CATHENA Simulation Results for CWIT Channel/Feeder Refill Tests (Non-Proprietary Presentation)

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Objectives

- Overview of the Canadian computer code qualification process
- Overview of the documentation provided to NRC
- General information on the CWIT tests used for validation of CATHENA MOD-3.5c Rev 0
  - Summarize the CWIT test used for validation of specific phenomena
- Selected CWIT simulation results to illustrate usage of CWIT in the CATHENA MOD-3.5c Rev 0 validation work

Presentation based on the CATHENA Validation Manual: "CATHENA MOD-3.5c/Rev 0 Systems Thermal-hydraulic Validation Manual", RC-2701, Rev 1, September 2003, and other validation reports.

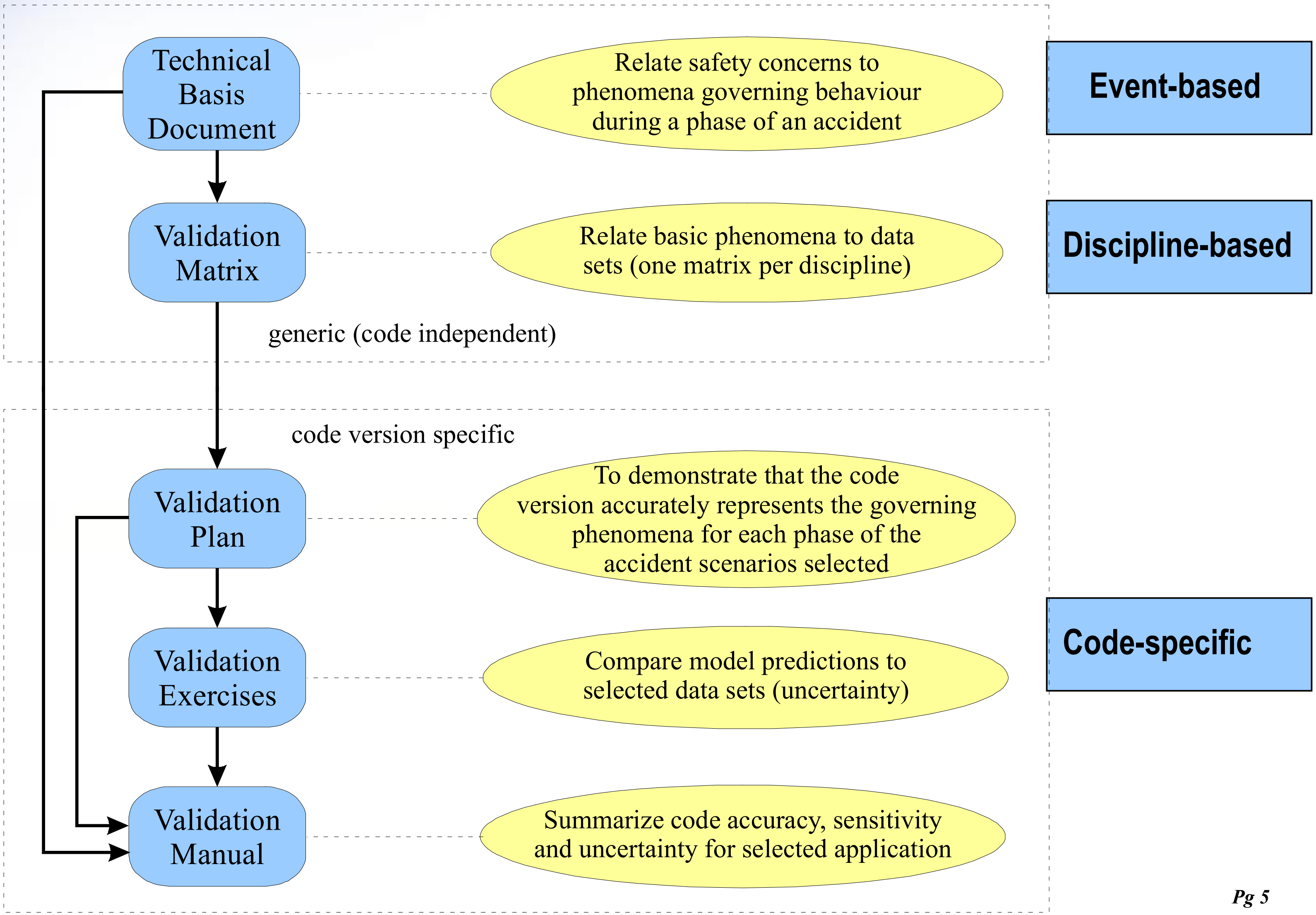
Background

- Canadian nuclear industry initiated a systematic and comprehensive code validation program in 1995
  - Code validation tasks were performed before 1995 were performed by each organization separately
- The program was conducted consistent with international and Canadian QA standards (CSA – N286.7)
- As a result of the effort since 1995, all legacy codes have been reviewed and revised to meet current QA standards
- The Technical Basis Document (TBD) and Validation Matrix (VM) documents were identified as key requirements at an early stage of the computer code qualification process

TBD and VM Overview and Status

- TBD and VM documents follow a phenomena-specific approach
  - Allows for flexibility and applicability of the code qualification process to different CANDU reactor designs (activity performed jointly by the Canadian nuclear industry partners)
- Technical Basis Document (TBD) and Validation Matrix (VM) documents are the top-level documents in the code validation process
  - TBD and VMs applicable for operating CANDUs are in use by the Canadian Nuclear Industry
  - Submitted to the Canadian Nuclear Regulatory Commission (CNSC) (key VMs were provided to USNRC)
- AECL has prepared an ACR-specific TBD
  - TBD submitted to the CNSC and USNRC
- Preparation of ACR-specific VMs is in progress

TBD and VMs Overview



TBD Overview

- Structured on an event-by-event basis
  - A separate section describes each key accident scenario
- Provides a high level phenomena identification and ranking
- ACR Technical Basis Document is an evolution of the current CANDU-specific TBD
  - CANDU-specific TBD is developed by AECL and the Canadian Nuclear Industry Partners (OPG, BP, HQ, NBP)
- ACR-specific TBD reflects the ACR design, accident scenarios, and phenomena importance ranking
  - No major new ACR-specific phenomena have been identified

TBD Scope

TBD covers the following types of <u>design-basis events</u>:

1. Large LOCA
2. Small LOCA & single channel events
3. Secondary side coolant failures
4. Fuel handling events
5. Loss of regulation events
6. Loss of flow events
7. Auxiliary system failures (moderator and shield cooling systems)
8. Limited core damage accidents

TBD Structure

- **The accident scenarios described in the TBD encompass the individual accident sequences in the particular group of events**
  - **For example, Large LOCA encompasses the range of large break sizes and locations**
- **Individual accident sequences are identified and discussed, as required**
- **Each TBD section describes:**
  - **Safety issues for a given accident scenario**
  - **Relevant system behavior**
  - **Role of key physical phenomena which govern the system behavior**

TBD Phenomena

- **Definition of phenomenon:**
  - An event or circumstance that:
    - affects the process of changing the physical state of the system
    - is either directly apparent to the senses or is indirectly apparent by means of measurements of the physical state of the system, and can be represented quantitatively by a model or correlation
- **Phenomena directly affect the key parameters of importance to safety analysis**
- **Phenomena importance is identified by:**
  - Understanding and description of expected system behavior
  - Determining the cause of a change in a physical state
  - Review of computer models used for safety analysis
- **A total of 188 phenomena have been identified across the eight safety analysis disciplines in the ACR TBD**

TBD Phenomena (cont'd)

- Phenomena designation is discipline-based:
  - PH: reactor physics
  - TH: system thermal-hydraulics
  - FC: fuel & fuel channel
  - MH: moderator and shield system
  - FPR/FPT: fission product release / transport
  - C: containment
  - RAD: radiation physics
  - AD: atmospheric dispersion

TBD Phenomena (cont'd)

- For each accident scenario in the TBD, phenomena are ranked as
  - Primary – phenomena of significant impact on one or more figures of merit during any phase of an accident sequence in any accident scenario (dominant effect; high impact)
  - Secondary – phenomena with some impact on one or more figures of merit during any phase of an accident scenario (non-dominant effect; medium impact)
  - Irrelevant - phenomena which are neither primary nor secondary are irrelevant with respects to the figures of merit (low impact or inactive component)

(Ranking based on the Canadian Nuclear Industry methodology)

TBD Phenomena (cont'd)

- **High level phenomena identification and ranking completed for ACR and documented in the TBD**
- **Phenomena Identification and Relative Ranking process:**
  - **Team of experts for each discipline (analysts, code developers, code validation analysts, reactor designers)**
  - **Review of safety analysis results, code models**
  - **Identification of safety issues and figures of merit**
  - **Description of system behavior**
  - **Ranking of phenomena based on importance for system behavior and figures of merit**
  - **Ranking done conservatively: if in doubt, select higher ranking**
    - **Particular attention focused to phenomena for which the impact is not fully understood, or the knowledge base is not fully developed**

Brief Overview of T/H Documents Submitted to NRC

- ACR-specific TBD
- CANDU-generic Thermal-Hydraulics VM
- ACR-specific Thermal-Hydraulics VM in preparation
- CATHENA code documentation and ACR input decks
- CATHENA Validation Manual, Rev 0
- US-style PIRTs for 25% inlet header break and severe flow blockage events
- Code Validation Methodology Document, 108US-03510-LS-001 Rev 0 (April 2004)
  - Overview of the AECL computer code qualification methodology (roadmap document)
  - Rev 1 will fully address DG-1120 requirements (scheduled for March 2005)
  - Scaling of RD-14M is in progress (based on H2TS)

CATHENA NRC RAI

- NRC completed a review of the CATHENA documentation and provided AECL with 97 RAIs received May 14, 2004
- NRC-AECL teleconference meeting held May 03, 2004 to discuss and clarify NRC questions and comments
- AECL committed to send responses to NRC
  - September 2004 – most important and short term comments
  - March 2005 – remaining comments and information
- AECL did not yet receive comments on the Code Validation Methodology document (108US-03510-LS-001, Rev. 0)

TH Validation Matrix

ID No	PHENOMENON	Large LOCA	Small LOCA & Single-Channel Events	Secondary Coolant Failures	Fuel Handling Events	Loss of Regu-lation	Loss of Flow	Auxiliary System Events	Limited Core Damage Accidents
TH1	Break Discharge Characteristics and Critical Flow	✓	✓	✓	✓				✓
TH2	Coolant Voiding	✓	✓		✓	✓	✓	X	✓
TH3	Phase Separation	✓	✓	✓	✓		✓	✓	✓
TH4	Level Swell and Void Holdup	X	X	✓	X			X	X
TH5	HTS Pump Characteristics (single and two phase)	✓	✓	✓	✓		✓	✓	✓
TH6	Thermal Conduction	✓	✓	✓	✓	X	X	X	✓
TH7	Convective Heat Transfer	✓	✓	✓	✓	✓	✓	✓	✓
TH8	Nucleate Boiling	X	✓	✓	✓	X	✓	✓	✓
TH9	CHF/Dryout and Post Dryout Heat Transfer	✓	✓		✓	✓	✓	✓	✓
TH10	Condensation Heat Transfer	✓	✓	✓	✓		✓	✓	++
TH11	Radiative Heat Transfer	✓	✓		✓	X	X	✓	✓
TH12	Quench/Rewet Characteristics	✓	✓		✓	✓	✓	✓	++
TH13	Zircaloy/Water Thermal-Chemical Reaction	✓	X		X				✓
TH14	Reflux Condensation		X	X	X		✓	✓	+++
TH15	Counter Current Flow	✓	✓	X	✓		✓	✓	+++
TH16	Flow Oscillations	X	X	X	X	X	✓	✓	+++
TH17	Density Driven Flows: Natural Circulation	X	✓	✓	✓		✓	✓	X
TH18	Fuel Channel Deformation	X	X		X				✓
TH19	Fuel String Mechanical-Hydraulic Interaction	X	X						++
TH20	Waterhammer		X	X	X				
TH21	Waterhammer (Steam Condensation Induced)	X		X					
TH22	Pipe Thrust and Jet Impingement	X	X	X					X
TH23	Noncondensable Gas Effect	✓	X		X			X	✓

✓ Primary Phenomena

X Secondary Phenomena

++ Primary for limiting single channel events (with ECC available)

+++ Secondary for limiting single-channel events (with ECC available)

Ranking of Phenomena - Large LOCA

Phase	Early Blowdown Cooling	Late Blowdown Cooling/ ECC Injection	Refill
Time Period (s)	0 - 30	30 - 200	> 200
	Phenomena		
Primary	Break Discharge Characteristics and Critical Flow	Break Discharge Characteristics and Critical Flow	Counter-Current Flow
	Coolant Voiding	Convective Heat Transfer	Phase Separation
	HT Pump Characteristics (Single & 2-phase)	Condensation Heat Transfer	Thermal Conduction
	Thermal Conduction	Quench Rewet Characteristics	Convective Heat Transfer
	Convective Heat Transfer		Quench Rewet Characteristics
	CHF & Post Dryout Heat Transfer		Non-Condensable Gas Effect
	Radiative Heat Transfer		
	Zirc/Water Thermal Chemical Reaction		
Secondary	Phase Separation	Phase Separation	Nucleate Boiling
	Level Swell and Void Hold-up	Thermal Conduction	Density Driven Flows: Natural Circulation
	Fuel Channel Deformation	Counter-current Flow	Flow Oscillations
	Fuel String Mechanical-Hydraulic Interaction		Waterhammer steam condensation Induced
	Pipe Thrust and Jet Impingement		

Thermalhydraulic Phenomena and Relevant Test Data For Code Validation: Separate Effects Tests

ID No	PHENOMENA	SE 1	SE 2	SE 3	SE 4	SE 5	SE 6	SE 7	SE 8	SE 9	SE 10	SE 11	SE 12	SE 13	SE 14	SE 15	SE 16	SE 17	SE 18	SE 19	SE 20	SE 21	SE 22	SE 23	SE 24	SE 25
TH1	Break Discharge Characteristics and Critical Flow	□				■	■																			
TH2	Coolant Voiding	■				□	□	□		■																
TH3	Phase Separation			□			■	■					□								■	■				
TH4	Level Swell and Void Holdup					■	■	■														□				
TH5	HT Pump Characteristics (Single and Two-Phase)								■						■											
TH6	Thermal Conduction											□	□	■											■	
TH7	Convective Heat Transfer											□					□					■				
TH8	Nucleate Boiling									■							□			■						
TH9	CHF and Post Dryout Heat Transfer										■			■			□	■								
TH10	Condensation Heat Transfer									■									■	■			■			■
TH11	Radiative Heat Transfer											□	□	□												
TH12	Quench Rewet Characteristics				■												■									
TH13	Zirc/water Thermal Chemical Reaction											■														
TH14	Reflux Condensation																		■							
TH15	Counter Current Flow		■	■															□					■		
TH16	Flow Oscillations								□																	
TH17	Density Driven Flows:Natural Circulation																									
TH18	Fuel Channel Deformation												■	■												
TH19	Fuel String Mechanical-Hydraulic Interaction															■										
TH20	Waterhammer																						■			■
TH21	Waterhammer Steam Condensation Induced																						■			
TH22	Pipe Thrust and Jet Impingement					■	■																			
TH23	Noncondensable Gas Effect																									

Thermalhydraulic Phenomena and Relevant Test Data For Code Validation: Separate Effects Tests

ID No	PHENOMENA	SE 26	SE 27	SE 28	SE 29	SE 30	SE 31	SE 32	SE 33	SE 34	SE 35
TH1	Break Discharge Characteristics and Critical Flow										
TH2	Coolant Voiding										
TH3	Phase Separation										
TH4	Level Swell and Void Holdup										
TH5	HT Pump Characteristics (Single and Two-Phase)										
TH6	Thermal Conduction										
TH7	Convective Heat Transfer	■									
TH8	Nucleate Boiling		■	■	■						■
TH9	CHF and Post Dryout Heat Transfer				■	■	■			■	■
TH10	Condensation Heat Transfer										
TH11	Radiative Heat Transfer								□		
TH12	Quench Rewet Characteristics										
TH13	Zirc/water Thermal Chemical Reaction										
TH14	Reflux Condensation										
TH15	Counter Current Flow										
TH16	Flow Oscillations										
TH17	Density Driven Flows:Natural Circulation										
TH18	Fuel Channel Deformation							■			
TH19	Fuel String Mechanical-Hydraulic Interaction										
TH20	Waterhammer										
TH21	Waterhammer Steam Condensation Induced										
TH22	Pipe Thrust and Jet Impingement										
TH23	Noncondensable Gas Effect										

CWIT Experimental Tests

Phenomenon	Type of CWIT Test	Test Outline
Phase Separation	Flow Stratification Tests	1. Used to assess predicted phase separation within reactor representative fuel elements (37-el bundle) 2. Variety of channel conditions such as pressure, power, liquid flow rate 3. Onset of flow stratification indicated by fuel element simulator temperatures 4. Either power raised or channel flow rate lowered
	Feeder Refill Tests	1. Blowdown/refill tests used to assess phase separation effects within reactor representative fuel elements (37-el bundle) 2. Flow stratification effects indicated by fuel element simulator temperatures 3. Loop preheated in dry steam to establish desired conditions

CWIT Experimental Tests

Phenomenon	Type of CWIT Test	Test Outline
Convective Heat Transfer	Flow Stratification Tests	Only measured fuel element simulator temperatures below saturation used in the validation
	Feeder Refill Tests	
Condensation Heat Transfer	Feeder Refill Tests	1. Slow refilling process allows for a strong influence of condensation rates 2. Quench/rewet tests used to isolate the condensation rates
Quench/Rewet Characteristics	Feeder/Channel Refill Tests	Single- and double-break, double-injection blowdown/refill used
Density Driven Flows: Natural Circulation	Standing Start Tests	Single test channel used
Non-Condensable Gas Effects	Feeder Refill Tests	Special tests performed to assess the effect of non-condensables

Validation of CWIT Refill Experiments

- Eight single-break, double-injection tests were selected
- Experiments provided quench/rewet data at temperatures > 500°C
- Imposed measured header pressure and injection pressure

Conditions for CATHENA MOD-3.5c Rev 0 Simulated CWIT Refill Tests

Protected-Proprietary

Predicted and Measured Inlet Header Pressure & Injection Flow Rate for CWIT Test

Protected-Proprietary

Lower Elevation FES Temperatures - CWIT Feeder/Channel Refill Test

Protected-Proprietary

Upper Elevation FES Temperatures - CWIT Feeder/Channel Refill Test

Protected-Proprietary

CATHENA MOD-3.5c Rev 0
Predicted Quench/Rewet Times

Protected-Proprietary

CATHENA MOD-3.5c Rev 0 Predicted Channel Refill Times – Comparison with CWIT Tests

Protected-Proprietary

Comparison of CWIT Feeder Quench/Rewet Times

Protected-Proprietary

Quench/Rewet Times for Horizontal Tube and CWIT Feeders

Protected-Proprietary

Comparison of CWIT Channel Refill Times

Protected-Proprietary

Channel Refill Times

Protected-Proprietary

Experimental and Predicted CWIT Standing Start Test Results

Protected-Proprietary

Experimental and Predicted Channel Refill Times (CWIT Feeder Refill Tests with Non-condensables)

Protected-Proprietary

CWIT Flow Stratification Tests
Onset of Flow Stratification

Protected-Proprietary

CWIT Data/Database

- Data reports issued for each test series
- Data archived on CD-ROM in a standardized ASCII format
- Electronic database (MS Access), developed for the RD-14M program, also contains information on CWIT
  - Details of test setups, procedures, and conditions
  - Instrumentation for each test
- Facility description report

LASH Experiments

- Primary purpose of LASH experiments
  - understand the phenomena related to header behavior and flow distribution in the headers
- Limited and indirect use of LASH experiments in the CATHENA code development and validation
  - CATHENA is one-dimensional code (headers modeled as one component “pipe” model)
  - Understanding of header behavior important for flow regime transition criteria
- Inlet and outlet headers refill relatively fast compared to feeders and channels

Summary

- Several series of CWIT tests were completed and used in the CATHENA validation program: flow stratification tests, feeder / channel refill tests, standing start tests
- CATHENA predicted feeder / end fitting quench times were within the expected accuracy range
- CATHENA predicted channel refill times tend to overestimate the experimental results

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