UNENE Graduate Course Reactor Thermal-Hydraulics Design and Analysis

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Critical Heat Flux

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Outline

- Background
- Terminologies
- Mechanisms
- Experimental techniques
- Prediction Methods
- Applications for design and safety analyses
- Summary

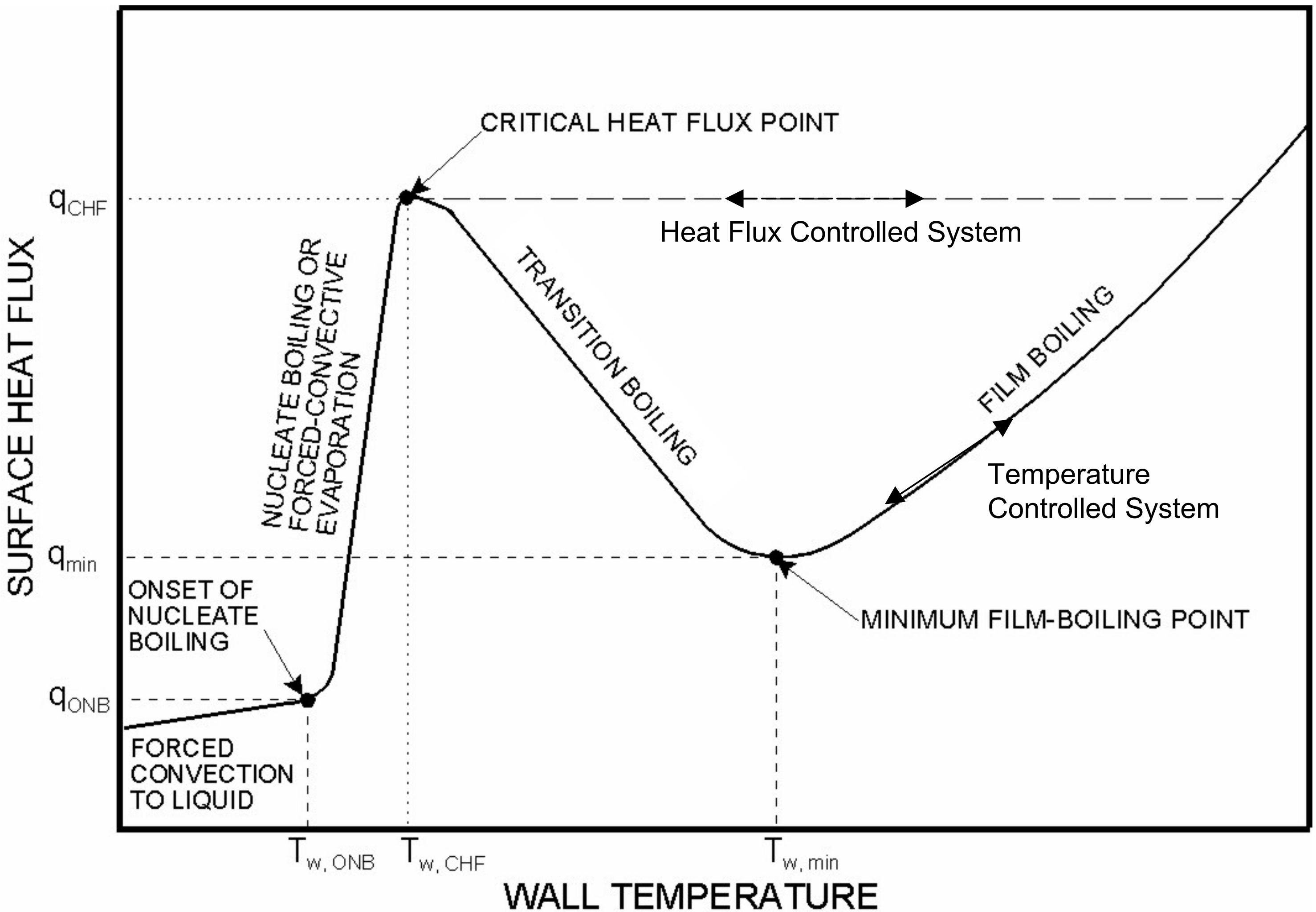
Critical Heat Flux

- Critical heat flux (CHF)
  - A phenomenon corresponding to the point where a continuous liquid contact cannot be maintained at the heated surface
  - Strictly speaking, this particular term refers to the heat flux corresponding to the occurrence of the phenomenon
  - Other terms often used: burnout, dryout, boiling crisis, and departure from nucleate boiling (DNB)
- Applications
  - Chemical, mechanical, and nuclear industries
  - Nuclear reactors and heat exchangers (boilers and condensers)
  - This presentation focuses on nuclear reactor applications

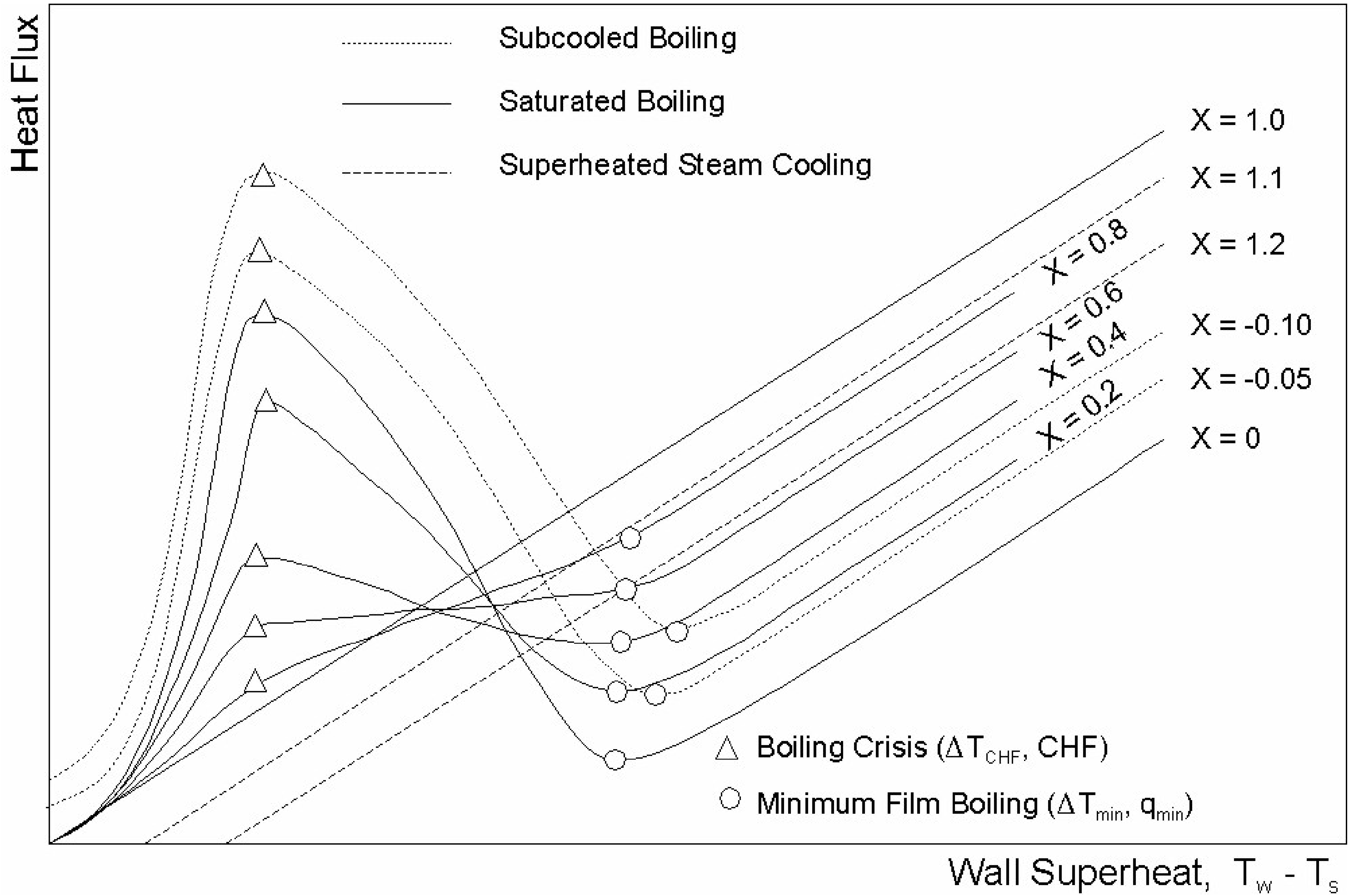
Consequences of exceeding CHF

- Heat transfer rate between surface and coolant drops suddenly
  - Small increase in heat flux leads to large increase in surface temperature for a heat-flux-controlled surface (e.g., electric heaters)
  - Small increase in surface temperature leads to decrease in heat flux for a temperature-controlled surface (e.g., steam condensers)
- Surface may overheat and become damaged
- Corrosion may occur in CHF region
- Reduction in operating efficiency

Boiling Curve



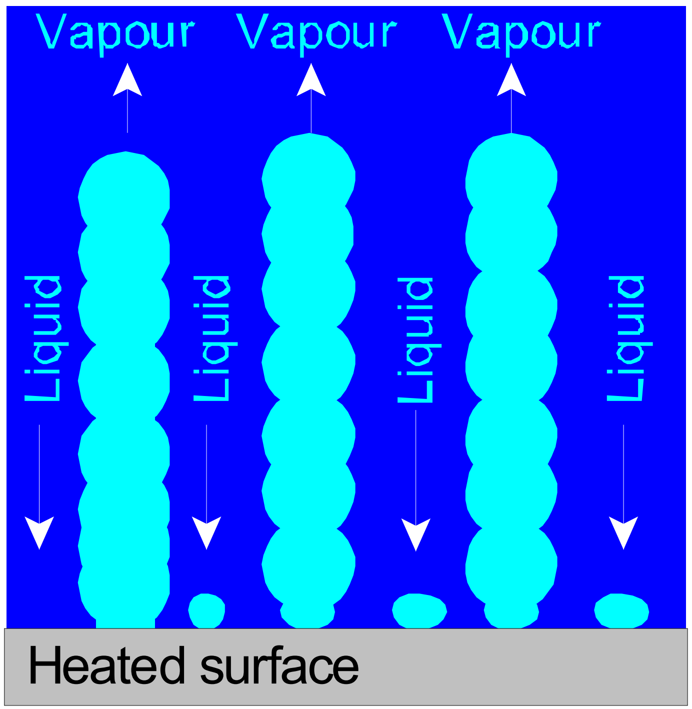
Quality Effect on Boiling Curves

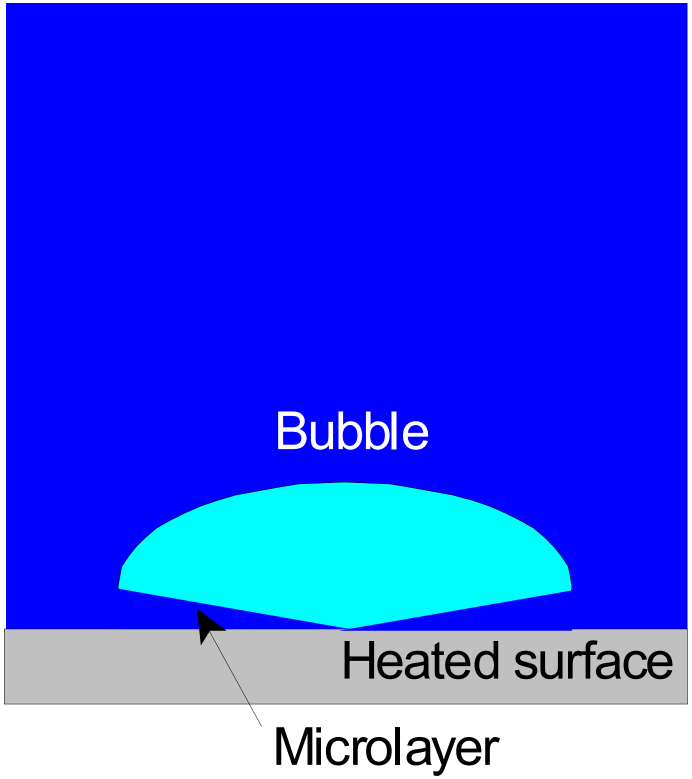


CHF Mechanisms

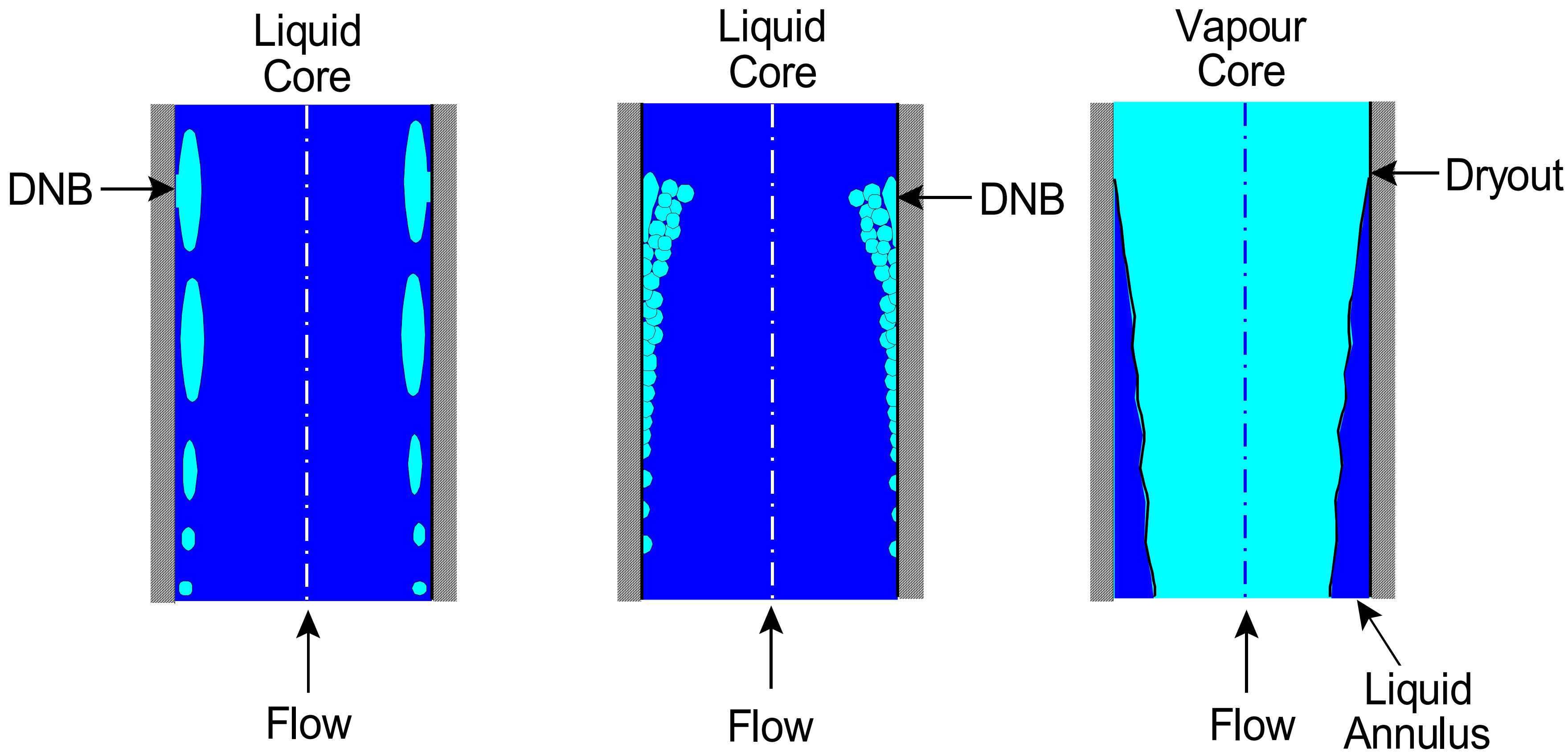
- Pool Boiling
  - Countercurrent flow (helmholtz) instability
  - Micro-layer evaporation (highly subcooled conditions only)
- Flow Boiling
  - Collapse of liquid sub-layer
  - Bubble crowding
  - Film depletion

Pool Boiling CHF Mechanisms

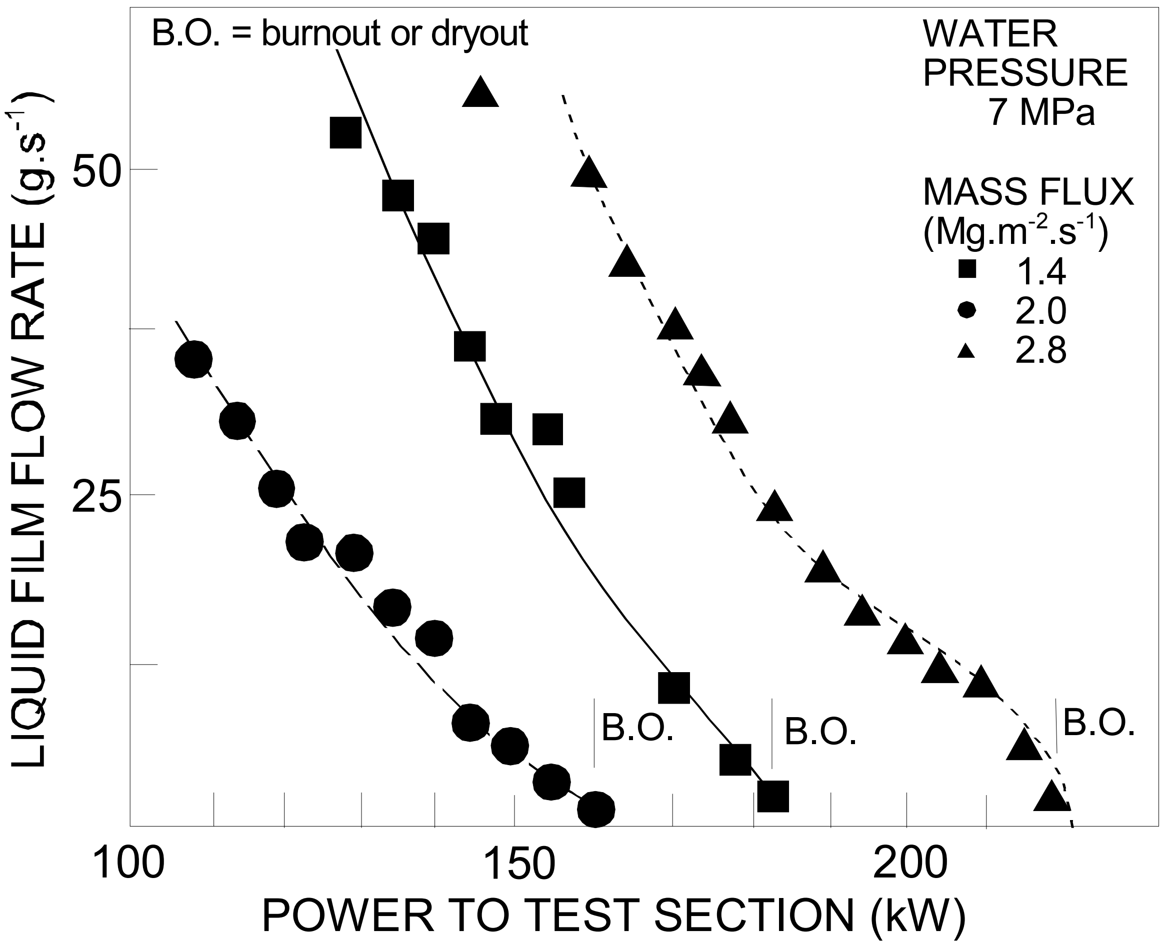




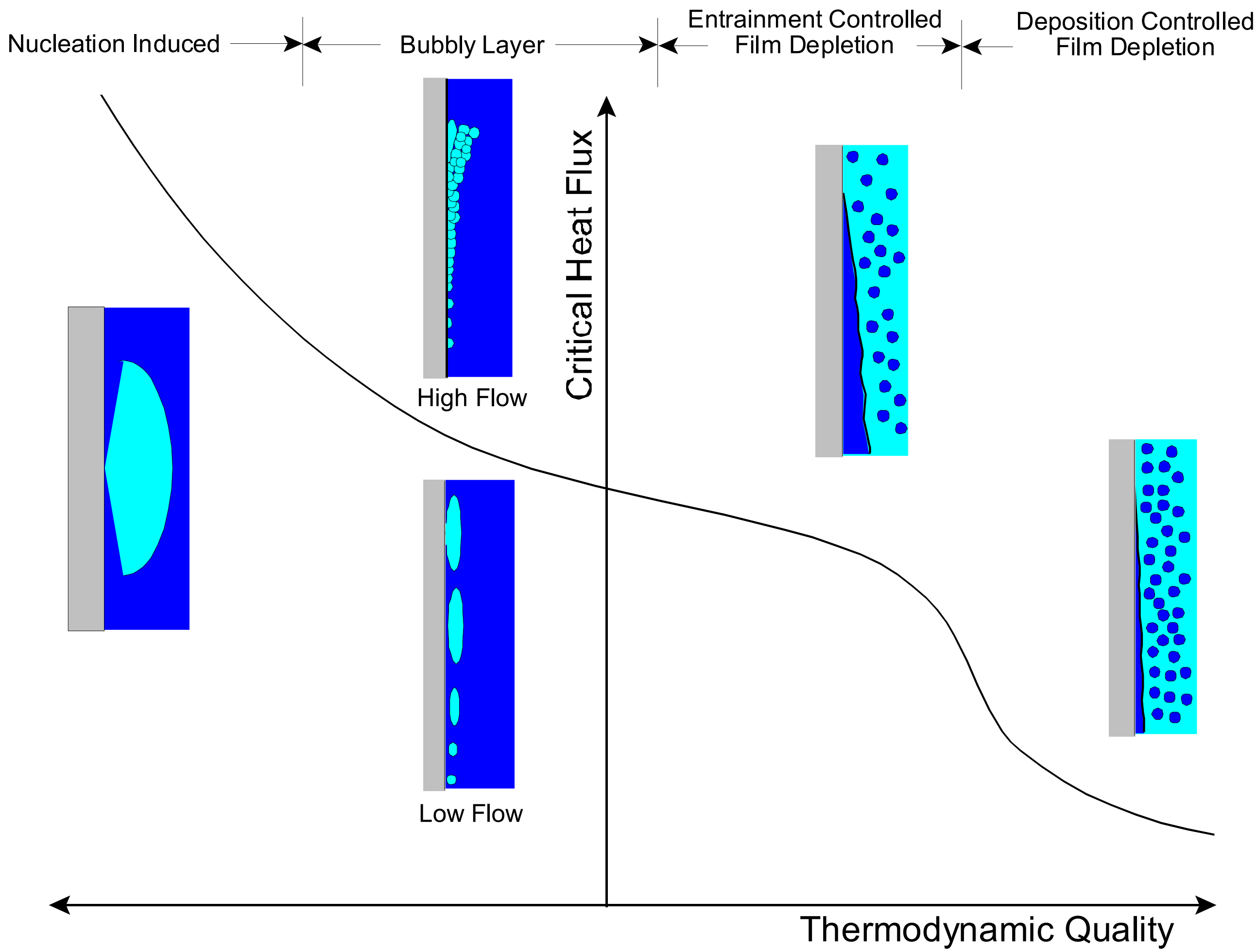
Flow Boiling CHF Mechanisms



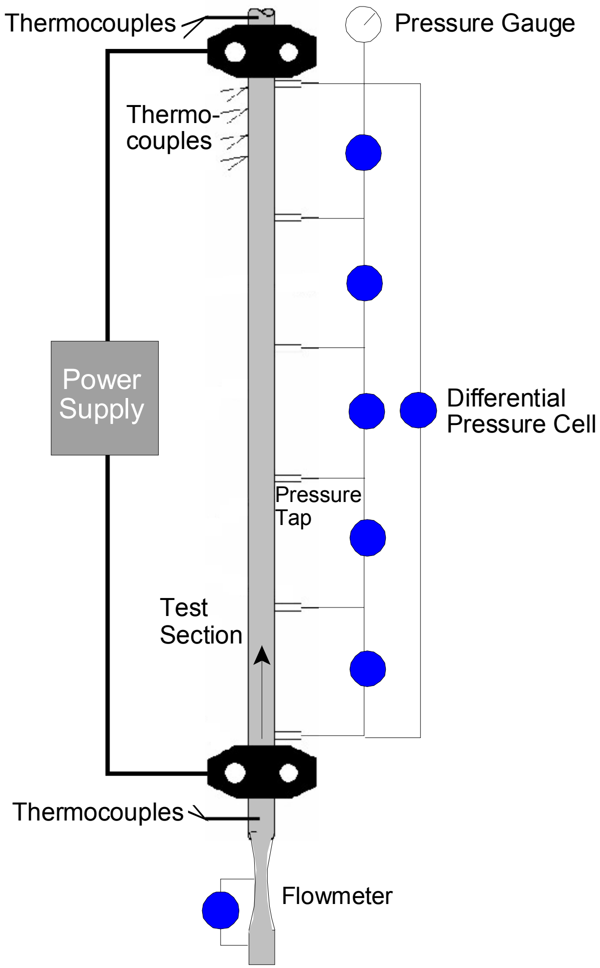
Variation of Film Flow Rate



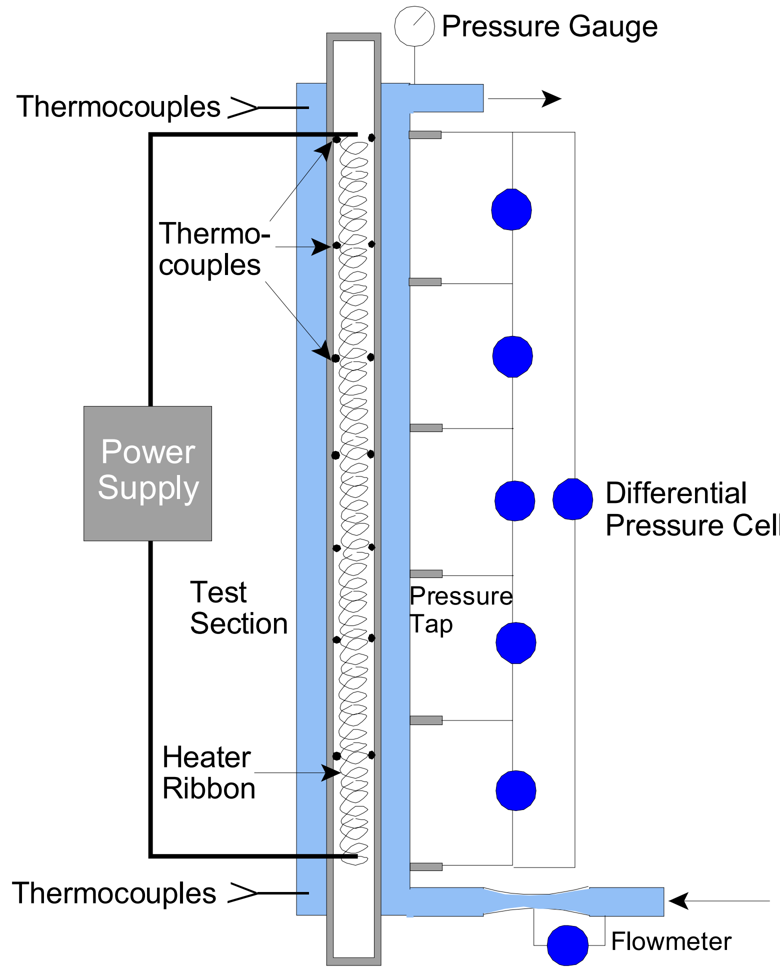
Transition of CHF Mechanisms



CHF Experiments in Simple Geometry



Direct Heating

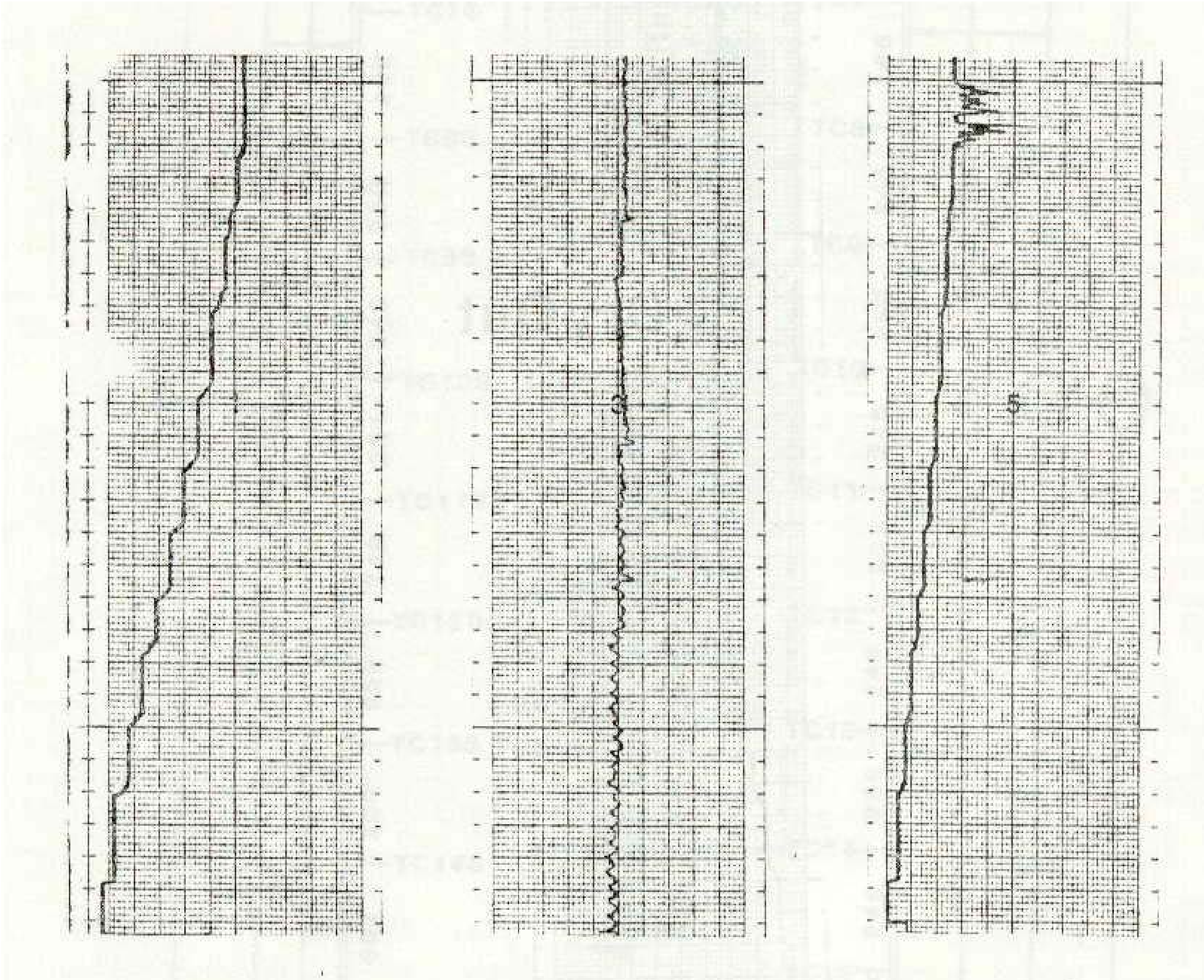


Indirect Heating

Measurements of Temperature Rise

- Stationary thermocouples
  - Burnout/dryout at specific locations
  - May not represent initial CHF value
  - No information on subsequent CHF and drypatch spreading
- Moveable thermocouples
  - Provide coverage almost over the entire heated sheath
  - Provide initial CHF, subsequent CHF and drypatch spreading
  - More conservative
  - Time consuming (scanning of the entire area)

Temperature Traces in Tube CHF Test

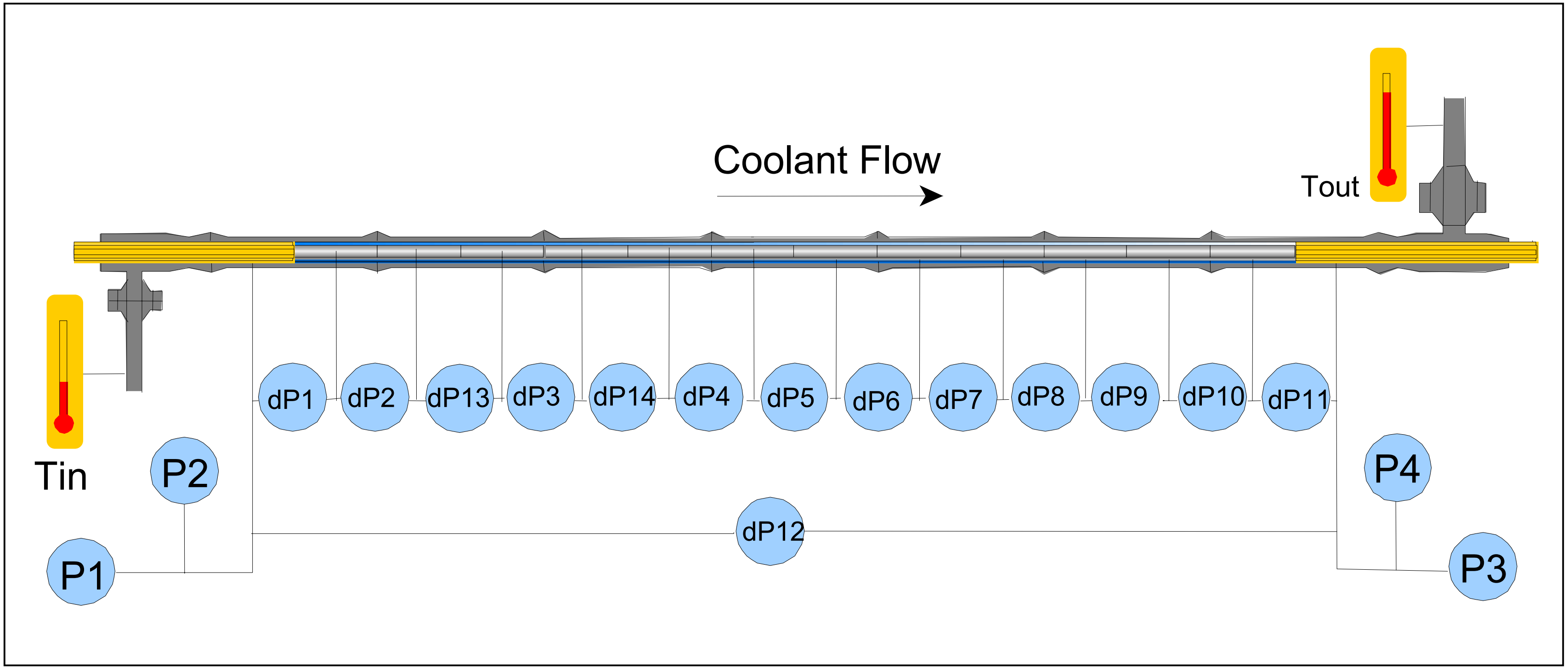


Power

Flow

Surface Temperature

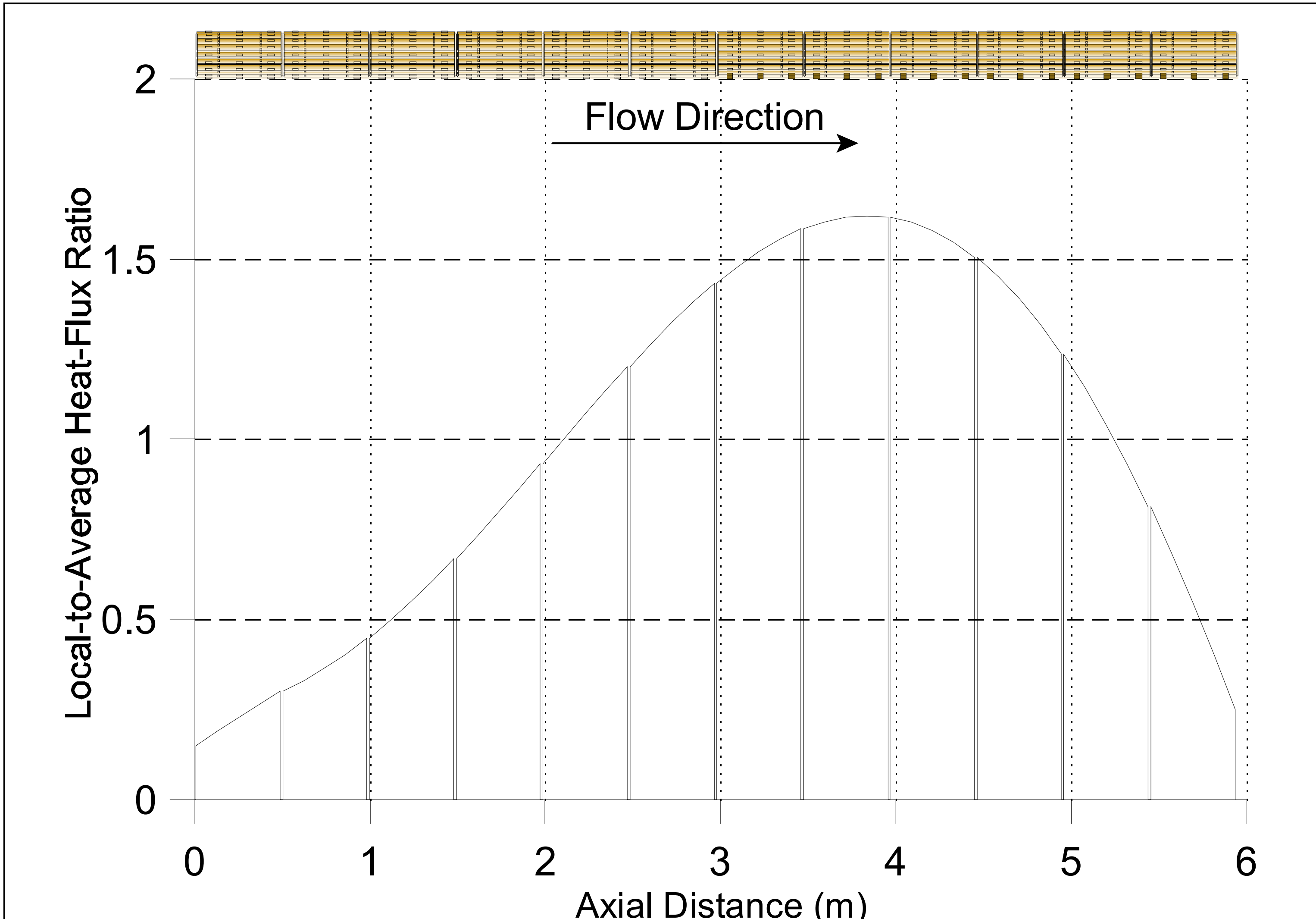
SL Water Test Station



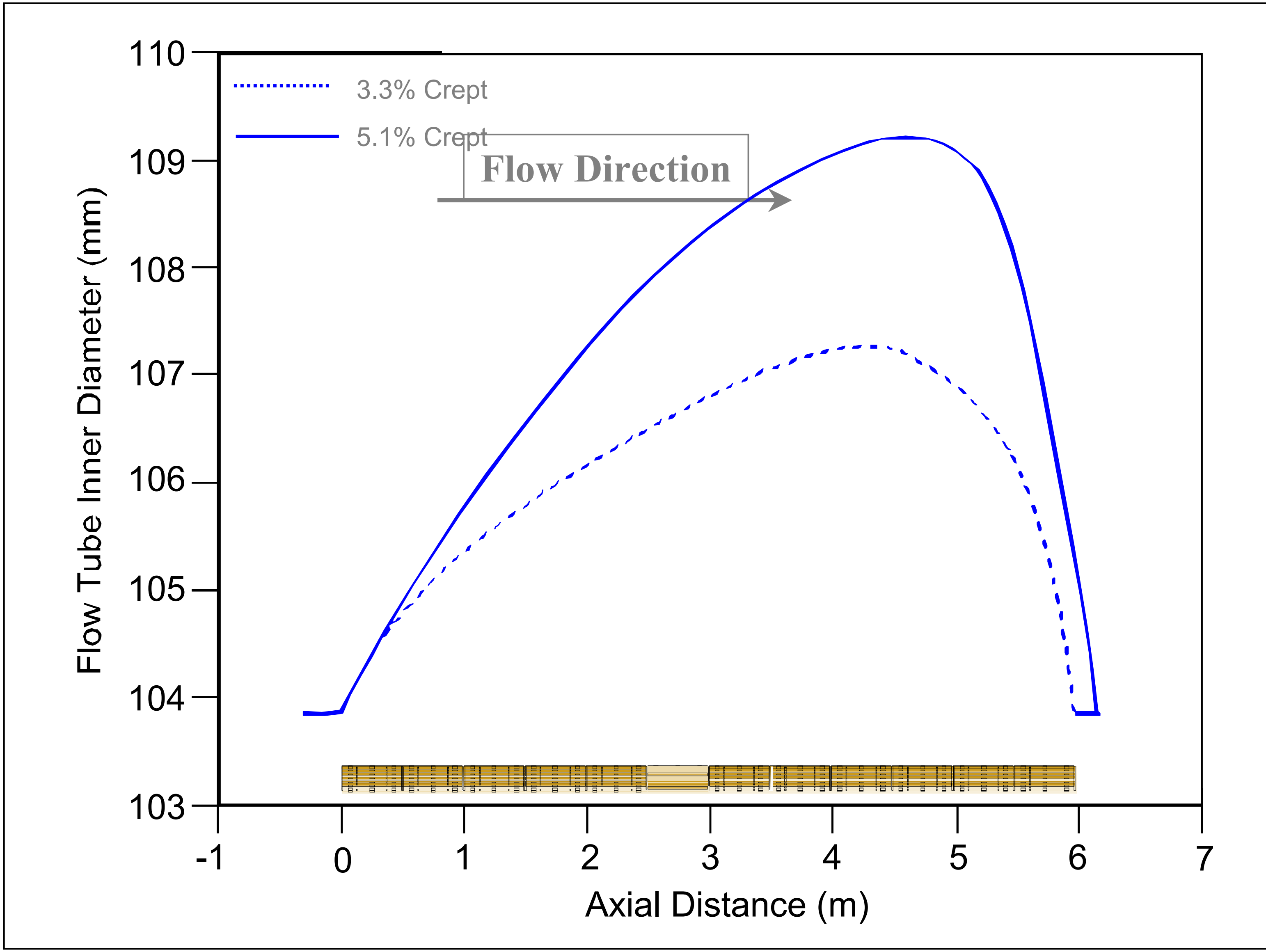
Bundle Simulators

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

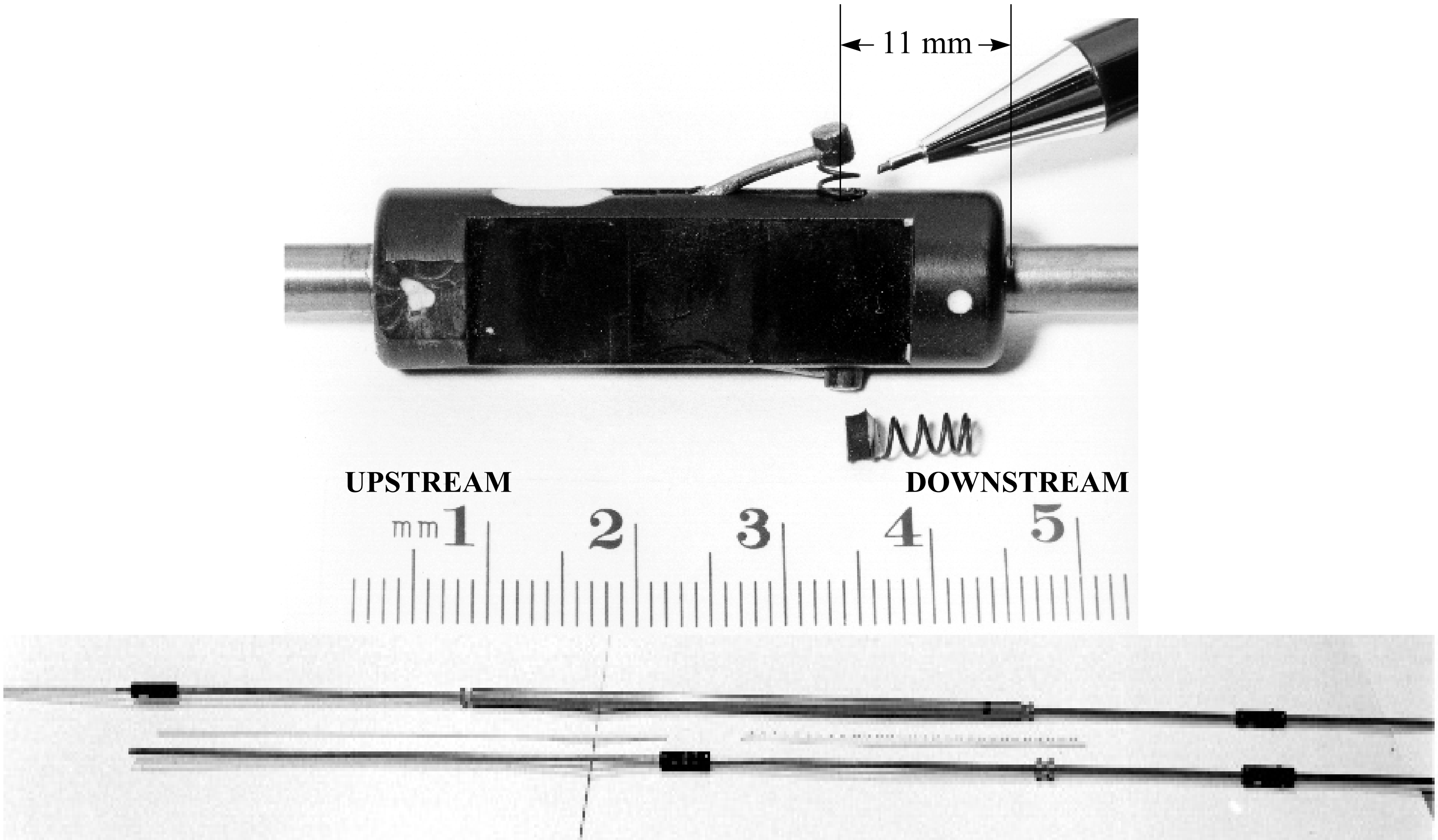
AFD in SL Full-Scale Bundle Test



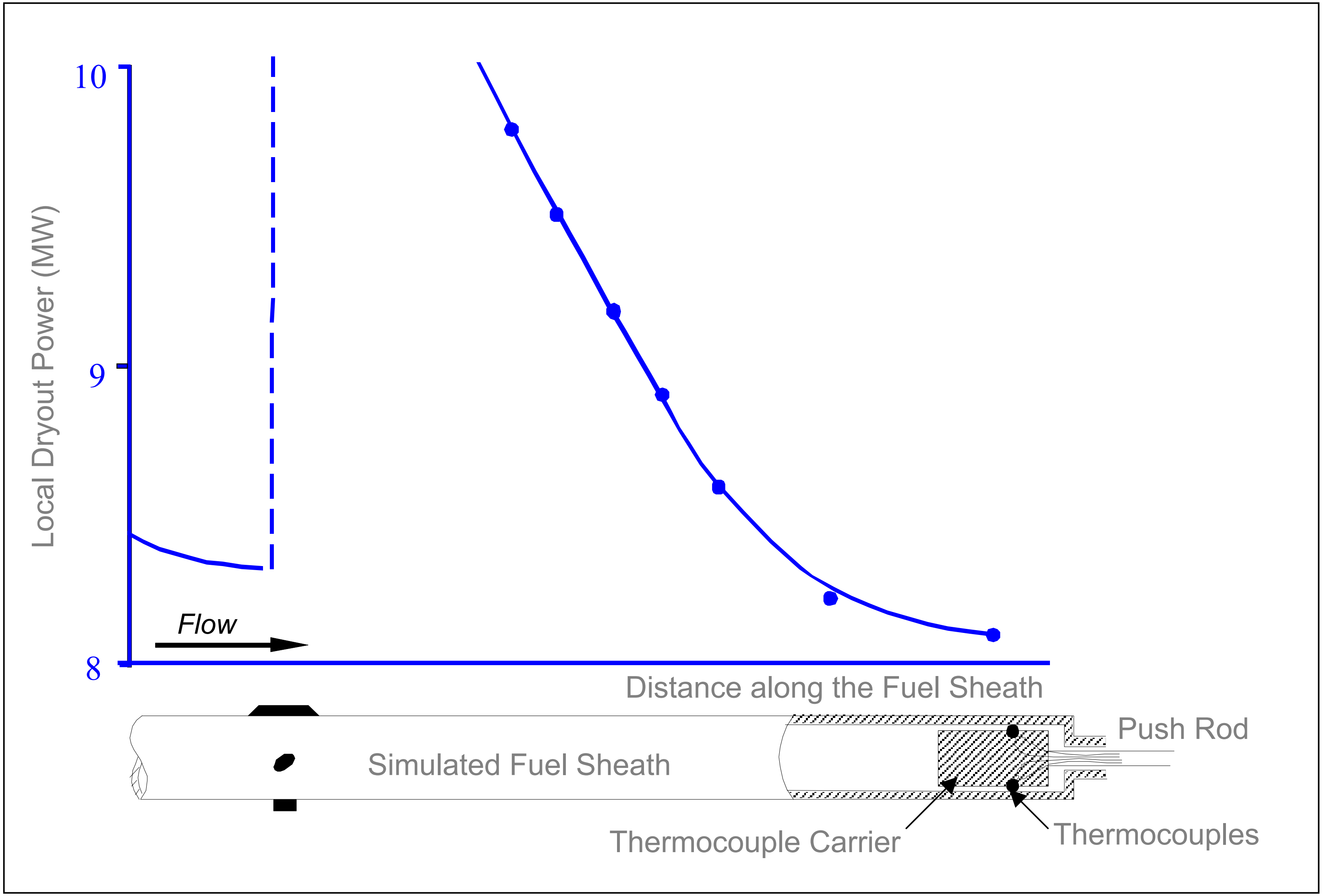
Axial Flow Tube Diameter Variation



Moveable Thermocouples



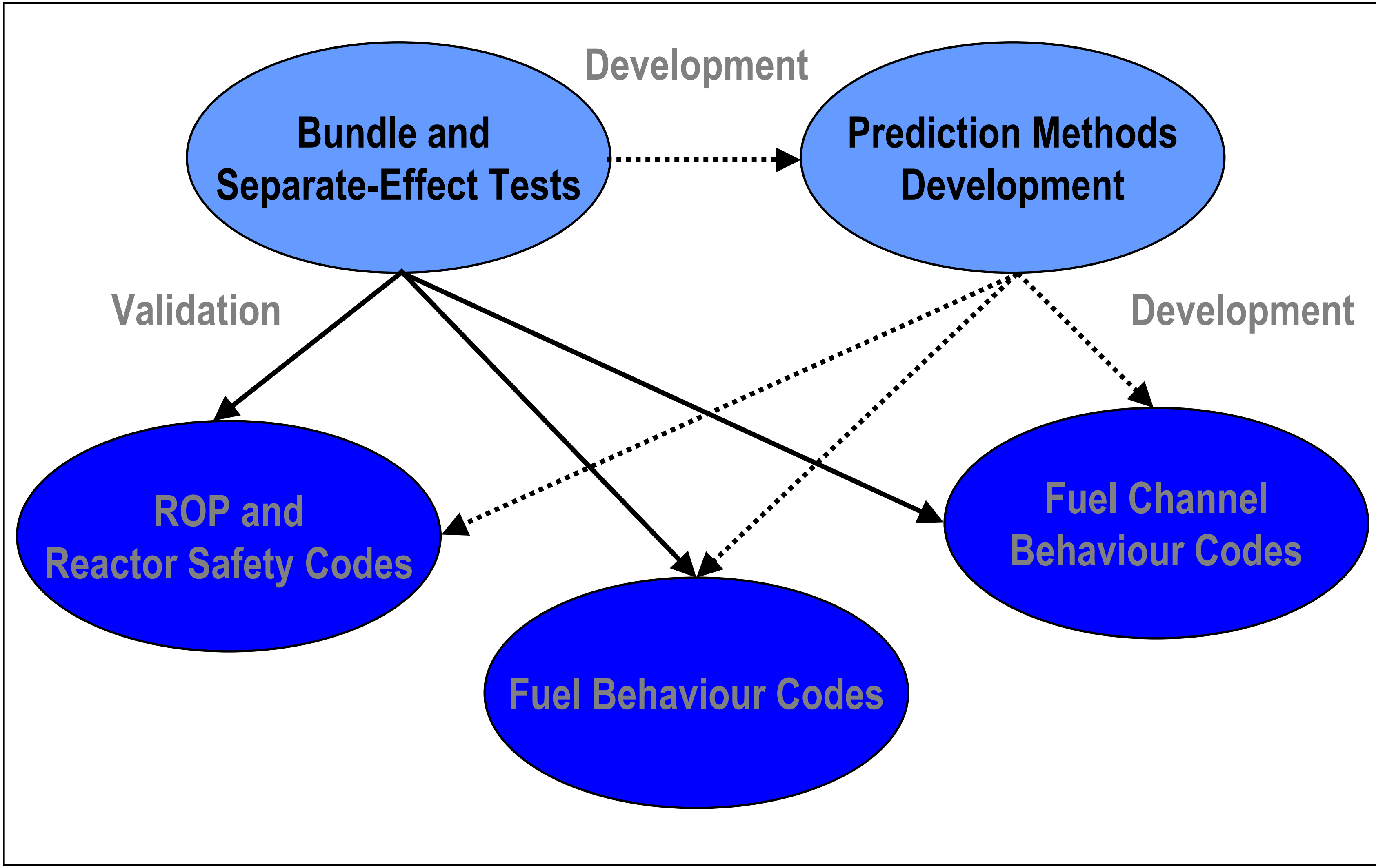
CHF Variations Along Heated Surface



Applications of CHF Data

- Licensing submissions of nuclear reactors
  - Mainly full-scale bundle data
  - Quantification of impact of separate effects
- Understanding the phenomenon
  - Fundamental and bundle specific studies
  - Parametric and separate effects
- Developing correlations and models
  - Ad hoc equations for specific applications
  - Generalized methods for wide range of applications
- Validating correlations, models and reactor safety codes

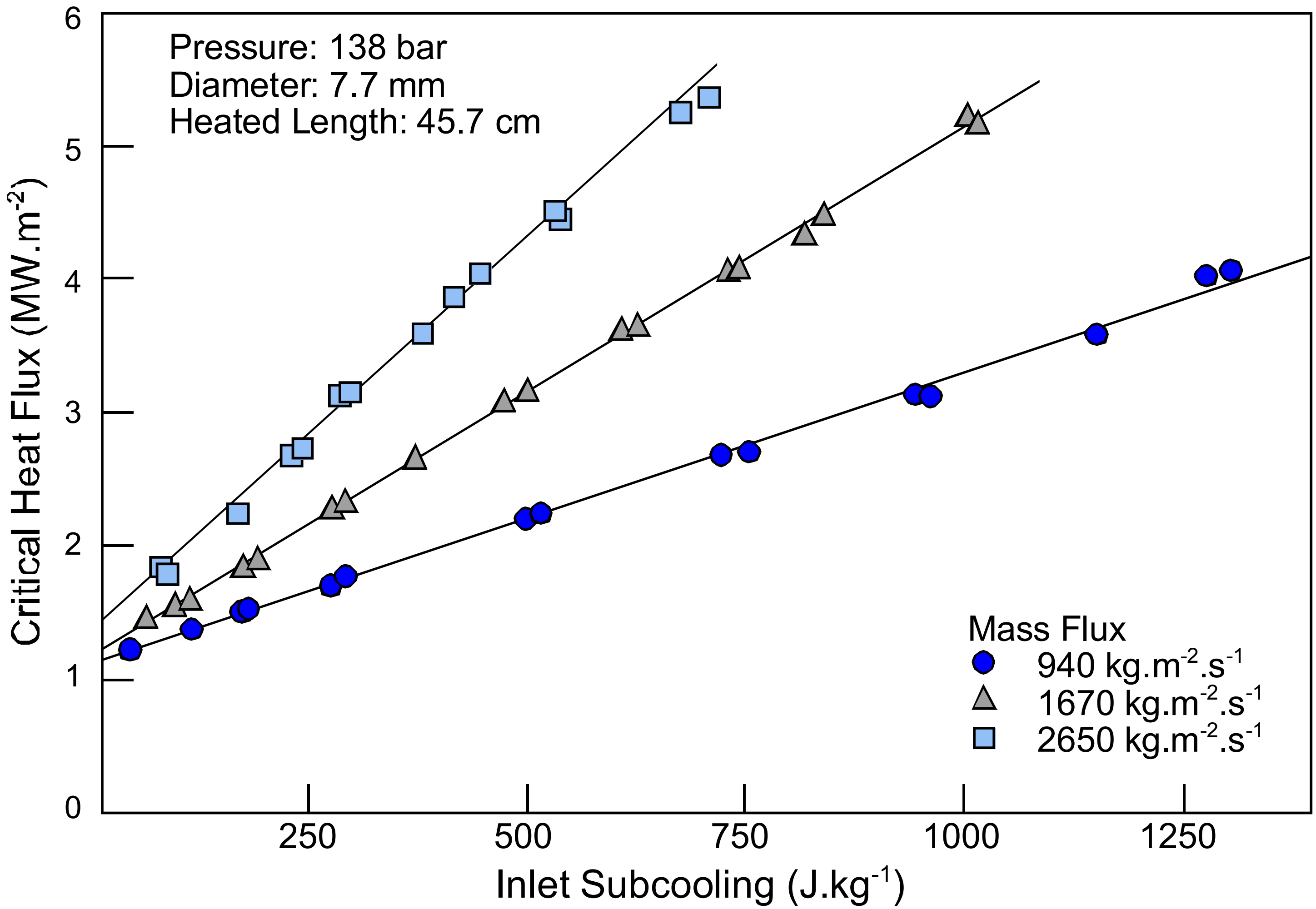
Overview of CHF Data Applications



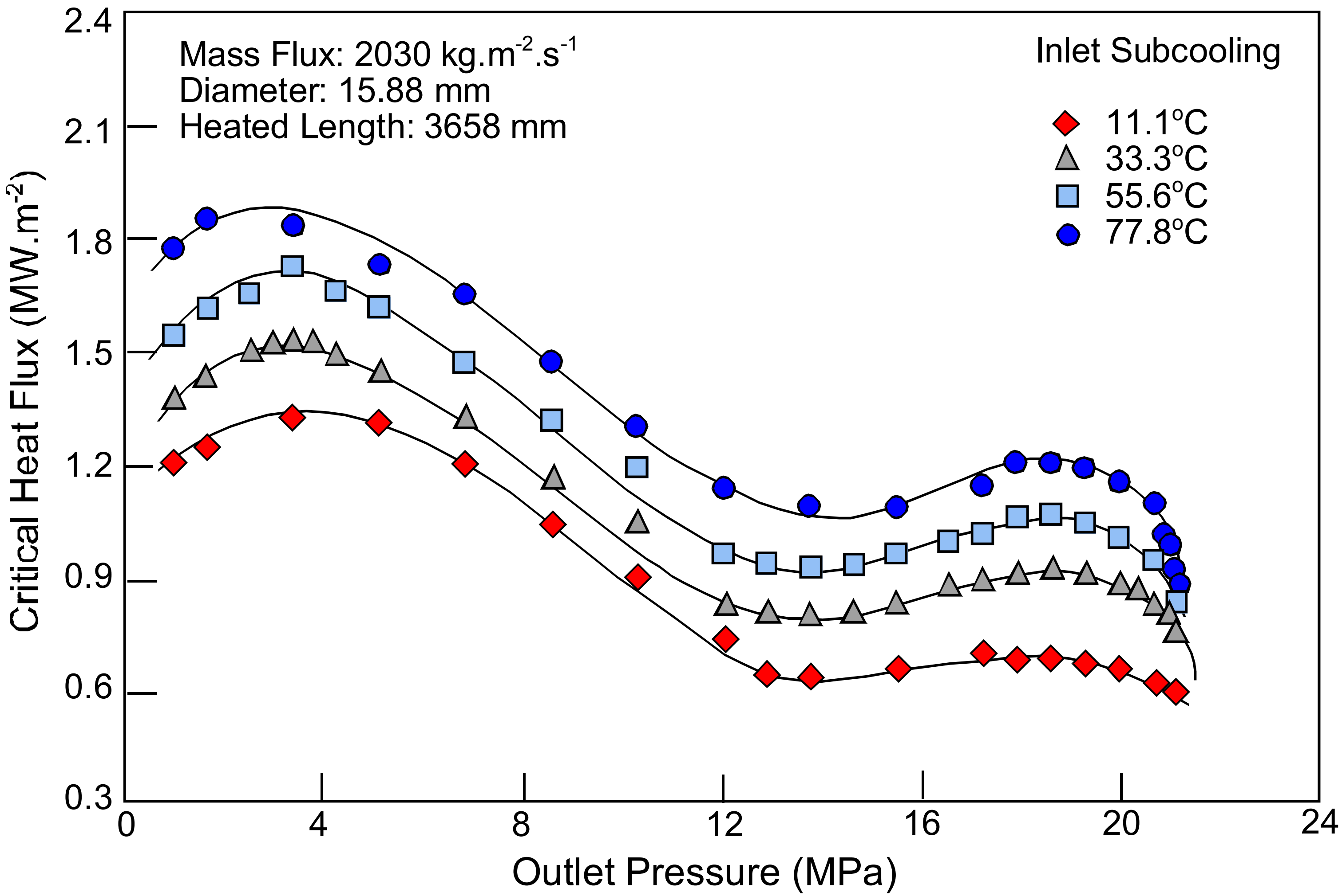
Parametric Trend of CHF

- CHF experiments based on constant inlet-flow conditions (outlet pressure, mass flow rate, and inlet-fluid temperature)
- Constant geometric factors (hydraulic diameter and heated length) in each test series
- Measurement of CHF power is the prime interest
- CHF locations (both axially and radially) are also needed
- Other measurements of interest
  - Circumferential CHF location
  - Subsequent CHF
  - Pressure drops

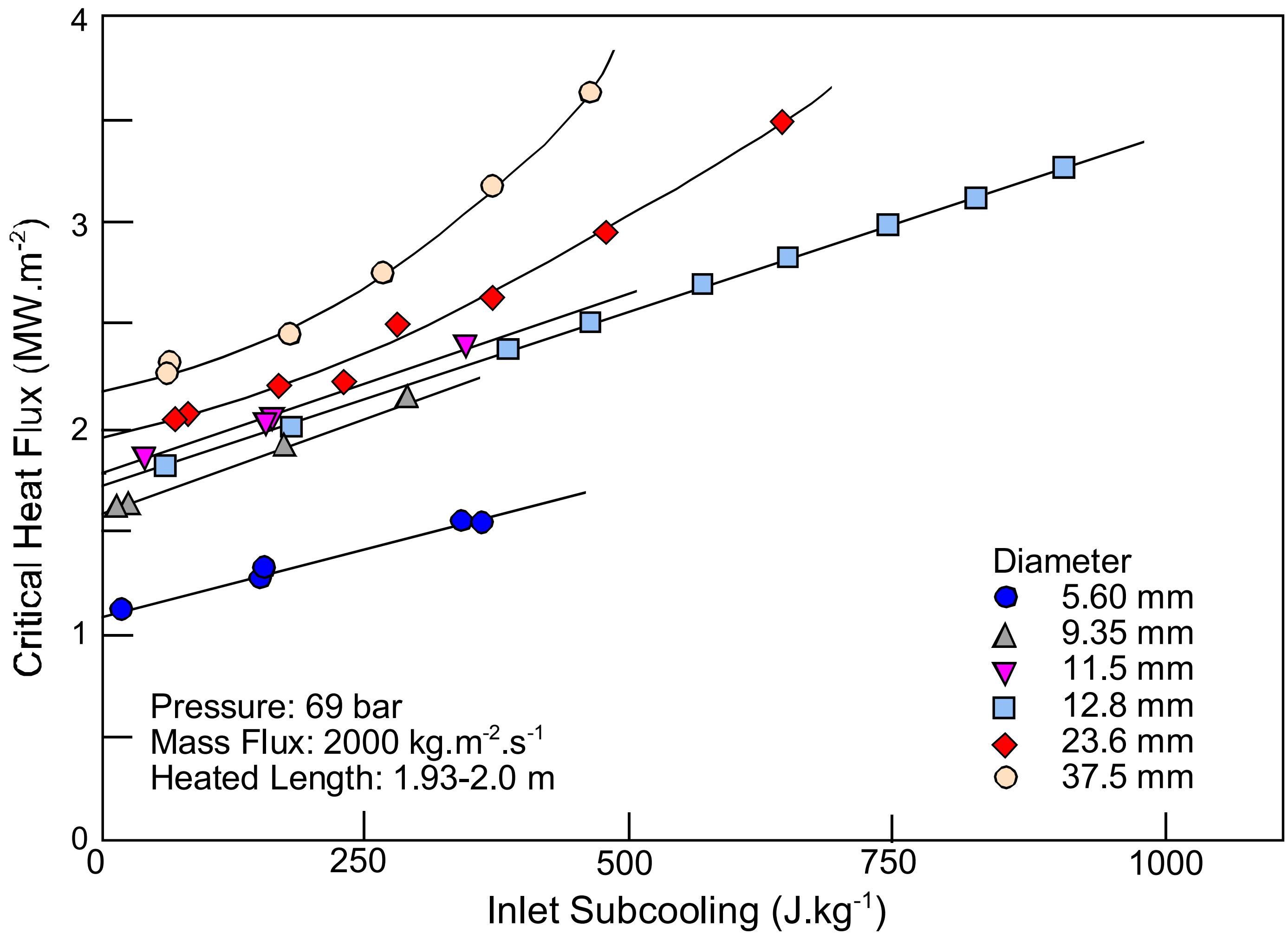
Effect of Inlet Temp. and Mass Flux



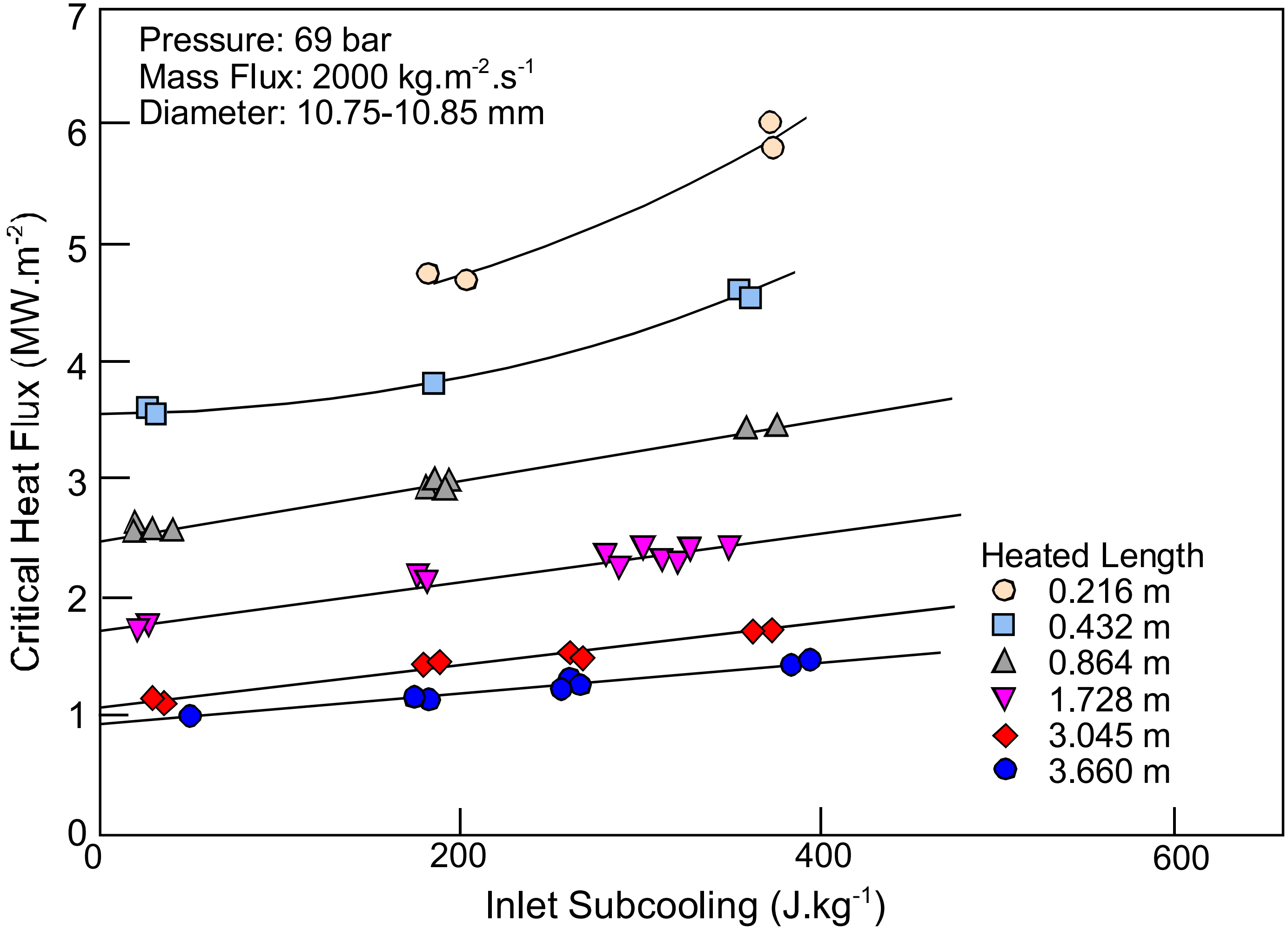
Effect of Outlet Pressure



Effect of Tube Diameter



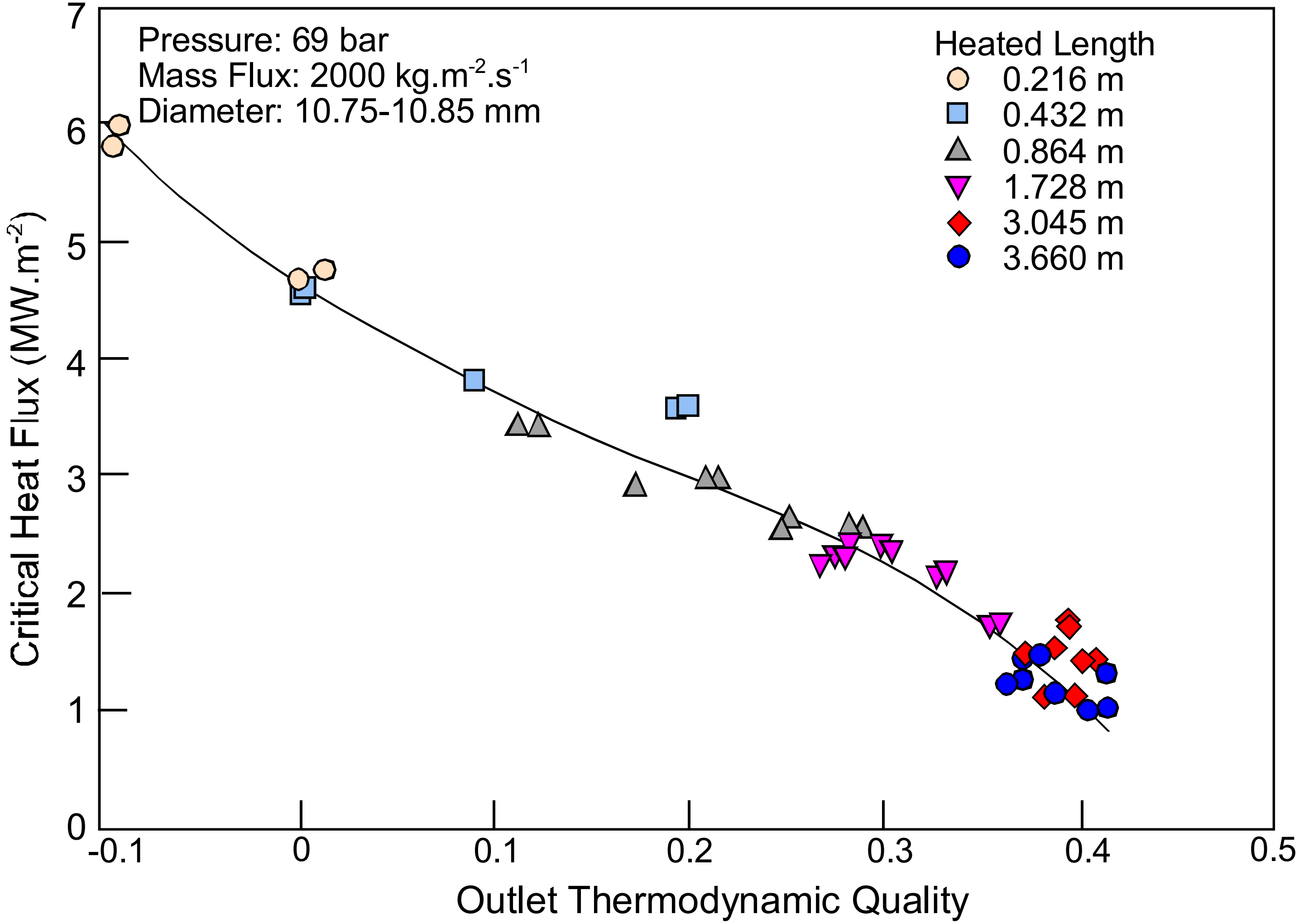
Effect of Heated Length on CHF



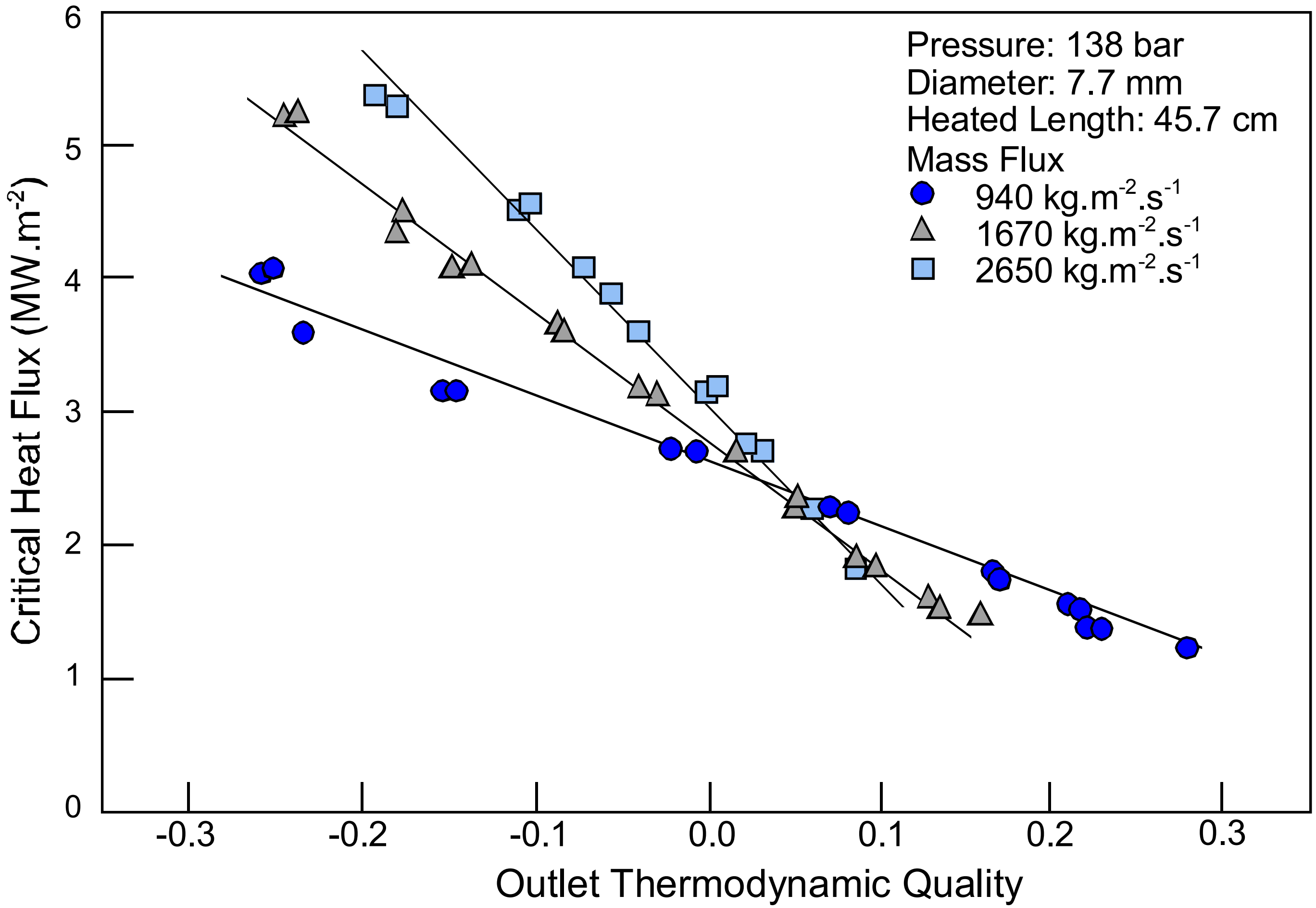
Local CHF Condition Analyses

- CHF values based on inlet-flow conditions are limited to a specific channel geometry and heated length
- Problem lies in the difference in local CHF conditions, mainly thermodynamic quality (or enthalpy)
  - Low quality (or enthalpy) for short heated length
  - High quality (or enthalpy) for long heated length
    - Thermodynamic quality evaluated with inlet-flow conditions and power
- Reactor safety analyses employ the local conditions approach, based on local pressure, mass flux and quality to predict local CHF

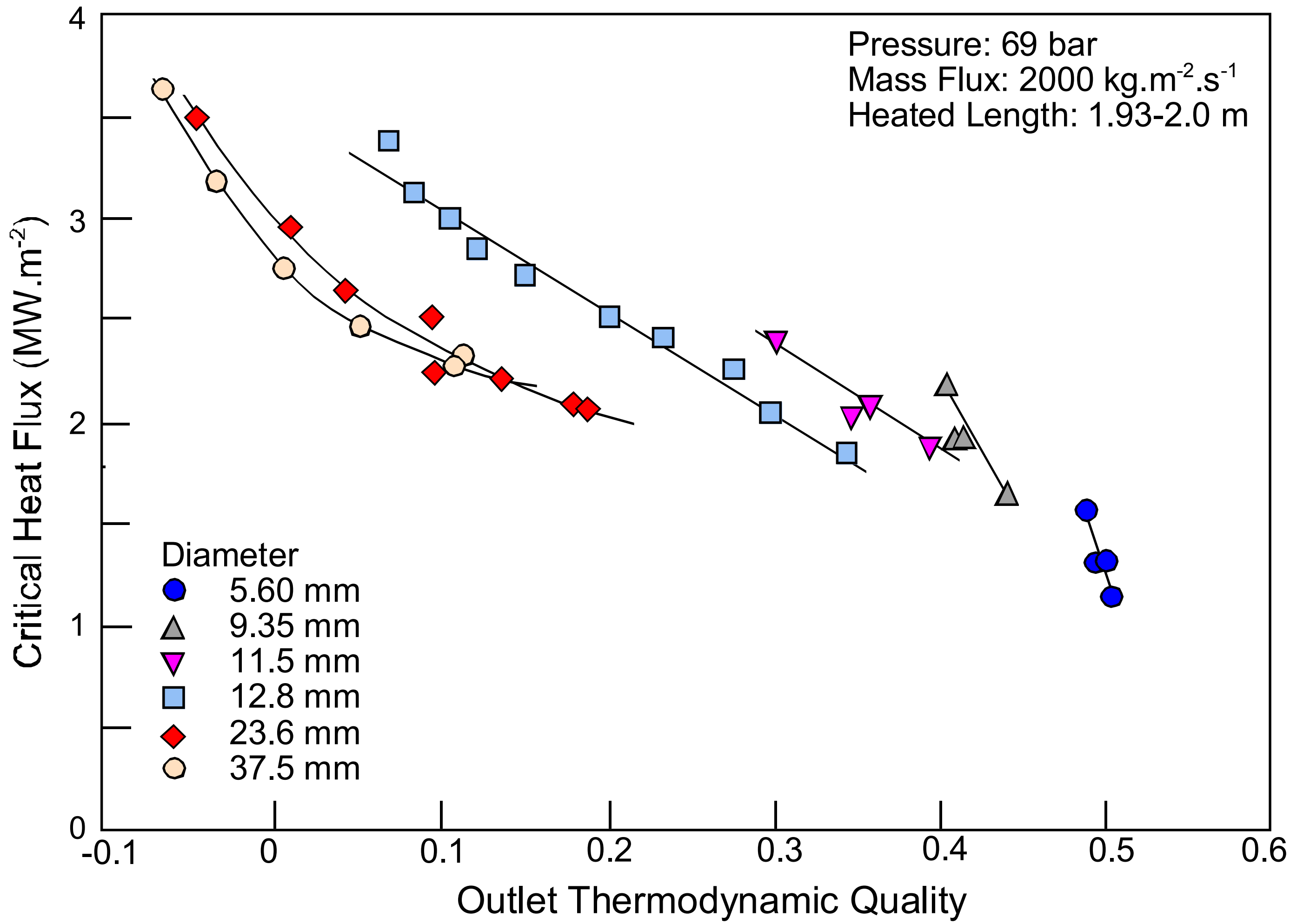
Heated Length Effect on Local CHF



Quality Effects on Local CHF



Tube Diameter Effect on Local CHF



CHF Prediction Methods

- Analytical Models
- Empirical Correlations
- Look-up Table Method
- Scaling Methods

Analytical CHF Models

- Analytical models have more academic appeal, but are usually limited to narrow range of conditions of data base for which constitutive relations are measurable
- Annular Film Dryout Model (e.g., Hewitt, Whalley and co-workers)
  - Accounts for evaporation, entrainment and deposition
  - CHF occurs due to liquid film depletion
- Bubbly-Layer Model (Weisman and co-workers)
  - CHF occurs when near-wall void reaches 82%
- Equations based on Helmholtz instability
  - Pool boiling: CHF occurs when countercurrent flow (liquid in, vapour out) becomes unstable

$$CHF = K\, H_{fg}\, \rho_g^{1/2} \left(\sigma\, g\, [\rho_l - \rho_g]\right)^{1/4}$$

Correlations

- More than 500 correlations available for water flow inside tubes
  - Overall power hypothesis
  - Local conditions hypothesis
- Accurate over range of database
- Each correlation has a limited range of application
- Correlations are empirical - extrapolation not recommended
- Generally, empirical correlations apply to one fluid only.

Overall Power Correlations

- Critical power expressed in terms of system parameters (i.e., pressure, mass flow rate, inlet temperature or inlet subcooling, heated length, and diameter)

  Critical Power = f (P, W, ΔH_{in}, Geometry)

- Reference formulation based on the linear trend of critical power (or CHF) with inlet temperature (or subcooling)
- Additional terms included for separate effects (such as axial and radial heat-flux distributions)
- Good prediction accuracy
- Examples
  - The Bowring correlation for tubes
  - The EPRI-2 correlation for bundles

Limitations of Overall Power Correlations

- Applicable for reactor design calculations
  - Sensitivity analyses with minor variations in inlet-flow conditions
  - Quick calculations (no iteration required)
- Valid only for a specific geometry, heated length, heat-flux profiles, and the range of conditions of the database
  - Any variations may affect the CHF location and hence power
- Extrapolation is not recommended
  - Incorrect asymptotic and parametric trends
- Axial and radial CHF locations cannot be predicted

Local CHF Correlations

- CHF expressed in terms of local parameters (i.e., pressure, mass flux, thermodynamic quality, and diameter)

  $$CHF = f\,(\,P, G, X_{DO}, D_{hy}\,)$$

- Reference formulation based on the linear trend of CHF with critical quality (transformed from the linear trend of critical power with inlet subcooling)
- Additional terms included for separate effects (such as axial and radial heat-flux distributions)
- Larger prediction scatter than the overall power correlations
- Apply together with the heat-balance equation to determine critical power and CHF location (require iterations)
- Examples
  - The Biasi correlation for tubes
  - The Becker correlation

Limitations of Local CHF Correlations

- Applicable for design and safety calculations
  - Sensitivity analyses with minor variations in inlet-flow conditions
  - Quick calculations (no iteration required)
- Valid only for a specific geometry, heat-flux profiles, and the range of conditions of the database
  - Any variations may affect local flow and enthalpy distributions and hence CHF
  - Generalized methods available to extend the applications
- Extrapolation is not recommended
  - Incorrect asymptotic and parametric trends
- Radial CHF location cannot be predicted

CHF Look-Up Tables

- Normalized CHF data banks for reference channels
  - Tubes
  - Triangular-array bundles
  - CANDU bundles of natural-uranium fuel in a nominal channel
- Generalized correlations applied to develop the base table
- Experimental data implemented to improve accuracy and update parametric trends
  - Statistically extended to table matrix conditions
- Currently being used extensively in design and safety analyses
- Used as look-up table or computer-code subroutine
- Applicable for other geometries or flow conditions via modification factors

Tube CHF Look-Up Tables

- Present CHF values for uniformly heated, vertical, tubes of 8 mm inside diameter, cooled with upward flow of water
- Cover the widest range of flow conditions (all possible CHF regimes)
- Exhibit correct asymptotic and parametric trends (smooth transition between various CHF regimes)
- Detail prediction uncertainty available at sub-region levels

Database for Tube CHF Table

- Database (28014 Light-water CHF data from 46 data sets)
  - Ranges of test conditions:
    - Pressure 0.1 to 21.2 MPa
    - Mass Flux 0.006 to 24.27 Mg.m-2.s-1
    - Critical Quality -1.65 to 1.57
    - Diameter 0.62 to 92.4 mm
    - Heated Length 0.011 to 20 m
    - Inlet Subcooling -1211 to 2711 kJ.kg-1
- Range of data included in development (21904 points)
    - Pressure 0.1 to 20 MPa
    - Mass Flux 0 to 8 Mg.m-2.s-1
    - Critical Quality -0.5 to 1
    - Diameter 2 to 32 mm
    - Length/Diameter Ratio > 80
    - Inlet Quality < 0
    - Vertical upwards flow only

Section of CHF Look-up Table

PRESSURE (kPa)	MASS FLUX (kg.m^{-2}.s^{-1})	QUALITY -0.5	-0.4	-0.3	-0.2	....	....	0.6	0.7	0.8	0.9
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....
7000	2500	10882	9986	8709	7496	....	....	261	204	99	51
7000	3000	11730	10850	9620	8170	....	....	346	263	112	52
7000	3500	12535	11558	10344	8740	....	....	409	317	135	57
7000	4000	13317	12216	10929	9320	....	....	470	317	136	58
7000	4500	14070	12839	11469	9769	....	....	492	317	137	59
7000	5000	14792	13465	11954	10124	....	....	521	326	138	63
7000	5500	15509	14000	12474	10713	....	....	582	348	153	70
7000	6000	16208	14521	12931	11464	....	....	655	379	179	84
7000	6500	16875	15091	13336	12214	....	....	725	422	210	99
7000	7000	17529	15640	13763	12432	....	....	795	476	243	116
7000	7500	18170	16174	14182	12682	....	....	866	530	277	132
7000	8000	18806	16673	14610	12995	....	....	936	581	312	149
8000	0	5101	4795	4484	4175	....	....	542	456	423	364
8000	50	5714	5359	5025	4744	....	....	1183	980	938	720
8000	100	6229	5834	5487	5235	....	....	1678	1457	1449	1050
8000	300	6685	6179	5792	5654	....	....	2144	1877	1538	1083
8000	500	6958	6354	5920	5763	....	....	2068	1858	1427	917
....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....

(CHF Values in kW.m^{-2})

Prediction Accuracy of Tube CHF Methods

CHF tables and correlations	No. of data	Error (%)	
		Average	RMS
Tube CHF table of Doroshchuk et al.	7419	-0.63	11.02
1995 Tube CHF table	7419	0.20	5.33
Tube CHF table of USSR Academy of Science	8848	-0.26	9.51
1995 Tube CHF table	8848	0.46	5.13
Tube CHF table of Groeneveld et al.	22452	1.59	9.49
1995 Tube CHF table	22452	0.48	7.38
Tube CHF table of Kirillov et al.	19295	1.41	8.87
1995 Tube CHF table	19295	0.77	7.11
Correlation of Biasi et al.	14977	6.48	14.38
1995 Tube CHF table	14977	0.38	8.17
Correlation of Becker	11221	5.24	12.48
1995 Tube CHF table	11221	-1.14	7.19
Correlation of Bowring	13129	37.61	48.09
1995 Tube CHF table	13129	-0.23	6.80

General Applications of Tube CHF Table

- Reference CHF is assumed for a uniformly heated vertical tube of 8 mm inside diameter and cooled with upward flow of water
- Extension to other cases using modification factors
- Simplification
  - all separate effects are mutually independent
- CHF correlation

$$CHF = CHF_{TABLE}\; K_1\, K_2\, K_3\, K_4\, K_5\, K_6\, K_7\, K_8\, K_9$$

K_1 to K_9 are modification factors to account for subchannel specific effects (e.g., element gap size, subchannel equivalent diameter, adjacent heated/unheated surface, upstream spacer, etc.)

CHF Modification Factors

CHF correction factor	$K_i = 1$ for
K_1 – Tube diameter factor	$D_{hy} = 8$ mm
K_2 – Bundle geometry factor	Open bundle
K_3 – Spacer-effect factor	Large spacer pitch
K_4 – Heated-length factor	Length-to-Diam. Ratio > 80
K_5 – Axial-flux-shape factor	Uniform AFD
K_6 – Circumf.-flux factor	Uniform CFD
K_7 – Horizontal Flow factor	Vertical flow
K_8 – Low-flow factor	Mass Flux > 50 $kg.m^{-2}.s^{-1}$
K_9 – Transient-effect factor	Steady state

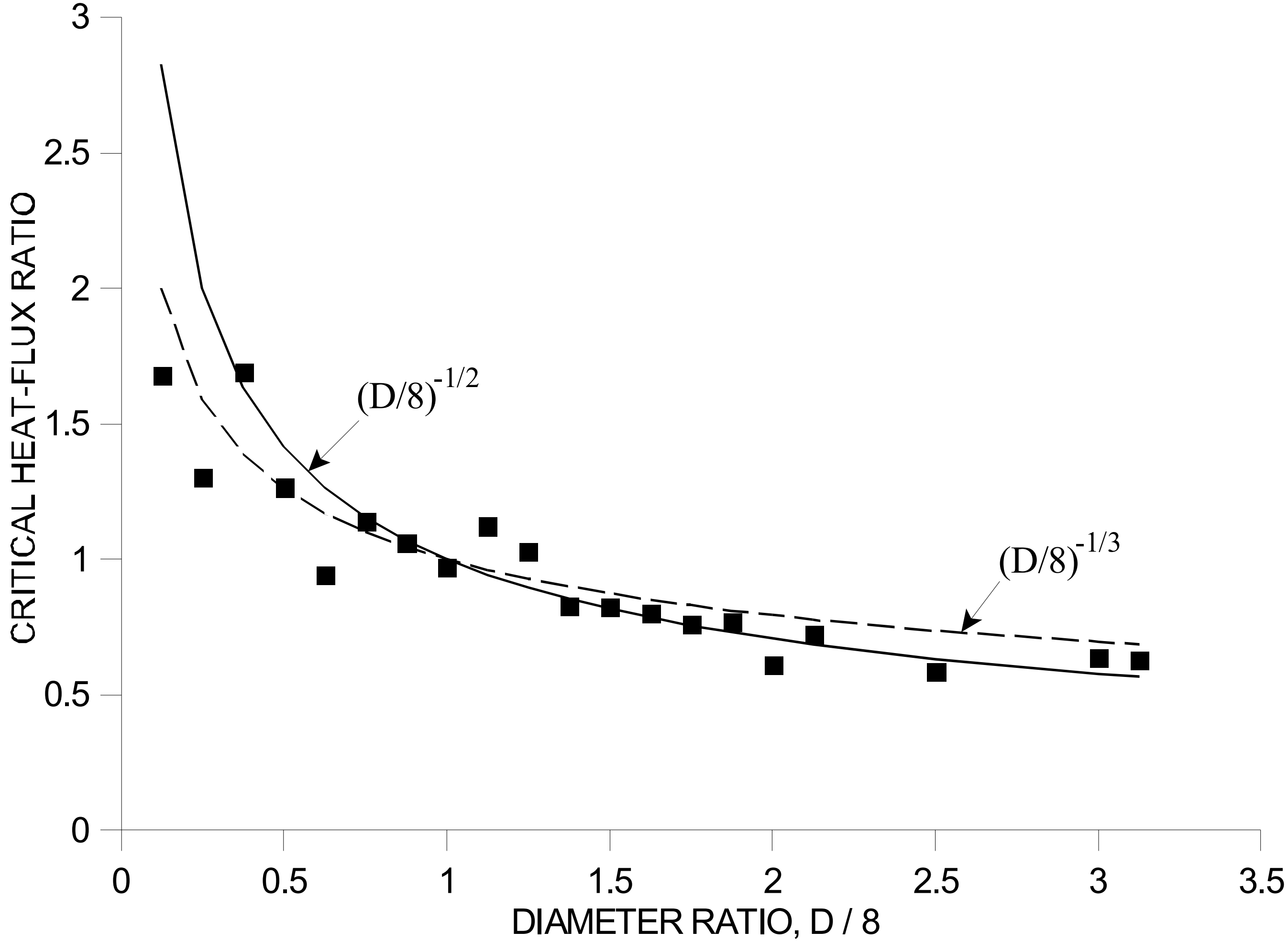
Diameter Effect

- Depends on CHF regimes
  - CHF seems to increase with increasing diameter at highly subcooled conditions
  - CHF decreases with increasing diameter at positive quality regions
- Simplified correlation representing the overall effect

$$K_1 = \frac{CHF}{CHF_{D_{hy}=8\,mm}} = \left(\frac{D_{hy}}{8}\right)^{-1/2}$$

where D_{hy} is the hydraulic diameter in mm

CHF Ratio with respect to 8-mm Tubes



Bundle CHF Methodologies

- Empirical bundle CHF prediction methods
  - Require extensive data base on bundles of interest
  - Suitable for design and CHF power evaluations
  - Applicable only within the range of the database
- Subchannel codes
  - Predict enthalpy and flow at each subchannel
  - Require subchannel CHF prediction method (tube based) and spacer mixing/enhancement model
- Enthalpy imbalance approach
  - Enthalpy imbalance, in terms of thermodynamic quality, between critical subchannel and bundle cross-sectional average values
  - Apply the tube-data-based CHF prediction method with a modified thermodynamic quality accounting for the enthalpy imbalance

CHF Correlations

- Mainly for critical channel power calculations
- Based on full-scale bundle data
- Flux-corrected local CHF correlation for uncrept channels

$$CHF_{local} = \left(a_1 P^{a2} G^{a3} + a_4 P^{a5} G^{a6} x_{cr}\right)\left(\frac{q_{local}}{q_{average}}\right)^{a7}$$

- Boiling-length-average CHF correlation for uncrept and crept channels

$$CHF_{BLA} = \left(b_1 P^{b2} G^{b3} + b_4 P^{b5} G^{b6} x_{cr}\right)\left(1 - b_7\left(\frac{q_{local}}{q_{average}}\right)^{b8}\right)$$

Prediction Errors in Channel Dryout Power of Bundle CHF Correlations

Data Set	Number of data	BLA CHF		Flux-Corrected Local CHF	
SL (Non-uniform, Uncrept)	407	-1.29	3.04	-1.91	4.68
U-1 (Non-uniform, Uncrept)	108	-0.87	5.74	-3.05	7.51
U-1 (Uniform, Uncrept)	256	-1.19	5.17	-22.43	24.79
SL (Non-Uniform, Crept)	386	-1.92	4.50		

Bundle CHF Table

- Applicable over a wide range of flow conditions:
  - Pressure: 0.1 to 20 MPa
  - Mass flux: 0 to 8 $Mg.m^{-2}.s^{-1}$
  - Critical quality: -0.5 to 1.0
- Table entries based on a generalized bundle CHF model, providing correct asymptotic and parametric trends.
- Experimental data were implemented to improve the prediction accuracy.
- Modification factor have been derived to account for the creep effect
- Transformation factor is provided to convert tabulated BLA CHF values to local CHF values for transient analyses.

Prediction Errors in Channel Dryout Power of Bundle CHF Table

Data Set	Number of data	BLA heat-flux approach		Local heat-flux approach	
SL (Non-Uniform, Uncrept)	304	0.00	2.50	-1.25	2.86
U-1 (Non-Uniform, Uncrept)	108	0.17	6.26	-3.70	7.32
U-1 (Uniform, Uncrept)	256	-0.80	4.65	-0.80	4.65
SL (Non-Uniform, Crept)	302	-2.84	5.65	-1.95	5.08
Freon (Uniform)	249	0.82	3.18		
Freon (Non-Uniform)	485	-1.05	5.73		

Other Bundle Effects

- Spacing devices
  - Enhancement of CHF
  - Apply the correlation previous described
- Radial power distribution
  - Groeneveld defined a bundle imbalance factor with reference to the optimal 37-element bundle
  - Dryout occurs simultaneously at all rings in the optimal bundle
  - The same technique has been extended to other bundles
- Transient effect
  - Slow flow and power transients
  - Transient CHF is either the same or higher than steady-state CHF at the same local conditions

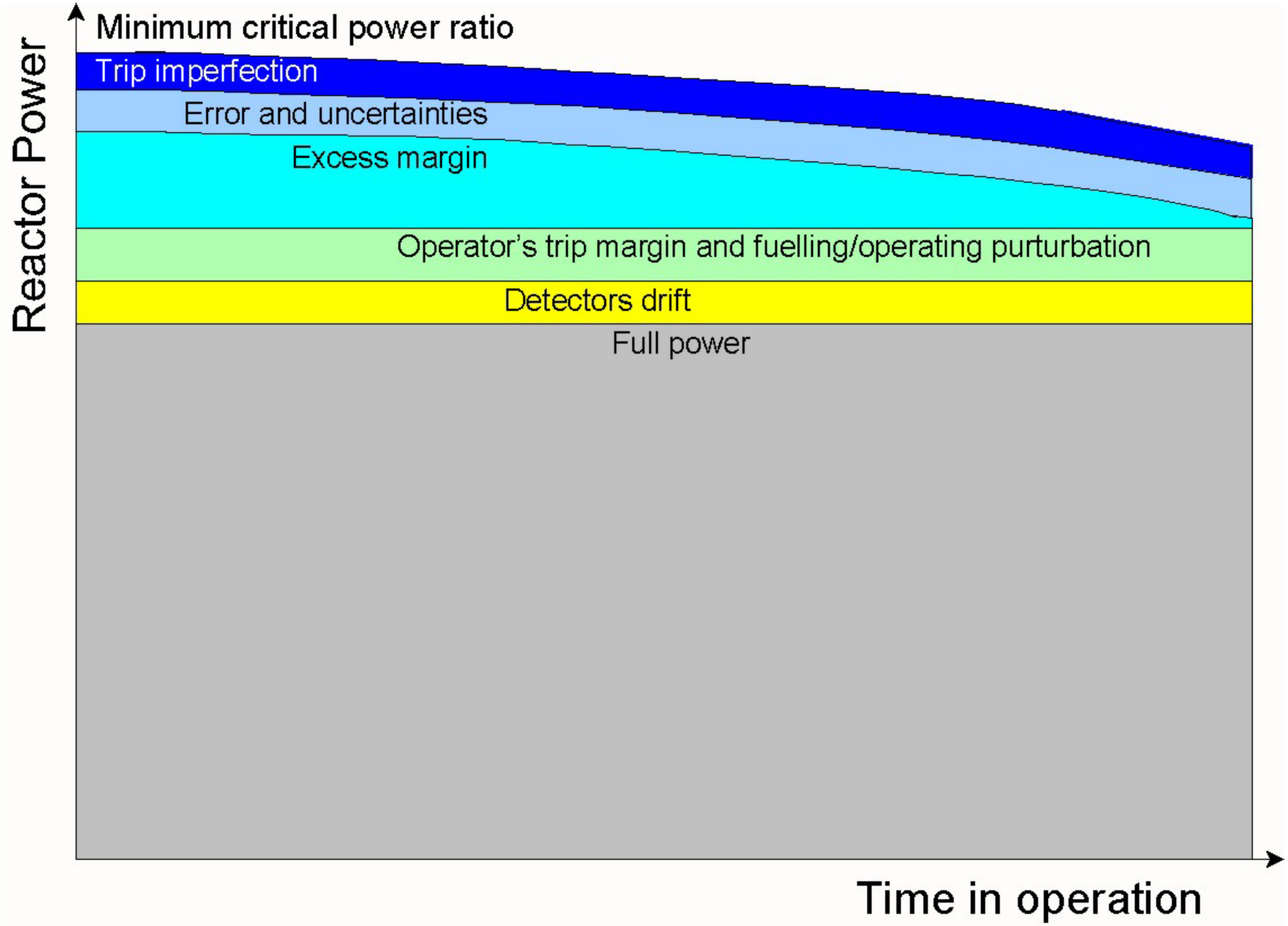
Application of CHF prediction methods

- To set the operating power with a comfortable margin to avoid CHF occurrence
  - Margin expressed as
    - MCHFR – at constant pressure, mass flux, and critical quality,
    - MCHFPR – at constant pressure, mass flux, and inlet fluid temperature
    - MCPR – at constant pressure, pump characteristic, and inlet fluid temperature
- To evaluate the maximum sheath temperature during LOCA, LOFA or LORA
  - Usually occurs first at initial CHF location (low overpowers)
- To evaluate the thermalhydraulic and neutronic responses to CHF occurrence in a reactor core
  - Requires knowledge of how CHF spreads in the reactor core
  - Requires best-estimate predictions of average CHF and/or area in dryout as a function of power.

CHF in Reactor Analyses

- Establish reactor power under normal operating conditions
  - Common licensing criteria:
    - No burnout/dryout during operation (at all conditions of interest, including uncertainty)
    - Sheath temperature below a preset value (e.g., 600^{o}C)
    - Fuel centreline temperature below the melting value
  - Burnout/dryout is the limiting criterion
  - Operating margin (minimum 20% plus uncertainty and operating flexibility)
- Determine sheath and fuel temperatures in transient analyses
  - CHF is considered as the reference point for post-dryout analyses
  - Postulate accident scenarios: loss-of-regulation, loss-of-flow, loss-of-Class-IV-power, loss-of-coolant (small and large breaks), etc.

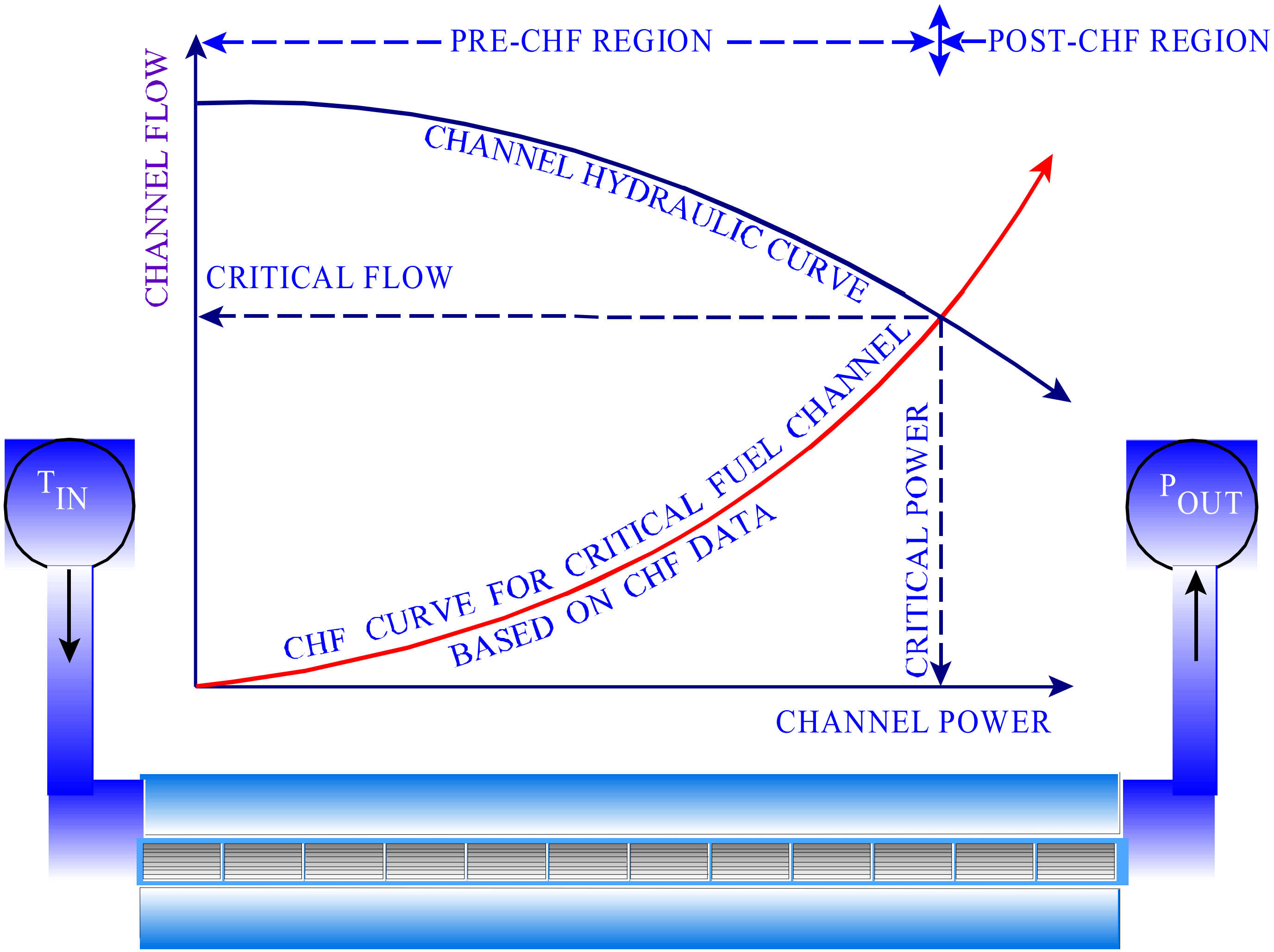
Operating Margin



Terminology

- Dryout (or critical heat flux, CHF)
  - Fuel sheath can no longer maintain a continuous liquid contact
  - Current licensing criteria: no burnout/dryout at any locations in the fuel string
- Critical power (CP)
  - Critical power corresponding to the first CHF occurrence (at constant pump head)
  - Require knowledge on various disciplines (physics, fuel, fuel channel, thermalhydraulics, etc.)
- Critical power ratio (CPR)
  - Ratio of CP to operating power
- Regional Overpower Protection (ROP)
  - Prevent burnout in any fuel assembly during a slow LOR event
  - Full-core analysis of all possible scenarios
  - Establish trip setpoints for various detectors

Critical Channel Power



Thermal-hydraulic Parameters

- Pressure drop
  - Establish channel flow
  - Components outside of the core are independent from fuel bundles
  - Pressure drop components
    - Friction, form losses due to spacing devices, acceleration, gravity
    - Geometry dependent
- Critical heat flux
  - Establish critical power (based on pressure, flow and inlet-fluid temperature)
  - Bundle design dependent
  - Depend on many parameters: local flow conditions, spacing devices, axial and radial heat-flux distributions, bundle eccentricity, and others.

CHF Margin Definitions

- CHF ratio is defined as

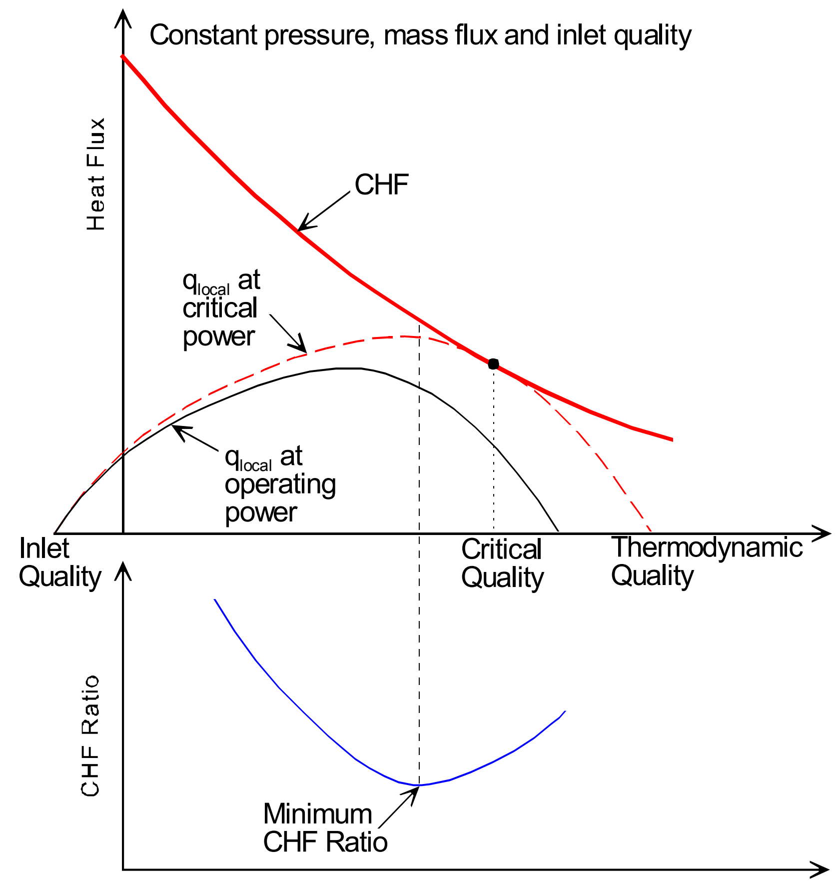
$$\text{CHF Ratio} = \frac{\text{CHF}}{q_{local} \text{ at operating power}}$$

at constant thermodynamic quality

- Critical power ratio is defined as

$$\text{CP Ratio} = \frac{\text{Critical Power}}{\text{Operating power}}$$

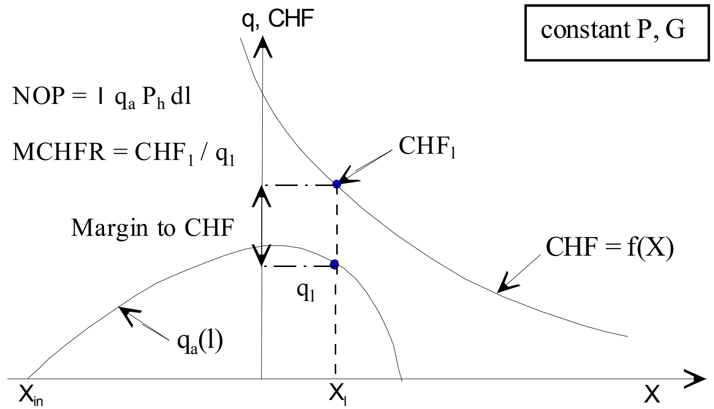
- at constant inlet-fluid temperature



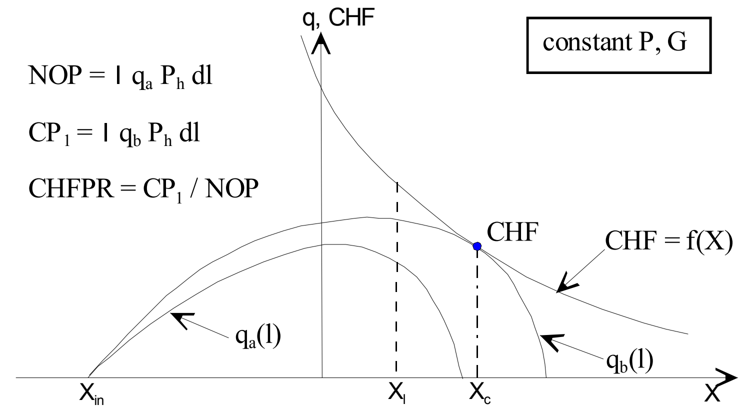
Uncertainties in Reactor Calculations

- Uncertainties in CHF measurements using bundle simulators
  - errors in flow, power, pressure and inlet temperature measurements
  - inadequate CHF detection methods
  - variations in flux distribution across/along bundle
  - geometric tolerances
- Prediction uncertainties of CHF correlations or subchannel codes
- Uncertainties in reactor conditions
  - reactor flow, pressure and temperature (from system safety codes)
  - reactor power measurements (from detectors)
- Uncertainties in extrapolation to in-reactor conditions
  - electrical vs nuclear heating
  - flux tilts across elements, bundle, and core
  - reactor aging effect (creep, fouling of pipes, etc.)

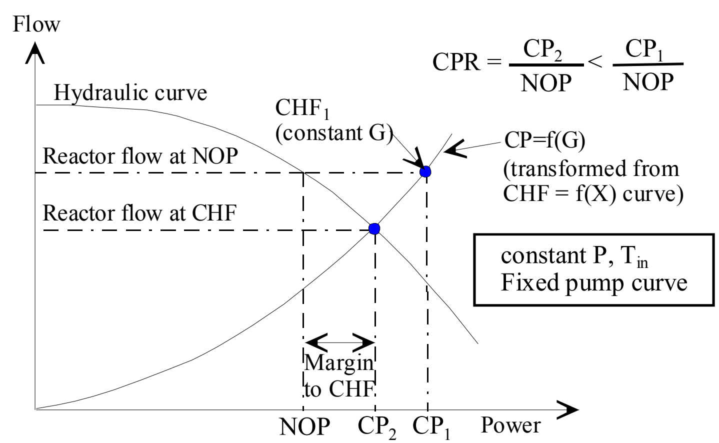
Reactor Operating Margins



(a) Schematic representation of definition of MCHFR



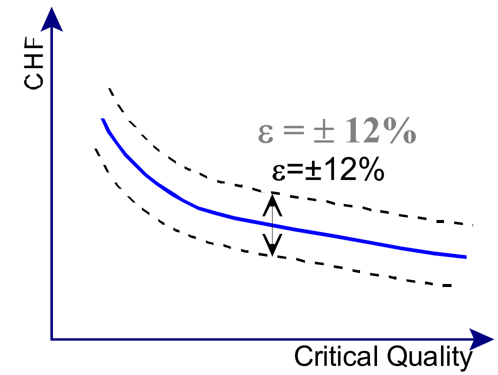
(b) Schematic representation of definition of CHFPR

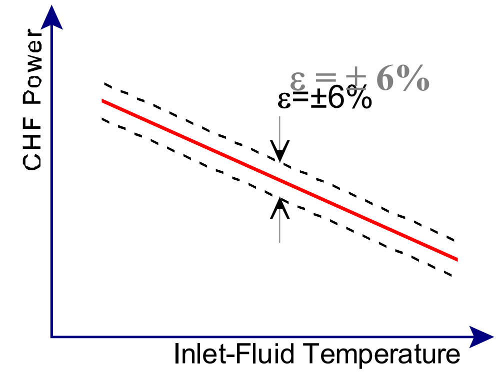


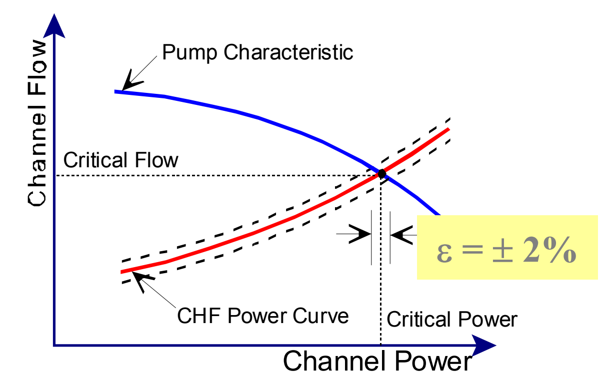
(c) Schematic representation of definition of CPR

CHF Margin/Error Propagation

- Experiments are conducted with constant inlet conditions (pressure, mass flow rate and inlet-fluid temperature)
- Reactors operate with constant pump curve and constant pressure and inlet-fluid temperature
- Propagation of uncertainties:
  - 12% error in CHF (constant local critical conditions)
  - 6% error in CHF power (constant inlet-flow conditions)
  - 2% error in critical power (constant pump curve)
- Applies similarly to margins to CHF occurrence



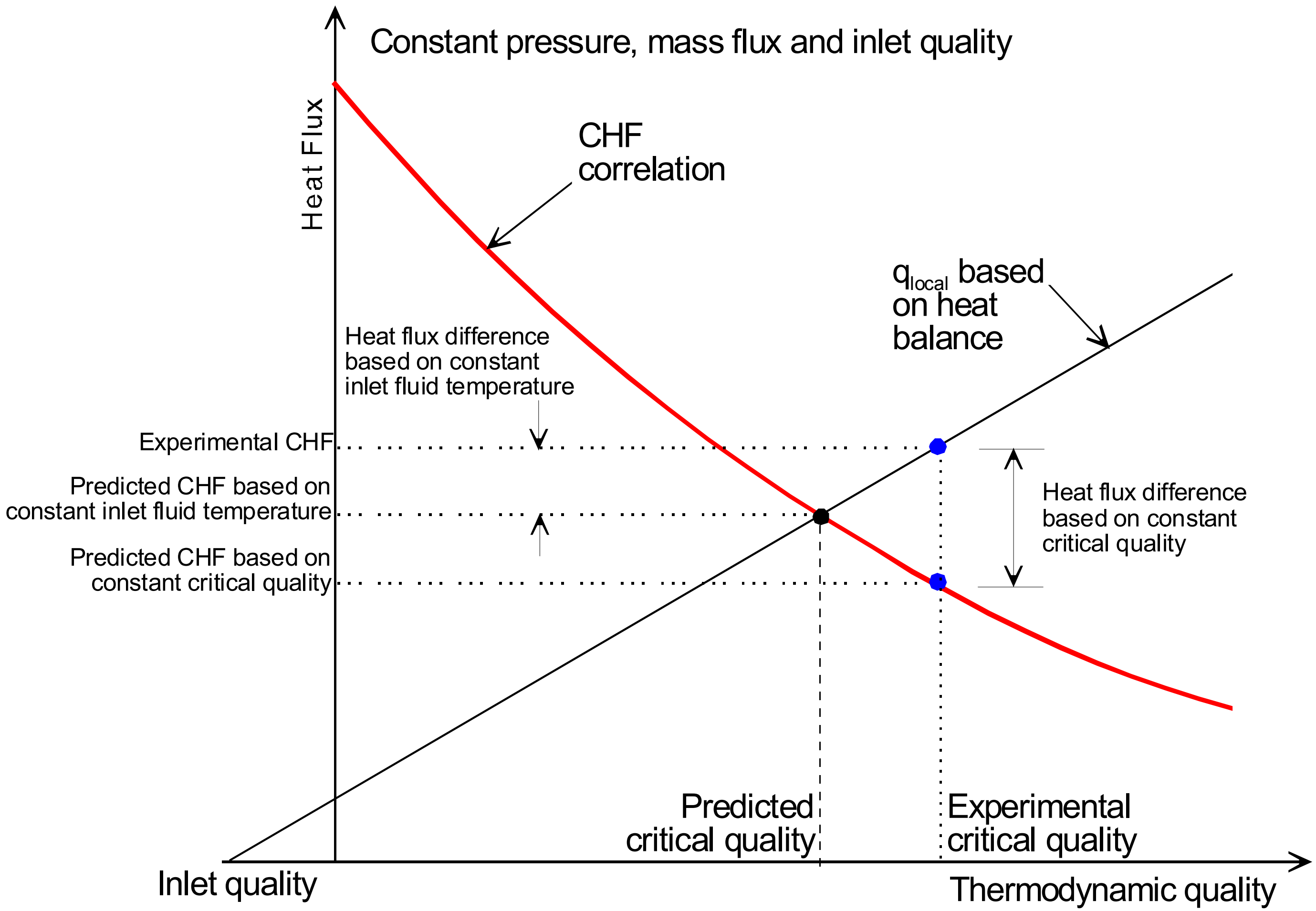




Uncertainty in CHF Correlations

- Most developers of CHF prediction methods apply the following approach to quantify the uncertainties
  - Direct substitution method (DSM) or constant dryout conditions approach
  - Heat-balance method (HBM) or constant inlet conditions approach
- Uncertainty based on the heat-balance method is used in establishing the operating power
  - No prior knowledge of critical quality (or CHF location) and hence direct substitution method is not applicable
- Uncertainty based on direct substitution method is applicable for safety analyses
  - Sensitivity analyses examining the impact of CHF uncertainty on maximum sheath-temperature predictions

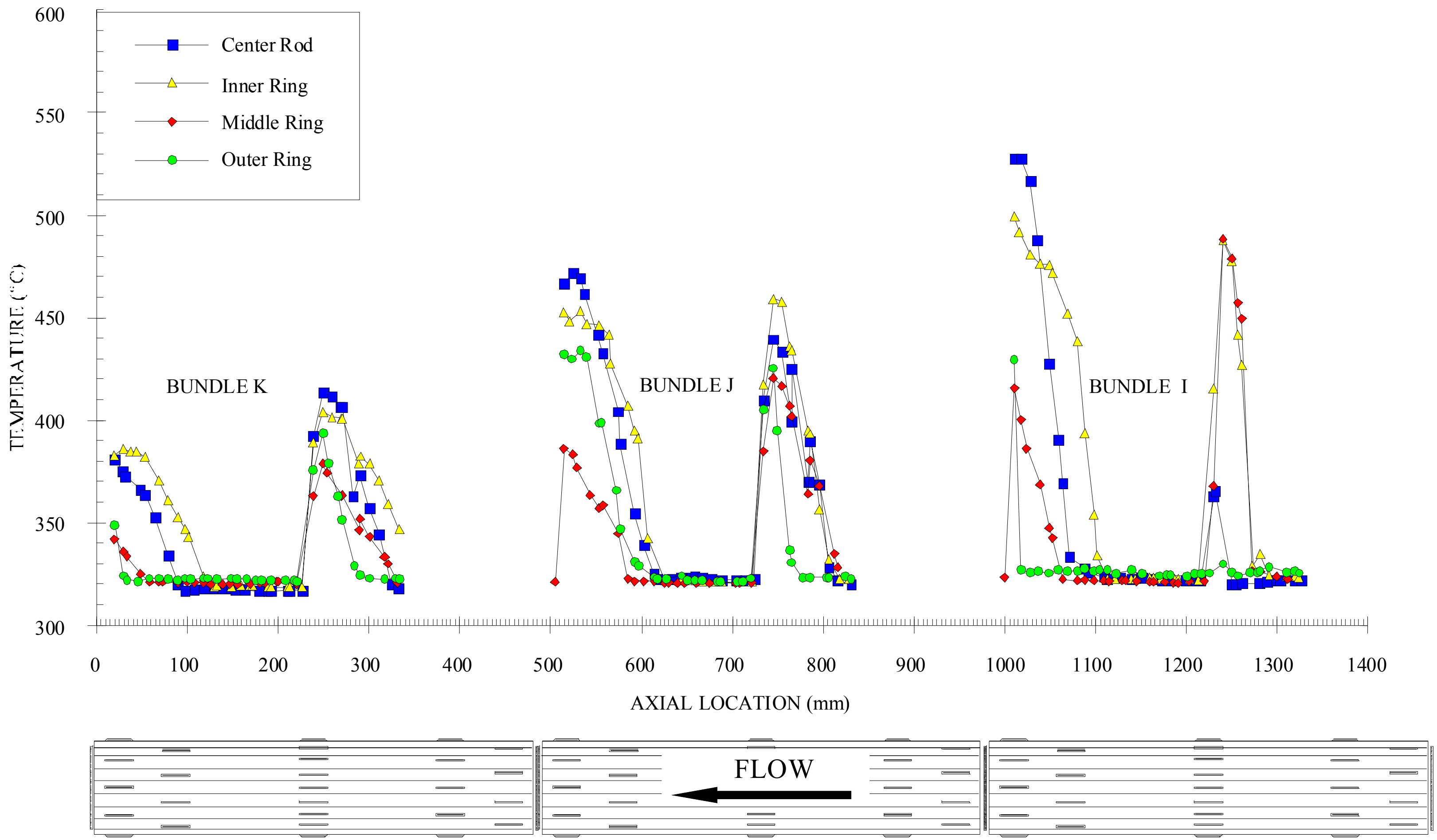
Prediction Error Definitions



Application to Accident Analyses

- Effect of transient on CHF
  - Slow transients, cycle>10s, no significant effects
  - Fast transients, cycle<1s, significant effect on CHF is likely
- Thermal-hydaulic and neutronic responses to CHF occurrence (partial bundle dryout)
  - Depends on how well we can predict the spread of dryout
  - CHF_{avg} can be much higher than $CHF_{initial}$ at some cross-section locations
    - e.g., CHF just downstream of grids/spacers may be 200% higher than $CHF_{initial}$
  - Subchannel codes are the most promising tool for the analyses

PDO Temperature Variations in Bundles



Summary

- CHF mechanisms in pool and flow boiling have been examined
- CHF experimental techniques have been described
- Parametric trends of CHF data have been illustrated
- Prediction methods have been presented for CHF in tubes and bundles
- Applications of CHF in design and safety analyses have been provided

Questions?