Technical Basis Document and Validation Matrices for ACR Application

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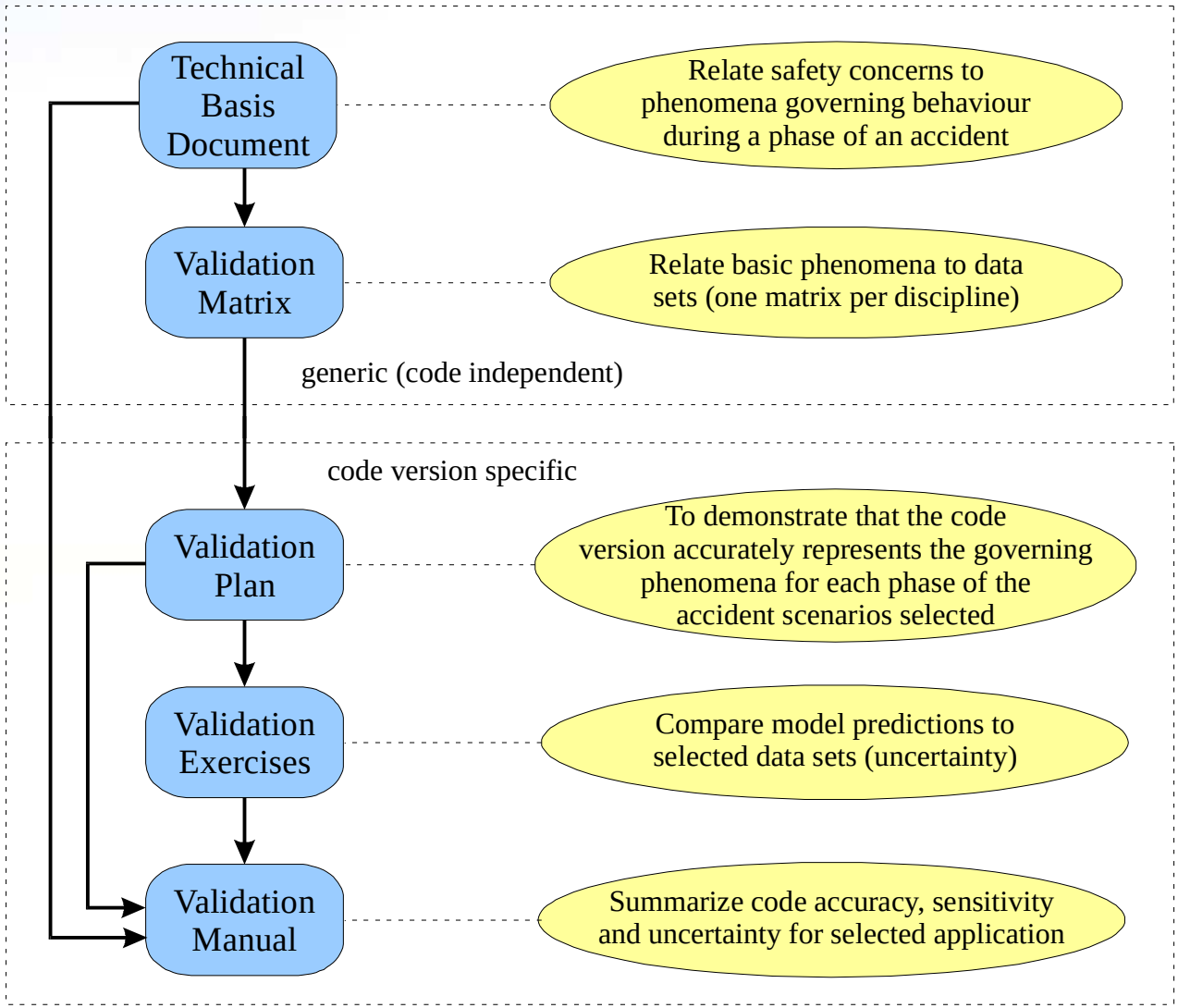
Background

- Canadian nuclear industry initiated a systematic code validation program in 1995
- 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 requirements at an early stage

TBD and VMs Overview

- **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**
  - **AECL has prepared an ACR-specific TBD, and will prepare ACR-specific VMs over the next six months**

TBD and VMs Overview



TBD Overview

- TBD is structured event by event
- A separate section describes each of the accident scenarios
- TBD identifies and ranks the phenomena which play a role in each scenario

VMs Overview - 1

- **Eight VMs, one for each safety analysis discipline:**
  - **Reactor physics**
  - **System thermal-hydraulics**
  - **Fuel & fuel channel thermomechanical**
  - **Moderator and shield system**
  - **Fission product release & transport**
  - **Containment**
  - **Radiation physics**
  - **Atmospheric dispersion**

VMs Overview - 2

- VMs provide a synopsis of each phenomenon
- VMs identify and describe sources of data which can be used to validate the modeling of each phenomenon

TBD Specifics

- ACR Technical Basis Document is an evolution of the current CANDU TBD
  - TBD developed by AECL and by all of the partners of the Canadian nuclear industry
- ACR TBD reflects the ACR design: accident scenarios and phenomena rankings
- No new ACR-specific phenomena have been identified

TBD Specifics – Structure - 1

- **TBD main sections based on accident scenarios:**
  - **1. Introduction**
  - **2. Initial conditions**
  - **3. Large LOCA**
  - **4. Small LOCA & single channel events**
  - **5. Secondary side coolant failures**
  - **6. Fuel handling accidents**
  - **7. Loss of regulation**
  - **8. Loss of flow**
  - **9. Auxiliary system failures**
  - **10. Limited core damage accidents**

TBD Specifics – Structure - 2

- 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:
  - The safety concerns for the given accident scenario
  - the relevant system behavior
  - the role of the primary physical phenomena which govern the system behavior

TBD Specifics – Phenomena - 1

- **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 the safety concerns**

TBD Specifics – Phenomena - 2

- Phenomena are identified by:
  - Describing and understanding expected system behavior
  - Determining the cause of a change in physical state
  - Examining models used for safety analysis
- A total of 188 phenomena have been identified across the eight safety analysis disciplines

TBD Specifics – Phenomena - 3

- Phenomena designation based on discipline:
  - 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 Specifics – Phenomena - 4

- Phenomena numbering has been adopted from the current CANDU TBD
- There are gaps in the numbering, which occurred in the process of identifying the phenomena

TBD Specifics – Phenomena - 5

- For each accident scenario, phenomena are ranked as primary or secondary or irrelevant depending on their importance
  - Primary means the phenomenon has a significant impact on one or more safety concerns during any phase of any basic accident sequence encompassed by the accident scenario (dominant effect)
  - Secondary means the phenomenon has some impact on one or more safety concerns during any phase of the accident scenario (non-dominant effect)
  - Phenomena which are neither primary nor secondary are irrelevant to the safety concerns

TBD Specifics – Phenomena - 6

- Phenomena identification and 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 concerns
  - Description of system behavior
  - Identification of phenomena
  - Ranking of phenomena based on importance for system behavior and safety concerns
  - Ranking is done conservatively: if any doubt, select the higher ranking
    - Particular attention focused to phenomena for which the impact is not fully understood, or the knowledge base is not fully developed

TBD Specifics – Phenomena - 7

Discipline/ Phenomenon	Large LOCA	Small LOCA, Single Channel Accident	Secondary Coolant Failures	Fuel Handling Accidents	Loss of Regulation	Loss of Flow	Auxiliary System Failures	Limited Core Damage Accidents
Reactor Physics								
System Thermal-hydraulics								
Fuel & Fuel Channel								
Moderator & Shield System								
Fission Product Release / Transport								
Containment								
Radiation Physics								
Atmospheric Dispersion								

TBD Specifics – Phenomena - 8

	Phenomenon	Large LOCA Ranking
	Reactor Physics	
PH1	Coolant-Density-Change Induced Reactivity	secondary
PH2	Coolant-Temperature-Change Induced Reactivity	secondary
PH3	Moderator-Density-Change Induced Reactivity	
PH4	Moderator-Temperature-Change Induced Reactivity	
PH5	Moderator-Poison-Concentration-Change Induced Reactivity	secondary
PH6	Moderator-Purity-Change Induced Reactivity	
PH7	Fuel-Temperature-Change Induced Reactivity	secondary
PH8	Fuel-Isotopic-Composition-Change Induced Reactivity	secondary
PH9	Refuelling-Induced Reactivity	secondary
PH11	Device-Movement Induced Reactivity	primary
PH12	Prompt/Delayed Neutron Kinetics	secondary
PH13	Flux-Detector Response	secondary
PH14	Flux and Power Distribution (Prompt/Decay Heat) in Space and Time	primary
PH15	Lattice-Geometry-Distortion Reactivity Effects	secondary
PH17	Core Physics Response to Moderator Level Change	

TBD Specifics – Phenomena - 9

	Phenomenon	Large LOCA Ranking
	Fuel Channel and System Thermalhydraulics	
TH1	Break Discharge Characteristics and Critical Flow	primary
TH2	Coolant Voiding	primary
TH3	Phase Separation	primary
TH4	Level Swell and Void Holdup	secondary
TH5	RCS Pump Characteristics (Single and Two Phase)	primary
TH6	Thermal Conduction	primary
TH7	Convective Heat Transfer	primary
TH8	Nucleate Boiling	secondary
TH9	CHF/Dryout and Post Dryout Heat Transfer	primary
TH10	Condensation Heat Transfer	primary
TH11	Radiative Heat Transfer	primary
TH12	Quench/Rewet Characteristics	primary

TBD Specifics – Phenomena - 10

	Phenomenon	Large LOCA Ranking
	Fuel Channel and System Thermalhydraulics	
TH13	Zircaloy/Water Thermal-Chemical Reaction	primary
TH14	Reflux Condensation	
TH15	Counter Current Flow	primary
TH16	Flow Oscillations	secondary
TH17	Density Driven Flows (Natural Circulation)	secondary
TH18	Fuel Channel Deformation	secondary
TH19	Fuel String Mechanical-Hydraulic Interaction	secondary
TH20	Waterhammer	
TH21	Waterhammer (Steam Condensation Induced)	secondary
TH22	Pipe Thrust and Jet Impingement	secondary
TH23	Non-Condensable Gas Effect	secondary

TBD Specifics – Phenomena - 11

	Phenomenon	Large LOCA Ranking
	Fuel and Fuel Channel Thermal-Mechanical Effects	
FC1	Fission and Decay Heating	primary
FC2	Diffusion of Heat in Fuel	primary
FC3	Fuel-to-Cladding Heat Transfer	primary
FC4	Fuel-to-End Cap Heat Transfer	secondary
FC5	Fission Gas Release to Gap and Internal Pressurization	primary
FC6	Cladding Deformation	primary
FC7	Cladding Failure	primary
FC8	Fuel Deformation	primary
FC9	Cladding Oxidation or Hydriding	secondary
FC10	Fuel Oxidation or Reduction	primary
FC11	Fuel or Cladding Melting and Relocation	
FC12	Bundle Mechanical Deformation	primary
FC13	Cladding-to-Coolant and Coolant-to-Pressure Tube Heat Transfer	primary

TBD Specifics – Phenomena - 12

	Phenomenon	Large LOCA Ranking
	Fuel and Fuel Channel Thermal-Mechanical Effects	
FC14	Channel and Subchannel Flow Effects	primary
FC15	Local Melt Heat Transfer to Pressure Tube	
FC16	Pressure Tube-to-Calandria Tube Heat Transfer	secondary
FC17	Calandria Tube-to-Moderator Heat Transfer	secondary
FC18	Pressure Tube Deformation or Failure	secondary
FC19	Calandria Tube Deformation or Failure	
FC20	Pressure Tube Oxidation or Hydriding	secondary
FC21	Element-to-Pressure Tube Radiative Heat Transfer	primary
FC22	Element or Bearing Pad-to-Pressure Tube Contact Heat Transfer	primary
FC23	Flashing Coolant Hydrodynamic Transient in Moderator	
FC24	High Temperature Channel Debris Interaction with Water	
FC25	Ruptured Channel Projectile Formation and Impact	

TBD Specifics – Phenomena - 13

	Phenomenon	Large LOCA Ranking
	Moderator and Shield System Thermal-hydraulics	
MH9	Moderator Pump Cavitation	
MH10	Interaction of Moderator Flow with Calandria Tubes	secondary
MH11	Turbulence	secondary
MH12	Moderator Buoyancy	secondary
MH13	Moderator Inlet Jet Development	secondary
MH15	Injection of Poison	primary
MH19	Moderator/ Coolant/Poison Mixing	primary
MH22	Calandria Tube/Moderator Heat Transfer	secondary
MH30	Failed Channel Interaction With Core Components	

TBD Specifics – Phenomena - 14

	Phenomenon	Large LOCA Ranking
	Moderator and Shield System Thermal-hydraulics	
MH34	Hydrogen Deflagration	
MH36	Moderator Heat Exchanger Response	secondary
MH41	Liquid, Vapour and Two-Phase Discharge	
MH42	Moderator Swell	
MH43	Thermal Conduction	
MH44	Convective Heat Transfer	
MH45	Radiative Heat Transfer	
MH46	Moderator Degassing and Transfer Processes in Moderator Cover Gas	
MH47	Interaction of End-Shield Flow with End-Shield Solid	
MH48	Moderator Cover Gas Pressure	

TBD Specifics – Phenomena - 15

	Phenomenon	Large LOCA Ranking
	Fission Product Release	
FPR1	Athermal Release	secondary
FPR2	Diffusion	primary
FPR3	Grain Boundary Sweeping and Grain Growth	primary
FPR4	Grain Boundary Coalescence and Tunnel Interlinkage	primary
FPR5	Vapour Transport and Columnar Grains	secondary
FPR6	Fuel Cracking (thermal)	primary
FPR7	Gap Transport (failed elements)	primary
FPR8	Gap Retention	primary
FPR9	UO_{2+x} Formation	primary
FPR10	U_4O_9 and U_3O_8 Formation	
FPR11	UO_{2-x} Formation	
FPR12	UO_2-Zircaloy Interaction	
FPR13	UO_2 Dissolution by Molten Zircaloy	
FPR14	Fuel Melting	
FPR15	Fission Product Vaporization/ Volatilization	secondary
FPR16	Matrix Stripping	
FPR17	Temperature Transients	secondary
FPR18	Grain Boundary Separation	secondary
FPR19	Fission Product Leaching	primary

TBD Specifics – Phenomena - 16

	Phenomenon	Large LOCA Ranking
	Fission Product Transport	
FPT1	Fuel Particulate Suspension	secondary
FPT2	Vapour Deposition and Revaporization of Deposits	primary
FPT3	Vapour Structure/ Interaction	primary
FPT20	Aerosol Resuspension	secondary
FPT21	Pool Scrubbing	primary
FPT22	Transport of Deposits by Water	primary
FPT23	Chemical Speciation	primary
FPT24	Release of Structural Materials	secondary
	(Aerosol Nucleation and Growth)	
FPT4	Aerosol Nucleation	secondary
FPT10	Aerosol Growth/Revaporization	secondary

TBD Specifics – Phenomena - 17

	Phenomenon	Large LOCA Ranking
	Fission Product Transport (Aerosol Agglomeration)	
FPT5	Gravitational Agglomeration in the RCS	secondary
FPT6	Brownian Motion in the RCS	secondary
FPT7	Turbulent Agglomeration in the RCS	secondary
FPT8	Laminar Agglomeration	secondary
FPT9	Electrostatic Agglomeration	secondary
	(Aerosol Deposition	
FPT11	Thermophoretic Deposition in the RCS	secondary
FPT12	Diffusiophoretic Deposition	secondary
FPT13	Gravitational Deposition	secondary
FPT14	Brownian Motion Deposition	secondary
FPT15	Turbulent Deposition in the RCS	secondary
FPT16	Laminar Deposition	secondary
FPT17	Electrostatic Deposition	secondary
FPT18	Inertial Deposition	secondary
FPT19	Photophoretic Deposition	secondary

TBD Specifics – Phenomena - 18

	Phenomenon	Large LOCA Ranking
	Containment (Thermalhydraulics)	
C1	Flashing Discharge	primary
C2	Evaporation from Pools	primary
C3	Convection Heat Transfer	primary
C4	Conduction Heat Transfer	primary
C5	Condensation Heat/Mass Transfer	primary
C6	Air Cooler Heat Transfer	primary
C8	Laminar/ Turbulent Leakage Flow	primary
C9	Choked Flow	primary
C10	Liquid Re-Entrainment	secondary

TBD Specifics – Phenomena - 19

	Phenomenon	Large LOCA Ranking
	Containment (Hydrogen Behavior)	
C11	Buoyancy Induced Mixing	secondary
C12	Momentum Induced Mixing	secondary
C13	Hydrogen Vented Deflagration	secondary
C14	Turbulent Combustion	secondary
C15	Standing Flame	
C16	Deflagration/Detonation Transition	
C17	Removal by Recombiners	primary

TBD Specifics – Phenomena – 20

	Phenomenon	Large LOCA Ranking
	Containment (Iodine Chemistry)	
C18	Interfacial Mass Transfer	primary
C19	Partition Coefficient	
C20	Adsorption	primary
C21	Carbon Filter Removal Efficiency	primary
C22	Total Waterborne Iodine	primary
C23	Fraction Airborne Organic Iodine	
C24	Total Airborne Iodine	

TBD Specifics – Phenomena - 21

	Phenomenon	Large LOCA Ranking
	Containment (Aerosol Behavior)	
C25	Jet Impingement	primary
C26	Gravitational Settling	primary
C27	Thermophoresis	secondary
C28	Diffusiophoresis	secondary
C29	Diffusional Agglomeration	secondary
C30	Removal in HEPA Filters	secondary
C31	Removal in Demisters	secondary
C32	Removal in Leakage Paths	secondary
C33	Condensation	secondary
C34	Evaporation	secondary
C35	Turbulent Agglomeration	secondary
C36	Turbulent Deposition	secondary
C37	Formation in a Flashing Jet	secondary
C38	Formation in a Steam Jet	secondary
C39	Gravitational Agglomeration	secondary
C40	Inertial Deposition	secondary
C41	Diffusional Deposition	

TBD Specifics – Phenomena - 22

	Phenomenon	Large LOCA Ranking
	Radiation Physics	
RAD1	Radiation Emission	primary
RAD2	Isotopes Generation and Depletion	primary
RAD3	Neutron Transport and Streaming	secondary
RAD4	Photon Transport, Streaming and Skyshine	secondary
RAD5	Electron Transport	
RAD6	Heating (Energy Deposition)	primary
RAD7	External Exposure	secondary
RAD8	Radiolysis	secondary

TBD Specifics – Phenomena - 23

	Phenomenon	Large LOCA Ranking
	Atmospheric Dispersion	
AD1	Plume Rise	primary
AD3	Downwash	secondary
AD4	Modification of Effective Release Height Due to Building Entrainment	primary
AD5	Plume Broadening Due to Building Entrainment	primary
AD6	Fumigation	primary
AD7	Height of the Thermal Internal Boundary Layer	secondary
AD8	Reflection at an Elevated Inversion	secondary
AD9	Plume Transport	primary
AD10	Plume Diffusion	primary
AD11	Wet Deposition	primary
AD12	Dry Deposition	primary
AD13	Plume Depletion	secondary
AD14	Exposure to Cloudshine	primary
AD15	Exposure to Groundshine	primary
AD16	Internal Exposure due to Inhalation	primary

VM Specifics

- Like the TBD, ACR Validation Matrices (VMs) are an evolution of the current CANDU VMs
  - Eight generic VMs developed by teams of experts from AECL and the Canadian nuclear industry partners
- ACR VMs reflect the ACR design: accident scenarios, phenomena rankings and sources of experimental and other data for validation
- No new ACR-specific phenomena have been identified

VM Specifics - Structure

- **VM main sections:**
  - **Phenomena rankings, by accident scenario (similar to TBD)**
  - **Phenomena synopses**
  - **Sources of Data for Validation**

VM Specifics - Phenomena

- **Phenomena synopses cover:**
  - **Phenomenon description**
  - **Technical background**
  - **State of knowledge and uncertainties**
  - **Related phenomena**
  - **Validation tests**
  - **References**

VM Specifics – Data Sources - 1

- Data sources are of four main types:
  - Separate effects experiments
  - Integral effects experiments
  - Component tests
  - Analytical solutions/code-to-code comparisons
- In-reactor and out-reactor tests
- U.S. and international experiments are included, as well as experiments performed specifically for CANDU and for ACR

VM Specifics – Data Sources - 2

- Selection of data takes into account:
  - Availability
    - Many CANDU-specific experiments are available, plus ACR-specific tests
  - Quality
    - Review availability of documentation, measurement accuracy, etc.
  - Applicability
    - Review relevance for ACR phenomena and conditions
    - Detailed review of applicability of tests is performed in individual validation exercises

VM Specifics – Data Sources - 3

- A synopsis is given of each, giving:
  - Facility description
  - Test description
  - Summary of tests performed
  - Instrumentation
  - Data uncertainty
  - Relevant phenomena
  - References
- Incremental experiments performed specifically for ACR to be included in VMs

VM Specifics – Process

- Overall planning has been completed
- Existing VMs are being revised as required for ACR
- Revisions in each analysis discipline are supervised by a discipline expert
- Revisions are performed by a multidisciplinary team
- Formal review and comment process includes design, analysis and licensing (feedback to licensing analysis)

VM Specifics – Large LOCA

- TBD and VMs provide the information necessary to perform validation for the code suite used for any accident scenario, e.g. large LOCA
- Each discipline VM specifies the phenomena and datasets for large LOCA code validation
- Table shown previously indicates importance of each discipline for large LOCA

Summary

- Technical Basis Document and Validation Matrix documents are the high-level documents which guide code validation
- ACR-specific TBD and VMs are an evolution of the current CANDU TBD and VMs
- ACR-specific TBD has been issued
- Eight VMs are being being revised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