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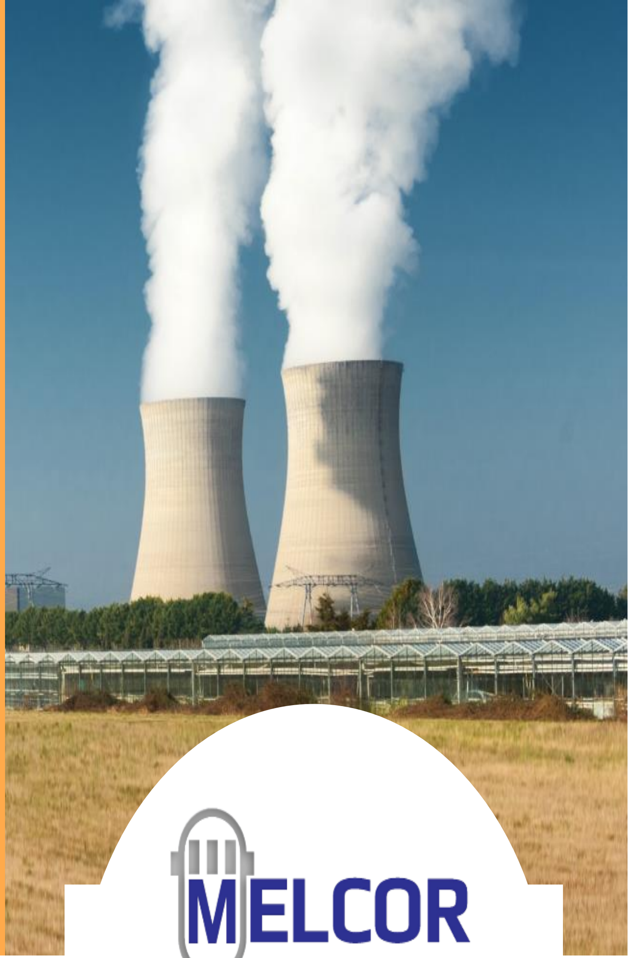


MELCOR

MELCOR Workshop – SMR Containment II
Helical Coil SGs, PCCS/ICS, and Rain

2025 European MELCOR Users' Group Meeting

April 7th-11th, 2025

SAND2025-04012PE

Overview

Review some important SMR-related MELCOR models

- HS convection correlation(s) for helical coil steam generator
  - Inside coils – convective boiling
  - Outside coils – flow across tube bank
- CND models for passive containment cooling system (PCCS), isolation condensers (ICS)
- SPR model for rain droplets
  - Heat/mass transfer and radionuclide removal
  - Aerosol washout and atmosphere decontamination

Demonstrations

Summary

Helical Coil SG

Employed in LWR and non-LWR SMR designs

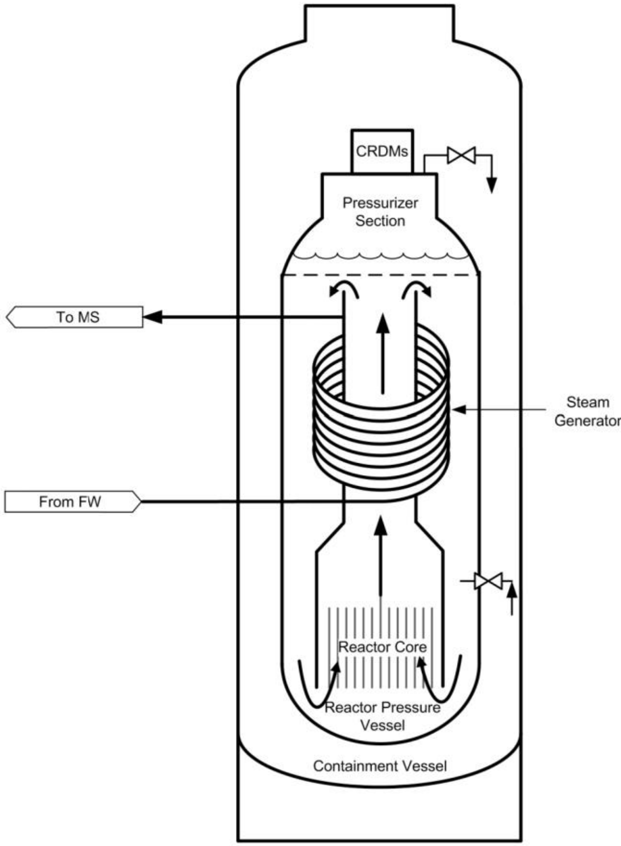
- Nuclear steam supply system of the NuScale design
- Steam generator of the Xe-100 design

Inside helical coils

- Steam generation occurs
- Subcooled feedwater enters, superheated steam exits
- Mori-Nakayama Nusselt number correlations
  - Liquid in tubes of helical coils (~ subcooled feedwater)
  - Gas in tubes of helical coils (~ superheated steam)
- Two-phase convective boiling
  - Along the lines of Chen correlation
  - Dittus-Boelter-like with Reynolds factor F (macro or convective)
  - Forster-Zuber with Suppression factor S (micro or pool boiling)

Outside helical coils

- Single phase liquid cross-flow over a tube bundle
- Zukauskas Nusselt number correlation



NuScale Plant Design Overview. NP-ER-000-1198.
https://www.nrc.gov/docs/ml1221/ml12216a392.pdf

Helical Coil SG Inside

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Two-phase convective boiling computed between two single-phase convection correlations

- Mori/Nakayama for single-phase liquid (subcooled feedwater) through coiled geometry:

$$Nu = (1/41)(k/d_i)Pr^{0.4}Re^{5/6}(d_i/D_c)^{1/12}\left[1 + 0.061/\{Re(d_i/D_c)^{2.5}\}^{1/6}\right]$$

- Modified Chen-type approach for two-phase convective boiling
  - Convection:
    - Dittus-Boelter type (Seban/McLaughlin)

$$h_c = 0.023\left(k_f/d_i\right)(1-x)^{0.8}Re^{0,85}Pr^{0.4}(d_i/D_c)^{0.1}$$

    - Reynolds factor with turbulent Martinelli parameter dependence (Bjornard/Griffith fit)

$$F = 2.35(1/X_{tt} + 0.213)^{0.736}\ ;\ X_{tt} = \left(\rho_g/\rho_f\right)^{0.5}\left(\mu_f/\mu_g\right)^{0.1}(1/x - 1)^{0.9}$$

  - Boiling: Forster/Zuber type, two-phase Reynolds number, and Suppression factor (Bjornard/Griffith fit)

$$h_b = 0.00122\left[\frac{k_f^{0.79}C_{p,f}^{0.45}\rho_f^{0.49}}{\sigma^{0.25}\mu_f^{0.29}h_{fg}^{0.24}\rho_g^{0.24}}\right]\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75}\ ;\ S = \begin{cases} 1 + 0.12Re_{tp}^{-1.14} & , Re_{tp} < 32.5 \\ \left(1 + 0.42Re_{tp}^{0.78}\right)^{-1} & , 32.5 \le Re_{tp} \le 70.0 \\ 0.0797 & , Re_{tp} > 70.0 \end{cases}$$

$$Re_{tp} = \left(G\,(1-x)d_i/\mu_f\right)F^{1.25} * 10^{-4}\ ; G = \alpha\rho_g v_g + (1-\alpha)\rho_f v_f$$

  - Overall:

$$h = Fh_c + Sh_b$$

- Mori/Nakayama for single-phase gas (superheated steam) through coiled geometry:

$$Nu = (1/26.2)(k/d_i)\left(\frac{Pr}{(Pr^{2/3} - 0.074)}\right)Re^{4/5}(d_i/D_c)^{0.1}[1 + 0.098/\{Re(d_i/D_c)^2\}^{0.2}]$$

HS_LB – Left (Inside) Boundary Surface Data

(d) 3 or HelicalSG

A convective boundary condition is applied with the heat transfer coefficients calculated by the HS package. The Helical Steam Generator heat transfer correlations are used for flow inside the tube.

Region	Default Value	SC
Subcooled Convection	1.0	C4186(1)
Two-Phase Convection	1.0	C4186(2)
Superheated Convection	1.0	C4186(3)

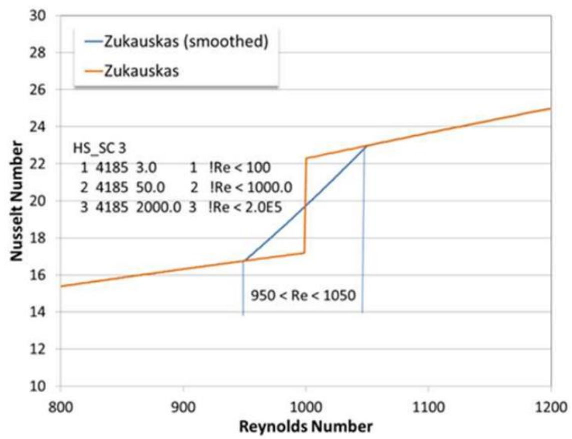
Helical Coil SG Outside

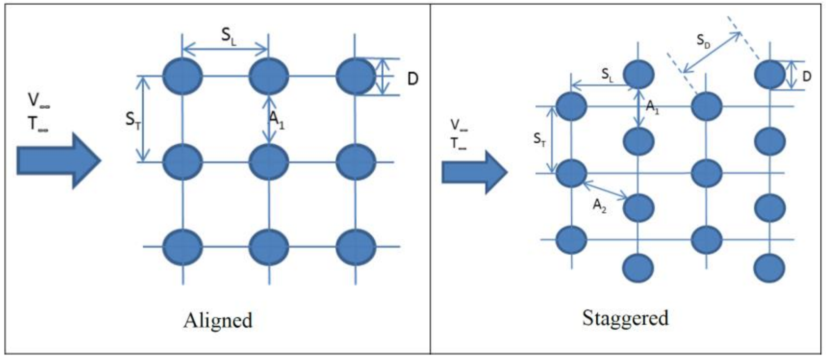
Single phase cross-flow over tube bank – Zukauskas correlation

- Aligned or staggered bank
- HS_[L|R]B option and HS_ZUKL
- Correction factor $C_2(N_L)$
- Optionally smooth at discontinuities

$$Nu = (C_2(N_L))C Re_{D,max}^{m} Pr^{n} \left(\frac{Pr}{Pr_s}\right)^{0.25}$$

	$Re_{D,max}$	Condition	C	m	n
Aligned	$10 < Re_{D,max} < 100$		0.8	0.4	0.36
	$100 < Re_{D,max} < 1000$	Pr<10	0.51	0.5	0.37
		Pr > 10	0.51	0.5	0.36
	$1000 < Re_{D,max} <= 2 \times 10^5$		0.27	0.63	0.36
	$2\times10^5 < Re_{D,max} <= 2 \times 10^6$		0.021	0.84	0.36
Staggered	$10 < Re_{D,max} < 100$		0.9	0.4	0.36
	$100 < Re_{D,max} < 1000$	Pr<10	0.51	0.5	0.37
		Pr > 10	0.51	0.5	0.36
	$1000 < Re_{D,max} <= 2 \times 10^5$	$S_T/S_L < 2$	$0.35(S_T/S_L)^{1/5}$	0.6	0.36
		$S_T/S_L > 2$	0.4	0.6	0.36
	$2\times10^5 < Re_{D,max} <= 2 \times 10^6$		0.022	0.84	0.36





4185 – Zukauskas Heat Transfer Coefficient Smoothing Ranges

Smoothing ranges are specified for Zukauskas heat transfer correlation. For each Re_i that specifies a boundary in the inequality, the function is linearly smoothed over the range $Re_i - eps_i < Re < Re_i + eps_i$.

C4185(1)	Limit eps1 for Re1 of 100. (default = 0.0, units = none, equiv = none)
C4185(2)	Limit eps2 for Re2 of 1000. (default = 0.0, units = none, equiv = none)
C4185(3)	Limit eps3 for Re3 of 200000. (default = 0.0, units = none, equiv = none)

Aligned:

$$V_{max} = \frac{S_T}{S_T - D} V$$

Staggered:

$$if\ S_D = \left[S_L^2 + \left(\frac{S_T}{2}\right)^2\right]^{1/2} < \frac{S_T + D}{2} \qquad V_{max} = \frac{S_T}{2(S_D - D)} V$$

else

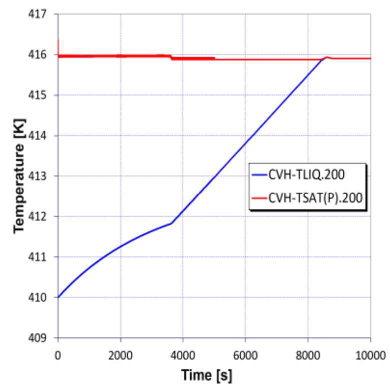
$$V_{max} = \frac{S_T}{S_T - D} V$$

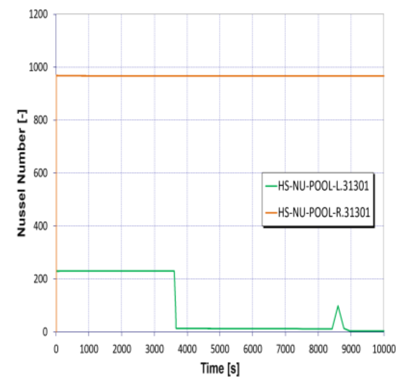
Helical Coil & Zukauskas Example

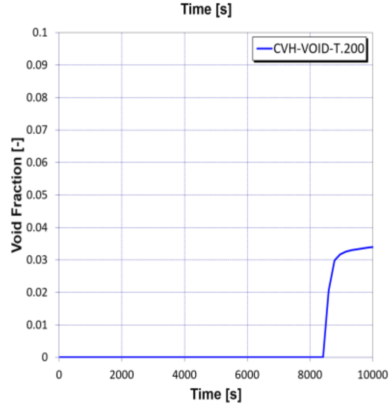
Simple-minded heat exchanger – few CV and 1 HS

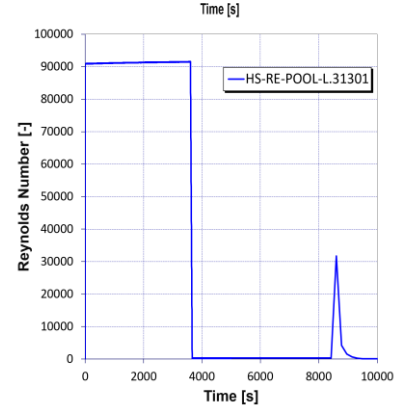
- HS LHS uses helicalSG (feedwater subcooled in/up at 410 K)
- HS_RHS uses Zukauskas (primary subcooled in/out/down at ~ 440 K)
- Input illustration
- Control feedwater flow path inlet velocity
    - Throttle back feedwater inlet velocity from 1.0 m/s starting at 3600 s
    - Saturation occurs in feedwater CV
    - Helical SG single-phase correlation responds to void and Re adjustment

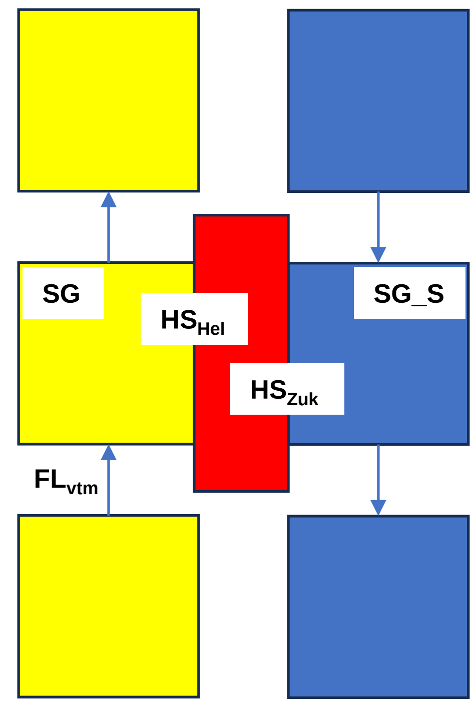
```
HS_ID 'SG'  31301
HS_GD CYLINDRICAL YES
HS_EOD -3.375 1.0
HS_SRC NO
HS_ND  4
     1  1   1.00E-02     - 'STAINLESS-STEEL'
     2  2   0.1033E-01   - 'STAINLESS-STEEL'
     3  3   0.1067E-01   - 'STAINLESS-STEEL'
     4  4   0.110E-01    -
HS_RB Zukauskas 'SG_S'   YES
!              D         ST    SL
HS_ZUKR  .015      .1    .1  Aligned MULT 1.0
HS_RBR   0.500  EQUIV-BAND  1.00E-02
HS_RBP EXT  0.500  0.500
HS_RBT 100.0  100.0  1.00  1.00
HS_RBS 1.0 0.02 0.30
HS_LB HelicalSG 'SG' YES
HS_LBP INT    0.500    0.500
HS_LBT 100.0    100.0    1.00    1.00
HS_LBS 1.0 0.02 0.30
HS_FT OFF
```







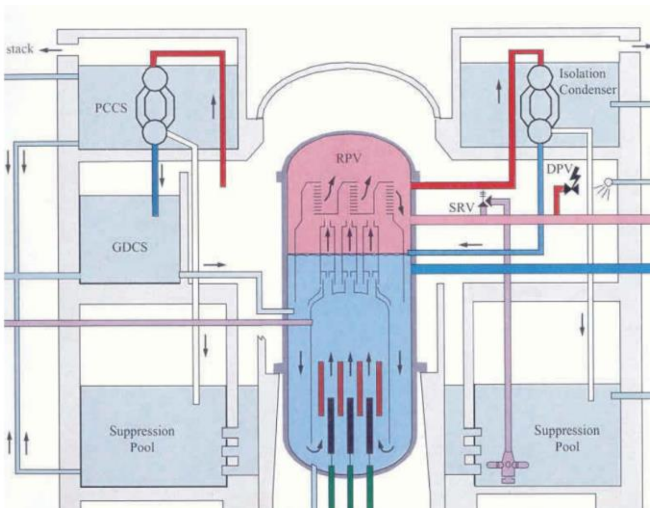




CND PCCS and ICS Models

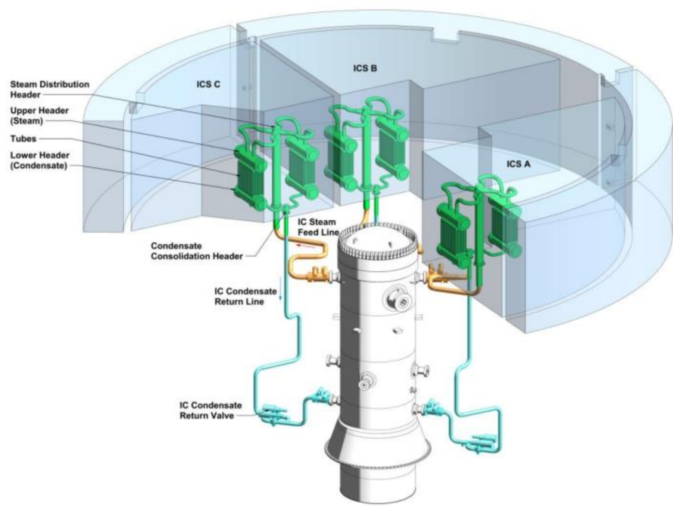
BWR-type concepts

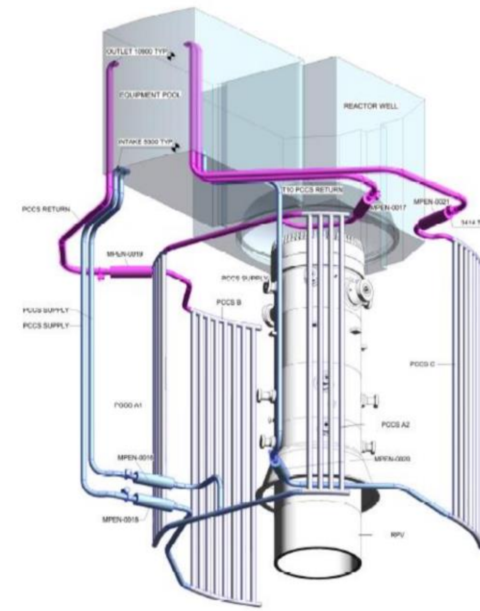
- ICS takes steam from RPV and returns condensate to primary (nat. circ + condensation driven)
- PCCS cools and depressurizes drywell
  - Heat transfer driven by natural circulation and condensation
  - PCCS of SMRs can substantially differ from gen III+ BWRs
    - BWRX-300 PCCS does heat exchange in containment and returns no condensate to RPV
    - ESBWR PCCS HX submerged in pool, sends condensate to GDCS and any vapor to suppression pool
    - MELCOR PCCS model formulated with ESBWR-style PCCS in mind



Iodine Transport Analysis in the ESBWR. SAND2009-1702

https://www.osti.gov/servlets/purl/953728





BWRX-300 General Description. GE Hitachi Nuclear Energy

https://www.gevernova.com/content/dam/gepower-new/global/en_US/images/gas-new-site/en/bwrx-300/005N9751_Rev_BWRX-300_General_Description.pdf

CND PCCS and ICS Model

ICS model an extension of the PCCS model

Capture gross effects of PCCS/ICS operation in accident conditions

"Component model" rather than a response model built of code "building blocks"

- Capacity limited by pressure considerations
- Capacity increases as pressure change across PCCS/ICS increases
- Capacity decreases as NCG partial pressure increases in DW
- PCCS/ICS can "bind" by NCG fill-up…ICS has capabilities to clear with venting operations
- PCCS outer tube to pool heat transfer coefficient at 4500 W/m^2/K
- Other physical considerations

PCCS/ICS performance – i.e. heat transfer capacity Q [J] – assumed known in Δt

- User describes how Q varies with:
    - Differential pressure – DW to WW (PCCS) or RPV to WW (ICS)
    - NCG mole fraction at T's of 323.15 K and 373.15 K
    - Decreased pressure in PCCS/ICS source volume
- User "connects" PCCS/ICS to CV's of interest, e.g. DW, WW, GDCS, RPV upper head, RPV downcomer
- User describes total unit volume and max capacity plus vent line equivalent lengths

CND PCCS and ICS Model

CND RM describes 28-step process to ascertain heat transfers and fluid flows, briefly:

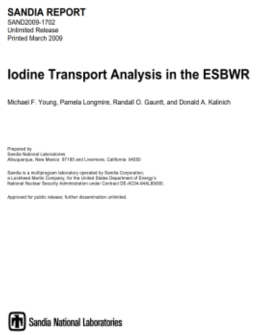
- Figure beginning-of-step conditions (steps 1-4)
  - Remaining PCCS/ICS capacity
  - Equilibrated PCCS/ICS contents with PCCS/ICS pressure equal to that of drywell
  - Taken up any DW atmosphere mix to achieve pressure equilibration
- Procedure if no vent line flow occurring (to WW for PCCS or to RPV downcomer for ICS)
  - Steps 5-9 then terminate at step 28
  - If no steam, PCCS/ICS could be “bound” and full of NCG
- Procedure If vent line flow occurring (steps 10-27)
  - Steps 10-27
  - Vent out uncondensed steam and NCGs to WW pool/atmosphere (PCCS) or RPV downcomer (ICS)
  - Drain condensed steam to GDCS (PCCS) or RPV downcomer (ICS)
  - Based on capacity and venting mass transfer requirements, draw in, cool, condense, etc.

Each PCCS/ICS system can have up to 3 units, arbitrarily many systems allowed

ICS has extra logic related to vent line valve opening/closing

Exercise care with PCCS model

- SMR PCCS can be very different from SBWR/ESBWR
- Building-block approach to PCCS/ICS modeling can be viable


SANDIA REPORT
SAND2009-1702
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Iodine Transport Analysis in the ESBWR

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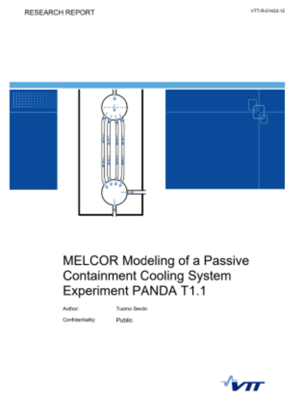
RESEARCH REPORT

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

Author: Tuomo Sevón
Confidentiality: Public

VTT

SPR Rain Drop Heat/Mass Transfer

Predicts heat and mass transfer associated with falling droplets

- Pressure suppression sprays in-containment, or
- Droplet drip from inverted surfaces after film-wise condensation on containment surfaces

HECTR 1.5 code model

- Spherical, isothermal drops that fall at terminal velocity with no horizontal velocity components
- See EMUG ‘24 materials for comprehensive review of SPR package
- For SMR containments without active spray ESFs, focus on modeling “rain” after film condensation
- Generally requires:
    - HS film tracking active
    - “IN” TP to hand-off from HS to TP (mass, temperature information)
    - “OUT” TP to hand-off from TP to SPR
    - HS_FT[L|R]BF record to specify drainage fraction of film to SPR (via TP) as rain
    - SPR input to characterize the rain as a “spray source”
        - Spray object name, host CV, and elevation
        - Temperature and flow come from TP
        - User-specified size distribution
- Rain drops can scrub aerosols/vapors in host atmosphere, no radionuclides brought from HS

SPR Rain Drop Heat/Mass Transfer

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For each droplet "type", i.e. each representative drop for a size bin:

$$\frac{dm}{dt} = -2\pi\ \rho_g D\left(1 + 0.25\,Re^{1/2}\ \ Sc^{1/3}\right)D_c\,ln(1+B)$$

$$\frac{dT}{dt} = \frac{1}{m\ c_{pl}}\left[\frac{c_{pv}(T - T_{cv})}{(1+B)^{1/Le} - 1} + h_{fg}\right]\frac{dm}{dt}$$

$$\frac{dz}{dt} = \left[\frac{4\left(\rho_d - \rho_g\right)g\ D}{3\rho_g C_d}\right]^{1/2}$$

$$B = \frac{x_b - x_i}{x_i - 1}$$

Where:

- m = Drop mass
- T, Tcv = Drop & CV atm temperatures
- z = Drop fall height
- ρ_D, ρ_g = Drop & atmosphere densities
- C_{pl} = Drop specific heat capacity
- C_{pv} = CV atmosphere specific heat capacity
- H_{fg} = Latent heat of vaporization
- D = Drop diameter
- Re = Reynolds number
- Sc = Schmidt number
- Le = Lewis number
- Dc = Diffusion coefficient
- C_d = Drag coefficient
- x_b = H_2O mass fraction in bulk atmosphere
- x_i = H_2O mass fraction at liq/atm interface

Forced convection heat transfer

Evaporation/condensation corr. for high T atm

Drag coefficient for drop/sphere:

$$C_d = \begin{cases} 27 * Re^{-0.84}, & Re < 78 \\ 0.271 * Re^{0.217}, & 78 \le Re \le 10{,}000 \\ 2\,, & 10{,}000 < Re \end{cases}$$

Formulate initial value problem and integrate rate equations, ascertain heat/mass transfer

Rain Drop Aerosol/Vapor Interactions

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Interactions (removal) modeled as 1st-order rate process calculated class-wise

$$\frac{dM_k}{dt} = -\lambda_{k,i} M_k$$

- Vapors and aerosols have different removal rate constants
- Vapor removal
  - Adsorption efficiency (stagnant film model) atop injection spray rate
  - Efficiency depends on gas and liquid boundary layer mass transfer
    - Ranz/Marshall approx. to Frossling for gas BL
    - Griffith's approx. for diffusion in rigid drop

$$\lambda_{k,i} = \frac{F_i E_{k,i} H}{V} \qquad E_{k,i} = 1 - exp\left(\frac{-6k_g t_e}{2r_i\left(H + k_g/k_l\right)}\right)$$

$$k_g = \frac{D_{k,gas}}{2r_i}\left(2 + 0.06 * Re^{1/2} Sc^{1/3}\right) \qquad k_l = \frac{\pi^2 D_{k,H2O}}{3r_i}$$

- Aerosol removal a combination of various efficiencies ε_{ijk} (see RM)
  - Interception and inertial impaction (10 to 100 μm)
  - Diffusion (< 0.1 μm)
  - Diffusiophoresis (1 to 10 μm)

$$\lambda_{k,i} = \frac{3F_i h E_{i,j}}{4Vr_i}$$

$$E_{i,j} = 1 - \prod_k \left(1 - \varepsilon_{ijk}\right)$$

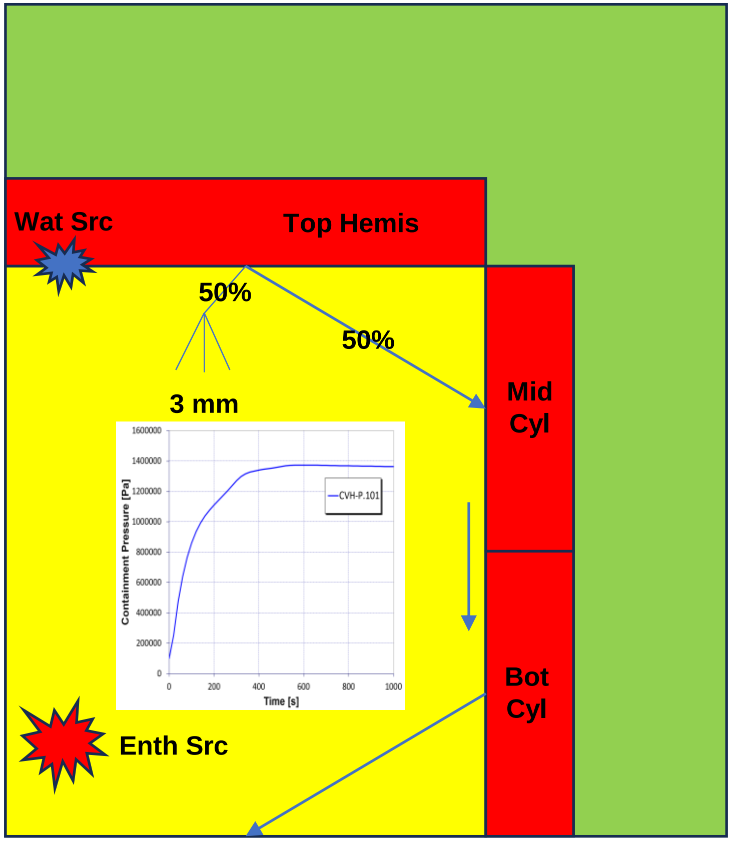
Where:

F_i	= Vol. flow rate for drops, bin i
$E_{k,i}$	= Adsorption efficiency, class k
H	= Vapor partition coeff
V	= Volume of CV
r_i	= Drop radius
t_e	= Drop exposure time
$D_{k,gas}$	= Diff, class k through gas
$D_{k,H2O}$	= Diff, class k through H_2O
Re	= Reynolds number
Sc	= Schmidt number
v_d	= Drop velocity
k_g	= Gas BL mass trans coeff
k_l	= Liq BL mass trans coeff
h	= Fall height of drops
$E_{i,j}$	= Collection efficiency, section j by drops of size i

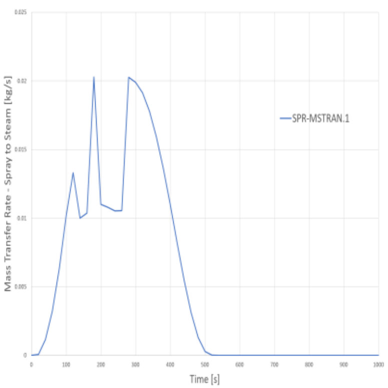
SPR Rain Example

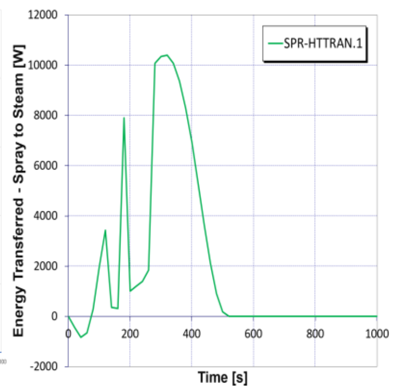
Simple example of an inverted top-hemisphere HS “raining” its film-wise condensation

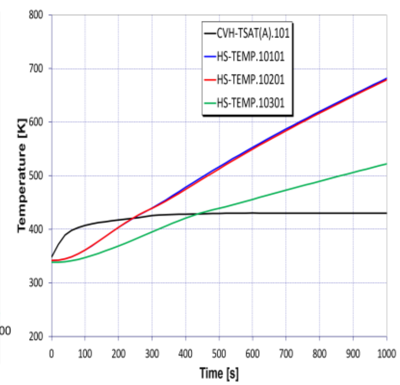
- Containment CV receives has an enthalpy source and a humid atmosphere
  - Initially saturated at atmospheric pressure
  - Atmosphere enthalpy source kicks in at ~ 10 s and held at constant rate of 10 MW
- Environment CV
- 3 HS: Top hemisphere, mid cylinder, bottom cylinder (together representing containment walls)
- Film tracking ON (top hemisphere rains/drains 50/50)



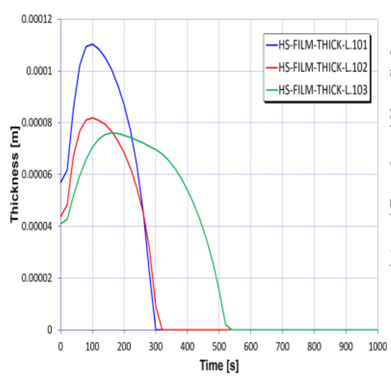
Containment response:

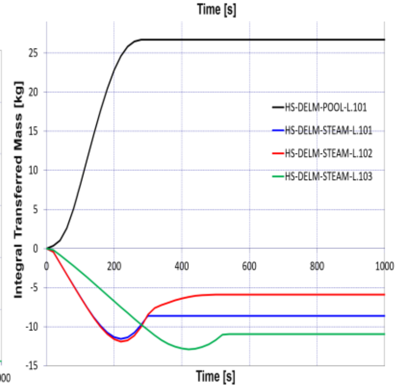






Films:





Summary

Reviewed:

- HelicalSG heat structure boundary condition and correlation
- Zukauskas heat structure boundary condition and correlation
- CND package PCCS and ICS component models
- Rain (spray) droplet heat/mass transfer and aerosol/vapor scrubbing from atmosphere

Back-Up Slides

Aerosol Collection Efficiencies

Collection efficiencies

- Viscous flow around sphere for interception & impaction :

$$\varepsilon_{In,vis} = (1+I)^2 \left[1 - \frac{3}{2(1+I)} + \frac{1}{2(1+I)^3}\right] \qquad \varepsilon_{Im,Vis} = \left[1 + \frac{0.75 \log_e(2\ Stk)}{Stk - 1.214}\right]^{-2}$$

where $I = r_p / r_d$

r_p and r_d are the radii of the particle and the drop

- Potential flow around sphere for interception and impaction :

$$\varepsilon_{In,Pot} = (1 + I)^2 - (1 + I)^1 \qquad Stk = \frac{2\, r_p^2 \rho_p (v_d - v_p)}{9 \mu r_d}$$

$$\varepsilon_{Im,Pot} = \left[\frac{Stk}{Stk + 0.5}\right]^2$$

For Stk > 0.2, else interpolation for Stk >= 0.0834, else 0

- Combining potential/viscous interception/impaction:

$$\varepsilon_x = \frac{\varepsilon_{x,Vis} + \varepsilon_{x,Pot}(Re/60)}{1 + (Re/60)}$$

For Re the droplet Reynolds number

- Diffusion:

$$\varepsilon_{diff} = 3.02\, \mathrm{Re}^{1/6} Pe^{-2/3} + 1.14\, (\mathrm{Re}/Pe)^{1/3} I + 0.57\, \mathrm{Re}^{1/3} I^2$$

where Pe is the Peclet number, $2r_d(v_d - v_p)/D$.

- Diffusiophoresis:

$$\varepsilon_{diffusio} = \frac{4}{3}\frac{r_d}{F\ \ h}\left[\frac{M_s^{1/2}}{X_s M_s^{1/2} + X_g M_g^{1/2}}\right]\frac{W_s}{cM_s}$$

where W_s is the mass condensation rate of steam onto drops, M is molecular weight, X is mole fraction, c is the molar concentration of bulk gases, and subscripts s and g refer to steam and noncondensible bulk gases, respectively.