Python for physics: Project

axel wohlin

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UPPSALA
UNIVERSITET

Contents

1 Introduction **3**

2 Task 1 **3**
2.1 Discussion 3

3 Task 2 **6**

1 Introduction

Reactor physics is the applied study and engineering applications of utilizing fission chain reactions for a nuclear reactor to produce energy [1]. In a nuclear reactor while running there are neutrons travelling with varying energies, and in the nuclear fuel there are nuclides which nucleuses have a probability of absorbing these neutrons. This is called the absorption cross section of said nuclide, σ_a, and it is comprised of the probability that the nucleus absorbs the neutron and "captures" it, σ_c, or that it absorbs it and then undergoes a fission reaction, σ_f.
It is evident that for a chain reaction process relating to these cross sections, the average neutron has to cause at least 1 new neutron to emerge from fission for this chain reaction to be self sustaining. This is why it is of great interests to reactor scientists and engineers to study the absorption cross section and measurements relating to it for nuclides which can be used as fuel in nuclear reactors. One way to more accurately represent this is with the reproduction factor,

$$\eta = \nu \frac{\Sigma_f}{\Sigma_a}$$

, where ν is the neutron multiplicity (how many neutrons arise on average from a fission reaction), and $\Sigma = \Sigma \sigma N$, where σ is the cross section and N is the nuclide density in the material.
In modern nuclear fuel, natural uranium is almost alwasy enriched with super-natural levels of U235. For the reproduction factor this means that in nuclear fuel U235 will have a higher nuclide density than for natural uranium. In this report I will show why this enrichment process is beneficial.
All the code used for calculations and plotting can be find in the minted section at the end of the report.

2 Task 1

2.1 Discussion

It is clear from Figure 2 that on average U235 has a much higher fission cross section than U238, and we see from Figure 1 that even though it often has a higher capture cross section than U238 as well this difference is much smaller. A noteworthy observation is how the fission cross section for U235 increases for very low energy neutrons. In a nuclear reactor you almost always have a moderator (always in BWRs and PWRs), which is a material (often water or heavy water) used for slowing down the neutrons. This fission cross section data showcases why a potent moderator material is so beneficial to ensure a greater probability that the neutrons travelling interact with U235 and cause fission.
To answer the task it is clear from the data that U235 is better nuclear fuel and that a moderating material is key for slowing down the neutrons which increases the fission cross section of the U235.

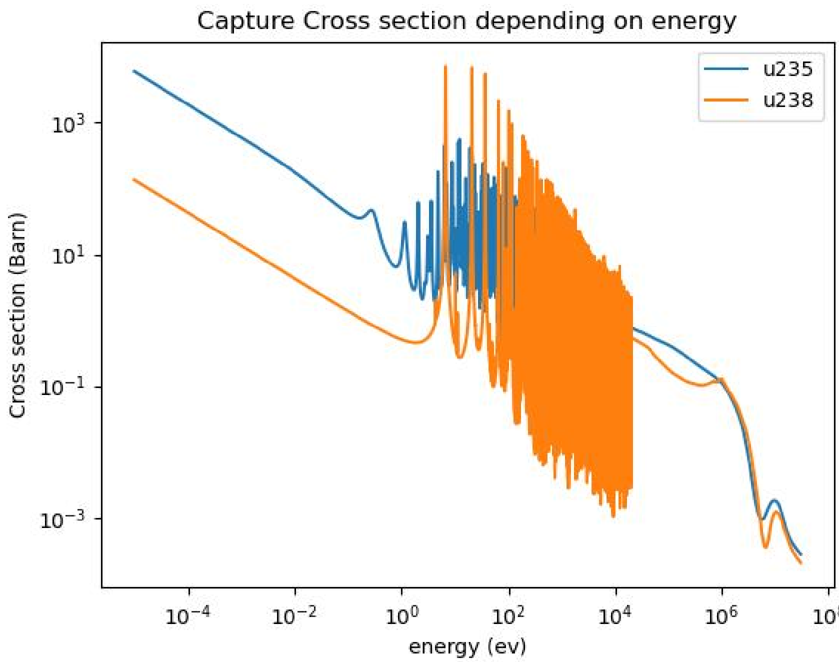

Figure 1: Capture cross section for u238 and u235 as a function of neutron energies

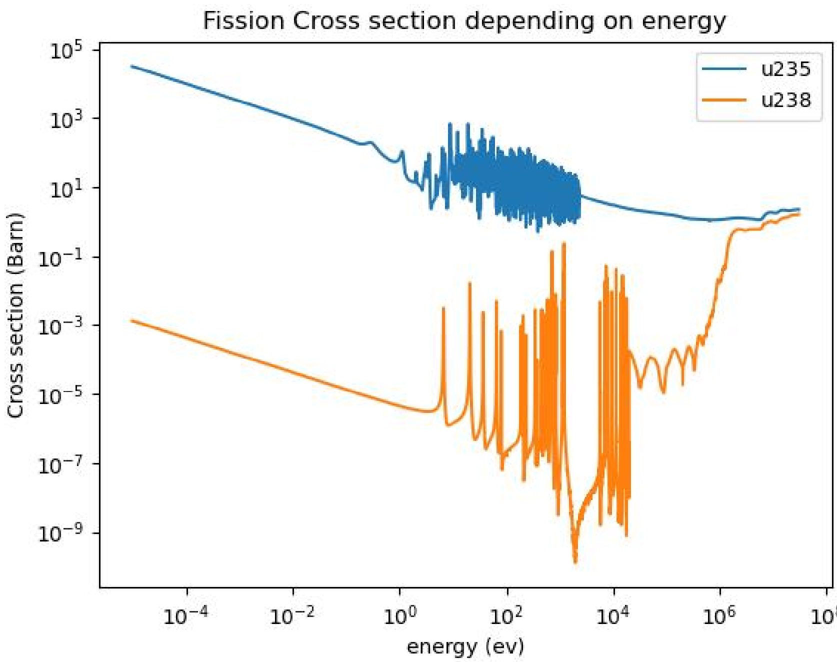

Figure 2: Fission cross section for u238 and u235 as a function of neutron energies

3 Task 2

Below in Figures 3 and 4 I have plotted the reproduction factor of nuclear fuel for varying enrichment levels, it was a bit hard to distinguish between the enrichment levels in Figure 4 so I used only low energy neutrons for Figure 3 to more clearly see the differences.

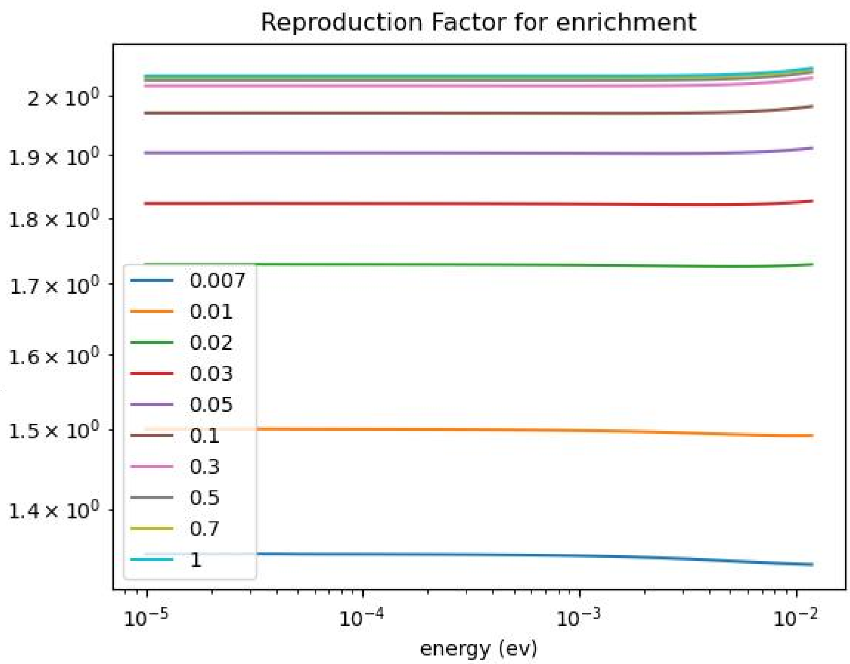

Figure 3: A close up of the reproduction rate as a function or enrichment level for low energy neutrons

As we can see from Figure 3, the differences in the reproduction factor for the low enrichment levels (natural uranium level - 3%) is quite large. However we quickyl see diminishing returns for higher levels of enrichment, with the jump from 3% enrichment to 10% enrichment being noticeably smaller than the jump from 1% to 3%.
Based of this data we and the fact that uranium enrichment is a very very costly process [1], it is understandable that nuclear reactor engineers only want to enrich the nuclear fuel until the benefits start to diminish. This is likely why most modern reactors use nuclear fuel with an enrichment level between 3-5%.

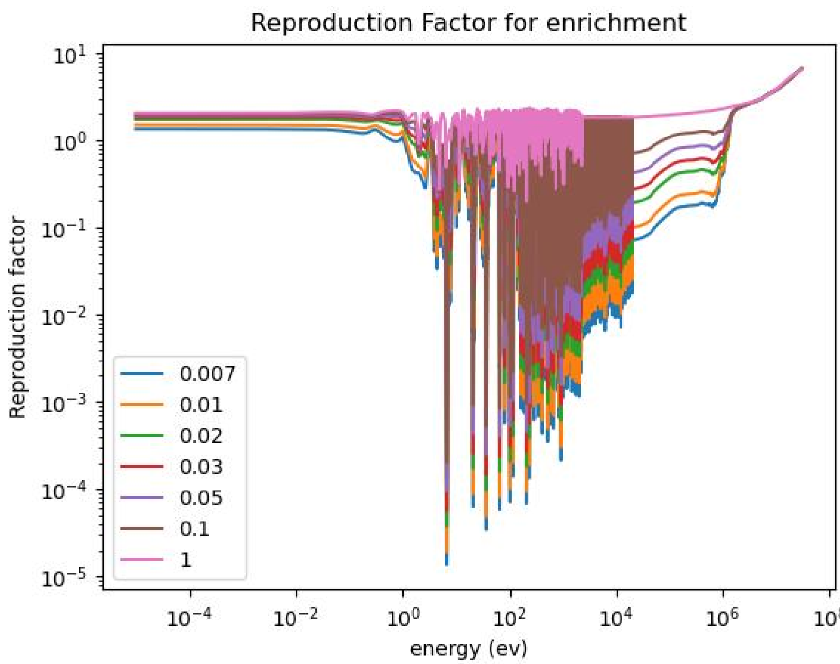

Figure 4: A plot of the reproduction factor as a function of varying enrichment levels for a broad energy-spectrum of neutrons

Below in Figure 5 I found an image showcasing the reproduction factor depending on U235 enrichment in nuclear fuel plotted for some average energy of neutrons (look at the reference for further information). There it is very clear that there really are diminishing returns, as at 1% the curve looks almost exponential, whereas at 1% it looks linear, and at 5% it starts looking like a limit asymptote. I feel like this figure further illustrates why most nuclear reactors use fuel enriched between 3-5%, as after that point the costs greatly increase for diminished returns.

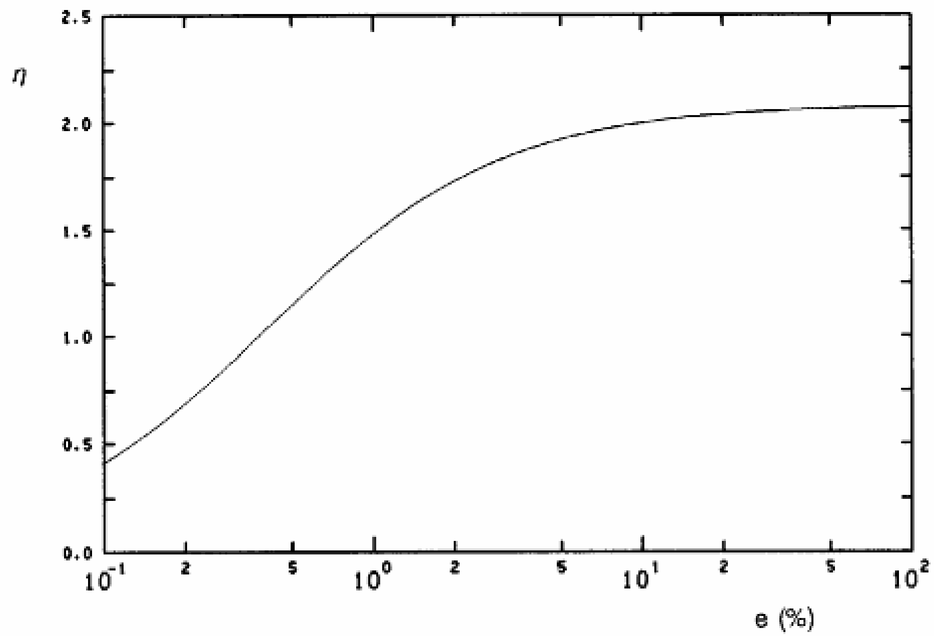

Figure 5: The reproduction factor as a function of u235 enrichment in nuclear fuel[2]

```
#Project file for Axel Wohlin
#Latest edited 03/08-22

import numpy as np
import matplotlib.pyplot as plt
from scipy import interpolate


#Below I open the files and extract all the contents, I think there's a better way to open
.csv files but I was more familiar with this
filenames = ["U5_U8_nubar.csv","U235_xs_cap.csv","U235_xs_nf.csv","U238_xs_cap.csv",\
"U238_xs_nf.csv"]
filecontents = []
for file in filenames:
    temporary = open(file, "r")
    filecontent=temporary.read()
    temporary.close()
    filecontents.append(filecontent.strip().split())

nubar_U238=list(np.float_(filecontents[0][12::3]))
nubar_U235=list(np.float_(filecontents[0][11::3]))
energy1 = list(np.float_(filecontents[0][10::3]))

energy2 = list(np.float_(filecontents[1][7::2]))
u235_sigma_c = list(np.float_(filecontents[1][8::2]))
energy3 = list(np.float_(filecontents[2][7::2]))
u235_sigma_f = list(np.float_(filecontents[2][8::2]))

energy4 = list(np.float_(filecontents[3][7::2]))
u238_sigma_c = list(np.float_(filecontents[3][8::2]))

energy5 = list(np.float_(filecontents[4][7::2]))
u238_sigma_f = list(np.float_(filecontents[4][8::2]))

#Below I make a loglog plot of the fission cross section for both u235 and
u238 to show how they compare for all energy levels
plt.figure()
plt.title('Fission Cross section depending on energy')
plt.xlabel('energy (ev)')
plt.ylabel('Cross section (Barn)')
plt.loglog(energy3,u235_sigma_f)
plt.loglog(energy5,u238_sigma_f)
plt.legend(['u235','u238'])
plt.savefig("sigma_f.jpg")

#Do the same thing for the capture cross section
```

```
plt.figure(2)
plt.title('Capture Cross section depending on energy')
plt.xlabel('energy (ev)')
plt.ylabel('Cross section (Barn)')
plt.loglog(energy2,u235_sigma_c)
plt.loglog(energy4,u238_sigma_c)
plt.legend(['u235','u238'])
plt.savefig("sigma_c.jpg")
plt.show()

#Below this point my code gets a bit messy because I was really having
trouble with data types and dimensions not working
#so I basically made an interpolated function out of everything to
ensure that it always worked and could easily be modified.
#I used scipy's interpolate function because I knew how it worked.
NU_238 = interpolate.interp1d(energy1, nubar_U238)
NU_235 = interpolate.interp1d(energy1, nubar_U235)

f_inter_u235f = interpolate.interp1d(energy2, u235_sigma_f)
f_inter_u238f = interpolate.interp1d(energy5, u238_sigma_f)
f_inter_u235c = interpolate.interp1d(energy2, u235_sigma_c)
f_inter_u238c = interpolate.interp1d(energy5, u238_sigma_c)

plt.figure()
plt.title('Reproduction Factor for enrichment')
plt.xlabel('energy (ev)')
plt.ylabel('Reproduction factor')

enrichment_levels = [0.007,0.01,0.02,0.03,0.05,0.1,0.3,0.5,0.7,1]

for enrichment in enrichment_levels:
    temp = (enrichment*f_inter_u235f(energy4)*NU_235(energy4) + (1 - enrichment)*f_inter_u23
        (enrichment*f_inter_u235c(energy4) + (1 - enrichment)*f_inter_u238c(energy4) + enric
    plt.loglog(energy4,temp)

plt.legend([andel for andel in enrichment_levels])
plt.savefig("repro_fac.jpg")
plt.show()

#Again I used a loglog plot and just made a new plot in the same figure
for each enrichment level
```

References

[1] Wikipedia, "Wikipedia nuclear reactor physics." https://en.wikipedia.org/wiki/Nuclear$_{r}eactor_{p}hysics. \quad visitedon01/08 -$ 2022.

[2] Nuclear-power.com, "Reproduction factor as function of uranium enrichment." https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-fission-chain-reaction/reproduction-factor/. visited on 01/08-2022.