RAMM-TM for Canister Gas Leakage Detection and Radiological Consequences

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Background and Introduction

- This presentation describes work performed under a Cooperative Research and Development Agreement (CRADA) between Argonne National Laboratory and the Central Research Institute of Electric Power Industry (CRIEPI), Japan.

- This presentation includes results published in 2 NED journal papers in 2021:

- Aging management – detection of aging effects – inspection and monitoring

Outline of Presentation

Methods
- $\Delta T_{B1}$
- TT, TB

Scale Model

RAMM-TM

Test Results

STAR-CCM+ Simulation

Radiological Consequences
Ageing Management - Inspection/Monitoring

- Periodic inspection of selected canisters
- Mitigation & repair (M/R), if CISCC indication found
- Costly and labor-intensive

- Continuous monitoring of many canisters
- M/R before exceeding allowable leakage rate
- Cost-effective and reduce risks to public safety, health, and environment.

Periodic Inspection → CISCC indication → M/R → Continuing storage → Disposal

Leakage Monitoring → CISCC indication → M/R → Continuing storage → Disposal

Alarm

Allowable leakage rate
Canister Helium Leakage Detection Methods

**ΔTBT Method**
Temperature difference between TT and TB. *NED Vol. 238 (2008)*

**TT Method**
Temperature difference between TLB and TLM. *NED Vol. 352 (2019)*

**TB Method**
Temperature difference between TIN and TB. *NED Vol. 362 (2020)*

\[ ΔT_{BT} = T_B - T_T \]
1/4.5-Scale Model Cask

- Based on T-H similarity law with independent control of test parameters
  - Decay heat load (up to 90 years of dry storage)
  - Fill-gas (air and helium) and pressure (up to 6 atm)
  - Instrumentation (power, pressure, and temperature)
  - Controlled leakage path (size of simulated CISCC crack) and start of leakage
Evaluation of Leak Detection by $\Delta T_{BT}$ Method

The leak amount ratio of 0.5% (2 kPa) could be detected in the laboratory tests.

$\Delta T_{BT} = T_B - T_T$

The actual temperature can be calculated from the test results by the transform expression.

$$\frac{\Delta T_p}{\Delta T_m} = \left(\frac{\xi_p}{\xi_m}\right)^{\frac{1}{3}} \left(\frac{\beta_p \rho_p c_p^2}{\beta_m \rho_m c_m^2}\right)^{\frac{1}{3}} \left(\frac{L_p}{L_m}\right)^{\frac{5}{3}} \left(\frac{Q_p}{Q_m}\right)^{\frac{2}{3}}$$

$$= \left(\frac{\rho_p c_p^2}{\rho_m c_m^2}\right)^{\frac{1}{3}} \left(\frac{L_p}{L_m}\right)^{\frac{5}{3}} \left(\frac{Q_p}{Q_m}\right)^{\frac{2}{3}} = 0.76$$
Gas Leakage Path and “Simulated” CISCC Crack

Small-diameter pipelet with varying lengths

ANSI N-14.5 volumetric leakage rate

\[ L_u = (F_c + F_m) (P_u - P_d) \left( \frac{P_a}{P_u} \right) \]

\[ F_c = \left[ 2.49 \times 10^6 D^4 \right] / (a \mu) \]

\[ F_m = \left[ 3.81 \times 10^3 D^3 (T/M)^{0.5} \right] / (a P_a) \]

CISCC “equivalent” pinhole diameter of 45.8–47.1 µm can be derived assuming crack length = wall thickness (e.g., 0.5 in.) of MPC of actual dry storage system
Remote Area Modular Monitoring (RAMM) for Temperature Measurement (RAMM-TM)

Functional Block Diagram of RAMM

Customized “Stand-alone” RAMM-TM

Edge computing
RAMM-TM Data Flows during Gas Leakage Experiment

Data sharing between Argonne (Chicago) and CRIEPI (Tokyo) in real time

http://[RAM-TM IP address]
Web Application User Interface and “Virtual Sensors” (analytical functions of data measured by physical sensors – i.e., TCs)

- Adjustable alarm thresholds
- Automatic alarms and notifications

- $\delta T_{BTA}$ (TC5 – TC6)
- $\delta T_{BT}$ (TC5 – TC1)
- DTBOUT (TC5 – TC3)
- DTTOUT (TC1 – TC3)
- DTMLTT (TC7 – TC1)
Gas Leakage Depressurization, $\Delta TBT$, and Alarms

He/391W

Air/385W

Air/189W
STAR-CCM+ simulation [395W/He; (a): 6 atm/(b) 1 atm]

- Each simulation employed ~5 million elements, executed on 32-core parallel machine at Argonne’s Laboratory Computing Research Center (LCRC).

- Based on study of residuals of energy, continuity, X-, Y-, and Z- momentum, and turbulence $T_{dr}$ (vortex) and $T_{ke}$ (kinetic energy), convergence was achieved after 18,000 iteration steps with 3.1 s/step.
# STAR-CCM+ Simulation vs. Temperature Measurement in 1/4.5-Scale Model Cask (394W/air)

<table>
<thead>
<tr>
<th>Thermocouple Locations (h)</th>
<th>Calc. Temp. (°C)</th>
<th>Exp. Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 atm</td>
<td>1 atm</td>
</tr>
<tr>
<td>Canister top center, TT (TC1)</td>
<td>82.7</td>
<td>80.7</td>
</tr>
<tr>
<td>Canister wall, h=0.78, TCSTM/TC2</td>
<td>80.3</td>
<td>80.4</td>
</tr>
<tr>
<td>Canister wall, h=0.52, TCSM/TC8</td>
<td>80.4</td>
<td>81.1</td>
</tr>
<tr>
<td>Canister wall, h=0.26, TCSDM/TC4</td>
<td>81.0</td>
<td>82.5</td>
</tr>
<tr>
<td>Canister bottom center, TB (TC5)</td>
<td>102.8</td>
<td>109.4</td>
</tr>
</tbody>
</table>

*h = z/H where H = 1048 mm
Radiological Consequences of Gas Leakage (Pressure Drop) due to CISCC (Scenario 1)

Pressure (atm) vs. Time (day)

- He leakage starts.
- Detect He leakage
- Mitigatory action for the leakage
- Air-ingress starts.

Reproduced from Ref. S.CHU, EPRI 3002002785 (2017)
Radiological Consequences of Gas Leakage (Pressure Drop) due to CISCC (Scenario 2)

Can the temp. monitoring method detect the small He leakage due to CISCC?

Offsite dose limit 1.00 mSv/y (Japan)

Mitigatory action for the leakage

He leakage starts. Detect He leakage
Conclusions

▪ Both helium and air gas leakage from a canister were detected within hours after the start of the leakage. The change in ΔTBT during gas leakage (depressurization) triggered automatic alarms, providing a sound basis for early detection of gas leakage from the canister.

▪ This methodology would allow consequence management through the implementation of mitigatory actions to continue effective aging management and to reduce risks to public safety, health, and the environment.

▪ Additional gas-leakage experiments are being conducted to explore the use of multiple “Virtual Sensors” for gas-leakage detection and for confirmation of gas leakage in actual spent-fuel canisters.

▪ STAR-CCM+ simulation of temperatures, density, and flow fields inside and outside the canister will continue to deepen the understanding of gas leakage and thermal response in actual MPCs of spent-fuel dry cask storage systems.
Current Status of Spent Fuel Storage

World

Concrete casks are used in Spain, East Europe etc.

Yucca Mountain Project
- 1987 Site was selected.
- 2009 halted.

In the US:
- 90% of storage containers is Concrete Cask and Concrete module (About 3,000 casks)

In Near Future
- 10,000 Casks

Japan

Storage facility until reprocessing is needed

Mutsu Interim Storage Facility
(Capacity 3000tU:300 metal casks)

2002-2003 Full Scale Tests

Study on Leak detection

Joint work with ANL

1/4.5 scale model tests

Joint work with Kyoto

CRIEPI

Joint work with Hitz

SCC countermeasures (2007~)

KEPCO 2000tU Facility
- 2030: Operation

Hamaoka 400 tU →

Tokai No.2 70 t

Mutsu 2000t U Secon dFacili

AMP

New CRP

IAEA CRP (DEMO) & SPAR I ~

ESCP 2009~

2011


CISF
- WCS Project: 40,000tU
- ELEA Project:
Acknowledgment
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References
10. Yung Liu, Brian Craig, Zenghu Han, Jie Li, Kevin Byrne, Hirofumi Takeda, and Toshiari Saegusa, “RAMM-TM for detection of gas leakage from canisters containing spent nuclear fuel,” Nuclear Engineering and Design 385 (2021) 111534.
Backup Slides
Setting $\Delta T_{BT}$ Alarm Thresholds

![Graph showing $\Delta T_{BT}$ and Pressure over time with Leakage start and Adjustable alarm thresholds marked]