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Elserafy, Hatem
Interdisciplinary Graduate school of Engineering Sciences, Kyushu University

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(Review Article)

Assessment of DEMO Reactors for Fusion Power Utilization

Hatem Elserafy
Interdisciplinary Graduate school of Engineering Sciences, Kyushu University, Japan
*Author to whom correspondence should be addressed,
E-mail: elserafy@triam.kyushu-u.ac.jp

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Given the undeniable climate change caused by global warming, decreasing the carbon footprint by using alternative energy sources became necessary. Thermonuclear fusion energy is one of the strongest candidates when it comes to alternative energy sources since it is safe, has negligible carbon footprint and its yield is incomparable to any other alternative. Credential as fusion performance may be; feasibility and economic attractiveness are something to be considered. The next stage fusion reactors are called DEMOnstration (DEMO) and are being assessed by various sources in terms of performance. In this work, DEMO fusion reactors are to be reviewed and their specifications are to be analyzed in terms of feasibility, while demonstrating how the tritium fueling stage not only presents a challenge for calculating fusion power costs, but also that fusion energy requires further R&D before it can be integrated into the power grid.

Keywords: thermonuclear fusion, DEMO, TBR.

1. Introduction

Global temperature rise is directly related to cumulative emissions of greenhouse gases [1], [2]. A limit of 2°C of average global temperature rise was agreed upon by the united nations. To avoid surpassing the 2°C limit, consuming less than two thirds of oil reserves, half of the gas reserves and only 20 percent of coal reserves should be maintained until 2050 [3]. According to the U.S Energy Information Administration (EIA), consumption of fossil fuels indicates the huge energy demand and therefore difficulty to meet the conditions required for 2°C average temperature rise. There are several alternatives to combat the energy crisis including renewables such as solar, wind, tidal, geothermal, nuclear fission and thermonuclear fusion. Thermonuclear fusion energy yield has been widely known to be unparalleled since the 1950s, not to mention its virtually nonexistent carbon footprint [4]. Moreover, fusion technology gained a lot of credibility after revealing how operationally safe it is in terms of explosions and dealing with radioactive materials [5]. Despite the fact that fusion energy has been researched for more than 60 years without being commercialized, it is still thought of as a promising source of energy that is to be deployed. The delay in commercialization is because in order to utilize fusion energy and integrate it into the power grid, fine plasma confinement and control are required in order to reach a steady state, which has proven to be difficult as plasma instabilities are significant. Moreover, fusion reactors are expensive as the reactor size is proportional to plasma confinement. Nonetheless, those issues are not considered critical and fusion energy is still thought of as the most promising unexploited energy source [6]. To overcome these issues, 35 countries contributed to build the largest fusion reactor, ITER, located in southern France. ITER is just a transient experimental step towards the realization of fusion energy. The next step is DEMOnstration (DEMO) reactors, which is a step closer to the realization of fusion power as DEMO is a bigger and more powerful reactor than ITER. As DEMO has a larger scale and is more expensive than ITER, however, it is not thought of as the final stage. The final stage (the full scale commercial fusion power plant) is known as PROTOtype (PROTO), which is expected to have better performance at a fraction of the cost. A strategy proposed in 2001 called ‘fast track’ proposed merging the DEMO and the PROTO to one stage [7], due to significant delays in the fusion schedule, which is partially why the PROTO is not going to be discussed in this work. The other reason why PROTO is not going to be mentioned is because its preceding step, DEMO, is still underdeveloped so the focus of the fusion society is on DEMO. Despite the significant progress in fusion science [8], an important aspect to consider is its feasibility as well as its economic standpoint and to compare it to the renewable counterparts. In this work, a review of the available DEMO reactor plans and designs is conducted and how feasible it is to integrate it into the grid is discussed. The key features considered are the DEMO reactor design and how much power it can generate, and the assessment of the fueling system specifications and requirements in order to accurately assess the feasibility of fusion power for utilization. The next section gives an overview of thermonuclear fusion while stating the requirements for realization after narrowing down reactor types to tokamaks. Section 3 states the details of the specifications of ITER from the economic standpoint as ITER is not only the biggest tokamak with 35 countries contributing to its build, but it will be the first tokamak to witness burning plasma. Section 4 then provides a review of the design and specifications of the biggest DEMO reactors in the world. Section 5 then provides an overview of the DEMO economics and compares it to other renewables. Section 6 then discusses about the tritium breeding problem, which is often overlooked as fusion research is currently directed towards improving the plasma parameters, while mentioning its effect on DEMO economics discussed in section 5. Section 7 then concludes this work.

2. Theory

Thermonuclear fusion reactions, based on Einstein's famous E=mc^2 equation, goes as follows:

$$\begin{gathered} {}^1D_2+{}^1T_3 \rightarrow {}^2He_4 \text{ (3.5 MeV)} + {}^0n_1 \text{ (14.1 MeV)} \\ D_2+D_2 \rightarrow He_3 + n_1 + 3.27 \text{ MeV} \\ D_2+He_3 \rightarrow He_4 + H_1 + 18.3\text{MeV} \end{gathered} \tag{1}$$

where D (deuterium) and T (tritium) are Hydrogen isotopes, n is neutron. The primary difficulty with achieving this reaction is that to overcome the coulomb forces repelling the nuclei, a temperature in the order of 10^6 ℃ is required which can be considered as an external catalyzing factor for the reaction. It can be seen that several versions exist based on the Hydrogen isotope input, making D-He the most attractive as it has the largest energy yield. However, despite D-He dominating in terms of energy yield, D-T has higher cross section at lower energies, making its fusion condition achievable at comparatively lower temperatures. Correspondingly, D-T fusion is to be the focus of this work, where the bioavailability and cost of both are to be considered.

Thermonuclear fusion is particularly attractive in the field of renewable energies because once a certain condition is achieved (ignition), the plasma will reach a state where it can internally self-sustain its temperature against the energy losses. Ignition would in turn allow for the removal of the applied heating, significantly reducing the input power. This sustained condition is due to the emission of the ${}^0n_1$ particle (alpha particle) in the D-T reaction such that

$$P_H+P_\alpha=P_L \tag{2}$$

where P_H is the heating power, P_α is the power generated by the alpha particle, and P_L is the power loss. Achieving ignition condition depends on several factors including the size and structure of the reactor, plasma temperature, plasma density and the magnetic field strength. A reliable indicator of how well a particular reactor is performing is the Lawson criterion (also known as the triple product), which is as follows:

$$nT\tau \geq 3\times10^{21}\text{keV s/m}^3 \tag{3}$$

where T is ion temperature in eV, τ is plasma confinement time, and n is ion density [9]. This critical criterion not only indicates the threshold for self-sustained fusion, but also indicates the possibility to trade off different parameters. This is particularly useful as each reactor has its unique structure and specifications mastering one or two of the triple-product parameters. Noteworthy is to say that not a single reactor was yet able to produce plasma with satisfying values to all three key parameters simultaneously.

Achieving the plasma conditions requires temperatures orders of magnitude higher than the highest material's melting point, rendering it impossible to contain the hot plasma using a material container. The alternative is to confine the plasma a fair distance away from the reactor wall and towards the center, then cool the wall. The pursuit of engineers to achieve nuclear fusion led them to create various designs of reactors, varying in both geometry and underlying mechanism.

Thermonuclear fusion reactors can essentially be categorized by their plasma-confining techniques as magnetic-confining reactors or inertial-confining reactors. Inertial-confining reactors (laser-driven) were proven to be inferior to magnetic-confining reactors and therefore the focus of this work is narrowed down to magnetic-confining reactors [10]. Within the magnetic-confining reactor classification, further narrowing down shall be done towards toroidal machines rather than open field line machines. In addition, toroidal machines vary in shape and structure giving several standard reactor types like tokamaks, stellarators, reversed field pinch, spheromaks and others [11]. Further narrowing down towards tokamaks is to be done since based on Lawson criterion, tokamaks have the highest potential for achieving fusion condition. This work will be limited to tokamaks as tokamaks have the capability of suppressing plasma instabilities as well as having the possibility of reducing the overall cost of the reactor by further optimizing it into spherical tokamaks (STs) due to its intrinsic compact structure [12]. Moreover, ITER, the world's largest tokamak reactor that is to be the first to achieve output power 10× that of the input power, as well as DEMO, the next stage reactor are in fact tokamaks [13].

3. Tokamak economics

The current fission power plant commercial standards output about 3 GW thermal power output that narrows down to about 1 GW electrical power output [14]. Not to mention, this yield is generated in a steady state form of about 1 year. In comparison, the biggest tokamak in the world, ITER, has the promise of having a Q-factor of more than 10. Nonetheless, ITER, the 10-billion-euro project, promises a modest thermal output power of 500 MW that corresponds to 840 m^3 plasma, as opposed to the initial plan of 1.5 GW corresponding to 2000 m^3 plasma, because the original goal did not meet the funds and therefore a reduction in scale was done. Not to mention, the conversion from thermal power to electric power is yet to be explored. Furthermore, this is not a steady-state long-duration output. The primary sources of heating ITER plasma is neutral beam injection (NBI) and electron cyclotron resonance heating (ECRH) that would only maintain the Q-factor of 10 for 400 seconds [15]. The reason why billions are spent on ITER is to test whether these conditions are plausible or not, and the ability to overcome plasma instabilities, which are only milestones that pave the fusion road for an even larger scale reactor, the DEMO, which is another transient step to the full fusion power plant (PROTO). However, in order to properly assess thermonuclear fusion energy from an economic standpoint, in this section, ITER is to be considered as it is the largest available tokamak at hand. According to [16] tokamak economy is divided as shown in Fig. 1.

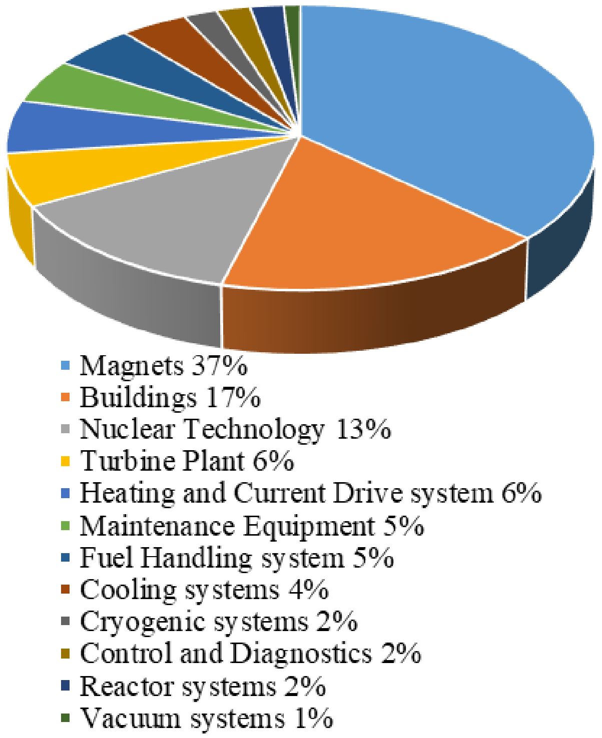

Fig. 1 Different costs of different components of a typical fusion reactor

Major radius	6.2 m
Minor radius	2.0 m
Magnetic field	5.3 T
Plasma current	15 MA
Net electric power	500 MW

Table 1 ITER's specifications

ITER was first proposed in the late 1980's, its design was shown in the early 2000's and its construction began in 2013. The facility is expected to witness its first plasma in 2025, and D-T experiment will start 10 years after that. ITER's reactor specifications are shown in Table 1 and the reactor design is shown in Fig. 2 based on [17]. ITER's 2016 financial report filed in 2017 [18] as presented in Table 2 shows that the tangible fixed assets, corresponding to property, plant and equipment are about €2.8 billion. This figure does not contain the cost of land as it has been provided free of charge by the French State through the 'Commissariat à l'Energie Atomique et aux Energies Alternatives'(CEA) until the end of October 2042 (the expected end date of the project). Not to mention, ITER, as well as DEMO, are relying on D-T fusion for power generation. In which case ITER gets its supply of about 8 kg of tritium from CANDU [19]. After assessing ITER and putting it into perspective, next is to evaluate the various DEMO designs.

Assets		
Fixed Assets		
Tangible	2,768,961	
Intangible	8182	
Total		2777143
Current Assets		
Cash and cash equivalents	209164	
Exchange transactions	73987	
Prepayments	1821	
Total		284972
Total Assets		**3062115**
Liabilities		
Fixed Liabilities		
Deferred revenue	2913394	
Total		2913394
Current Liabilities		
Payables	145573	
Employee benefits	3148	
Total		148721
Total liabilities		**3062115**

Table 2 Balance sheet of ITER's financial year of 2016, where the amounts are in thousands of Euro

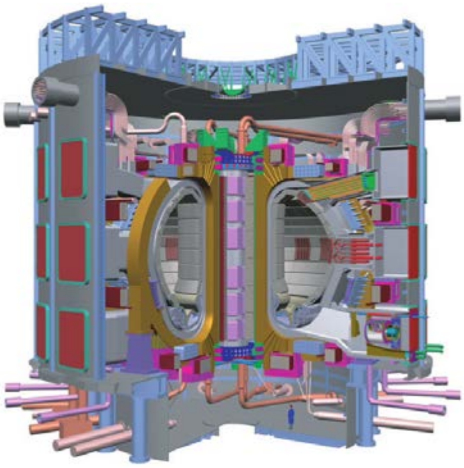

Fig. 2 ITER's design courtesy of R. Aymar [13]

4. DEMO fusion reactors

A DEMO fusion reactor is a generic name for proposed thermonuclear fusion power plants that are a buildup on ITER. A minimum of 2GW of output power in a continual basis is the baseline expectation for a DEMO reactor, as compared to ITER's 0.5GW [20]. Upon standardizing the ITER structure and applying linearization to the consequential results based on the design parameters, a DEMO must be a 15% larger reactor than ITER and must contain 30% denser plasma.

4.1 K-DEMO

K-DEMO, initiated in 2012, is the Korean DEMO reactor to be constructed in 2037 as agreed by the Korean fusion energy development promotion law (FEDPL) in 2007. K-DEMO is expected to generate a net electric power of 500 MW and to have a self-sustained tritium cycle [21]. Fig. 3 shows the design based on [22] and Table 3 shows its specifications. In K-DEMO, 10 layers of Li_4SiO_4 mixed with $Be_{12}Ti$ pebbles for cooling with different thicknesses result in a global tritium breeding ratio (TBR) of ~1.0 as calculated by [23]. A further step is the full scale fusion power plant to be implemented in 2040.

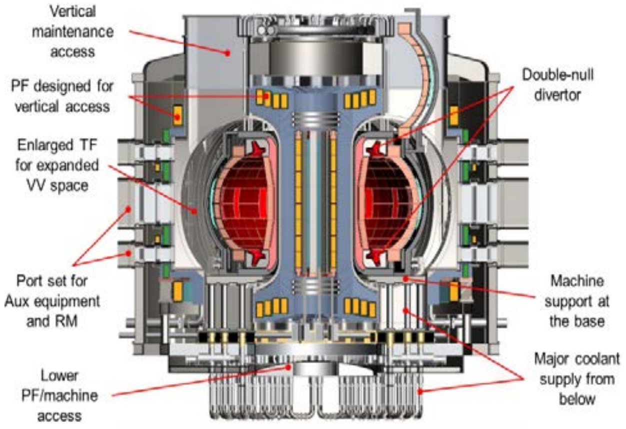

Fig. 3 K-DEMO design courtesy of Brown T. and H. C. Kim [24]

Major radius	6.8 m
Minor radius	2.1 m
Magnetic field	7.4 T
Plasma current	12 MA
Net electric power	400~700 MW

Table 3 K-DEMO reactor specifications

4.2 SST-2

A follow-up on India's steady-state superconducting Tokamak SST-1 [25], a 1.1 m major radius and 220 kA plasma current device, is SST-2 that is to be employed in 2035 following the roadmap of [26], which is later to be followed by a full-scale power plant in 2050. SST-2 is a medium sized reactor as shown in Table 4 with a Q-factor of 3~5. In the case of SST-2, TBR is slightly less than unity at 0.94 [26]

Major radius	4.42 m
Minor radius	1.47 m
Magnetic field	5.42 T
Plasma current	11.2 MA
Net electric power	300 MW

Table 4 India's SST-2 reactor specifications

4.3 FDS-II

The Chinese fusion power plants organization is following a strategy [27] on constructing the reactor series FDS [28]. The highest energy yield of its series is FDS-II, which is considered the DEMO reactor in the case of China. FDS-II has Q-factor of 30, TBR of 1.1 and is integrating the liquid LiPb breeder blanket technology to minimize maintenance and replacement costs to the inner wall of the reactor. Fig. 4 and Table 5 show the design and specifications of FDS-II.

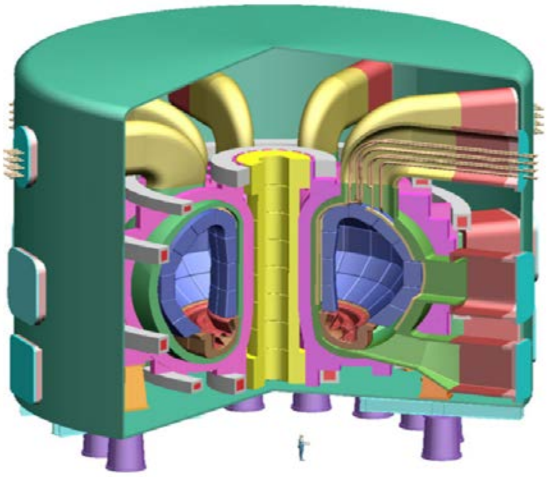

Fig. 4 FDS-II design courtesy of Y. Wu [29]

Major radius	6 m
Minor radius	2 m
Magnetic field	5.93 T
Plasma current	11.2 MA
Net electric power	1000 MW

Table 5 China's FDS-II reactor specifications

4.4 JAERI

The Japanese fusion DEMO version of a power plant is called JAERI [30], which has 3 different configurations, CS-less, slim CS, and full CS. Considered below is the full CS as it has the largest Q-factor of 54 as opposed to 48 for CS-less and 52 for slim CS. Moreover, JAERI is designed to have TBR of 1.1 [31]. JAERI's specifications are shown in Table 6.

Major radius	5.1 m
Minor radius	2.1 m
Magnetic field	5.6 T
Plasma current	17.4 MA
Net electric power	1000 MW

Table 6 JAERI's reactor specifications

4.5 ARIES

The US fusion DEMO version of a power plant is called ARIES, which has 4 different configurations, ARIES-I, ARIES-RS, ARIES-AT and ARIES-ST [32]. Considered below is the ARIES-ST as it has the largest plasma current of 29 MA as opposed to 12.6 MA for ARIES-I, 11.3 MA for ARIES-RS and 13 MA for ARIES-AT. Moreover, the ARIES series is designed to have TBR of 1.1. Fig. 5 and Table 7 show the design and specifications of ARIES-ST.

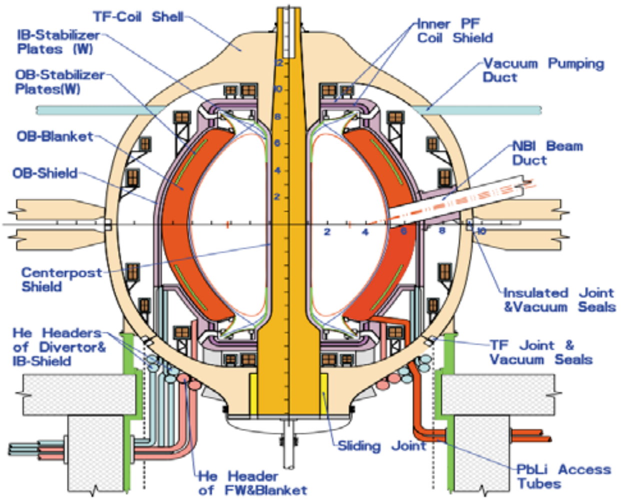

Fig. 5 ARIES-ST design courtesy of F. Najmabadi [32]

Major radius	3.2 m
Minor radius	2.0 m
Magnetic field	7.4 T
Plasma current	29 MA
Net electric power	1000 MW

Table 7 ARIES-ST's reactor specifications

Other DEMO models exist but all the other models known to the author have similar specifications to the ones mentioned above, which makes it possible to generalize and proceed with the next section on assessing the DEMO economics based on standards that match the models presented in this section.

5. DEMO economics

A typical DEMO reactor would have its total capital investment costs as shown in Table 8 rounding up to about 8.3 billion USD.

Reactor and building	1900
Pumping system	130
Heating system	400
Cooling system	200
Magnets	2300
Fuel handling system	300
Maintenance and other	300
Turbine plant	300
Direct costs	**5830**
Indirect costs	**1500**
Contingency	**1000**
Total	**8330**

Table 8 Typical DEMO reactor expenses in millions of USD as of 2015

The cost of electricity COE was calculated for fusion power generated from DEMO, as well as other sources of energy in [33] such that the expenses for a DEMO are as shown in Table 9.

Operation and maintenance	23.4
Fuel costs	0.44
Waste disposal	0.56
Decommissioning	0.78
Depreciation	34.11
COE w/o cost of money	**59.29**

Table 9 COE for a DEMO reactor in $/MWh

According to Table 9, fuel costs are only 0.74% of the total cost of electricity for a DEMO reactor. With the considerations above, the levelized total cost of electricity (TCOE) is calculated at the 2015 constant USD prices such that

$$\mathrm{TCOE}=\frac{\sum_{t=0}^{T_L-1}\left(IN_t+C_t+I_t+E_t.C_t^{Ext}\right)(1+r)^{-t}}{\sum_{t=0}^{T_L-1}E_t(1+r)^{-t}} \qquad (4)$$

where t is the current year, C is the annual operating cost, I is the interest, T is the rate of income tax, IN is the annual investment, E is the net annual electricity production, and C^{Ext} is the external electricity production related costs. The calculation results for various methods of harvesting energy are shown in Fig. 6.

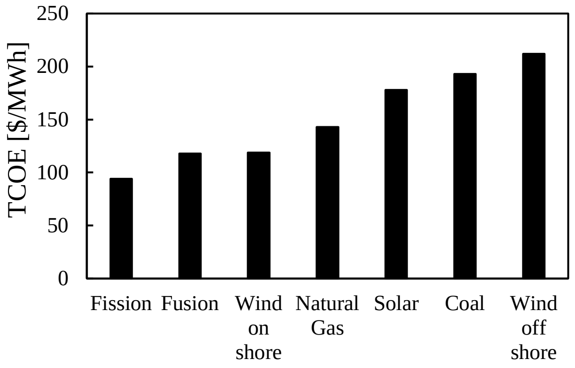

Fig. 6 Levelized TCOE including external costs for various types of energy sources including fossil fuels [33]

Fig. 6 shows that fusion energy is the runner-up in terms of cheap levelized TCOE including external costs. However, these results are based on the fact that fusion fuel makes for about 1% of the total costs, which is not the case for D-T reactions. In [33], the account for tritium supply and expenses is approximated, which if taken into account, it will make a significant impact on the results shown in Fig. 6 (as will be explained in detail in the next section).

6. Tritium fueling for fusion energy

Tritium self-sufficiency plays a significant role in fusion energy utilization as tritium itself is extremely expensive (about 30,000 USD per gram [34]). A significant amount of tritium is to be supplied initially for a DEMO reactor to reach ignition condition, then a lithium blanket is to be used as a tritium multiplier. The output neutrons of energy 14 MeV are to bombard the blanket, make an inelastic collision with a lithium nucleus, dividing it into tritium and Helium.

Tritium self-sufficiency is about breeding more Tritium than one consumes, thus a very strict condition is to have Tritium Breeding Ratio (TBR) of more than unity. The reason why more than unity is required is because tritium will be required for igniting other reactors as well as to account for several losses like storage decay [35]. It can be seen from Fig. 7 that the current state-of-the-art DEMO reactors have less than 1.15 TBR.

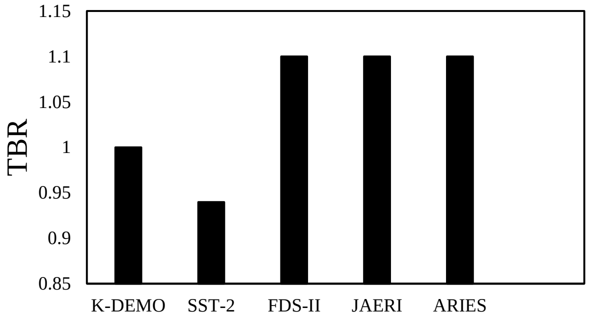

Fig. 7 TBR for various DEMO reactors

To proceed any further, several terms need to be defined in order to understand the criticality of TBR in DEMO reactors:

- “required TBR (rTBR)” is the minimum number of tritium nuclei to maintain the system’s activity
- “doubling time” is how many years it takes to double the tritium inventory
- “fractional burnup” is how much tritium is burned within the plasma
- “reserve time” is how many days’ worth of tritium reserve in case of a malfunction that correlates with tritium loss
- “achievable TBR (aTBR)” is how much tritium can be bred according to 3d simulation models

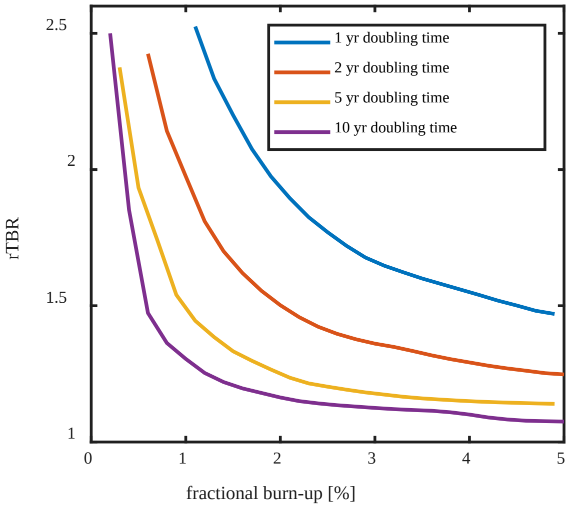

Fig. 8 rTBR vs fractional burn-up for different doubling times and reverse time of 5 days [36]

Fig. 8 shows rTBR vs fractional burn-up for a 5-day reserve time and different doubling times. Given a fractional burn-up of 0.5% and reserve time of 5 days, rTBR is 1.475 at a 10 year doubling time. Not to mention, state-of-the-art blankets have shown a maximum TBR of 1.15. To further complicate matters, the front wall (FW) thickness has a degrading impact on TBR as well. FW needs to be thick enough (a few cm) to resist the 100-million-degree plasma collisions, which will further reduce the TBR by 16% [36]. Furthermore, blankets utilizing Li and LiPb require electric insulators that are shown to further reduce TBR by about 8%. Various other setups as vertical stabilizing shells for plasma control allow for a further reduction in TBR of about 6% [36]. Accounting for all of these losses (without considering storage decay losses) shows that

$$aTBR=rTBR*(1-L_{FW})(1-L_{EI})(1-L_S) \qquad (5)$$

where L_{FW} is the FW losses, L_{EI} is the electric insulator losses, and L_S is the shell losses. This shows that 28% reduction in TBR exist, which would either require a modification in other parameters like doubling time or fractional burn-up or a fairly high aTBR of 1.5 before applying the losses. As shown in Fig. 9, a doubling time of less than 3 years is required. This dictates the requirement of an alternative source of tritium, which can be supplied by fission reactors or heavy water reactors. ITER has its 12.3 kg tritium supplied by Ontario Hydro as planned in 1996 [19], and this will leave inventory to supply only 8 kg to all of the available DEMOs initially, which is sufficient to fuel DEMO for less than 10 years. Not to mention, starting a DEMO reactor with no tritium requires around 2 billion USD's worth of tritium inventory [37] making the fueling process as expensive as the entire reactor and not just 0.74%. To sum up this section, DEMO reactors are required to improve their fueling efficiency, their fractional burn-up and reduce their doubling time as the external sources of supplying tritium inventory are insufficient.

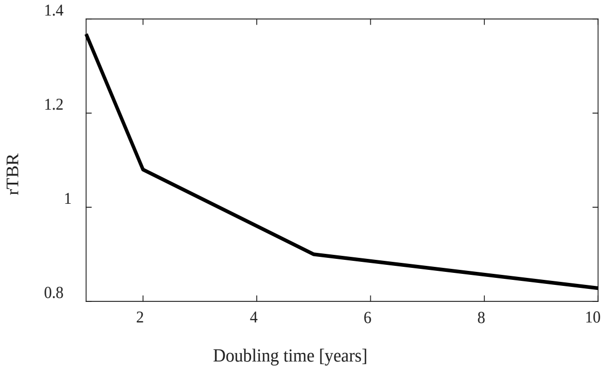

Fig. 9 rTBR vs Doubling time at a fractional burn-up of 2% while accounting for the losses found in equation 5

7. Summary

A review of some of the DEMO reactors was conducted. It was shown that the highest aTBR in DEMO is less than 1.15 while rTBR is 1.475 at 0.5% fractional burn-up and 10 years doubling time. Furthermore, it was demonstrated that less than 3 years doubling time is required to prevent one DEMO reactor from consuming more tritium than it breeds after accounting for the 28% losses within the DEMO design restrictions like FW losses and EI losses. Not to mention, the external supply of tritium from sources like heavy water reactors is not only costly but also discrete. To conclude, fusion is currently at an immature stage that prevents one from accurately assessing the cost of fusion per kWh making it difficult to compare to renewable counterparts. In order to overcome the aforementioned problem, various suggestions exist such as further optimizing of the blanket parameters such as lithium concentration and blanket thickness. Another suggestion is expanding the horizon to fusion devices other than tokamaks like Z-pinch and work on achieving a high Lawson criterion there as a reported TBR of higher than 1.6 is achievable with 80 cm thick LiPb and more than 60% lithium enrichment [38].

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References

[1] M. Dittmar, "Science of the Total Environment Development towards sustainability : How to judge past and proposed policies ?," *Sci. Total Environ.*, vol. 472, pp. 282–288, 2014.

[2] M. Meinshausen *et al.*, "Greenhouse-gas emission targets for limiting global warming to 2°C," *Nature*, vol. 458, no. 7242, pp. 1158–1162, 2009.

[3] C. McGlade and P. Ekins, "The geographical distribution of fossil fuels unused when limiting global warming to 2°C," *Nature*, vol. 517, no. 7533, pp. 187–190, 2015.

[4] N. H. A. Bowerman, D. J. Frame, C. Huntingford, J. A. Lowe, and M. R. Allen, "Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 369, no. 1934, pp. 45–66, 2011.

[5] H. D. Matthews, N. P. Gillett, P. A. Stott, and K. Zickfeld, "The proportionality of global warming to cumulative carbon emissions," *Nature*, vol. 459, no. 7248, pp. 829–832, 2009.

[6] W. P. Nel and G. Van Zyl, "Defining limits : Energy constrained economic growth," *Appl. Energy*, vol. 87, no. 1, pp. 168–177, 2010.

[7] E. Council and C. Note, "European Council 28-29 October 2010 Conclusions," 2010.

[8] D. Meade, "50 Years of Fusion Research," *Nucl. Fusion*, vol. 50, no. 1, 2010.

[9] J. D. Lawson, "Some criteria for a power

producing thermonuclear reactor," *Proc. Phys. Soc. Sect. B*, vol. 70, no. 1, pp. 6–10, 1957.

[10] R. Betti *et al.*, "Thermonuclear ignition in inertial confinement fusion and comparison with magnetic confinement," *Phys. Plasmas*, vol. 17, no. 5, 2010.

[11] R. Yoneda, "Research and technical trend in nuclear fusion in Japan," *Evergreen*, vol. 4, no. 4, 2017.

[12] A. Sykes, "Progress on spherical tokamaks," *Plasma Phys. Control. Fusion*, vol. 36, no. 12 B, 1994.

[13] R. Aymar, P. Barabaschi, and Y. Shimomura, "THe ITER design," *Plasma Phys. Control. Fusion*, vol. 44, pp. 519–565, 2002.

[14] S. W. White and G. L. Kulcinski, "Birth to death analysis of the energy payback ratio and CO2gas emission rates from coal, fission, wind, and DT-fusion electrical power plants," *Fusion Eng. Des.*, vol. 48, no. 3, pp. 473–481, 2000.

[15] U. Fantz *et al.*, "Physical performance analysis and progress of the development of the negative ion RF source for the ITER NBI system," *Nucl. Fusion*, vol. 49, no. 12, p. 125007, 2009.

[16] J. Wesson, *Tokamaks*, 4th ed. Oxford University Press, 2011.

[17] R. Aymar, P. Barabaschi, and Y. Shimomura, "The ITER design," *Plasma Phys. Control. Fusion*, vol. 519, no. 44, pp. 519–565, 2002.

[18] Pfizer, "ITER 2016 Financial Report," 2017.

[19] P. Gierszewski, "TRITIUM SUPPLY FOR ITER FROM ONTARIO HYDRO CFFTP G-9616," 1996.

[20] K. Tobita *et al.*, "SlimCS - Compact low aspect ratio DEMO reactor with reduced-size central solenoid," *Nucl. Fusion*, vol. 47, no. 8, pp. 892–899, 2007.

[21] C. E. Kessel, K. Kim, J. H. Yeom, T. Brown, P. Titus, and G. H. Neilson, "Systems analysis exploration of operating points for the Korean DEMO program," *2013 IEEE 25th Symp. Fusion Eng. SOFE 2013*, vol. 95, 2013.

[22] T. Brown *et al.*, "Availability Considerations in the Design of K-DEMO," no. September, 2014.

[23] S. Jeffrey, J. Lawrence, J. W. Jr, H. G. Iii, C. Russell, and C. Brian, "Initial MCNP6 Release Overview - MCNP6 Version 1.0," 2013.

[24] K. Kim *et al.*, "Design concept of K-DEMO for near-term implementation," *Nucl. Fusion*, vol. 55, no. 5, 2015.

[25] S. Pradhan *et al.*, "The first experiments in SST-1," *Nucl. Fusion*, vol. 55, no. 10, 2015.

[26] R. Srinivasan, "Role of Fusion Energy in India," *J. Plamsa Fusion Res.*, vol. 9, no. November 2009, pp. 630–634, 2010.

[27] C. H. Pan, Y. C. Wu, K. M. Feng, and S. L. Liu, "DEMO development strategy based on China FPP program," *Fusion Eng. Des.*, vol. 83, no. 7–9, pp. 877–882, 2008.

[28] Y. Wu, "Conceptual design activities of FDS series fusion power plants in China," *Fusion Eng. Des.*, vol. 81, no. 23–24, pp. 2713–2718, 2006.

[29] C. Mingliang, Z. Shijie, H. Qunying, and H. Desuo, "Conceptual design study on the fusion power reactor FDS-II," no. 36111416, 2005.

[30] K. Tobita *et al.*, "Design study of fusion DEMO plant at JAERI," *Fusion Eng. Des.*, vol. 81, no. 8–14 PART B, pp. 1151–1158, 2006.

[31] H. Nakamura, S. Sakurai, S. Suzuki, T. Hayashi, M. Enoeda, and K. Tobita, "Case study on tritium inventory in the fusion DEMO plant at JAERI," *Fusion Eng. Des.*, vol. 81, no. 8–14 PART B, pp. 1339–1345, 2006.

[32] F. Najmabadi *et al.*, "Spherical torus concept as power plants - The ARIES-ST study," *Fusion Eng. Des.*, vol. 65, no. 2, pp. 143–164, 2003.

[33] S. Entler, J. Horacek, T. Dlouhy, and V. Dostal, "Approximation of the economy of fusion energy," *Energy*, vol. 152, pp. 489–497, 2018.

[34] S. Willms, "Tritium Supply Considerations," 2003.

[35] W. Kuan and M. A. Abdou, "A new approach for assessing the required tritium breeding ratio and startup inventory in future fusion reactors," *Fusion Technol.*, vol. 35, no. 3, pp. 309–353, 1999.

[36] M. E. Sawan and M. A. Abdou, "Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle," vol. 81, pp. 1131–1144, 2006.

[37] M. Kovari, M. Coleman, I. Cristescu, and R. Smith, "Tritium resources available for fusion reactors," 2018.

[38] M. Sawan, L. El-Guebaly, and P. Wilson, "Three-dimensional nuclear assessment for the chamber of Z-Pinch power plant," *Fusion Sci. Technol.*, vol. 52, no. 4, pp. 763–770, 2007.