Time Dependence of Fission Energy Deposition in Nuclear Thermal Rockets

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Question: How much energy do we get per fission?

Answer: Less than most estimates and there is a notable time dependence.
## Current Estimates

<table>
<thead>
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<th>Total recoverable energy from a fission (MeV)</th>
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Problem

Do these estimates apply to an NTR?

• No Time Dependence
  – NTRs have a shorter operation than a utility reactor but longer operation than a pulse reactor
  – Fission fragments not in equilibrium
  – ~7% of power is decay heat at time of shut down

• Leakage out of the system
  – NTRs are small and are unreflected on one side

• Different spectrum and core materials
  – ~4% of power is radiative capture
Knowing recoverable energy per fission is fundamental to many nuclear engineering calculations

- Heat deposition
- Shielding
- Decay Heat
- Burnup/\(^{135}\)Xe
- Transients/Control systems
Fission

\[ Q_{eff}^f(t) = Q_p^f(t) + Q_d^f(t) \]

\( Q_{eff}^f(t) \) Effective energy absorbed in the reactor after a fission event as of time \( t \) after the fission event.

\( Q_p^f(t) \) Prompt energy absorbed in the reactor within 1 millisecond.
- Fission Fragments
- Prompt gammas and betas
- Non-fission exothermic reactions with prompt neutrons and gammas

\( Q_d^f(t) \) Delayed energy absorbed in the reactor after 1 millisecond.
- Decay of fission fragments
- Delayed neutron interactions
- Decay of activated material
Fission to Power

\[ Q_{\text{eff}}^f(t) = Q_p^f(t) + Q_d^f(t) \]

\( t \) is time after the fission event

\[ R(t) = \frac{d}{dt} Q_{\text{eff}}^f(t) \]

\( R(t) \) is rate of energy absorption per fission

\[ P(T) = \int_0^T R(T - t') F(t') dt' \]

\( T \) is a time along the operational timeline of the reactor

\( P(T) \) is power of the reactor

\( F(T) \) is fission rate
1.) MCNP6 based model specifically for a NTR

2.) A simple analytical model using information available in the literature

3.) ANS decay heat standard combined with the MCNP6 model
Activation Control Card (ACT Card) to estimate $R(t)$ and $Q_{eff}(t)$

Uses CINDER90 database to simulate fission product decay

MCNP model of a Representative NTR

Does not correct for neutron absorption in fission fragments
A LEU W-UO₂ cermet fuel, ZrH₁.₈ moderated rocket using H₂ propellant

Fuel: UO₂-ThO₂-W (56-4-40), 19.75%²³⁵U, 95% TD

Roughly 1 m long and 1 m in dia.
Analytical Model

A simple model based on information available in the literature

Decay heat model from “Nuclear Systems” Todreas

A quoted accuracy of “within a factor of 2”

$Q_p^f$ taken from the ATR paper (188.94 MeV)

\[
R(t) = \begin{cases} 
1.889364 \times 10^5 \frac{MeV}{s} & \text{if } t < 0.001 \text{ s} \\
0 \frac{MeV}{s} & \text{if } 0.001 \leq t \leq 10 \text{ s} \\
2.66t^{-1.2} \frac{MeV}{s} & \text{if } 10 \text{ s} < t < 100 \text{ days} \\
0 \frac{MeV}{s} & \text{if } 100 \text{ days} \leq t
\end{cases}
\]

Valid for $t \geq 1$, MCNP6 model used for $t < 1$

Decay of $^{239}$U and $^{237}$Np and neutron absorption in fission fragments ignored and expected to be negligible

1 sigma uncertainty is ~2% for most points but 15.6% to 4.3% in the first 4 seconds

$$R(t) = \begin{cases} \text{Same as MCNP6 model if } t < 1, & \\ ^{235}\text{U ANSI/ANS-5.1-2005 if } t \geq 1 \end{cases}$$
Results

Rate of Recoverable Fission Energy Deposition

- MCNP6 Burnup Assumption
- ANS Decay Heat Model
- MCNP6 Model
- Analytical Model

\[ R(T) \text{(MeV/s)} = \begin{cases} \text{constant} & \text{for } T < 1 \times 10^{-5} \\ \text{decreases to zero} & \text{for } T \geq 1 \times 10^{-5} \end{cases} \]
Results

Effective Recoverable Fission Energy Deposition

- **MCNP6 Burnup Assumption**
- **ANS Decay Heat Model**
- **MCNP6 Model**
- **Analytical Model**

The graph shows the variation of $Q_{\text{eff}}^f(T) \text{ (MeV)}$ with respect to $T \text{ (seconds)}$.
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Results

Reactor Power Profile

\[ P(T) \text{ (MW)} \]

\[ T \text{ (minutes)} \]
Results

Reactor Power Profile

\[ P(T') = \int_{0}^{T} R(T - t')F(t')\,dt' \]

Solve For
Results

Normalized Fission Rate Needed for Power Profile

- **Analytical Model**
- **MCNP6 Model**
- **ANS Decay Heat Model**
- **MCNP6 Burnup Assumption**
Results

Normalized Fission Rate Needed for Power Profile

- Analytical Model
- MCNP6 Model
- ANS Decay Heat Model
- MCNP6 Burnup Assumption
Results

Fractional Difference Between Solutions

- Analytical Model
- MCNP6 Model
- ANS Decay Heat Model
- MCNP6 Burnup Assumption
Discussion

MCNP6 model predicts a fission rate that is at minimum 0.99 and at maximum 1.07 times the default MCNP6 assumption.

Important information for high fidelity models

Fission rate changes by ~1.5% during steady state operation

• May affect the way that radiometric probes predict thermal power
Difference in Models

The NTR is a high leakage system
- 0.67 MeV/fission in gammas and neutrons
- 7.8% of all neutrons (??? MeV/fission if captured)
- ATR model had no leakage

Very different spectrum and core composition than a LWR

Decay heat relations generally agree with in ~15%
Future work

Investigate the effect on Burnup/$^{135}$Xe and spatial power deposition calculations

More thorough comparison to decay heat estimations
  • ANSI/ANS-5.1-2005
  • ORIGEN2
  • Serpent

Examine effect on calorimetric vs. radiometric power monitors
Questions?

\[ Q_{\text{eff}}^f (t_f) = Q_p^f (t) + Q_{\text{d}}^f (t) \]

\[ R(t) = Q_{\text{eff}}^f (t) \frac{d}{dt} \]

\[ P(T) = \int_0^T R(T - t')F(t') \, dt' \]

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   and depletion code*, Oak Ridge National Laboratory Report ORNL-5621
   LA-CP-13-00634 (2013)
5. Sterbentz J. W., *Q-value (MeV/fission) Determination for the Advanced Test Reactor*,