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Functional Materials for Fusion Nuclear Power Cores (A Technical Memorandum)

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ABSTRACT

Nuclear energy science is nothing new, since World War II (WW II) and the successful Manhattan Project started in the deserts of New Mexico around 1940's with Fermi introducing his experimental fission reactor in basement of University of Chicago in state of Illinois. Following that project and the exploring application of atom energy for peaceful goals using famous Einstein's theory E=mc^2 has turned a new chapter for nuclear power energy by introducing a new source for electricity production. Fusion nuclear power generation that totally works in opposite direction that of fission nuclear power by splitting atoms nuclei of high Z-materials such as Uranium (U) or Plutonium (Pu), it uses the technology of thermonuclear reaction concepts driven by two isotopes of Hydrogen elements mainly Deuterium (D) and Tritium (T). Recent progress in research towards the development of fusion power driven by means of magnetic confinement approach, using reactor such as Tokamak device and the impressive advances research made in this particular reactor in the past few years, seems very promising to strike break-even of thermonuclear driven fusion reaction taking into consideration approach of Magnetic Confinement Fusion (MCF). Tokamak devices currently under construction will demonstrate the break-even condition or scientific feasibility of fusion power. Exciting and innovative ideas in mirror magnetic confinement are expected to culminate in high-Q devices making open-ended confinement a serious contender for fusion reactors. However, with such an innovative approach comes its own technical challenges associated with the machinery such as Tokamak that internally requires in a harsh temperature that in nature can be seen at the surface of our Sun, thus we are in need of materials that can sustain such high-temperature heat and be able to maintain their integrity and extend the life-cycle of such device while in full commercial operation within period of 24x7x360. Here in this Technical Memorandum (TM), we discuss potential materials that are possibly can deliver such sustainability one need them to operate within high-temperature and maintain their both physical and chemical properties from physics of solid-states point of view. With also today's research in Nanotechnology and Memory-metals reaching to such a goal seems to be achievable, which is subject of this Technical Memorandum (TM).

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Introduction

The goal of the fusion research effort is to derive energy from the fusion of light atomic nuclei such as Deuterium (D) and Tritium (T), the two isotopes of hydrogen fuse most readily under terrestrial conditions taking place at the surface of our Sun (Figure-1). In fact, nuclear fusion is an essential natural process. Many chemical elements originate from hydrogen through fusion in the process of nucleosynthesis and as we stated, fusion is the energy source of the sun and stars [1].

In process, a Helium nucleus will be produced and it is accompanied by release of a neutron and energy, which in case of D+T fusion process is written as D [2] (2.014102 amu) + T (3.016050 amu) → ${}_2\mathrm{He}^4$ (4.002603 amu) + ${}_0\mathrm{n}^1$ (1.008665 amu) + 17.58 MeV. (i.e., Figure 2).

However, bear in mind that the energy release per a kilogram of Deuterium is calculated as:

$$E = \frac{17.58 \times 10^{6}\ \text{eV/atom} \times 6.022 \times 10^{23}\ \text{atoms/mole} \times 1.602 \times 10^{-19}\ \text{joules/eV}}{2.014 \times 10^{-3}\ \text{kg/mole}} = 8.42 \times 10^{14}\ \text{joules/kg}$$

Comparatively, 1 kg of coal produces 28.8MJ; 1 kg of crude oil produces 43.2MJ; and 1 m^3 of natural gas produces 37MJ [3].

Note that one single gram of fusion fuel could generate 90,000 kW. Hrs. of energy in a power plant; equivalent to the combustion heat of 11 metric tons or 11,000,000 grams of coal.

Magnetic Confinement Fusion

Magnetic Confinement Fusion (MCF) is an approach to generate thermonuclear fusion power that uses magnetic fields to confine fusion fuel in the form of a plasma. Magnetic confinement is one of two major branches of fusion energy research, along with inertial confinement fusion. The magnetic approach began in the 1940s and absorbed the majority of subsequent development. See

Figure-3, where hot plasma, magnetically confined in a Tokamak and it is subject of this TM.

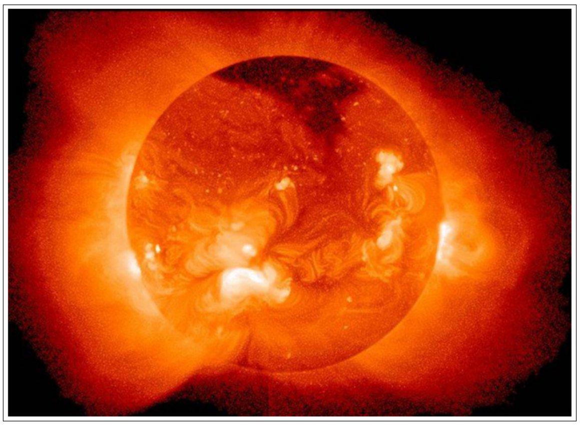

Figure 1: Sun Surface Fusion Activities

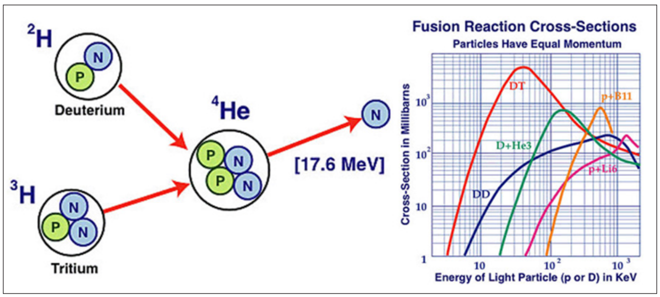

Figure 2: Depiction of all Isotopes Hydrogen Thermonuclear Reactions

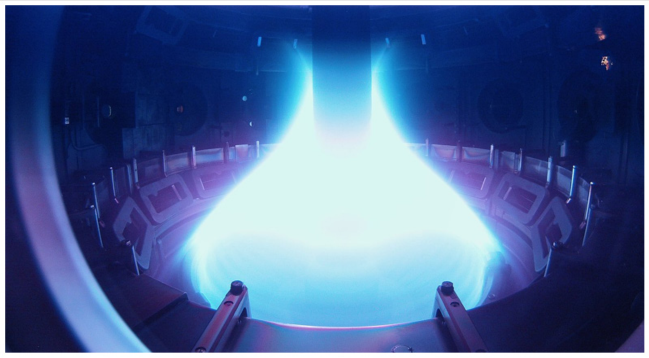

Figure 3: Hot Plasma, Magnetically Confined in a Tokamak

Fusion reactions combine light atomic nuclei such as hydrogen to form heavier ones such as helium, producing energy. To overcome the Coulomb electrostatic repulsion between the nuclei, they must reach a temperature of tens of millions of degrees, creating a plasma. In addition, the plasma must be contained at a sufficient density for a sufficient time, as specified by the Lawson criterion (triple product) [4].

MCF attempts to use the electrical conductivity of the plasma to contain it through interaction with magnetic fields (i.e., Figure-4). The magnetic pressure offsets the plasma pressure. Developing a suitable arrangement of fields that contain the fuel without excessive turbulence or leaking is the primary challenge of this technology.

Figure 4: Magnetic Confinement of Ionized Plasma (Courtesy of Jason Ginsberg)

The development of magnetic fusion energy (MFE) came in three distinct phases. In the 1950s it was believed MFE would be relatively easy to achieve, setting off a race to build a suitable machine. By the late 1950s, it was clear that plasma turbulence and instabilities were problematic, and during the 1960s, "the doldrums", effort turned to a better understanding of plasma physics.

In 1968, a Soviet team invented the tokamak magnetic confinement device, which demonstrated performance ten times better than alternatives and became the preferred approach.

Construction of a 500-MW power generating fusion plant using this design, the International Thermonuclear Experimental Reactor (ITER), began in France in 2007. Its most recent schedule is for it to begin operation in 2025.

In summary, putting fusion driven plasma energy for producing electricity in a perspective, we may say that our modern society requires environmentally friendly solutions for energy production as a source of generating electricity that is also driven by growth in population globally. Naturally, we constantly looking for source of energy either renewable or non-renewable that are free of producing any carbon released into its surrounding. In case of nuclear energy that arguably considered as renewable source of energy, can be released not only from the fission of heavy nuclei, but also from the fusion of light nuclei as it was described at introductory of this technical memorandum as well.

Nuclear fusion is an important option for a clean and safe solution for our long-term energy needs, once we could manage to satisfy Lawson Criteria and physics of break-even (i.e., amount of energy that we need to put in for fusing of the two light nucleuses of hydrogen isotopes, at least is equal to amount of energy out from it as it was shown in above equation and Figure-2) in respect to fusion reaction [1, 4]. The extremely high temperatures required for the fusion reaction are routinely realized in several magnetic-fusion machines. Since the early 1990s, up to 16 MW of fusion power has been released in pulses of a few seconds, corresponding to a power multiplication close to break-even.

Our understanding of the very complex behavior of a magnetized plasma at temperatures between 150 and 200 million ^{0}C surrounded by cold walls has also advanced substantially. This steady progress has resulted in the construction of ITER, a fusion device with a planned fusion power output of 500 MW in pulses of 400 s as demonstrated in Figure-5.

ITER should provide answers to remaining important questions on the integration of physics and technology, through a full-size demonstration of a tenfold power multiplication, and on nuclear safety aspects. Here we review the basic physics underlying magnetic fusion: past achievements, present efforts and the prospects for future production of electrical energy. We also discuss questions related to the safety, waste management and decommissioning of a future fusion power plant in a more holistic way, while we will be concerned about type of comprehensive materials that maybe used for Magnetic Confined Fusion (MCF) type reactor such as Joint European Torus (JET)'s fusion reactor as demonstrated in Figure-6, where physicist recreate conditions inside the Sun.

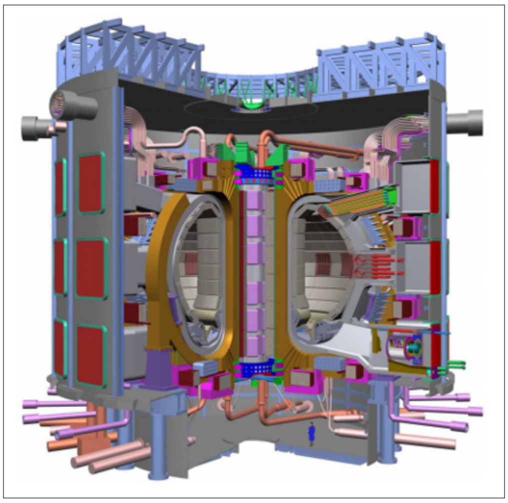

Figure 5: ITER Cross-Section Cut Image

Figure 6: JET's Fusion Reactor

Note that: The Joint European Torus (JET) fusion reactor near Oxford in the UK has produced the highest level of sustained energy ever from atom fusion, Nature has reported. On December 21st, 2021, the "tokamak" reactor produced 59 mega joules of energy during a five second fusion pulse, more than double what it managed way back in 1997 [5].

The JET reactor is the flagship experimental device of the European Fusion Program (EURO fusion) funded by the EU. It's mainly designed to help scientists prove that their modeling is correct, with an eye toward future experiments with the much larger ITER reactor being built in France, set to start fusion testing in 2025.

Furthermore, the greatest effort toward actualizing practical magnetic confinement fusion today is the International Thermonuclear Experimental Reactor (ITER) based in France. The objective of ITER is to sustain a Q-factor of 10 (500 MW of fusion power from 50 MW of input power) for 400 seconds and a Q-factor greater than 5 in steady state operation [6]. The plasma containing vessel for ITER will be ten times larger than the current largest operating Tokamak. ITER will not, however, generate usable energy at first, but act instead as an experimental test bed for researchers. The project, though promising, has faced myriad scientific, economic, and technological difficulties. The timetable for ITER goes beyond 2025. And the initial estimated cost has been reevaluated from $5.6 billion in 2006 to a current budget of $16.5 billion [7]. Even if successful, the EIA estimates that fusion production at the time of ITER's completion will cost twice as much as natural gas and coal per kWh, not, withstanding a carbon tax [8]. Even if magnetic confinement fusion one day provides an abundant, clean, high-yield, and relatively safe energy source, one significant concern will remain unresolved. ITER would produce a large number of fast neutrons, which can be used to breed fissile fuel. Though Li-6 could be used as a blanket to replenish the tritium in the fusion reaction, only one neutron per fusion reaction will be captured by fertile material. More likely, Th-232 or U-238 will surround the toroidal chamber to produce fissile material. If Th-232 is used the U- 233 generated (or if U-238 is used the Pu-239) is easy to extract and use for weapons. If operational, ITER and other magnetic confinement fusion devices would be vulnerable to bad actors [9]. Thus, it is not only practical and physical but also geopolitical constraints, which restrict the successful operation of ITER.

Magnetic Confinement Controlled Fusion

For the past half-century, experimentalists have tried to control the nuclear fusion process in an effort to create a copious and near-limitless source of clean energy. Deuterium (D) exists abundantly in water and Tritium (T) readily produces from lithium. At present, 10^{12} tons of deuterium can be extracted from the surface water of the earth. Furthermore, unlike fission reactors, fusion reactors produce little and short-lasting radioactive waste. The requisite environmental conditions of fusion, however, unsurprisingly make taming the process a nearly impossible task. The Lawson Criterion strictly defines such a minimum condition for a nuclear fusion device to work. In order to reach ignition, a fusion device must exceed a determined triple product of plasma electron density, plasma temperature, and the rate of energy loss. To be self-sustaining, this specific threshold is $3 \times 10^{21}\ m^{-3}$ keV s-1 [1, 11]. Beyond satisfying condition, the nuclear reactor must also generate energy. The Q-factor, reflecting this merit, is defined as the ratio:

$$Q = \frac{\text{(Energy released by fusion)}}{\text{(Kinetic energy of injected atoms)}}$$

If a particular nuclear fusion device fails to exceed a Q-factor of 1, then the device possesses no practical value. More importantly, the ratio of electric energy output to input, Q' can be expressed approximately as 1/4(1+Q). This effective break-even ratio fixes the desired Q value to be at least 2 [12]. For a deuterium-tritium reaction to release energy at a level of practical use, the gas must be heated to nearly 100 million Kelvin. At such high temperatures, the plasmatic deuterium and tritium particles move erratically, and most materials fail to confine the ionized gas [5]. The primary solution to confine the plasma for fusion has been to produce a magnetic field. (Figure-4) Even still, the confinement lasts only a few seconds as the instability of the plasma accrues.

Magnet and Magnetic Materials

The magnetic confinement driven fusion of thermonuclear plasma requires intense magnetic fields as it can be observed in technology of Tokamak machine and its present and modern technology being utilized in ITER by augmenting superconducting magnets for fusion as a newly clean energy with a common goal to decarbonize energy generation, while maintaining reliability and low-cost service to produce electricity to growing demand by end user cliental. See Figure-7, where it shows overview of the magnetic field system equipping the ITER reactor.

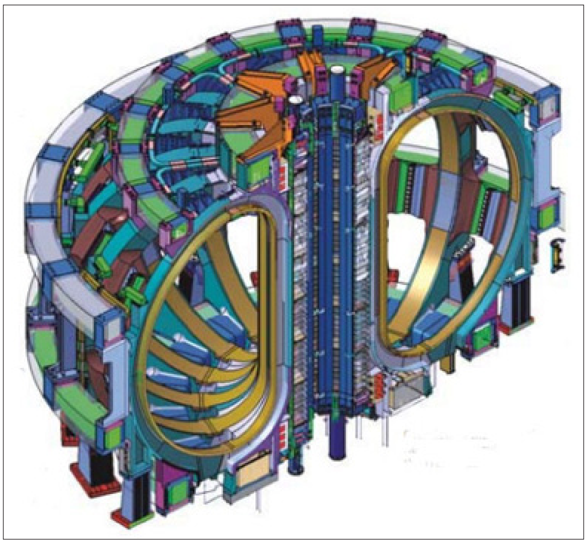

Figure 7: ITER Reactor Overview

The production of these magnetic fields in the large vacuum chamber (i.e., 837 m3) of the International Thermonuclear Experimental Reactor (ITER), currently being built at the Cadarache French site in the Bouches-du-Rhóne is in itself a major technological challenge. The ITER's magnetic field system comprises three giant superconducting system as:

- The Toroidal magnetic Field (TF),
- The Poloidal magnetic Field (PF), and
- The Central Solenoid (CS), where they focus *Superconductivity* and Superconductors.

These could be said to represent the backbone of the newly designed and innovative approach ITER Tokamak reactor as it is artistically drawn in Figure-8.

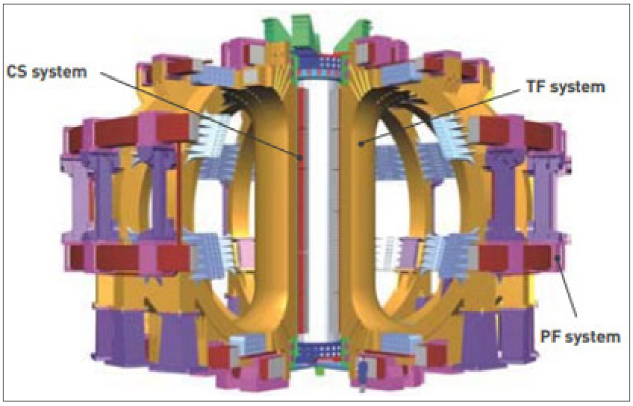

Figure 8: The Three Main Superconducting ITER Magnetic Field Systems

Figure-8 shows the three main superconducting magnetic field systems equipping the ITER experimental reactor. The Eighteen Toroidal Filed (TF) coils system wound around the torus confine the plasma. The Central Solenoid (CS) system creates a very high current which heats the plasma as it circulates through it, thus generating another magnetic field which contributes to the confinement. The Six Poloidal Filed (PF) coils system wound around the torus stabilize the plasma accordingly.

As far as integration and augmentation of superconductivity for fusion applications is concerned, from history of magnetic confinement driven fusion, we know that up to the early 1980s, all magnetic confinement machines or suggested reactors relied on resistive magnets, which were generally built using silver-doped copper in order to improve their mechanical properties. The machines' small size and, in particular, the fact that they operated in a pulsed regime guaranteed the viability of this solution which was pushed to its limits with the European tokamak of the Joint European Torus (JET) as illustrated in Figure-6. At present, the total energy required to power the JET's magnets, which is above 1GW, can only be delivered to the machine via energy storage flywheels due to the short duration of the plasma discharge (i.e., 10 to 30 seconds), where discharge plasma indicates the presence of a plasma within the confinement chamber. However, it is obvious that the resistive magnet solution cannot effectively be applied to the continuous operation reactor.

This is what drive the Europe to extend its fusion program to include the development of the first machine to be powered by *superconducting* magnets that we know it as tokamak formerly Tore Supra at the CEA center in Cadarache, which has a major plasma radius R of 2.5 m as depicted in Figure-9 here.

Figure 9: WEST (Formerly Tore Supra) Plasma Chamber Tokamak Type Reactor

Technical specification of Tore Supa is as follows:

Major radius:	2.5 m
Minor radius:	0.50 m
Magnetic field:	3.7 T (toroidal)
Heating power:	17 MW

Again, this machine is tokamak type reactor and started its operation since 2016 up to now and located in Cadarache, France.

Tore Supra holds the record of the longest plasma duration time for a tokamak (6 minutes 30 seconds and over 1000 MJ of energy injected and extracted in 2003), and it allowed researchers to test critical parts of equipment such as plasma facing wall components or superconducting magnets that will be used in its successor, ITER.

On 16 December, 2018, the Tore Supra—the first superconducting tokamak—achieves a six and a half minute-long plasma discharge. Operated by Euratom-CEA in Cadarache, France, this represents an important step in the direction of the long pulses an industrial reactor will require. Figure-10

Figure 10: Tore Supra Partial Cross-Section

The Tore Supra's TF system contains 40 tons of superconducting materials (Figure-11). The machine has been producing plasmas since 1988, thus following on from the extra-small TRIAM tokamak developed in 1986 in Japan, which has a major plasma radius R of 0.8 m. The outstanding operating performance of the Tore Supra superconducting system over a period of years paved the way for introducing the novel magnetic confinement technology vital to the success of fusion programs

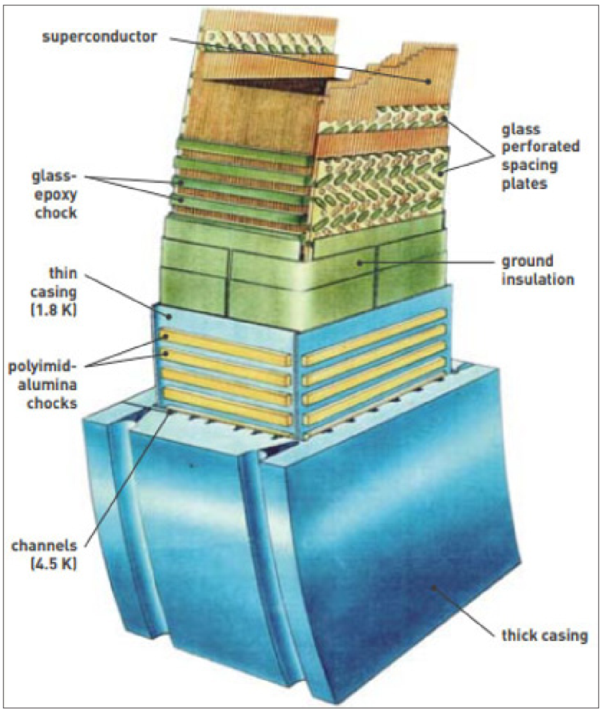

Figure 11: Tore Supra Superconducting Coil TF System

Figure-11 is sketch of a superconducting coil used in the Tore Supra TF system, illustrating the 26 double-pancake coils shown in their double casing system.

Bear in mind that, WEST, Tungsten (chemical symbol "W") Environment in Steady-state Tokamak, (formerly Tore Supra) is a French tokamak that originally began operating as Tore Supra after the discontinuation of TFR (Tokamak of Fontenay-aux-Roses) and of Petula (in Grenoble). The original name came from the word's torus and superconductor, as Tore Supra was for a long time the only tokamak of this size with superconducting toroidal magnets, allowing the creation of a strong permanent toroidal magnetic field. After a major upgrade to install tungsten walls and a diverter, the tokamak was renamed WEST.

Today's large-scale magnetic confinement fusion projects no longer use resistive magnets, which have been systematically replaced by superconducting coils. The Large Helical Device (LHD) torsatron, which is a peculiar feature of the configuration (i.e., Figure-12) built in Japan to similar dimensions as those of the Tore Supra, started plasma production in 1998, followed by the Chinese-developed EAST tokamak in 2006. Several machines are currently under construction worldwide. The most important are the stellarator W7-X (Germany) and the three tokamaks: KSTAR (South Korea), SST1 (India) and JT-60SA (Japan). Rounding up the field is the ITER which still operates on a pulsed regime and is a fully superconducting tokamak. Quite apart from the problems of yield and electric consumption, there is not one single electricity network in the world that can viably supply the 2 GW power input that would be required by a resistive machine for a 500-second plasma discharge [4].

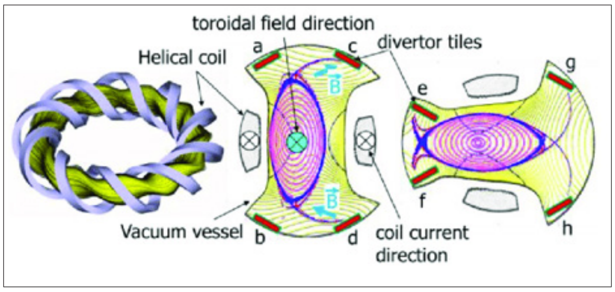

Figure 12: Left Image is Helical Coils Feature Configuration

Note that: Torsatron and *stellarator* are defined as the torsatron is being a magnetic confinement system in which the toroidal and poloidal field lines confining the plasma are generated by magnets spiralling around the vacuum chamber. This is a simplified version of the *stellarator*, which has two magnet systems [4].

Comprehensive Nuclear Materials

In this section, we take a very holistic approach and describing the comprehensive nuclear materials as the major classes of materials suitable for usage in nuclear fission and in case of this technical memorandum fusion reactors, although these types of comprehensive materials can be used in high power accelerators, and for diverse functions in fuels, cladding, moderator and control materials, structural, functional, and waste materials, which is addresses the full panorama of contemporary international research in nuclear materials, from Actinides to Zirconium alloys, from the worlds' leading scientists and engineers [12].

Until the mid-1990s, only few fusion devices used high-Z elements in Plasma-Facing Materials (PFMs). These devices either operated at high plasma currents and high plasma densities such as Alcator C-Mod2 and Frascati Tokamak Upgrade (FTU) or used high-Z materials only as test limiters such as Tokamak Experiment for Technology Oriented Research (TEXTOR).

Since then, high Z refractory metals have been attracting growing interest as candidates for PFMs because of their resistance against erosion and the need for low erosion and stability against neutron irradiation. Considerable effort has been made to study the behavior of high Z impurities in the core and edge plasmas, erosion/redeposition processes at the limiter/divertor surfaces, hydrogen isotope retention, and on material development and testing. In particular, the modification of ASDEX-Upgrade (AUG) into a fully tungsten machine, which was achieved in 2007, provided positive answers to critical questions on the reliability of tokamak operation with high-Z Plasma-Facing Components (PFCs) and the compatibility with standard and advanced H-mode scenarios and with the available heating methods.

Among the challenges, for tokamak devices, that still remain are the strong increase of the Tungsten (W) source and W concentration resulting from Ion Cyclotron Resonance Heating (ICRH) and the need for rigorous modeling to support the extrapolation of current results to ITER conditions. However, going over more granular aspect of these materials are beyond scope of this memorandum and authors referring the readers to reference in references section of this article [12].

Conclusion

Fusion Research and Development (R&D) has continually thrown up new challenges to test the ingenuity and skills of at least two generations of scientists and engineers. There are many challenges still to be faced, and there may be some which are unseen from today's perspective.

The most advanced of magnetic confinement devices today, the Tokamak, utilizes a combination of toroidal and poloidal confinement fields. One of the major limiting factors in building such a device is material selection. At temperatures exceeding 16 times the interior temperature of the sun (generated by a neutral beam process), materials must withstand operation lest they melt or contaminate the plasma. More complicating is the fact that the superconducting magnetics surrounding the Tokamak must be set at temperatures near absolute zero [6]. The solution to managing the extreme temperature differences has been to surround the plasma vessel in a cryostat vacuum, use a divertor to control exhaust waste gas, and cover the interior walls with a neutron shielding blanket. As of late 2016, the highest Q-value achieved by a Tokamak given these conditions stands at 0.65 [10].

The next step in magnetic confinement fusion or ITER is essential to realizing the key technologies of a viable energy source and has to be operated successfully first. Only then will it be possible to check with confidence the accuracy of the prediction on Russian physicist Lev Artsimovitch, grandfather of the Tokamak concept, who said in 1972 that "*FUSION WILL BE THERE WHEN SOCIETY NEEDS IT*".

As final statement in our conclusion, more than 200 tokamaks around the world have paved the way to the ITER experiment.

Conceived as the last experimental step to prove the feasibility of fusion as a large-scale and carbon-free source of energy, ITER will be the world's largest tokamak, with ten times the plasma volume of the largest tokamak operating today.

A consortium of nations—China, the 28 states of the European Union plus Switzerland, India, Japan, Korea, Russia and the United States—is building ITER collaboratively, in an ambitious wager to advance fusion science and technology to the point where demonstration fusion power plants can be designed.

In summary, the shape of the plasma boundary in fusion energy experiments, such as KSTAR and ITER, must be carefully controlled to achieve the plasma temperatures and densities required to access and sustain fusion burn. As plasma shapes become taller, or more "elongated," larger plasma currents can be sustained leading to increased fusion power output, but the requirements for stable control of the vertical position become more stringent. Compared to conventional tokamaks that use magnetic field coils made from copper and located close to the plasma surface, the magnetic field coils in superconducting tokamaks are fewer in number and are located further away to accommodate coil cooling and radiation shielding systems. This coil configuration tends to couple plasma control loops that are largely decoupled in conventional tokamaks. The new digital control algorithm developed in the KSTAR plasma control system integrates multiple control schemes to effectively decouple the vertical position control from other control loops used to maintain the plasma current, plasma shape, and radial position.

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