Systematic approach to TA establishment: major findings

In the frame of « Target Accuracies establishment »
Layout

General statements
Briefly about the concepts

MSR concepts
MSFR, current status
others: MOSART, MUSE

SFR and LFR
Breeder, burner, izo+

Outline
TAs by concepts and tasks
Challenge Impacting Phenomena and FOMs

Subject
- Design and critical parameters; assembling and reloading;
- Reactivity and power control; feedbacks; measurements
- Reactivity swing, fuel cycle optimization, pre-D&RDM
- Accidental states assessment; and instrumentation

CIP or/and FOM
- Criteria => half of SA for zone of flattening
- CR worth in dependence on power flattening, AU/RN
- Reactivity swing => to identify power history (around 5-10%)
- Reactivity spatially spanned worth profiles

TAGs to be considered in a context of a Decision Making process
MSFR: design features and role in the power generation fleet

Features and motivations

- Flexible tool to deploy new options in fuel cycle
- Bed-kind system
- Comprises three areas: nuclear heater, draining tank and storage and reprocessing plant
- To be controlled: multiplication, isotopic inventory and delay, inputs for other physics => freezing, residual heat, REDOX, gas-bubble as a control body
- The fundamentally multi-physics modeling

Solutions

- Fundamental multi-physics modeling
- Flexible tool to deploy new options in fuel cycle
- Bed-kind system
- Comprises three areas: nuclear heater, draining tank and storage and reprocessing plant
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OEC-D-NEA/NSC/WPEC/SG46, NOVEMBER 25-26, 2019, BOULOGNE-BILLANCOURT
Historical overview, some notes

- **1954**: Aircraft Reactor Experiment (ARE)
  - Operated during 1000 hours
  - Power = 2.5 MWth

  Not considered: fission gas storing tank, reprocessing control

- **1964 – 1969**: Molten Salt Reactor Experiment (MSRE)
  - Experimental Reactor
  - Power: 7.4 MWth
  - Temperature: 650°C
  - U enriched 30% (1966 - 1968)

- **1970 - 1976**: Molten Salt Breeder Reactor (MSBR)
  - Never built
  - Power: 2500 MWth
  - Thermal neutron spectrum

Note: MSRE zero power test to be published in IRPhE Handbook
Different concepts => same CIPs

Concepts and CIPs

- Bed-type or channel-type
- High-temperature
- Circulating/solid fuel
- Continuous/discrete processing
- Fundamental non-linearity
- Bubbles, rods, circulation velocity as “control bodies”

Zoning:
- Active “core” and HX
- Draining tank
- Fission gas collector
- Reprocessing plant

Comments
Coupled reactor + fuel cycle

Options and CIPs

- Bed-type U/Th system
  - Narrow operating REDOX range (band control by Bi, Th, Zr etc.) => reactivity issue
  - $^{233}$Pa decay: breeding and capture => neutron and nuclide components of reactivity and balance

- Bed-type Pu/U system
  - Fine nuclide balance control => spatially spanned material worth
  - $^{239}$Np caused fluctuations etc. => nuclide and neutron reactivity

- Both cases:
  - Correlations between critical size and inventory => specific slow feedbacks => nuclide and neutron reactivity

- Radiation-induced corrosion =>
  - $\Phi$, rad and Q along the circuit => ~ 10%

Comments
Circulating fuel peculiarities

Phenomena

- Circulating fuel in normal operation while static salt in a start-up
  - an elimination of ≥ ½ min precursors
  - all precursors in core

- CIPs =>
  - detection of state zones
  - control and power stabilization

Summary

- accuracy for start-up ~ 2%
- accuracy for operation ~ 5%

Comments & illustrations

LMFRs paradigm dependent

Concepts and physics

- **Burner**
  - Operation with “dirty Pu vector”

- **Breeder**
  - Breeding in blankets optimizing the spectra

- ASTRID-like = LFR
  - Objective => an exclusion of a large non-compensated reactivity
  - Low reactivity swing and low CR worth

CIPs and main issues

- **Design goal => low impact <= Pu**
  - Sensitivity for Q and \( \Phi \) distributions <= driven by CRs

- **TH and safety issues**
  - Fine reactivity and \( Q(R,Z,t) \)
  - \( TA \) to \( \rho_{MAT}(R) \leq 5-10\% \)

- **Control \( \rho \) and Q and \( \Phi \) by CRs**
  - Reactivity swing < $, an associated TA better than $\$
  - \( TA(CRs) < 3\% \) (influence on in-core BG)
  - Replacing TA to \( \Phi(x) \) by \( \rho_{MAT}(R) \leq 5-10\% \)
An application object for Levels 1-3 [the most penalized configuration]

Phénix sodium worth distribution

SNR-300 sodium worth distribution

Core without blankets, sodium worth distribution
**Facts and statements**

- EigenValue Separation used as a criteria of reactivity measurement consistency
  - ASTRID-like system should have high EVS => should be “decoupled”
  - Deeply subcritical ADS => no fundamental mode => decomposition is needed

- Alternative form is in coupled system
  - To address the sensitivities for “local” parameters

**Comments**

\[
P(t) \cdot \Delta t = (A_1 \cdot e^{\alpha_1 \cdot \Delta t} + A_2 \cdot e^{\alpha_2 \cdot \Delta t}) \cdot \Delta t \neq A_0 \cdot e^{\alpha_0 \cdot \Delta t} \cdot \Delta t
\]

\[
\begin{align*}
\frac{dq_c}{dt} &= \rho_c - \beta_c \cdot \frac{\Lambda_c}{q_c} + \frac{k_{bc}}{\Lambda_c} \cdot q_b + \sum_i \lambda_i \cdot c_{c,i} \\
\frac{dc_{c,i}}{dt} &= \frac{\beta_c}{\Lambda_c} \cdot q_c - \lambda_i \cdot c_{c,i} \\
\frac{dd_b}{dt} &= \frac{k_{cb}}{\Lambda_b} \cdot q_c + \rho_b - \beta_b \cdot \frac{\Lambda_b}{q_b} + \sum_i \lambda_i \cdot c_{b,i} \\
\frac{dc_{b,i}}{dt} &= \frac{\beta_b}{\Lambda_b} \cdot q_b - \lambda_i \cdot c_{b,i}
\end{align*}
\]
Example: SVR in the 2-nd zone

ABR Metallic-Fuel Core

\[ \Delta \rho = \sum a_i \times \gamma_i + \sum b_{ij} \times \gamma_i \times \gamma_j \]

\( \gamma_i \) is a volumetric part of void

\( a_i, b_{ij} \) are coefficients to be found
Accidental state concept => snapshots
Specificity of correlated data and correlated phenomena

Application objects

- LMFR => instrumentation
- LMFR => kinetic parameters
- LMFR => subsequent accidental states
- LWRs reactivity analysis
- LWRs unflattening factors

Sensitivity ↔ uncertainty
Summary (a part of one)

Subjects

- MSR: start-up and operational regimes
- MSR: input for multi-physics
- MSR: storage tank and shut-down state
- LMFRs (izogenerator)
- LMFR instrumentation
- LMFR assembling and reloading

TA to be established

- Total and reduced beta $\beta_{total} \leq 3\%, \beta_{\min} \leq 3\%, \lambda_{del} \leq 7\%$
- Worth($x$) (HMs, void, etc.) $\leq 10\%$
- Criticality and worth (traditional $\Rightarrow$ $fp$, HMs, ...)
- CRs interferences etc. $\leq 5\%$
- Local kinetic (AO specific)
- Criticality $\sim \leq 0.3\%$
Some additional remarks

**MSFR benchmark**

- MSFR => $^{233}\text{U}/\text{Th}$ concept with an option of Pu/U/Th commissioning
- Reactivity, power distribution, BR and BG, kinetic parameters for circulating fuel
- Published in M. Brovchenko, Jan-Leen Kloosterman, et al, Neutronic benchmark of the molten salt fast reactor in the frame of the EVOL and MARS collaborative projects, EPJ Nuclear Sci. Technol. 5 2 (2019)
Technological families and “common mode” issues

NERVA program

HTGR, VHTR, GFR => Gas cooled systems

Gas leaks

The Nuclear Engine for Rocket Vehicle Application (NERVA)
Nuclear Thermal Propulsion (NTP)

\[ I_{sp} = \frac{F}{\dot{m}} = \frac{V_i}{g} \]

\[ F = \frac{\dot{m}}{g} V_{ex} + (p_e - p_o) A_e \]

<table>
<thead>
<tr>
<th>Propulsion</th>
<th>Specific energy (J/kg)</th>
<th>Specific impulse (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical, ( \text{H}_2(g) + 1/2\text{O}_2(g) \rightarrow \text{H}_2\text{O}(g) )</td>
<td>1.3×10^7</td>
<td>&lt;520</td>
</tr>
<tr>
<td>Nuclear, fission of (^{235}\text{U} )</td>
<td>8.8×10^{13}</td>
<td>800÷9000</td>
</tr>
</tbody>
</table>
Technological families and “common mode” issues

Kilopower: KRUSTY etc.

Micro power heat pipe systems: eVinci etc

the Kilowatt Reactor Utilizing Stirling TechnoloY, or KRUSTY
Thank you for your time

Questions?
Data preservation: IRPhE collection

KRUSTY is ongoing
Decomposition of SNEAK 7A Model

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<thead>
<tr>
<th></th>
<th>C-R</th>
<th>I-II</th>
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</thead>
<tbody>
<tr>
<td>$\beta_{rec}, \text{ pcm}$</td>
<td>412.9</td>
<td>411.4</td>
</tr>
<tr>
<td>$\Delta \beta_{\exp}/\beta_{Cf}$ %</td>
<td>-4.6</td>
<td>-4.6</td>
</tr>
<tr>
<td>$\Delta \beta_{\text{noise}}/\beta_{Cf}$ %</td>
<td>-0.02</td>
<td>-0.39</td>
</tr>
</tbody>
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Core

C-R

Reflector

before

after

I-II