Driven nuclear power at sea for electricity and shipping

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Abstract

Nuclear power was analyzed as an alternative to fossil fuel combustion for propulsion of large boats. In particular, ...

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1 Introduction

There are many obstacles to decarbonising a modern economy. Two of these are the Carbon intensity of transportation and the lack of zero-Carbon power that may shutdown during periods of high demand. The solution to both of these problems may lie in nuclear power. We propose a small reactor system with a **60-MWe output** that may sell power to the shore during periods of peak electricity demand or use its power for the propulsion of short-range vessels during off-peak hours.

Offshore nuclear power has advantages beyond its capacity to propel shipping vessels. Namely, these plants are remote from any major population centers, far enough offshore that they do not face risks from tall waves and tsunamis, and their mobility allows them to supply power to remote locations or to cities that have recently survived a natural disaster. Additionally, a plant that sits in the ocean has fantastic thermal safety relative to a terrestrial plant thanks to the infinite heat sink provided by the ocean. To complement this thermal safety we have elected to design a core that achieves the greatest criticality safety possible by designing a subcritical core that is driven by an external neutron source.

In particular, we imagine an annular assembly in which the inner region (which we shall call the "passive core") is designed such that the infinite multiplication factor $k_\infty = 1$. This passive system will be driven by a source of neutrons blanketed around it. These neutrons may be supplied either by a higher-enriched assembly of Uranium or by the radiocative decay of a coupled Alpha-Neutron source such as Plutonium and Berrylium. In either case, this source must be easily removed from the passive core such that the a meltdown due to excessive fission heat is impossible.

2 Background and State of the Art

2.1 Shipping

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Background and state of the art

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3.1.1 Oceanic tug boat

3.1.2 Offshore power plant and coastal tug boat

3.2 Reactor concept

3.2.1 Core concept

3.2.2 Neutronics analysis

The following analysis determines the enrichment required to reach $k_\infty = 1$:

$$k_\infty = \eta f = 1 \tag{1}$$

$$= \nu \frac{\sigma_f^F}{\sigma_a^F} \frac{\Sigma_a^F}{\Sigma_a} \tag{2}$$

Approximate values of these parameters are given in table 1.

Table 1: Approximate values of nuclear properties germaine to equation 2, [9]

Parameter	Value	Unit
ν	2.4	-
σ_f, 235	1.2	barns
σ_a, 238	0.1	barns

The macroscopic cross section is by definition $\Sigma = N\sigma = \frac{\rho N_{av}}{A}\omega$. Equation 2 then reduces to:

$$1 = \nu \frac{{}^{235}\sigma_f}{{}^{235}\sigma_a} \frac{\frac{\omega}{235}{}^{235}\sigma_a}{\frac{1-\omega}{238}{}^{238}\sigma_a + \frac{\omega}{235}{}^{235}\sigma_a} \tag{3}$$

$$= \nu \frac{{}^{235}\sigma_f}{{}^{238}\sigma_a} \frac{238\omega}{235(1-\omega)} \tag{4}$$

This equation may be solved for ω rather easily, obtaining a numerical value of 4.705 % with the data in table 1.

If the fuel is UO_2, then the mass of Uranium per mass of fuel is:

$$\frac{m_U}{m_{UO2}} = \frac{238(1-\omega)+235\omega}{238(1-\omega)+235\omega+32} \quad (5)$$

$$= 0.8814 \frac{grams}{gram} \quad (6)$$

It is now easy to find the number of U_{235} atoms per gram of fuel:

$$n_{235} = \omega \frac{m_u}{m_{UO_2}} \frac{N_{av}}{235} \quad (7)$$

$$= 1.063 \times 10^{20} \quad (8)$$

We can now determine the required mass of Uranium to produce a certain amount of energy. Knowing that each fission produces $200MeV = 3.2 \times 10^{-11}$ Joules. Knowing the number of U_{235} atoms per gram of fuel to be 1.063×10^{20}, we can conclude that each gram of fuel will supply $3.2 \times 10^{-11} \times 1.063 \times 10^{20} = 3.4 \times 10^9$ Joules. An output of 120-MWe-years would therefore require at least 3705 kg of fuel, assuming a thermal efficiency of 30 %.

The volume of UO_2 that corresponds to this mass is 0.338 cubic meters. **We will assume that the volume of our cylindrical core is equal to the volume of a sphere of the same radius, which is to say** $H = \frac{4}{3}R$. Under this assumption, the radius of our core is $(\frac{3}{4}\pi V)^{1/3} = 0.432meters$, giving a height of $0.58meters$. This first estimate of the height (which will most likely be shorter than the final value) will be very useful in the thermal analysis.

3.2.3 Thermal analysis

Let us begin by estimating the mass flow rate required to remove the fission heat at steady state. With a simple energy balance, it becomes apparent that heat flux is related to the heat capacity and mass flow rate of the coolant and the temperature change across the length of the channel as follows:

$$q = \dot{m} c_p \Delta T \quad (9)$$

$$\dot{m} = \frac{q}{c_p \Delta T} \quad (10)$$

Our coolant, Lead-Bismuth Eutectic, is liquid between approximately 200-1670 Degrees C. Conservatively, the ΔT may then approach 1,000 Kelvin. The isobaric heat capacity of this fluid in this temperature range is approximately $130\frac{J}{kgK}$ [?].

The Mass flow rate needed to achieve 60 MWe is therefore:

$$\dot{m} = \frac{q}{c_p \Delta T} \tag{11}$$

$$= \frac{200 \times 10^6 \frac{J}{s}}{130\frac{J}{kgK} \times 10^3 K} \tag{12}$$

$$= 340\frac{kg}{s} \tag{13}$$

Dividing this flow rate by the density of LBE (approximately 9000 kg/m3) gives an approximate mass flow rate of 0.038 $\frac{m^3}{s}$.

3.2.4 Materials analysis

3.2.5 Alternatives

Conceptual design

4 Conclusions

Conclusions

5 Acknowledgements

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References

[1] P. ALEKSEEV, N. E. KUKHARKIN, Y. N. UDYANSKII, T. D. SHCHEPETINA, I. A. BELOV, S. A. SUBBOTIN, A. A. D. A. A. SEDOV,

M. M. KASHKA, and V. V. BASHAEV, "ADVANCED NUCLEAR POWER SYSTEMS WITH MICROPELLETED FUEL FOR NUCLEAR-POWERED SHIPS," *Atomic Energy Voll 99 No. 1* (2005).

[2] J. CARLTON, R. SMART, and V. JENKINS, "The nuclear propulsion of merchant ships: Aspects of engineering, science and technology," *Journal of Marine Engineering and Technology* (2011).

[3] J. GRAVINA, J. BLAKE, A. SHENOI, S. TURNOCK, and S. HIRDARIS, "CONCEPTS FOR A MODULAR NUCLEAR POWERED CONTAINERSHIP," (2013).

[4] W. SHI HAN and T. LIU, "A new marine propulsion system," (2003).

[5] M. HUSSAIN, F. REITSMA, M. H. SUBKI, and H. KIUCHI, "Advances in Small Modular Reactor Technology Developments," (2018).

[6] S. HIRDARIS, Y. CHENG, P. SHALLCROSS, J. BONAFOUX, D. CARLSON, B. PRINCE, and G. SARRIS, "Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion," (2013).

[7] J. JACOBS, "Nuclear Short Sea Shipping: The integration of a Helium cooled reactor in a 800 TEU Container Feeder," (2007).

[8] J. R. RUSSELL, "Holtec International Response to the DOE RFI," (2017).

[9] JAEA, "Japan Atomic Energy Agency Nuclear Data Center," (2018).