NE 250, F17
Prompt and Delayed Neutrons

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1 Introduction

In reactors and other fission systems, neutron populations vary over time. We're not going to dive into this too much, but we will introduce some preliminary concepts that will set you up for a guest lecture next class. In particular, this lesson will cover the concepts of prompt and delayed neutrons, as well as the importance of delayed neutrons for reactor control.

Note that much of this can be found in Duderstadt and Hamilton.

1.1 Transient Analysis

Transient analysis is necessary when the neutron flux varies with time. Commonly studied transient scenarios include normal startup and shutdown of a reactor as well as abnormal scenarios that cause reactivity increases and decreases during otherwise normal operation.

2 Delayed Neutrons

Reactor control relies on a balance of neutrons. When an isotope fissions, it produces neutrons, energy, and fission products. Most of the neutrons emitted due to fission are *prompt*, nearly all released within $10^{-10}s$ of the fission. The average lifetime of prompt neutrons in a thermal reactor is $10^{-4}s$ and in a fast reactor is $10^{-7}s$.

2.1 Delayed Neutron Emission

However, a fraction of the neutrons appear later. Some fission products are unstable and decay within seconds or minutes of the fission. Among those, a few decay by neutron emission. These particular fission products are called "delayed neutron precursors". ^{87}Br, for example, has a half-life of 55.9 seconds and tends to decay by neutron emission.

2.2 Delayed Neutron Precursor Data

Typically, we group delayed neutron precursors into 6 or 8 groups according to their half-lives. Standardized data exist for these calculations, as in Table 1.

j	$t_{1/2}$ $[s]$	λ_j^d $[1/s]$	η_j $[n/f]$	β_j
1	55.72	0.0124	0.00052	0.000215
2	22.72	0.0305	0.00546	0.001424
3	6.22	0.111	0.00310	0.001274
4	2.30	0.301	0.00624	0.002568
5	0.614	1.14	0.00182	0.000748
6	0.230	3.01	0.00066	0.000273

Table 1: Delayed neutron data, ^{235}U thermal fission [**?**].

In the above table:

$$
\begin{aligned}
j &= \text{group index} \\
t_{1/2} &= \text{half life}[s] \\
\lambda_j^d &= \text{decay constant}[1/s] \\
\eta_j &= \text{fission factor}[neutrons/fisson] \\
\beta_j &= \text{delayed neutron fraction} \\
&\quad [\text{neutrons from delayed fission / neutrons from all fission}]
\end{aligned}
$$

These parameters are used to incorporate the contributions of delayed neutrons into transient calculations. Note that in this case the sum of the β_j terms is 0.0065. That means 0.0065 of every 1.0 neutrons coming from fission is delayed.

When we add in delayed neutrons, the average neutron lifetime because approximately 0.1 s, which is much higher than the prompt value of $10^{-6}s$ to $10^{-4}s$.

3 Delayed Neutrons and Reactor Control

These delayed neutrons are critical to controlling the reactor. To capture the reasons why, we will need the following definitions.

$$\begin{aligned}
\rho =& \text{reactivity} \\
=& \frac{k-1}{k} \\
k =& \text{multiplication factor} \\
& (k < 1) \rightarrow \text{negative reactivity} \\
& (k > 1) \rightarrow \text{positive reactivity} \\
& (k = 1) \rightarrow \text{critical} \\
\beta =& \text{delayed neutron fraction} \\
& (\rho < \beta) \text{ delayed supercriticality} \\
& (\rho > \beta) \text{ prompt supercriticality} \\
l =& \text{mean neutron lifetime}
\end{aligned}$$

3.1 Units of Reactivity

Note that the units of ρ can be confusing.

Unit	Definition	Example
Δk	actual PRKE units	0.0005
$\%\Delta k$	percent notation of Δk	0.05%
pcm	per cent mille	50pcm
Dollars	$\frac{\Delta k}{\beta}$	\$1
Cents	100 cents per dollar	100 cents
Milli-beta	1000 milli-beta per dollar	1000 milli-beta

Table 2: Common units of reactivity.

3.2 Thought Experiment

Reactor power behaves as:

$$l = \text{mean generation time} \tag{1}$$

$$n(t+l) = n(t) + l\frac{dn}{dt} = kn(t) \tag{2}$$

such that

$$\frac{dn}{dt} = \left(\frac{k-1}{l}\right) n(t) \tag{3}$$

which gives

$$n(t) = n_0 e^{\frac{(k-1)t}{l}} \tag{4}$$

characterized by the time constant

$$\begin{aligned} T &= \text{reactor period} \qquad (5) \\ &= \frac{l}{k-1} \,. \qquad (6) \end{aligned}$$

In a universe without delayed neutrons, the mean neutron lifetime (l) would be the prompt neutron lifetime, l_p. Noting that the prompt neutron lifetime is about $2 \times 10^{-5} s$, take a moment to think about the implications of this. What would it be like to try to control a reactor like that?

Exercise *If a control rod were moved to introduce an excess reactivity of* $0.0005\Delta k$*, what would the power be one second later?*
(a) with l = 0.1s
(b) with l = 1 $\times$ 10^{-4}s

Here's what it looks like when something goes prompt supercritical on purpose: `https://www.youtube.com/watch?v=6I3JKYdGWTE`