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POLICY

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Abstract A fundamental revamping of magnetic plasma fusion research is needed, because the current focus of world fusion research—the ITER-tokamak concept—is virtually certain to be a commercial failure. Towards that end, a number of technological considerations are described, believed important to successful fusion research. Beyond critical attention to plasma physics challenges, there must be a much sharper focus on electric utility acceptance criteria, which strongly reflect the public interest. While the ITER-tokamak experience has provided important understanding of a variety of technology issues, it is expensive and time-consuming. Engineers with commercial-world experience must become involved in future fusion research and must have a major influence on program decision-making and evaluation. Fusion engineers will have to be imaginative while being rooted in an understanding of fission reactor development, nuclear regulation, and electric utility realities, the proper consideration of which will impact fusion program success. Properly developed, fusion power holds great promise as an attractive electric power source for the long-term future.

Keywords Fusion strategy · Fusion policy · Utility requirements · Regulatory constraints · Fusion fuel cycles · Fusion neutrons · Fusion technology · Fusion materials

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Introduction

A practical fusion power system must be economical, publically acceptable, and as simple as possible from a regulatory standpoint. In a preceding paper [1] the ITER-tokamak plasma fusion concept was examined against these criteria and found to be severely wanting. Accordingly, there needs to be a fundamental revamping of future magnetic confinement fusion research.[1] Towards that end, we identify a number of important considerations. Some have been long recognized but are important to explicitly recognize. Others have more clearly emerged from the utility-criteria-based review of ITER-tokamak fusion [1]. In the following we expand beyond those lessons using three fusion fuel cycles in an effort to develop a set of important considerations.

The development of practical fusion electric power remains an extraordinarily difficult and complicated task. Enormous progress that has been made over the Past 60 + years, nevertheless, the underlying plasma physics is certain to continue to be challenging. With so many issues to be addressed, tradeoffs will abound.

Lessons from Pursuit of the Tokamak Fusion Concept

Paraphrasing from the previous paper:

1. The EPRI "Criteria for Practical Fusion Power Systems" [2] should be the subject of periodic discussion by fusion research personnel and

[1] Here we use the term magnetic confinement to differentiate from inertial fusion, which typically involves the very rapid compression of DT-containing pellets. Laser fusion is one example of inertial fusion.

management. Potentially interesting fusion concepts should be judged in part against the established concerns of regulators and potential utility investors.
2. The inherently large size of the tokamak and a few other fusion concepts is a major disadvantage. Concepts that are smaller can progress more rapidly at lower cost.
3. Plasma configurations that can inherently disrupt are undesirable, because of the attendant regulatory burdens they will carry.
4. Superconducting magnet quenching can be hazardous, disruptive, expensive, and taxing from a regulatory point of view. If S/C magnets are to be used, configurations with the greatest stability should be favored.
5. The use of existing industrial materials and technologies is a positive when introducing a complicated new energy concept such as the first practical fusion power plant.

Fusion Fuel Cycles

Fusion reactions involve the joining of light elements and their subsequent splitting into different elements with the release of significant amounts of energy. Fusion is the energy source in the sun and the stars and the basis of the hydrogen bomb. Reactions of interest in the quest for practical fusion power on earth involve isotopes of hydrogen, helium, boron, and a few other light elements, heated to very high energies in a gaseous plasma. The cross sections for various fusion reactions as a function of energy are shown in Fig. 1.

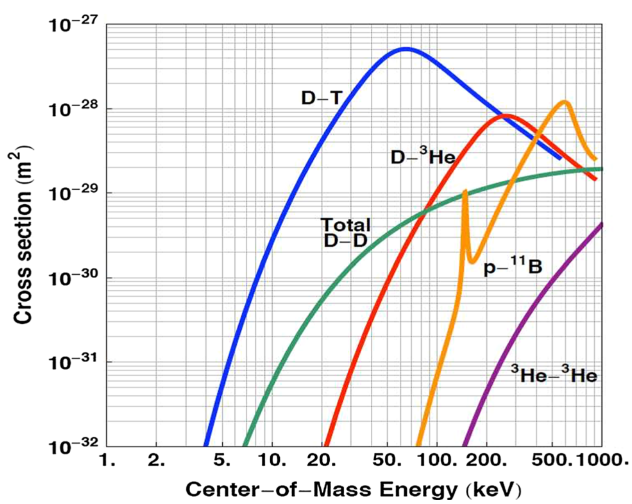

Fig. 1 Fusion reaction cross-sections as a function of center-of-mass energy (in this frame the center of mass is at rest)

Three fusion reactions are selected for discussion, because they illustrate a number of important points, as the following will make clear:

$$(1) \quad D + T \rightarrow He^4 + n + 17.6\ \text{MeV}$$

$$(2) \quad D + D \begin{cases} \nearrow He^3 + n + 3.24\ \text{MeV} \\ \searrow T + p + 4.0\ \text{MeV} \end{cases}$$

$$(3) \quad p + B^{11} \rightarrow 3He^4 + 8.7\ \text{MeV}$$

DT fusion is the primary reaction most government fusion programs support. It yields 14 MeV neutrons, which must be properly managed and used to breed tritium, which does not occur in useful quantities in nature. DD fusion utilizes a readily available isotope of hydrogen, and one reaction branch produces tritium, which can react in the plasma or be recycled, enhancing the energy production rate. It should be noted that there are more than ten times as many neutrons produced per kWh of energy produced in the DD reaction as in a fission reactor. Finally, the reaction p-^{11}B produces no neutrons directly but does produce a small number in secondary reactions, a fact that greatly eases neutron management problems [3].

Magnetic fusion requires an investment of electrical energy to heat and hold a plasma under conditions necessary for fusion reactions to occur. The resulting energy release must be converted to electric power, a part of which must be recycled to maintain fusion reactor operation. A fusion power system is thus an energy multiplier, more so that fission power.

A rough measure of the potential energy multiplication for the various fusion reactions can be determined by dividing each reaction energy release by the likely energy required for the respective reactions. Taking the energy required for each reaction to be roughly 10 keV for DT, 50 keV for DD, and 150 keV for p-^{11}B, and neglecting tritium utilization in the DD system, a measure of the energy multiplication for the three reactions is order of 2000 for DT, 100 for DD, and 50 for p-^{11}B. With tritium product use in a DD system, its energy multiplication would be higher. On this basis the DT and DD reactions have the highest energy multiplication factors, while the p-^{11}B reaction is less robust. These considerations are obvious to most plasma physicists and were noted by Nevins [4].

A number of plasma physics considerations are omitted from these discussions, but they must clearly be part of any comprehensive program reevaluation. For instance, while the p-^{11}B fusion cycle is potentially attractive, because of the dearth of neutrons, it is well known that p-^{11}B plasmas in thermodynamic equilibrium are not viable for a power production, because of high levels of radiation from high temperature electrons (bremsstrahlung). Therefore, a key to the possible success of that reaction requires a non-equilibrium situation wherein p-^{11}B plasma electrons are held at a lower temperature than the ions or the volume of high temperature electrons is made smaller than the total plasma volume or a large fraction of the radiation is absorbed before it leaves the plasma.

Consideration 1 The DT and DD cycles have the potential for the highest energy gains. The p-^{11}B cycle has a lower gain.

14 MeV Neutrons

Both DT and DD fusion create copious neutron emissions. 14 MeV DT neutrons carry the majority of the DT reaction energy and are the most penetrating. Roughly a meter of moderator-blanket is needed to slow down 14 MeV neutrons, heating the moderator-blanket materials in the process. A coolant circulating through the moderator-blanket captures that energy and carries it to a thermal energy conversion system to produce electric power.

The moderator-blanket region in a DT system must include a means to create tritium via fusion neutron absorption. Typically, the tritium breeding element of choice is lithium. In situations where the fusion neutron supply is marginal, beryllium can be added to the moderator-blanket, because its n, 2n reaction provides additional neutrons to ensure that tritium production is sufficient (or more than sufficient) to supply continuing needs.

In DD systems, blanket-moderator thickness must be of similar thickness to that in DT systems to accommodate the 14 MeV neutrons produced in the DT fusions that will occur from the tritium produced in the DD fusion reaction. However, DD moderator-blankets need not breed tritium, so their complexity can be reduced.

In both DT and DD systems, moderator-blanket regions should be engineered to operate at as high a temperature as practical to achieve high energy conversion efficiencies.

Consideration 2 Both DT and DD fusion plasmas require a surrounding moderator-blanket of roughly a meter thickness to slow and capture 14 MeV neutrons; DT blankets must breed tritium, while DD blankets do not.

Radiation Damage and Radioactive Waste

It has long been recognized that the copious neutron emissions in DT and DD fusion systems will cause significant radiation damage to materials near to the plasma. In addition to physically embrittling those materials, neutrons will induce radioactivity in them, the level being dependent on materials choice, composition, and impurities.

Radiation damage will necessitate the periodic replacement of blanket region components. Related operations will have to be performed remotely, because of high levels of induced radioactivity and the presence of tritium, which will permeate those materials, due to tritium's high mobility in solids and liquids at high temperatures.

In the early years of DT fusion reactor conceptual designs, 316 SS was chosen as the primary material of moderator-blanket construction. The attraction of 316 SS was its ready availability and its wide industrial use, minimizing the need for more complicated fabrication and maintenance often required with more exotic materials. The biggest negative associated with 316 SS was the buildup of high levels of induced radioactivity and neutron-induced material damage, necessitating frequent replacement, handling, and disposal.

In subsequent DT fusion reactor conceptual designs, SiC was proposed, because of its low induced radioactivity under neutron bombardment [5]. Drawbacks of SiC include very limited industrial experience with its fabrication or its use as a structural material. Developing and qualifying SiC for high neutron flux environments would be both expensive and time-consuming, and success is not assured.

Recent conceptual designs of DT ITER-like tokamak demonstration reactors assume reduced-activation ferritic/martensitic (RAFM) steel, which would reduce but not eliminate induced radioactivity compared to 316 SS.

No material for DT or DD fusion reactor construction will be immune from neutron damage and induced radioactivity. As a result, periodic plant shutdowns will be required to replace damaged materials in regions adjacent to the plasma. Those operations will have to be performed with remote handling equipment and will yield large volumes of radioactive waste. The induced radioactivity in most of the materials under consideration will be relatively short-lived, becoming relatively inert in the order of a century, as compared to the hundred thousand year lifetime associated with fission waste. While a considerable improvement over fission, the handling, storage, disposal, or reuse of fusion reactor construction materials will represent considerable cost and regulatory-mandated procedures.

Consideration 3 DT and DD systems will produce large volumes of radioactive materials, which will have to be handled, stored, buried, or reused at considerable expense with significant regulatory oversight.

Vacuum Pumping

Most magnetic fusion concepts require establishing a high vacuum in the plasma chamber prior to initial plasma creation, and most require significant vacuum pumping during machine operation. High throughput vacuum pumping requires large, open ducts[2] between the plasma chamber and the vacuum pumps. In DT and DD fusion systems, large vacuum ducts provide passageways for neutrons to stream out of the plasma chamber-blanket region. While vacuum ducts can be twisted and turned to reduce neutron streaming, twists and turns also reduce gas throughput, further taxing vacuum pumps and/or requiring larger vacuum ducts. This mode of neutron streaming/leakage cannot be eliminated in a number of fusion concepts. Accordingly, there will be induced radioactivity in structures and equipment outside the plasma-blanket region, further inhibiting human maintenance during system shutdown.

In addition to large vacuum ducts, some fusion concepts require open channels for transmitting energy or particles for plasma heating. While typically smaller than vacuum channels, these penetrations will result in additional neutron streaming.

In p-^{11}B systems no neutrons are produced directly, but there will be a modest level of low energy neutrons created from secondary reactions. Low energy neutrons can be easily absorbed, but they will nevertheless create low levels of induced radioactivity, which will have to be carefully managed.

Consideration 4 Large vacuum ducts and other penetrations in DT and DD systems will provide pathways for neutron leakage and induced radioactivity outside of moderator-blankets.

Handling Helium Fusion Products

In all three of the fusion reactions considered here, energetic helium ions are produced and will be constrained by magnetic fields. If plasma confinement is good, magnetic fields can maintain the plasma boundary a reasonable distance from chamber walls and energetic helium fusion products will be contained to a degree in the plasma, losing energy to the plasma and beneficially heating it.

Nevertheless, in most magnetic fusion options a significant flux of energetic fusion-product helium ions will exit the plasma. Tokamaks include a scrape-off region outside the plasma to guide leaking plasma and energetic helium ions to a "dump" (called a divertor), where leaking plasma and helium strike a solid material, emerging as neutral gas to be pumped away.

Researchers at the University of Wisconsin recently simulated the bombardment of energetic helium on tungsten and other materials and found that none could operate under expected tokamak reactor divertor conditions for a reasonable period of steady operation [6, 7]. The problem is that energetic helium nuclei become buried in the target material, causing surface morphology changes, including the formation of blisters, which result in target material loss values greatly exceeding previous estimates. In the process an unacceptable amount of radioactive dust is created, which could quench the fusion plasma or act as a source of troublesome radioactive dust. Assuming that the Wisconsin results are confirmed, a new constraint will have emerged, impacting a number of fusion confinement concepts.[3]

Consideration 5 Energetic helium fusion products from the DT, DD, and p-^{11}B cycles cannot be allowed to strike solid materials in high flux.

Magnets for Fusion Plasma Confinement

Magnetic fields for plasma confinement are created by coils often located outside the moderator-blanket, which shields the coils from intense heat and high neutron fluxes. The resultant magnetic coils are typically very large, very expensive, and involve very high levels of stored energy.

As indicated in the previous article [1], regulators identify sources of accidental energy release and will be especially concerned with fusion concepts that involve large amounts of stored magnetic energy, which might be suddenly and destructively released in accident situations.

Consideration 6 DT, DD and p-^{11}B fusion concepts requiring magnets outside the plasma and blankets will be encumbered by high magnet costs and significant regulatory requirements, aimed at mitigating damage associated with accidental magnetic energy release.

Superconducting Magnets

Superconducting magnets can accidentally quench (suddenly "go normal"), releasing stored electrical energy and high-pressure helium gas, suddenly produced from liquid

[2] Large in the context of neutron streaming/leakage is a relative term. In the case of a vacuum duct running through a one meter blanket, 10 cm diameter (10/100 ratio) might qualify as "large".

[3] Some researchers have suggested that a flowing lithium stream might be utilized as a viable dump for helium fusion products. That might be possible, but regulators and plant operators are sure to require extensive safety measures related to the use of liquid lithium, because of its associated fire and explosive hazards.

helium, quickly vaporized. To date, quenches have occurred on at least 17 occasions in tokamak experiments constructed with superconducting magnets [8].

The ITER tokamak fusion experiment includes very large superconducting magnets, which produce toroidal fields for plasma confinement. As previously stated [1]: "If a quench in ITER were to cause all of its magnets to go-normal, the magnetic energy released would exceed 40 gigajoules, which is of the order of 10 tons of TNT. How fast that energy is released depends on a number of factors, the most extreme of which regulators would consider and aim to protect against. For reference, Blockbuster bombs used during World War II released of the order of 10 tons of TNT. While likely a low probability accident, regulators will nevertheless require a variety of expensive safeguards to minimize the potential exposure of the public to the effects of such an energy release." This will be particularly significant in DT and DD fusion systems, because of the potential for the release of large quantities of radioactive materials, created by neutron activation.

Another downside of large superconducting magnets in DT and DD fusion reactors is the cost impact of reactor shutdown and restart. In the case of the large ITER-tokamak superconducting magnets, shutdowns even due to minor malfunctions will likely require bringing the magnets to near room temperature, possibly requiring a matter of days. Restart, involving cooling the magnets back down to liquid helium temperatures and electrically recharging them, will be very time consuming, assuming all goes smoothly. In the case of ITER, cooling the toroidal field coils from room to liquid helium temperature is estimated to require roughly 30 days [9].

Thus, even a modest repair could well require significant downtime for toroidal magnet deactivation and restart. Coupled with reactor cooling and other restart requirements, the system could conceivably be off line for over a month with attendant loss of output power and revenue to the utility operator.

Consideration 7 The use of large superconducting magnets in fusion reactors will (1) represent a large capital cost; (2) introduce significant regulatory requirements to minimize problems associated with accidental quenches; and (3) require significant cool down and restart delays, requiring long off-line periods and increasing plant power costs.

Plasma Beta

An important parameter in magnetic confinement fusion is beta, defined as the ratio of plasma pressure divided by the confining magnetic field pressure. High beta is desirable because it represents an efficient use of magnetic fields, which are typically expensive. According to one source [10], "beta can be thought of as a ratio of money out to money in for a reactor, and beta can be thought of (very approximately) as an economic indicator of reactor efficiency."

Beta for an ITER-like tokamak reactor is projected to be around 10 % [11], which is one reason for the machine's high capital cost. Beta for pinch and cusp concepts is typically of the order of 100 %, but those options are not without their own special challenges.

Consideration 8 To minimize capital and operating costs, magnetic confinement fusion concepts with a high beta are preferred.

The Fusion Reactor Building

Regulators will place significant requirements on the buildings housing commercial fusion reactors that involve large amounts of radioactivity, e.g., DT and DD fusion systems. As illustrated by considerations of ITER-tokamak fusion power [1], regulators will focus on the considerable amount of energy that could explosively release large quantities of induced radioactivity and tritium to the public. In spite of what are certain to be heroic efforts to minimize such undesirable events, their probability of occurrence will never be zero, so a reactor enclosure (building) may have to be roughly as structurally strong as the enclosures of commercial nuclear power plants. Because of the very large size of an ITER-tokamak fusion power reactor, such a building will be extremely expensive, likely adding significantly to the already high cost of such a system.[4]

The Relevance of a DT Burning Fusion Plasma Experiment

A number physicists contend that a DT burning plasma experiment is urgently needed to investigate the "frontier physics" associated with significant levels of energetic fusion reaction products in fusion plasmas, because they believe such experiments are fundamental to the development of fusion energy [12].

[4] The cost of such a regulator-approved building cannot be estimated until a reactor design and adjacent maintenance and storage facilities are designed. However, as determined by Galambos, J.S. et al., The Impact of Advance Physics on Commercial Tokamak Fusion Reactors, November 4, 1993, the large size of ITER compared to a comparable fission reactor—over 150 times the volume—argues for an ITER-tokamak fusion power reactor building at least one, if not two orders of magnitude larger than a building to house a comparable fission reactor.

The assumption underlying this assertion is that the DT reaction will be the chosen reaction for the first commercial fusion power system. Based on the considerations described herein, that assumption is by no means certain. Furthermore, assuming an other-than-tokamak DT fusion concept is determined to be potentially viable, as likely will be the case, the relevance to that concept of DT burning in ITER would have to be solidly justified.

Utility Considerations

The EPRI criteria reflect utility values. Regulation at the Nuclear Regulatory Commission (NRC) level will supersede state regulation and impose requirements well before state licensing of the first commercial fusion power plant. If there are significant NRC strictures and concerns, utilities will take note and could turn negative to the technology. If the first commercial fusion system is not initially economic or does not have the potential to be economic after a generation of further development, interest by utilities and state utility regulators may not only evaporate, it could become actively negative.

Program Revamping

Revamping fusion research will not be an easy, overnight activity, because of the complexity, uncertainties, and tradeoffs involved. Inherent to the revamp will be a new direction for the US fusion research program with increased emphasis on fusion economics and greater involvement of utility partners to influence program direction and evaluation.

Fusion program revamping will require a great deal of analysis of various confinement concepts by groups of plasma physicists objectively considering the potential strengths and weaknesses of each. In addition, experienced, objective and imaginative engineers will need to evaluate each concept, considering their potential economics, regulatory aspects, and public acceptance. Clearly, such a process will be iterative and time-consuming. It is unlikely that any concept will emerge as a clear winner at the outset; if that were the case, it is probable that someone somewhere would have already reached such a conclusion. More likely, tradeoffs will be required and engineering considerations will point to areas of focus in order to more optimally guide related concept research and development. While this uncertain state of affairs may not be satisfying to many, the significant complexity of fusion power makes it inevitable, at least to this observer.

It is worth noting that a number of fusion concepts have received private and federal support outside of the mainline DOE fusion program, which is focused on ITER-tokamak and related low-beta concepts. Examples of those other concepts include the Tri Alpha field-reversed configuration, the EMC2 polywell cusp system, the Lawrenceville dense plasma focus, and a number of pulsed concepts funded or in process of being funded by the fusion program in DOE ARPA-E [13–17].

The outcome of the revamping should include the following, not necessarily in priority order:

- Identification of the most attractive medium–high beta concepts and an openness to related proposals from organizations outside the existing fusion community.
- Establishment of a substantial fusion engineering effort for independent analysis and project review; this effort should involve both commercial and academic engineers.
- An up-front and continuing recognition of utility considerations and possibly a utility fusion advisory committee.
- A program of relatively basic plasma physics studies, needed for fusion concept research as well as to advance the science of plasma physics.
- A program of fusion-related materials research.
- A program on superconducting magnet development aimed at minimizing quenching and quench damage.
- Options for program management restructuring to more sharply focus on practical fusion power research and development.

Conclusions

A practical fusion power system must be economical, publically acceptable, and as simple as possible from a regulatory standpoint. In light of the likely failure of ITER-tokamak fusion to qualify, a major revamping of fusion research is needed. In the foregoing, three fusion reactions were used to develop important considerations that should be factored into a fusion program revamp. Some are well known while others emerged from consideration of nuclear regulatory factors.

In the near future, fusion physicists need to rethink, innovate, and plan beyond their previous focus on ITER-tokamak fusion. The ITER-tokamak experience is useful but expensive and time-consuming. Commercial-world engineers must become involved and have a major influence on future fusion program direction and evaluation. Those engineers will have to be imaginative, while being rooted in an understanding of fission reactor development, nuclear regulation, and electric utility realities.

Properly developed, fusion power continues to hold great promise as an attractive power source for the long-term future. Before that can happen, a major fusion program revamping is required.

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