ACR Fission-Product Release and Transport Codes

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Outline

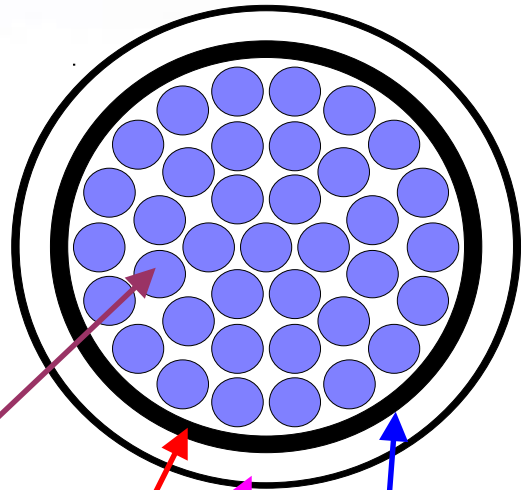
- Fission-product release from fuel - SOURCE
- Fission-product transport in RCS - SOPHAEROS
- Fission-product behavior in containment - SMART

Fission Product Release and Transport

- Fission product release from fuel and transport in the reactor coolant system and containment are assessed to determine FP release into the environment under accident conditions
- FP release and transport calculations are part of the source term analysis methodology
- FP release and transport simulations are used in estimating doses to the public, station staff and plant equipment

Fuel Channel (End View)

CANDU 6



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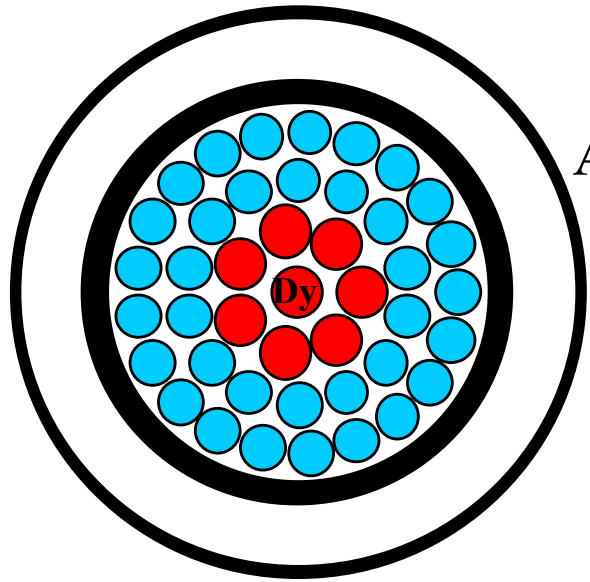


- 37-rod NU fuel
- Zr – 2.5% Nb pressure tube
- Zr-2 calandria tube
- Insulating gap between pressure tube and calandria tube

- 43-rod SEU fuel
- Thicker Zr – 2.5% Nb pressure tube
- Stronger Zr-4 calandria tube
- Larger gap between pressure tube and calandria tube

Fission-Product Release Behavior

- Diffusion in fuel grains
  - Fuel oxidation increases diffusion rate
- Accumulation and venting from grain boundaries
- Grain-boundary sweeping
- Accumulation on fuel surface and in fuel-clad gap
- Redox conditions (hydrogen/steam/air) of fuel environment after cladding failure affect volatility
  - Noble gases (Kr, Xe) and volatile elements (I, Cs, Te, etc.) are released from the fuel in significant amounts at high temps.
  - Other elements (e.g., Ru) may also be released if the fuel is exposed to oxidizing conditions for extended periods

SOURCE IST 2.0

- SOURCE IST 2.0 is the Canadian Industry Standard Toolset (IST) code for calculating fission-product release from fuel
- SOURCE IST 2.0 simulates all of the primary phenomena affecting FP release from CANDU fuel under accident conditions
- Release fraction is the key output of SOURCE

SOURCE IST 2.0

- Basis Unit: A geometric subdivision of a fuel bundle. The smallest unit that the user has chosen to model. It could be a fuel element, an axial segment, or an annulus within a fuel element or axial segment. In the case of fragment tests, it could be the entire fragment.
- Bins (inventory partitions) (subdivisions of a basis unit):
  - Grain Matrix
  - Grain Boundary
  - Fuel Surface
  - Gap
  - Released

SOURCE IST 2.0

- Some models in SOURCE IST 2.0 assume bounding behavior
- An appropriate bound is to assume:
  - more complete release or
  - earlier release

    where the release mechanism is not modeled to the level of detail required for accurate predictions.
- Over-estimation of the release is expected in some cases

FP Release Phenomena (1)

- Athermal Release (knockout, recoil and fission-spike)
- Diffusion (from fuel grains to grain boundaries)
- Grain-Boundary Sweeping / Grain Growth
- Grain-Boundary Bubble Coalescence / Tunnel Interlinkage
- Vapor Transport / Columnar Grains
- Fuel Cracking (thermal)
- Gap Transport (failed elements)
- Gap Retention (secondary phenomenon, neglected in SOURCE IST 2.0)

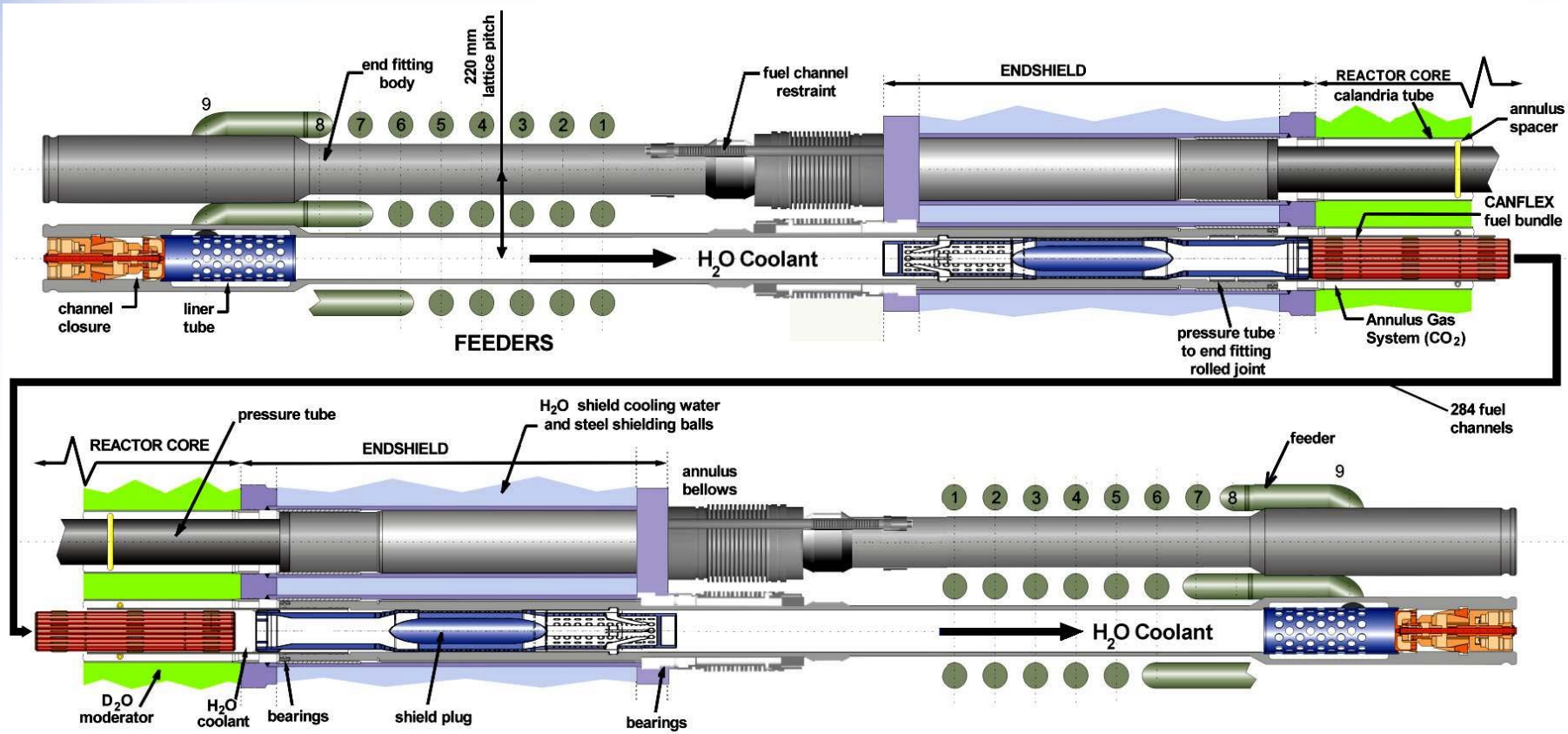
FP Release Phenomena (2)

- Uranium Oxidation State
  - $UO_{2-x} \leftrightarrow UO_2 \leftrightarrow UO_{2+x} \leftrightarrow U_4O_9 \leftrightarrow U_3O_8$
- UO_2 – Zircaloy Interaction
- UO_2 Dissolution in Molten Zircaloy
- Fuel Melting
- Fission Product Vaporization / Volatilization
- Matrix Stripping
- Temperature Transients
- Grain-Boundary Separation
- Fission-Product Leaching

SOURCE IST 2.0

- Validation in progress:
  - Canadian hot-cell FP release tests
    - Steam: UCE12 TF01, HCE2 BM5, HCE2 BM4, HCE4 J03, HCE3 H03 & MCE2 TM19
    - Air: GBI3 DL5, HCE3 H02 & MCE1 T4
    - Inert (Ar/H_2): UCE12 TU09, HCE1 M12 & MCE2 TM03
  - International hot-cell FP release tests
    - Vercors 04, Vercors 05 & ORNL VI-5
  - Integral in-reactor tests
    - BTF-104, BTF-105B & PHEBUS FPT1

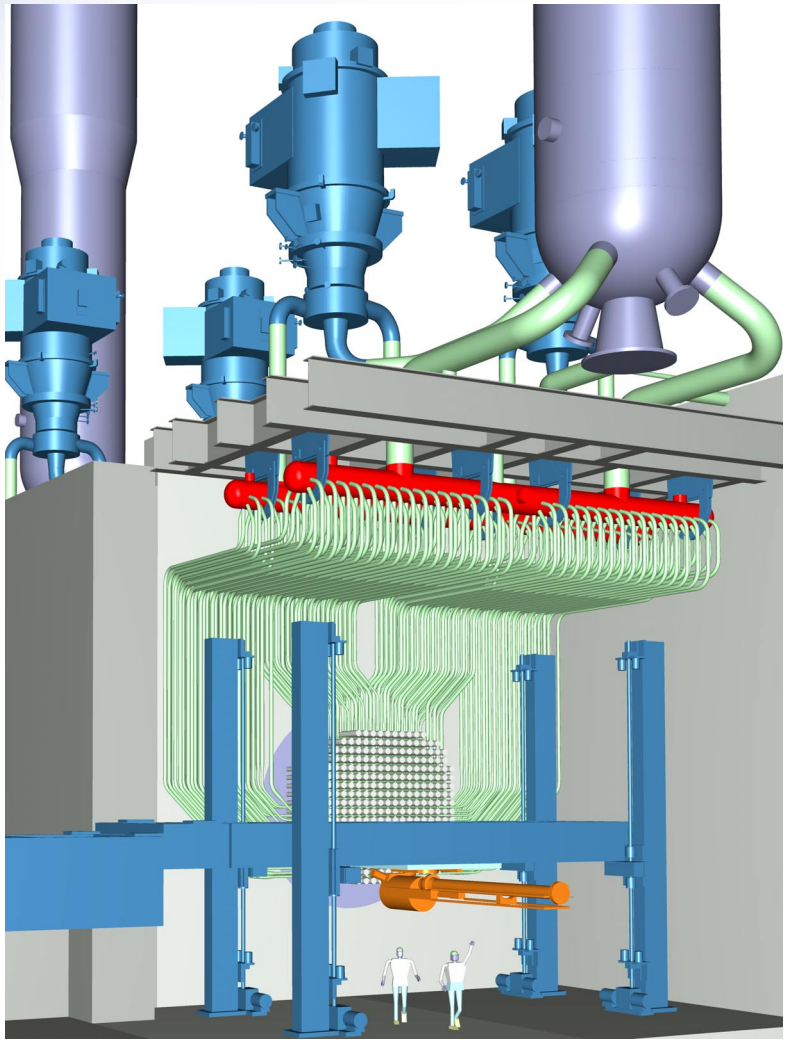
ACR Fuel Channel



ACR Shield Plug

- The ACR shield plug is based on a flow through design
- The shield plug is attached in the bore of the end fitting to locate the fuel bundles and to provide shielding

ACR Reactor Coolant System Layout



Similar to LWR above the headers

Below headers, feeders and horizontal fuel channels instead of a pressure vessel

Fission-Product Transport Behavior

- Noble gases transported to the break
- Retention of other fission products can occur in the reactor coolant system between the fuel and the break location
- Aerosol deposition, especially in
  - Complex geometries (e.g., shield plug / end fitting)
  - Condensing steam (e.g., in feeder pipes)
  - Water-filled components (e.g., headers and steam generators)
- Fission-product vapor condensation
- Fission-product vapor reactions with piping surfaces

SOPHAEROS-IST 2.0

- SOPHAEROS initially developed by IRSN (France) to simulate fission-product transport and retention in the RCS under LWR severe accident conditions
- SOPHAEROS-IST 2.0 adopted as Canadian Industry Standard Toolset code for calculating fission-product transport and retention in the RCS
- When development is complete, SOPHAEROS will simulate all of the primary phenomena affecting FP transport and retention in CANDU RCS under accident conditions
- Fractional retention is the key output of SOPHAEROS

RCS FP Transport Phenomena (1)

- Fuel Particulate Suspension
- Vapor Deposition and Revaporization of Deposits
- Vapor / Structure Interaction
- Aerosol Nucleation
- Aerosol Agglomeration
  - Gravitational, Brownian motion (diffusional), turbulent, laminar, and electrostatic mechanisms
- Aerosol Growth / Revaporization

RCS FP Transport Phenomena (2)

- Aerosol Deposition
  - Thermophoresis, diffusiophoresis (Stefan flow), gravitational deposition, Brownian motion deposition, turbulent deposition, laminar deposition, electrophoresis, inertial deposition and photophoresis
- Aerosol Resuspension
- Pool Scrubbing
- Transport of Deposits by Water
- Chemical Speciation
- Transport of Structural Materials

SOPHAEROS-IST 2.0

- Validation in progress:
  - Canadian laboratory FP transport tests
    - Mulpuru, End-fitting aerosol retention
  - Canadian hot-cell FP release and transport tests
    - HCE3 H01 & H03, HCE4 J01 & J03
  - International FP transport tests
    - LACE LA3B, Falcon ISP1 & ISP2, Marviken 2b & 7, DEVAP 23, 25 & 26, STORM ISP, TUBA-D
  - International hot-cell FP release and transport tests
    - VERCORS 04 & HT1, ORNL VI-2 & VI-5
  - Integral in-reactor tests
    - BTF-104, BTF-105B, PHEBUS FPT0 & FPT1

ACR FPR&T Phenomena

- Essentially the same as for LWR:
  - A.L. Wright, et al., "Primary System Fission Product Release and Transport - A State-of-the-Art Report to the Committee on the Safety of Nuclear Installations", NUREG/CR-6193, 1994 June.
- Except:
  - No control rods in ACR RCS $\Rightarrow$ simplified FP chemistry and less aerosol material transport
  - No boric acid in ACR RCS $\Rightarrow$ simplified FP chemistry
  - No grid spacers in ACR RCS $\Rightarrow$ simplified FP chemistry and less eutectic formation
  - Dy-doped fuel in ACR $\Rightarrow$ little effect (unreactive, non-volatile)

SMART

S imple

M odel, for

A ctivity

R emoval, and

T ransport

SMART Code
Introduction / Background

- Predicts fission product / aerosol behavior in CANDU reactor containments
- Predicts nuclide releases to the outside atmosphere
- Provides nuclide release data to other codes for public dose calculations

SMART Theoretical Basis

- Calculates transport of radionuclides
  - Contained / dissolved in water droplets
  - Existing in gas phase
  - Using mass conservation equations with source terms
- Calculates water droplet size distribution
  - Using aerosol general dynamics equation

Interfaces With Other Codes

- SMART interfaces with
  - Containment thermal hydraulics code
    - Obtains input from GOTHIC-IST
  - Atmospheric dispersion and dose code
    - Provides radionuclide release data to ADDAM-IST

Geometry

- Containment geometry model
  - A network of volumes (nodes) inter-connected by links
  - Able to represent
    - Break in the RCS
    - Nuclide escape paths to the outside atmosphere
    - Different types of wall surfaces for deposition of nuclides

Thermal Hydraulics

Thermal hydraulic input data from GOTHIC-IST

- **Break discharge**
  - **Flow rates of each phase**
  - **Thermodynamic Properties**
- **Dousing flow rates and temperature**
- **Nodal properties**
  - **Pressure**
  - **Temperature**
- **Link flow rates**

Nuclide/Aerosol

- Nuclide and aerosol input data
  - Nuclide information
    - Name, half-life, build-up / decay chain information, release rate
  - Physical / chemical form
    - Contained in aerosol
    - Stable gas
    - Noble gas
    - Iodines
      - Inorganic iodide
      - Molecular iodine
      - Organic iodine

Aerosol Phenomena

Aerosol agglomeration

- Brownian agglomeration
- Gravitational agglomeration
- Turbulent agglomeration

Aerosol deposition

- Gravitational settling
- Turbulent deposition
- Jet impingement
- Stefan flow
- Thermophoresis

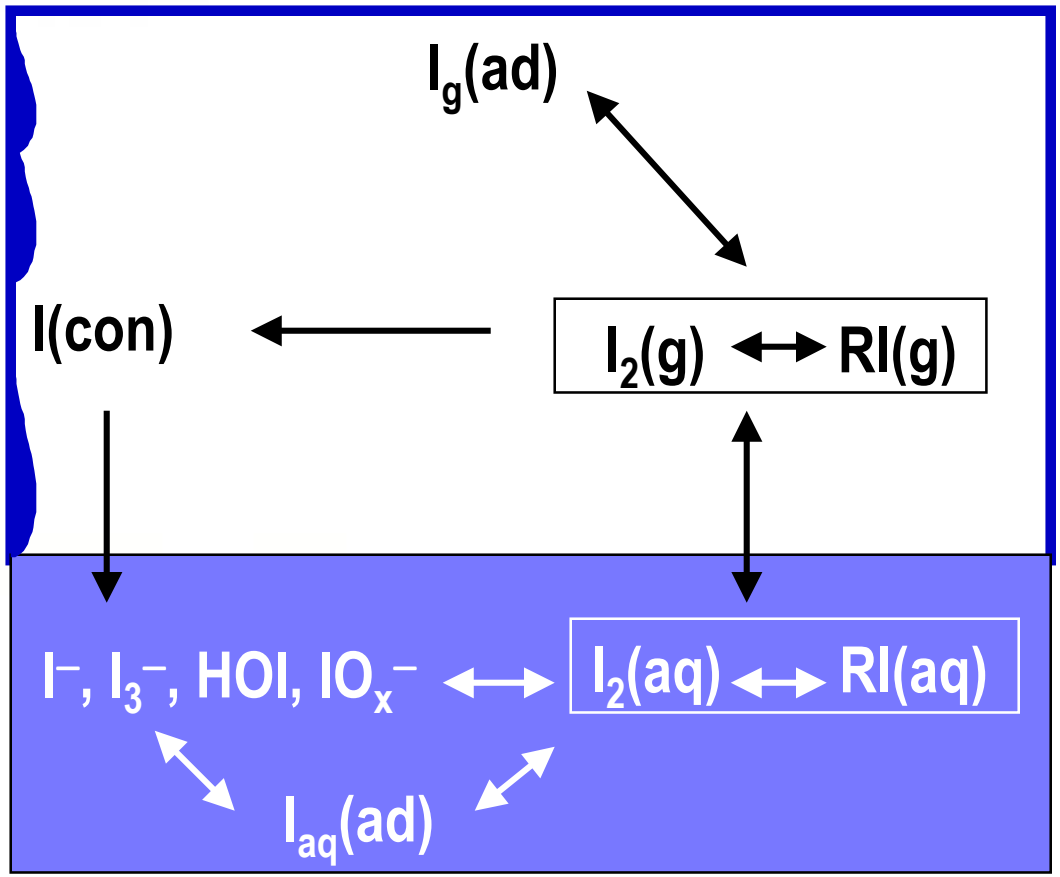
Fission Product Removal

- Radionuclide decay and buildup
  - Four chain types modeled
  - Exact solutions for ordinary differential equations
- Plate-out / sorption on wall surfaces

Iodine Model - IMOD2

- IMOD2 – A simplified model based on the LIRIC detailed mechanistic model of containment iodine behavior
- Calculates concentrations of iodine in different forms
- Model characteristics
  - Chemical forms of iodine considered
    - Non-volatile iodine
    - Molecular iodine
    - High-volatile organic iodine
    - Low-volatile organic iodine

Iodine Behavior



Iodine Model - IMOD2

- Model characteristics
  - Differential rate equations describing
    - Aqueous iodine reactions in pools and liquid aerosols
    - Organic dissolution into pool from painted surfaces
    - Organic radiolytic degradation
    - Carbonate equilibria
    - Organic iodide formation and decomposition
    - Aqueous-air interfacial mass transfer
    - Air – surface mass transfer

Transport Through Containment

- SMART calculation of aerosol and nuclide transport through containment based on:
  - Convective flow among containment rooms
  - Mass conservation equation for aerosols
  - Mass conservation equation for gaseous fission products
- Calculation of nuclide releases to the outside atmosphere for the purpose of public dose calculations

SMART-IST VER-0.300

- Validation conducted:
  - Jet impingement
    - Stern Labs Water Aerosol Leakage Experiments (WALE)
  - Gravitational settling
    - Analytical solution
  - Diffusiophoresis
    - PITEAS tests
  - Turbulent deposition
    - Forney and Spielman tests
    - Liu and Agarwal tests
- IMOD2 model validated separately
  - Canadian and international iodine behavior tests

Summary

- Good technology base for understanding of fission-product release and transport behavior in ACR reactor accidents
  - Phenomena
  - Experimental database
  - Computer codes

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