Research Progress on Radioactive Source Terms in Lead-Bismuth Fast Reactors and Environmental Impact

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• 15 years research experience in the nuclear safety field
  • Previously working 10 years on radioactive safety issues for fusion energy
  • Finished two Tritium management tasks for ITER IO, Cadarache, France
  • Now focus on the radioactive source terms for Lead-based fast reactor
  • Still works with ITER on tritium retention problem as ITER scientist fellow

• Ph.D in Nuclear Science & Engineering, University of Sci & Tech of China

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My expectations from the Meeting: Collaboration in the nuclear safety issues of advance nuclear system
Outlines

• Introduction of IFCEN-SYSU
• Source terms in LBE fast reactor
  – Corrosion and Activated Corrosion Products (ACPs)
  – Polonium & aerosol
  – Tritium permeation
  – Environmental impact
• Summary
Sino-French Institute of Nuclear Engineering & Technology, Sun Yat-sen University

2009: Witnessed by prime ministers of both China and France, SYSU and FINUCI Created IFCEN Jointly on SYSU Zhuhai Campus

2015: Phase II agreement signed

2022 Phase III agreement signed, IFCEN entering a new phase!

- Grenoble INP-UGA
- CEA-ISTN
- IMT Atlantique
- Ecole de Chimie de Montpellier
- Ecole de Chimie de Paris
CTI Accreditation Renewal in 2022:
A 6-Year accreditation received --- the longest possible!
The high-quality of the IFCEN program fully recognized!
IFCEN 14th 5-Year Plan for R&D

Lead-bismuth Fast Reactor: One of the Main Candidate Concepts for SMR

In the fourth generation nuclear power system, lead cooled fast reactor (LFR) is expected to become one of the first reactor types to achieve industrial demonstration.

For SMR: Good neutron economy; Strong transmutation capability; Widely application

One Theme, N Fields

Advanced Nuclear Energy (Lead-based Fast Reactor)

- Thermal hydraulics
- R&D of Fuel & Materials
- Nuclear Safety

Goal: SYSU/IFCEN Characteristics

- Corrosion & Source term
- Nuclear Materials: R&D, evaluation
- Nuclear software & simulation
- Advance accelerator & application
Main Radioactivities from LFR to Environment

Source Terms: Po210, FPs, ACPs, Tritium
Transportation Medium: LBE coolant, Cover gas, Atmosphere, Ocean...

Marine Migration
Atmospheric dispersion
Through Food Chain
Exchange on underlying surface
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- Introduction of IFCEN-SYSU
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  - Radioactive aerosol
  - Tritium behavior
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- Summary
Activated Corrosion products (CPs): Activated elements dissolved in LBE such as Fe Cr and Ni and their solid oxide particles.
High Temp. Corrosion of Structural Materials in LBE

High temp. LBE corrosion tanks (with Oxygen control)

Forced convection testing loop (Under construction)

Corrosion Rate

<table>
<thead>
<tr>
<th>Year</th>
<th>Corrosion Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0Y</td>
<td>12.9 ± 1.2 μm</td>
</tr>
<tr>
<td>1Y</td>
<td>14.8 ± 1.1 μm</td>
</tr>
</tbody>
</table>

Element diffusion

Grain expansion     Strain release   Diffusion channel    Oxygen reacts with solute atoms

Grain boundary oxidation

Si Oxidation  Cr Oxidation

SiO\(_2\)  Fe  Cr\(_2\)O\(_3\)
High Temp. Corrosion Products behavior in LFR

The effect of particle size

Density of particle: 5200 kg/m³ LBE density 10⁴ kg/m³

The final distribution of particles

- 0.01 μm (left)
- 100 μm (middle)
- 1000 μm (right)

For \( D_p < 100 \) μm, size influences less
For \( D_p > 100 \) μm, larger size, larger buoyance, particles tend to float

The effect of particle density

Ratio of entering in the core

For \( D_p < 100 \) μm, density influences less
For \( D_p > 100 \) μm, smaller density, greater buoyance, particles tend to float on LBE

Final particle distribution of 1000 μm, density 9530 kg/m³ (left), 7400 kg/m³ (right).

Aggregation of solid particles.

The effect of release position

Simulation conditions: Diameter of particles: 40 μm, density of particles 5200 kg/m³

The final distribution of particles

- The particles above the core has the greatest probability of entering the core.
- The particles in the stagnant region tends to suspend in the LBE.

Initial site for filtration material

Simulation conditions: Diameter of particles: 40 μm, density of particles 5200 kg/m³

Preliminary installation site for filtration material
- Low temperature
- Less influence of flow field in case of blockage
- Capture the particle entering in the core

The final distribution of particles
Force Convection Testing Loop for LFR

**Goal:** simulate the real LFR operation environment in Lab., to study the behaviors of Radioactive source term, corrosion & ACPs, to support the nuclear safety of LFR

- **Temperature:** 400 ~ 550°C
- **High V:** 2m/s
- **Low V:** 0-1m/s

Diagram:
- Source term Exp
- Low Velocity
- High Velocity
- Heater
- Oxygen Control
- EM Bump
- VALVE
- Cooler

LBE EM Bump (9bar, 300-550°C)

EM Flow Meter
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Polonium in Lead Bismuth Fast Reactor

Evaporation

Argon

Po/PbPo Aerosol
H₂Po

Leakage

Deposition

Convection
Diffusion
Decay
Evaporation

Physical mechanisms

Chemical reactions

99.8% PbPo
0.2% Po

LBE

n
Aerosol is the main carrier of Volatile Source Term

Lead bismuth aerosol experimental platform

- Evaporation Temp: 200-1000℃
- Aerosol formation: 0-100℃
- Moisture: 30-100%
- Nuclides: PbBi, with Te, I, Cs
- Measurement: 8nm-1200nm; 0.2μm-40μm
- Deposition rate

Lead-bismuth aerosol kinetic parameters

- PbTe aerosol in high temp
- PbTe aerosol@1223K

The environmental cavity

 AKG2000  USMP  Promo2000
Hard X-ray Platform for Chemical Properties of Source Term

Small Angle X-ray scattering platform

Diffraction platform

Imaging and spectroscopic platform

Graph showing intensity (a.u.) vs. 2q (degree) for LFP(74μm)@Al(16μm)/Li(1mm) cell.
Study on chemical characteristics of typical source terms (Po, Te) in LBE

XAFS/XPS technology measures and analyzes sample components

- Synchrotron radiation XAFS measurement of PbTe samples
- Laboratory Table-XAFS measurements of PbTe samples
- Laboratory XAFS measurement of absorption spectra for PbTe samples (Left: k-space quadratic-weighted signal; Right: K-side absorption spectrum of PbTe sample)
- XPS measurement of PbTe samples

Experiments have shown that there are indeed compounds with +4 valence Te

Heat and keep warm for 30 min at 873 K

XPS measurements (Te, Pb, O in PbTe samples at 873K)
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Tritium Behaviors in LBE Fast Reactor

Hydrogen in Cover Gas

- Oxidation: $\text{HT} \Leftrightarrow \text{HTO}$
  (controlled by $\text{O conc}$)
- Behaviors: Solution, diffusion, absorption, permeation, evaporation, decay

Hydrogen in LBE

- Produced by: ternary fission, Li impurity
- Chemical foam: $\text{T} \cdot \text{HT} \text{ or } \text{HTO}$
- Behavior: Solution, diffusion, absorption, permeation, evaporation, decay

Permeat. Release

Absorp. deposi.
LBE-Hydrogen Testing Facility with oxygen control

- **Function I**: $D_H$, $k_s$ & $\Phi$ of structural materials in inert gas from 300K~1000K
- **Function II**: $D_H$, $k_s$ & $\Phi$ of liquid lead bismuth in inert gas from 523K~873K

Hydrogen Solubility, Diffusivity & Permeability in LBE

Max. Permeation Flux vs. Hydrogen partial pressure

Permeation Flux@1000Pa $H_2$

\[
S_{(T)} = 0.8198 \exp\left(-\frac{47754.5}{RT}\right)
\]

\[
D_{(T)} = 4.192 \times 10^{-8} \pm 2.959 \times 10^{-9} \exp\left(-\frac{2326.8 \pm 221.42}{RT}\right)
\]

\[
\Phi_{(T)} = 5.953 \times 10^{-8} \pm 2.06 \times 10^{-12} \exp\left(-\frac{50081.4 \pm 1194.4}{RT}\right)
\]
Deuterium Chemical foam in LBM at High Temp. with Oxygen control

- H/D permeation experiments in LBE at different temp, partial pressure, oxygen conc.
- The tritium \( D_T \), \( k_s \) & \( \Phi \) were derived from H/D experiment
Comparison of **diffusivity, permeability, and solubility** of hydrogen in lead-bismuth, lead-lithium, and 316L stainless steel.
Multi-Testing platform for Tritium in LFR

Testing Facility for Tritium in Liquid Metal

- **Module 1**: Lead, bismuth, heavy metal, hydrogen isotope permeation (existing)
  Function: Hydrogen isotope permeability of liquid metal lead bismuth in high temperature inert gas environment, diffusion, solubility measurement
- **Module 2**: Hydrogen isotope permeation of lead-bismuth environmental structural materials
  Function: Permeability, diffusivity, solubility measurement of hydrogen isotopes in lead-bismuth coolant structural materials (including the surface state of materials after corrosion by lead-bismuth)

Testing Facility for Tritium in Gas

- **Module 1**: Gas Phase Permeation (Existing)
  Function: Measurement of hydrogen isotope permeability, diffusivity and solubility in the high temperature gas environment of structural materials
- **Module 2**: Thermal Desorption (TDS)
  Function: Measurement of adsorption energy of hydrogen isotopes in materials (capture energy in material defects, physical adsorption)
- **Module 3**: PCT
  Function: Material absorption and discharge of hydrogen PCT curve measurement (hydride formation and decomposition)
Outlines

• Latest progress of LBE SMR in IFCEN-SYSU
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Source Term migration simulation platform for LFR

- **Development of Source Term migration for LFR**
  - **Multi-physic:** Two-phase flow heat and mass transfer, chemical equilibrium
  - **Geometry:** 1/2/3D coupling
  - **Source term:** Po, Tritium, ACPs, FPs
Rapid pollutant dispersion prediction

A. Mobile ground emergency monitoring system
   Auto-mobile station

B. Expert system for nuclear accident emergency command and decision-making
   Emergency Training

C. Contaminant dispersion based on typical atmospheric models
   Fine transport model of power station combined with mobile calibration technology

D. Fine transport model of power station

E. Radioactive contaminant dispersion simulation based on high-precision local forecasting
   Diffusion of nuclear material
Radionuclide polonium diffusion in marine

Features
Different release modes for various scenarios
- Decay model
- Tidal influences
- Biosorption *
- Chemical foam

“atmosphere-marine” model

Ocean proliferation
Land subsidence
Atmospheric diffusion
Interface coupling

Po concentration in marine vertical section
Po transport in marine in weeks

Concentration distribution of Po "2022/07/07 02:00"

Po concentration vs time

Po concentration at different stations
Summary

This presentation introduces the main radioactive source terms from Lead-bismuth fast reactor and their migration mechanism.

- A numerical model for the source terms migration had been established for LBE reactor.
- Experimental research on key nuclides such as Te(Po), Tritium, Cs&I had been conducted.
- We still need more data to support the safety of advanced lead-bismuth reactors.
IFCEN’s New Premises

Welcome new collaboration