Post-Dryout Heat Transfer for CANDU Applications

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UNENE Thermalhydraulic Course

Canada
AECL Atomic Energy of Canada Limited
EACL Énergie atomique du Canada limitée

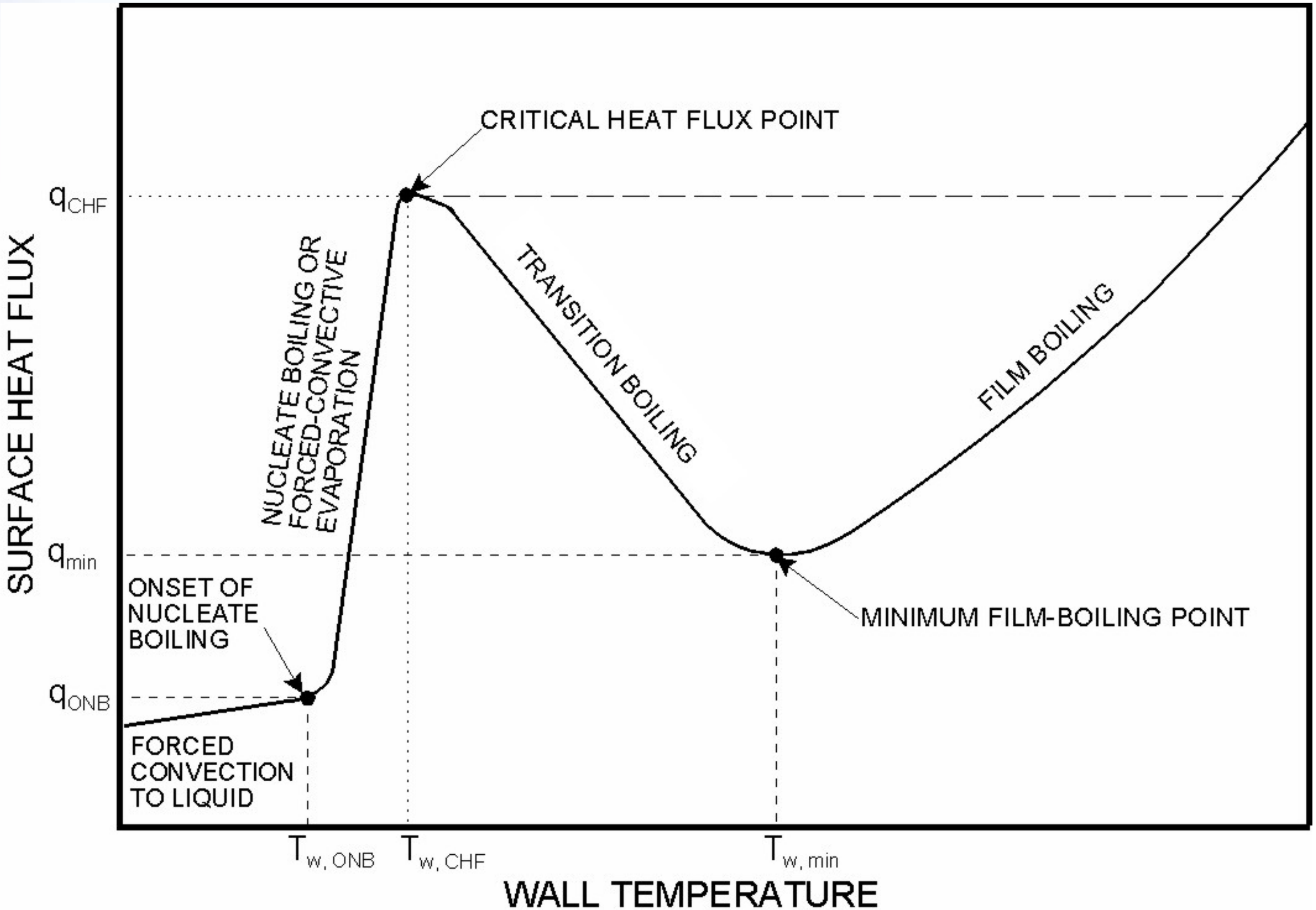
Outline

- Introduction
- Transition boiling
  - Mechanism
  - Prediction method
- Film boiling
  - Mechanism
  - Prediction method
- Drypatch spreading in the 37-element bundle
- Summary

Introduction

- **Post-dryout heat transfer**
  - **Heat-transfer regime where the heated surface is cooled mainly by the vapor flow**
  - **Low heat-transfer coefficient resulted in high surface temperature; may lead to damage to fuel sheath**
  - **Other term often used: post-CHF heat transfer**
- **Post-dryout heat-transfer modes**
  - **Transition boiling (under rewetting after ECC injection)**
  - **Film boiling**
- **Transition point between these modes**
  - **Minimum film-boiling point**

Boiling Curve



Post-Dryout in Reactor Analyses

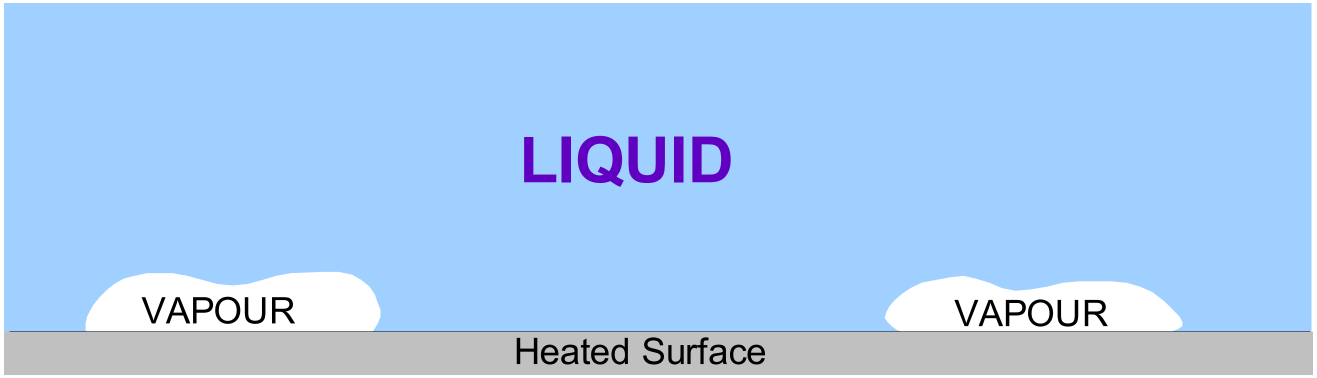
- Analyses of postulated accident scenarios
  - Loss of regulation
  - Loss of flow (e.g., loss of Class-IV power, small break loss of coolant)
  - Large break loss of coolant
- Steam generator analyses
- Primary information
  - Maximum post-dryout sheath temperature (or minimum post-dryout heat-transfer coefficient)
  - Average (or best-estimate) post-dryout heat-transfer coefficient
- Supplemental information
  - Drypatch spreading
  - Drypatch fractions (axial and radial on element and bundle basis)

Transition Boiling

- **Definition of transition boiling (Berenson)**

  "Transition boiling is a combination of unstable film boiling and unstable nucleate boiling alternately existing at any given location on a heating surface.

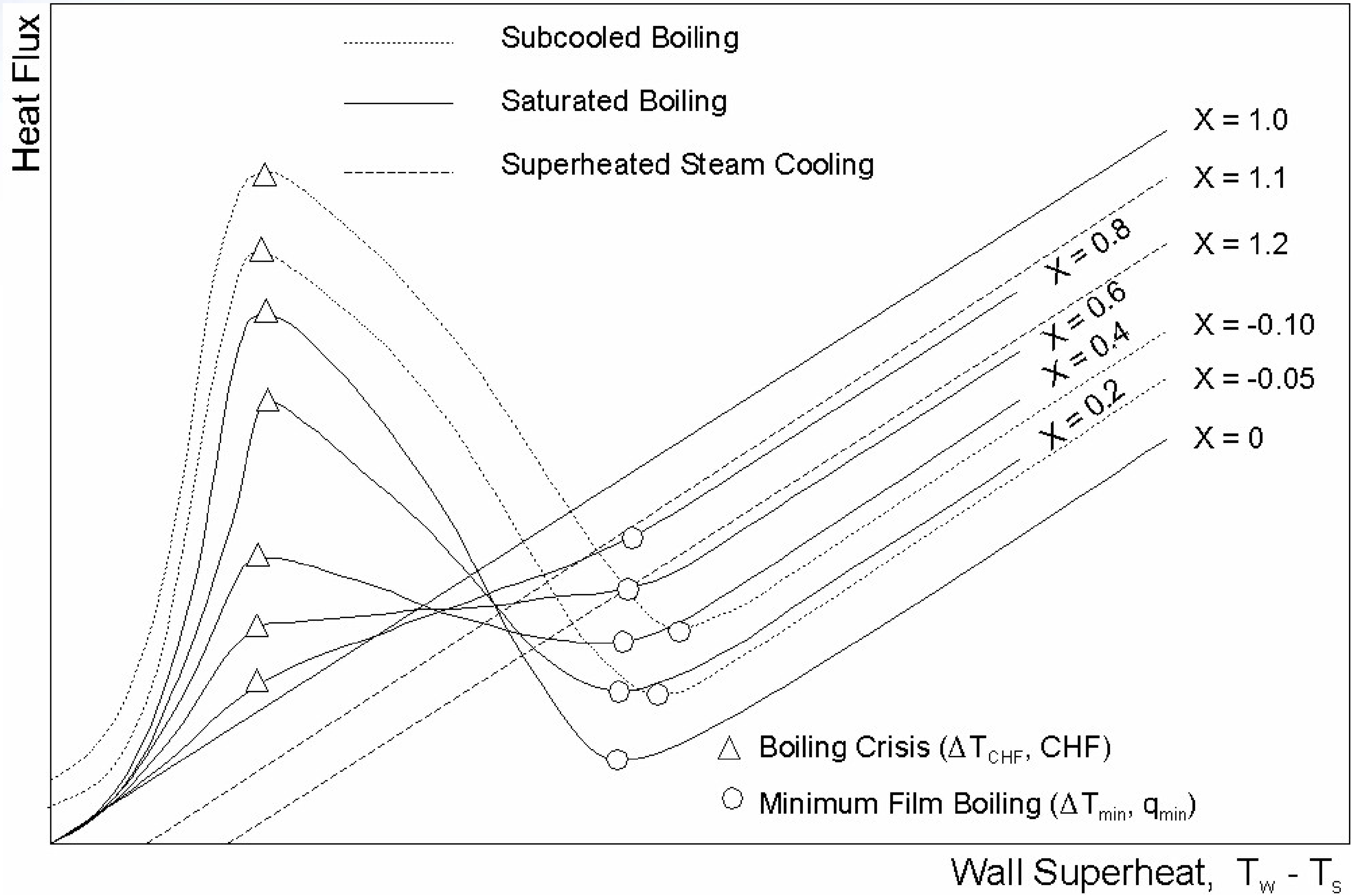
  The variation in heat transfer rate with temperature is primarily the result of a change in the fraction of time each boiling regime exists at a given location"



Occurrence of Transition Boiling

- Temperature-controlled surface at conditions beyond CHF
  - Examples of temperature-controlled surfaces
    - High thermal inertia surface
    - Surface heated by condensing steam
    - Fuel element during fast transients
- Heat-flux-controlled surface at conditions beyond CHF
  - Only for conditions when the slope of transition boiling curve is positive (dq/dt > 0)
  - Slope of the transition boiling curve is negative (dq/dt < 0)
    - Rapid transition from nucleate boiling to film boiling
    - Transition boiling is not encountered (or very briefly)
  - Examples of heat-flux controlled surfaces
    - Electrical heaters
    - Fuel elements during slow transients

Quality Effect on Boiling Curves



Transition Boiling Limits

- **Lower temperature limit: $T_{W,\ CHF}$**

  $(T_{w,\ CHF} - T_{SAT}) = q_{CHF} / H_{NB}$

  q_{CHF} - CHF

  H_{NB} – nucleate boiling heat-transfer coefficient

- **Upper temperature limit: $T_{W,\ MIN}$**

  $(T_{W,\ MIN} - T_{SAT}) = q_{MIN} / H_{FB}$

  q_{MIN} – minimum film-boiling heat flux

  H_{FB} – film-boiling heat-transfer coefficient

  Note: $H_{NB} > H_{TB} > H_{FB}$

- **Transition boiling is only encountered within a relatively narrow range of temperatures**
  - For example: $300 < T_{TB} < 373^{o}C$ for water at 10 MPa

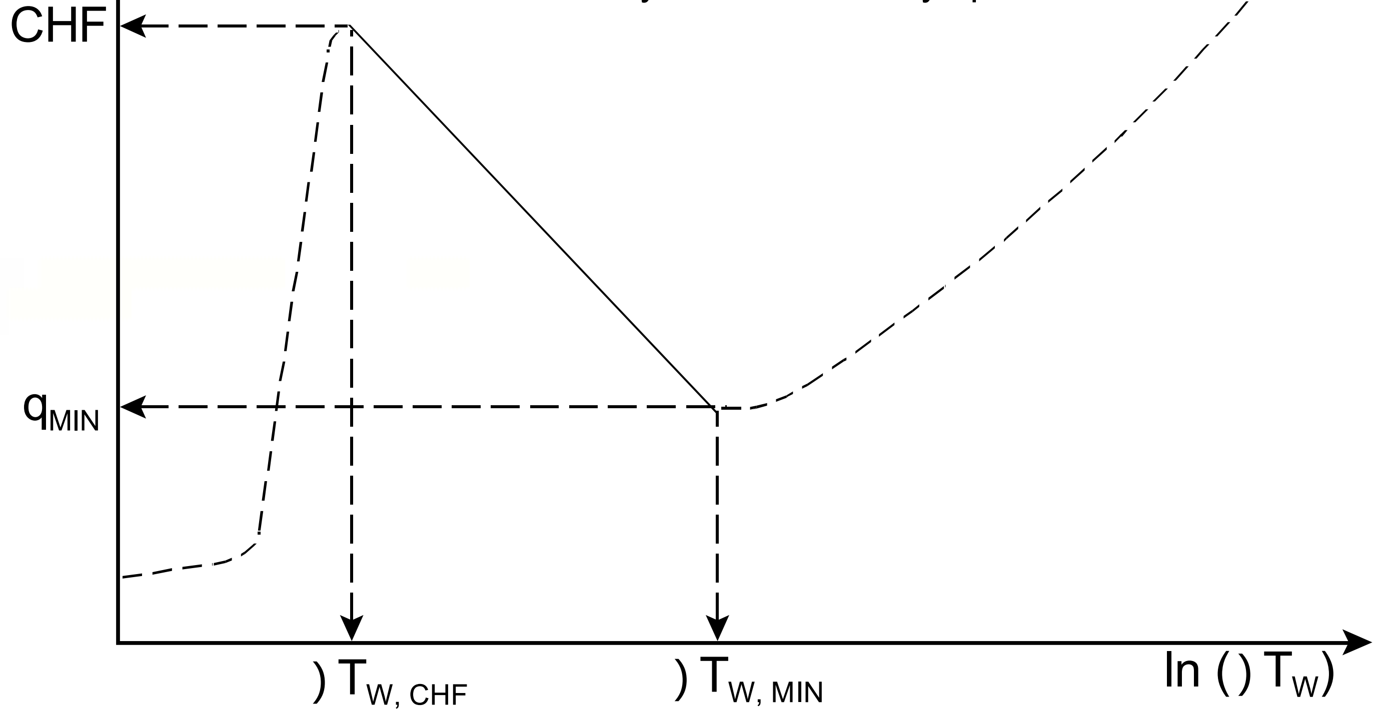
Transition Boiling Correlations

- Correlations containing boiling and convective components (valid for transition and film boiling)
  - $H_{TB} = A\ EXP\ (-B\ \Delta T_{SAT}) + (K_V / D)\ a\ Re_V^b\ Pr_V^c$
- Phenomenological correlations (valid for transition and film boiling), e.g., Tong & Young (1974) and Iloeje (1975)
  - $q = q_{dc} + q_{ndc} + q_{conv.}$
- Empirical correlations (valid for transition boiling only)
  - Independent of CHF and minimum film boiling, e.g., Ellion (1954)
    - $q_{TB} = 4.56*10^{11}\ (\Delta T_{SAT})^{-2.4}$
  - Function of CHF and $T_{W,\ CHF}$, e.g., MacDonough (1960)
  - Function of CHF, $T_{W,\ CHF}$, q_{MIN} and $T_{W,\ MIN}$

Recommended Correlation

$$\frac{\ln(CHF/q_{TB})}{\ln(CHF/q_{MIN})} = \frac{\ln(\ )T_{W,TB} /\ )T_{W,CHF})}{\ln(\ )T_{W,MIN} /\ )T_{W,CHF})}$$

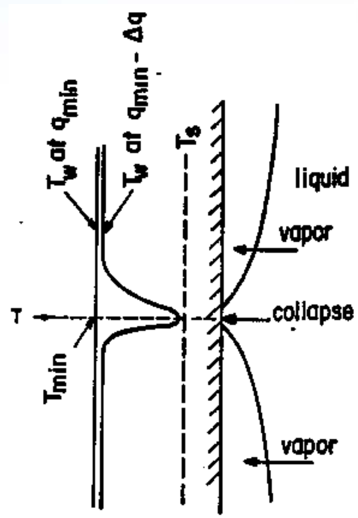
This correlation always has correct asymptotic trends.



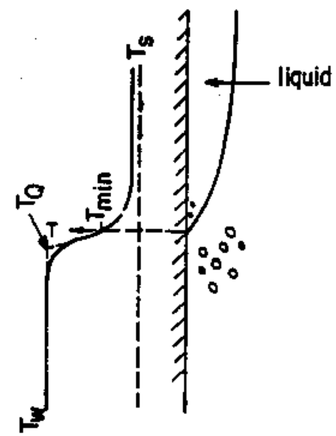
Minimum Film Boiling Point

- **Transition point between transition boiling and film boiling**
- **Sheath temperature as transition criteria, $T_{W, MIN}$**
  - **No liquid/sheath contact for $T_W > T_{W, MIN}$**
  - **Possible liquid/sheath contact for $T_W < T_{W, MIN}$**
  - **Corresponding heat flux evaluated with film-boiling heat-transfer correlation**
- **Other terminologies:**
  - **Leidenfrost temperature**
  - **Sputtering temperature**

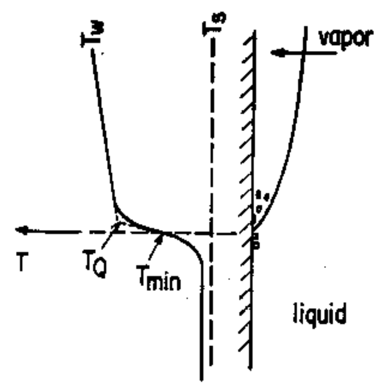
Film Boiling Termination Types



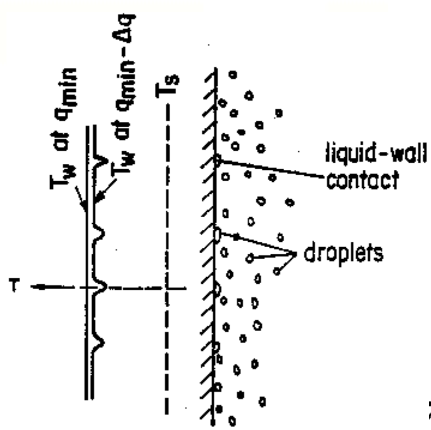
Type I: Collapse of vapor film



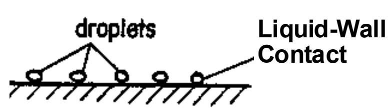
Type II: Top flooding



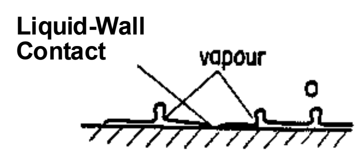
Type III: Bottom flooding



Type IV: Droplet cooling



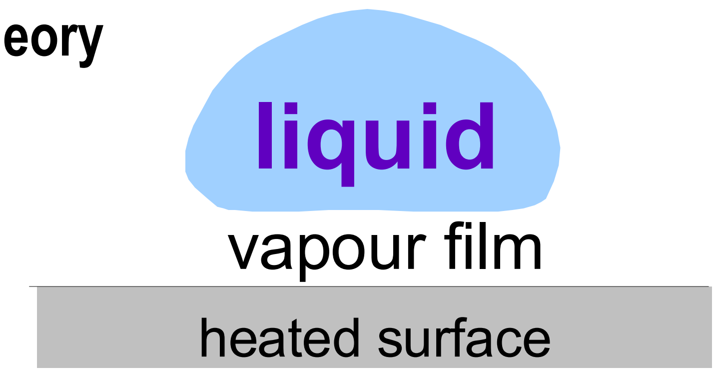
Type V: Leidenfrost boiling



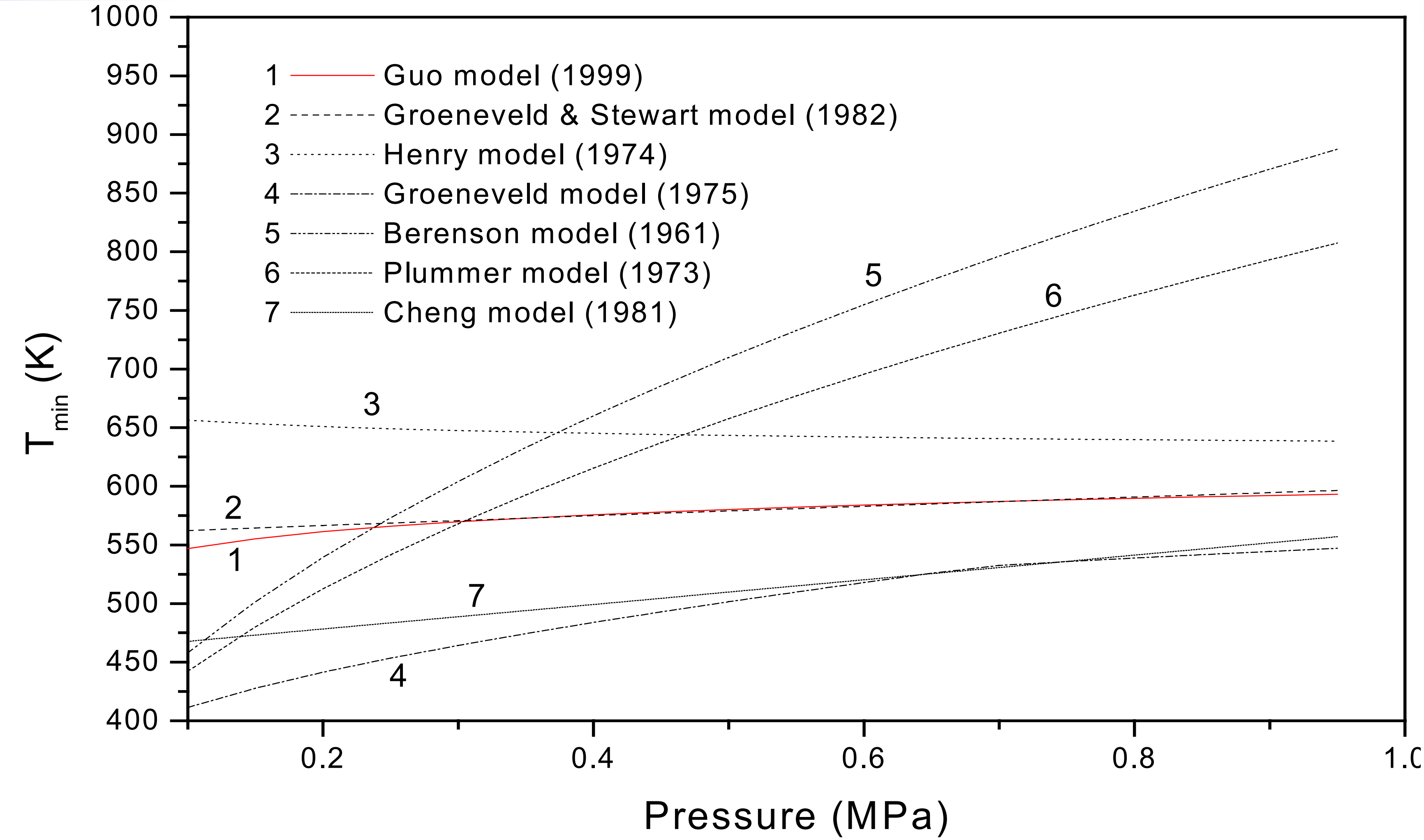
Type VI: Pool boiling

Minimum Film Boiling Mechanisms

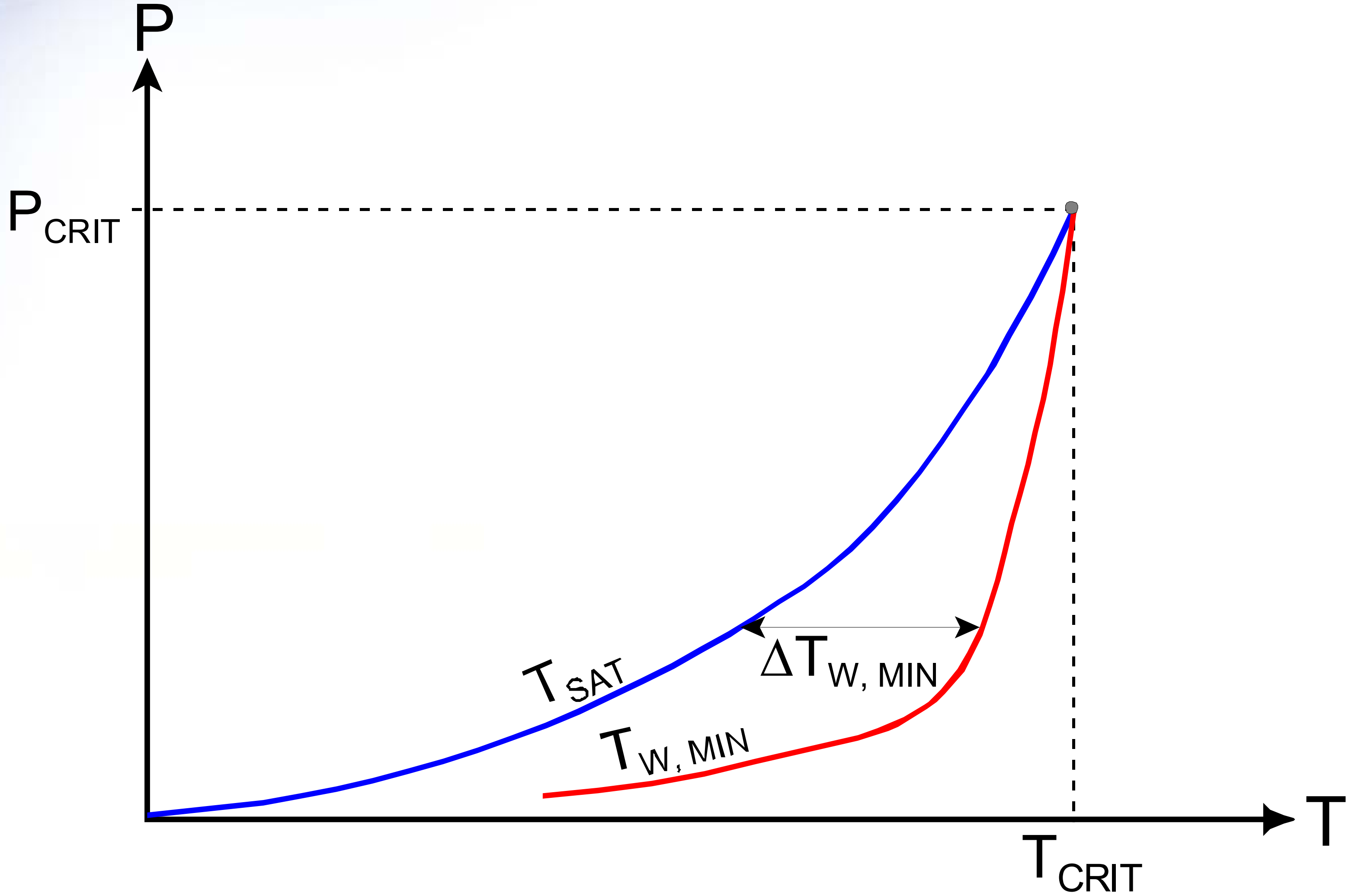
- Hydrodynamic mechanisms:
  - $\Delta T_{W,\,MIN} = q_{MIN} / H_{FB}$
  - q_{MIN} (predicted from Taylor's instability criterion)
- Thermodynamic mechanisms:
  - $\Delta T_{W,\,MIN}$ = maximum liquid superheat (beyond which nucleation rate is infinite and liquid cannot exist)
  - from equation of state
  - from homogeneous nucleation theory



Comparison of Models for $T_{W, MIN}$



Minimum Film Boiling Superheat



Recommended Correlation

- **Pressure < 9000 kPa**

$$T_{W,MIN} = 284.7 + 0.0441P - 3.72 \cdot 10^{-6} P^2 + \frac{\Delta h \cdot 10^4}{(2.82 + 0.00122\,P)h_{fg}}$$

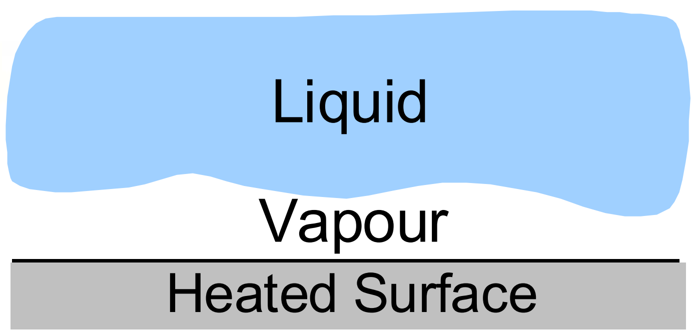
- **Pressure ≥ 9000 kPa**

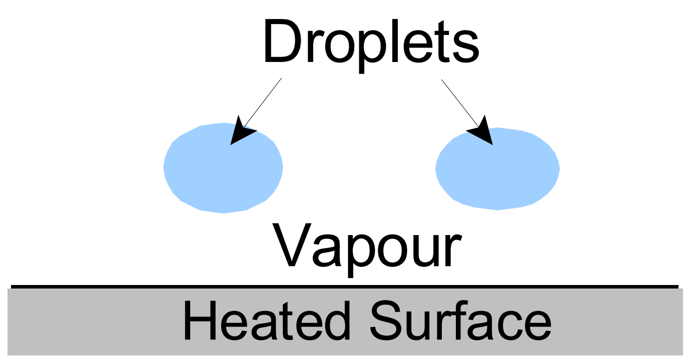
$$T_{W,MIN} = T_{SAT} + \Delta T_{W,MIN,9000\,kPa} \frac{P_{CRIT} - P}{P_{CRIT} - 9000}$$

- **Database**
  - **P = 100 to 9000 kPa**
  - **G = 50 to 4500 kg.m^{-2}.s^{-1}**
  - **X = -0.15 to 0.40**
  - **ΔT_{SUB} = 0 to 50^{o}C**
  - **D = 9 - 12 mm**

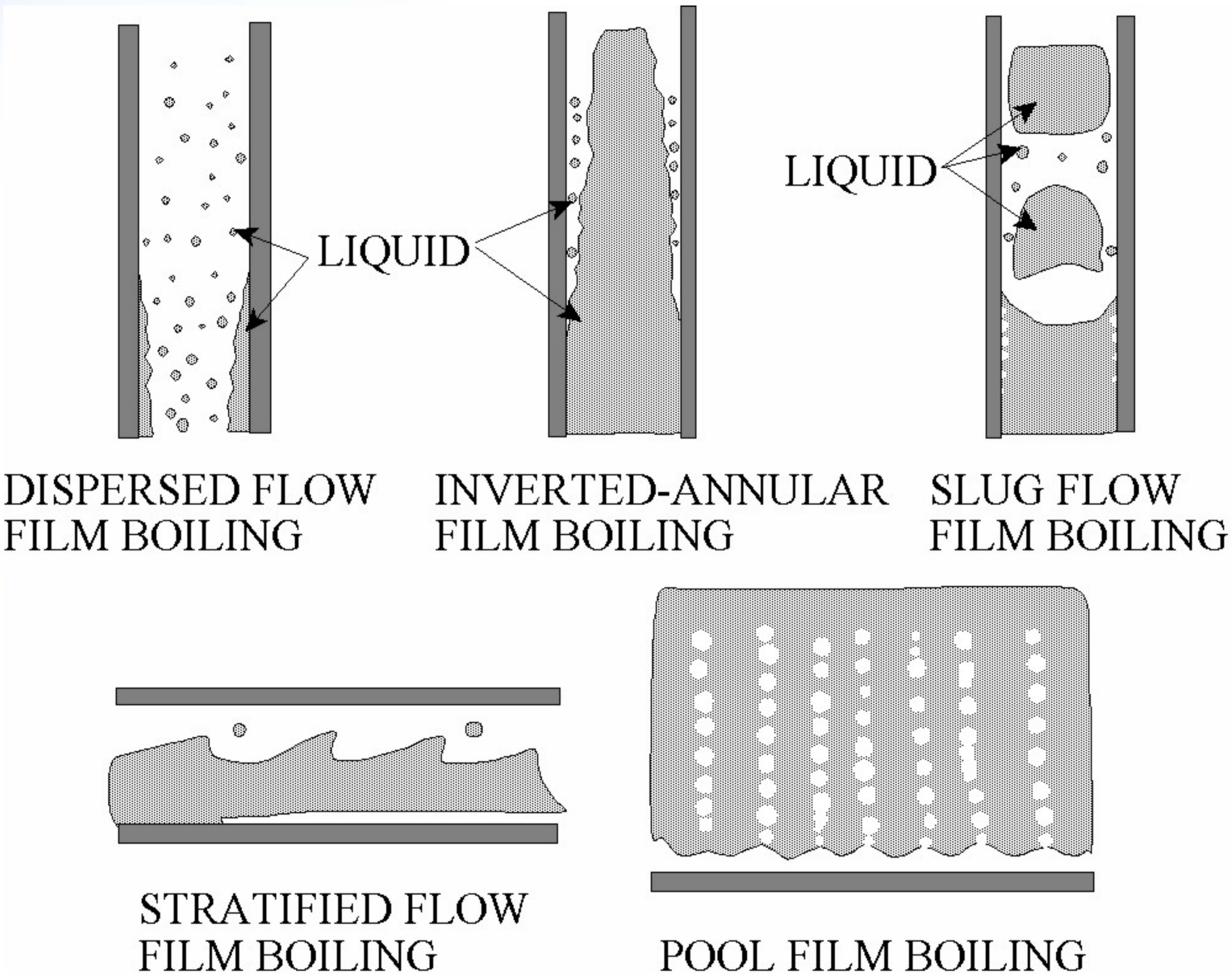
Film Boiling

- Heated sheath cooled by a continuous vapour film
- Sheath temperature is too high to permit any liquid/surface contact

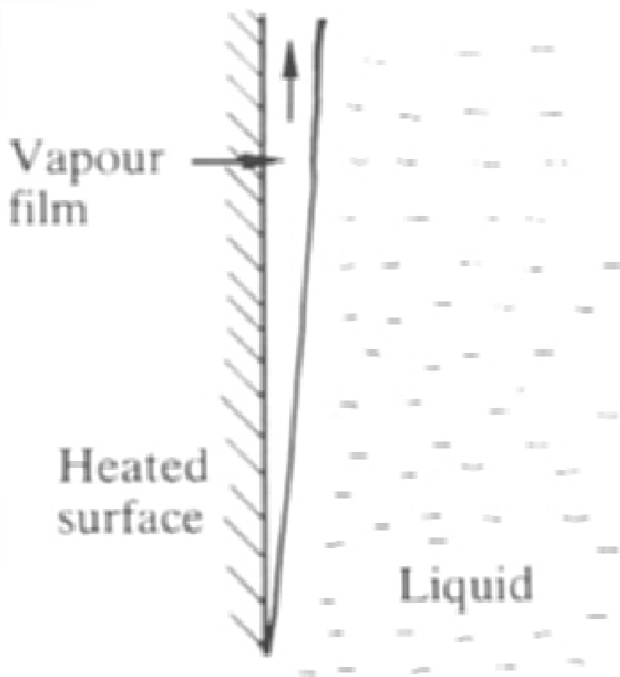




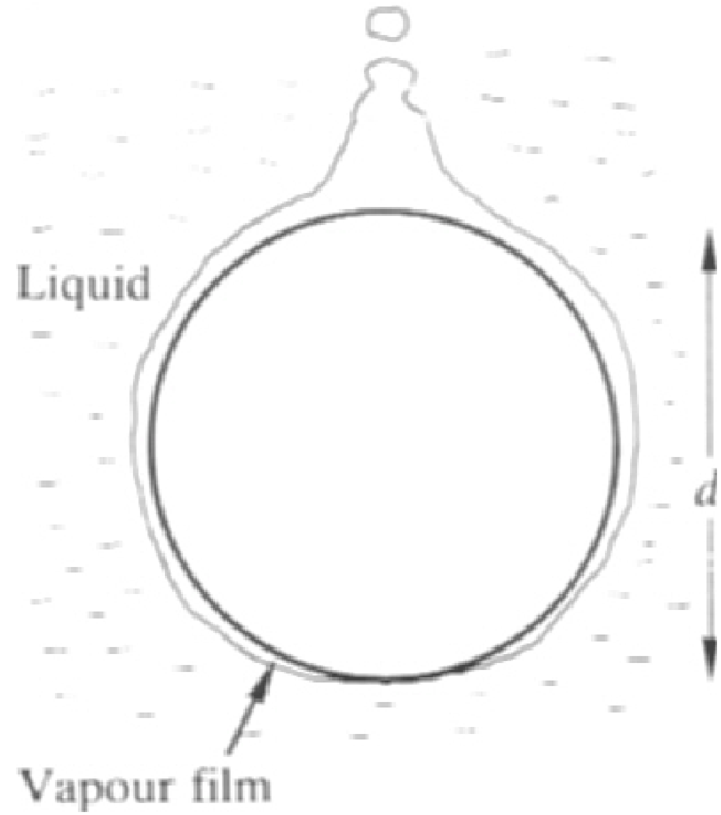
Film Boiling Type



Pool Film Boiling Patterns

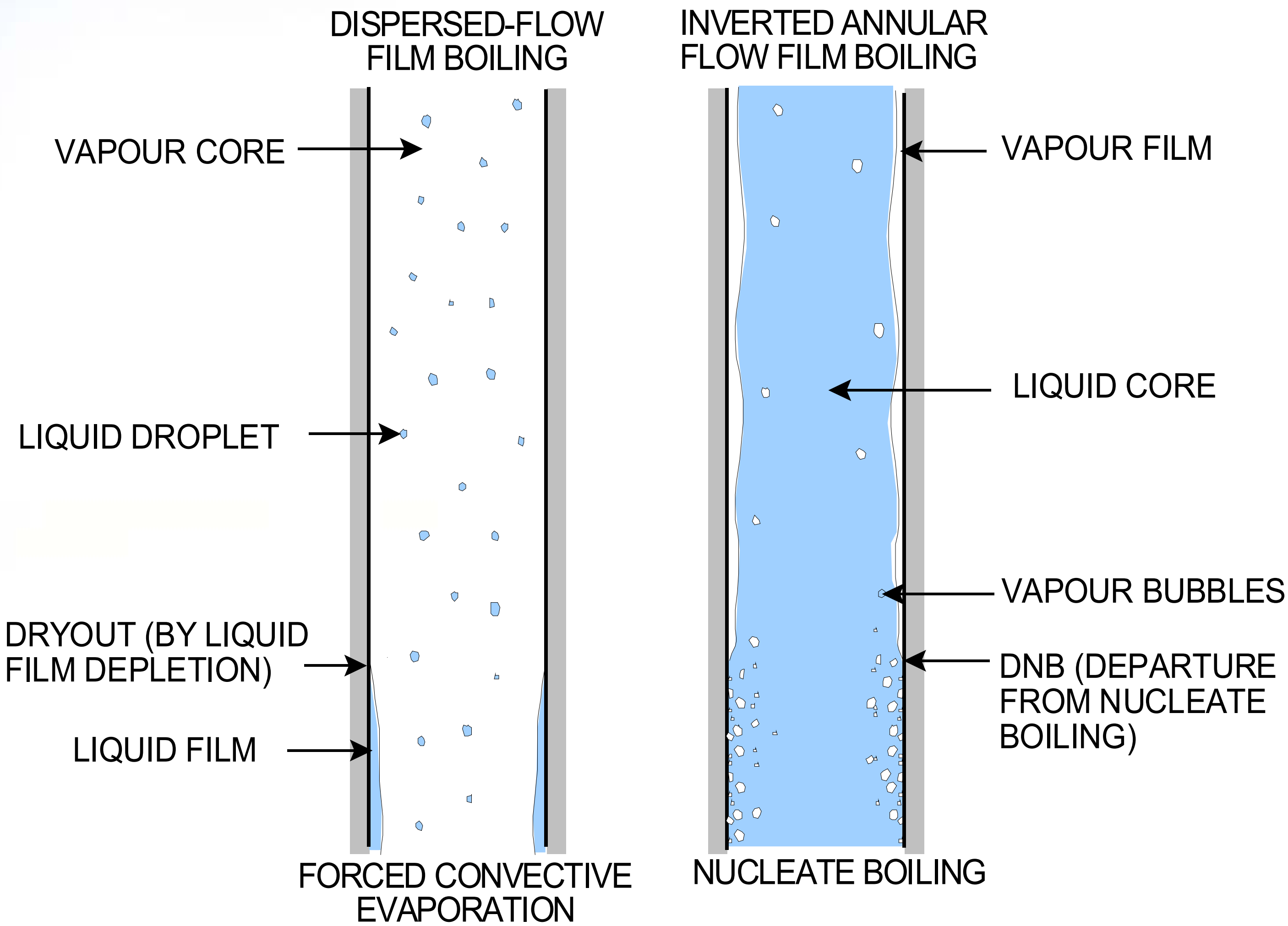


Vertical Plate



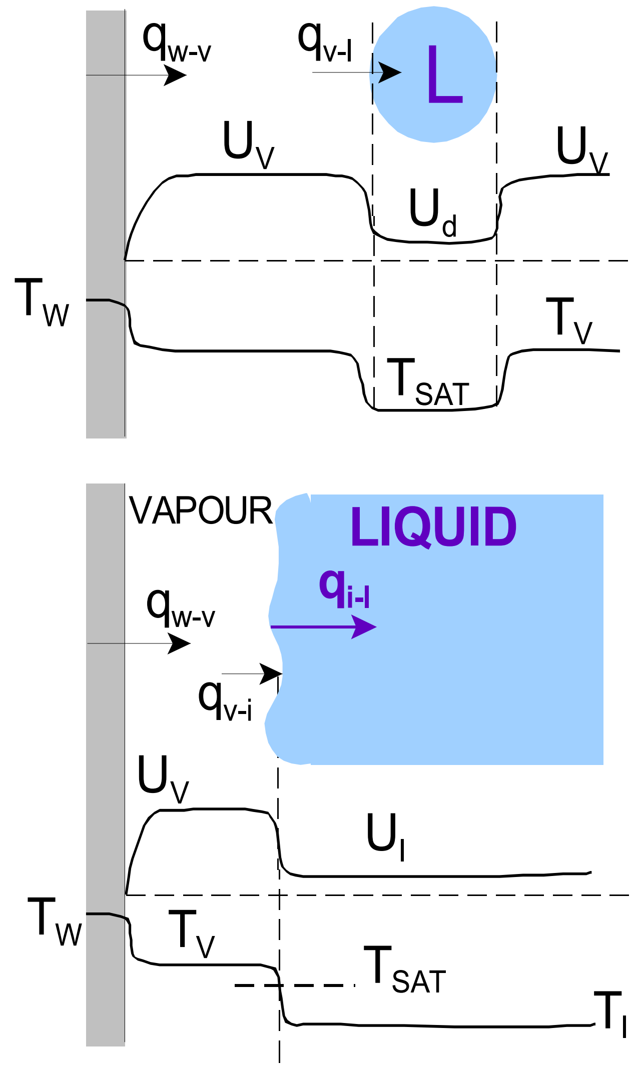
Horizontal Cylinder

Flow Film Boiling Patterns

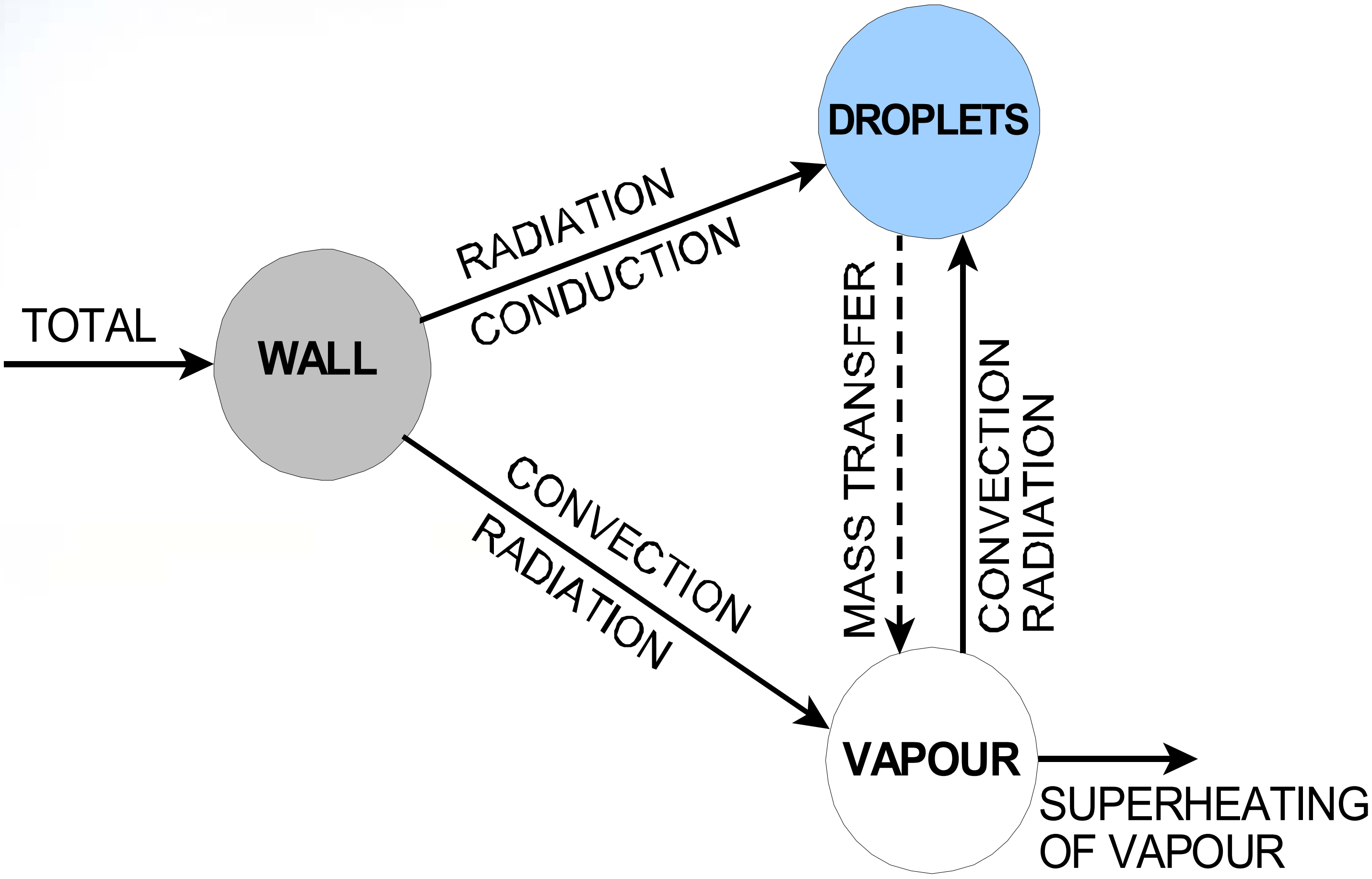


Characteristics of Film Boiling Regime

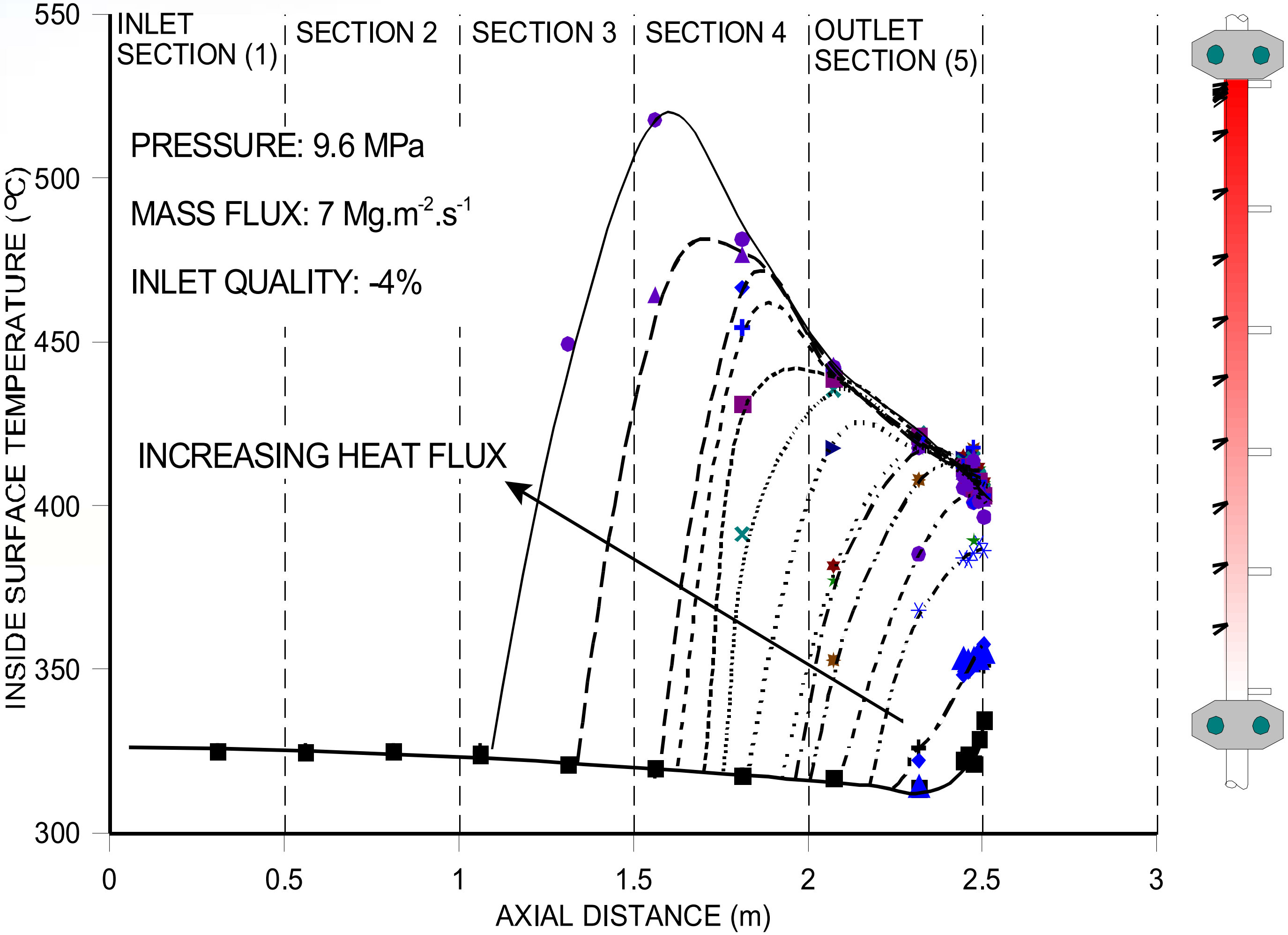
- Heat transfer takes place from wall to vapour and from vapour to liquid phase
- Liquid and vapour may be in non-equilibrium
  - Subcooled liquid and superheated vapour
- Heat transfer unaffected by surface conditions
- Reduced pressure drop due to low vapour viscosity



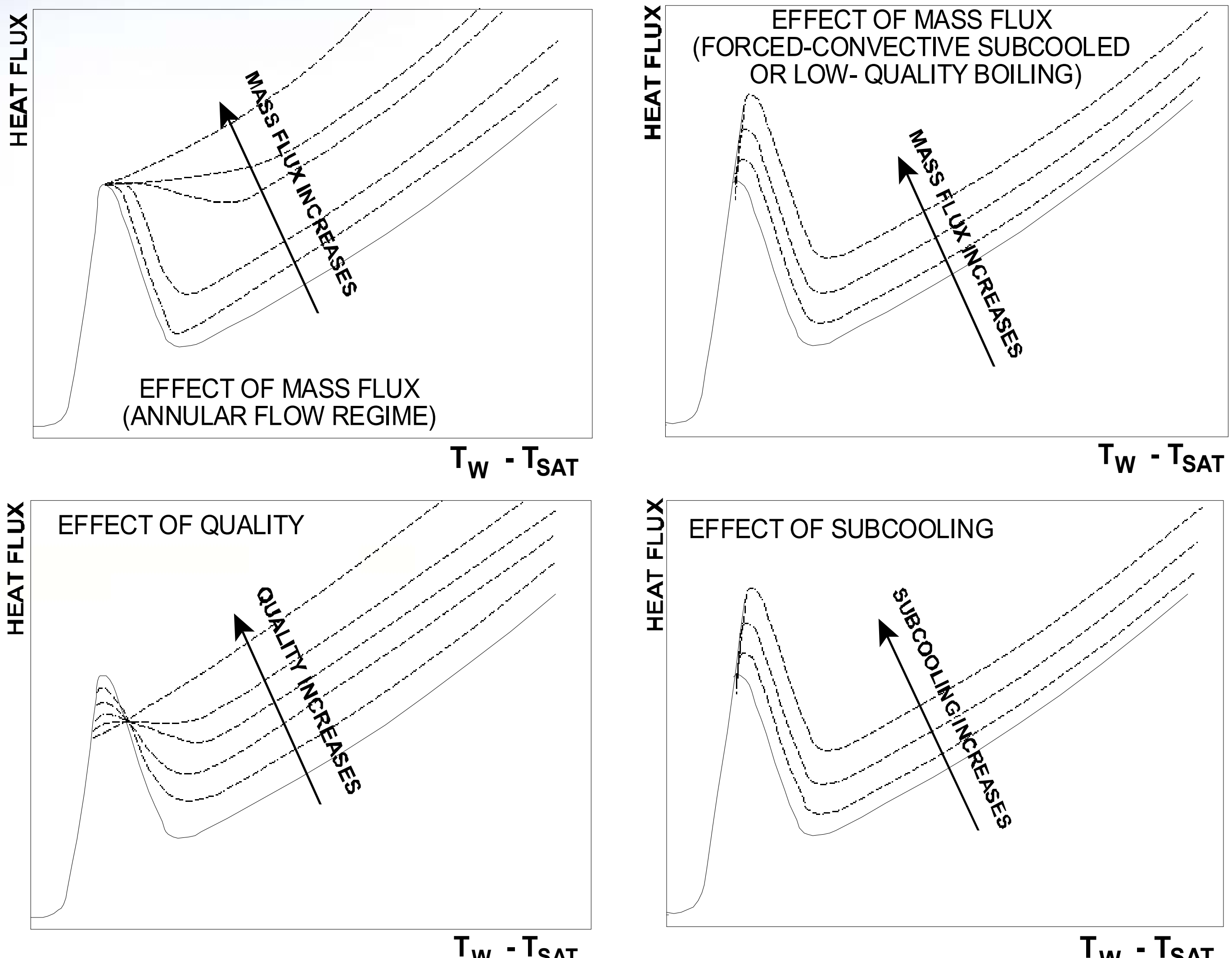
Detailed Heat-Transfer Mechanisms



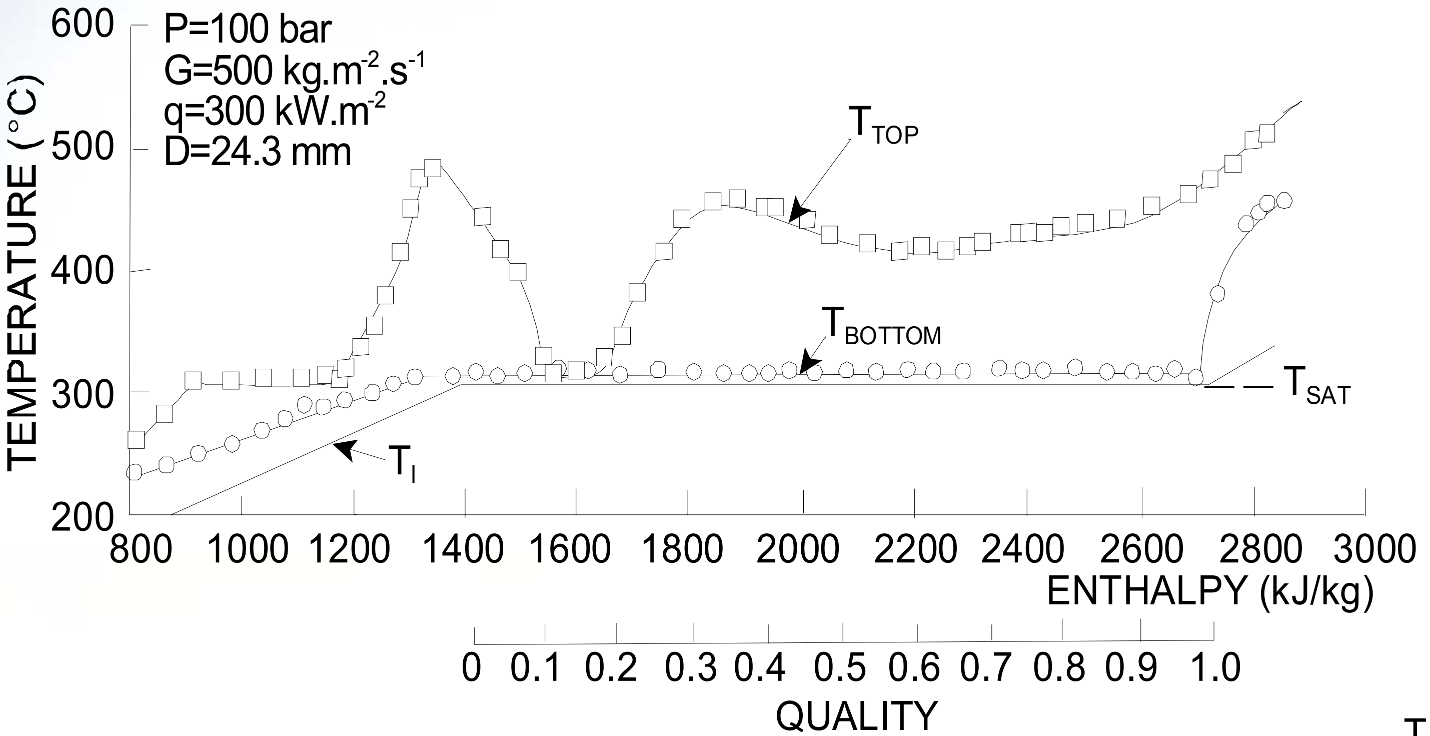
Vertical Tube Measurements

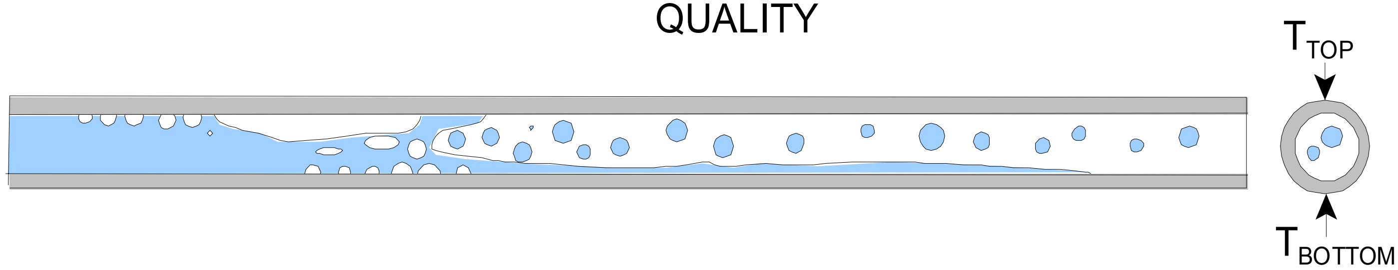


Parametric Trends of Boiling Curve



Horizontal Tube Measurements





How do we predict film boiling heat transfer (DFFB regime)?

- **Thermal equilibrium correlations**
  - no vapour superheat
  - ~ 25 correlations (e.g., Dougall, Miropolskiy, etc.)
- **Thermal non-equilibrium equations**
  - allow vapour superheat
  - ~ 7 equations (e.g., Groeneveld-Delorme, Shah, etc.)
- **Mechanistic models**
  - predict axial variations in U_v, U_d, T_v, d, etc.
  - ~ 15 models (e.g., Saha, Varone-Rohsenow, etc.)

How do we predict film boiling heat transfer (IAFB regime)?

- Pool Boiling
  - low flow and subcooled conditions
- Empirical Correlations
  - ~ 11 correlations (e.g., Collier, Kalinin, etc.)
- Mechanistic Models
  - laminar and turbulent vapour-film assumptions
  - ~ 15 models (e.g., Groeneveld, Analytis- Yadigaroglu, etc.)

How do we predict film boiling heat transfer (final)?

- Have ~30 models and ~50 equations/correlations
- Some are for DFFB, others for IAFB
- All correlations and models valid only within the range of their database/flow regime
- None of these prediction methods are valid over a wide range of conditions
- Hence for reactor safety analysis we need a combination of different film-boiling prediction methods
- SOLUTION: LOOK-UP TABLE

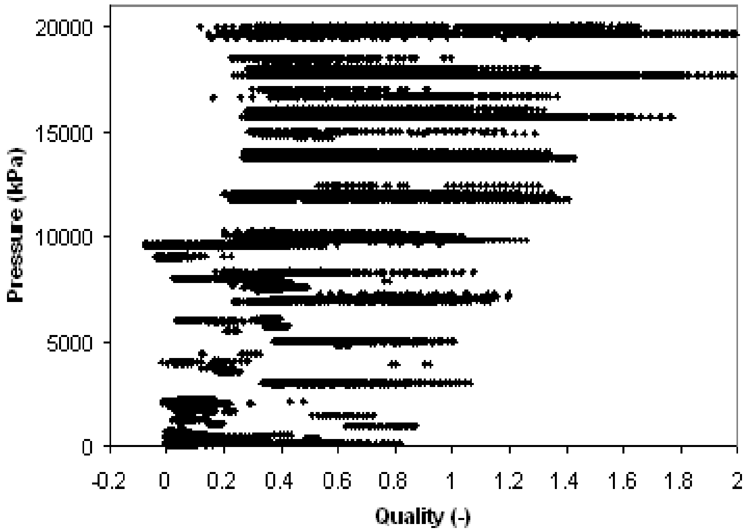
Evolution of Film-Boiling Look-Up Table

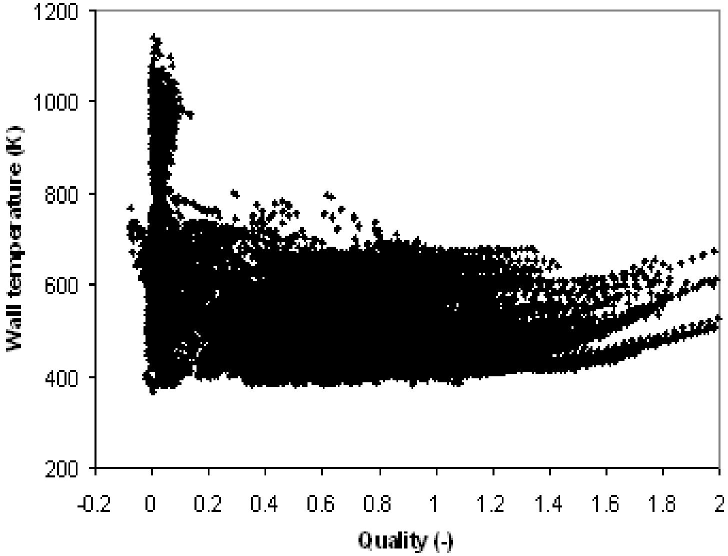
Table Version	# of Exp Data Total Used	# of Data Sets	Table Accuracy	Comments
Leung 1988	4384	8	RMS error in Tw: 5.5%	q-based table, pressure: 7-12 MPa, mass flux: 1-6 $Mg/m^2/s$
PDO-LW-96, Leung 1997, IAEA	21525 14687	16	RMS error in Tw: 6.7%; RMS error in h: 16.9%	q-based table, smoothed pressure: 0.1-20 MPa, mass flux: 0-7.5 $Mg/m^2/s$
PDO-LW-99, Vasic 2000	21182 15116	18	RMS error in Tw: 6.1%	q-based table, smoothed pressure: 0.1-20 MPa, mass flux: 0-7.5 $Mg/m^2/s$
Groeneveld 2002	71120 21116	25	RMS error in h: 10.6% Sm. Index: 0.12	Changed from T-based to q-based table Smoothed
U. of Ottawa 2003	71120 20014	25	RMS error in h: 10.6% Sm. Index: 0.12	T-based table with additional smoothing and data screening; in progress

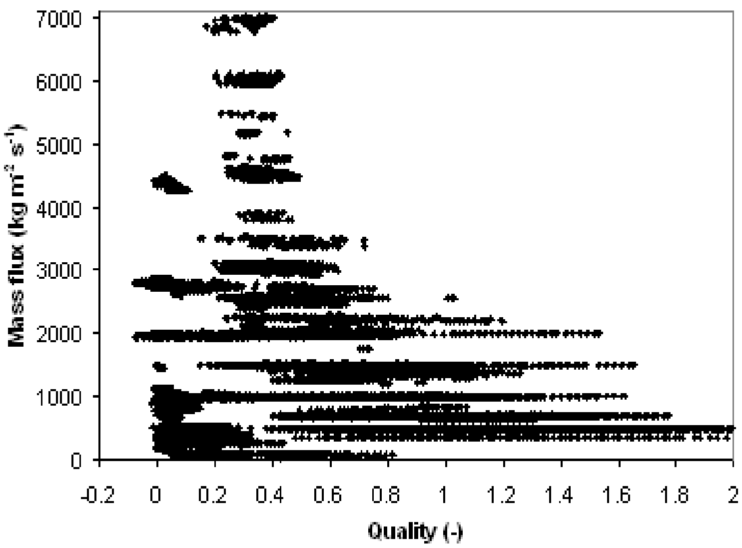
U of O Film Boiling Data Bank

- Largest tube film-boiling databank in the world
- Covers all convective film-boiling regions
- Covers wide ranges of flow, pressure, quality and wall superheat
- Has taken ~10 years to compile
- Includes data of non-aqueous fluids as well
- Contains ~ 80 000 tube data from ~40 data sets
- Many data were obtained in developing film-boiling region
- A subset of ~24 000 fully developed film-boiling data (water only) was selected for table development

Ranges of Flow Conditions in the Tube Film Boiling Database (~75 000 points)







Why did we develop a new (2001) film boiling look-up table?

- In all previous tables: $H_{FB} = f(P, G, X, q)$
- 2001 table: $H_{FB} = f(P, G, X, T_w)$
  - Codes require use of T_w as independent parameter
- Upper limit of quality range changed from 1.2 to 2.0
- Larger primary database
  - selected 23 505 vs. 14 687 fully developed film boiling data in previous tables
- Better screening of the data
- Trends for table based on best of 5 models

Derivation of the 2001 Look-Up Table

- 5 preliminary tables were constructed based on the most promising models and equations:
  - Hammouda,
  - Chen-Chen,
  - Shah-Sidiqui,
  - Kohler-Hein, and
  - Groeneveld-Delorme
- Preliminary tables were compared to the database; for each of 64 sub-regions (in G, P, X , ΔT_W) the best table was selected
- A hybrid table was constructed based on the best table for each sub-region
- A multi-dimensional smoothing procedure is used to reduce large fluctuations in the skeleton table

Derivation of the 2001 Look-up Table

- Use skeleton table as basis
- Update each table entry (e.g. $H(P_i, G_j, X_k, (\Delta T_w)_m)$) with experimental data obtained around P_i, G_j, X_k, and $(\Delta T_w)_m$
- Smooth the table by removing discontinuities (a multi-dimensional smoothing procedure is used to reduce large fluctuations)
- Apply correct parametric and asymptotic trends

2001 Film-Boiling Look-Up Table

- Contains 29,744 entries of heat-transfer coefficient
- $H_{i, j, k, m} = f(P_i, G_j, X_k, (\Delta T_w)_m)$
- Pressure: 100, 200, 500, 1000, 2000, 5000, 7000, 9000, 10 000, 11 000, 13 000, 17 000, 20 000 kPa;
- Mass flux: 0, 50, 100, 200, 500, 1000, 1500, 2000, 3000, 4000, 5000, 6000, 7000 kg m^{-2} s^{-1};
- Thermodynamic quality: -0.2, -0.1, -0.05, 0.0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0;
- Wall superheat: 50, 100, 200, 300, 400, 500, 600, 750, 900, 1050, 1200K.

Section of the 2001 Film-Boiling Table

(P=9000 kPa, G=1500 $kg.m^{-2}.s^{-1}$, H in $kW.m^{-2}.K^{-1}$)

Xe=	ΔT_w= 50K	ΔT_w= 100K	ΔT_w= 200K	ΔT_w= 300K	ΔT_w= 400K	ΔT_w= 500K	ΔT_w= 600K	ΔT_w= 750K	ΔT_w= 900K	ΔT_w= 1050K	ΔT_w= 1200K
-0.10	1.564	1.504	1.474	1.358	1.177	1.134	1.280	1.395	1.532	1.705	1.833
-0.05	1.414	1.311	1.275	1.194	1.026	0.981	1.131	1.210	1.356	1.499	1.625
0.00	1.257	1.164	1.106	1.071	1.006	1.048	1.120	1.198	1.283	1.369	1.456
0.05	1.513	1393	1.223	1.126	1.141	1.270	1.273	1.352	1.371	1.397	1.430
0.10	1.654	1.547	1.318	1.264	1.361	1.476	1.459	1.492	1.483	1.483	1.472
0.20	1.700	1.617	1.427	1.394	1.504	1.655	1.643	1.704	1.704	1.712	1.688
0.40	2.629	2.582	2.547	2.368	2.334	2.393	2.401	2.447	2.456	2.470	2.479
0.60	4.229	4.008	3.750	3.483	3.324	3.285	3.344	3.046	3.119	3.188	3.249
0.80	5.507	5.203	4.488	4.088	3.983	3.936	3.963	3.906	3.955	4.012	4.088
1.00	8.103	7.061	5.500	4.692	4.446	4.605	4.796	5.061	5.264	5.457	5.627
1.20	10.27	8.893	6.784	5.176	5.028	5.471	5.639	6.038	6.296	6.549	6.775
1.40	10.80	9.683	7.906	6.412	5.854	6.206	5.983	6.632	6.846	7.065	7.275
1.60	8.327	8.087	7.856	7.222	6.694	6.780	6.763	6.936	7.107	7.277	7.477

Regions of Uncertainty in the Film-Boiling Table

- Conditions with experimental data (least uncertainty)
- Regions based on predictions of best of five selected FB equations or models (uncertainty depends on level of extrapolation from data base)
- Severe or impossible conditions (included only to permit extrapolation)
  - Flow greater than critical flow,
  - Wall temperature < bulk fluid temperature,
  - Wall temperature < minimum film-boiling temperature

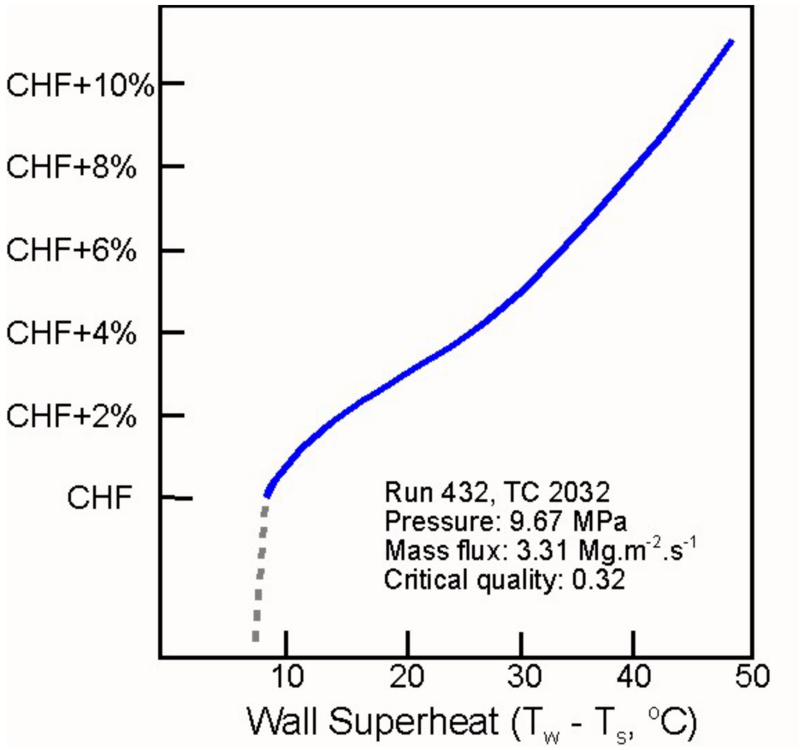
Accuracy of Various Methods for Fully Developed PDO Data in Tubes

Prediction methods	Average error* (%)	Rms error (%)
Miropolskiy model	48.36	91.11
Dougall-Rohsenow model	28.34	51.76
Groeneveld-Delorme model	15.74	46.93
Kohler-Hein model	-7.63	28.61
Hammouda model	22.97	58.16
Chen-Chen model	3.11	78.73
Shah-Siddiqui model	11.73	33.24
PDO-LW-00 (heat-flux based)	**6.87**	**20.65**
PDO-LW-01 (wall-superheat based)	**1.71**	**10.58**

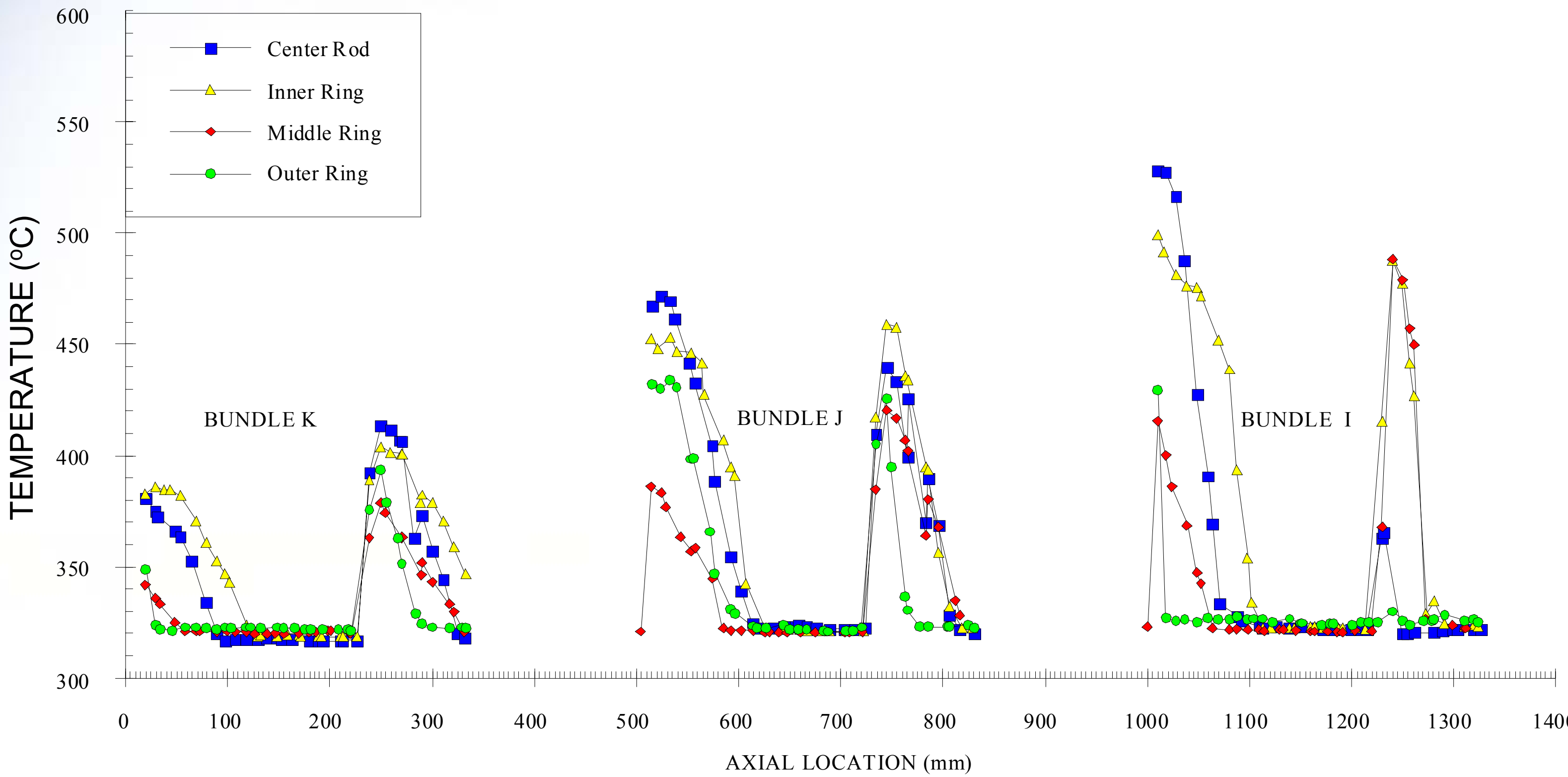
*In terms of heat-transfer coefficient

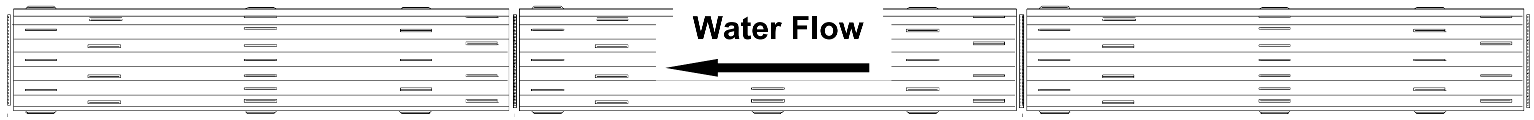
PDO Heat Transfer in CANDU Bundles

- Dispersed flow film boiling
- Clad temperature rise is gradual and controllable with flow conditions variation
- Maximum clad temperature is predictable and occurs at locations just upstream of appendage planes
- Drypatches are stable and propagate gradually with flow conditions variations



PDO Temperature Distribution in 37-Rod Bundles





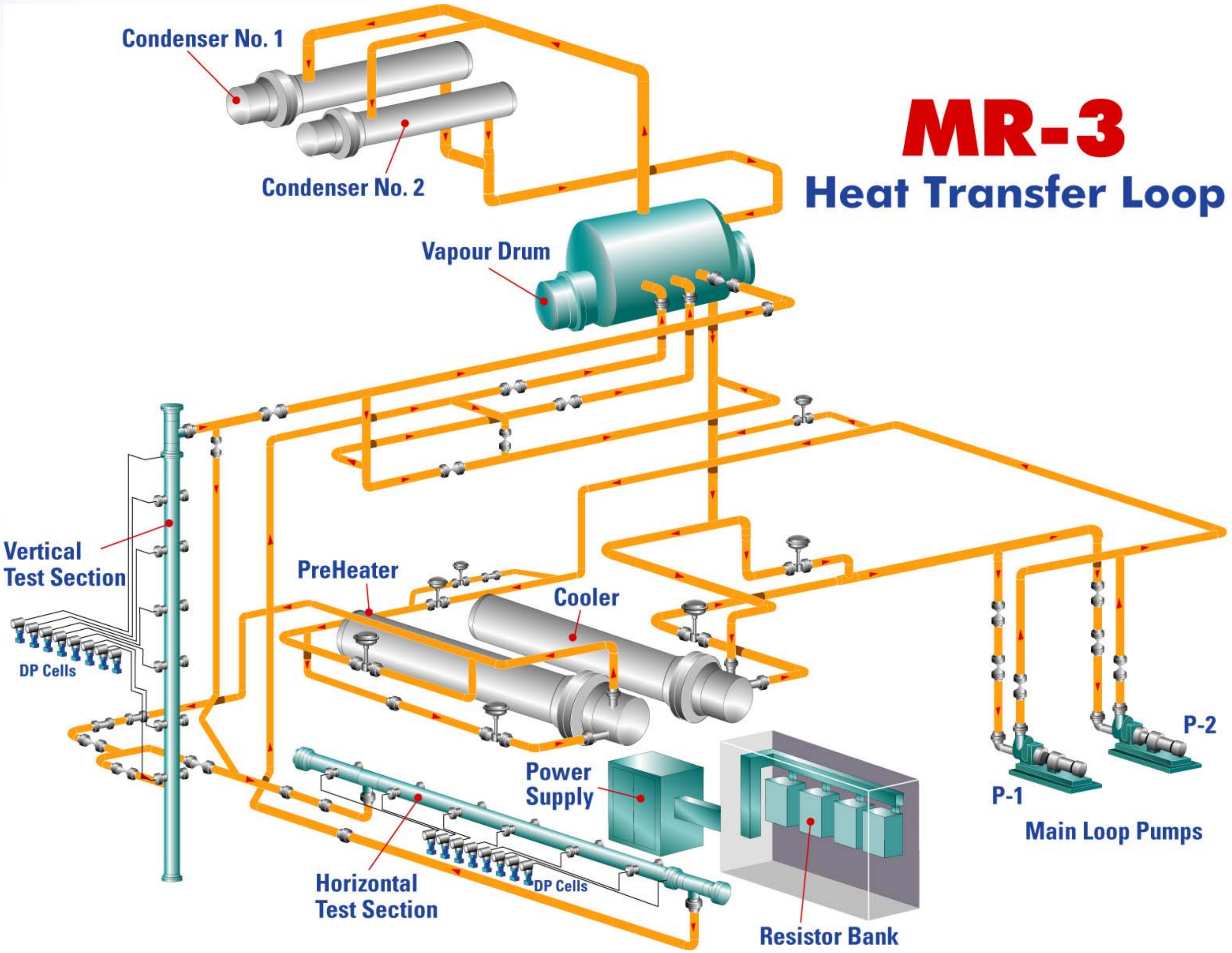
Water Bundle PDO Experiments

- Almost all studies employed fixed thermocouples attached to the clad
  - Surface coverage was limited
  - Details of clad-temperature variation downstream of appendages and spacer grids were not available
  - Extent of dry patches, in both axial and circumferential directions, could not be quantified
- Experiments were performed previously with CANDU 37-element bundles in high-pressure steam-water flow using moveable thermocouples
  - Increased surface coverage
  - Limited range of powers (to avoid damaging the simulator)

Freon Bundle PDO Experiments

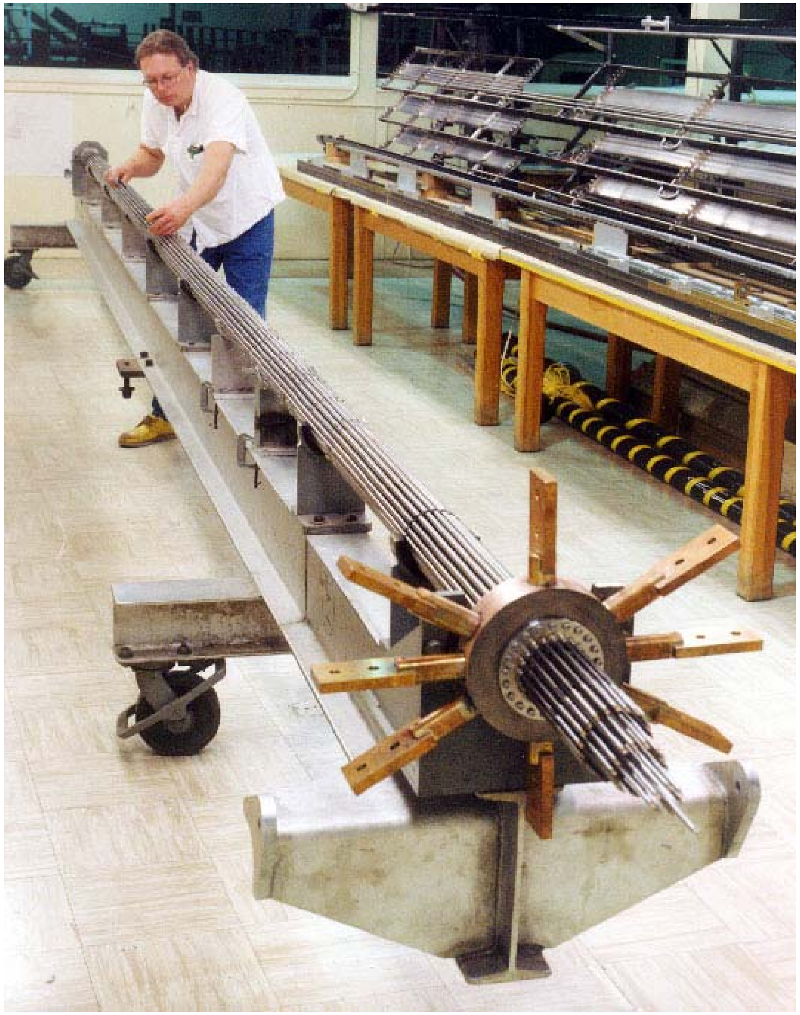
- **Moveable thermocouples inside elements of a CANDU 37-element bundle simulator**
  - Fine axial and radial movements, providing detailed temperature profiles
- **Freon-134a as coolant**
  - Low operating power and clad temperature
  - High over-power ratios (I.e., local-to-critical power ratios)
- **Relative wide range of test conditions**
  - Of interest to CANDU safety analyses

Test Facility

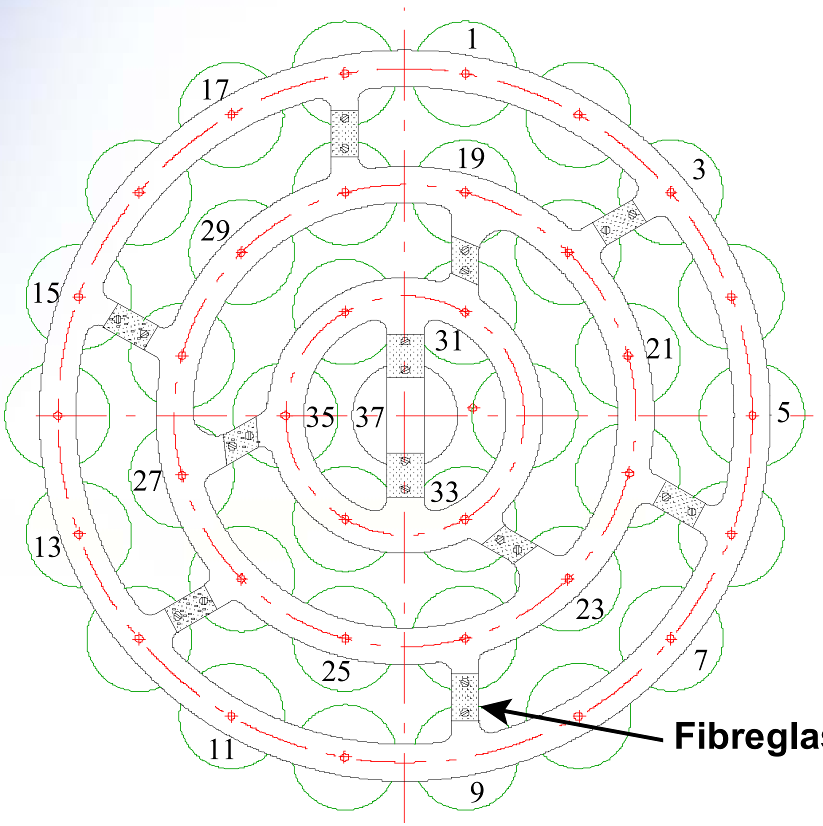


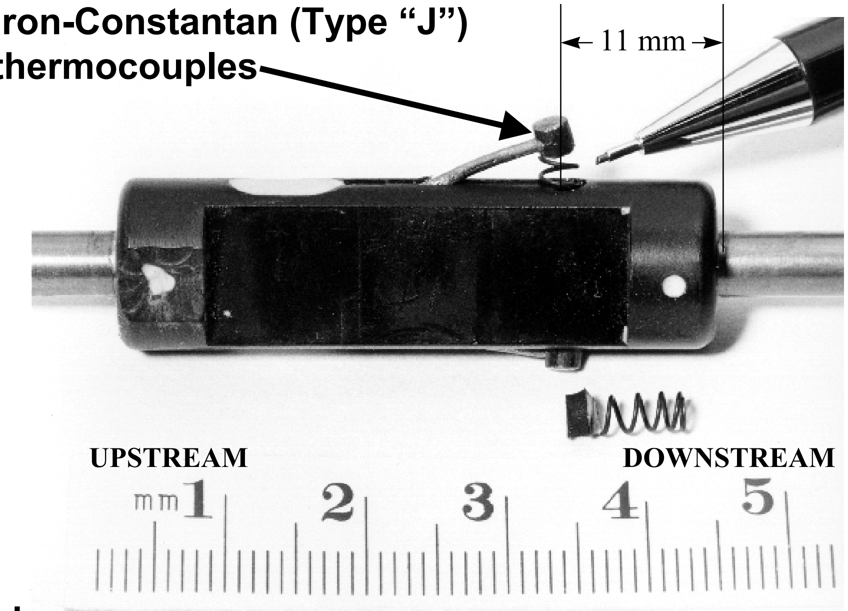
Bundle Simulator

- 6-m (20 ft) long full-scale bundle strings with junction and appendages
- Uniform axial power profile
- Non-uniform radial power profile simulating natural uranium fuel
- Sliding thermocouples inside rods at several downstream bundles in the string

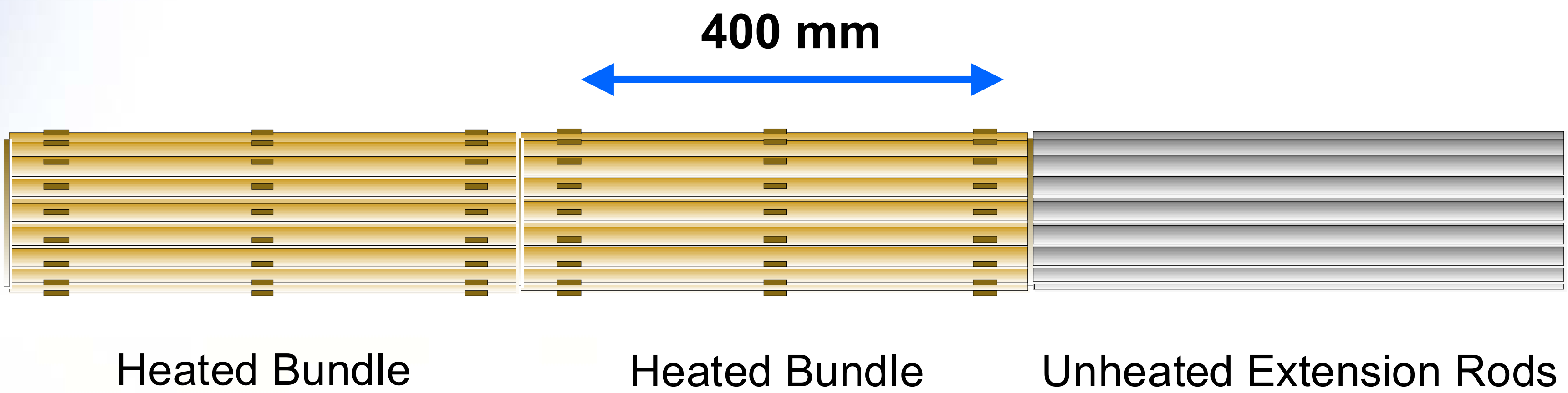


Instrumented Elements





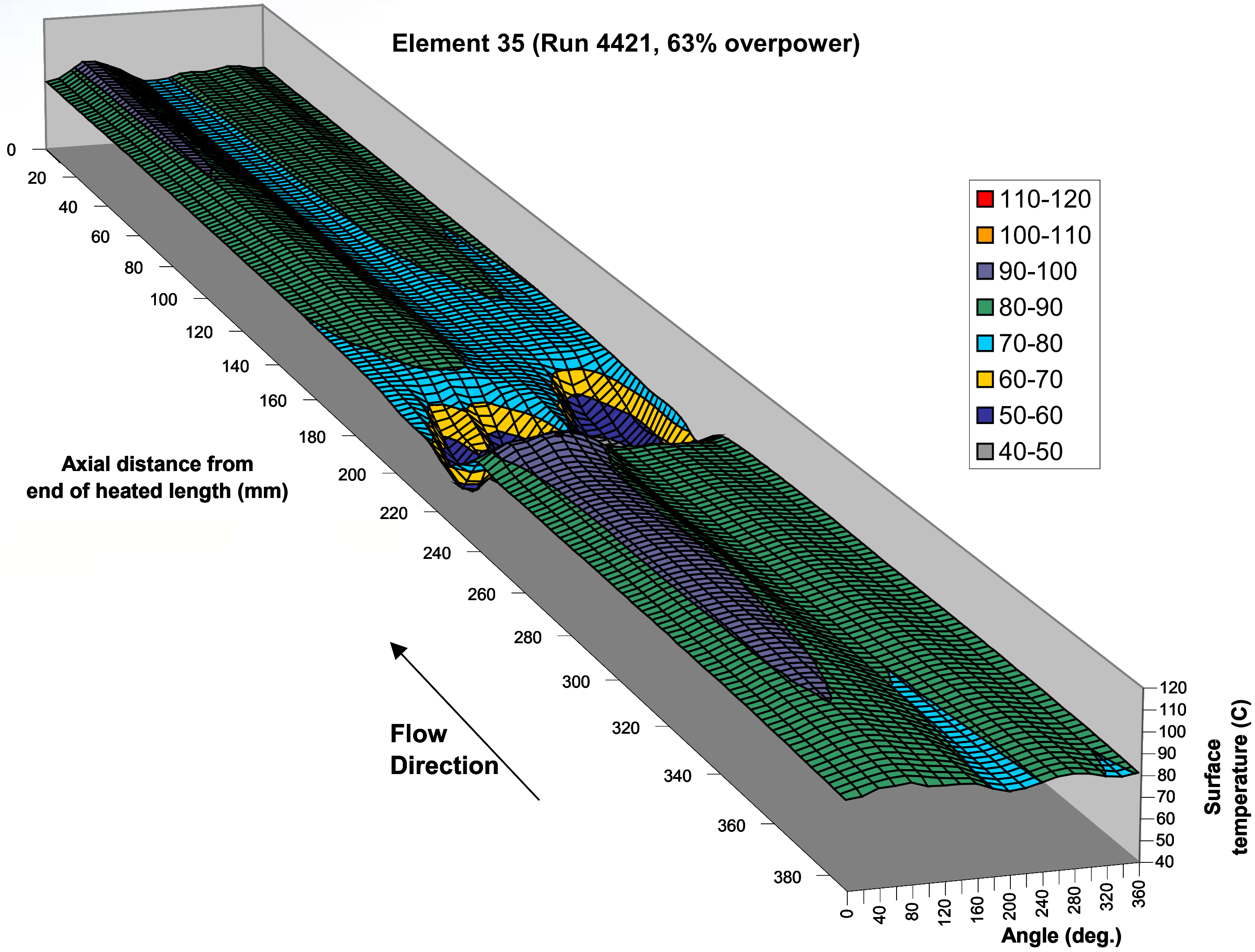
Axial Thermocouples Movement



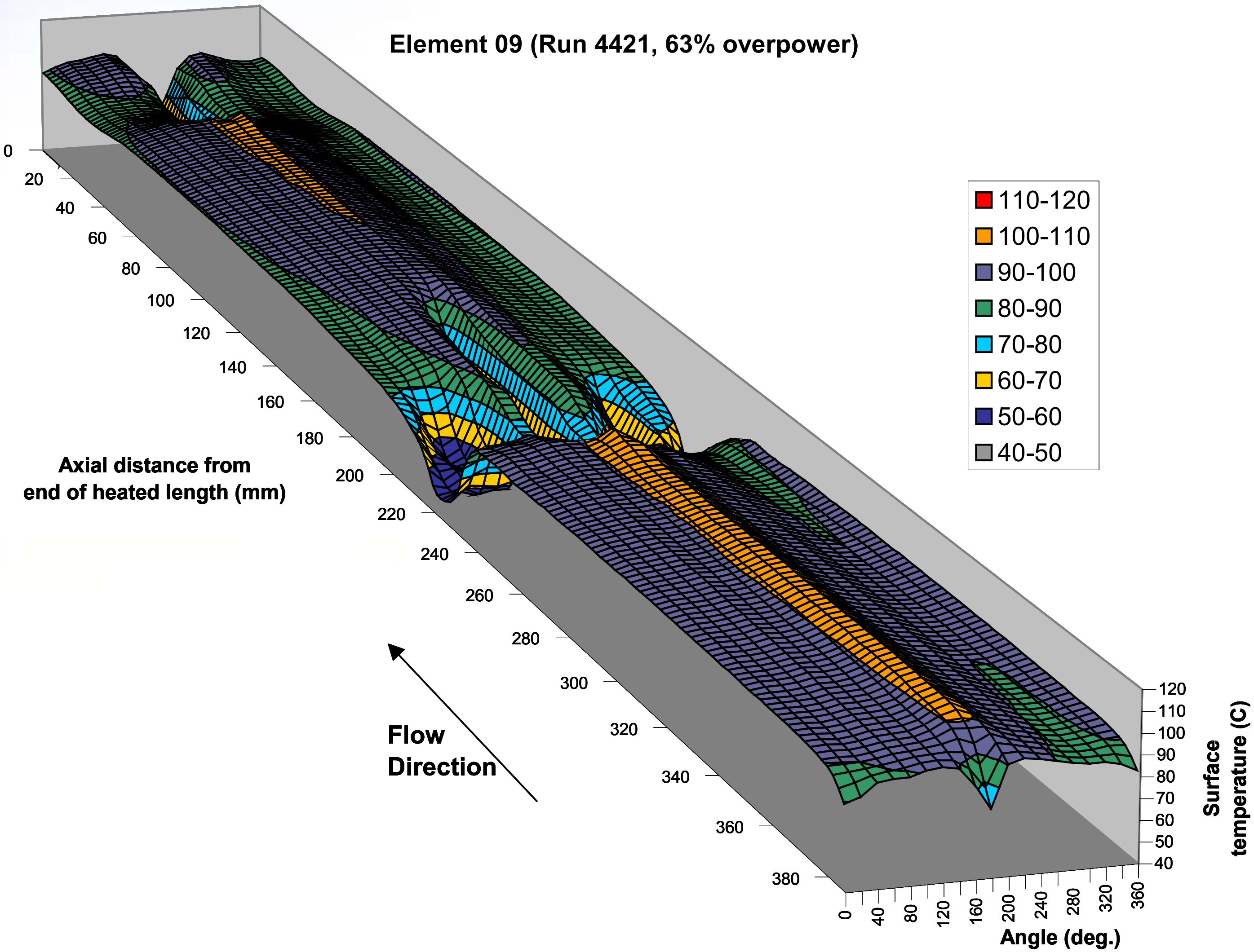
Test Conditions

	Freon-134a	Water Equivalent
Channel outlet pressure	0.97, 1.50, 1.77 MPa	6.0, 9.1, 10.7 MPa
Mass flow rate	7.1, 9.6, 12 $kg.s^{-1}$	10.6, 14.0, 17.5 $kg.s^{-1}$
Inlet quality	-0.02 to –0.41	-0.02 to –0.41

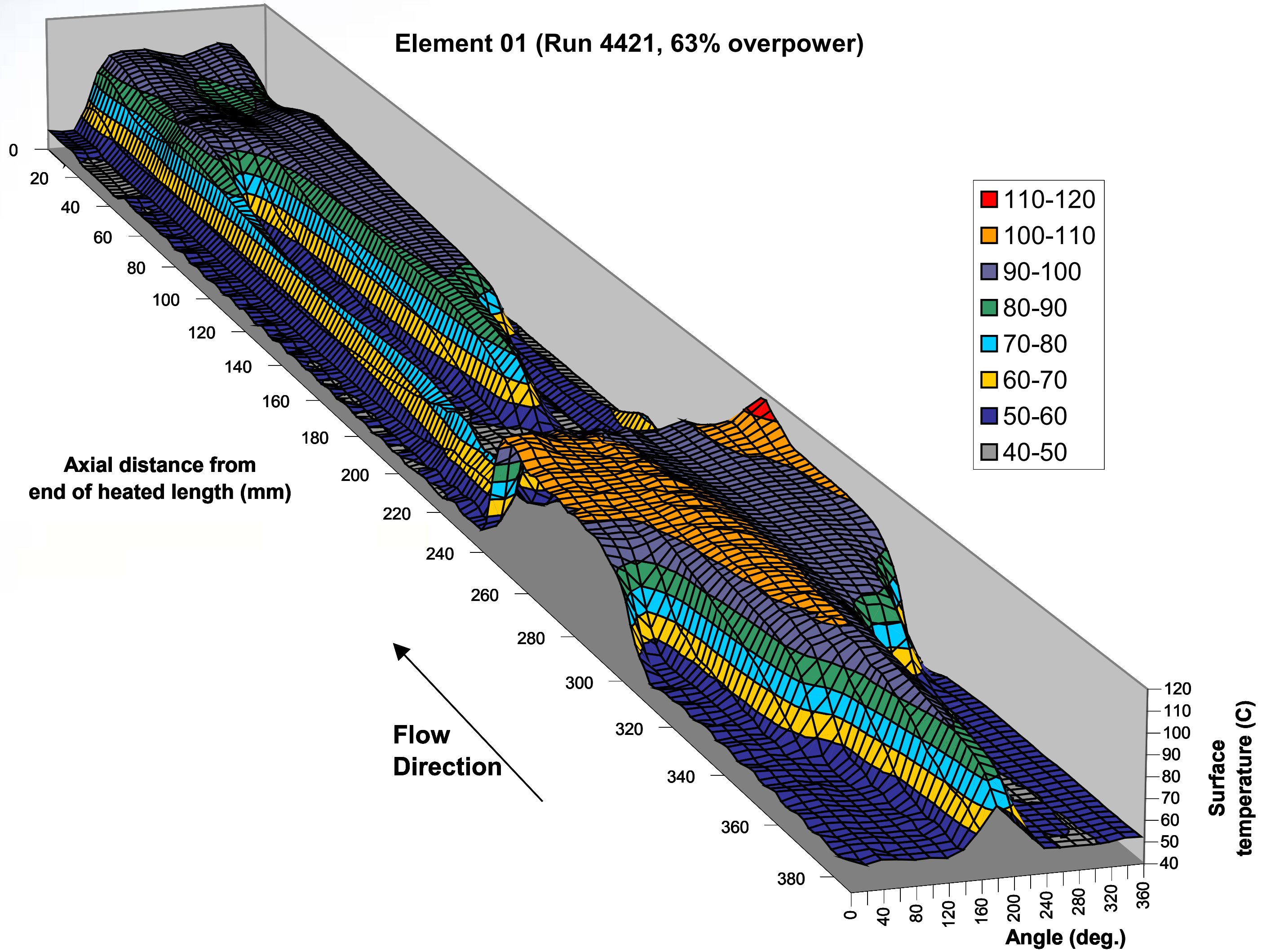
Axial and Circumferential Drypatches at an Inner-Ring Element



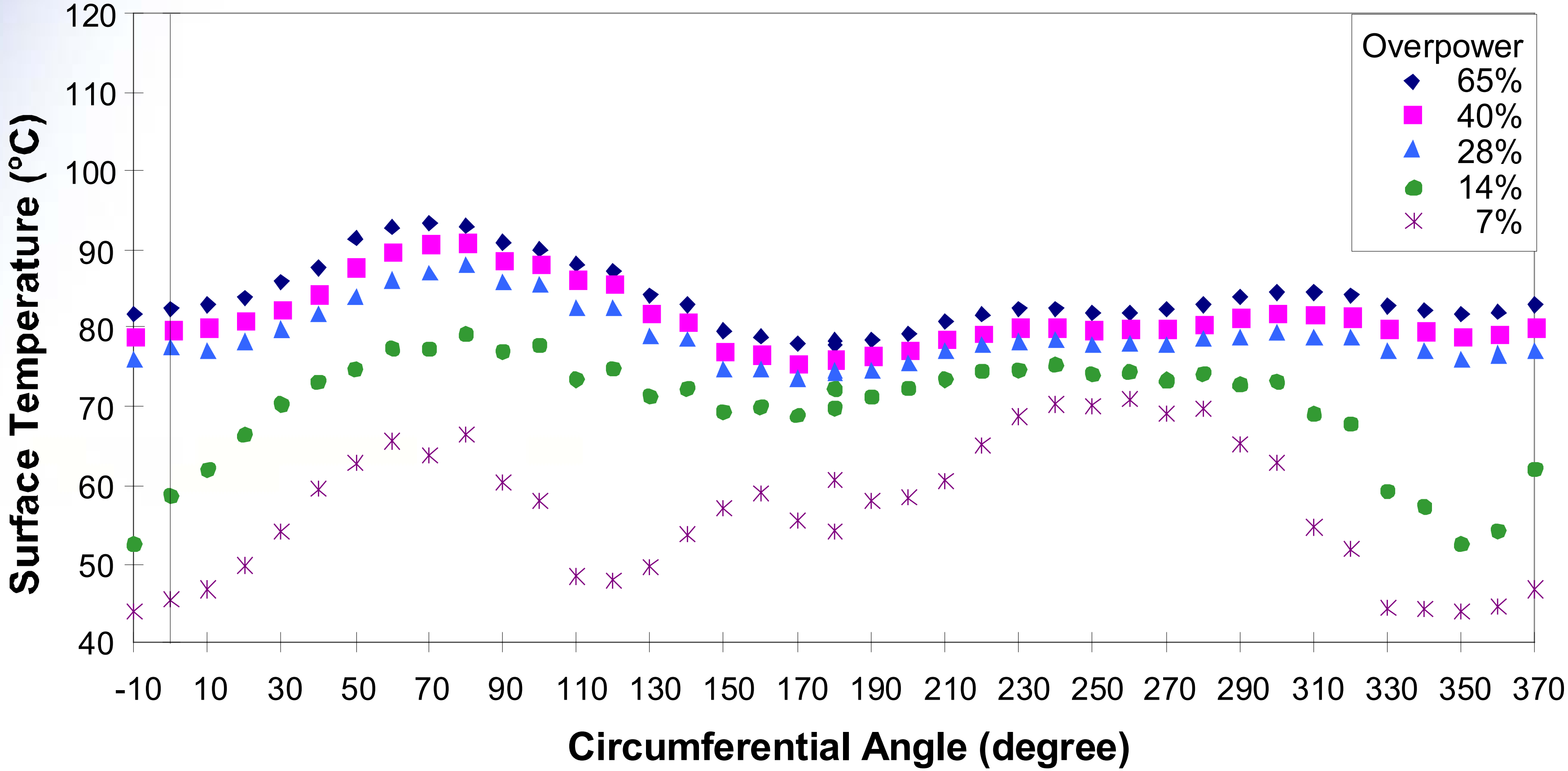
Axial and Circumferential Drypatches at the Bottom Element



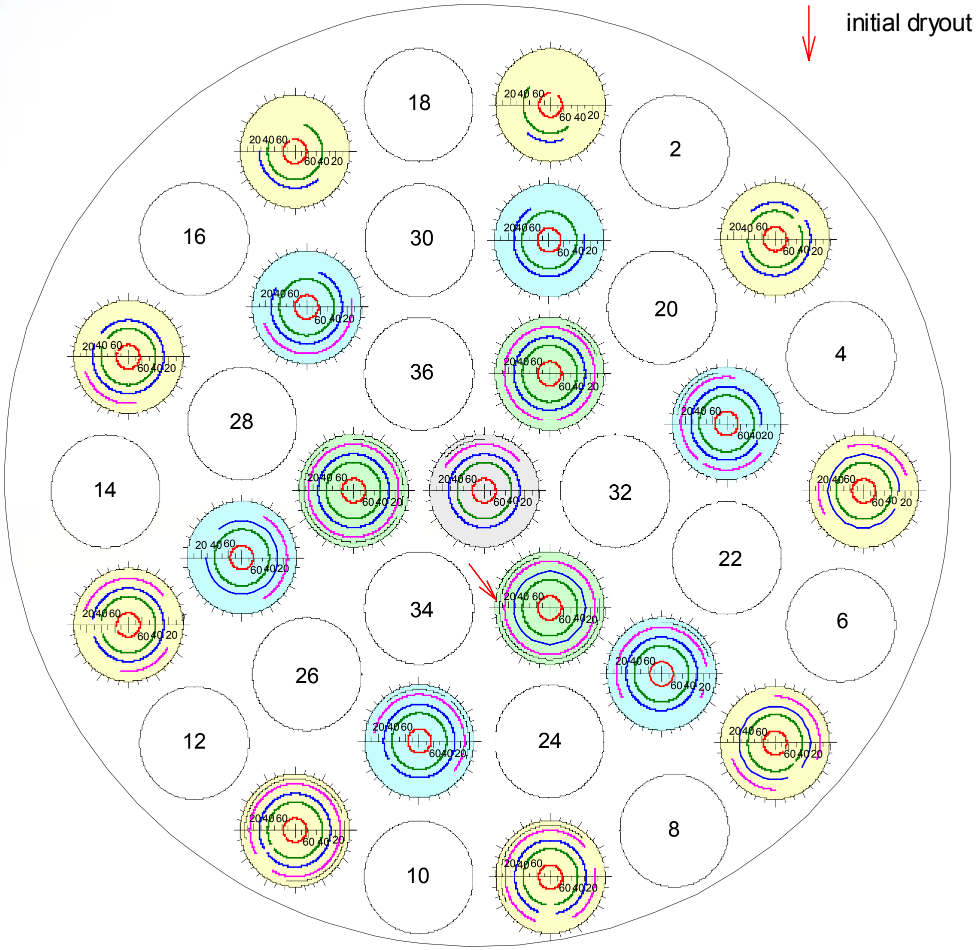
Axial and Circumferential Drypatches at the Top Element



Circumferential Temperature Profiles



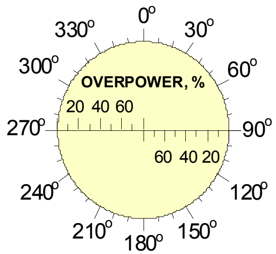
Bundle Circumferential Drypatches at the Initial Dryout Plane



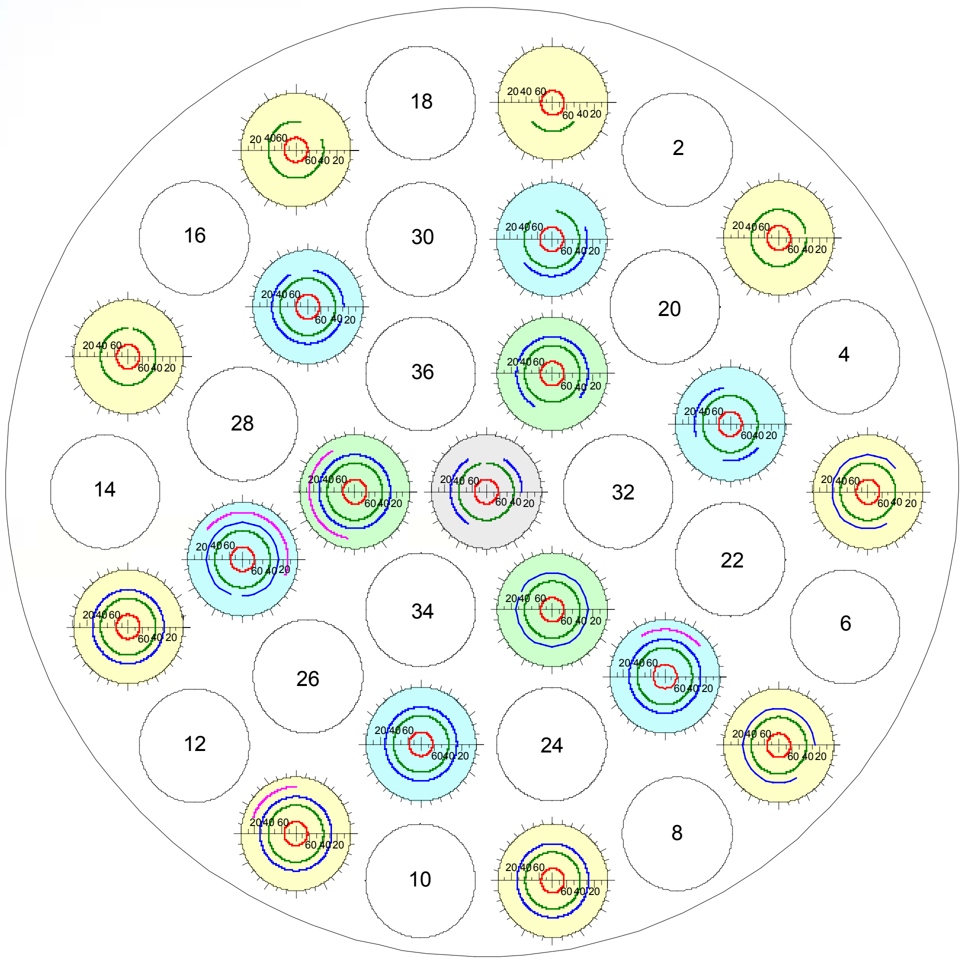
R-134a
Run 4421
Inlet Temperature 21.4°C
Mass Flow Rate 9.60 kg s^{-1}
Pressure 0.984 MPa
Dryout Power 713 kW
Axial Location 250 mm

Water

Inlet Temperature 228°C
Mass Flow Rate 13.93 kg s^{-1}
Pressure 6.11 MPa
Dryout Power 9819 kW



Bundle Circumferential Drypatches at the Spacer Plane



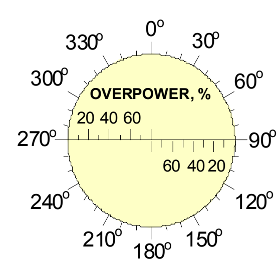
- 14% OVERPOWER
- 28% OVERPOWER
- 40% OVERPOWER
- 65% OVERPOWER

R-134a

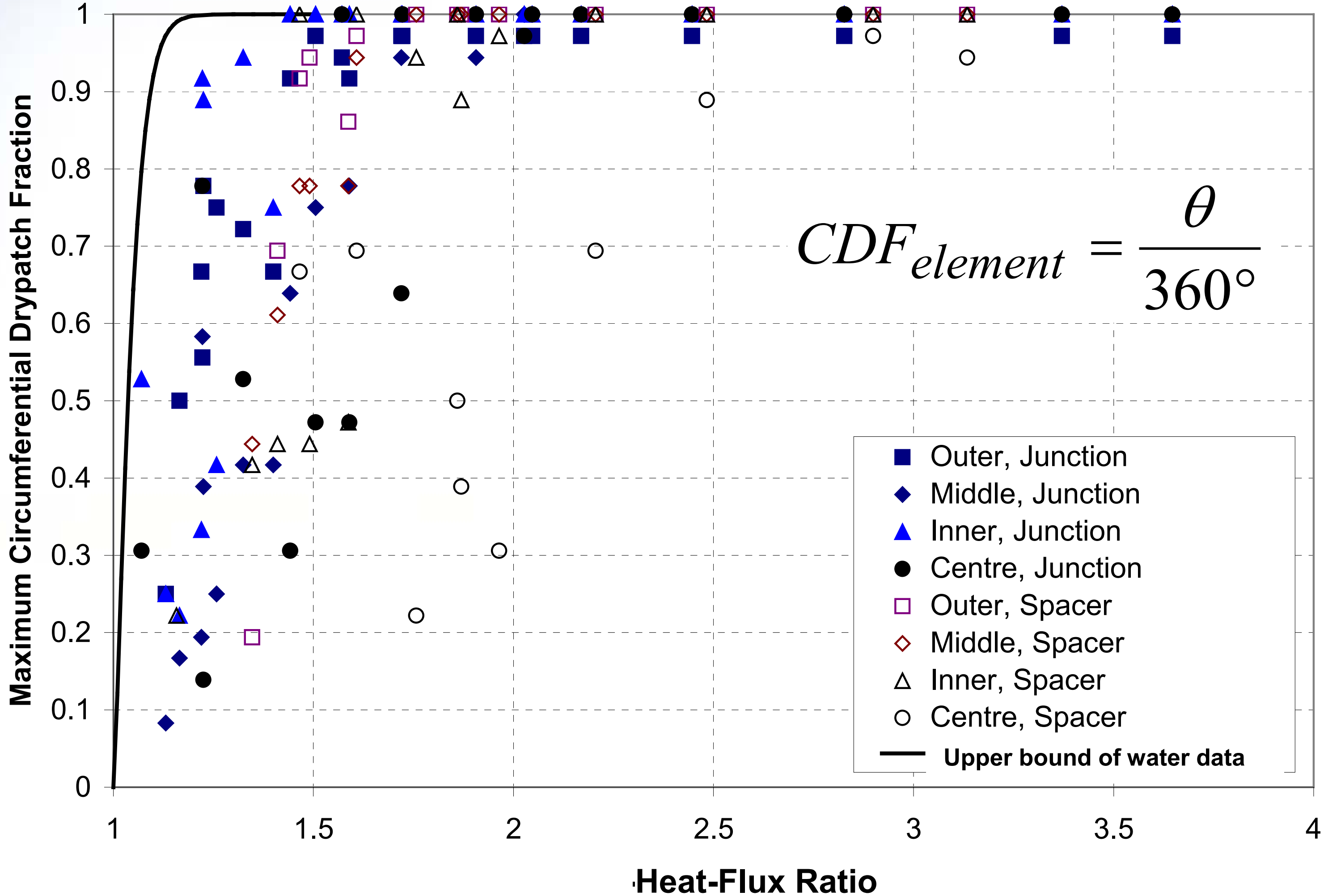
Run 4421
Inlet Temperature 21.4°C
Mass Flow Rate 9.60 kg s^{-1}
Pressure 0.984 MPa
Dryout Power 713 kW
Axial Location 250 mm

Water

Inlet Temperature 228°C
Mass Flow Rate 13.93 kg s^{-1}
Pressure 6.11 MPa
Dryout Power 9819 kW

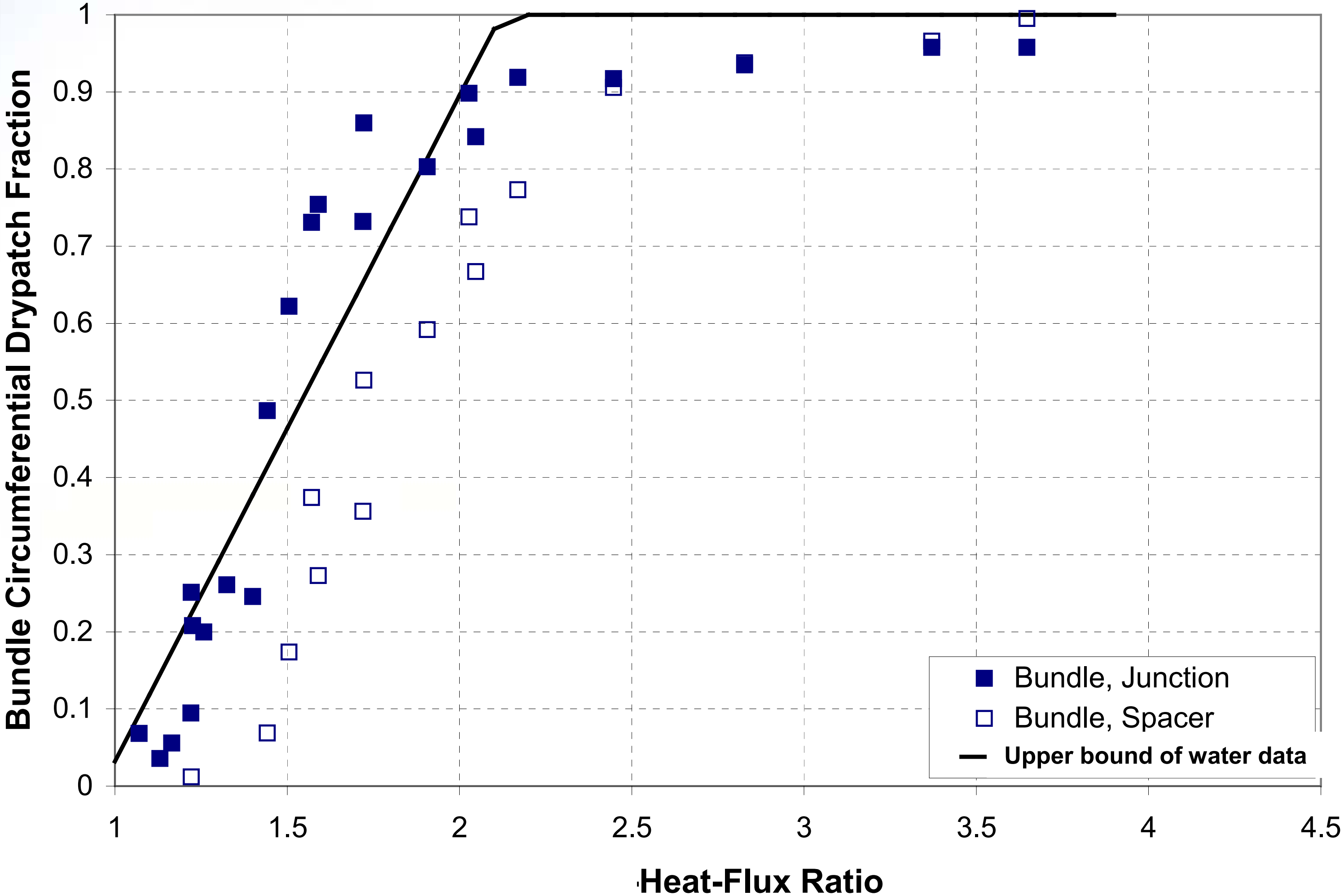


Maximum Circumferential Drypatch Fraction

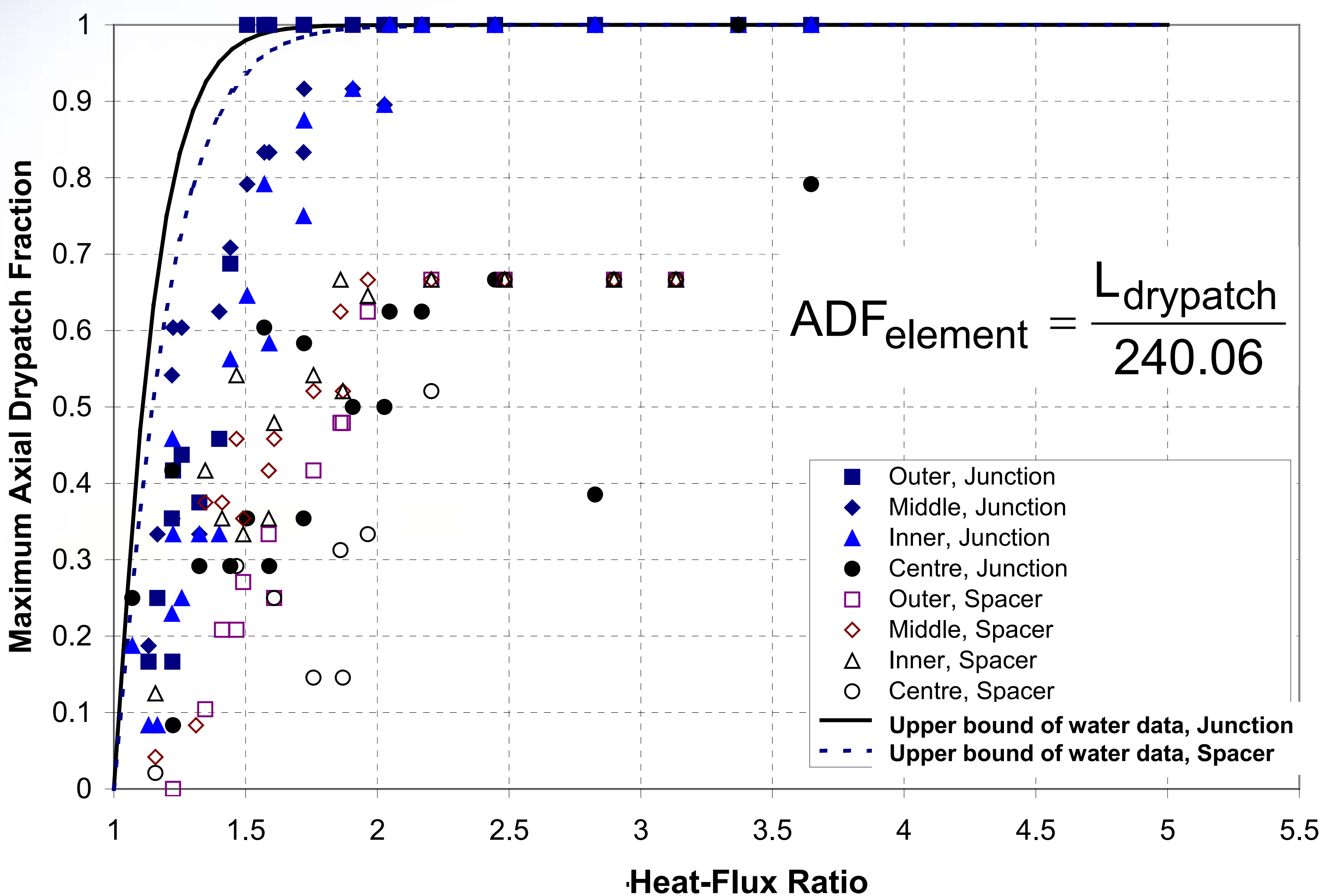


$$CDF_{element} = \frac{\theta}{360^\circ}$$

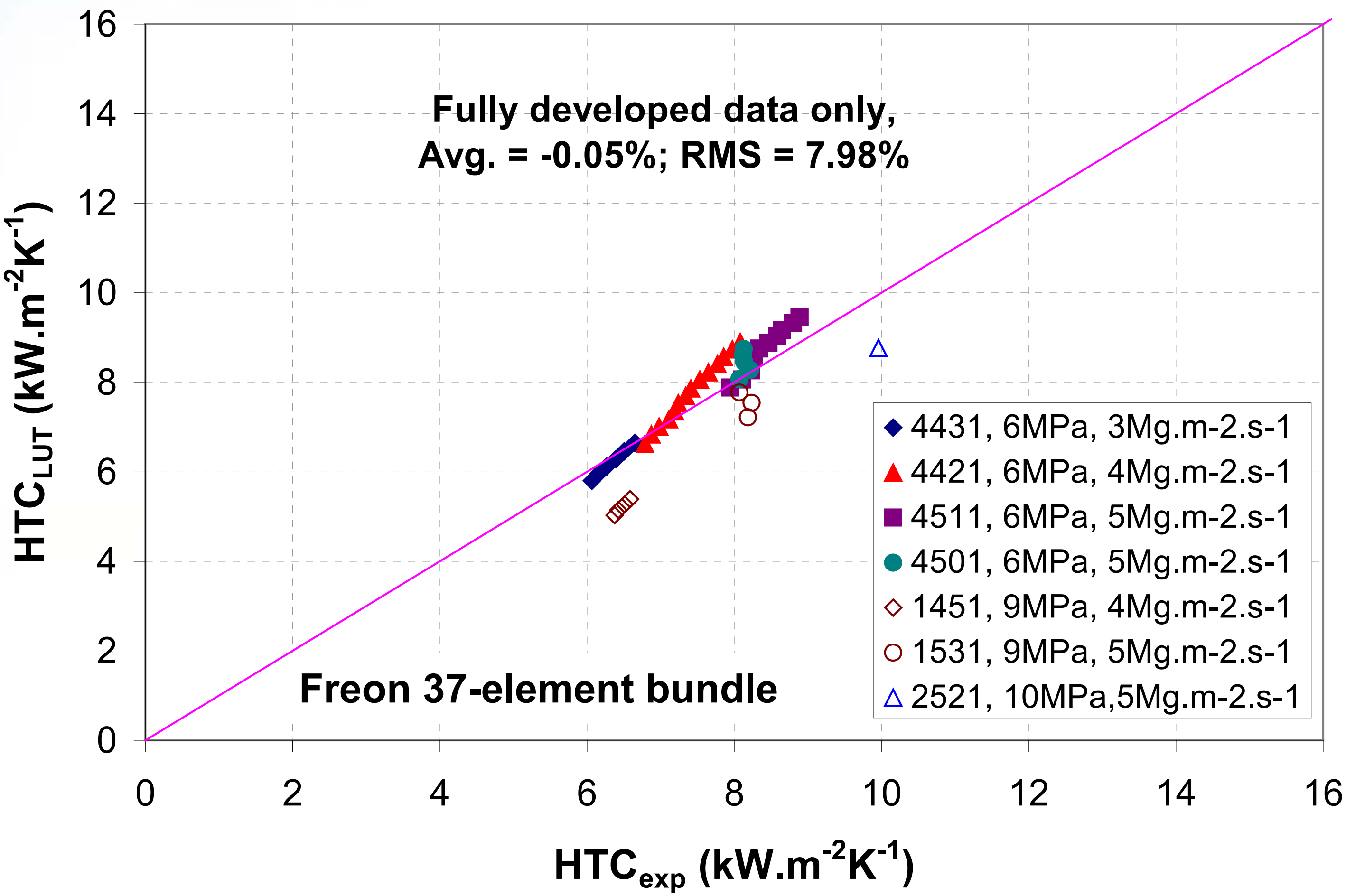
Bundle Circumferential Drypatch Fraction



Maximum Axial Drypatch Fraction



Verification of the Film-Boiling Table Against 37-Element Bundle Data



Summary

- **Mechanism and flow patterns of post-dryout heat transfer have been described**
  - **Transition boiling**
  - **Film boiling**
- **Correlations for post-dryout heat transfer coefficient and minimum film-boiling temperature have been presented**
- **Post-dryout temperature measurements have been illustrated for tubes and bundles**
- **Detailed post-dryout sheath temperature maps and drypatch fractions have been presented**

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