



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH


IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 5, May 2024

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.423

 9940 572 462

 6381 907 438

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Purpose of Fusion Energy

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ABSTRACT: Fusion energy, the process that powers the sun, promises a nearly limitless and clean source of energy by fusing atomic nuclei. Unlike nuclear fission, which splits heavy atoms and produces long-lived radioactive waste, fusion combines light elements, typically isotopes of hydrogen like deuterium and tritium, to form helium and release vast amounts of energy. This reaction requires extremely high temperatures and pressures to overcome electrostatic forces between positively charged nuclei. Advances in magnetic confinement with tokomaks and inertial confinement using lasers are bringing practical fusion closer to reality. Recent breakthroughs in achieving sustained fusion reactions and improvements in plasma confinement and heating are crucial steps towards building viable fusion reactors. Fusion offers significant environmental advantages, including minimal greenhouse gas emissions and reduced radioactive waste compared to conventional nuclear power. Additionally, the abundance of fusion fuel sources—deuterium from seawater and lithium for tritium breeding—ensures energy security and sustainability. Continued research and development, alongside international collaboration projects like ITER, are essential to overcome remaining scientific and engineering challenges, potentially making fusion a cornerstone of future energy systems.

I. INTRODUCTION

Fusion energy represents one of the most promising avenues for generating clean, abundant, and sustainable power. It mimics the processes powering the sun and other stars, where atomic nuclei combine under extreme temperatures and pressures to release tremendous amounts of energy. The primary fuels for fusion—deuterium and tritium—are isotopes of hydrogen. Deuterium is readily available from seawater, while tritium can be bred from lithium, making fusion fuel sources abundant and widely accessible. Unlike nuclear fission, which splits heavy atomic nuclei and produces long-lived radioactive waste, fusion involves merging light nuclei to form a heavier nucleus, typically helium, with minimal radioactive byproducts. The reaction requires temperatures exceeding millions of degrees Celsius, creating a plasma in which the fusion process occurs. Containing this hot plasma is one of the major challenges, tackled through methods like magnetic confinement in tokamaks and inertial confinement using powerful lasers. Recent advancements have brought the dream of practical fusion energy closer to reality. Experiments have achieved record durations of plasma confinement and significant energy outputs, although net positive energy production remains a goal. The international ITER project exemplifies the collaborative effort needed to overcome the scientific and engineering hurdles, aiming to demonstrate the feasibility of fusion as a large-scale energy source. Fusion energy promises numerous benefits, including minimal environmental impact due to its lack of carbon emissions and substantially lower radioactive waste compared to fission. Its potential to provide a stable and virtually inexhaustible energy supply positions it as a crucial component in addressing global energy needs and combating climate change. As research progresses,

The decade of fusion:

A fusion future can soon be realized. Thanks to private sector efforts, a commercially-practical fusion reaction that creates more energy than it consumes could be achieved as soon as 2024. A race for scale and commercialization will follow. If the United States organizes, it can win this race. The next decade will determine which countries become importers versus exporters of fusion. The Biden Administration's Bold Decadal Vision for Commercial Fusion is a key step in the right direction. Now the nation must execute and build upon that vision to reap the economic, social, and geopolitical benefits that fusion can offer.

Structural materials:

A critical challenge for establishing the feasibility of fusion energy as an environmentally attractive and cost-competitive energy source is the development of robust structural materials. Safety (decay heat, mobilization) and waste disposal (reduced long-term activation products). These reduced activation structural materials have been the subject of considerable international study by fusion materials scientists. Three main reduced activation materials systems have

emerged the leading candidates. 1. 2) Ferritic/martensitic steels (the most mature on a scientific and engineering basis, and the leading candidate for proposed first-generation demonstration fusion reactors), V alloys offer potential for higher thermodynamic efficiency, but immature database and inherent problems with atmospheric contamination during processing, joining, and SiC composites (potentially high payoff in terms of thermodynamic efficiency, but highest risk and least technological maturity of the 3 materials system) Refractory alloys such as W have attractive thermo physical properties and high-temperature capability, but have well-known fabrication, joining, and entrapment issues.

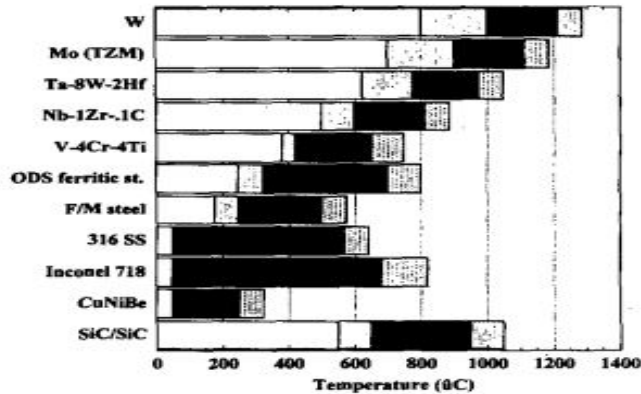


Fig 1: physical properties

Several factors define the allowable operating temperature window for structural alloys nuclear reactor. The lower operating temperature limit in all body-centered cubic and many face-centered cubic alloys is determined by radiation embrittlement (decrease in fracture toughness), which is generally most pronounced for irradiation temperatures below 0.3 T_m where T_m is the melting temperature. This low temperature radiation embrittlement is generally pronounced even for doses of 0.11 displacements per atom (dpa) in many BCC alloys. Thermal conductivity degradation in SiC is most pronounced at low temperature, and may limit the operating temperature of SiC/SiC composites for first wall and blanket structures to temperatures above 600°C. The upper temperature limit will be determined by thermal creep or helium embrittlement concerns for alloys, and by void swelling in SiC composites. Fig. 1 summarizes the operating temperature windows of several materials at relatively low damage levels, based on radiation damage and thermal creep considerations. Chemical compatibility with coolants and breeder or neutron multiplier materials may cause further reductions in the operating temperature window.

II. STEINER: TECHNOLOGICAL REQUIREMENTS FOR POWER BY FUSION

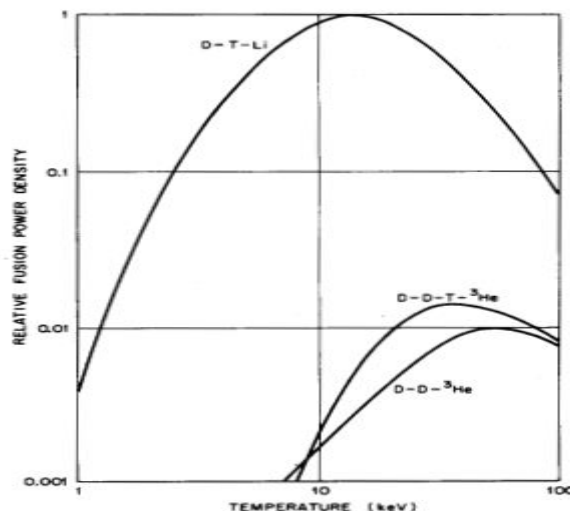


Fig 2: Relative Fusion Power Densities

Fig. 2 shows the relative fusion power densities' for the D-T-Li, D-D-T-³He, and D-D-³He fuel cycles in the temperature range 1 KeV to 100 KeV. Note that, in the vicinity of the maxima, the fusion power density of the D-T-Li fuel cycle is between one and two orders of magnitude greater than that of the other two fuel cycles. For this reason, the D-T-Li fuel cycle is generally regarded as the most likely fuel cycle for fusion power production. The three fuel cycles described above 1) produce substantial amounts of neutrons which result in radiation damage and induced radioactivity within the reactor structure; and 2) require the handling of the radioisotope tritium. It has been suggested that higher-Z materials such as lithium, beryllium, and boron be used as fusion fuels in order to provide fuel cycles which are essentially free of neutrons and tritium. To be of interest, such fuels must operate at ion temperatures in the vicinity of - 0.5 MeV. The higher-Z fuels generally exhibit more demanding requirements for confinement and heating than do the lower-Z fuels. The potential of fusion-fission (hybrid) concepts is also being evaluated. In such concepts fusion-produced neutrons may be used to "bum" fertile and fissile material incorporated within the blanket, The fission power produced in fusion-fission concepts relaxes the plasma confinement requirements but introduces the complexities and additional costs associated with fission fuel cycles.

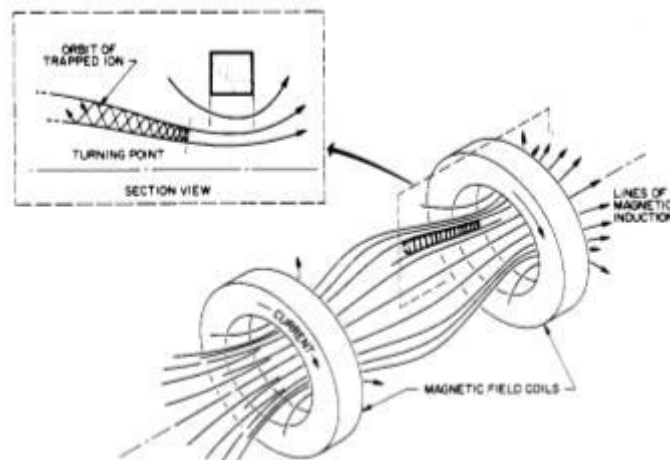


Fig 3 : Principle of mirror Confinement Scheme

Fuel (unreacted fuel and reaction products). Note that, in the mirror concept, plasma end losses provide an inherent spent-fuel removal mechanism. The energy required to start up and sustain the plasma would be provided by injecting beams of energetic neutral fuel particles into the plasma. The neutral beam injectors would also serve as the fuel source in reactors. The most promising approach for mirror startup appears to be the use of target plasma for trapping the injected beam and thus building the plasma up to the desired operating conditions. Two techniques are currently being investigated for production of the target plasma: laser heating of a pellet and magnetic compression of plasma. Once startup has been achieved, fusion power would be produced in a continuous fashion. Thus the confining field coils would also operate in a continuous fashion. These coils must be superconducting in order to minimize the Joule heating losses which would be unacceptably high if normal conductors were employed for this purpose. As in all neutron-producing fusion power concepts, the plasma would be surrounded by a blanket to utilize the fusion neutrons. The power associated with the fusion neutrons appears as heat in the blanket and would be converted to electricity via a thermal energy conversion system. The power leaving the plasma in the form of energetic charged particles (this includes essentially all the power associated with the injected neutral beams) is fed to a direct energy conversion system based on electrostatic concepts. Unreacted fuel would be recovered from the direct converter and recycled to the plasma region. The mirror reactor described will be adopted as the reactor model for the mirror concept. The features of this reactor are illustrated in Fig. 3. The magnet coils shown are of the "Yin-Yang" design and are considerably more complicated than the simple mirror coils indicated in Fig. 2. Simple mirror coils do not provide stability against magneto hydrodynamic (MHD) motion of the plasma and are not currently employed in mirror experiments. The Yin-Yang coil design is considered to be a very efficient scheme for achieving an MH stable field configuration. The operating characteristics of the reactor are summarized in Table I. The following points are noted.

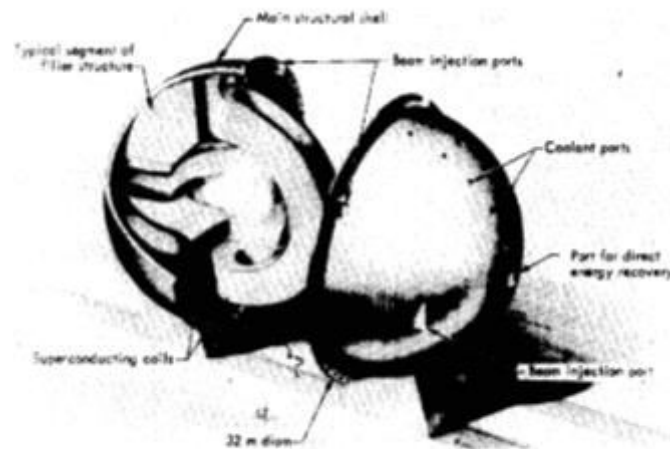


Fig. 3. Mirror reactor model.

1) Theory predicts that the confinement in mirrors increases with the three-half power of the mean ion energy and, therefore, mirror reactors must operate at high energy. Operation at mean ion energies in the range -100 Kev to 1 MeV has been examined. The relatively high mean ion energy (-600 Kev) listed in Table I was to a large extent dictated by the operating characteristics of the direct energy conversion system employed in the study. Lower mean ion energies (-200 Kev) become attractive when alternate direct energy conversion systems are considered. 2) Theory predicts that confinement in mirrors increases with the logarithm of the mirror ratio, that is, the ratio of mirror field (the maximum field seen by a parcel) to central field (the minimum field seen by a particle). The value of central field given in Table I is the value in vacuum (that is, in the absence of plasma) and, therefore, the associated.

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