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A Review on the Modelling Practices of iPWRs in MELCOR

13th Meeting of the European MELCOR and MACCS User Group (EMUG), 27th-29th April 2022

Semester Project

Supervisor: Mateusz Malicki, PhD

Safety Systems in iPWRs

Integrated Systems

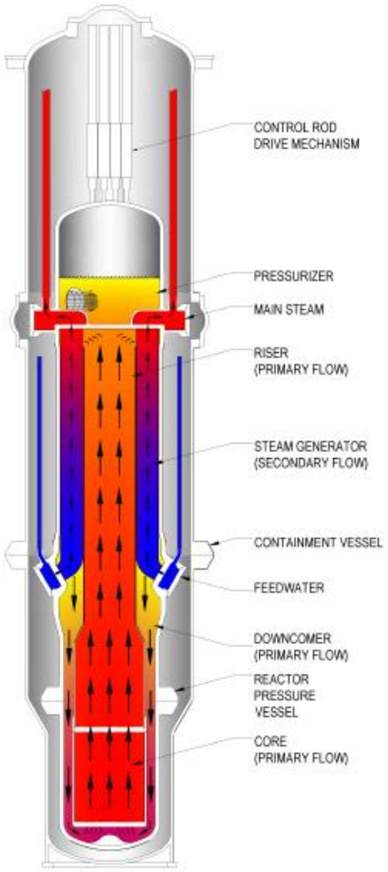
Many SMRs integrate systems into the RPV:

- Steam generator (SG)
- Pressurizer
- Conrol rod drive mechanism (CRDM)
- Natural circulation (NC)

Passive Safety Systems

Passive Safety systems include:

- NC cooling (no pumps)
- Passive DHRS/PRHRS
- CR insertion
- IVMR (depends on injection type)
- …



[2]

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Motivation – Scope of the Project

MODELING AND PHENOMENOLOGICAL ASPECTS OF SEVERE ACCIDENTS IN INTEGRAL PRESSURIZED WATER REACTORS[1]

I. K. Madni
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission
Rockville, Maryland 20852

and

M. Khatib-Rahbar
Energy Research Inc.
P.O. Box 2034
Rockville, Maryland 20847

Abstract

This paper focuses on modeling and phenomenological issues relevant to analysis of severe accidents in integral Pressurized Water Reactors (iPWRs). It identifies relevant thermal-hydraulics, melt progression and fission product release and transport phenomena, and discusses the applicability of the MELCOR computer code to modeling of severe accidents in iPWRs. Areas where the current MELCOR severe accident modeling framework has limitations in the representation of phenomenological processes are identified and examples of possible modeling remedies are discussed. The paper identifies modeling and phenomenological issues that contribute to differences in the calculated reactor coolant system and containment response for iPWRs as compared to traditional PWRs under severe accident conditions.

[8]

Natural circulation

Molten pool convection and debris cooling

SG heat transfer

Failure modes of the RPV lower head

Sparger venting

Debris cooling in containment

Heat removal from the fuel

Metal oxidation

Fission product release and transport

Motivation – Scope of the Project

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- Natural circulation
- Molten pool convection and debris cooling
- Helical coil steam generators
- Failure modes of the RPV lower head
- Sparger venting
- Debris cooling in containment
- Heat removal from the fuel
- In-vessel melt retention
- Metal oxidation
- Fission product release and transport

[8]

Sensitivity Determining Methods

Methods of interest:

- Analytical Hierarchical Process (AHP) Project Ref. [27]
- Artificial neural networks Project Ref. [27]
- Failure Mode and Effect Analysis (FMEA) Project Ref. [24]
- Flow map Project Ref. [17]
- Hazard and Operability analysis (HAZOP) Project Ref. [24]
- Least-squares method Project Ref. [27]
- Monte Carlo Project Ref. [8], [27]
- Morris method Project Ref. [8], [27]
- Pearson and Spearman coefficients Project Ref. [8], [16], [27], [31]
- Phenomena Identification and Ranking Table (PIRT) Project Ref. [24], [27]
- Reliability Methods for Passive Safety Systems (RMPS) Project Ref. [24]
- Software System for Uncertainty and Sensitivity Analysis (SUSA) Project Ref. [31]
- Variance-based methods Project Ref. [27]

In-Vessel Melt Retention – PWR vs. iPWR

PWR

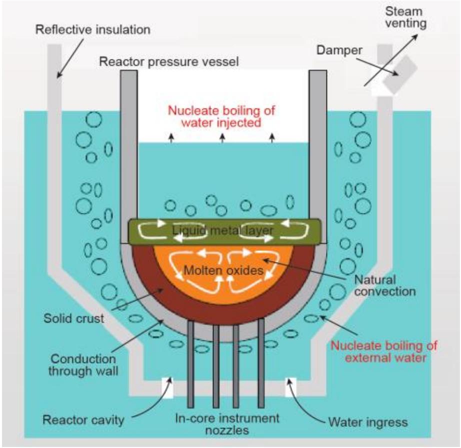
Generally:

- Active injection of coolant into or around the vessel
- Large volumes
- Difference in power-to-coolant and power-to-surface ratio

iPWR

Generally:

- Passive injection of coolant
- Small volumes
- Smaller power-to-coolant ratio



[5]

In-Vessel Melt Retention – Literature Overview

9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

MELCOR models

Particulate debris porosity, molten cladding (pool) drainage rate, molten Zircaloy melt breakthrough temperature, refreezing heat transfer coefficient for stainless steel, core plate creep properties, core barrel heat transfer, …

Non-MELCOR models

Melt properties, gap thermal resistance, radiative heat transfer for thin metallic layers, …

In-Vessel Melt Retention – Results

9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

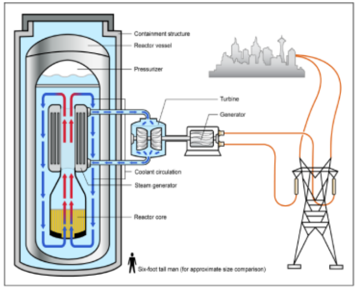
Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer

- Simple scaling factors from PWR to iPWR may not be enough

Smaller power output

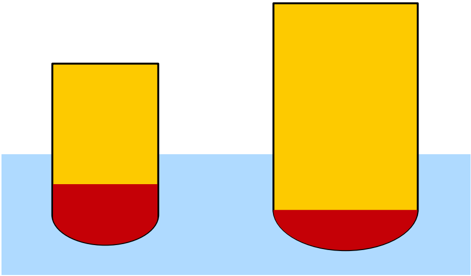


Source: GAO, based on Department of Energy documentation. | GAO-15-652

[2]

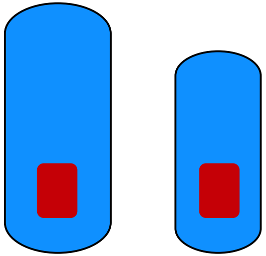
Reduced RPV surface for ex-vessel cooling

vs.



Power-to-coolant ratio

vs.



In-Vessel Melt Retention – Results

- 9 papers reviewed
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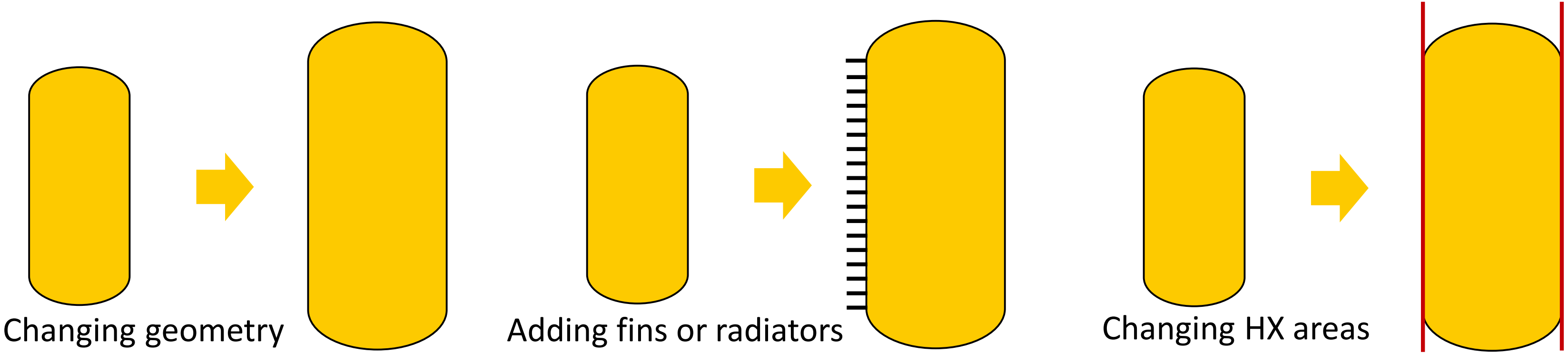
Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer



In-Vessel Melt Retention – Results

9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio | **Heat flux of corium** | **Core barrel heat transfer**

- Surface:
  - Area of HS
    - Scaling factors HS_LBT → XHTFCL, XMTFCL, XHTFCLR
    - Additional data HS_LBS → ASURFL, CLNL, BNDZL
  - Material and Thickness
    - Node data HS_ND → MATNAM, XI
- Power:
  - COR_ELPOW → IPOW
  - LHC_DH
  - CV and HS
    - External Data Files (EDF)
    - Tabular Functions (TF)
    - Control Functions (CF)

In-Vessel Melt Retention – Results

9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer

Corium composition

Mass proportions of metals and oxides

Thermal conductivity

Density

Specific heat

Influences max. heat flux

Influences heat flux angular distribution

In-Vessel Melt Retention – Results

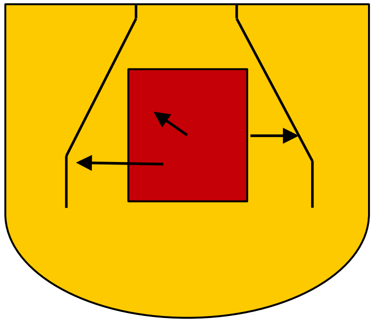
9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer

- MELCOR implementations:
  - Study on COR package components
  - Parameters:
    - HTC from debris to penetration structures
    - HTC from debris to lower head
    - HTC from oxidic molten pool to lower head
    - HTC from metallic molten pool to lower head
    - Atmosphere heat transfer scaling factor (convective, radiative)



In-Vessel Melt Retention – Results

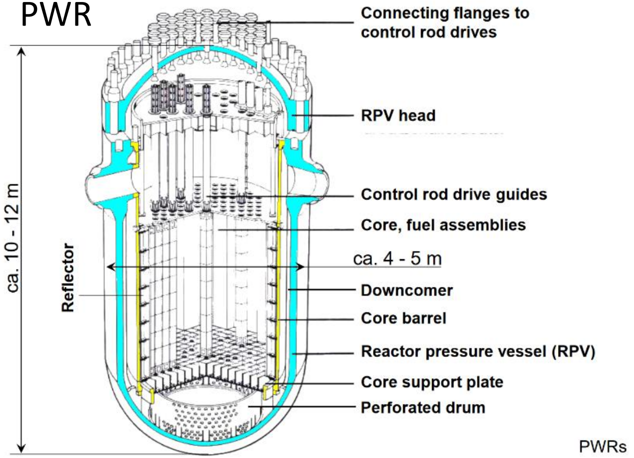
9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio

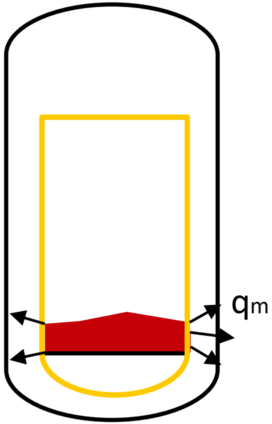
Heat flux of corium

Core barrel heat transfer

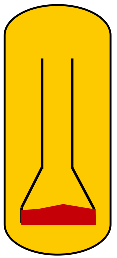
PWR



[10]



iPWR



In-Vessel Melt Retention – Results

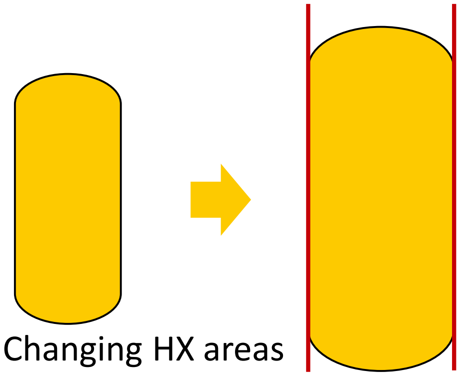
9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer

- MELCOR implementations:



Changing HX areas

- Area of HS
  - Scaling factors HS_LBT → XHTFCL, XMTFCL, XHTFCLR
  - Additional data HS_LBS → ASURFL, CLNL, BNDZL
- Material and Thickness
  - Node data HS_ND → MATNAM, XI

In-Vessel Melt Retention – Results

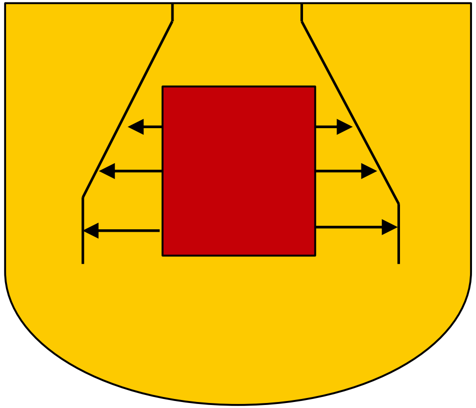
9 papers reviewed → Published 2014-2021 → 3 MELCOR specific papers → 1 MELCOR paper related to SMRs

Surface-to-power ratio

Heat flux of corium

Core barrel heat transfer

- Heat Transfer Paths:
  - Radiative Exchange Factors COR_RF → FCNCL, FSSCN, FCELR, FCELA, FLPUP
  - MELGEN Arbitrary Conduction or Radiation Heat Transfer Path COR_HTR



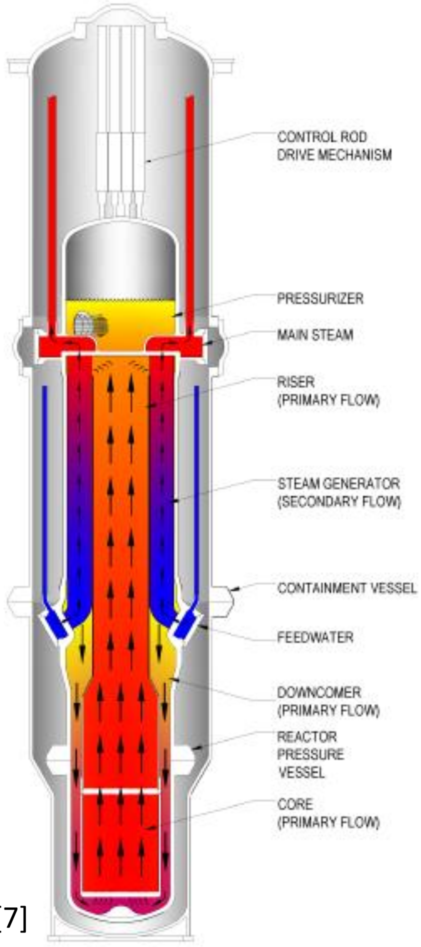
Natural Circulation – PWR vs. iPWR

PWR

Generally:
- Only 20% of power can be removed by NC alone
- PRHRS and HX pool
- Smaller coolant-to-power ratio

iPWR

Generally:
- NC for heat removal in normal operation
- Marine based SMRs
- Larger coolant-to-power ratio
- Difference in SG height (driving head)
- Reactor pool



[7]

Natural Circulation – Literature Overview

16 publications reviewed → Published 2004-2021 → 1 MELCOR specific papers → 1 MELCOR paper related to SMRs

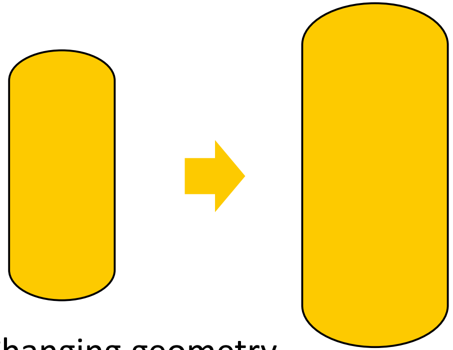
Ocean based plants	Rolling amplitude, rolling period, pressure in the primary coolant system, initial steam pressure, HTC factor in boiling, …
PRHRS	MSIV actuation time, HX area, HX height, compensation tank volume, hydraulic resistance, containment pressure, …
Flashing driven NC	Spray flow rate, pressurisation space volume, downcomer flow area, …
UHS pool modelling	Nodalisation

Natural Circulation – Results

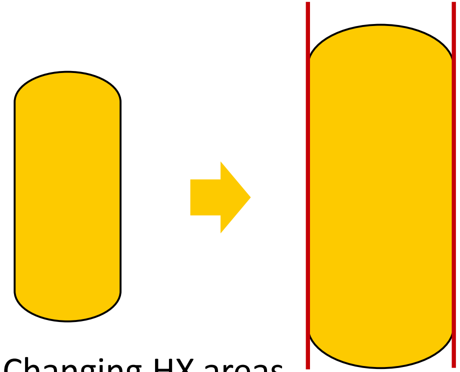
16 publications reviewed → Published 2004-2021 → 1 MELCOR specific papers → 1 MELCOR paper related to SMRs

Heat exchange area and coefficients | **Coolant mixing** | **Nodalisation**

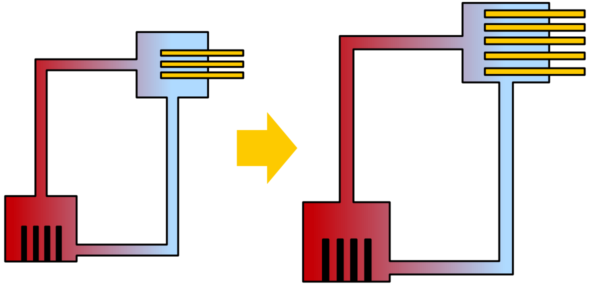
- MELCOR implementations:



Changing geometry



Changing HX areas



Changing number of pipes

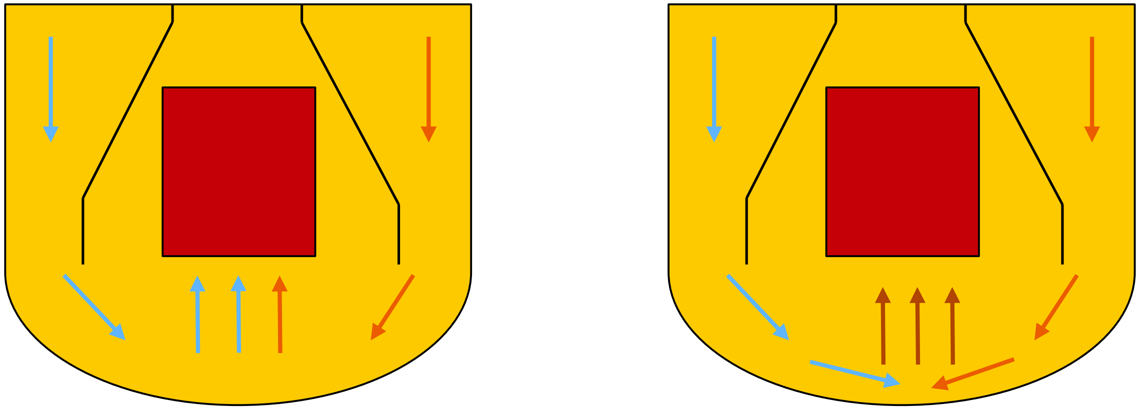
Natural Circulation – Results

16 publications reviewed → Published 2004-2021 → 1 MELCOR specific papers → 1 MELCOR paper related to SMRs

Heat exchange area and coefficients

Coolant mixing

Nodalisation



Natural Circulation – Results

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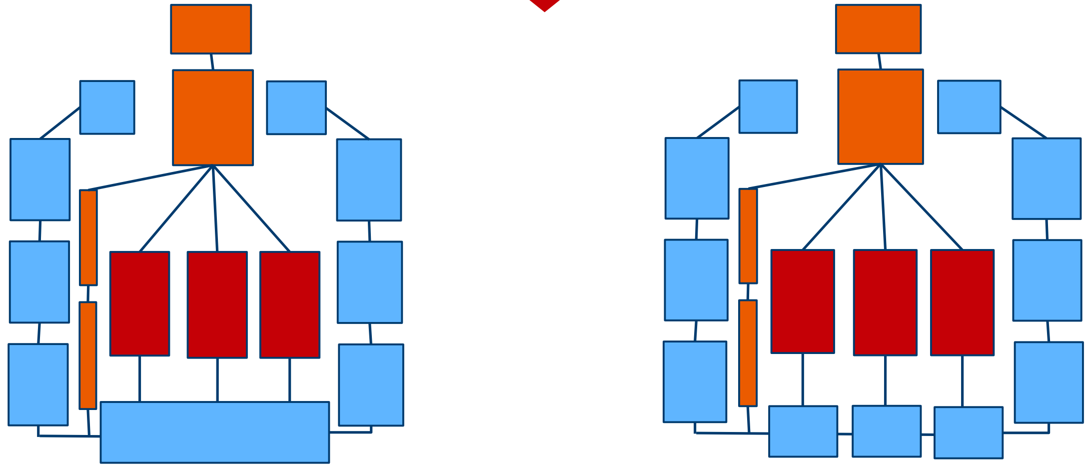
Heat exchange area and coefficients

Coolant mixing

Nodalisation



Natural Circulation – Results

16 publications reviewed → Published 2004-2021 → 1 MELCOR specific papers → 1 MELCOR paper related to SMRs

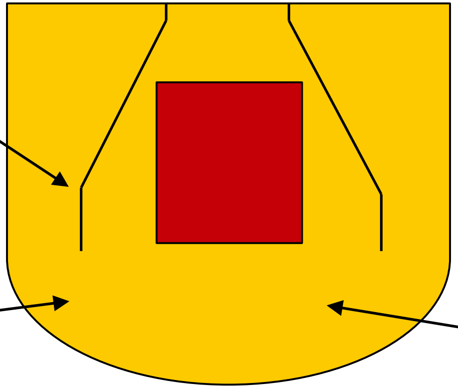
Heat exchange area and coefficients

Coolant mixing

Nodalisation

- MELCOR implementations:

Change hydraulic resistance and friction factor



Change flow coefficients

Change laminar flow in the lower head

- Laminar/turbulent flow: change Reynolds number
- For reactor ultimate heat sink pool: changed with atmosphere laminar and turbulent range
- Sensitivity coefficients → global

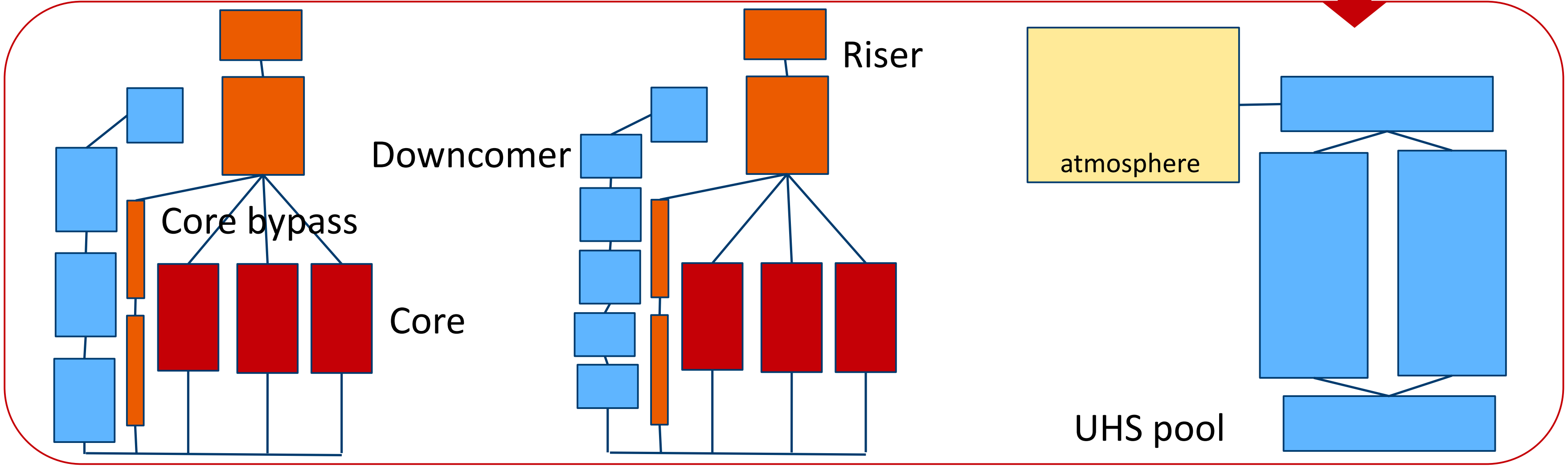
Natural Circulation – Results

16 publications reviewed → Published 2004-2021 → 1 MELCOR specific papers → 1 MELCOR paper related to SMRs

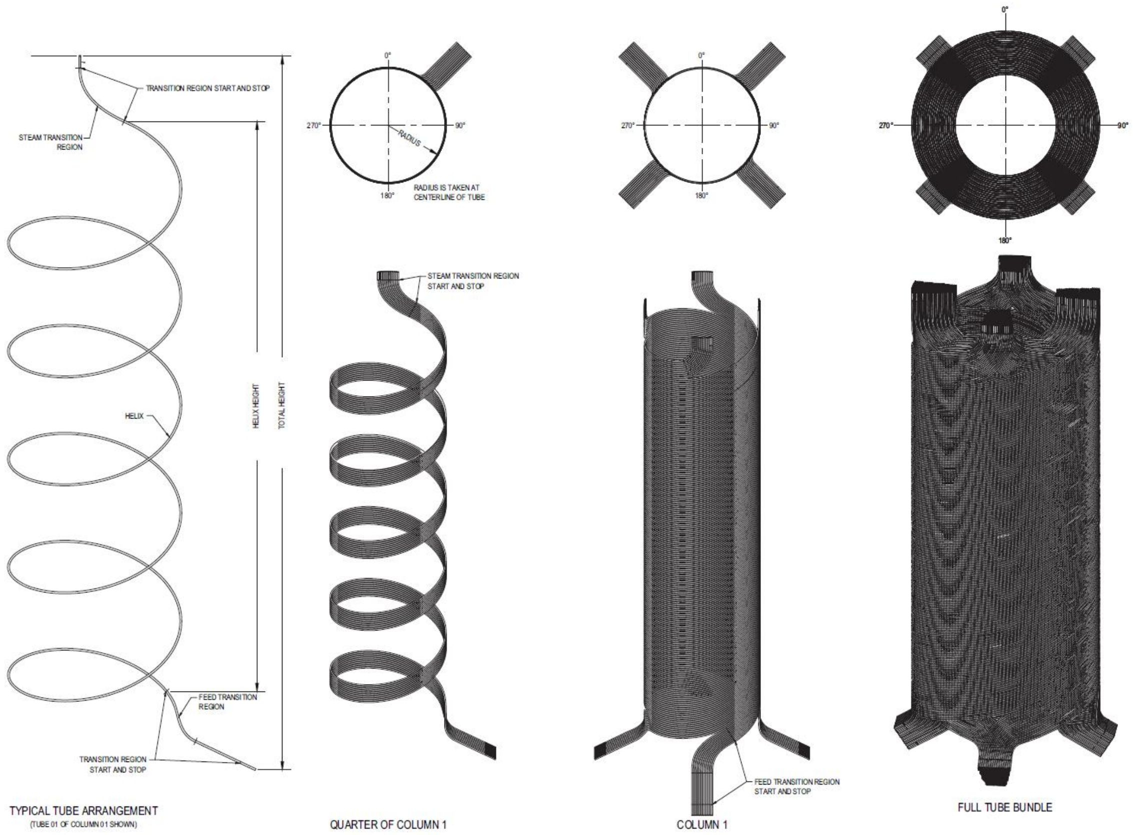
Heat exchange area and coefficients

Coolant mixing

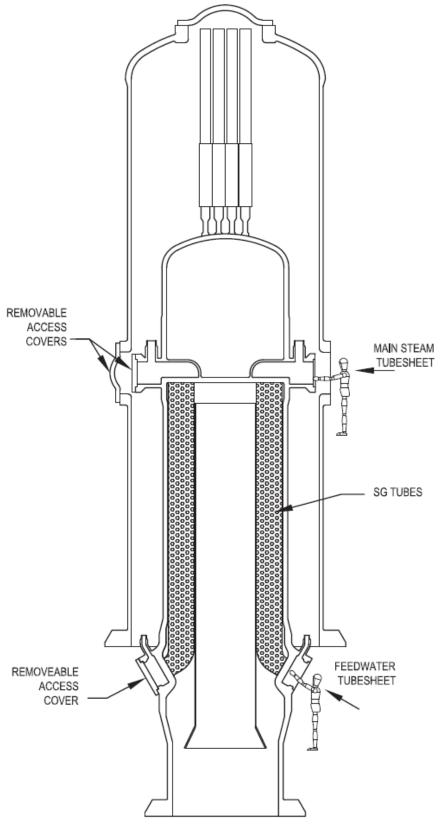
Nodalisation



Helical Coiled Steam Generators – Concept



[11]



[11]

Helical Coiled Steam Generators– Literature Overview

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors	Tube diameter, number of tubes, coil pitch, coil length, coil diameter, shell side inner and outer diameters, radial and axial pitch ratio, …
Modelling practices	“Entangling” of the HCSG, nodalisation according to the Courant-Frederick-Levy condition, sliced nodalisation, …
Mathematical models	Heat transfer coefficient, friction factor, dynamic instabilities, …
Parameter Analysis	SG break position, power level, pressuriser pressure, core inlet coolant temperature, …

Helical Coiled Steam Generators– Results

12 papers reviewed | Published 2000-2021 | 0 MELCOR specific papers | 0 MELCOR paper related to SMRs

Geometrical Factors | Nodalisation and model implementation | Channel interactions | Friction factor and heat transfer coefficient models

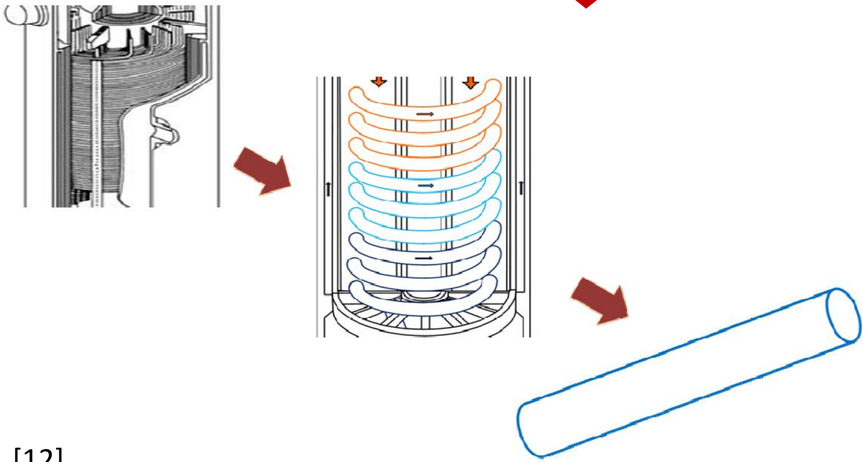
- Geometry usually design specific
- Influenced by:
  - Number of steam generators
  - Number of coils
  - Coil pitch
  - Coil diameter

- MELCOR implementation:
  - General geometrical changes
  - Multiplication factor for tubes
  - HCSG model
    - HS_LB → IBCL = 2 (Zukauskas)
    - HS_LB → IBCL = 3 (HelicalSG)
    - HS_ZUKL
  - HCSG transfer coefficients (C4186)

Helical Coiled Steam Generators– Results

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**



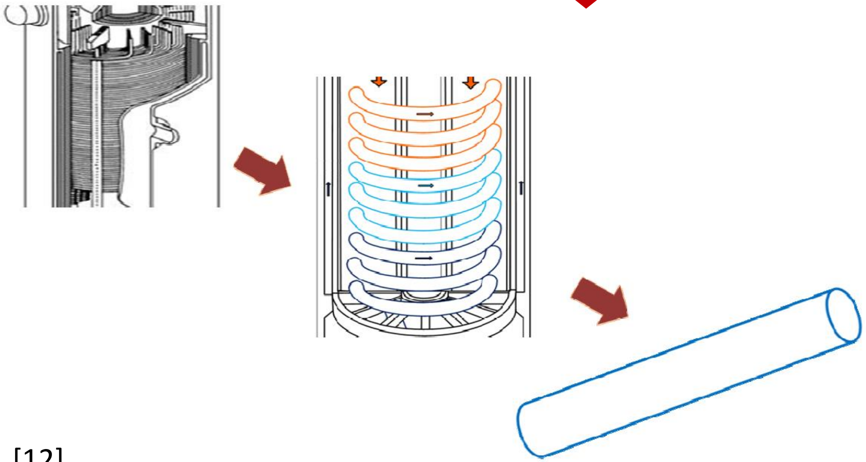
[12]

1. Original sized tube bundle modelled as one tube
   With equivalent:
   - flow area
   - heat transfer surface area
   - hydraulic diameter
   - heated hydraulic diameter

Helical Coiled Steam Generators– Results

12 papers reviewed | Published 2000-2021 | 0 MELCOR specific papers | 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**



[12]

2. Single equivalent tube bundle "unraveled" to make a single inclined tube
   With equivalent:
   - Length
   - Vertical change in height
   - Corresponding to bundle height

Helical Coiled Steam Generators– Results

12 papers reviewed

Published 2000-2021

0 MELCOR specific papers

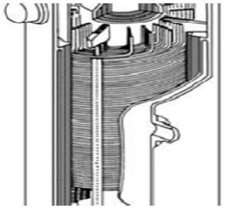
0 MELCOR paper related to SMRs

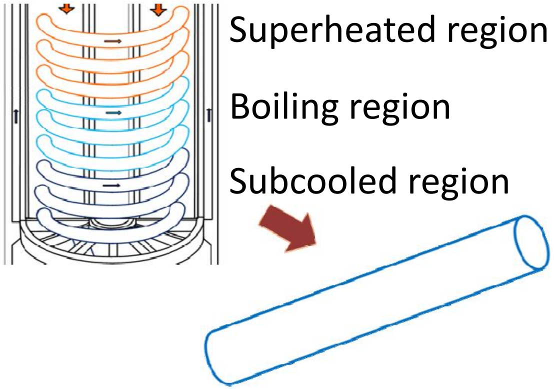
Geometrical Factors

Nodalisation and model implementation

Channel interactions

Friction factor and heat transfer coefficient models





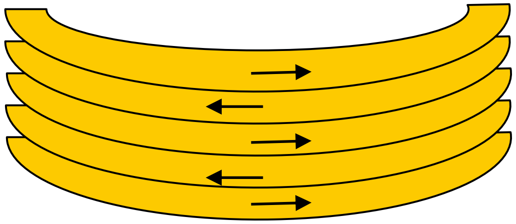
3. Unraveled tube divided into 3 parts
   - subcooled region
   - boiling region
   - superheated

[12]

Helical Coiled Steam Generators– Results

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**



- Oscillations between tubes
- Especially for large differences in temperatures, pressures etc.

- MELCOR implementations:
  - May not be resolvable (yet!)
  - Possible in designs with external SG

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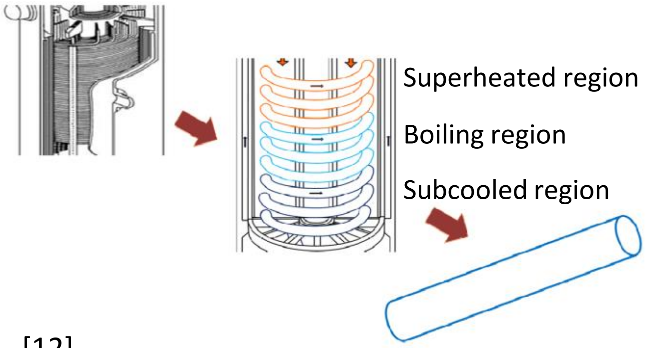
Helical Coiled Steam Generators– Results

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**

- Correct modelling is important for licensing



[12]

Table 19: Correlations used by and taken from Yoon et al. for their ONCESG computer code.

Project Ref. [41]

Thermal hydraulic region/quantity	Thermal hydraulic phenomenon	Recommended Correlations: Tube Side	Recommended Correlations: Shell Side
Superheater	Convective heat transfer to vapour	SKBK, Mori-Nakayama, Modified Bishop	SKBK, Zukauskas
Evaporator	Mist evaporation	Linear interpolation	SKBK, Zukauskas
	x_{dryout}	Biasi	
	Forced convective heat transfer through liquid film saturated nucleate boiling	SKBK, Kozeki, Chen	
Economiser	Fully developed subcooled nucleate boiling	Thom	SKBK, Zukauskas
	x_{NVG}	Saha and Zuber	
	Convective heat transfer to water	SKBK, Mori-Nakayama, Seban-McLaughlin	
Friction factor	-	SKBK, Mori-Nakayama	SKBK, Zukauskas

Helical Coiled Steam Generators– Results

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**

- MELCOR implementations:
  → Until recently no inclusion of counter current flow
  - Zukauskas model for the shell side
  - Helical coil SG heat transfer model for the tube side

Helical Coiled Steam Generators– Results

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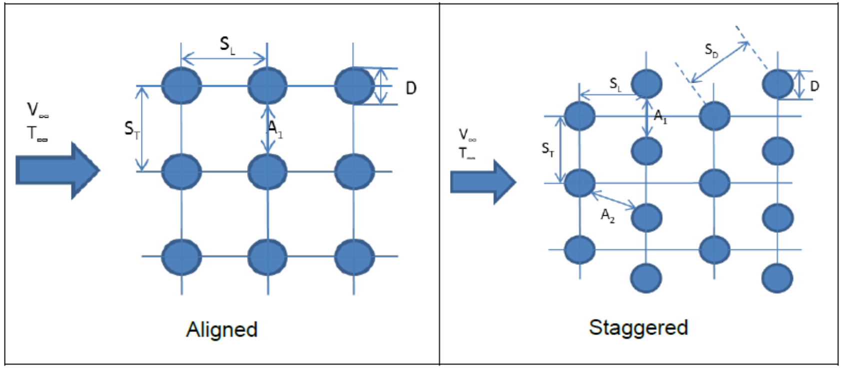
Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**



[13]

- Zukauskas model HS_ZUKL/R:
  - Diameter (DIAM)
  - Transverse (ST) and longitudinal (SL) pitch for tube bundle
  - Aligned or staggered
  - Correction factor (CORRECTION)
    - Multiplier (MULTIPLIER)
    - Number of rows (ROWS)

Helical Coiled Steam Generators– Results

12 papers reviewed → Published 2000-2021 → 0 MELCOR specific papers → 0 MELCOR paper related to SMRs

Geometrical Factors | **Nodalisation and model implementation** | **Channel interactions** | **Friction factor and heat transfer coefficient models**

- Tube side helical coil SG model:
  - Subcooled water flow HTC
  - Two-phase flow HTC
    - Annular flow with nucleate boiling
    - Evaporating film condition

→ Final two-phase HTC with the help of two functions (F and S)

Conclusion and Outlook

Conclusion

- Goal: Review sensitive parameters in MELCOR for modelling improvements
- Not many sensitivity or parameter studies performed with MELCOR
- However, many studies conducted with RELAP, ATHLET, MARS, etc.
  → confirms interest and necessity
- Due to lack of papers: Potential of model developments considerable
- Common parameters to be investigated:
  - Heat transfer
  - Nodalisation

Outlook

- Follow up investigation of these parameters while modelling an experimental facility

Image References

[1] United States Government Accountability Office, Technology Assessment Nuclear Reactors Status and challenges in development and deployment of new commercial concepts, GAO-15-652, July 2015.
[2] NuScale Power LLC, NuScale Standard Plant Design Certification Application, Chapter One, Introduction and General Description of the Plant, Part 2, Tier 2, Revision 5, July 2020.
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Wir schaffen Wissen – heute für morgen

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