LEAD CONTAINING MAINLY ISOTOPE PB-208: NEW REFLECTOR FOR IMPROVING SAFETY OF FAST NUCLEAR REACTORS

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OUTLINE

1. How to slow down chain reaction?
2. Improved safety: kinetics
3. Improved safety: dynamics
4. Sources of $^{208}\text{Pb}$
How to slow down chain reaction?
How we can slow down chain reaction
- fast neutrons from the core should penetrate deeply into reflector
- they should have high probability to return to the core as a result of diffusion (in some way “delayed” neutrons)

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Thermal</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>$\sim$ ms</td>
<td>$\sim$ $\mu$s</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.65%</td>
<td>0.36%</td>
</tr>
</tbody>
</table>

Safety improvement by slowing down chain reaction
REQUIREMENTS TO SLOW DOWN CHAIN REACTION

1. “Penetrate deeply into reflector”
   Neutron age $\tau$ ($E_{\text{fi}} \rightarrow E_{\text{th}}$) as large as possible

2. “High probability to return to the core”
   Diffusion length $L$ larger than $\sqrt{\tau}$

Core

Mean migration of neutrons
at slowing down

$\sqrt{6\tau}$

Reflector

“Delayed”

Fast neutrons

“Delayed”

at diffusion

$\sqrt{6L}$
CHARACTERISTICS OF CHAIN REACTION RATE

1. Neutron age \( \tau(E) \sim A \int_{E_1}^{E_2} \frac{1}{\Sigma_s^2} \cdot \frac{dE}{E} \)  \( \tau \uparrow \) \( A \uparrow \)

\( \sqrt{6\tau} \) – mean migration of neutrons at slowing down

2. Diffusion length \( L \sim \frac{1}{\sqrt{\Sigma_a^{th} \cdot \Sigma_s^{th}}} \)  \( L \uparrow \Sigma_a^{th} \downarrow \)

\( \sqrt{6L} \) – mean migration of neutrons at diffusion

3. Lifetime of thermal neutrons \( T_{th} \sim \frac{1}{\Sigma_a^{th}} \)  \( T_{th} \uparrow \Sigma_a^{th} \downarrow \)

\( 208 \text{Pb} \)
Extremely small capture of $^{208}\text{Pb}$
# REFLECTOR PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sqrt{6}\tau$ (cm)</th>
<th>$\sqrt{6}L$ (cm)</th>
<th>Slowing down probability (2 MeV → 0.025 eV)</th>
<th>Lifetime of thermal neutrons (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>213</td>
<td>843 !</td>
<td>0.993</td>
<td>597 !</td>
</tr>
<tr>
<td>$\text{Pb}_{\text{nat}}$</td>
<td>213</td>
<td>33</td>
<td>0.304</td>
<td>0.9</td>
</tr>
<tr>
<td>Na</td>
<td>227</td>
<td>43</td>
<td>0.297</td>
<td>0.3</td>
</tr>
<tr>
<td>Bi</td>
<td>223</td>
<td>96</td>
<td>0.160</td>
<td>4.7</td>
</tr>
<tr>
<td>C</td>
<td>49</td>
<td>138</td>
<td>0.998</td>
<td>13</td>
</tr>
</tbody>
</table>
THERMAL NEUTRON ALBEDO

208Pb is an effective reflector
208Pb is very specific and effective neutron reflector

\[ \text{Pb}_{\text{nat}} = 1.4\%^{204}\text{Pb} + 24.1\%^{206}\text{Pb} + 22.1\%^{207}\text{Pb} + 52.4\%^{208}\text{Pb} \]
High threshold of inelastic scattering of $^{208}\text{Pb}$
# MODERATOR PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Logarithmic energy decrement $\xi$</th>
<th>Moderating ability $\xi \cdot \Sigma_s$ (cm$^{-1}$)</th>
<th>Moderating ratio $\xi \cdot \Sigma_s / \Sigma_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>0.95</td>
<td>1.39</td>
<td>70</td>
</tr>
<tr>
<td>D$_2$O</td>
<td>0.57</td>
<td>0.18</td>
<td>4590</td>
</tr>
<tr>
<td>BeO</td>
<td>0.17</td>
<td>0.12</td>
<td>247</td>
</tr>
<tr>
<td>C</td>
<td>0.16</td>
<td>0.063</td>
<td>242</td>
</tr>
<tr>
<td>Pb$_{nat}$</td>
<td>0.01</td>
<td>0.004</td>
<td>0.61</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>0.01</td>
<td>0.004</td>
<td>477</td>
</tr>
</tbody>
</table>

$^{208}$Pb is an effective moderator
Improved Safety: Kinetics
CONTRIBUTION OF NEUTRONS WITH DIFFERENT LIFETIMES INTO REACTOR CRITICALITY

Contributions to reactivity, %

Neutrons from reflector of FR: (resonance neutrons)

Fast Reactor (FR)

Pb-nat: 0.5m, 21β

Pb-208:

+1.5m, 4β

1.5m, 34β

+1m, 3β

1.5m, 2β

+2m, 0.3β

Delayed neutrons

β

Neutron lifetime, s

1E-7 1E-6 1E-5 1E-4 0.001 0.01 0.1 1 10 100
# PECULIARITIES OF REFLECTOR NEUTRONS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>Prompt and delayed neutrons</td>
</tr>
<tr>
<td>Place of birth</td>
<td>Reflector</td>
</tr>
<tr>
<td>Fraction</td>
<td>&quot;&lt; prompt, but &quot;&gt;&gt; delayed</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&quot;&gt; prompt, but &lt; delayed&quot;</td>
</tr>
<tr>
<td>Energy</td>
<td>&quot;&lt;&lt; prompt and delayed neutrons&quot;</td>
</tr>
<tr>
<td>Time of input into nuclear chain reaction</td>
<td>After returning to the core (there’s a “dead” time)</td>
</tr>
<tr>
<td>Place of input into nuclear chain reaction</td>
<td>Mainly at the edge of the core</td>
</tr>
<tr>
<td>Forming</td>
<td>It’s possible to change their fraction and energy by changing reflector</td>
</tr>
<tr>
<td>Role</td>
<td>Additional delayed neutrons</td>
</tr>
</tbody>
</table>
REACTOR RUNAWAY

Critical reactor with reflector

Runway on delayed and reflector neutrons

\[ K_{\text{ef}} \]

\[ K_{\text{total}} \]  
\[ K_{\text{prompt}} \]  
\[ \Delta K_{\text{eff}} \]  
\[ \beta \]

Runway on prompt neutrons

\[ \Delta K_{\text{eff}} \]

\[ K_{\text{total}} \]
FAST REACTOR RUNAWAY WITHOUT FEEDBACKS INDUCED BY STEP INSERTION OF REACTIVITY ($\beta = 0.36\%$)

**Similar**

**A big difference**
3

Improved Safety: Dynamics
MODEL OF NEUTRON FLASH (P0 > B)

- this is the state of prompt super-criticality
- heat does not have time to reach the coolant
- only Doppler effect has enough time to act
- duration of neutron flash $\Delta t \sim \Lambda$ neutron lifetime
- energy yield of neutron flash $Q \sim W_{\text{max}} \cdot \Delta t \neq f (\Lambda)$
Model of neutron flash is correct in the case of Pb\textsubscript{nat}

<table>
<thead>
<tr>
<th>Reflector</th>
<th>Neutron lifetime $\Lambda$</th>
<th>Duration of neutron flash $\Delta t$ at $\rho_0 = 2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb\textsubscript{nat}</td>
<td>$\sim \mu$s</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>$\sim$ ms</td>
<td>1.1 s</td>
</tr>
</tbody>
</table>

Time constant of fuel element $\tau_{th} \sim 0.1$ s (metal) ÷ 1 s (oxide)

→ at $\Delta t \geq \tau_{th}$ part of the heat has time to reach the coolant

→ negative coolant feedback has enough time to act

(in addition to Doppler effect)

2 feedbacks in the case of $^{208}$Pb
FAST REACTOR POWER AT THE NEUTRON FLASH

Graph showing reactor power as a function of time after reactivity insertion. The graph compares different scenarios:

- **0.5m Pb_{nat}** with a time constant $\Lambda = 0.5 \, \mu s$, indicated by a red curve with peak power level of approximately 10,000.
- **4m $^{208}$Pb** with a time constant $\Lambda = 1 \, ms$, indicated by a blue curve with peak power level of approximately 100.

The time axis shows times after reactivity insertion in seconds, ranging from $1E^{-5}$ to 1. The power is measured in relative units.

Key points:

- **8W\Delta t** for the $0.5m Pb_{nat}$ scenario.
- **6W\Delta t** for the $4m ^{208}$Pb scenario.

The reactor power levels are given in relative units, with removed power levels of 0.04% and 26% for $0.5m Pb_{nat}$ and $4m ^{208}$Pb, respectively.

The +2.0 $\beta$ notation is used to indicate a change in power level.
FUEL TEMPERATURE AT THE NEUTRON FLASH

Fuel temperature ($^\circ$C)

- 0.5m Pb$_{nat}$, $\Lambda = 0.5$ $\mu$s
- 4m $^{208}$Pb, $\Lambda = 1$ ms

$T_{operation} = 877$ $^\circ$C

1500$^\circ$C

+ 2.0 $\beta$

Time after reactivity insertion (s)
ASYMPTOTIC PROCESS OF REACTOR RUNAWAY

- Fast reactor: 0.5 m $\text{Pb}_{\text{nat}}$ ($\Lambda = 0.5$ $\mu$s)
- Fast reactor: 4.0 m $^{208}\text{Pb}$ ($\Lambda = 0.5$ ms)
- CANDU: $\Lambda = 1$ ms

R. Ph. Feynman (USA):
«Experimental fast assembly is a «Drowsy dragon»»
Sources of $^{208}\text{Pb}$
Relative content of lead isotopes in radiogenic lead depends on age of ore deposits and on admixture of natural lead.

From Th-ores and (Th-U)-ores:

\[ \text{Pb}_{\text{nat}} = 1.4\%^{204}\text{Pb} + 24.1\%^{206}\text{Pb} + 22.1\%^{207}\text{Pb} + 52.4\%^{208}\text{Pb} \]
ORE DEPOSITS CONTAINING RADIOGENIC LEAD

<table>
<thead>
<tr>
<th>Ore</th>
<th>U / Th / Pb (% wt.)</th>
<th>$^{204}\text{Pb}$/ $^{206}\text{Pb}$/ $^{207}\text{Pb}$/ $^{208}\text{Pb}$ (% at.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monazite (Guarapari, Brazil)</td>
<td>1.3 / 59.3 / 1.5</td>
<td>0.005 / 6.03 / 0.46 / 93.5</td>
</tr>
<tr>
<td>Monazite (Manitoba, Canada)</td>
<td>0.3 / 15.6 / 1.5</td>
<td>0.010 / 10.2 / 1.86 / 87.9</td>
</tr>
<tr>
<td>Monazite (Mt. Isa Mine, Australia)</td>
<td>0.0 / 5.73 / 0.3</td>
<td>0.038 / 5.44 / 0.97 / 93.6</td>
</tr>
<tr>
<td>Monazite (Las Vegas, USA)</td>
<td>0.1 / 9.39 / 0.4</td>
<td>0.025 / 9.07 / 1.13 / 89.8</td>
</tr>
<tr>
<td>Monazite (South Bug, Ukraine)</td>
<td>0.2 / 8.72 / 0.9</td>
<td>0.010 / 6.04 / 0.94 / 93.0</td>
</tr>
<tr>
<td>Natural Lead</td>
<td>—</td>
<td>1.4 / 24.1 / 22.1 / 52.4</td>
</tr>
</tbody>
</table>

There are ores ~ 93% $^{208}\text{Pb}$
DO WE NEED TO ENRICH LEAD?

It seems that we should enrich lead.

1. bare core
2. core + 0.5 m Pb\text{nat}
3. core + 2.0 m Pb\text{nat}
4. core + 4.0 m Pb\text{rad}
5. core + 4.0 m \text{^{208}Pb}
6. 5 + \sigma_c \text{(^{208}Pb)} = 0
7. 5 + 0.2\% \text{^{207}Pb}
It’s reasonable to use enriched lead of 2 - 3 m
The new approach is proposed to improve nuclear safety of fast reactors thanks to slowing down chain reaction.

$^{208}$Pb reflector in fast reactors can considerably prolong lifetime of prompt neutrons (by three orders of magnitude).

Long neutron lifetime and short time constant of fuel elements substantially improve nuclear safety even by insertion of reactivity $> \beta$. 
<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 September 2019</td>
<td>GEN IV Coolants Quality Control</td>
<td>Dr. Christian Latge, CEA, France</td>
</tr>
<tr>
<td>23 October 2019</td>
<td>Passive Decay Heat Removal System</td>
<td>Dr. Mitchel Farmer, ANL, USA</td>
</tr>
<tr>
<td>13 November 2019</td>
<td>Czech Experimental Program on MSR Technology Developments</td>
<td>Dr. Jan Uhlir, Research Center Řež, Czech Republic</td>
</tr>
</tbody>
</table>