Reactor Physics Design Parameters for GFRs
22.39 Elements of Reactor Design, Operations, and Safety

Fall 2005

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Outline

• Objectives of this lecture
• Traditional breeder designs and traditional safety concerns
• Reactor physics design in relation to Gen IV goals
  ■ Addressing sustainability and proliferation resistance
  ■ Addressing economy
  ■ Addressing safety
• Example of helium direct cycle GFR (CEA)
Lecture Objectives

• Last Monday lecture – Design challenges of GFR
• This lecture
  ■ How reactor physics design challenges are addressed
  ■ Reactor physics - not a standalone discipline
  ■ We will look at Reactor physics design in view of other key Gen IV goals
    ◆ How does reactor physics interact with other Gen IV goals
    ◆ How to design the reactor (on GFR example) to meet the set of top level goals in a balanced manner

GFR is a new reactor, design almost from scratch, design in progress, hence no definitive answers

Traditional sodium FBR designs

• Large power rating (~3000MWt)
• Very high power density (~300kW/l)
  ■ To reduce fuel cycle cost
  ■ To minimize doubling time
• Short doubling time (~25 years)
• Oxide fuels - UO2-PuO2 driver fuel, use of UO2 blankets
• Breeding ratio >1 (1.25)
• Pool type reactor
• Active safety
• Intermediate loops
• Rankine cycle
• Difficult maintenance (opaque coolant)
• Complex and expensive

Diagram removed for copyright reasons.
Traditional reactor physics (safety) concerns for early liquid metal cooled FBRs

- Small effective delayed neutron fraction
  - Small value of dollar unit for reactivity, hence concern that prompt critical state can be easier to reach
- Short prompt neutron lifetime
  - Concern over extremely rapid power rise if reactivity increase exceeds prompt critical value
- Hypothetical core disruptive accidents
  - Core geometry not in most reactive configuration
  - Loss of core geometry may hypothetically lead to reactivity increase and large energy generation
  - Although of extremely low probability, these scenarios received substantial attention
- Reactivity insertion > 1$ from coolant voiding

Reactor physics and Gen IV goals

- Reactor physics design interacts with all Gen IV goals
- There is also strong interaction among goals – not covered here
Sustainability link to physics design

- Traditionally – high utilization of resources (motivated early development of fast reactors with high breeding ratio - blankets)
- Emphases in Gen IV
  - High resource utilization
  - Waste minimization
  - Proliferation resistance
  - New
- To reduce waste long-term radiotoxicity to that of natural U in <1000yrs – full recycling of TRU (including MA) with losses <0.1% needed
- Enhanced proliferation resistance favors elimination of depleted U blankets, avoidance of Pu separation and maintenance of dirty plutonium isotopics throughout the cycle

Impact of recycling TRUs

It reduces long-term radiotoxicity (only reprocessing TRU losses To repository + fission products)

Impact of Removing & Transmuting Actinides

![Graph showing relative ingested toxicity over time, comparing natural uranium ore, reactor waste, and nuclear waste.]
Sustainability-driven design choices

GFR for both waste management and resource utilization

- Use accumulated TRU from spent LWR for 1st FR core
- Design GFR with BR=1, no blankets to avoid clean Pu
- Recycle TRU without Pu separation, Depleted U feed
- If enough GFRs deployed, LWR legacy TRU inventory eliminated
- After full transition to GFR, enrichment could be eliminated

Consequences of sustainability-driven choices

- Small effective delayed neutron fraction
  - TRUs have small $\beta$
  - TRUs in LWR spent fuel
    49%Pu239, 23%Pu240, 7%Pu241, 6.6%Np237, 5%Pu242, 4.7%Am241, 2.7%Pu238
  - Smaller margin to superprompt criticality, hence reactor control more challenging
  - What can be done to increase $\beta_{eff}$?
    - Not much
    - Harden spectrum to fission more U238, but coolant void worth worse
    - Increase leakage, not good for neutron economy

Graph removed for copyright reasons.
Consequences of sustainability-driven choices (Cont’)

• **Increased positive coolant void worth**
  - Coolant void worth is a safety issue
  - Void worth in GFR is typically much smaller than in LMRs
  - But is of high concern since coolant voiding can be fast
  - Smaller $\beta$ makes coolant void worth larger in terms of reactivity in dollars
  - More positive coolant void worth is due to **TRU loading** (primarily Pu239, Np237 and Am241)
  - Why?

Neutron spectrum in GFR

- Spectrum is hard
- Most neutrons between 0.1 and 1MeV
Positive coolant void worth in FRs

Three components of coolant void worth

• Spectrum hardening
  - Loss of coolant reduces neutron population with lower energy – spectrum becomes harder

[Diagram with Pu239 capture and fission cross sections]

• Pu239 capture and fission cross sections
  - Neutron population shifts
  - Spectrum hardening
  - Fission/capture ratio increases
  - Reactivity increases

• This differs from U235, hence much lower void worth for U235 fueled core

[Diagram with U235 capture and fission cross sections]

• U235 27=absorption, 18=fission $\mathcal{M} = 27$ 18

[Diagram with U235 capture and fission cross sections]
Positive coolant void worth in FRs

Minor actinides (mainly Np237 and Am241) exacerbate the problem

- Am 241 same behavior
- What about U238? Also an issue but $\sigma_f$ comes up after 1MeV and only to 0.5barn

Positive coolant void worth in FRs

- **Coolant absorption**
  - Less coolant $\rightarrow$ smaller parasitic absorption, hence reactivity increases
  - Small for GFR but can be significant for LMRs – coolants with higher absorption cross section worse

- **Neutron leakage**
  - Less coolant $\rightarrow$ increased neutron leakage, hence reduced reactivity
  - Smaller or pancake cores have lower coolant void worth
  - Coolants with larger scattering cross section have larger reactivity reduction from leakage

Neutron leakage is the main tool available to designer to reduce coolant reactivity void worth
Ways to reduce CVW in GFRs

- Although CVW is small (in comparison to LMRs), its reduction is difficult. Why?
- Leakage component has is very small (negligible for some gases, such as He)
- Possibilities:
  - Use core and reflector materials that exhibit increase of absorption cross section upon spectrum hardening
    - Example - titanium alloys
  - Use gas that has high scattering macroscopic cross section to increase benefit of leakage effect
    - Example – SCO2 core-average density at 20MPa = 0.137 g/cc (1/5th of water), but also increases spectrum hardening, hence balance needs to be found
  - Minimize coolant fraction in the core
    - Example inverted fuel assembly, but more challenging to cool
  - Soften the spectrum (use of appropriate diluent)
    - Example – UO2 fuel with BeO diluent

CVW-Why titanium reflector helps?

- Harder spectrum reduces neutron scattering in reflector, hence higher leakage

This would be nice core material but nature does not provide such
CVW – Leakage effect for He and SCO2


Leakage effect negligible for He cooled reactors, but works for S-CO2 cooled cores. Calculations for infinite lattice make SCO2 much worse.

CVW – Use of diluent to soften spectrum

- Also very efficient for peaking reduction (enrichment zoning does not work)

- Without diluent, uniform enrichment, BOL CVW=1.6$, radial peaking =1.56
- With BeO diluent, BOL CVW=0.5$, radial peaking =1.15
- Diluent can also reduce axial peaking
- Would use of burnable poison reduce or increase CVW?

SCO2 cooled, MIT GFR, inverted fuel

Radial Power Profile with Uniform enrichment (15.4% TRU) and 30/20/10% BeO

Graph removed for copyright reasons.
Consequences of sustainability-driven choices (Cont’)

- Difficulty to achieve conversion ratio (CR) of 1.0 in the absence of blankets
  - Balance between leakage and CVW
    - Large cores with low leakage preferred for good neutron economy
    - Large, low leakage cores have larger coolant void worth
  - Balance thermal hydraulics and neutronics
    - High CR favors high fuel volume fraction and low coolant volume fraction
    - Thermal hydraulics favors high coolant volume fraction
    - Use high density fuels (UC,UN) or inverted fuel assembly

Economy link to neutronic design

- Indirect link
  - Capital cost via safety - examples
    - Reduced peaking allows higher power density for given structural material temperature limits, hence more energy from the same vessel and lower cost
    - Low reactivity swing reduces number of control rods (CRDs expensive)

- Direct link
  - Fuel cycle cost
    - Strive for low enrichment (TRU weight fraction)
    - Strive for high specific power
      - Beware of battery core trap
Example of long life, low power density design

- Synergistic twin to thermal GT-MHR
- Same low power density – 8kW/l
- Passive decay heat removal by conduction and radiation
- Excellent safety
- Neutronically feasible
- Very long core life – 50 years

But very high fuel cycle cost!!!

GFR
- For U235 enriched fuel
  - $\eta=45\%$, $L=0.90$
  - $B_d=180$MWd/kgHM
  - discount rate $x=10\%/yr$
  - $C=3936$ $\$/kg for $e=13\%$

PWR
- $\eta=33\%$, $L=0.90$
- $B_d=50$MWd/kgHM
- discount rate $x=10\%/yr$
- $C=1200$ $\$/kg for $e=4.5\%$
- Fabrication 200$\$/kg
- $SP=38$kW/kgHM

Twin to MHR-GT not economically feasible
Specific power should not be much below 20kW/kg. Shoot for 25kW/kgHM (BWR)
!! SUPERSAFE reactor of no use without a buyer
What works for thermal reactor may not work for fast reactor
Safety link to neutronic design

- Reactivity increase from coolant depressurization (CVW – discussed earlier)
- Primary issue is post LOCA decay heat removal
  - Gen IV emphasis is on enhanced safety
  - Current trend – rely on passive means
    - Claim is that they are more resistant to human error and allow simplification, and thus cost reduction
    - But may result in lower power densities (economy)
    - Conduction to core periphery eliminated due to high FCC
    - The most promising passive decay heat removal for SP>20kW/kgHM via natural circulation

GFR with natural circulation decay heat removal at elevated pressure

- 4x50% cooling loops
- After depressurization of primary system, containment pressure increases and provides elevated pressure needed for natural circulation

Requires

Low pressure drop core, hence large coolant volume fraction – but neutronics favors small coolant volume fractions
Approaches to reconcile neutronics thermal hydraulic requirements

- Problem
  - Neutronics needs high fuel volume fraction
  - Post-LOCA thermal hydraulics favors low pressure drop
- Use inverted fuel assembly or plate fuel assembly

MIT approach

CEA approach

Spacer pressure drop eliminated, also larger De

Feasibility domain for plate core at 50kW/l

- Feasibility domain for carbide CERCER (50/50) 2400MWt core \( q^\prime\prime = 50 \text{W/cc} \)

![Graph showing feasibility domain for plate core at 50kW/l](image)

Courtesy of CEA Cadarache. Used with permission.
Feasibility domain for plate core at 100kW/l

- Feasibility domain for carbide CERCER (50/50) 2400MWth core $q'''' = 100W/cc$
- CEA results
- Neutronics limit
- HD: MIN
- Thermal-hydraulic limit
- HD: MAX
- $T = 0.3$ bar
- $T = 0.7$ bar
- $T = 1.1$ bar

Feasibility domain rapidly evaporates with increasing power density
- Consequence of passive decay heat removal by natural convection and CR=1 without blankets
- Use of active system would provide more freedom for reactor physics design
- 2400MWth core possible to design at 100W/cc (but not 600MWth)
- 100W/cc preferable economically
- TH constraint can be essentially removed using active blowers

Neutronic Design for Safety

- We do have slightly positive CVW
- Is this acceptable after Chernobyl?
- How to assure safety with slightly positive CVW?
  - Rely on other reactivity coefficients, which are negative
    - Doppler feedback
    - Fuel thermal expansion coefficient
    - Core radial expansion coefficient
    - CRD driveline expansions coefficient
  - Strive for a design with such a combination of reactivity coefficients that leads to reactor shutdown without exceeding structural materials and fuel temperature limits
  - Similar as IFR - competitor

Courtesy of CEA Cadarache. Used with permission.
Possible Safety Approach

• Follow IFR approach of reactor self-controllability
• Goal: reactor should have sufficiently strong passive regulation of power to compensate for operator errors or equipment failures even if the scram fails.
• Core designed such that it inherently achieves safe shutdown state without exceeding temperature limits that would lead to core or vessel damage
• This must be achieved under the most restricting anticipated transients without scram (ATWS)
• The all encompassing accidents
  - Unprotected (without scram) loss of flow (ULOF)
  - Unprotected loss of heat sink (ULOHS)
  - Unprotected overpower (UTOP) – largest worth CRD withdrawal

Safety Approach (cont’)

• Note that this is much stronger requirement than for LWRs (e.g. complete loss of flow + failure to scram does not result in cladding damage)
• Loss of coolant is not credible in IFR since coolant under no pressure and if vessel fails, the coolant remains in guard vessel (but it is an issue in GFR, hence it needs to be accommodated)
• Inherent shutdown is determined by:
  - Reactivity feedbacks
  - Material and coolant-related limits (e.g., clad, boiling, freezing T for IFR)
• Need to find such combination of reactivity feedbacks and limits that makes it possible to achieve self-controllability
Safety Approach (cont’)

- Quasi-static balance for reactivity encompassing all paths that affect reactivity is

\[ 0 = \Delta \rho_{\text{power}} + \Delta \rho_{\text{flow}} + \Delta \rho_{\text{temp}} + \Delta \rho_{\text{external}} \]

- Since time constants of heat flow changes and temperature induced geometry changes and of delayed neutrons are in the range of half second to several minutes, and transients are slower, most feedbacks are linear permitting above equation to be represented as

\[ 0 = \Delta \rho = (P - 1)A + (P / F - 1)B + \delta T_{\text{inlet}} C + \Delta \rho_{\text{external}} \]

Where:
- \( P,F \) – power and coolant flow normalized to full power and flow
- \( \delta T_{\text{inlet}} \) – change from normal coolant temperature
- \( A,B,C \) – integral reactivity parameters that arise from temperature and structural changes - discussed next

Three criteria for \( A,B,C \) can be derived to achieve self-controllability


IFR criteria for passive self-regulation

**S1-criterion** \( A/B < 1.0; A,B \) negative

- A-net power reactivity coefficient (Doppler, fuel thermal expansion)

\[ A = (\alpha_d + \alpha_{\text{th}}) \Delta T_f [\varepsilon] \]

- B-power/flow coefficient of reactivity - controls asymptotic temperature rise in ULOF (coolant density, CRD-driveline, core radial expansion coefficients)

\[ B = [\alpha_d + \alpha_{\text{in}} + \alpha_{\text{den}} + 2(\alpha_{\text{crd}} + 2/3\alpha_{\text{rad}})] \Delta T_f/2 [\varepsilon] \]

- Key strategies:
  - Small negative A - metallic fuel, hard spectrum
  - Large negative B - minimize coolant density coefficient

- Large B also favors large temperature rise across the core
- But penalties on efficiency, hence compromise needed
Example of derivation of S1 criterion

• **Slow transients**
  - The reactivity must stay at zero
  - As flow, $F$, inlet temperature, $T_{in}$, and reactivity, $\Delta p_{ext}$, are altered by external forces, power, $P$, adjusts up or down to maintain net reactivity at zero

• **Unprotected Loss of Flow**
  - Primary flow lost, $W$ coasts down $W \rightarrow$ nat. circulation flow
  - Reactor needs to be designed such that asymptotically power decreases to decay heat level – ideally $P \rightarrow 0$ (positive reactivity from power reduction should balance the negative reactivity of core heatup)
  - Heat is being removed, ideally at the same inlet temperature, hence $\delta T_{in} \rightarrow 0$.
  - No scram, no rod movements, hence $\delta p_{ext} \rightarrow 0$
  - For GFR, no depressurization, hence $\delta p_{CVW} \rightarrow 0$

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Example of derivation of S1 criterion (Cont’)

• Substitute in reactivity balance equation
  $$0 = (0 - 1)A + (0 / F - 1)B + 0 C + 0 + 0$$
  $$P / F = 1 + A / B$$
  $$\Delta T_{out} = (A / B)\Delta T_{c}$$

• Core temperature rise: IFR $\Delta T_{c}$=150C; for MIT GFR; $\Delta T_{c}$=160C
• Core outlet temperature: IFR - 500C, GFR - 650C
• Cladding limit 725C for IFR, 1200C for GFR
  - Margin to cladding limit
    - IFR – $\delta T_{out}$ = 2/3*225C = 150C=$\Delta T_{c}$ (2/3 – safety factor)
    - GFR – $\delta T_{out}$ = 2/3*650 = 370C = 2.3 $\Delta T_{c}$
  - Substitute to $\Delta T_{out} = (A / B)\Delta T_{c}$

<table>
<thead>
<tr>
<th>IFR</th>
<th>GFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(A/B) \Delta T_{c} \leq \Delta T_{c}$</td>
<td>$(A/B) \Delta T_{c} \leq 2.3 \Delta T_{c}$</td>
</tr>
<tr>
<td>$A/B \leq 1$</td>
<td>$A/B \leq 2.3$</td>
</tr>
</tbody>
</table>
IFR criteria for passive self-regulation

**S2-criterion** \(1.0 < (C \Delta T_c/B) < 2.0; \ C \) negative

- \( C \) – inlet temperature coef. of reactivity = \(-\left[\frac{\partial \Delta \rho}{\partial T_{in}}\right]\)
- provides balance between the ULOHS and the chilled inlet temperature inherent response (Doppler, fuel thermal exp., coolant density core radial exp.)
  \( C = (\alpha_d + \alpha_{in} + \alpha_{den} + \alpha_{rad}) [\phi/K] \)
- range comes from cladding limit and coolant temperature rise
- **Main efforts:**
  - Minimize coolant density coefficient
  - Increase core radial expansion coefficient, if needed

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IFR criteria for passive self-regulation

**S3-criterion** \(\Delta \rho_{TOP} / |B| < 1.0\)

- Controls asymptotic temperature rise in UTOP
- The rod worth of the most reactive control rod must be limited
- **Strategies:**
  - Minimize reactivity swing
  - Use fertile, maximize \(\eta\), CR=1 is
  - Increase \(V_f\) - limited by cladding stress constraint
  - Low-leakage core favored, but hurts coolant void worth
  - Large \(B\) - minimize coolant density coefficient
  - Increase number of CRDs
Self-controllability criteria for LMRs

- ABR – fertile free, lead cooled actinide burner
- LMRs can be designed to satisfy these criteria in spite of positive CVW
- Transient calculations still needed to confirm the performance

1. **S1: A/B**
   - Controls $T_c$ rise in ULOFs

2. **S2: $\Delta T_c/B$**
   - Balance between ULOHs and chilled Tinlet

3. **S3: $\Delta \rho_{TOP}/|B|$**
   - Controls UTOP

Typical reactor response to ULOF

- Cladding must remain below temperature limit
GFR self controllability

• Can GFR be designed in a similar manner?
• Differences
  ■ Additional term in reactivity balance to account for CVW
  ■ Direct cycle – separate ULOHS and ULOF may not be possible – loss of heat sink (precooler) will lead to loss of flow to prevent compressor surge, hence ULOF and ULOHS will be always combined
  ■ Self-controllability criteria need to be updated
  ■ Decay heat removal may not be fully passive
• Issues
  ■ MIT design with UO2 fuel has too large Doppler feedback (low conductivity, softer spectrum)
  ■ Work in progress – good Ph.D. topic

Example of GFR design for passive decay heat removal

CEA and Framatome helium cooled design
Courtesy of CEA Cadarache. Used with permission.
Example – key design data for CEA design

Table 2.2: Design data and Thermal-hydraulics – 2400 MWt Plate Core

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First cycle</th>
<th>Equilibrium cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (MW/m^3)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Active core volume (m^3)</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Core diameter/height (m)</td>
<td>4.44</td>
<td>1.55</td>
</tr>
<tr>
<td>H/D</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>(U,Pu)C (% vol.)</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
<td>SiC structures (% vol.)</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Gas (% vol.)</td>
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</tr>
<tr>
<td>He coolant / He gaps</td>
<td>40.1</td>
<td>11.1</td>
</tr>
<tr>
<td>Plate thickness (mm)</td>
<td>7 (including 2 x 1 mm for plate closure)</td>
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</tr>
<tr>
<td>Plates per S/A (in a plane)</td>
<td>27</td>
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</tr>
<tr>
<td>Number of fuel S/A</td>
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<tr>
<td>Core pressure drop (bar)</td>
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<tr>
<td>Tmax** cladding BOL (°C)</td>
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</tr>
<tr>
<td>Tmax* fuel BOL (°C)</td>
<td>1210</td>
<td></td>
</tr>
</tbody>
</table>

**taking into account a correction for plate macro-structure heterogeneity

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