SAFETY ANALYSIS METHOD STUDY OF SPACE NUCLEAR REACTOR

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1. Introduction
2. Method Description
3. Safety Considerations by Mission Phases
4. Several Transient Calculation Results
5. Conclusions
With the development of technologies and urgent demand for resources exploitation, many countries have initiated their ambitious space exploration plans.

Development of space missions demands large amounts of power. Nuclear power system has lots of advantages over alternative power sources in providing high power.
According to different application environment, there are many differences between space nuclear reactors and terrestrial nuclear reactors.

Although terrestrial nuclear reactor safety methods are valuable supplements, they do not address some of the most important space nuclear reactor safety considerations.

- Mass, dimension, power output,
- Operation environment (space or planet, earth)
Introduction

In the past half century, lots of space nuclear reactors of different type have been developed.

- Neutron spectrum: thermal, fast
- Core cooling method: water, gas, liquid metal
- Power conversion: thermoelectric couple, thermionic, Stirling engine, Rankine cycle, Brayton cycle, AMTEC...
Though different reactor types, yet similar application circumstance – similar safety concerns.

In this paper, we choose one to do some study.

TOPAZ-II: an in-core thermionic space nuclear power system developed by Russia in 1960s~1980s.
The reactor is moderated by ZrH and has an epithermal neutron spectrum.

Reactor control is provided by beryllium control drums, each with a B\textsubscript{4}C segment. The control drums are located in the beryllium radial reflector.

The reactor is cooled by NaK.

37 thermionic fuel elements within the ZrH moderator transform heat to electricity.

The overall system mass is 1061kg. The reactor core is 36.5cm high and the diameter is 40.8cm. The reactor is designed to produce 4.5~5.5kWe up to three years.
Introduction

Fig. 1 A Radial Cross Section of The TOPAZ-II Nuclear Reactor Core (Unit: mm)
Except of the only three types of nuclear reactors (SNAP-10A, RORSATs, TOPAZ-I) which have been launched to space, TOPAZ-II reactor is one of the few space nuclear reactors which have been fully tested on the ground.
In the early of 1990s, the U.S. purchased six complete TOPAZ-II reactor systems from Russia and started the Topaz International Program (TIP) to investigate the possible use of the modified TOPAZ-II reactor system in support of the Nuclear Electric Propulsion (NEP) space test mission.

Numerous nuclear safety-related analyses were conducted to assess the safety of a TOPAZ-II flight reactor, as in [3-12].
A thermionic reactor system analytic code-TATRHG(S) was developed based on the thermionic reactor core analytic code-TATRHG(A)[13] to do safety analysis for an in-core single-cell thermionic reactor:

- a nuclear reactor six-group point-kinetics model
- a quasi subchannel transient thermal-hydraulic model of reactor core
- a thermionic performance model
- a coolant loop model
Point Kinetics Model

A six-group point kinetics model

\[
\frac{d}{dt} n(t) = S(t) + \frac{(\rho - \beta)}{\Lambda} n(t) + \sum_{i} \lambda_i C_i(t)
\]

\[
\frac{d}{dt} C_i(t) = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t) \quad i = 1, 2, ..., 6
\]

\[
\rho = \Delta \rho_M + \Delta \rho_U + \Delta \rho_{FS} + \Delta \rho_{JG} + \Delta \rho_{EL} + \rho(\theta)
\]
Thermal Model

A two dimensional finite difference method
Thermal Model
Thermal Model

**UO₂ fuel**

$$\rho_U(T)c_U(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}[\lambda_U(T)\frac{\partial T}{\partial z}] + \frac{1}{r}\frac{\partial}{\partial r}[r\lambda_U(T)\frac{\partial T}{\partial r}] + q_v$$

**Boundary condition between fuel and emitter**

$$-\lambda_U(T_U)\frac{\partial T_U}{\partial r}\bigg|_{r=r_u} = \frac{\lambda_G}{\delta_G}(T_S - T_E) + \varepsilon_{SE}\sigma(T_S^4 - T_E^4)$$

**Boundary condition between fuel and axial BeO reflector**

$$\lambda_U(T_U)\frac{\partial T_U}{\partial z}\bigg|_{z=z_{UFS}} = \lambda_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial z}\bigg|_{z=z_{UFS}}$$

**Axial BeO Reflector**

$$\rho_{UFS}(T_{UFS})c_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial t} = \frac{\partial}{\partial z}[\lambda_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial z}] + \frac{1}{r}\frac{\partial}{\partial r}[r\lambda_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial r}]$$

**Boundary condition between fuel and axial BeO reflector**

$$\lambda_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial z}\bigg|_{z=z_{UFS}} = \lambda_{UFS}(T_{UFS})\frac{\partial T_{UFS}}{\partial z}\bigg|_{z=z_{UFS}}$$
Thermal Model

Boundary condition between axial reflector and emitter

$$-\lambda_{UFS}(r_{UFS}) \frac{\partial T_{UFS}}{\partial r} \bigg|_{r=r_U} = \frac{\lambda_G}{\delta_G} (T_{SFS} - T_E) + \varepsilon_{SFSE} \sigma(T_{SFS}^4 - T_E^4)$$

Emitter corresponding to fuel zone

$$\rho_E(T_E)c_E(T_E) \frac{\partial T_E}{\partial t} = \frac{\partial}{\partial z} (\lambda_E \frac{\partial T_E}{\partial z}) + \frac{\Pi_E}{A_E} \frac{\lambda_G}{\delta_G} (T_{SFS} - T_E) + \frac{\Pi_S}{A_E} \varepsilon_{SE} \sigma(T_S^4 - T_E^4) + \frac{1}{\beta_E} \left( \frac{d\varphi_E}{dz} \right)^2$$

$$- \frac{\Pi_E}{A_E} \left[ \varepsilon_{EC} \sigma(T_E^4 - T_C^4) + \frac{\lambda_{CS}}{\delta_{CS}} (T_E - T_C) + j(\chi_C + \varphi_E - \varphi_C + \frac{2kT_E}{e}) \right]$$

Emitter corresponding to axial reflector zone

$$\rho_E(T_E)c_E(T_E) \frac{\partial T_E}{\partial t} = \frac{\partial}{\partial z} (\lambda_E \frac{\partial T_E}{\partial z}) + \frac{\Pi_E}{A_E} \frac{\lambda_G}{\delta_G} (T_{SFS} - T_E) + \frac{\Pi_S}{A_E} \varepsilon_{SFSE} \sigma(T_{SFS}^4 - T_E^4) + \frac{1}{\beta_E} \left( \frac{d\varphi_E}{dz} \right)^2$$

$$- \frac{\Pi_E}{A_E} \left[ \varepsilon_{EC} \sigma(T_E^4 - T_C^4) + \frac{\lambda_{CS}}{\delta_{CS}} (T_E - T_C) + j(\chi_C + \varphi_E - \varphi_C + \frac{2kT_E}{e}) \right]$$

Collector

$$\rho_C(T_C)c_C(T_C) \frac{\partial T_C}{\partial t} = \frac{\partial}{\partial z} (\lambda_C \frac{\partial T_C}{\partial z}) + \frac{1}{\beta_C} \left( \frac{d\varphi_C}{dz} \right)^2 - \frac{\Pi_C}{A_c} h_{CS} (T_C - T_{INS})$$

$$+ \frac{\Pi_E}{A_c} \left[ \varepsilon_{EC} \sigma(T_E^4 - T_C^4) + \frac{\lambda_{CS}}{\delta_{CS}} (T_E - T_C) + j(\chi_C + \frac{2kT_E}{e}) \right]$$
Thermal Model

**Insulator**

\[ \rho_{\text{INS}}(T_{\text{INS}}) c_{\text{INS}}(T_{\text{INS}}) \frac{\partial T_{\text{INS}}}{\partial t} = \frac{\partial}{\partial z} [\lambda_{\text{INS}} \frac{\partial T_{\text{INS}}}{\partial z}] + \frac{\Pi_C}{A_{\text{INS}}} h_{\text{CS}} (T_C - T_{\text{INS}}) - \frac{\Pi_{\text{INS}}}{A_{\text{INS}}} \frac{\lambda_{\text{He}}}{\delta_{\text{He}}} (T_{\text{INS}} - T_{\text{SI}}) - \frac{\Pi_{\text{INS}}}{A_{\text{INS}}} \varepsilon_{\text{IS}} \sigma (T_{\text{INS}}^4 - T_{\text{SI}}^4) \]

**Stainless steel inner wall**

\[ \rho_{\text{SI}}(T_{\text{SI}}) c_{\text{SI}}(T_{\text{SI}}) \frac{\partial T_{\text{SI}}}{\partial t} = \frac{\partial}{\partial z} [\lambda_{\text{SI}} \frac{\partial T_{\text{SI}}}{\partial z}] + \frac{\Pi_{\text{INS}}}{A_{\text{SI}}} \frac{\lambda_{\text{He}}}{\delta_{\text{He}}} (T_{\text{INS}} - T_{\text{SI}}) + \frac{\Pi_{\text{INS}}}{A_{\text{SI}}} \varepsilon_{\text{IS}} \sigma (T_{\text{INS}}^4 - T_{\text{SI}}^4) - \frac{\Pi_{\text{SI}}}{A_{\text{SI}}} \alpha_{\text{fI}} (T_{\text{SI}} - T_f) \]

\[ \Pi_{\text{SI}} \alpha_{\text{fI}} [T_{\text{SI}} - T_f (z + \frac{\Delta z}{2})] - \Pi_{\text{SOI}} \alpha_{\text{fO}} [T_f (z + \frac{\Delta z}{2}) - T_{\text{SO}}] = \]

\[ m_{\text{f}} c_{p,f} [T_f (z + \Delta z) - T_f (z)] + \rho V c_{p,f} \frac{\partial T_f}{\partial t} \]

**NaK coolant**

**Stainless steel outer wall corresponding to moderator**

\[ \rho_{\text{SO}}(T_{\text{SO}}) c_{\text{SO}}(T_{\text{SO}}) \frac{\partial T_{\text{SO}}}{\partial t} = \frac{\partial}{\partial z} [\lambda_{\text{SO}} \frac{\partial T_{\text{SO}}}{\partial z}] + \frac{\Pi_{\text{SOI}}}{A_{\text{SO}}} \alpha_{\text{fO}} (T_f - T_{\text{SO}}) - \frac{\Pi_{\text{SOO}}}{A_{\text{SO}}} \frac{\lambda_{\text{CO}_2}}{\delta_{\text{CO}_2}} (T_{\text{SO}} - T_{\text{MN}}) - \frac{\Pi_{\text{SOO}}}{A_{\text{SO}}} \varepsilon_{\text{SM}} \sigma (T_{\text{SO}}^4 - T_{\text{MN}}^4) \]
Thermal Model

Stainless steel outer wall corresponding to axial beryllium reflector

Moderator inside

Boundary condition between moderator and stainless steel outer wall of coolant channel

Boundary condition between moderator and core container

\[ \rho_{SO}(T_{SO})c_{SO}(T_{SO}) \frac{\partial T_{SO}}{\partial t} = \frac{\partial}{\partial z} [ \lambda_{SO} \frac{\partial T_{SO}}{\partial z} ] + \frac{\Pi_{SO}}{A_{SO}} \alpha_{fo}(T_f - T_{SO}) \]

\[ -\frac{\Pi_{SO}}{A_{SO}} \frac{\lambda_{CO_2}}{\delta_{CO_2}} (T_{SO} - T_{DFN}) - \frac{\Pi_{SO}}{A_{SO}} \varepsilon_{SDF} \sigma (T_{SO}^4 - T_{DFN}^4) \]

\[ \rho_{M}(T_{M})c_{M}(T_{M}) \frac{\partial T_{M}}{\partial t} = \frac{\partial}{\partial z} [ \lambda_{M}(T_M) \frac{\partial T_{M}}{\partial z} ] + \frac{1}{r} \frac{\partial}{\partial r} [ r \lambda_{M}(T_M) \frac{\partial T_{M}}{\partial r} ] + q_{v,M} \]

\[ -\lambda_{M}(T_M) \frac{\partial T_{M}}{\partial r} \mid_{r=k_{ij}} = \frac{\lambda_{CO_2}}{\delta_{CO_2}} (T_{MN} - T_{SO}) + \varepsilon_{MSO} \sigma (T_{MN}^4 - T_{SO}^4) \]

\[ -\lambda_{M}(T_M) \frac{\partial T_{M}}{\partial r} \mid_{r=b} = \frac{\lambda_{CO_2}}{\delta_{CO_2}} (T_{MS} - T_{RQ}) + \varepsilon_{MRQ} \sigma (T_{MS}^4 - T_{RQ}^4) \]
Thermal Model

Boundary condition between moderator and axial reflector

\[ \lambda_M(T_M) \frac{\partial T_M}{\partial z} \bigg|_{z=z_{MDF}} = \lambda_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial z} \bigg|_{z=z_{MDF}} \]

Axial beryllium reflector

\[ \rho_{DF}(T_{DF})c_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial t} = \frac{\partial}{\partial z} \left[ \lambda_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial z} \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \lambda_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial r} \right] \]

Boundary condition between axial reflector and stainless steel outer wall

\[ -\lambda_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial r} \bigg|_{r=k} = \frac{\lambda_{CO_2}}{\delta_{CO_2}} (T_{DFN} - T_{SO}) + \varepsilon_{DFSO} \sigma (T_{DFN}^4 - T_{SO}^4) \]

Boundary condition between axial reflector and core container

\[ -\lambda_{DF}(T_{DF}) \frac{\partial T_{DF}}{\partial r} \bigg|_{r=b} = \frac{\lambda_{CO_2}}{\delta_{CO_2}} (T_{DFS} - T_{RQ}) + \varepsilon_{DFRQ} \sigma (T_{DFS}^4 - T_{RQ}^4) \]
Thermal Model

Core container corresponding to moderator

\[ \rho_{\text{RQ}}(T_{\text{RQ}})c_{\text{RQ}}(T_{\text{RQ}}) \frac{\partial T_{\text{RQ}}}{\partial t} = \frac{\partial}{\partial z} \left[ \lambda_{\text{RQ}}(T_{\text{RQ}}) \frac{\partial T_{\text{RQ}}}{\partial z} \right] + \frac{\Pi_{\text{MW}}}{A_{\text{RQ}}} \varepsilon_{\text{MRQ}} \sigma (T_{\text{MS}}^4 - T_{\text{RQ}}^4) \]

\[ + \frac{\Pi_{\text{MW}}}{A_{\text{RQ}}} \frac{\lambda_{\text{CO}_2}}{\delta_{\text{CO}_2}} (T_{\text{MS}} - T_{\text{RQ}}) - \frac{\Pi_{\text{RW}}}{A_{\text{RQ}}} \varepsilon_{\text{RQCF}} \sigma (T_{\text{RQ}}^4 - T_{\text{CFIN}}^4) \]

Core container corresponding to axial reflector

\[ \rho_{\text{RQ}}(T_{\text{RQ}})c_{\text{RQ}}(T_{\text{RQ}}) \frac{\partial T_{\text{RQ}}}{\partial t} = \frac{\partial}{\partial z} \left[ \lambda_{\text{RQ}}(T_{\text{RQ}}) \frac{\partial T_{\text{RQ}}}{\partial z} \right] + \frac{\Pi_{\text{MW}}}{A_{\text{RQ}}} \varepsilon_{\text{DFRQ}} \sigma (T_{\text{DFS}}^4 - T_{\text{RQ}}^4) \]

\[ + \frac{\Pi_{\text{MW}}}{A_{\text{RQ}}} \frac{\lambda_{\text{CO}_2}}{\delta_{\text{CO}_2}} (T_{\text{DFS}} - T_{\text{RQ}}) - \frac{\Pi_{\text{RW}}}{A_{\text{RQ}}} \varepsilon_{\text{RQCF}} \sigma (T_{\text{RQ}}^4 - T_{\text{CFIN}}^4) \]

Radial reflector

\[ \rho_{\text{CF}}(T_{\text{CF}})c_{\text{CF}}(T_{\text{CF}}) \frac{\partial T_{\text{CF}}}{\partial t} = \frac{\partial}{\partial z} \left[ \lambda_{\text{CF}}(T_{\text{CF}}) \frac{\partial T_{\text{CF}}}{\partial z} \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \lambda_{\text{CF}}(T_{\text{CF}}) \frac{\partial T_{\text{CF}}}{\partial r} \right] \]

\[ - \lambda_{\text{CF}}(T_{\text{CF}}) \frac{\partial T_{\text{CF}}}{\partial r} \bigg|_{r=r_{\text{CFIN}}} = \varepsilon_{\text{CFRQ}} \sigma (T_{\text{RQ}}^4 - T_{\text{CFIN}}^4) \]

Boundary condition between side reflector and core container
Outside boundary condition of side reflector (exposed to outer space)

Through iterative calculation from inner ring to outer ring, the whole reactor core temperature distributions can be solved.

\[-\lambda_{CF}(T_{CF}) \frac{\partial T_{CF}}{\partial r} \bigg|_{r=r_{CFOUT}} = \varepsilon_{CF} \sigma(T_{CF}^4 - T_{BD}^4)\]
### Local Isothermal j-V Characteristics (VAC) of TFE

#### TABLE 2.1 EXPERIMENT DATA OF LOCAL ISOTHERMAL j-V CHARACTERISTICS OF TFE

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</table>
On the assumption that point y has the highest potential difference between emitter and collector, electrodes are distributed to two zones.
Emitter

(0~y) current distribution

\( J_E(x) = I_1 - \int_0^x \pi D_E j(\xi) d\xi = \int_x^y \pi D_E j(\xi) d\xi \)


(0~y) potential distribution

\( \varphi_E(x) = \varphi_E(y) - \frac{\beta_E}{A_E} \int_x^y J_E(\xi) d\xi \)


(y~L) current distribution

\( J_E(x) = \int_y^x \pi D_E j(\xi) d\xi \)


(y~L) potential distribution

\( \varphi_E(x) = \varphi_E(y) - \frac{\beta_E}{A_E} \int_y^x J_E(\xi) d\xi \)
**TFE Performance Model** *(a Single-Cell TFE)*

**Collector**

### (0~y) current distribution

\[
J_C(x) = I_1 - \int_0^x \pi D_E j(\xi) d\xi
= \int_x^y \pi D_E j(\xi) d\xi
\]

### (0~y) potential distribution

\[
\varphi_C(x) = \varphi_C(0) - \frac{\beta_C}{A_C} \int_0^x J_C(\xi) d\xi
\]

### (y~L) current distribution

\[
J_C(x) = \int_y^x \pi D_E j(\xi) d\xi
\]

### (y~L) potential distribution

\[
\varphi_C(x) = \varphi_C(L) - \frac{\beta_C}{A_C} \int_x^L J_C(\xi) d\xi
\]
Interelectrode voltage along the element length

\[ V(x) = \varphi_E(x) - \varphi_C(x) \]

\( (0 \sim y) \) second derivation of interelectrode voltage and boundary conditions

\[
\begin{align*}
V''(x) &= \varphi''_E(x) - \varphi''_C(x) = -\frac{R_{E1}\theta_{E1}}{y^2} j(x) - \frac{R_{C1}\theta_{E1}}{y^2} j(x) \\
V''(x) + \frac{(R_{E1} + R_{C1})\theta_{E1}}{y^2} j(x) &= 0 \\
V'(0) &= \varphi'_E(0) - \varphi'_C(0) = \frac{R_{E1} + R_{C1}}{y} I_1 \\
V'(y) &= \varphi'_E(y) - \varphi'_C(y) = 0 \\
V'(L) &= \varphi'_E(L) - \varphi'_C(L) = -\frac{R_{E2} + R_{C2}}{L - y} I_2
\end{align*}
\]

\( (y \sim L) \) second derivation of interelectrode voltage and boundary conditions

\[
\begin{align*}
V''(x) &= \varphi''_E(x) - \varphi''_C(x) = -\frac{R_{E2}\theta_{E2}}{(L - y)^2} j(x) - \frac{R_{C2}\theta_{E2}}{(L - y)^2} j(x) \\
V''(x) + \frac{(R_{E2} + R_{C2})\theta_{E2}}{(L - y)^2} j(x) &= 0 \\
V'(y) &= \varphi'_E(y) - \varphi'_C(y) = 0
\end{align*}
\]
Zone \((0 \sim y)\), one dimensional (axial direction) finite-difference equations

\[
V_2 - V_1 = \frac{R_{E1} + R_{C1}}{y^2} I_1 \cdot DNZDF - \frac{R_{E1} + R_{C1}}{y^2} \theta_{E1} j_1 \cdot DNZDF^2
\]

\[
V_{i-1} - 2V_i + V_{i+1} = -\frac{R_{E1} + R_{C1}}{y^2} \theta_{E1} j_i h^2 \quad i = 2, 3 \ldots n_1 - 1
\]

\[
V_{n-1} - V_n = -\frac{R_{E1} + R_{C1}}{y^2} \theta_{E1} j_{n1} \cdot DNZU^2
\]

\[
I_1 = \sum_{i=1}^{n_1} j_i \pi D_E h
\]

\[
j_i = f(V_i) \quad i = 1, 2, 3 \ldots n_1
\]
TFE Performance Model *(a Single-Cell TFE)*

Zone \((y \sim L)\), one dimensional (axial direction) finite-difference equations

\[
\begin{align*}
V_2 - V_1 &= -\frac{R_{E2} + R_{C2}}{(L - y)^2} \theta_{E2} j_2 \cdot DNZU^2 \\
V_{i-1} - 2V_i + V_{i+1} &= -\frac{R_{E2} + R_{C2}}{(L - y)^2} \theta_{E2} j_i h^2 \quad \text{for } i = 2,3,\ldots,n_2 - 1 \\
V_{n-1} - V_n &= \frac{R_{E2} + R_{C2}}{L - y} I_2 - \frac{R_{E2} + R_{C2}}{(L - y)^2} \theta_{E2} j_{n_2} \cdot DNZDF^2
\end{align*}
\]

\[
I_2 = \sum_{i=1}^{n_2} j_i \pi D_E h \\
j_i = f(V_i) \quad \text{for } i = 1,2,3,\ldots,n_2
\]
Output voltage of a single TFE

\[ U = V_0 - \Delta V_K = V_L - \Delta V_K \]

\[ \Delta V_K = I \cdot R_K \]

We usually assume that TFE’s output voltage \( U \) is known to get output current \( I \) through solving the upper equations.
TFE Performance Model (Electrical Circuit)
When TFEs start to operation, startup switch (figure 2.5) is closed

\[
\begin{align*}
U \\
U_{1,1}, U_{1,2}, U_{1,3}, \ldots, U_{1,n} \\
U_{2,1}, U_{2,2}, U_{2,3}, \ldots, U_{2,n} \\
I \\
I_1 \\
I_2
\end{align*}
\]

\[
\begin{align*}
U & = I \cdot R_0 \\
I & = I_1 + I_2 \\
U & = \sum_{i=1}^{n} U_{1,i} \\
U & = \sum_{i=1}^{n} U_{2,i} \\
U_{1,i} & = f(I_1) \quad i = 1, 2, \ldots, n \\
U_{2,i} & = f(I_2) \quad i = 1, 2, \ldots, n
\end{align*}
\]

(2n+4) variables \rightarrow (2n+4) irrelative equations
When the output potential equals rated number, the startup switch is opened and the output potential stays at rated number through selfadjustable stepless resistance.

\[
\begin{align*}
I &= I_1 + I_2 \\
U &= \sum_{i=1}^{n} U_{1,i} \\
U &= \sum_{i=1}^{n} U_{2,i} \\
U_{1,i} &= f(I_1) \quad i = 1, 2, \ldots, n \\
U_{2,i} &= f(I_2) \quad i = 1, 2, \ldots, n
\end{align*}
\]

\( (2n+3) \) variables \hspace{1cm} (2n+3) \text{ irrelative equations}
Safety Considerations by Mission Phases

For space nuclear reactor, safety assessments are typically discussed by mission phases. Here, we address the mission phases as follows:

- Ground phase *(similar to terrestrial reactors)*
- Pre launch phase
- Launch/Deployment phase
- Startup phase
- Operation phase
- Disposal phase
An event tree analysis was used to delineate the sequences of events that could potentially result in radiological consequences to the public or the environment for space nuclear reactors in all phases except ground phase.

- Propellant fires
- High-speed impact
- Transient overpower
- Loss of coolant
- Premature reentry
- Propellant explosions
- Submersion
- Loss of flux
- Debris/meteoroid impact
The current version of code-TATRHG(S): propellant fires accident, transient overpower accident, loss of flux accident, and loss of coolant accident.

Reentry accident analysis may be divided into four sections: trajectory analysis, heating analysis, thermal response analysis, and high-speed impact analysis. Code-TATRHG(S) can calculate the third section - thermal response analysis.

Other codes: MCNP, MCU, trajectory calculation code, aerodynamic calculation code, impact calculation code…
TOPAZ-II startup procedure

- original stage
- withdraw safety drums
- withdraw control drums to 154°
- drive control drums inward to 145°

TOPAZ-II startup procedure:

- power increases to rated power at a rate of 80 W/s after 35 kW
- power increases at a rate of 600 W/s until 35 kW
- power reaches 5 kW

TFEs startup procedure:

- interelectrode gap is filled with helium (1730s)
- connected to cesium reservoir (2030s)
- interelectrode is full of single cesium vapor
## Reactor startup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>America(^5)</th>
<th>Russia(^{5,7})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant Flow Rate, (g/s)</td>
<td>Total Reactor, 1500 (g/s)</td>
<td>Total Reactor, 1300 (g/s)</td>
<td>Single TFE, 40.15 (g/s)</td>
<td>Total Reactor, 1300 (g/s)</td>
</tr>
<tr>
<td>Rated Power, (kW)</td>
<td>115 (kW)</td>
<td>115 (kW)</td>
<td>107 (kW)</td>
<td>115 (kW)</td>
</tr>
<tr>
<td>Total Temperature Reactivity Feedback, ($)</td>
<td>1.45 ($)</td>
<td>1.54 ($)</td>
<td>1.46 ($)</td>
<td>1.4 ($)</td>
</tr>
<tr>
<td>Control Drums Position at Steady-state Condition, deg</td>
<td>88.5 (\deg)</td>
<td>86.7 (\deg)</td>
<td>88 (\deg)</td>
<td>90 (\deg)</td>
</tr>
<tr>
<td>Output Potential, (V)</td>
<td>Total Reactor, 27.6 (V)</td>
<td>Total Reactor, 27.5 (V)</td>
<td>Single TFE, 0.815 (V)</td>
<td>Total Reactor, 27 (V) ± 0.8 (V)</td>
</tr>
<tr>
<td>Output Current, (A)</td>
<td>223.7 (A)</td>
<td>228.4 (A)</td>
<td>190 (A)</td>
<td>6 (A) ± 0.7 (A)</td>
</tr>
<tr>
<td>Electric Power, (kW)</td>
<td>6.17 (kW)</td>
<td>6.29 (kW)</td>
<td>5.55 (kW)</td>
<td>6 (kW) ± 0.7 (kW)</td>
</tr>
<tr>
<td>System Efficiency, (%)</td>
<td>5.36 (%)</td>
<td>5.47 (%)</td>
<td>5.2 (%)</td>
<td>5.22 (%) ± 0.61 (%)</td>
</tr>
</tbody>
</table>
Reactor startup

Reactor Fission and Electric Power Output during Startup (Case 1)
Reactor startup

Reactivity Change during Startup (Case 1)

- Feedback
- Total Reactivity
- External Reactivity
- Control Drums 1.4 deg/s
- Startup of TFEs
Reactor startup

Control Drums Position during Startup (case 1)

Angular Position of Control Drums (deg)

Time (s)

Startup of TFEs

1.4 deg/s

Control Drums
Maintain $k_{eff} = 1.0$
Average Temperatures Change of Different Components during Startup (Case 1)
Reactor startup

Temperature Reactivity Feedback of Reactor components during Startup (case 1)
Reactor startup

Temperature Distributions of the First Ring TFE Channel at Steady-state Condition (case 1)
Reactor startup

Temperature Distributions of the First Ring TFE Channel at Steady-state Condition (case 1)

![Graph showing temperature distributions](image)
Radial Beryllium Reflector Behavior under Propellant fires Accident

Three Cases

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector</td>
<td>Beryllium</td>
<td>Beryllium</td>
<td>Beryllium Oxide</td>
</tr>
<tr>
<td>Propellant Type</td>
<td>liquid</td>
<td>solid</td>
<td>solid</td>
</tr>
<tr>
<td>Flame Temperature, $K$</td>
<td>3000</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>Duration Time, $s$</td>
<td>20</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
Radial Beryllium Reflector Behavior under Propellant fires Accident

Case 1

Radial Be Reflector Temperature as a function of Radial Position at Different Time Points
Radial Beryllium Reflector Behavior under Propellant fires Accident

Case 2

Radial Be Reflector Temperature as a function of Radial Position at Different Time Points
Radial Beryllium Reflector Behavior under Propellant fires Accident

Radial BeO Reflector Temperature as a function of Radial Position at Different Time Points

Case 3
Case 1: The beryllium reflector and whole reactor stay intact (liquid propellant fire).

Case 2: The solid propellant fires can melt the whole toxic beryllium radial reflector. Production and dispersion of beryllium particle, vapor or aerosol are possible. This will result a huge disaster to the environment.

Case 3: We replace beryllium reflector of TOPAZ-II by beryllium oxide reflector. Results show that part of beryllium oxide reflector melts under solid propellant fire accident.
We are considering abandoning using beryllium as reactor reflector material in space application.

If we have to use it, we should choose a liquid propellant launch vehicle whose flame temperature is relatively lower than that of a solid propellant vehicle.

Beryllium oxide is better. But the best choice is to select safer substitute materials such as $\text{Zr}_3\text{Si}_2$...
Three LOFA sequences are simulated to evaluate the simple modifications to the TOPAZ-II ACS.

- different detecting measures (temperature regulator located adjacent to the TFE outlet, flowmeter)
- different control drum rotate mechanism (rotate inside at speed 1.4°/s or fully inside in 1s)
# Loss of Flux Accident

## Table 1. Input Parameters of Cases

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Coolant Flow Rate, $g/s$</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Rated Fission Power, $kW$</td>
<td>115</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Shut Down Signal</td>
<td>Temperature</td>
<td>Flux</td>
<td>Flux</td>
</tr>
<tr>
<td>Control Drum Maximum Speed, $°/s$</td>
<td>1.4</td>
<td>1.4</td>
<td>fully inside in 1s</td>
</tr>
<tr>
<td>ACS Time Delay, $s$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Loss of Flux Accident (Case 1)

Reactor Fission Power and Reactivity Change (Case 1)
Loss of Flux Accident (Case 1)

Maximum Temperature Change of Different Components (Case 1)
Loss of Flux Accident (Case 2)

Reactor Fission Power and Reactivity Change (Case 2)
Maximum Temperature Change of Different Components (Case 2)
Maximum Temperature Change of Different Components (Case 2)
Loss of Flux Accident (Case 3)

Reactor Fission Power and Reactivity Change (Case 3)
Loss of Flux Accident (Case 3)

Maximum Temperature Change of Different Components (Case 3)
Results show that the reactor can be shut down safely for case 3 (combined with flowmeter and control drum fast rotate mechanism).

These simple modifications can increase the capability of quick response to LOFA.
Three LBLOCA sequences are simulated to evaluate the simple modifications to the TOPAZ-II ACS.

- introducing reactor shutdown signal (pressure, flux)
- different control drum rotate mechanism (rotate inside at speed 1.4°/s or fully inside in 1s)
## Table 4 Input Parameters of Different Cases

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Coolant Flow Rate, $g/s$</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Rated Fission Power, $kW$</td>
<td>115</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Shut Down Signal</td>
<td>No</td>
<td>Flux or Pressure</td>
<td>Flux or Pressure</td>
</tr>
<tr>
<td>Control Drum Maximum Speed, $°/s$</td>
<td>1.4</td>
<td>1.4</td>
<td>fully inside in 1 s</td>
</tr>
<tr>
<td>ACS Time Delay, $s$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Large-Break Loss of Coolant Accident

Fig. 13 Maximum Temperature Change of Different Components (Case 1)
Fig. 16 Maximum Temperature Change of Different Components (Case 2)
Large-Break Loss of Coolant Accident

Fig. 19 Maximum Temperature Change of Different Components (Case 3)
Results show that the reactor can be shut down safely for case 2 and 3 (shutdown signal, control drum rotating mechanism).

Simple modifications can increase the capability of quick response to LBLOCA.
Safety of space nuclear power is the focus of attention.

Some work has been done.
- Safety analysis code
- Safety considerations by mission phases
- Some calculations

Further work is undergoing.
- Modeling improvement
- Special analysis code
- More calculations
- Comprehensive safety evaluation
Thanks!

Questions and Comments