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Analyzing the different ways to supply nuclear fusion reactors

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ABSTRACT

Since the 1940's, nuclear fusion has been viewed as a potential energy source, with the first patent for a fusion reactor being filed in 1946. Since then, substantial progress has been made with an ignition breakthrough happening at the Lawrence-Livermore National Laboratory (LLNL). The viability of using nuclear fusion to assist in the transition away from fossil fuels is becoming an increasingly appealing prospect; however, there are multiple questions on how such a project will work, including choice of the most appropriate fuel mixture to use and identifying factors influencing selection. In this paper we compare the three popular fuel mixtures: deuterium-tritium, deuterium-helion, and proton-boron on the basis of the chances each has of releasing the maximum amount of energy while taking in the lowest amount of energy possible, their environmental impacts, and commercial viability, and recommend deuterium-tritium mixture based on the aforementioned factors.

Keywords: *Deuterium-Tritium, fuel mixture, Coulomb barrier, Gamow-Sommerfeld factor, isotope separation, nuclear fusion*

INTRODUCTION

Nuclear fusion, a process based on the fusing of two smaller atoms to make one, happens naturally in the core of every star and releases very large amounts of energy.

This energy is released due to a quantity called binding energy. Binding energy is the amount of energy needed to break bonds between all the subatomic particles in the nucleus of an atom and is equated to the mass defect of that nucleus by the formula $E = mc^2$ (E is energy, m is mass and c is the speed of light). When bonds are broken, energy is absorbed; when bonds are formed, energy is released.

Every nucleus has a binding energy and in the periodic table, there is a trend that nuclei binding energies per nucleon follow - increasing rapidly from deuterium (lowest binding energy of any atom) till oxygen, slowly increasing and peaking at iron-56, then slowly decreasing afterwards (Lépine-Szily 2012). Due to this trend, it is most efficient to use elements with very low masses such as hydrogen or helium so that maximum energy can be released in every nuclear reaction.

ASSESSING THE SUITABILITY OF EACH MIXTURE IN A REACTOR

The following metrics can be used to assess the suitability of each mixture in the reactor:

1) Work done to overcome coulomb barrier
2) Gamow-Sommerfeld factor
3) Energy released in one nuclear reaction

WORK DONE TO OVERCOME COULOMB BARRIER

This is calculated using the formula of electric potential energy between two point charges. Due to both nuclei being positively charged, repulsion occurs, which results in this value always being positive.

The formula used is:
Where:

$$U_{\text{coul}} = \frac{Z_1 \, Z_2 \, e^2}{4\pi\epsilon_0 r}$$

Z_1 and Z_2 are the atomic numbers of the two nuclei e is the principal charge (1.6×10^{-19} C)
ε_0 is the permittivity of free space (8.85×10^{-12} Fm^{-1})
r is the separation and calculated by adding the radii of the two nuclei based on data from the International Atomic Energy Association, ie. IAEA (Marinova 2013)

Table-1: Energy Values to Break the Coulomb Barrier

Fuel mixture	$r/10^{-15}$ m	Z_1	Z_2	$U\text{coul}/10^{-15}$ J	U_{coul}/keV
Deuterium-Tritium	3.90	1	1	59.0	369
Deuterium-Helion	4.11	1	2	112	700
Proton-Boron	3.28	1	5	350	2190

These values (table 1) provide an insight into which reaction will happen the most at the temperature in experimental reactors (such as the International Thermonuclear Experimental Reactor, ie. ITER). However, the probability of a reaction between two particles can be more representative and is calculated by calculating the Gamow-Sommerfeld factor.

Gamow-Sommerfeld Factor

$$P_g(E) = e^{-\sqrt{\frac{E_g}{E}}}$$

Where:

E is the sum of the kinetic energy of the two colliding particles

Assuming that the thermodynamic temperature is 150 million kelvin (achieved in ITER) and all particles are heated equally, we can use the following formula to calculate the energy for every mixture: $E = 3kT$
Where:
k is the Boltzmann Constant (1.38×10^{-23} JK^{-1}) T is the thermodynamic temperature

Therefore, $\mathbf{E = 6.21\times10^{-15}\ J}$

E_g is the Gamow energy.
The Gamow energy can be calculated by the following formula:

$$E_g \equiv 2m_r c^2 (\pi\alpha Z_a Z_b)^2$$

Where:
m_r is the reduced mass of the two nuclei and calculated by this formula:

$$m_r = \frac{m_a m_b}{m_a + m_b}$$

wherein m_a and m_b are the masses of the two nuclei, which can be obtained from the IAEA (Audi 2003)

and α is the fine structure constant, which is calculated by the formula:

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

where ħ is the reduced Planck's constant (1.05×10^{-34} Js)
The value of α is approximately 0.0073

Table-2: Gamow-Sommerfeld Factors for Each Fuel Mixture

Fuel mixture	Z_a	Z_b	$m_r/10^{-27}$ kg	$E_g/10^{-13}$ J	P(g)
Deuterium-Tritium	1	1	2.00	1.90	3.98×10^{-3}
Deuterium-Helion	1	2	2.00	7.59	1.58×10^{-5}
Proton-Boron	1	5	1.53	36.2	3.27×10^{-11}

The above values shown in table 2 indicate that there is a much greater difference between the probability for a reaction to occur in each fuel mixture than the difference between the energy needed to break the coulomb barrier for each fuel mixture.

In addition to the energy needed for a reaction to occur and the probability of one happening, the third important variable is the amount of energy released in one nuclear reaction.

ENERGY RELEASED PER REACTION

This can be calculated using Albert Einstein's mass-energy equation:

$\Delta E = \Delta mc^2$

Where:

ΔE is the energy released

and Δm is the change in mass

Table-3: Energy Released in One Nuclear Reaction for Each Fuel Mixture

Fuel mixture	$\Delta m/10^{-29}$ kg	$\Delta E/10^{-12}$ J	ΔE/MeV
Deuterium-Tritium	3.13	2.82	17.6
Deuterium-Helion	3.29	2.96	18.5
Proton-Boron	1.55	1.39	8.70

While all of the values shown in tables 1 through 3 are important, there is much more that needs to be considered. For instance, the practicality of obtaining fuel along with the economic and environmental impacts of using each fuel mixture in a reactor.

OBTAINING THE FUELS

Deuterium is naturally occurring in heavy water (D_2O). Heavy water is present in trace amounts of water with the ratio of deuterium molecules to hydrogen molecules being 1:6500. From water, deuterium can be obtained by isotope separation by the Girdler-Sulfide process (Rae 1978).

Tritium is much less abundant and has to be bred using a separate nuclear reaction that involves enriched lithium (^{6}Li), which is currently obtained by the COLEX process (only officially used in China and banned in the United States due to environmental concerns owing to excessive use of mercury required in the process). Not surprisingly, this has led to a renewed interest in other techniques such as laser separation (Yamashita 1979).

For any fusion reactor that involves tritium, a breeding blanket will also have to be added so that the nuclear reaction to form tritium can occur (as storing tritium is problematic due to its 12.33 year-long half-life).

The reaction is as follows: $^6\text{Li} + {}^1\text{n} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.8$ MeV.

Helium-3 is produced by the decay of tritium.

Protons, which are simply the nuclei of Hydrogen atoms, are very abundant and can be obtained by steam methane reforming or electrolysis of water.

Boron is obtained by recovery from brines with high magnesium content by solvent extraction using aliphatic alcohol (Xu 2021).

ENVIRONMENTAL AND ECONOMIC IMPACTS FOR THE FUELS

While obtaining each fuel, there are several environmental and economic factors that must be considered before any project to obtain these fuels on a large scale is considered.

One of the initial aspects to consider is that there are several environmental issues pertaining to the mining of lithium such as increased water usage, respiratory issues and biodiversity (Tedesco 2022).

The other aspect that poses a challenge for any reactor involving lithium is its increasing demand and the associated financial implications. Increasing demand for lithium due to the use of lithium-ion batteries for electric cars (Armstrong 2022), has caused substantial increase in lithium prices, posing challenges in making lithium commercially viable for any future reactor involving lithium (Garside 2023).

The use of boron is not without its challenges either. This is because boron is recovered from brine, which would result in the issues of obtaining brine being associated with any reactor involving boron. These issues include eutrophication and pH fluctuations in water, both of which will harm marine biodiversity (Giwa 2017).

Due to its several applications, particularly power generation, the demand for boron will also rise substantially, which will harm the commercial viability of any proton-boron reactor (Borates Today 2022).

DISCUSSION

Table-4: Comparison of the Key Metrics for Each Fuel in Reactor

Fuel Mixture	U_{coul}/keV	P(g)	E/MeV
Deuterium-Tritium	369	3.98×10^{-3}	17.6
Deuterium-Helion	700	1.58×10^{-5}	18.5
Proton-Boron	2190	3.27×10^{-11}	8.70

From this table, we can observe that the energy to break the coulomb barrier is least for deuterium-tritium, almost double for deuterium-helion and approximately triple that of deuterium-helion for proton-boron, which means that a substantially lower amount of energy is needed for a reaction to happen for deuterium-tritium.

It is also observed that the Gamow-Sommerfeld factor (at 150 million kelvin) is greatest for deuterium-tritium, approximately two orders of magnitude lower for deuterium-helion, and approximately six orders of magnitude lower than deuterium-helion for proton-boron. This means that the probability of a nuclear reaction happening between any two nuclei is much higher for deuterium-tritium than other mixtures by a large margin.

As for energy released, one deuterium-helion reaction releases 0.9 MeV more than one deuterium-tritium reaction. However, one proton-boron reaction releases less than half the energy released by one deuterium-tritium reaction. This means that both deuterium-tritium and deuterium-helion mixtures release large amounts of energy, with deuterium-helion releasing more.

However, when we consider the Gamow-Sommerfeld factor and energy required to break the coulomb barrier, the marginally lower amount of energy released from a deuterium-tritium reaction makes it more viable with respect to how it will be used in the reactor.

When we take environmental concerns into account, all fuel mixtures have significant drawbacks due to lithium mining and brine extraction, which will all be exacerbated if large scale exploitation of these fuels begins.

In terms of commercial viability, many issues will be faced with both lithium and boron due to their applications in other decarbonization projects. This will result in competing demand if employed which will result in prices rising even further. This has been observed and predicted for both lithium and boron.

CONCLUSION

Due to its greater potential for a larger amount of energy to be released, a deuterium-tritium mixture offers the most efficient pathway towards decarbonization of the electricity grid out of the three popular fuel mixtures described. While cost is a big problem for all three, due to the larger amount of energy output that can come from a deuterium-tritium mixture, such a reactor can sell more energy to more houses and businesses, which will result in it being more commercially viable than any other option in the long term. Therefore, it is the most feasible mixture for any future nuclear fusion reactors.

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