ACR Technology Base: Containment

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Introduction

- The containment of a CANDU reactor is designed to mitigate the consequences of an accident.
- During an accident the containment building could be subjected to a harsh environment of hot vapor, fission products from failed fuel, and hydrogen released from oxidation reactions.
- Research is performed to ensure that we understand:
  - The time dependent nature of the environment.
  - The behavior of fission products.
  - Any threats posed by released hydrogen (primarily a concern for severe accidents).
Containment Performance

- R&D focused on determining behavior of effluent from the reactor coolant system in containment
- **Experimental:**
  - Large-scale gas mixing facility
  - Used to study mixing, buoyancy-induced flows, stratification, condensation, effects of containment partitions
  - Data used to validate GOTHIC
- **Modeling:**
  - GOTHIC, with addition of CANDU-specific models for hydrogen behavior, used to model containment thermal hydraulics and hydrogen transport
Large Scale Gas Mixing Facility

- Volume: 1000 m³ (35000 ft³)
- Atmosphere: air, steam and helium
- Internal partitions simulate sub-compartments
Example of a Gas-Mixing Experiment

- Steam injected and formed a stratified layer
- Helium injected, breaks through stratified layer after ~200 seconds, and rises
- After 1200 seconds, blowers create uniform mix
Fission Product Behavior

- In the event of a LOCA, fission products from failed fuel are discharged from the break.
- Fission products that remain in the vapor phase are more subject to release from containment than those that partition to water.
- Iodine has been a focus because of its relative abundance, high biological activity and gaseous forms.
Iodine Behavior in Containment

- Primary concern is the time dependent concentration of gaseous iodine
- Released from fuel into containment mainly as CsI, which dissolves as non-volatile iodide in water
- Under the oxidizing and high radiation environment following an accident, non-volatile iodide would react and become volatile and partition into the gas phase
Iodine Reactions and Transport

I\(^{-}/g45\), I\(_3^-/g45\), HOI, IO\(_x^-\)

I\(_2(aq)\) \rightleftharpoons RI\(_2(aq)\)

I\(_2(g)\) \rightleftharpoons RI\(_2(g)\)
Factors affecting Iodine Behavior

- Iodine exists in various chemical states
- Post-accident containment is under irradiation and not in chemical equilibrium
- Iodine chemistry is driven by water radiolysis
- Many reactions and processes are inter-dependent
- Iodine behavior cannot be easily scaled from correlations based on integrated tests
- Requires a correct representation of aqueous chemistry (which can be scaled)
AECL Iodine Program Components

- Intermediate-scale integrated-effects tests in the Radioiodine Test Facility (RTF)
- Supporting bench-scale tests to separate and quantify individual effects
- Development and validation of containment iodine behavior models, LIRIC & IMOD, for safety analysis
- International collaboration
  - EPRI ACEX
  - PHEBUS
  - International Standard Problem code comparison exercise
Radioiodine Test Facility
50 RTF Tests

- **Type of Vessel Surface**
  - Stainless Steel (electropolished, untreated)
  - Organic Coatings on carbon steel or concrete (Vinyl, Epoxy, Polyurethane)
  - Inorganic Coatings (zinc primer)
- Radiation on, Radiation off
- pH controlled, pH uncontrolled: range 4.5 – 10.5
- **Temperature**
  - constant throughout experiment: 25, 60, 90°C (80, 140, 190°F)
  - steps from 25 to 80°C (80 to 170°F)
- Condensing, Non-condensing
- Organic and Inorganic Additives
Bench-Scale R&D Areas

- Aqueous Phase Chemistry
  - Inorganic Iodine Reactions
  - Water Radiolysis
  - Effects of Organic Impurities
    - Sources of organic compounds dissolved in water
    - Radiolytic decomposition of organic impurities
    - Organic iodide formation & decomposition

- Aqueous-Gas Phase Partitioning of Volatile Species

- Iodine – Surface Interaction
Model Development & Validation

LIRIC

- A comprehensive mechanistic model, based on our extensive knowledge of relevant chemical reactions and mass transport
- Performs well when tested against bench-scale and RTF tests carried out over a wide range of conditions
- Due to its complexity and size, integration of LIRIC into a safety analysis code is considered to be impractical

IMOD

- Reduced reaction set based on extensive LIRIC analysis and simulations of various RTF tests
- A smaller and simpler model, but maintains many of the capabilities of LIRIC
**Aqueous Phase**

- Water radiolysis reactions (~40 rxns)
- Inorganic iodine reactions (~80 rxns)
- Organic reactions
  - Dissolution
  - Radiolytic decomposition
  - Organic iodide behavior

**Gas Phase**

- All volatile species (I₂, RI, H₂, O₂, CO₂)
- Mass transfer

**Surfaces**

- Dry, wet, submerged (SS, Al, paints, Polymers)

**Adsorption and Desorption**

- Condensate flow
- Ads
- Des
IMOD

Aqueous Phase

NONVOLI(aq) ↔ I₂(aq)
I₂(aq) → HVRI(aq), LVRI(aq)
HVRI(aq), LVRI(aq) → NONVOLI(aq)

Dissolution
Radiolytic decomposition
Acid-Base Equilibria

Total 16 reactions

Gas Phase

Mass transfer

Volatile Iodines
(I₂, HVRI, LVRI)

Surfaces

Dry, wet, submerged
(SSF, Al, paints, Polymers)

Condensate Flow

Des

Ads

Ads

Des
IMOD Simulation of an RTF Test
(organic addition in a stainless steel vessel)

<table>
<thead>
<tr>
<th>pH Control</th>
<th>Slow MIBK Addition</th>
<th>pH Control</th>
<th>Fast (5X) MIBK Addition</th>
<th>pH Control</th>
</tr>
</thead>
</table>

![Graph showing pH over time with experimental data and IMOD-2.0 simulation.]

- **Experimental Data**
- **IMOD-2.0**
IMOD Simulation of an RTF Test
(organic addition in a stainless steel vessel)

Total Aqueous Iodine

- Experimental Data
- IMOD-2.0

Concentration (mol/dm³)

Time (h)
IMOD Simulation of an RTF Test
(organic addition in a stainless steel vessel)

Total Gaseous Iodine

Concentration (mol/dm³)

Time (h)
International Collaboration

- EPRI ACE (Advanced Containment Experiments) & ACEX
  - RTF tests, critical review of the current understanding of iodine chemistry and model developmental work were performed in support of ACE & ACEX (extension) projects

- PHEBUS-FP
  - RTF & Bench Scale experiments investigating LWR severe accident phenomena

- International Standard Problem (ISP) 41 and 41F Phase 1 & 2
  - Iodine code comparison exercises endorsed by NEA (Nuclear Energy Agency) CSNI (Committee on the Safety of Nuclear Installations)
  - AECL has lead the very successful exercises
  - AECL’s iodine codes, LIRIC and IMOD are participating
AECL Iodine Program Status

- We have a good understanding of iodine behavior in containment
- Models have been developed and shown to predict iodine behavior well
Hydrogen Behavior In Containment

Sources of Hydrogen
- Short-term: reactions between hot fuel and RCS components and steam
- Long-term: water/steam radiolysis and metal corrosion in containment

Areas of Investigation
- Transition from deflagration to detonation (DDT)
- Effects of deflagration and standing flames on containment structures
- Development and evaluation of Passive Auto-catalytic Recombiners
Results of Hydrogen R&D

- Acquired fundamental understanding of key combustion phenomena:
  - the mechanisms for flame acceleration and transition to detonation
  - the dynamics of flame jet ignition
  - the mechanisms and dynamics of standing flames
  - the mechanisms and dynamics of vented combustion

- Developed computer models for implementation in GOTHIC to predict gas distribution and combustion pressure

- Program based on a variety of facilities
Containment Test Facility (CTF)

- 6-m³ (200 ft³) sphere and a 10-m³ (350 ft³) cylinder
- pressures up to 10 MPa (1500 psi)
- temperatures up to 150°C (300°F)
- vessels may be inter-connected by 30 cm (12 in) and 50 cm (20 in) diameter ducts
Diffusion Flame Facility (DFF)

- silo: 5 m (16 ft) in diameter and 8 m (26 ft) high
- Tests with H₂ / steam jet flames (up to 15 cm (6 in) diameter) in air / steam atmosphere (up to 30% steam by volume)
Large Scale Vented Combustion Facility

- rectangular enclosure with an internal volume of 120 m³ (4200 ft³)
- electrically trace-heated and insulated to maintain temperatures in excess of 100°C (212°F)
- can be subdivided into 2 or 3 compartments
Combustion Codes

GOTHIC

- Used to calculate hydrogen distribution inside containment and the combustion pressure in the event of an ignition

DDTINDEX

- Used to calculate a set of criteria for assessing the possibility of supersonic flames via flame acceleration and subsequent transition to detonation
• Hydrogen distribution in containment during a large LOCA (header break)
DDTINDEX Outputs
Passive Autocatalytic Recombiners

• recombine hydrogen with oxygen in a controlled fashion

• based on AECL’s wet-proofed catalyst technology developed for heavy water production

• have been qualified with tests in the large-scale vented combustion facility
AECL PAR - Self-Start Test

Initial Conditions: 1.4% H₂, 100% R.H., T=14°C, P=98.4 kPa

Test #: RQT006

Hydrogen Concentration (vol %) vs Time (min)

- G1: Inlet
- G2: Outlet
- G3: Floor
- G4: Top Corner
- G4: Front

mixing fans on at 70 minutes
mixing fans off at 10.5 minutes
Summary

- Research programs into areas relevant to containment are mature and widely-recognized.
- Models and computer programs have been developed and validated for CANDU safety, licensing and design.
- Only work required to support ACR is minor anticipatory R&D (e.g., qualification of passive recombiners for ACR conditions).