Safety-related SFR Design and Experimental Experiences in Korea

IAEA-GIF Workshop on Operational and Safety Aspects of SFRs

IAEA Headquarters, Vienna
23-25 June, 2010

H.-Y. Jeong

Korea Atomic Energy Research Institute
Outline

I. Design Experiences

II. Experimental Studies

III. Summary
Design Experiences
**Goal**
- Construction of demo. SFR by 2028

**Work Scope**
- Advanced design concept development
- Design validation
- Metal fuel development

- Proliferation resistant core without blankets
- MA bearing metal fuel
- Enhanced safety with passive systems

**SFR Technology Development Status**

- **Proliferation resistant core without blankets**
- **MA bearing metal fuel**
- **Enhanced safety with passive systems**

**Timeline**
- Basic Research: '92
- KALIMER-150 Conceptual Design: '97
- KALIMER-600 Conceptual Design: '02
- Advanced SFR Concept: '07
- Standard Design Approval: '11
- Sodium T/H Experiment Facility: '15
- Demonstration SFR: '20
- Construction of demo. SFR: '28
**Key Design Features**

- **600MWe, Pool-type Reactor**
- **Fuel**: U-TRU-Zr
- **Core I/O Temp**: 390/545 °C
- **DHR System**: PDRC
- **2-loop IHTS/SGS**
- **Net Efficiency**: 39.4%

**Conceptual NSSS Layout**

**Heat transport system of advanced pool type SFR**
KALIMER-600 Safety Systems

- **Inherent safety features**
  - Large poop-type PHTS
  - Reactivity feedbacks

- **Key Engineered Safety Features**
  - Reactor Shutdown Systems
    - Primary and secondary with diversity
  - PDRC
    - Safety grade
    - 50% x 4
  - SWR PRS (Pressure Relief System)

- **Others**
  - SASS (Self-Actuated Shutdown Sys.)
  - In-vessel core catcher
  - Containment
PDRC Design Features

- Passive DHRS Features
  - Elimination of active components
  - Operation by natural circulation
  - No operator action
  - Major components
    • AHX, DHX, expansion vessel and piping

- System Operation
  - Normal operation
    • Minimized heat loss enough to prevent sodium freezing
  - Primary pump trip
    • Decay heat removal by natural circulation

- More reliable and efficient design is being searched

PDRC design concept
II

Experimental Studies
PDRC Experimental Facility

- **STELLA** (Sodium TEst Loop for safety simulation and Assessment)
  - STELLA-I: Component Performance Test
  - STELLA-II: Integral Effect Test

- **Objectives**
  - Assessment of initial & long term cooling capability by natural circulation
  - Verification of DHRS design concept
  - Establishment of database for validating system analysis code

- **PDRC basic design issues**

- **Long-term cooling Characteristics**

- **Initial core cooling characteristics**

- **RV fracture effect**

IAEA WS on SFR Safety, June 23-25, 2010, Vienna
## STELLA Construction Schedule

### Phase 1
- **Component Performance Test**
  - Verification of heat exchanger (IHX, AHX, DHX) design codes
  - Demonstration of mechanical sodium pump performance
  - Development or Improvement of sodium flow measuring techniques

### Phase 2
- **Integral Effect Test**
  - Verification of passive decay heat removal concept
  - Integral effect test for dynamic plant response after reactor shut down
  - Support of standard design approval for demonstration reactor

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Construction of STELLA-I and Performance Experiment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Construction of STELLA-II and Integral Effect Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Design Req’t**
  - STELLA-I Design
  - Construction of Power Supply & Sodium Storage Facility
  - Assessment of Scope for IET
  - STELLA-II Basic Design
  - Scoping Analysis

- **Start-up Test**
  - Research & Construction of STELLA-I
  - Installation of STELLA-I
  - Test Req’t

- **Experiment**
  - Manufacture and Installation of STELLA-I
  - Start-up Test
  - Detail Design
  - Detailed Design
  - STELLA-II Installation

- **Integral Effect Test**
  - Design Spec.
  - Start-up Test
  - Phase 1

- **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
Preliminary Design of STELLA

- **Major characteristics**
  - Reference reactor (Prototype): KALIMER-600
  - Working fluid: Sodium
  - Sodium mass: 15 ton
  - Core power: 1.9 MW
  - Reactor vessel height: 3.7 m
  - Reactor vessel diameter: 2.3 m
  - Temperature distribution: 1:1
  - Operating pressure: 1 bar

- **Key design parameters of the facility**
  - Parameter | Scaling Ratio (Model/Prototype)
  - Length Ratio | 1/5
  - Area Ratio | 1/25
  - Volume Ratio | 1/125
  - Temperature Rise/Drop Ratio | 1
  - Velocity Ratio | 1/2.24
  - Time Ratio | 1/2.24
  - Gravity Acceleration Ratio | 1
  - Core Power Density Ratio | 2.24
  - Power Ratio | 1/55.9
  - Flow rate Ratio | 1/55.9
  - Pressure Drop Ratio | 1/5
  - Aspect Ratio | 1
**Na–CO₂ Reaction Test – Objective**

- **Objectives**
  - Investigation of basic nature of sodium-CO₂ interaction
  - Development of the reaction model
  - Evaluation of design and safety issues regarding a potential CO₂ ingress event

- **Current Status**
  - Completion of the surface reaction tests for sodium-CO₂ interaction
  - Estimation of kinetic parameters for a combined diffusion-reaction process
  - Confirmation of temperature dependency on reaction mechanism
  - Preliminary tests for potential wastage and self-plugging issues

---

**Chemical reaction for a combined diffusion-reaction process**

\[
R_p = K_0 \cdot e^{-\frac{E_a}{RT}}
\]

\[
R_p = K_m \cdot (C_{i,in} - C_{i,t})
\]
Na–CO₂ Reaction Test – Results I

**Major Achievements**

- Proposal of Two-zone reaction model with Threshold temperatures
  - Zone 1: 300–460°C
  - Zone 2: 460–550°C
  - Sodium ignition > 590°C

- Importance of rupture position
  - Major difference from the features of SWR events

**Equation**

\[
R_{s,i} (\text{kg} / \text{sec}) = K_i \cdot \exp\left(-\frac{E_{a,i}}{R \cdot T}\right) \cdot A_i
\]

**Zone 1:**
- \( E_{a,1} = 27.34 \quad [kJ / mol] \)
- \( K_1 = 1.32 \times 10^{-4} \quad [kg / m^2 / sec] \)

**Zone 2:**
- \( E_{a,2} = 162.07 \quad [kJ / mol] \)
- \( K_2 = 5.80 \times 10^5 \quad [kg / m^2 / sec] \)
Na–CO₂ Reaction Test – Results II

Major Achievements

- Practical CO₂ injection tests for Potential design
  and safety issues
  • Material wastage scenario
  • Channel plugging and self-mitigation

- Test results and Major findings
  • Negligible combined corrosion/erosion effect → Rare
    wastage effect
  • For the condition of a large CO₂ release with
    boundary rupture
    ✓ No channel plugging or nozzle blockage
  • For the condition of a slow loss of CO₂ inventory
    ✓ Conditional Nozzle plugging

Comparison with Sodium-Water Reaction

Comparison with Sodium-Water Reaction

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Temp. (°C)</th>
<th>CO₂ gas flow rate (scc/min)</th>
<th>Inj. Velocity (m/sec)</th>
<th>Nozzle diameter (mm)</th>
<th>Self-plugging</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>250</td>
<td>~20.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>500</td>
<td>~40.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>500</td>
<td>~10.0</td>
<td>1.0</td>
<td>✗</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>500</td>
<td>~10.0</td>
<td>1.0</td>
<td>✗</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>250</td>
<td>~20.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>500</td>
<td>~40.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>500</td>
<td>~10.0</td>
<td>1.0</td>
<td>✗</td>
</tr>
<tr>
<td>8</td>
<td>500</td>
<td>500</td>
<td>~5.0</td>
<td>1.5</td>
<td>✗</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>250</td>
<td>~20.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>500</td>
<td>~40.0</td>
<td>0.5</td>
<td>✗</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>500</td>
<td>~10.0</td>
<td>1.0</td>
<td>✗</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>500</td>
<td>~5.0</td>
<td>1.5</td>
<td>✗</td>
</tr>
<tr>
<td>13</td>
<td>600</td>
<td>500</td>
<td>~5.0</td>
<td>1.5</td>
<td>✗</td>
</tr>
</tbody>
</table>

Results of self-plugging tests

x : No plugging  ○ : delayed plugging  • : prompt plugging
Further studies to be evaluated

- Large-scaled Free sonic jet test
  - Bulk reaction features inside a larger sodium pool
  - Injection pattern
    - CO₂ flowrate, nozzle size, etc.

- Modeling activities for the practical sodium-CO₂ interaction event
  - Measurements relevant to a bubble collapse, transport & corresponding reaction product formation
  - Use of Gas-liquid interfacial area density
  - Challenging issues for sodium opacity
Under-Sodium Viewing (USV) in SFR

- **Technical Issues**
  - Sodium Coolant of SFR: Opaque
  - USV Technology using Ultrasonic Waves
    - Observation of Reactor Core during Refueling
    - ISI of Reactor Internals: Visual Inspection

- **USV Sensors**
  - Immersion Sensor (PFR, MONJU)
    - Viewing and Ranging
    - High Resolution Imaging
    - Short Lifetime in Hot Sodium
  - Rod Waveguide Sensor (PX/SPX)
    - Ranging: Transducer over Reactor Head
    - Long Lifetime & Stable in Hot Sodium
    - Scanning Limitation

- **Development of enhanced ultrasonic waveguide sensor** for better under sodium viewing is essential.
Plate Ultrasonic Waveguide Sensor

- Overcome Limitation of previous USV sensors
- Long Lifetime & Versatile Application
- Using $A_0$ Lamb Wave (Plate Wave)
  - Fundamental Flexural Mode
- Mode Conversion
  - $A_0$ Wave: Leaky Wave in Liquid
  - High Radiation Efficiency
  - Radiation Beam $\theta$: Snell’s Law

\[
\sin \theta = \frac{V_L}{C_p}
\]
Feasibility Study of US Waveguide Sensor

- **Design of Waveguide Sensor Module**
  - Acoustical Shield Tube
  - Radiation Shield & Thermal Protection
  - 10m Long Plate

- **Experimental Setup**
  - High Power Ultrasonic System
  - C-Scanning System

- **Feasibility Tests of Waveguide Sensor**
  - Wave Propagation Test
  - Beam Profile Measurement
  - Radiation Beam Steering
  - C-Scan Imaging Resolution Test

Under-sodium Inspection of KALIMER-600 using Plate Waveguide Sensor
**Design of US Waveguide Sensor Module**

- **Ultrasonic Waveguide Sensor Module**
  - Slender Cylindrical Structure
  - Ultrasonic Transducer
  - Wedge:
    - Liquid Wedge or Solid Wedge (Teflon)
  - 10m Long Strip Plate \((t=1\text{mm}, W=15\text{mm})\)
  - Acoustical Shielding Tube
    - Inert Gas : Ar
  - Radiation Shielding Block
  - Separation Pad Plate

---

**10 m long waveguide sensor module**

[Diagram of waveguide sensor module]
Feasibility Test of US Waveguide Sensor–I

- **C-Scan Imaging Test**
  - Test specimen: Slits & Loose Parts
  - Waveguide Sensors
    - 30cm Plate Waveguide Sensor
    - 10m Plate Waveguide Sensor
    - 10m Waveguide Sensor Module
  - Resolution: < 2mm

- Images:
  - 30cm Plate Waveguide
  - 10m Plate Waveguide
  - 10m Waveguide Sensor Module

- Diagram:
  - Slits: 2mm, 1mm, 0.8mm, 0.5mm
Feasibility Test of US Waveguide Sensor-II

C-Scan Imaging Test
- "SFR" Character Target
- Core Mock-up Target

Test Block

Immersion UT Sensor (10MHz, 0.25" Dia.)

10m Waveguide Sensor Module (1MHz)

C-Scan Image of Core Mock-up

C-Scan Image (Gated on Top Surface)

Distorted Core Assembly
III. Summary

- **Long-term Plan for SFR Development** was approved by the KAEC in December 2008
  - Standard design approval by 2020
  - Construction of demonstration SFR by 2028

- **Activities for the development of Advanced SFR Concept**
  - Advanced concept design studies
  - Development of advanced technologies
  - Development of basic technologies

- **Experimental studies for the validation of PDRC concept and performance test** are undergoing

- **Feasibility Study on Ultrasonic Waveguide Sensor Technology** has been performed. Technology for under sodium viewing is being refined with design improvement of Ultrasonic Waveguide Sensor Module