

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 Beryllium. In either case, this source must be easily removed from the passive core such that the a meltdown due to excessive fission heat is zero.

2 Background and State of the Art

2.1 Shipping

2.2 Marine nuclear power

2.2.1 Propulsion

2.2.2 Electricity generation

2.2.3 Driven systems

Background and state of the art

3 Conceptual Design

3.1 Naval concept

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 $k_\infty = 1$:

$$k_\infty = \eta f = 1 \quad (1)$$

$$= \nu \frac{\sigma_f^F \Sigma_a^F}{\sigma_a^F \Sigma_a} \quad (2)$$

Approximate values of these parameters are given in table 1.

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

Parameter	Value	Unit
ν	2.4	-
$\sigma_f, 235$	1.2	barns
$\sigma_a, 238$	0.1	barns

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

$$1 = \nu \frac{{}^{235}\sigma_f \frac{\omega}{235} {}^{235}\sigma_a}{{}^{235}\sigma_a \frac{1-\omega}{238} {}^{238}\sigma_a} \quad (3)$$

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

Upon defining a new variable $\xi = \nu \frac{^{235}\sigma_f}{^{238}\sigma_a}$, we find:

$$\frac{1}{\xi} = \frac{238\omega}{235(1-\omega)} \quad (5)$$

$$\omega = \frac{235}{238\xi + 235} < 1 \quad (6)$$

Upon inserting the tabulated values for these cross sections, we find $\xi = 4.2$ and $\omega = 0.0336 = 3.4\%$. The bulk of the reactor can thus be fueled without HEU.

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

$$\frac{m_U}{m_{UO_2}} = \frac{238(1-\omega) + 235\omega}{238(1-\omega) + 235\omega + 32} \quad (7)$$

$$= 0.8817 \frac{\text{grams}}{\text{gram}} \quad (8)$$

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

$$n_{235} = \omega \frac{m_u}{m_{UO_2}} \frac{N_{av}}{235} \quad (9)$$

$$= 7.906 \times 10^{21} \quad (10)$$

If we **assume that $\frac{3}{4}$ of the fissions occur in U_{235}** , then the total fissile atoms per gram of fuel is 1.05×10^{22} .

We can now determine the required mass of Uranium to produce a certain amount of energy. The core's power is related to the fission rate by a factor of 200 MeV per fission. We will **assume a core power of 0.175 GWth** for this analysis. This value roughly corresponds to 50 MWe for typical values of efficiency, which is close to the power output of the reactors we seek to imitate. The fission rate in our reactor is then $1.75 \times 10^8 \frac{\text{Joules}}{\text{sec}} \times \frac{1 \text{MeV}}{1.6 \times 10^{-13} \text{Joules}} \times \frac{1 \text{Fission}}{200 \text{MeV}} = 5.5 \times 10^{18} \frac{\text{fissions}}{\text{second}}$. Now consider a **2 year refueling cycle**, which requires $5.5 \times 10^{18} \frac{\text{fissions}}{\text{second}} \times \frac{6.3 \times 10^7 \text{s}}{2 \text{years}} = 3.5 \times 10^{26} \frac{\text{fissions}}{\text{cycle}}$.

Returning to our value of fissile atoms per gram of UO_2 , we can find the mass of Uranium required to power our core for two years. Recall that we anticipate 1.05×10^{22} fissile nuclei per gram of fuel. The mass of fuel needed is then $\frac{3.5 \times 10^{26}}{1.05 \times 10^{22}} = 2.90 \times 10^4 \text{g} = 29 \text{kg}$. However, we do not expect to burn

every fissile isotope, **so this value should be adjusted by a factor of 1.7**, so that our first estimate of the mass of fuel is 49.3 kg.

The density of UO_2 is $10970 \frac{kg}{m^3}$. The Volume of this much fuel is therefore $V = \frac{49.3kg}{10970 \frac{kg}{m^3}} = 0.045m^3$

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 $(\frac{3}{4}\pi V)^{1/3} = 0.47meters$, giving a height of $0.63meters$. 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:

$$q'' = \dot{m}c_p\Delta T \quad (11)$$

$$\dot{m} = \frac{q''}{c_p\Delta T} \quad (12)$$

We can estimate q'' by dividing the thermal power by the surface area of the fuel, which gives us $q'' = \frac{1.75 \times 10^8}{2\pi N 0.63 \times 10^{-2}}$ if there are N fuel rods, each with 1-cm radius and 1.43 meters tall. For this preliminary analysis, **we will assume 100 rods**. It then follows that the heat flux from such a system is $4.42 \times 10^7 \frac{w}{cm^2}$.

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 $130 \frac{J}{kgK}$ [2]. The Mass flow rate needed is therefore:

$$\dot{m} = \frac{q''}{c_p \Delta T} \quad (13)$$

$$= \frac{4.42 \times 10^7 \frac{w}{cm^2}}{130 \frac{J}{kgK} \times 1000} \quad (14)$$

$$= 340 \frac{kg}{s} \quad (15)$$

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] JAEA, “Japan Atomic Energy Agency Nuclear Data Center,” (2018).
- [2] OECD, “Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal Hydraulics, and Technologies,” (2015).