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P5_5 Nuclear Fusion: A Finite Resource?

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Abstract

In this paper we explore the limits of nuclear fusion, specifically looking at deuterium and tritium fusion, the primary fuels used in nuclear fusion reactors. The calculations within this paper find that, on Earth, the abundance of lithium-6 is the limiting factor in this reaction and the ocean reserves would be able to fuel anthropogenic activities on Earth for 7.1 million years given the total energy usage on Earth from 2023.

Introduction

Nuclear fusion, the reaction of two light nuclei combining to form a heavier one, has long been discussed as the solution to the energy problems on Earth. The particular reaction studied in this paper is the fusion of deuterium and tritium [1].

$$D + T \rightarrow {}^4\text{He} + n \tag{1}$$

We explore this reaction because it has been shown as the most efficient for use in nuclear reactors [2]. In this paper, we find out how long Earth could be powered purely by this fusion reaction given the current energy requirements and the availability of the reactants from the oceans. We assume: all of Earth's resources can be used for this cause (calculated from the ocean's stores as other sources are negligible in comparison), that Earth's energy requirements do not increase over time, and that the reaction is 100% efficient.

Method

To determine the maximum amount of energy that could be released using the ocean as the source of deuterium and indirectly tritium, it is necessary to calculate the abundances of both nuclei and determine which is the limiting factor. As the fusion reaction between deuterium and tritium requires 1 mole of each reactant to produce 1 mole of each product (equation 1), the limiting factor will simply be the reactant with fewer atoms available.

For every cubic metre of seawater, there are 33 grams of deuterium obtainable from heavy water, equivalent to 9.867×10^{21} deuterium nuclei [2]. Assuming that all of the water on Earth can be converted into deuterium (1.335×10^{18} m^3, [3]), there would be 1.094×10^{19} moles of deuterium available for nuclear fusion.

$$n + \text{Li}^6 \rightarrow \text{He}^4 + \text{H}^3 \tag{2}$$

Tritium is sourced from lithium as shown by equation 2, whereby for every lithium-6 nucleus, a tritium nucleus can be formed. In a Tokamak fusion reactor, this reaction occurs when neutrons from the plasma escape and interact with a layer of lithium covering the inner surface [2]. Lithium constitutes approximately 0.15 ppm of the ocean, equivalent to 2.001×10^{14} kg, of which approximately 7.59% (1.51×10^{13} kg) is lithium-6, the isotope required for nuclear fusion [4]. This equates to 1.314×10^{39} tritium nuclei available for fusion when utilising the entire ocean's lithium reserves.

As the available number of tritium nuclei is less than the available number of deuterium nuclei (by a factor of 10^4), all of the lithium available in the ocean is used to form tritium and therefore is the limiting factor for this process.

The Q-value equation for a nuclear reaction is shown below:

$$Q = (m_x + m_a - m_b - m_y)\, c^2 \tag{3}$$

where 'm_x' and 'm_a' refer to the reactants and 'm_b' and 'm_y' are the products. Using the values listed in table 1; the Q value for the neutron capture producing tritium is 7.682×10^{-13} J, the Q value for the fusion reaction of deuterium and tritium is 2.822×10^{-12} J, resulting in an overall Q value for this process of 3.590×10^{-12} J.

Nuclei	Mass (u)
Deuterium (D)	2.013553
Tritium (T)	3.015501
Helium (^{4}He)	4.001506
Neutron (n)	1.008665

Table 1: Masses of nuclei in the fusion reaction [4]

Using all of the available tritium, 1.314×10^{39} reactions can occur, releasing 4.706×10^{24} Joules of energy, equivalent to 1.307×10^{12} TWh. Given the total energy usage on Earth in 2023 was 183000 TWh, converting all of the oceans available lithium-6 to tritium and fusing with deuterium, at 2023's energy consumption rate, Earth could be fuelled for 7.1 million years [5].

Discussion

Whilst it is clear that the nuclear fusion reaction of deuterium and tritium generates enough energy to replace all current energy production systems on Earth, this process has its difficulties. Extracting 30,000 metric tonnes of lithium annually from the oceans poses a significant challenge. Despite reports of progress in mining techniques with "inexpensive" methods developed, there is no currently commercialised method to extract lithium on this scale [6].

The calculations in this paper also assume that through the nuclear fusion processes, 100% of the released energy can be harnessed. In reality, nuclear fusion is still an unproven technology and has only generated positive energy returns for timescales less than 17 minutes [7].

Conclusion

The calculations provided in this paper show the possible rewards of implementing nuclear fusion in a scenario where 30,000 metric tonnes of lithium is extracted from the ocean each year to fuel the energy requirements of modern-day civilisation for the next 7.1 million years.

References

[1] Robert W Conn. *nuclear fusion — Development, Processes, Equations, Facts.* Encyclopædia Britannica, Dec. 2018. URL: https://www.britannica.com/science/nuclear-fusion.

[2] admin. *Fuelling.* ITER - the way to new energy, June 2023. URL: https://www.iter.org/machine/supporting-systems/fuelling.

[3] NOAA. *How much water is in the ocean?* Noaa.gov, 2019. URL: https://oceanservice.noaa.gov/facts/oceanwater.html.

[4] *Table of Isotopic Masses and Natural Abundances.* URL: https://www.chem.ualberta.ca/~massspec/atomic_mass_abund.pdf.

[5] Hannah Ritchie, Max Roser, and Pablo Rosado. *Energy Production and Consumption.* Our World in Data, Jan. 2024. URL: https://ourworldindata.org/energy-production-consumption.

[6] Vishwam Sankaran. *Scientists discover cheap and sustainable method to extract lithium from seawater.* The Independent, Aug. 2024. URL: https://www.independent.co.uk/tech/lithium-extraction-sustainable-seawater-brine-b2599965.html.

[7] International Energy Forum. *How Close are we to Unlocking the 'Limitless' Energy of Nuclear Fusion?* International Energy Forum, June 2022. URL: https://www.ief.org/news/how-close-are-we-to-unlocking-the-limitless-energy-of-nuclear-fusion.