraction of FW area occupied by the penetrations. In previous conceptual MFE power plant designs, the area taken by the heating and current drive penetrations amounts to 1-2% of the FW area and the net effect on the overall TBR is about 2-3% reduction. Small penetrations are practically feasible by employing compact folded wave guide systems rather than the antenna system. This is an important driver for fusion designs to reduce the impact of heating and current drive penetrations on breeding. The feasibility of employing such systems needs to be confirmed by R&D programs.

No heating or current drive systems are needed in IFE power plants. The 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. For indirect drive concepts, the fraction taken by the beam ports is much lower. Hence, the impact of chamber penetrations on the achievable overall TBR is minimal in IFE plants.

In commercial fusion power plants, maintenance schemes utilize ports that do not interfer with the breeding blanket. Maintenance is achieved through doors or ports in the vacuum vessel behind the breeding blanket. Hence, the maintenance systems do not impact the achievable TBR. 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 controled plasma profiles. The diagnostic penetrations are usually much smaller than those required for heating and current drive. Therefore, they are not expected to have a dominant impact on the TBR.

It is clear from the above discussion that penetrations in both MFE and IFE chambers have small impact on the achievable TBR.

2.5 Uncertainties in predicting the achievable TBR

How large are the current uncertainties in predicting the achievable TBR?

A provision should be made in the calculated TBR to account for uncertainties due to approximations and/or errors in the various elements of the calculations. These include the uncertainty associated with nuclear data, geometrical modeling, and calculational method.

2.5.1 Uncertainties in nuclear data (Youssef)

The uncertainties in the achievable TBR that is attributed to nuclear data can be classified as those uncertainties in the measured angle-integrated (smooth) cross sections, uncertainties in the energy and angle distributions of secondary neutrons (SED, and SAD), and uncertainties due to approximations introduced by the formats that represent these cross sections in the basic evaluated data files such as ENDF/B-VI, BROND, etc. In addition, another source of uncertainty arises when these cross sections are processed into suitable multi-group data libraries to be used by discrete ordinates transport codes.

Many cross section sensitivity/uncertainty analyses have been performed to provide an estimate of the uncertainty in the calculated TBR. Special codes are applied and tailored to couple results from sensitivity analysis with actual uncertainties (errors) currently implemented in various data bases. Cross section sensitivity profiles are generated to reveal the type of cross section and energy range of a particular material in which slight variation can result in large variation in TBR. On the other hand, the actual uncertainties in measured/evaluated data, which arise from the various measuring techniques used and the systematic errors involved in measurements, are quantified in terms of covariance and correlation data that reflect the size of uncertainties and the correlation that may exist among various cross section errors over specific energy ranges. Fortunately, these covariance and correlation data have been generated for the most important materials whose cross section uncertainties have the most impact on the TBR. This includes uncertainties in the most prominent partial cross sections of the breeding materials such as the ^{6}Li(n,α), and the ^{7}Li(n,n'α)t cross sections and structurural material's cross sections such as the Fe(n,inelastic), Fe(n,p), etc. However, uncertainty data and covariance information are still missing for some important materials and further effort is needed in this area.

The uncertainty in the TBR due to nuclear data is attributed to uncertainties in both the basic data and the data processing. The uncertainty due to uncertainties in the basic data has been quantified for several blanket concepts that have solid as well liquid breeder/coolants and was found to be in the range of ~2-6%. In these solid wall blanket concepts, most of the uncertainty is attributed to the uncertainties in the partial cross sections of the structural materials (iron, chromium, nickel, etc.) or in the partial cross sections of the elements in the breeder compound materials (e.g. oxygen in Li_2O). This cited range of uncertainty in the TBR is due to the uncertainties in the smooth cross section data. The uncertainty in the TBR due to uncertainties in the SAD and SED is minimal since the TBR is an integrated quantity over the blanket region. However, uncertainties in local tritium production rate is largely affected by the uncertainties in SED and SAD. For liquid FW/blanket concepts without structure, the uncertainty in the TBR is anticipated to be smaller since it is mainly driven by the uncertainties in the ^{6}Li and ^{7}Li cross sections whose size is generally small, particularly in liquid lithium. However, uncertainties in the cross sections of the other elements of the breeder compound (e.g. Be in Flibe, Sn in Li-Sn) are dominant and could lead to ~3-8% uncertainties in the TBR.

Data processing and representation could introduce uncertainty in the calculated TBR. The experimental data undergo various processes prior to their direct use as input to transport codes. These processes include tabulating data at a finite number of energy points or representation as analytic function. Processing these data to produce point-wise or multi-group data libraries involves interpolation and use of approximate weighting functions. Studies showed that ~4% uncertainty in the TBR could be attributed to processing of various multi-group data whereas the corresponding uncertainty arising from processing point-wise data for Monte Carlo calculation is less (~2%).

2.5.2 Uncertainties due to modeling and calculational methods

(El-Guebaly/Sawan/Youssef)

To guide the design process of a specific blanket concept, a series of parametric 1-D analyses is usually established at an early stage of the design. The 1-D model used in the calculations depends on the confinement concept. A toroidal cylindrical geometry modeled around the machine axis is more appropriate for toroidal machines such as tokamaks and STs. In this model, the IB and OB regions are modeled simultaneously to properly account for the toroidal effects. The cylindrical model around the plasma axis is more suitable for the large aspect ratio stellarators and linear machine such as the FRC. This model is used also in toroidal machines to determine the neutronics parameters at the top and bottom (divertor region). For IFE chambers, a spherical geometry is used with a point source at the center. The point source emmits neutrons and gamma rays with spectra determined by performing a separate target neutronics calculation.

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. It needs to be emphasized that the nuclear coverage fraction (NCF) should be used rather than the FW area fraction. The NFC is defined as the fraction of the source neutrons incident directly on the specific region. In toroidal facilities, the NCF of the OB and IB regions depend on the aspect ratio. Increasing the aspect ratio results in decreasing the OB NCF and increasing the IB NCF. When estimating the overall TBR, provisions should be made for the elements that degrade the breeding, such as penetrations, assembly gaps, and side walls. In addition, accurate modeling of the layered heterogeneous configuration of the breeding blanket in the 1-D model is essential for accurate estimation of the TBR. Some error will be introduced due to homogenization.

Upon converging on a reference design, a detailed 3-D model for the reference configuration is necessary to confirm the achievable TBR. Past experience with ITER, commercial MFE plants (ARIES), and commercial IFE designs (HIBALL and LIBRA) indicate that the overall achievable TBR estimated from the 1-D calculations coupled with coverage fractions are within 3% from the value obtained from detailed 3-D calculations. Assuming that a detailed 3-D calculation is used to determine the achievable overall TBR, uncertainties in the TBR resulting from possible modeling approximations such as zone homogenization are estimated to be ~1-2%.

With the application of 3-D Monte Carlo method, the uncertainty in the TBR due to the transport calculation itself is small, depending on the number of histories involved. Uncertainty of ~1% results from the statistical nature of the Monte Carlo method. Uncertainties in discrete ordinates calculations are larger and could be in the range of 2-3%.

Assuming that the above listed uncertainties are uncorrelated, the uncertainty in the TBR due to data, modeling, and calculational method uncertainties is ~5-9% for mult-group discrete ordinates calculations and ~3-6% for 3-D continuous energy Monte Carlo calculations.

3. Required TBR

How large a tritium breeding margin above unity is required?

3.1 Parameters affecting the required TBR[1] (Willms)

What are the most important parameters influencing the required TBR?

The overall balance for the tritium inventory at any time in an overall fusion reactor system can be expressed as:

$$I(t) = \sum \int F_i dt - \sum \int F_j dt \,. \tag{1}$$

Where:

I is the overall plant tritium inventory at any time, t
F_i is the rate of tritium addition to the plant via pathway i
Fj is the rate of tritium leaving the plant via pathway j

The pathways for tritium to be added to the system, F_i, are:

Importation from external sources (F_{im})
Tritium breeding (F_{br})

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[1] A more detailed analysis of this topic can be found in:

Abdou, M.A., E.L. Vold, C.Y. Gung, M.Z. Youssef and K. Shin; "Deuterium-Tritium Fuel Self-Sufficiency in Fusion Reactors"; *Fusion Technol.*, 9, 250 (1986).

Kuan, W., and M.A. Abdou; "A New Approach for Assessing the Required Tritium Breeding Ratio and Startup Inventory in Future Fusion Reactors"; *Fusion Technol.*, 35, 309 (1999).

The pathways for tritium to leave the system, F_j, are:

Decay (F_{de})
Burnup (F_{bu})
Loss to the environment (F_{en})
Loss to materials/waste (F_{mw})
Export of tritium to other sites (F_{ex})

These pathways are summarized schematically with figure 2.

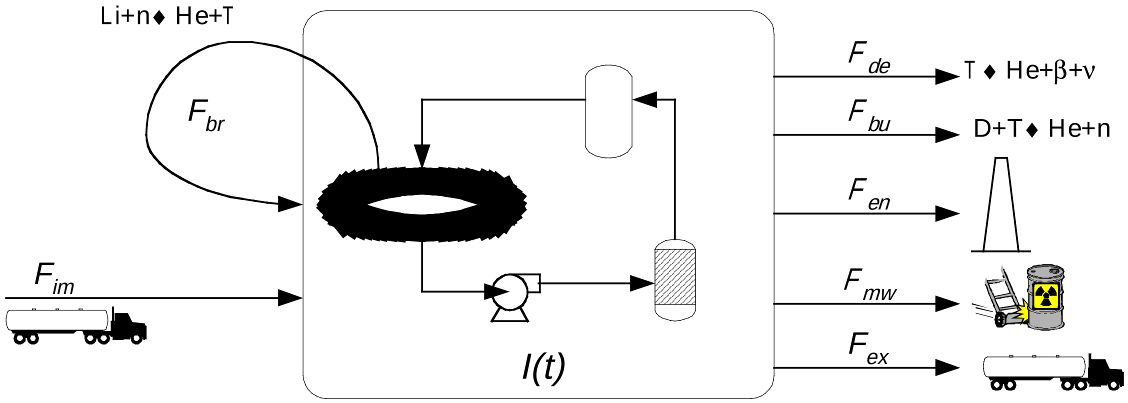

Figure 2 Tritium Pathways in a Fusion Plant

Using the nomenclature defined above, equation 1 becomes:

$$I(t) = \int_0^t (F_{im} + F_{br})dt - \int_0^t (F_{de} + F_{bu} + F_{en} + F_{mw} + F_{ex})dt \ . \tag{2}$$

There are two distinct regions to which equation 1 applies—the startup and steady state phases. The time to complete "startup" is defined as, t_{st}.

Startup: For the initial startup of a new fusion plant, external sources will be required to supply an initial tritium inventory (I_{st}). Until the plant starts breeding sufficient tritium of its own, this external tritium will:

1) fill the tritium processing systems including operating reserve (I_{tp}),
2) fill materials with tritium (e.g. surface sorption) (I_{ma}),
3) provide enough tritium to make up for decay ($\int_0^{t_{st}} F_{de} dt$), and
4) provide tritium to offset tritium burnup until the plant starts breeding its own tritium ($\int_0^{t_{st}} F_{bu} dt$).

Thus, the required startup tritium inventory is:

$$I(t_{st}) = I_{st} = I_{tp} + I_{ma} + \int_{0}^{t_{st}} (F_{de} + F_{bu})dt \ . \tag{3}$$

For the five-year ITER BPP phase this value has been estimated to be 27,000 g T.

Steady State: Following this startup period the external source term will become and remain zero. Beginning at time t_{st}, equation 2 becomes:

$$I(t > t_{st}) = I_{st} + \int_{t_{st}}^{t} F_{br} dt - \int_{t_{st}}^{t} (F_{de} + F_{bu} + F_{en} + F_{mw} + F_{ex})dt \tag{4}$$

At large times a fully developed steady state will be achieved where parameters are basically independent of time. This is defined as $t>t_{ss}$. In this regime there will be a fixed tritium inventory of:

$$I(t > t_{ss}) = I_{ss} = I_{tp} + I_{ma} , \tag{5}$$

and the tritium source and sink terms will be equal as:

$$F_{br} = F_{de} + F_{bu} + F_{en} + F_{mw} + F_{ex} . \tag{6}$$

This equation can be expressed in terms of a tritium breeding ration (TBR) as:

$$TBR = \frac{F_{br}}{F_{bu}} = 1 + \frac{F_{de} + F_{en} + F_{mw} + F_{ex}}{F_{bu}} . \tag{7}$$

This expression emphasizes the fact that each fusion reaction which produces one neutron must in turn breed one tritium to account for the "1" on the right-hand-side of equation 7. Beyond that further tritium must be bred to make up for the remaining terms in equation 7.

The sink terms in equation 6 (and 7) have the following general dependencies and ranges (an approximately 1 GW(fusion) plant has been used for this analysis):

Parameter	**Primary Dependence**	**Range for ~1 GW average plant**
F_{de}	Tritium inventory	For 2,000 g inventory, 100 g T/yr
F_{bu}	Fusion power	56,000 g T/yr
F_{en}	Tritium systems design, coolant system design, maintenance philosophy	Typically <0.5 g T/yr
F_{mw}	Materials of construction, component replacement rate, waste handling design	For carbon, could be 100's of g T/yr, other materials will likely be much lower
F_{ex}	Overall fusion strategy, world tritium supplies	100-2,000 g T/yr

From the numbers in this table it is observed that most of the tritium breeding is used to make up for the tritium that is burned. In other terms, the TBR must be at least unity. Then, more tritium must be bred to make up for the other smaller tritium losses. Of these smaller terms, the two largest factors are the rate at which tritium needs to be generated for export and the tritium that is lost to material/waste. Which will be largest will depend on what materials are used for the reactor components (codeposition on carbon components can make this term large) and how aggressively tritium is bred for other sources. Relative to these other terms, the tritium lost to decay is small and the tritium lost to the environment is negligible.

3.2 Tritium fractional burn-up in plasma (Nevins/Sawan)

What is the potential for achieving high tritium fractional burnup in the plasma for both MFE and IFE confinement concepts?

The tritium fractional burn-up in the plasma impacts the tritium inventory in some of the components, such as the plasma fueling system, and hence affects the required TBR. Increasing tritium burn-up reduces the required TBR and, hence, improves the potential for achieving tritium self-sufficiency. The tritium burn-up fractions projected for both MFE and IFE systems are high enough (>10%) that they should not greatly impact the required TBR.

A zero-D analysis shows that there are two general means of increasing the tritium burn-up fraction. One option is to operate with a tritium-lean fuel mixture, which increases the required confinement capability and reduces the fusion power density. The other approach is to manipulate the particle exhaust. Given the fact that confinement capability and fusion power density strongly drive the unit size and cost, it is implausible that increasing the tritium burn-up fraction through increased confinement capability and reduced fusion power density can provide much net gain in power plant attractiveness. Helium enrichment (relative to the DT fuel) in the particle exhaust stream (as measured by τ_{He}^*/τ_{DT}^*) can improve the tritium burn-up fraction. Any advantage assigned to a particular magnetic scheme for helium enrichment in the particle exhaust stream must be based on some qualitative difference in power and particle exhaust system.

Tritium burn-up fraction values as high as 30% are predicted in recent commercial MFE designs (30% in ARIES-RS and 18% in ARIES-ST). Even in the absence of helium enrichment in the particle exhaust stream, tritium burn-up fractions of 10% can be achieved. In IFE targets, the tritium burn-up fraction is expected to be about 30%.

3.3 Impact of chamber technology on tritium inventory (Sze)

How does the tritium inventory depend on the chamber technology concept?

There are three key components within the chamber technology area that have potentially high tritium inventory. These three components and with the estimated tritium inventory within these components are:

a. Blanket; The estimated tritium inveotry in the blanket varies from few g for Flibe and Pb-Li blankets, up to about 100 g for the lithium blanket.

b. The cryogenic pump: The typical regeneration time for the cryopump is about 30 minutes. The tritium flow rate to the cryopump is less than 600 g/hr (3000 MW fusion power, with plasma burn-up fraction of 3%.). Therefore, the tritium inventory on the cryopump is less than 300 g.

c. The divertor: Based on the selection of the divertor material, the tritium inventory in the divertor can be as high as 5 to 10 Kg, especially if graphite is used for the divertor material, and tritium co-deposition effects are as serious as we have been estimating.

Therefore, the tritium inventory is dominated by the PMI component. The selection of the divertor concept, especially the divertor material, will have dominant effect on tritium inventory.

For IFE system, there is no divertor and no need for cryopump. Therefore, the tritium inventory in the chamber is dominated by the blanket, which is a small fraction of the total on site tritium inventory in the entire power plant.

3.4 Impact of tritium extraction method on required TBR (Sze)

How does the method and time needed for tritium extraction and processing affect the required TBR?

The tritium recovery system from the breeding material includes the following sub-systems:

- The component to remove tritium from the breeding material.
- The components to remove all impurities, including He carrier gas, impurities, and activation products to form a stream of only pure hydrogen isotopes.
- A safety device, most likely a Pa diffuser, to assure no harmful impurities will pass to the isotope separation system (ISS).

- An ISS, to separate the hydrogen isotopes into the required isotopic compositions to be either reused as the fuel to the plasma, or to be released as waste.

The tritium inventories in the breeding material in the blanket range from few grams for Pb-Li, to maybe 200 g for a lithium blanket. The tritium residence time in the purification system (step 2) is about 3 hours, as assessed by the Breeding Blanket Interface (BBI) program. The tritium throughput from the blanket is about 500 g/FPD. Therefore, the tritium inventory in the purification system is about 60 g. There is essentially no tritium inventtory in the diffuser, step 3. The total tritium inventory in the ISS can be limited to about 100 g, based on ITER study. The additional tritium inventory due to the blanket stream is on the order of 10 g, based on the ITER calculation with a Li blanket.

Therefore, the total tritium inventory in the tritium extraction system, including the total tritium in the ISS, is about 500 g. This tritium inventory is much smaller than the expected tritium inventory in the PMI system. Therefore, it is expected that the tritium extraction system will have only minor impact on the required TBR.

3.5 Impact of safety requirements on required TBR (Sze)

How does achieving higher safety requirement could effect required TBR?

High safety requirement will limit the tritium inventory and the tritium loss rate. Therefore, high safety requirement will reduce the value of required TBR.

3.6 Uncertainties in determining the required TBR (Youssef)

What are the uncertainties in determining the required TBR?

The required TBR, Γ_r, should exceed unity by a margin, Go, to account for tritium losses through radioactive decay and to conform with the set of plasma and engineering component parameters selected for the entire tritium fuel cycle. The uncertainty in the required TBR, $\Gamma_r = 1+Go$, is thus expressed as Δ_G.

To estimate the uncertainty Δ_G, it is necessary to know the probability distribution, i.e. the "likelihood" of "occurrence" of a particular reactor parameter that affect the required TBR. A rigorous statistical treatment to quantify Δ_G is hard to achieve at this stage of R&D development for fusion since not all the key reactor parameters are precisely known or the likelihood of its occurrence can be well defined. However, in one of the recent studies on tritium fuel cycle, a lognormal distribution is assumed for each of these key parameters and the uncertainty, Δ_G, was quantified. In this study, it is assumed that the value of the actual parameter, Xi, is expected to fall 68% of the time within a factor of 2 from the most probable value, X_{ref}. This lognormal distribution will have a geometric standard deviation of $\sigma_g = 2$ and can be used as the weighting function to derive the average value of the required TBR, $\overline{\Gamma}i$, for the particular parameter Xi. The relative deviation of $\overline{\Gamma}i$ from the required TBR, Γ_{ref} , evaluated at reference value, X_{ref}, is expressed as $\Delta_{Gi} = (\overline{\Gamma}i - \Gamma_{ref})/\Gamma_{ref}$. This is repeated for each parameter. Assuming the uncertainties in the required TBR for the parameters under consideration are uncorrelated, the total uncertainty, Δ_G, is square root of the sum of the squares of these uncertainties.

We list in Table I the estimated uncertainty in the required TBR as obtained from a study on a dynamic model for the tritium fuel cycle that includes the various components of the fusion reactor that carry tritium. The Table shows the lognormal weighted mean breeding ratio and the corresponding uncertainty in the six most important parameters that impact the required TBR with a selected values for standard deviation, σ_g. . As shown, the probable uncertainty in the required TBR, Δ_G is ~ 0.048, i.e. ~5% based on the selected reference values of key parameters listed in the Table.

Table I: Lognormal Weighted Mean Breeding Ratio and Corresponding Uncertainty with Selected Values of the Standard Deviation (Required TBR for the reference values=1.08)

Parameter, X	X_g*	Selected** σ_g	$\overline{\Gamma}$	Δ_{Gi}
Doubling time	5 yr	2	1.089	0.011
Burn fraction	0.05	3	1.122	0.042
Days of tritium reserve	2 days	2	1.085	0.007
Extraction inefficiency in plasma exhaust processing	0.001	5	1.089	0.011
Residence time in plasma exhaust processing	1 day	2	1.081	0.004
Blanket residence time	10 days	3	1.084	0.006
All other parameters	--	--	1.09	0.012

* Reference value for Xi

** Weighed over range between 0.1 of reference value and 1- x the reference value

4. Potential for tritium self-sufficiency (Sawan/El-Guebaly)

Do we expect that present candidate chamber technology concepts can achieve tritium self-sufficiency?
Does any of the current and alternate confinement concepts have clear advantage in achieving tritium self-sufficiency?

To attain tritium self-sufficiency, the calculated achievable TBR must exceed the required TBR. Based on the discussion in sections 2 and 3 above, we will try to answer the following questions:

- Do we expect that present candidate chamber technology concepts can achieve tritium self-sufficiency?
- Does any of the current and alternate confinement concepts have clear advantage in achieving tritium self-sufficiency?

Regarding the chamber technology concepts, it is clear that concepts utilizing liquid lithium or LiPb as breeder have the largest potential for achieving tritium self-sufficiency even if a large amount (15-20%) of structural material is used. LiSn and Flibe can achieve tritium self-sufficiency without a need for a separate multiplier if utilized in designs with very small amount (<2%) of structure in the front ~10 cm of the FW/blanket. Eliminating the structure completely as in IFE systems or MFE systems with liquid walls enhances the potential of achieving tritium self-sufficiency with these breeders. Among solid breeder candidates, Li_2O has the best chance for achieving tritium self-sufficiency. However, the structural material and coolant required in solid breeder concepts imply that a neutron multiplier should also be used to achieve tritium self-sufficiency. If very small amount of structure is used coupled with near full blanket coverage (e.g. in IFE), a separate multiplier might not be needed with Li_2O. The FW/blanket concept may impact the required TBR through the effect of material choice on the tritium inventory. However, tritium inventory in the FW/blanket system represents a very small fraction of the total tritium inventory in the plant. Hence, the required TBR is, in general, independent of the chamber technology concept utilized.

For the plasma confinement concept to have a large potential for attaining tritium self-sufficiency, it needs to have high tritium burn-up fraction in plasma and allow for large breeding blanket coverage. While a large tritium burn-up fraction (~30%) can easily be achieved in the IFE targets, it seems to be more difficult to increase the tritium burn-up fraction to that level in several MFE systems. However, there is no significant reduction in the required TBR if the tritium burn-up fraction is increased above ~10%. Since all MFE and IFE confinement concepts are expected to achieve values above 10%, the tritium burn-up fraction is not the dominant factor in determining the confinement concept's potential for achieving tritium self-sufficiency.

The ability of a confinement concept to allow for large breeding blanket coverage is determined by the chamber geometrical configuration and amount of penetrations required. The IFE systems have a clear advantage since no divertors, limiters, or heating and current drive systems are employed. In addition, beamline penetrations are very small covering less than 0.5% of the FW. Blankets can be made as thick as needed in IFE chambers without impacting the high cost driver. The large blanket coverage in IFE chambers allows using breeding materials that have attractive thermal-hydraulic features but marginal breeding such as Flibe and LiSn. In addition, due to the lack of magnetic fields in IFE chambers, it is also easy to employ flowing thick liquid breeder concepts without structure. Among the different MFE concepts, FRCs and spheromaks do not require divertors or limiters. Other concepts such as stellarators, STs, and tokamaks require divertors or limiters resulting in limiting the overall TBR. There is no clear advantage for any of the MFE confinement concepts with respect to the number and size of chamber penetrations required. It should be emphasized that, even though some MFE confinement concepts suffer from reduced blanket coverage and limited blanket thickness, tritium self-sufficiency can still be achieved in such concepts with carefully designed blanket concepts that have high breeding potential.

The largest sources of uncertainty in predicting the achievable TBR are due to uncertainties in the nuclear data and the geometrical approximations associated with the calculational model. This amounts to a total uncertainty of up to 9%. As a result, the FW/blanket in a power plant should be designed for an overall TBR that exceeds unity by the calculation uncertainty in addition to the tritium breeding margin that depends on the operating parameters and tritium processing system. For example, if the required breeding margin is 0.03, the design should allow for an overall TBR of 1.12. This means that the actual TBR realized in the plant, which can not be verified until the plant starts operation, could be in the range between 1.03 and 1.21 for a +/-9% uncertainty. Underbreeding (TBR < 1.12 for the above example) will place the plant operation at risk as the tritium bred may not suffice for machine operation. It is, therefore, imperative to conservatively design the power plants with overbreeding (TBR >1.12 for the above example) providing that design solutions are established for reducing the breeding level if needed. The adjustment in the design could take place during the second period of operation after changing out the FW/blanket and realizing higher breeding than predicted.

5. R&D needs to increase the potential for tritium self-sufficiency

What are the R&D needs to increase the potential for tritium self-sufficiency?

5.1 Plasma R&D (Nevins)

The plasma R&D needs driven mainly by tritium self-sufficiency would be efforts to increase the tritium burn-up fraction by increasing the helium pumping efficiency (minimizing $\tau_{He}*/\tau_E$), and enriching the helium in the particle exhaust stream (minimizing $\tau_{He}*/\tau_{DT}*$).

Efforts to minimize the size of heating and current drive systems are already strongly driven by efforts to reduce the recirculating power. Some advantage for tritium self-sufficiency might be gained by efforts to integrate a tritium breeding capability into RF antenna systems.

5.2 Technology R&D (Youssef/Sze)

To assess R&D needs, it is important to estimate the tritium inventory in the system.

a. The total tritium inventory in the power plant	~ 10 kg
b. The allowable tritium loss rate	very small (~ 10 Ci/d)
c. The tritium production rate	~ 500 g/FPD

If the lifetime of the blanket is 2 years, the total tritium produced in the blanket is 370 kg. If the accuracy of the tritium production is 10%, the error during the two years blanket life is 37 kg. Therefore, the uncertainty due to the tritium breeding calculation far exceeds the total tritium inventory and tritium loss rate in the power plant. Hence, the key R&D needs are related to the neutronics calculation tools, including cross section data, modeling, and calculation method, to reduce the uncertainty in the calculated TBR.

Large achievable TBR with small uncertainties (due to uncertainties in data/modeling, and design choices), and small required TBR (with also small uncertainties in the governing plasma and engineering reactor parameters) will increase the prospect of success in achieving tritium self-sufficiency. Blanket concepts that yield a marginal net achievable TBR in detailed 3-D analysis with full engineering design details should receive more R&D emphasis aimed at improving their breeding potential. In addition, R&D is needed to reduce the uncertainties in calculating the achievable TBR. Furthermore, a goal for a small required TBR of <1.05 may imply requirements on the performance parameters of many plasma and engineering components that need to be verified by R&D.

Several guidelines for future R&D in various technical areas are as follows:

5.2.1 R&D areas to increase the achievable TBR and minimize associated uncertainties

(1) The breeding coverage around the plasma should be maximized. Blanket concepts that require the elimination of breeding in the inboard region should be viewed as a high-risk option. For self-cooled liquid metal concepts, for example, the critical issue associated with the inboard region due to the high magnetic field should be resolved by developing radiation-resistant electric insulators.

(2) The R&D for subsystems that involve penetrations and the use of nonbreeding materials around the plasma, e.g. impurity control/exhaust and plasma auxiliary heating, should focus on those design options that result in minimum impact on the breeding ratio (e.g., the use of strong neutron-absorbing materials should be avoided). Design choices that necessitate the use of large nonbreeding materials in the blanket region to stabilize the plasma operation and for equilibrium (e.g. using passive copper coils) should be explored early enough to assess their implication.

(3) Better evaluation of the magnitude of the uncertainties in estimating the achievable TBR should be pursued. A more reliable estimates to the uncertainties involved can be quantified through the use of integral experiments to validate nuclear data and transport codes. Data improvement through integral experiments and performing extensive cross section sensitivity/uncertainty analyses is viewed as an essential mean to minimize the uncertainties involved. Full covariance data for smooth and differential cross sections should be implemented in the current data libraries and for materials whose cross sections impact the estimated TBR (e.g. neutron multipliers, compounds of breeding materials, etc.). Code development is also needed to produce adequate computational tools for sensitivity/uncertainty analysis based on Monte Carlo techniques.

5.2.2 R&D areas to minimize the required TBR and the associated uncertainties

The guidelines for the needed R&D effort is based on results from the analysis referred to in section 3.1 on the factors that affect the required TBR.

(1) It is unlikely at present to ensure that the requirement of a doubling time, t_d, of <5 yr can be met. With a plasma burnup fraction of β=5%, a doubling time of t_d=20 yrs is the minimum requirement to be met if a required TBR of 1.05 is sought. There is a need to examine the strategy for introducing fusion power and its growth in the initial stages of fusion energy applications.

(2) The required TBR is very sensitive to the tritium fractional burnup in the plasma. A β of 20-40% can significantly reduce the burden on R&D in other technical areas and greatly increase the chance of success to meet the tritium self-sufficiency condition.

(3) The performance parameters of the plasma exhaust processing subsystem have large impact on the required TBR. The R&D effort needed in this area is to ensure that the parameters listed below is likely to be achieved:

  - A mean residence time of tritium in the subsystem below 1 day.
  - Loss of tritium in the subsystem due to inefficiency of tritium extraction must be kept below 0.1% .
  - Mean time for tritium reserve, t_r, must be kept below 1 day. This is strongly related to the probability of failure and downtime to repair the plasma exhaust processing unit since the failure of this unit will require keeping a large tritium inventory (inversely proportional to β) in the storage reserve for plasma fueling if power plant shutdown is to be avoided.

(4) The tritium inventory in the blanket, I_B, should be kept as low as possible. A goal value of $I_B < 5$kg is preferred.

(5) Tritium permeation to coolants and tritium retained in nonbreeding materials such as the structure, should be kept minimal.

5.3 Required facilities (Youssef)

Direct demonstration of tritium self-sufficiency requires a fully integrated reactor system, including the plasma and all reactor prototypical nuclear components. For at least one blanket type, testing an entire sector, fully integrated with tritium processing system, is required. Such testing could be planned in a fusion test facility such as ITER, or in smaller test stand, such as a compact volumetric neutron source (VNS) facility. A sector test, rather than only a module test, is necessary because:

(1) there are strong poloidal variations in tritium production rates due to variations in wall load, geometry, penetrations, etc. Thus, the extrapolation of results from each module to reactor conditions will be different, and

(2) the uncertainties arising from specifying the boundary conditions for modules are large and make extrapolation difficult.

Direct measurement of tritium breeding from a sector is possible by measuring all the tritium released and processed in the tritium processing system for that particular sector once equilibrium (or near equilibrium) is reached. This tritium processing system will also give direct measurements of parameters important to the required TBR such as tritium mean residence time and any inefficiency in tritium processing. It is suggested that a module of the same type of blanket used in the sector also be tested in parallel to the sector in various poloidal directions. This would be useful in developing correlation for extrapolation from module to sector to reactor. Other blanket types can then be tested in modules and the module-reactor correlation can be used for extrapolation of testing results.

In addition to tritium self-sufficiency demonstration outlined above in a closed cycle placed in a test facility such as ITER or VNS, there is a need to perform other neutronics tests for nuclear data and transport code verification. Results from these tests can significantly improve nuclear data bases and tools used to determine the achievable TBR. The 14 MeV neutron source facilities that exist around the world can be used for that purpose. There is no an operative 14 MeV point source facility at present in the U.S. but there are three major operational facilities around the world. They are the FNS facility (JAERI, Japan), FNG (Frascati, Italy) and SNEG-13 (Near Moscow, RF). The neutron yield among these facilities varies (~5 x 10^{12}, n/s, ~5 x 10^{11} n/s, and ~3 x 10^{13} n/s, respectively) and can be tailored for specific neutrons tests. The first two facilities can be used for verifying the prediction capability of present codes and databases for tritium production in solid breeder (or LM) to confirm tritium self-sufficiency issue and to generate safety factors for the design purposes. Additionally, irradiation of various samples for low-activation tests and updating/verification of our current dosimetry and activation/decay heat databases can be performed at these facilities. Because of the high yield of the SNEG-13 facility, it is most suited for deep penetration tests such as verifying the adequacy of radiation protection schemes for machine components (e.g. super conducting magnet) and personnel from transported and/or streamed neutrons and gamma rays. It can also be used to quantify the peaking factors used in shielding design to account for streaming through openings and gaps between blanket segments.

6. Tritium resources (Sze/Willms)

By the time an ignition machine is built, such as ITER, will there be enough tritium available in the world to supply its initial and operating multi-kg tritium requirements? What are the implications on the schedule for the development of tritium-producing chamber technology?

Based on comments from Drs Filatov and J. Anderson, there will be no extra tritium supply for ITER, from either RF or US defense program. Therefore, the only tritium supply available to the ITER type device will be from Canada. The tritium production rate from CANDU reactors is about 2.5 kg/y, assuming all the CANDU reactors are in operation. Therefore, the availability of tritium supply from Canada for ITER operation strongly depends on the lifetime of the CANDU reactors, as well as the starting time of the ITER device. Early shut down of the CANDU reactors, and/or delay starting of the ITER, will waste some of the tritium produced by CANDU due to decay.

If the lifetime of the CANDUs is 40 years and if ITER starts about 10 years from now, and assuming the parameters of ITER remains to be the same as the ITER-EDA device, there will be sufficient tritium supply to ITER from Canada. However, if the CANDU lifetime is only 30 years, or the ITER starting operating day is much further away than 10 years, the tritium supply from Canada to ITER will be very marginal.

A key question is where will we obtained tritium for post ITER operation. There will be either an extended phase of ITER, or there will be another fusion device following ITER. In either case, all the tritium supply from CANDU will be exhausted, and no sufficient tritium will be available for the starting tritium supply for the next device. Therefore, we can not only assess the fuel supply for ITER along. We also need to assess the fuel supply for the next device. For this reason, even there is sufficient tritium supply for the ITER like device from Canada, we may still have to breed tritium.