Assessment of the CTF post-CHF models using FEBA experimental data

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CONTENTS

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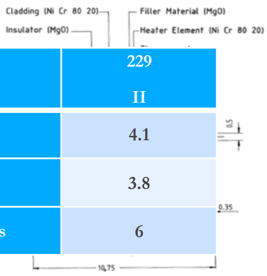
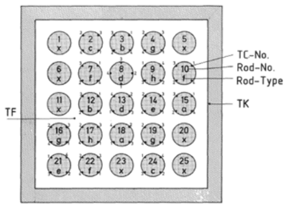
1. Experimental test section KIT-FEBA

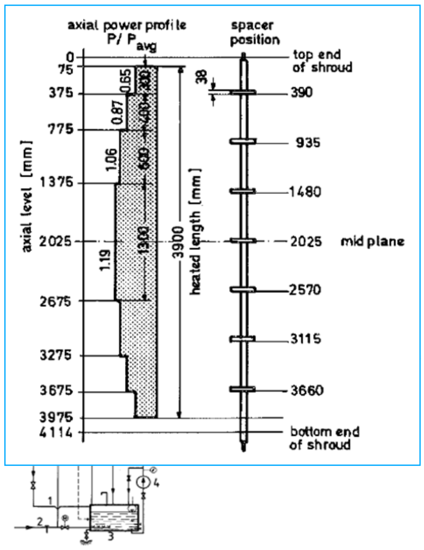
Description

- Settle up to investigate the thermal mechanism during a flooding process after a loss of coolant accident where the full length of the bundle is uncovered.
- Full length bundle (4m), 5X5 PWR pin dimensions electrically heated.
- Axial power profile & flat radial power profile.
- 7/6 spacer grids
- 8 test series with (4-9 experiments each one)
  - Different combinations of : Pressure / power / flooding mass flow rate
- Test series II experiment 229



CASE	229
SERIES	II
P [bar]	4.1
V [cm/s]	3.8
Spacer Grids	6



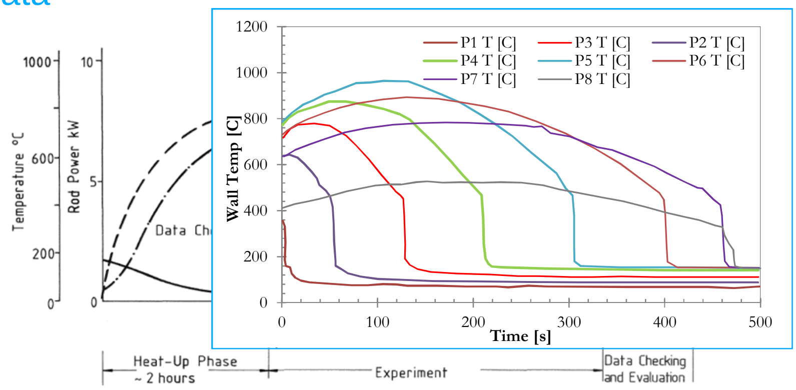


P. Ihle and K. Rust, "FEBA – Flooding Experiments with Blocked Arrays, Evaluation Report", KFK Report 3657, 1984.

1. Experimental test section KIT-FEBA

Description / Experimental data

- Initially the domain is filled with vapor.
- Preheating process develops an axial temp profile (not simulated). Vapor at 800°C, (saturation temperature is 145°C).
- Transient starts with the subcooled water injection (50-40°C)
- Power step at t=0s (200kW max)
- Pin temperature evolution is monitored at different locations and axial levels.
  - Tracking the quenching front is possible.



2. CTF modeling & simulations - Governing equations

Energy conservation equations (liquid/ vapour)

$$\underbrace{\frac{\partial}{\partial t}(\alpha_l\rho_l h_l)}_{1} + \underbrace{\frac{\partial}{\partial x}(\alpha_l\rho_l h_l u_l)}_{2} + \underbrace{\frac{\partial}{\partial x}(\alpha_e\rho_l h_l u_e)}_{3} + \underbrace{\sum_{k=1}^{nk}(\alpha_l\rho_l h_l w_l)_k}_{2} + \underbrace{\sum_{k=1}^{nk}(\alpha_e\rho_l h_l w_e)_k}_{3} = \underbrace{-\sum_{k=1}^{nk} q_l^{T'''}}_{4} \underbrace{- \Gamma''' h}_{5} + \underbrace{q'''_{wl}}_{6} + \underbrace{(\alpha_l+\alpha_e)\frac{\partial P}{\partial t}}_{7}$$

$$\frac{\partial}{\partial t}(\alpha_v\rho_v h_v) + \frac{\partial}{\partial x}(\alpha_v\rho_v h_v u_v) + \sum_{k=1}^{nk}(\alpha_v\rho_v h_v w_v)_k = -\sum_{k=1}^{nk} q_v^{T'''} + \Gamma''' h + \underbrace{q'''_{wv}}_{6} + \alpha_v\frac{\partial P}{\partial t}$$

1.Change of energy with time

2.Advection of energy for liquid field :

$\nabla \cdot \left(\alpha_k\rho_k h_k \vec{V}_k\right)$ (the lateral transfer terms are summed all over the gaps cell)

3.Advection of energy for droplet field, (the lateral transfer terms are summed all over the gaps cell)

4.Energy transfer due to Turbulent exchange

5.Evaporization/condensation contribution

<u>6.Wall heat flux transmission</u>

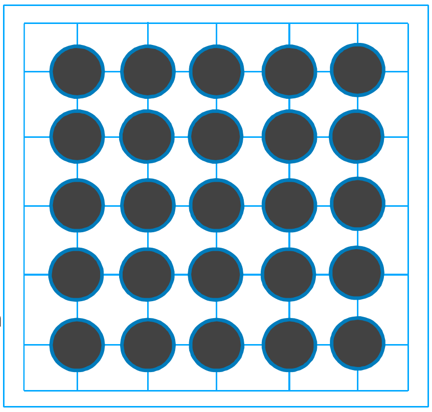
7.Pressure variation with time

2. CTF modeling & simulations

Nodalization and settings

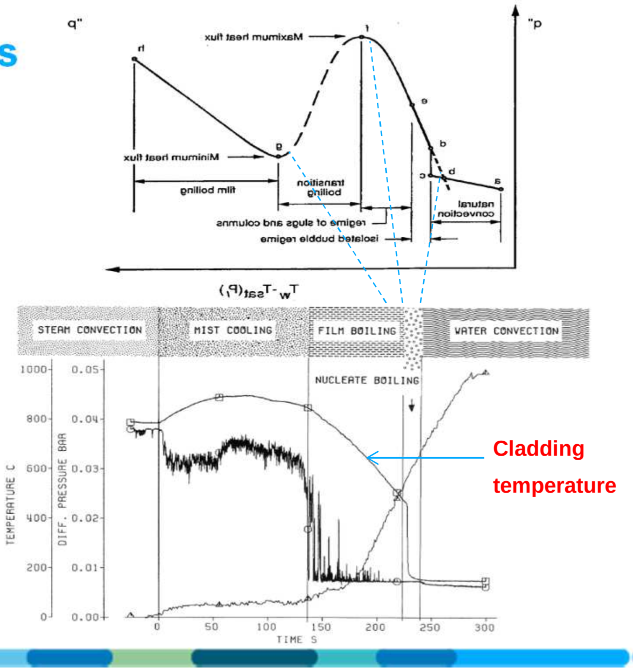
- Radial discretization:
  - 36 subchannels
- Axial
  - 46 axial levels
- Pin radial distribution
  - 6 nodes for the insulator
  - 4 nodes for the cladding
- Material properties
  - MgO (insulator)
  - Inconel
- Unheated wall included

- BC inlet
  - Enthalpy
  - mass flow rate
- BC outlet
  - Pressure condition
- Cross section of the nodalization increased at the outlet due to recirculation issues
- IAPWS IF97 option was not stable, option 0 in the code was used: “mix of different sources”
- No entrained phase (droplets)



2. CTF modeling & simulations
Wall heat transfer regimes

- Boiling curve (Nukiyama / Dre & Mueller)
  - Implemented in CTF following Bjornard & Griffith model (BEEST)
  - Important points to define the curve:
    - Critical Heat Flux point (q''_{CHF},T_{CHF})
      - Biasi: based on low/high quality flow correlations.
      - Tong: (W3) widely use for DNB in PWR
    - MSFB min.stable film boiling point (q''_{MSFB},T_{MSFB})
      - TMSFB (Leidenfrost/Berenson)->q''_{FB}
      - $q''_{FB}(T_{MSFB}) = q''_{MSFB}$



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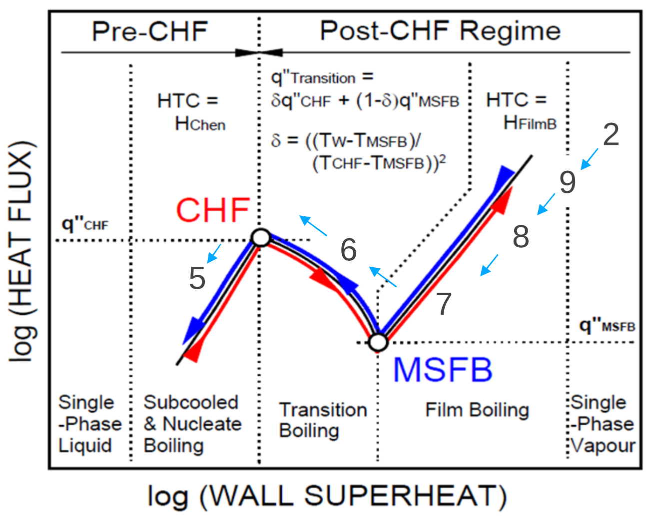
2. CTF FEBA modeling
Wall heat flux terms

- Boiling curve (Nukiyama / Dre & Mueller)
  - Bjornard & Griffith (BEEST)
    - Single phase vapor (Tag 2)
    - Dispersed flow film boiling (Tag 9)
    - Interpolation (Tag 8)
    - Inverted annular film boiling (Tag7)
    - Transition boiling (Tag 6)
    - Tag <=5 **Pre CHF**



Credit: Zoran V.Stosic (AREVA Erlangen)

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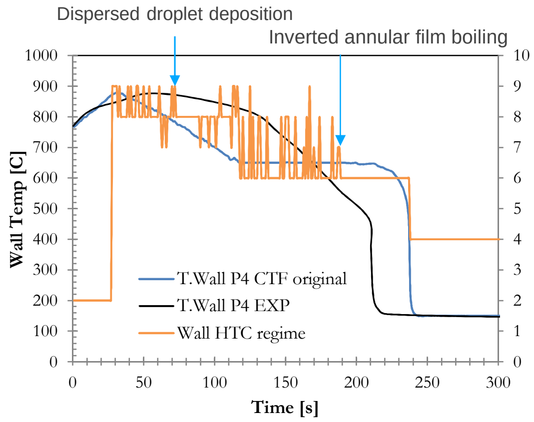
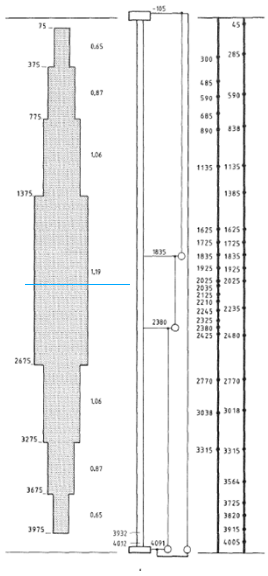
2. CTF FEBA modeling
Wall heat flux terms



- CTF FEBA P4 temperature evolution:
  - Abnormal wall temperature evolution.
  - Wall temperature saturates at the MSFB temperature
  - The HTC regime points out the **boiling transition** region as a possible issue.



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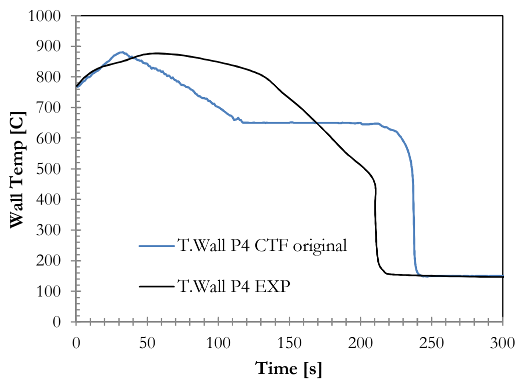
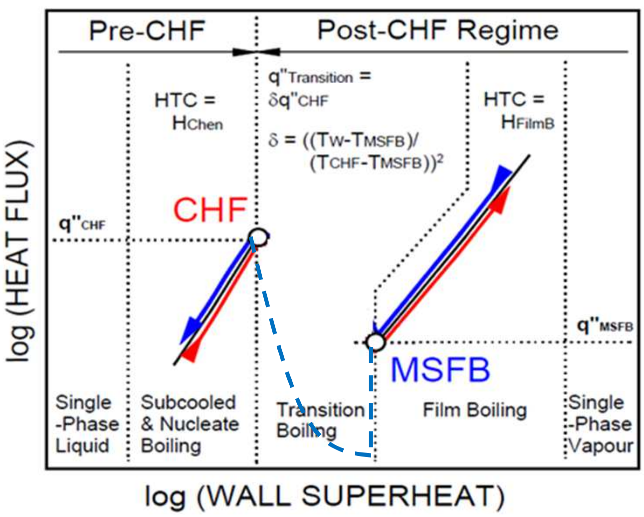
2. CTF FEBA modeling
Wall heat flux terms





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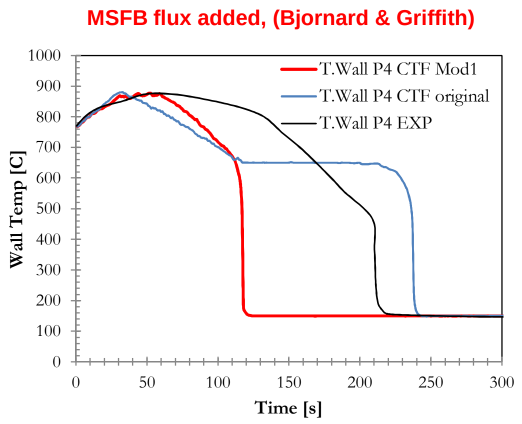
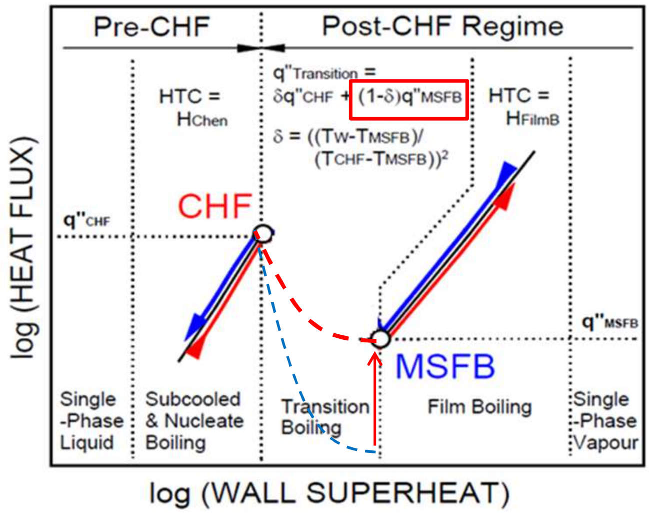
2. CTF FEBA modeling
Wall heat flux terms





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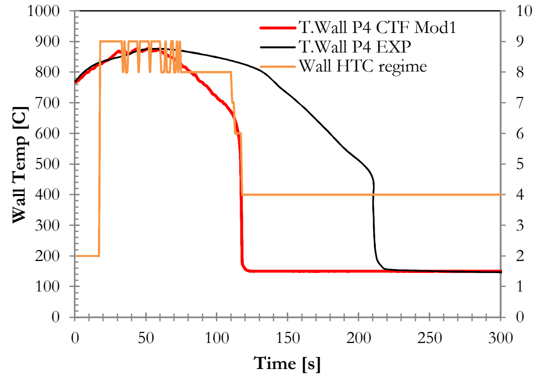
2. CTF FEBA modeling
Wall heat flux terms



- Possible actions:
  - T-msfb formulation:
    - (CTF) Leidenfrost = f(Berenson)
  - CHF approach:
    - Biasi (CHF)
    - The CTF W3 by Tong was not used! (Out of range due to Pressure) bellow 800 psia (60psia=4.1bars)
  - HTC inverted annular film boiling
  - Chen/Thom correlations
    - Used for subcooled nucleate boiling.
  - Interfacial terms
    - Reduce HTC and IA droplets / reducing heat and mass transfer term (droplet field shows more stability)
    - SAT or Subcooling HTC for vapor and liquid
    - …

Difficult to assess what the most important parameter,

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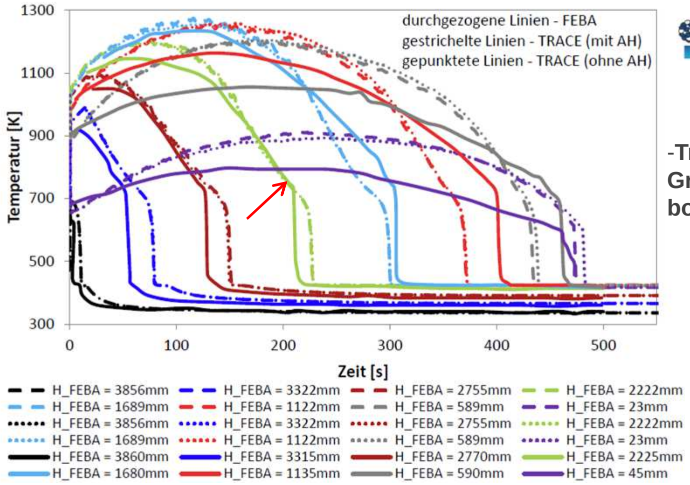
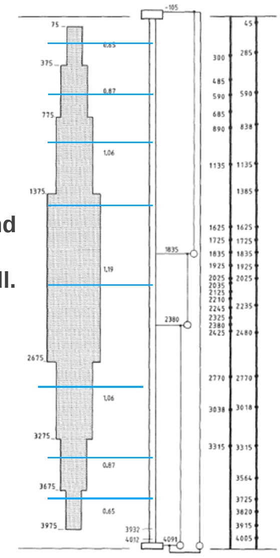
2. CTF FEBA modeling

KIT/INR TRACE results



-Trace uses Bjornard and Griffith to define the boiling transition as well.



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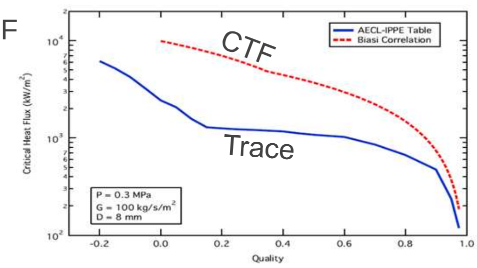
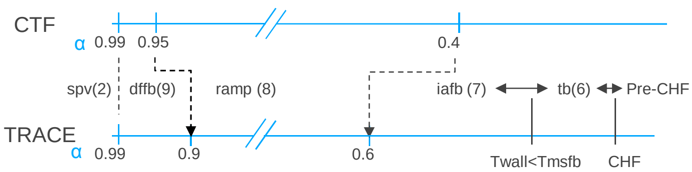
3. CTF FEBA modeling

TRACE Solution approach

CHF



- Modifications based on TRACE models:
  - Tmsfb formulation:
    - CTF uses: Leidenfrost = f(Berenson)
    - (CTF) Leidenfrost **> (TRACE) Stewart & Groeneveld**
  - CHF approach:
    - Biasi (CHF) **> IACL_IPPE tables by Groeneveld (TRACE)**
    - The CTF W3 by Tong was not used! (numerical issues)
  - HTC inverted annular film boiling **reduction**
  - **Void fraction criteria**



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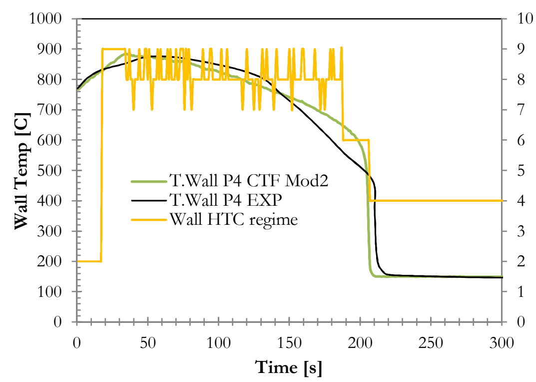
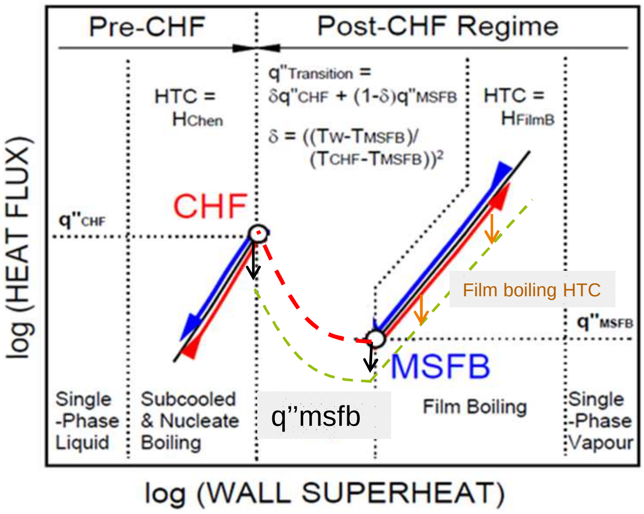
3. CTF FEBA modeling

Solution approach

- Code modification according to TRACE



The inverted annular film boiling regime is dominant, it conditions the ramp to dispersed flow film boiling.



Credit: Zoran V.Stosic (AREVA Erlangen)

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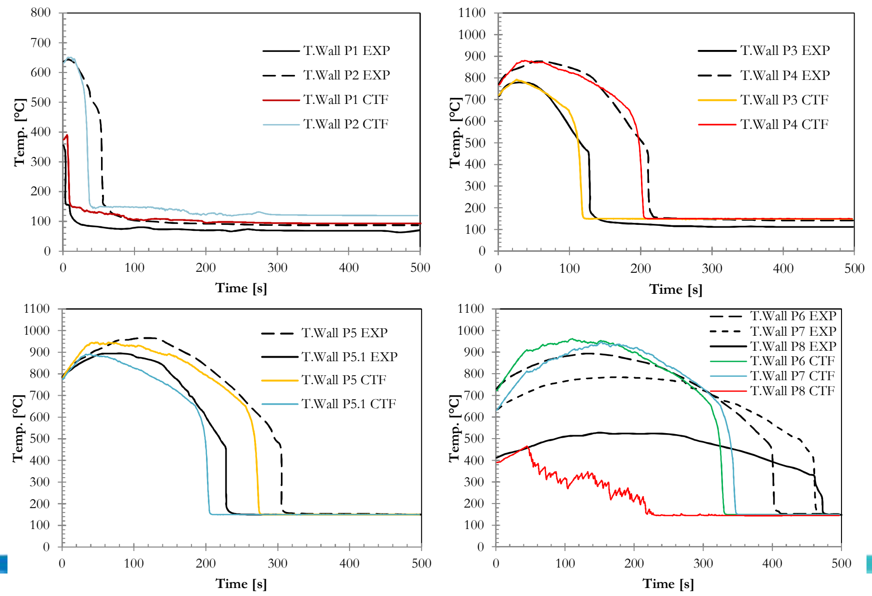
2. CTF FEBA modeling / Results



Modifications on the post-CHF models are not enough to solve properly the problem.

Abnormal switch between single phase vapor HTC and transition boiling HTC at P8.

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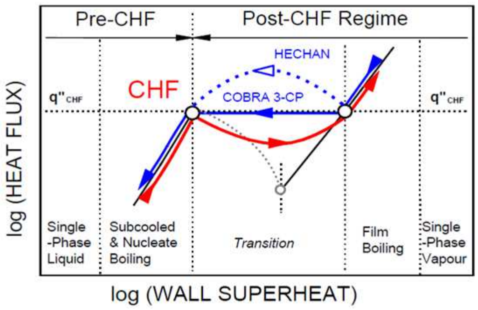
3. Summary & Outlook

- KIT/FEBA was used to investigate CTF models in flooding conditions.
- Despite changes applied, current configuration cannot fully describe properly the problem.
- Possible working areas:
  - Keep checking 1-D code TRACE physics ??
    - Not only post-CHF but pre-CHF, **heat and mass interfacial terms**
  - Try to run CTF important features: The 3rd field
  - Use the AECL-IPPE CHF (Groeneveld)
  - Use Dakota for sensitivity studies
- Areva Erlangen Germany boiling curve in Cobra →
  - "advanced boiling curve". Experimental data: JAERI BWR/ABWR 4x4 rods



Credit: Zoran V.Stosic

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Acknowledges

- **KIT/INR**:
  - J.Jimenez / V.Sanchez / W.Jeager
- **Areva Erlangen Germany**:
  - M.Schlencker

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Literature

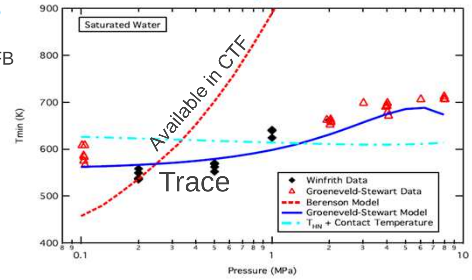
- Ihle and K. Rust, "FEBA – Flooding Experiments with Blocked Arrays, Evaluation Report“, KFK Report 3657, 1984.
- D. C. Groeneveld, et al., "The 1995 Look-Up Table for Critical heat Flux in Tubes," *Nucl.Eng. Des.*, 163, 1-23, 1996
- Bjornard, A. T., Griffith, P., PWR Blowdown Heat Transfer. ASME Symp. on Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol. 1, pp. 17-41, New York, USA, Nov. 1977.
- On the Frontier of Boiling Curve and beyond Design of its Origin. Zoran V. Stosic
- J. C. Stewart and D. C. Groeneveld, "Low-Quality and Subcooled Film Boiling of Water at Elevated Pressures," *Nucl. Eng. Des.*, 67, 259-272, 1981.

Routines

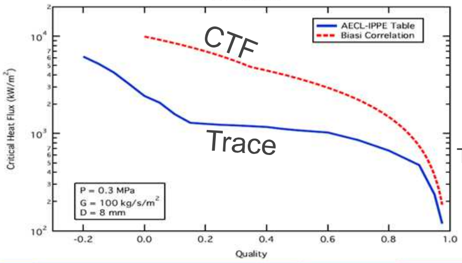
- Boling curve modification
  - Surface_type.f90 Boiling_curve
  - Mod_heat.f90 T_MSFB
  - Heat_functions.f90 T_CHF
- Interfacial area / HTC
  - Intr.f90
- Printing
  - results.f90
  - Results_channels.f90

3. CTF FEBA modeling
TRACE Solution approach

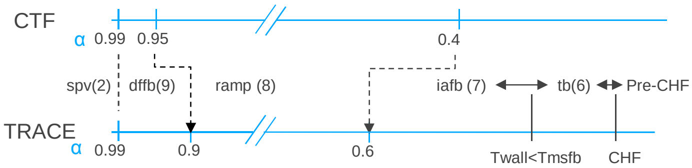
TMSFB



CHF



- Possible actions: **Attending to the KIT results:**
  - Tmsfb formulation:
    - CTF uses: Leidenfrost = f(Berenson)
    - (CTF) Leidenfrost **> (TRACE) Stewart & Groeneveld**
  - CHF approach:
    - Biasi (CHF) **> IACL_IPPE tables by Groeneveld (TRACE)**
    - The CTF W3 by Tong was not used! (numerical issues)
  - HTC film boiling **(noticeably higher in CTF)**
  - **Void fraction criteria**



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2. CTF modeling & simulations - Governing equations
Mass conservation equations (liquid / vapour)

1 2 3 4

$$\frac{\partial}{\partial t}(\alpha_l\rho_l) + \frac{\partial}{\partial x}(\alpha_l\rho_l u_l) + \sum_{k=1}^{nk}(\alpha_l\rho_l w_l)_k = -\Gamma'''(1-\eta) - S''' + \sum_{k=1}^{nk}\left(M_l^{T'''}\right)_k$$

$$\frac{\partial}{\partial t}(\alpha_v\rho_v) + \frac{\partial}{\partial x}(\alpha_v\rho_v u_v) + \sum_{k=1}^{nk}(\alpha_v\rho_v w_v)_k = \Gamma''' + \sum_{k=1}^{nk}\left(M_v^{T'''}\right)_k$$

$$\frac{\partial}{\partial t}(\alpha_e\rho_l) + \frac{\partial}{\partial x}(\alpha_e\rho_l u_e) + \sum_{k=1}^{nk}(\alpha_e\rho_l w_e)_k = -\Gamma'''\eta + S''' + \sum_{k=1}^{nk}\left(M_e^{T'''}\right)_k$$

1.Change of mass with time

2.Advection of mass $\nabla \cdot \left(\alpha_k\rho_k\vec{V}_k\right)$ (the lateral transfer terms are summed all over the gaps cell) $\sum_{k=1}^{nk}$

3.Mass change due to evaporation/condensation or entrainment.

4. Mass transfer due to turbulent mixing and void drift, (summed all over the gaps of the cell)

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2. CTF modeling & simulations - Governing equations

Axial momentum equations (liquid/ vapour)

$$\underbrace{\frac{\partial}{\partial t}(\alpha_l\rho_l u_l)}_{1}+\underbrace{\frac{\partial}{\partial x}(\alpha_l\rho_l u_l u_l)}_{2}+\underbrace{\sum_{k=1}^{nk}(\alpha_l\rho_l u_l w_l)_k}_{3}$$
$$=\underbrace{-\alpha_l\frac{\partial P}{\partial x}}_{4}-\underbrace{\alpha_l\rho_l g}_{5}-\underbrace{\tau'''_{\mathrm{wx,l}}+\tau'''_{\mathrm{ix,vl}}}_{6}-\underbrace{\Gamma'''(1-\eta)u-S'''u}_{7}+\underbrace{\sum_{k=1}^{nk}\left(M_l^{T'''}\right)_k}_{8}$$

$$\frac{\partial}{\partial t}(\alpha_v\rho_v u_v)+\frac{\partial}{\partial x}(\alpha_v\rho_v u_v u_v)+\sum_{k=1}^{nk}(\alpha_v\rho_v u_v w_v)_k$$
$$=-\alpha_v\frac{\partial P}{\partial x}-\alpha_v\rho_v g-\tau'''_{\mathrm{wx,v}}-\tau'''_{\mathrm{ix,vl}}-\tau'''_{\mathrm{ix,ve}}+\Gamma'''u+\sum_{k=1}^{nk}\left(M_v^{T'''}\right)_k$$

$$\frac{\partial}{\partial t}(\alpha_e\rho_l u_e)+\frac{\partial}{\partial x}(\alpha_e\rho_l u_e u_e)+\sum_{k=1}^{nk}(\alpha_e\rho_l u_e w_e)_k$$
$$=-\alpha_e\frac{\partial P}{\partial x}-\alpha_e\rho_l g-\tau'''_{\mathrm{wx,e}}+\tau'''_{\mathrm{ix,ve}}-\Gamma'''\eta u+S'''u+\sum_{k=1}^{nk}\left(M_e^{T'''}\right)_k$$

1.Change of momentum with time

2.Advection of momentum: $\nabla\cdot\left(\alpha_k\rho_k u_k\vec{V}_k\right)$

3.Advection term due to transverse momentum (all gaps k)

4.Pressure force

5.Gravitaty force

6.Shear stresses. (shear between liquid-droplets not modeled)

7.Phase change component + entrainment

8.Turbulent mixing of axial momentum, with turbulent mixing only in the lateral direction. (simplification of the turbulent diffusion model)

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2. CTF modeling & simulations - Governing equations

Lateral momentum equations (liquid/ vapour)

$$\underbrace{\frac{\partial}{\partial t}(\alpha_l\rho_l w_l)}_{1}+\underbrace{\frac{\partial}{\partial z}(\alpha_l\rho_l w_l w_l)+\frac{\partial}{\partial x}(\alpha_l\rho_l w_l u_l)}_{2}$$
$$=\underbrace{-\alpha_l\frac{\partial P}{\partial z}}_{3}-\underbrace{\tau'''_{\mathrm{wx,l}}+\tau'''_{\mathrm{ix,vl}}}_{4}-\underbrace{\Gamma'''(1-\eta)w-S'''w}_{5}$$

$$\frac{\partial}{\partial t}(\alpha_v\rho_v w_v)+\frac{\partial}{\partial z}(\alpha_v\rho_v w_v w_v)+\frac{\partial}{\partial x}(\alpha_v\rho_v w_v u_v)$$
$$=-\alpha_v\frac{\partial P}{\partial z}-\tau'''_{\mathrm{wx,v}}-\tau'''_{\mathrm{ix,vl}}-\tau'''_{\mathrm{ix,ve}}+\Gamma'''w$$

$$\frac{\partial}{\partial t}(\alpha_e\rho_l w_e)+\frac{\partial}{\partial z}(\alpha_e\rho_l w_e w_e)+\frac{\partial}{\partial x}(\alpha_e\rho_l w_e u_e)$$
$$=-\alpha_e\frac{\partial P}{\partial z}-\tau'''_{\mathrm{wx,l}}+\tau'''_{\mathrm{ix,ve}}-\Gamma'''\eta w+S'''w$$

1.Change of momentum with time

2.Advection of momentum: $\nabla\cdot\left(\alpha_k\rho_k u_k\vec{V}_k\right)$

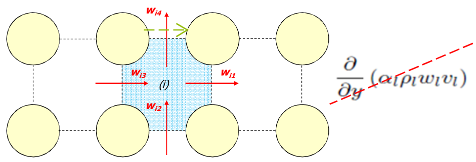
(only normal direction to the gap)

3.Pressure force

4.Shear stresses. (shear between liquid-droplets not modeled)

5.Phase change component + entrainment

Orthogonal direction to the gap are neglected in the momentum eq.



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T min calculation (fails when CHF Tong is used)

$$T_{\text{hn}} = 705.44 - 4.722 \times 10^{-2}(P_{\text{crit}} - P) + 2.3907 \times 10^{-5}(P_{\text{crit}} - P)^2 - 5.8193 \times 10^{-9}(P_{\text{crit}} - P)^3 \quad (4.34)$$

The critical pressure of water is 3203.6 psi. The homogeneous nucleation temperature is given in units of Fahrenheit. The effect of wall surface thermal properties are included by using a contact temperature correction.

$$T_{\text{min,hn}} = T_{\text{hn}} + (T_{\text{hn}} - T_l)\left[\frac{(k_p C_p)_l}{(k_p C_p)_w}\right]^{1/2} \quad (4.35)$$

The second method is by using Henry's modification of the Berenson correlation [29].

$$T_{\text{min,henry}} = T_B + 0.42(T_B - T_l)\left\{\left[\frac{(k_p C_p)_l}{(k_p C_p)_w}\right]^{1/2}\left[\frac{H_{\text{fg}}}{C_{\text{pw}}(T_B - T_{\text{sat}})}\right]\right\}^{0.6} \quad (4.36)$$

Where,

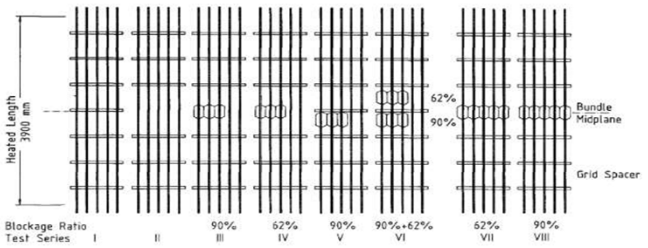
$$T_B = T_{\text{sat}} + 0.127\frac{\rho_v H_{\text{fg}}}{k_v}\left[\frac{g(\rho_f - \rho_g)}{(\rho_f + \rho_g)}\right]^{2/3}\left[\frac{g_c \sigma}{g(\rho_f - \rho_g)}\right]^{1/2}\left[\frac{\mu_v}{g(\rho_f - \rho_g)}\right]^{1/3} \quad (4.37)$$

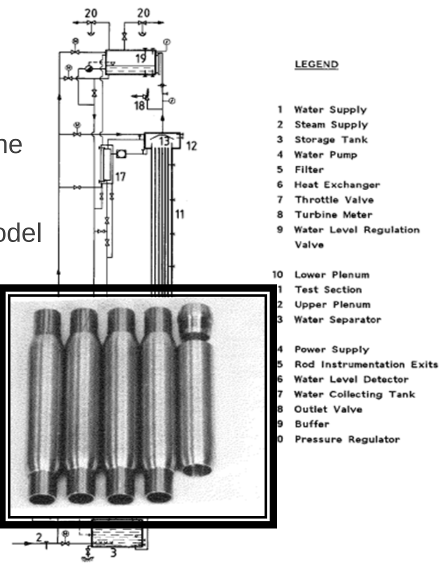
$$T_{\text{min}} = \max\begin{cases}\min\begin{cases}1158 \\ \max\begin{cases}T_{\text{min,hn}} \\ T_{\text{min,henry}}\end{cases}\end{cases} \\ 900 \text{ if } \alpha_v < 0.8 \\ 700 \text{ if } \alpha_v >= 0.8\end{cases} \quad (4.38)$$

1. Experimental test section KIT-FEBA

Specifications

- Deformed pins were placed in some experiments to simulate the ballooning effect and postulated blockage of the sub channel.
- For the CTF simulation a blockage free bundle is used as a model





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