Nuclear-powered Shipping

Louis Kissinger, Brad Ellis, and Adam Pichman
Course: NPRE 458; Advisor: Magdi Ragheb

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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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Background and state of the art

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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:

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

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

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

$$\frac{1}{\xi} = \frac{238\omega}{235(1-\omega)} \tag{5}$$
$$\omega = \frac{235}{238\xi + 235} < 1 \tag{6}$$

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:

$$\frac{m_U}{m_{UO2}} = \frac{238(1-\omega) + 235\omega}{238(1-\omega) + 235\omega + 32} \tag{7}$$
$$= 0.8817\frac{grams}{gram} \tag{8}$$

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

$$n_{235} = \omega\frac{m_u}{m_{UO_2}}\frac{N_{av}}{235} \tag{9}$$
$$= 7.906 \times 10^{21} \tag{10}$$

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^{21}.

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 1.75 GWth** for this analysis. This value roughly corresponds to 500 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 $1.75\times10^9\frac{Joules}{sec}\times\frac{1MeV}{1.6\times10^{-13}Joules}\times\frac{1Fission}{200MeV} = 5.5\times10^{19}\frac{fissions}{second}$.

In an **assumed 2-year refueling cycle** we would then need $5.5 \times 10^{19}\frac{fissions}{second} \times \frac{3.15\times10^7 s}{y} = 1.723 \times 10^{27}$ fissile atoms.

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. This number is $5.5 \times 10^{19}\frac{fissions}{second} \times \frac{6.3\times10^7 s}{2years} = 3.5 \times 10^{27}\frac{fissions}{cycle}$, which can be used to find the mass of fuel, and ultimately the volume of the reactor. Recall that we anticipate 1.05×10^{21} fissile nuclei per gram of fuel. The mass of fuel needed is then $\frac{3.05\times10^{27}}{1.05\times10^{21}} = 2.90 \times 10^6 g = 2900 kg$. 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 4930 kg.

The density of UO_2 is $10970\frac{kg}{m^3}$. The Volume of this much fuel is therefore $V = \frac{4930kg}{10970\frac{kg}{m^3}} = 4.50m^3$

We will assume that the volume of our cylindrical core is equal to the volume of a cylinder of the same radius, which is to say $H = \frac{4}{3}\pi R$. Under this assumption, the radius of our core is $(\frac{3}{4}\pi V)^{1/3} = 2.20 meters$, giving a height of $2.93 meters$. 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:

$$q'' = \dot{m} c_p \Delta T \tag{11}$$

$$\dot{m} = \frac{q''}{c_p \Delta T} \tag{12}$$

We can estimate q” by dividing the thermal power by the surface area of the fuel, which gives us $q'' = \frac{1.5\times10^9}{2\pi N 2.93\times10^{-2}}$ if there are N fuel rods, each with 1-cm radius 2.93 meters tall

3.2.4 Materials analysis

3.2.5 Alternatives

Conceptual design

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Conclusions

5 Acknowledgements

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