Sandia National Laboratories

Securing the future of Nuclear Energy

MELCOR

MELCOR Workshop – SMR Containment IV Validation

2025 European MELCOR Users' Group Meeting

April 7th-11th, 2025

SAND2025-04014PE

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Overview

Perspective on code validation in general

- Role and importance
- Historical validation suite and present status
- MELCOR assessments

SMR LWR containment modeling specific validation(s)

- DEMONA (containment thermal hydraulics and aerosol depletion)
- STORM (aerosol thermophoretic deposition and resuspension)
- LACE LA1/LA3 for aerosol flow through pipes and turbulent deposition
- LACE LA4 for aerosol in steamy containment atmosphere
- Others of potential importance to SMR LWR containment, a few examples:
  - AHMED on hygroscopic aerosols in various humid environments
  - JAERI – spray droplet heat/mass transfer and pressure suppression
  - CSE-A9 - spray scrubbing
  - MARVIKEN blowdown tests – critical flow during blowdown to containment
- Examples from MELCOR user base and academia
  - Texas A&M on condensation (Anderson/Wisconsin flat plate among others)
  - VTT (Sevon) on passive containment cooling system experiments
  - CNL Strong Condensation Containment Apparatus (SCCA) validation/benchmark

Summary

Perspective: Role and Importance

Importance of validation

- Code developers
  - Provide guidance in terms of 1) new model development, and 2) existing modeling improvement
  - Desirable to have verification and validation at time of code model implementation
- Code users
  - Increased confidence in applying code models
  - Improved understanding of model uncertainties

Users and developers should perform validation studies

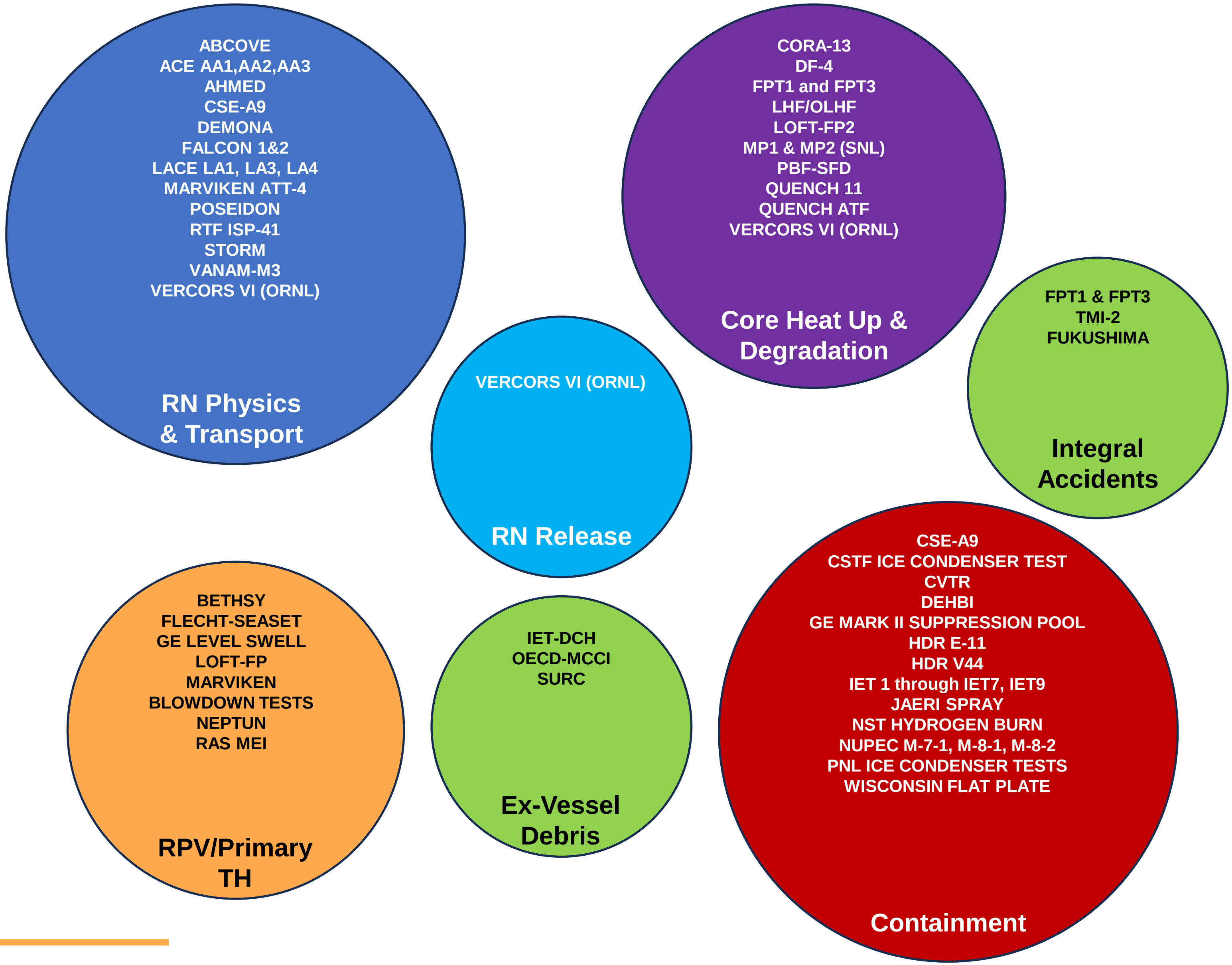
- Better idea of model nuances, strengths, and deficiencies
- Often involved in different activities with different opportunities to apply code models
- Share lessons-learned and involve users in development process

Validation should focus on what can be learned from straightforward application of code models (focus less on "fine tuning" to some experimental data or some desired response)

Typical categories of validation problems

- Separate effects tests (isolate phenomena, sometimes difficult geometry or boundary conditions)
- Integral effects tests (examine separate effects in combination, watch out for applicability)
- Actual events/accidents (integral, relevant physics, often poorly instrumented)
- International standard problems (well-documented, often comes along with code benchmarking)

Perspective: Validation Base



Perspective: Validation Base

SNL/NRC/MELCOR has a broad validation database historically, e.g:

Tills, J, Notafrancesco, A.,Longmire, P., "An Assessment of MELCOR 1.8.6: Design Basis Accident Tests of the Carolinas Virginia Tube Reactor (CVTR) Containment (Including Selected Separate Effects Tests)", SAND2008-1224 (2008).
Souto, F.J., Haskin, F.E., Kmetyk, L.N., "MELCOR 1.8.2 Assessment: Aerosol Experiments ABCOVE AB5, AB6, AB7, and LACE LA2," SAND94-2166 (1994),
Tautges, T.J., "MELCOR 1.8.2 Assessment: The MP-1 and MP-2 Late Phase Melt Progression Experiments," SAND94-0133 (1994)
Kmetyk, L.N., "MELCOR 1.8.3 Assessment: CSE Containment Spray Experiments," SAND94-2316 (1994).
Tills, J., Notafrancesco, A, Longmire, P., "An Assessment of MELCOR 1.8.6: Design Basis Accident Tests of the Carolinas Virginia Tube Reactor (CVTR) Containment (Including Selected Separate Effects Tests)," SAND2008-1224 (2008).
Tautges, T., "MELCOR 1.8.2 Assessment: The DFI-4 BWR Damaged Fuel Experiment," SAND93-1377 (1993).
Tautges, T., "MELCOR 1.8.3 Assessment: GE Large Vessel Blowdown and Level Swell Experiments," SAND94-0361 (1994).
Kmetyk, L.N., "MELCOR 1.8.2 Assessment: IET Direct Containment Heating Tests," SAND93–1475 (1993).
Kmetyk, L.N., "MELCOR 1.8.1 Assessment: LACE Aerosol Experiment LA4," SAND91–1532 (1991).
Kmetyk, L.N., "MELCOR 1.8.1 Assessment: LOFT Integral Experiment LP-FP-2," SAND92–1373 (1992).
Kmetyk, L.N., "MELCOR 1.8.1 Assessment: Marviken-V Aerosol Transport Tests ATT-2b/ATT-4," SAND92–2243 (1993).
Gross, R.J., "PNL Ice Condenser Aerosol Experiments," SAND92–2165 (1993).
Kmetyk, L.N., "MELCOR 1.8.1 Assessment: FLECHT SEASET Natural Circulation Experiments," SAND91-2218 (1991).
Kmetyk, L.N., "MELCOR 1.8.1 Assessment: ACRR Source Term Experiments ST-1/ST- 2", SAND91-2833 (1992).

Validation corpus is ever-expanding (e.g. non-LWR, QUENCH-ATF)

De Luna, B., Philips, J,, "Benchmarking MELCOR's NAC Package to ABCOVE Tests AB5 and AB6," SAND2024-04949 (2024).
De Luna, B., Beeny, B. "Benchmarking MELCOR's NAC Package to ABCOVE Test AB7," SAND2025-02249 (2025).
As-yet unpublished HTGR Gemini/HTTF benchmarking/validation, MSRE zero-power flow coast-down, etc.
Forth-coming QUENCH-ATF

MSRE Zero-power coast-down	MSRE experiments	AB-1 AB-5 AB-6 AB-7 T-3	LOF,LOHS,TOP TREAT M-Series ANL-ART-38	HTTU GEMINI	Air-Ingress Helical SG HT	PBMR-400 HTR-10
Molten Salt (Completed)	**Molten Salt (Planned)**	**Sodium Fires (Completed)**	**Sodium Reactors (Planned)**	**HTGR (Completed)**	**HTGR (Planned)**	**HTGR (In-progress)**

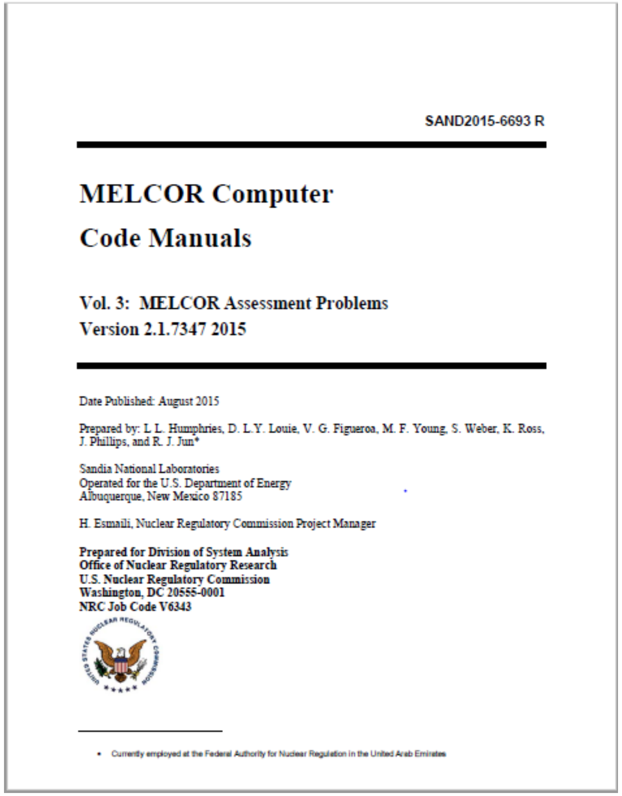
Users make some of the best contributions to the validation/benchmarking base

Perspective: MELCOR Assessments

Vol III of MELCOR documentation is a compilation of assessments (experimental validations)

Relatively recent efforts to revisit

- Review, refresh, and update
  - Best practices
  - Reestablish an assessment baseline
- Possibly add/expand scope, e.g
  - ABOVE AB1, AB5, AB6, and AB7 with new sodium models
  - LACE LA-1A, LA-3A, and LA-3B
  - Phebus FPT1 Fission Product Release
  - STORM resuspension phase
  - TMI-2
- Test new(er) modeling capabilities and features, e.g.
  - Aerosol physics
  - New CORSOR-Booth Fission Product Release Model
  - COR eutectics model
  - New turbulent deposition models
  - PSI Oxidation models
  - Resuspension models
  - Various non-LWR related models



SAND2015-6693 R

MELCOR Computer
Code Manuals

Vol. 3: MELCOR Assessment Problems
Version 2.1.7347 2015

Date Published: August 2015

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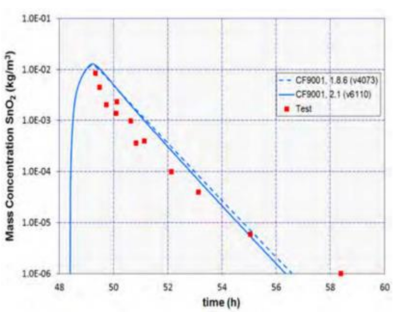
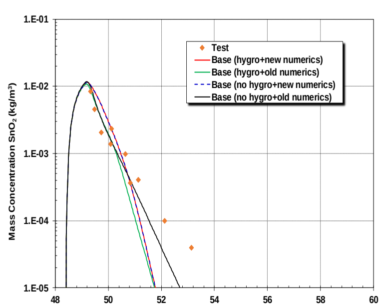
- Currently employed at the Federal Authority for Nuclear Regulation in the United Arab Emirates

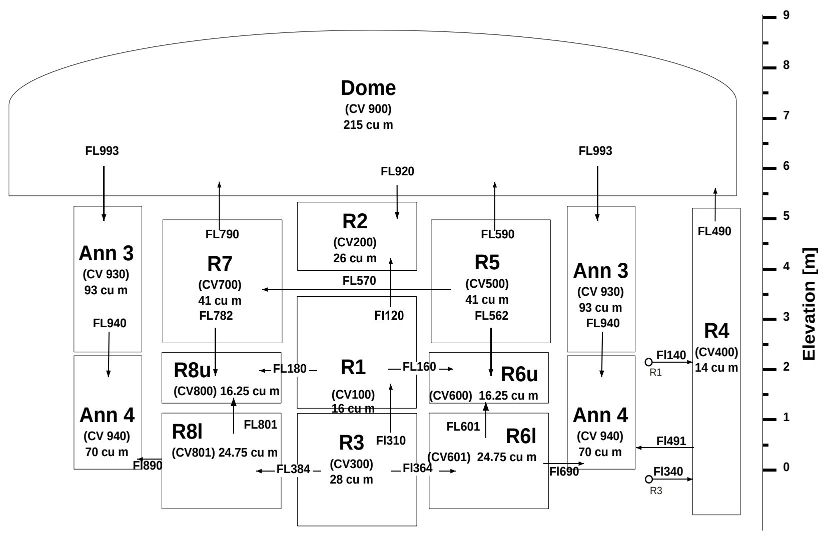
SMR LWR Validation: DEMONA-B3

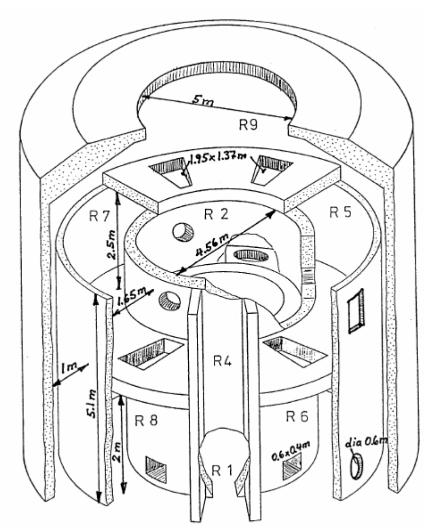
Emphasis is phenomena associated with steam condensation effects on aerosol settling

- Battelle Model Containment (BMC) in Frankfurt, Germany
- Non-hygroscopic aerosols (SnO_2/Sn) injected at 215 g/min, log-normal MMD = 0.35 μm and σ=2
- 1986, test B-3 conducted over 3 days consisting of 5 phases:
  - Phase 1: purge air to achieve pure steam atmosphere (0.4-7.1 hr)
  - Phase 2: inject steam over 2 days to heat up BMC structure at constant 1.7 bar
  - Phase 3: inject hot air & aerosol - 48.4 to 49.3 hr, P to 3 bar (P_{air} 1.3 bar, P_{stm} 1.7 bar), peak aero conc 9 g/m^3
  - Phase 4: aerosol depletion 49.3-71.1 hr
  - Phase 5: cooldown (ignored in modeling)









SMR LWR Validation: STORM

Emphasis is aerosol deposition and resuspension in pipes

- Simplified Test of Resuspension Mechanism at the Joint Research Center in Ispra, Italy
- Two phases: 1) deposition by thermophoresis and eddy impaction, 2) resuspension under gas flow

Deposition phase:

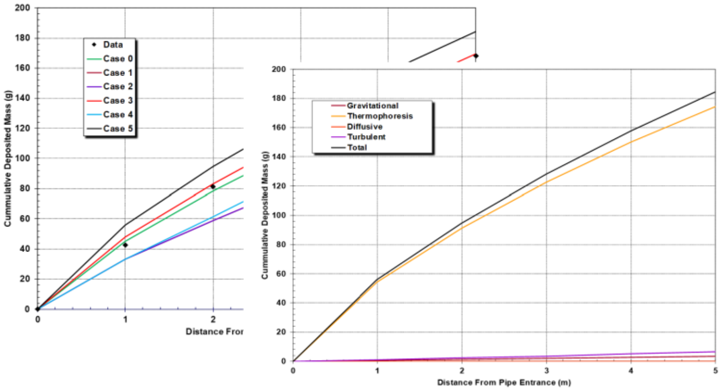
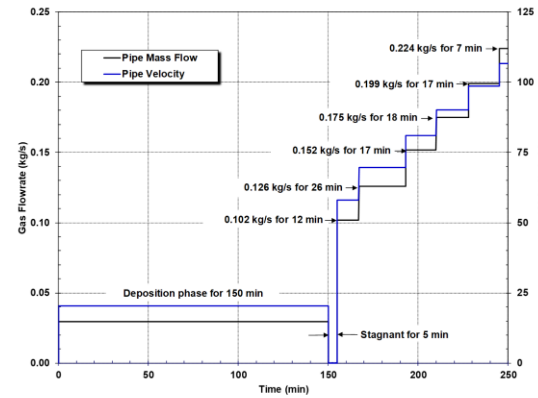


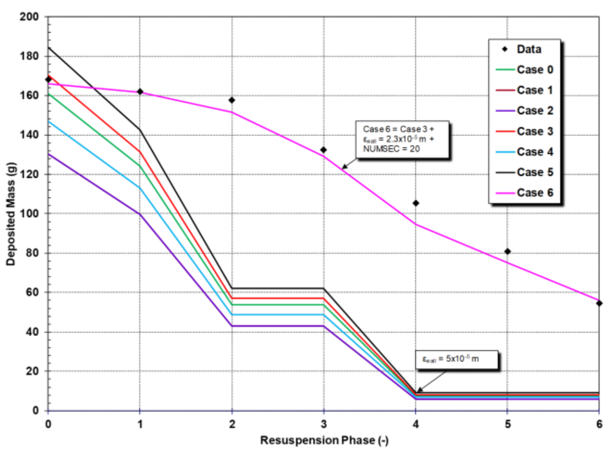
Table 2 Summary of the MELCOR Calculations

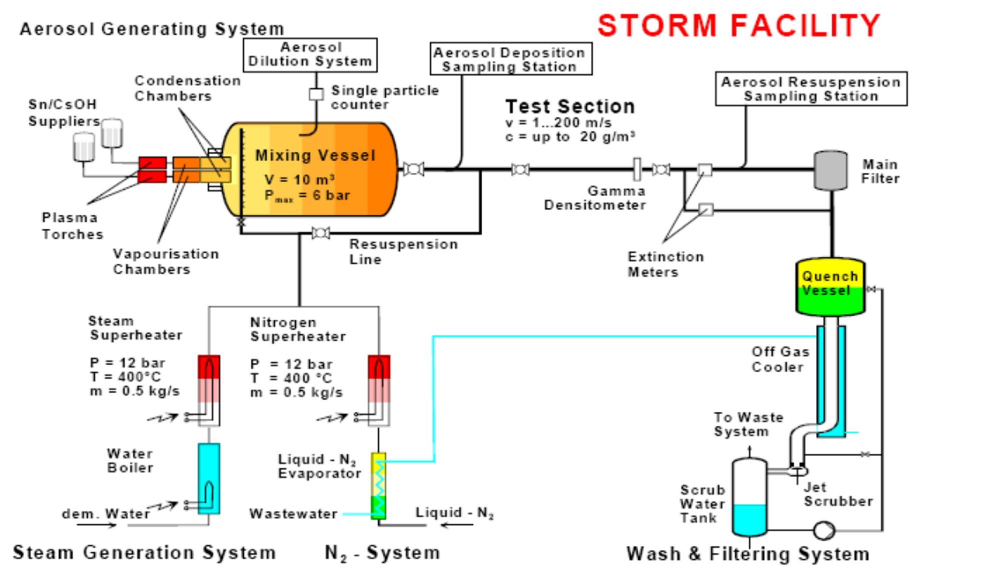
Case #	Turbulent Deposition Model [b]	Inside Wall HTC	Other
0	Version 2.2 only	Default code model	n/a
1	Version 2.2 only	Constant 30 W/m^2-K	n/a
2	All	Constant 30 W/m^2-K	n/a
3	Version 2.2 only	Constant 50 W/m^2-K	n/a
4	Version 2.2 only	Variable 30 – 44 W/m^2-K	n/a
5	Version 2.2 only	Constant 60 W/m^2-K	n/a
6 [a]	Version 2.2 only	Constant 50 W/m^2-K	Note c

Notes:
a. Only Version 2.2 was used for this calculation.
b. The Woods rough pipe turbulence model was used for all calculations with turbulent deposition. A pipe wall roughness of 5.e-5 m was specified in all cases but Case 6.
c. The wall roughness was slightly decreased to 2.2e-5 m and the number of aerosol sections was increased from 10 to 20.



Resuspension phase:





SMR LWR Validation: LACE LA1/LA3

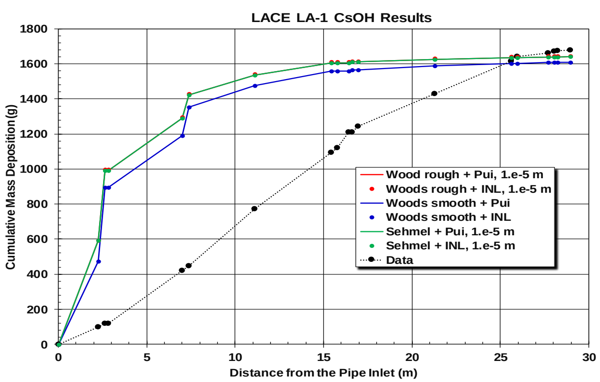
Emphasis is LWR aerosol transport and retention through pipes with high-speed flow

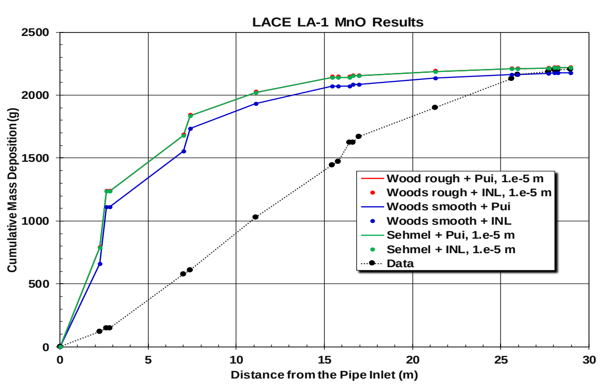
- Hanford Engineering Development Laboratory (HEDL) from 1981-1988
- Mixed CsOH (hygroscopic) and MnO (non-hygroscopic) aerosols, 30,000 < Re < 300,000

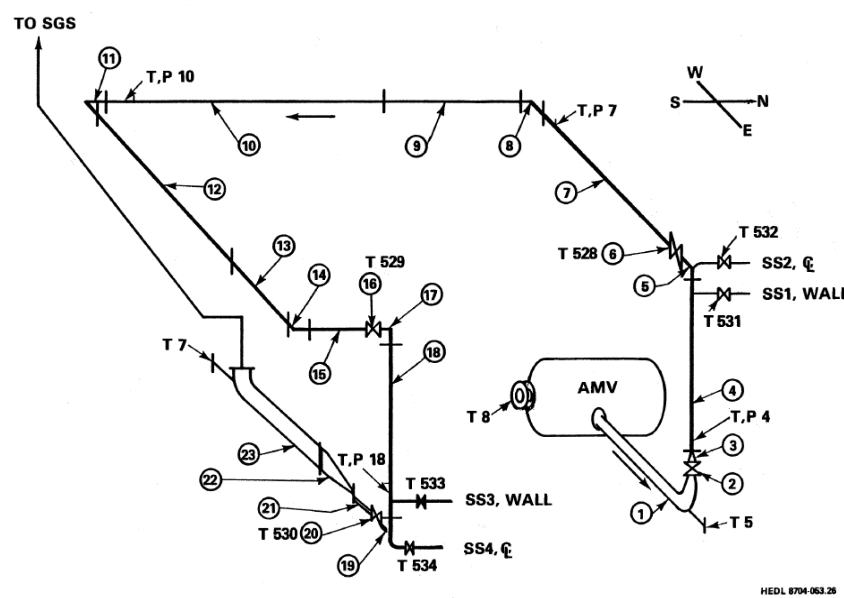
LA1 – Re ~ 300,000 (highest velocity)

- Overpredict early retention
- Total retention (~ complete) compares well

Test	Aerosol	NaOH or CsOH Mass Fraction	Carrier Gas	Gas Velocity (m/s)	Temp. (°C)	Aerosol Source Rate (g/s)	Aerosol Size AMMD (μm)	Mass Retention Fraction
LA1	CsOH	0.42	Air-steam	96	247	1.1	1.6	> 0.98
	MnO							
LA3A	CsOH	0.18	N_2-steam	75	298	0.6	1.4	> 0.7
	MnO							0.7
LA3B	CsOH	0.12	N2-steam	24	303	0.9	2.4	> 0.4
	MnO							> 0.7
LA3C	CsOH	0.38	N2-steam	23	300	0.9	1.9	> 0.7
	MnO							> 0.7



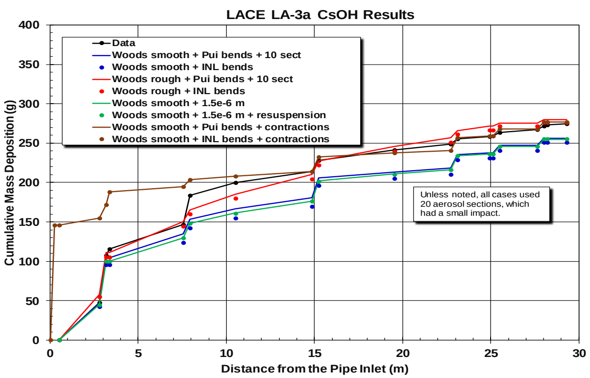


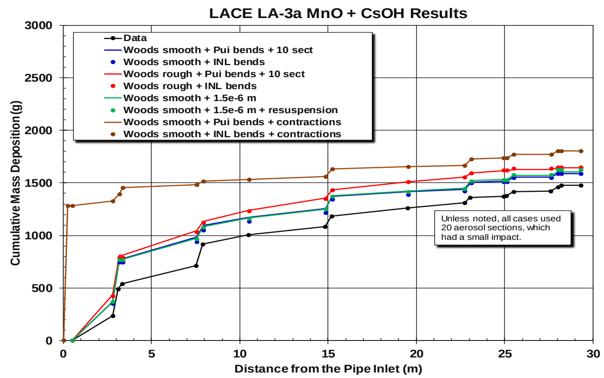


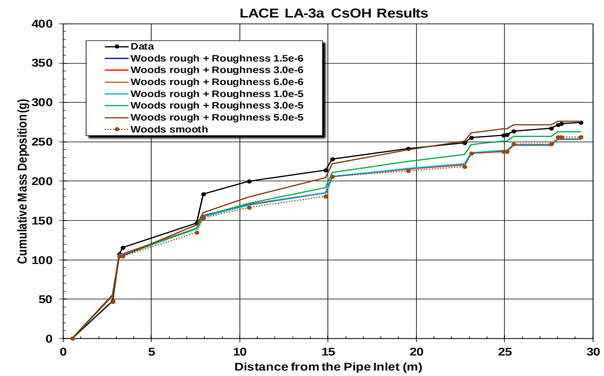
SMR LWR Validation: LACE LA1/LA3

LA3A – Re ~ 133,000

- Better retention predictions (vs higher velocity LA1)
- Woods rough pipe deposition model gave best comparison
- Sensitivity on roughness…higher roughness means more deposition





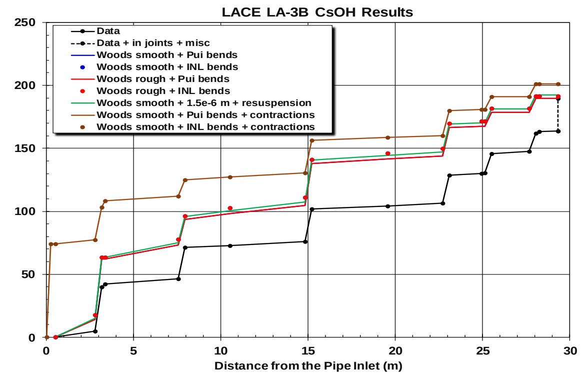


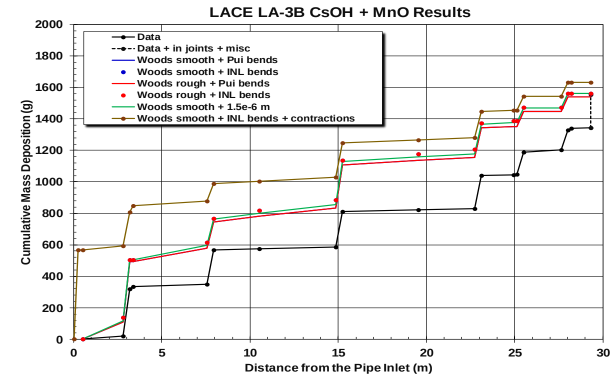
LA3B – Re ~ 33,000

- Lowest inlet velocity
- Overpredictions of retention…nearly complete retention of hygroscopic and non-hygroscopic

Liftoff model

- Good for liquid/dry aerosols
- Suited for “sticky” aerosol mix?
- Best results at medium Re

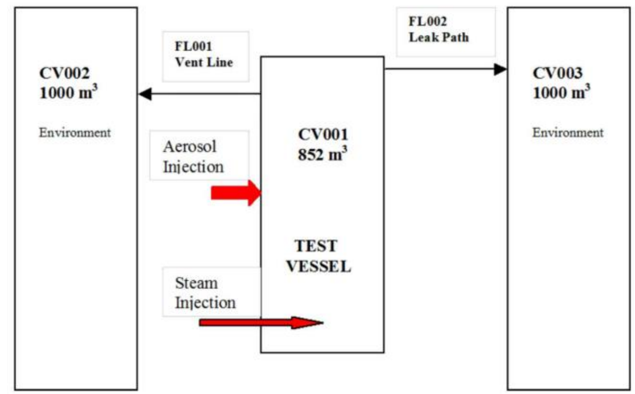




SMR LWR Validation: LACE LA4

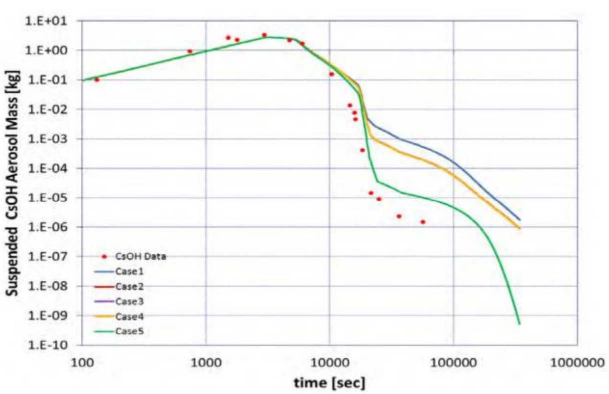
Emphasis is aerosol disposition in high steam concentration, hygroscopic & non-hygroscopic

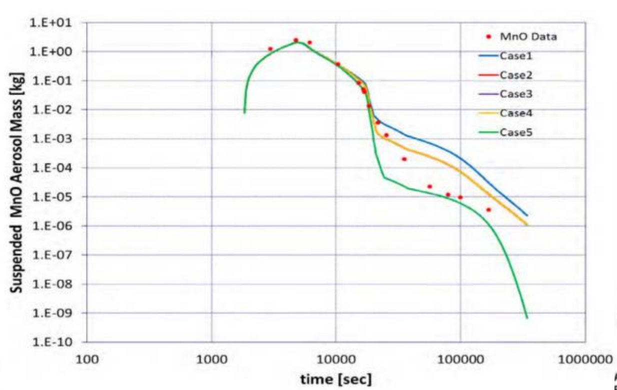
- Conducted at CSTF, 1986, CsOH (hygroscopic) and MnO (non-hygroscopic) aerosols
- Sensitivity cases on C4251 (min/max surf liquid film thickness)
- Sensitivity cases on C4252 on film/pool interactions

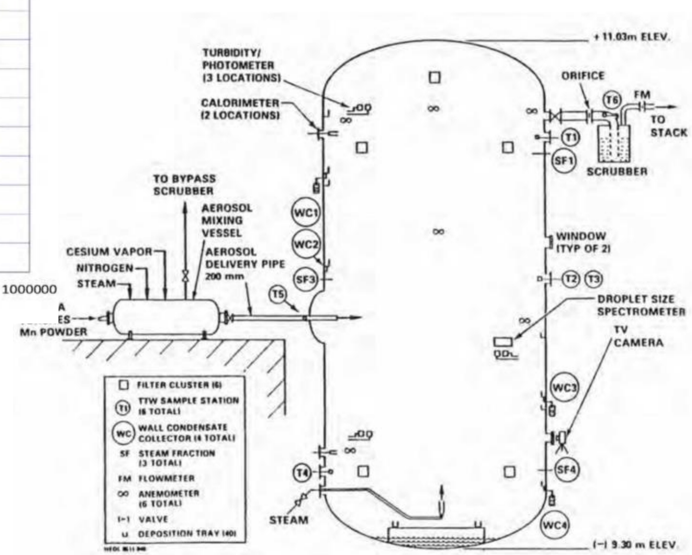


Case	MELCOR 2.1	MELCOR 1.8.6
Case 1 – default C4252(1) = 0.0, C4252(2) = 0.0, C4251(1) = 1×10^{-9} m	X	X
Case 2* – Same as Case 1, except C4252(2) = 0.70 (similar to 1.8.5)	X	X
Case 3 – Same as Case 2, except C4251(1) = 0.1×10^{-3} m	X	
Case 4 – Same as Case 2, except C4251(1) = 0.5×10^{-3} m	X	
Case 5 – Same as Case 1, except C4251(1) = 0.5×10^{-3} m	X	

*Additional cases were conducted in terms of sensitivity to the time-step used in the calculations. Case 2a assumes a constant Δt=1 s, Case 2b uses Δt=2 s, and Case 2c uses Δt=10s for MELCOR 2.1.







- Fair agreement on suspended hygro/non-hygro aero mass
- Better agreement on hygro aero mass when 5 mm $\delta_{film,min}$

SMR LWR Validation: Other Notables

Aerosol Heat Transfer Measurement Device (AHMED, VTT, Finland)

- Hygroscopic growth of aerosols in controlled conditions
- Settling/deposition
- Great agreement with experimental results

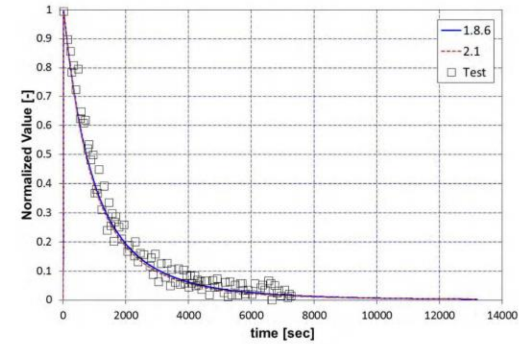
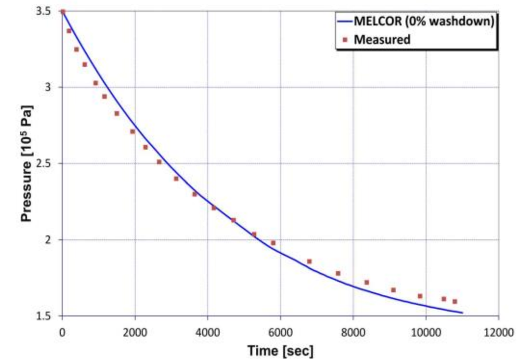


Figure 3.3-5. Normalized NaOH Concentrations at RH=96%.

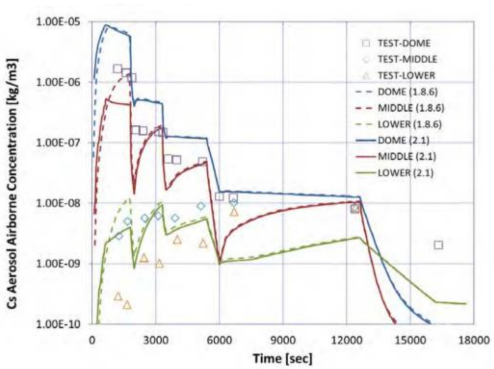
JAERI spray tests (Japan Atomic Energy Research Institute, 1970's)

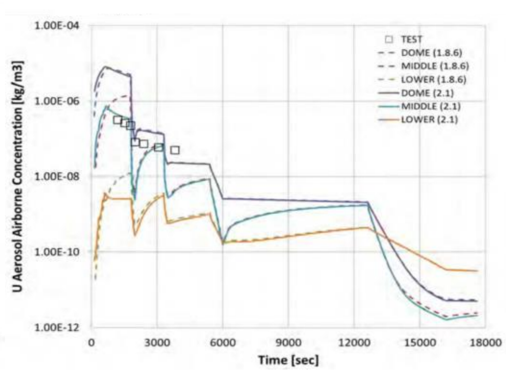
- Spray heat/mass transfer affecting pressure suppression
- No aerosol/vapor removal component to experiments
- Generally good pressure suppression prediction

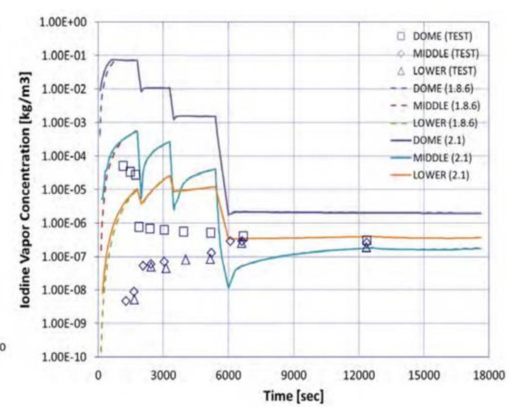


CSE-A9 spray (Containment System Experiment - PNL)

- Good thermal hydraulic response prediction
- Cs, U aerosol and I vapor in atmosphere predicted



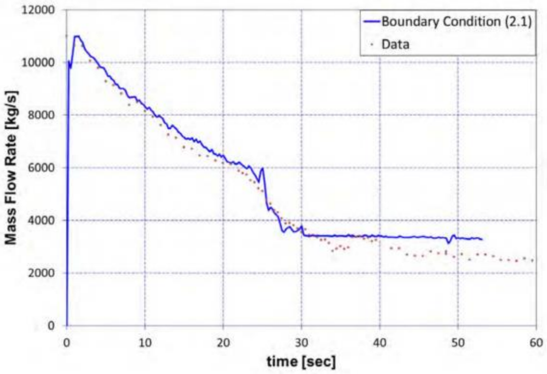


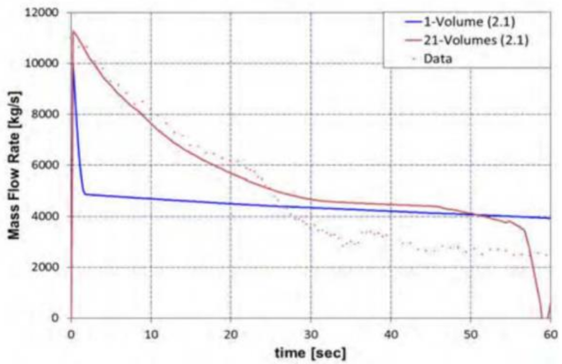


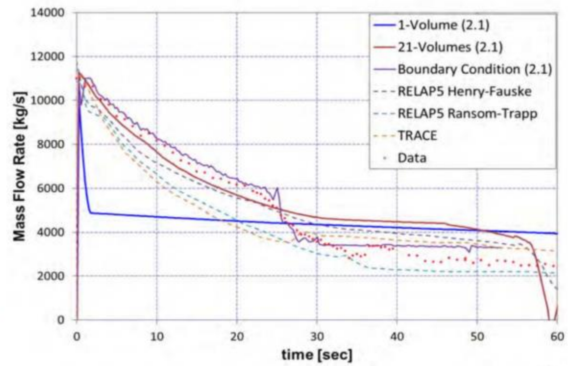
SMR LWR Validation: Other Notables

Marviken blowdown CFT-21 and JIT-11

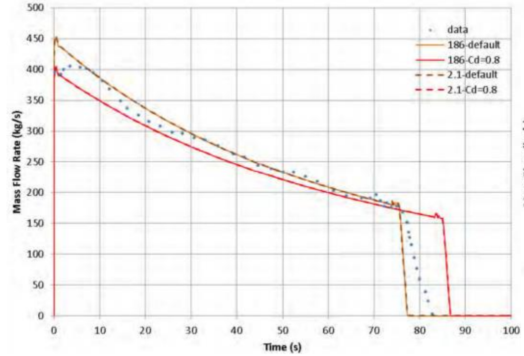
- CFT-21 for subcooled and two-phase flow
  - Boundary conditions imposed to isolate critical flow model
    - Excellent agreement for subcooled liquid
    - ~ 30 s - zero subcooling (two-phase) at discharge nozzle
    - Overpredicted mass flow rate thereafter
  - Full vessel response model
    - Single CV variation performs poorly
    - 21 CV variation performs much better

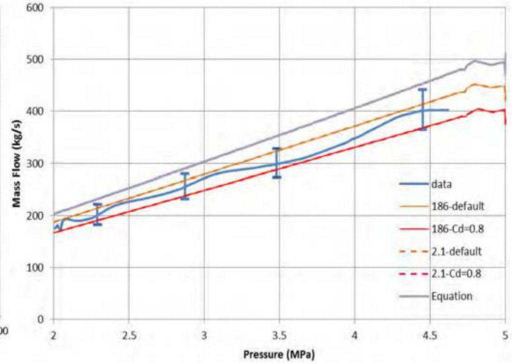






- JIT-11 for saturated steam
  - Single-phase atmosphere
  - Sensitivities on discharge coefficient
  - Good agreement
    - Discharge mass flow rate
    - Mass flow as function of pressure

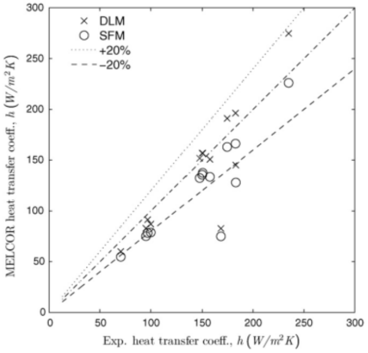


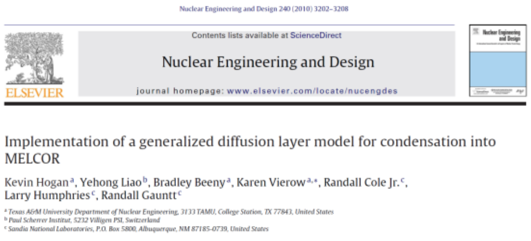


SMR LWR Validation: User Community

Texas A&M condensation

- Looks at condensation in presence of NCGs
- Considers MELCOR stagnant film model
- Results compared to several experiments
  - Anderson scaled AP-600 test section
  - Good agreement, vertical surface condensation




Nuclear Engineering and Design 240 (2010) 3202–3208

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

ELSEVIER

Implementation of a generalized diffusion layer model for condensation into MELCOR

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VTT passive containment cooling

- Lehtinen (Purdue)
- PANDA T1.1
  - Minimal thermal stratification
  - Excellent example of user ingenuity
    - Small, problematic levitating pools in PCCS condensate drain
    - Valuable insights on approach to PCCS modeling

	Condensation rate (g/min)		Deposition (particle loss %)	
Test name	Measured	MELCOR	Measured	MELCOR
Dry	0	0	4.3	5
Low steam	9.5	9.4	17.2	11.5
High steam	43.3	39.8	53	43.2


RESEARCH REPORT

MELCOR Modeling of a Passive Containment Cooling System Experiment PANDA T1.1

Author: Tuomo Sevón

Confidentiality: Public

VTT

CNL condensation validation/benchmark

- SCCA looks at SMR LWR containment modeling in particular
- Brings up issues of thermal stratification and mixing
- Raises questions related to aerosol deposition in presence of “strong condensation” and increased importance of diffusiophoresis


Nuclear Engineering and Design 427 (2024) 113440

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ELSEVIER

GOTHIC and MELCOR benchmarking of the CNL strong condensation containment apparatus experiments

Dening Eric Jia*, Luke Lebel, Andrew Morreale, Feng Zhou

Canadian Nuclear Laboratories, 286 Plant Road, Chalk River, Ontario, K0J 1J0, Canada

Summary

Reviewed the MELCOR validation base historically and currently

Looked at some noteworthy components of the validation base for SMR LWRs

- Thermal hydraulics and radionuclide transport
- So much more than addressed here
- Mentioned some examples of good validation/benchmark work external to SNL/NRC