Critical Heat Flux Overview

Mysterious World of CHF

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Acknowledgement

Some illustrations used in this presentation have been taken from textbooks and papers of the following authors:

- P.B. Whalley,
- L.S. Tong & Joel Weisman & Pei
- D.C. Groeneveld
- S.S. Doerffer and
- by courtesy of the Atomic Energy of Canada Ltd. (AECL)

Outline

- Introduction
  - Pool Boiling Process and its Crisis
  - Two-phase Flow Regimes & Flow Boiling Crisis in Tubes
- Analytical & Empirical Approaches to CHF in Tubes
- CHF Experiments & Prediction Methods for CANDU Fuel Channels and LWR Fuel Assemblies
- Considerations on CHF in Annuli as Applied to Certain CANDU Fuel Channel Distortions
- CHF Enhancement
- CHF Fluid-to-Fluid Modelling
- Final Remarks

What’s CHF?

CHF = Critical Heat Flux

CHF = **Phenomenon** → may occur in boiling systems (nuclear reactors with H_2O or D_2O coolants)

→ may lead to serious damage of the system
→ may drastically deteriorate heat transfer
→ limits nuclear reactor operating power
→ sets operating margins for nuclear reactors

<u>CHF is of paramount importance to safety of CANDUs and LWRs</u>

CHF expresses also a **Value** of the heat flux at which **CHF Phenomenon** occurs

<u>Other terms</u>: boiling crisis, departure from nucleate boiling (DNB), burnout, dryout

Pool Boiling Process & Its Crisis

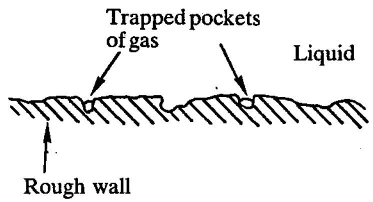
Boiling Process - Nucleation

Heterogeneous (solid-liquid):

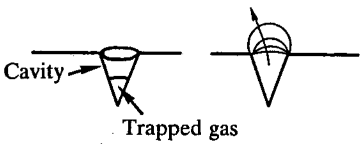
Needed: pits, cracks, crevices & trapped gas

Homogeneous (liquid)

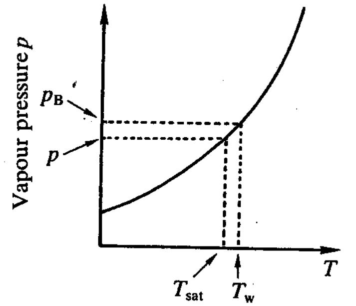
No nucleation sites - explosive growth rate



Enlarged view of a boiling surface.



Ideal nucleation cavity.

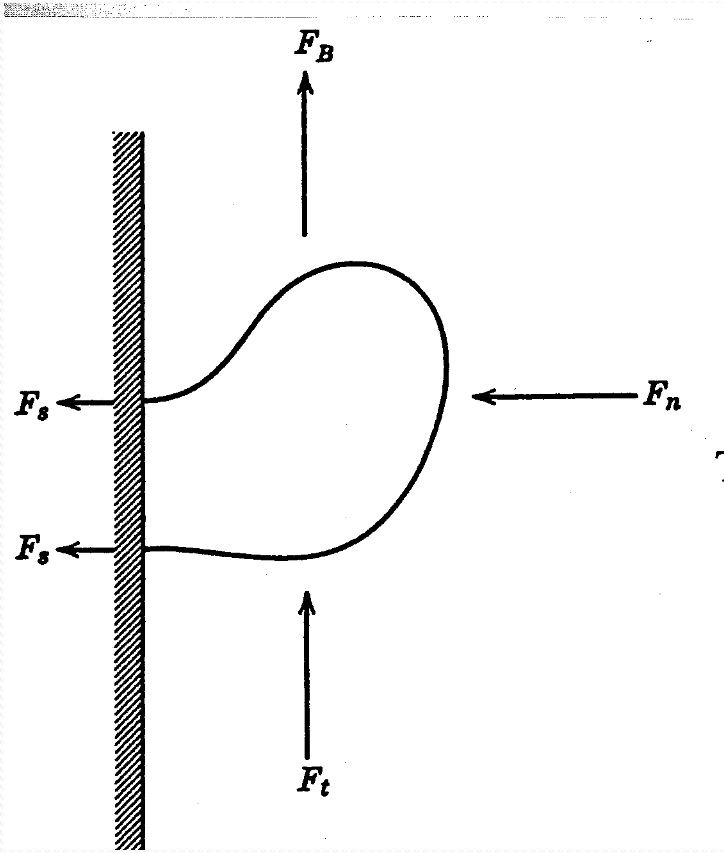


Vapour pressure curve: superheat required for nucleation.

$$p_B = p + \frac{2\sigma}{R_B} \qquad \Delta T_{Sat} = T_W - T_{Sat} > const \qquad \Delta T_{Sat} = 5K \text{ (For water at 1 bar)}$$

Bubble Departure from the Site

Departure bubble radius (r_b) is a result of the acting forces:



Buoyancy force : $$F_B = \frac{C_B (r_b)^3 (\rho_L - \rho_G) g}{g_c}$$

Surface tension force : $$F_S = C_s r_b \sigma$$

Tangential inertia force : $$F_t = \frac{C_t (r_b)^2 \rho_L (u_{\text{rel}})^2}{g_c}$$

Normal inertia force : $$F_n = \frac{C_n (r_b)^2 \rho_L (v_{\text{rel}})^2}{g_c}$$

$$r_b \to \sum F_k > F_S \quad (k = B, i, n)$$

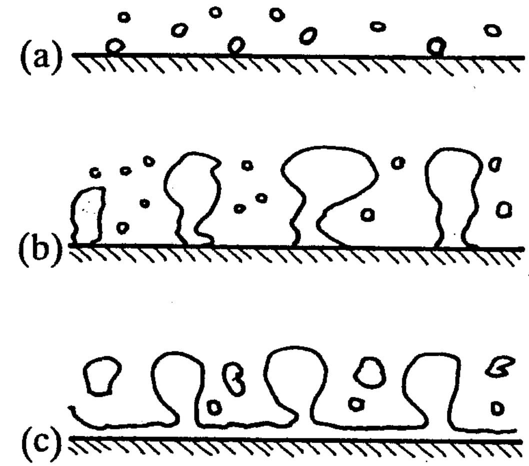
r_b depends on flow conditions

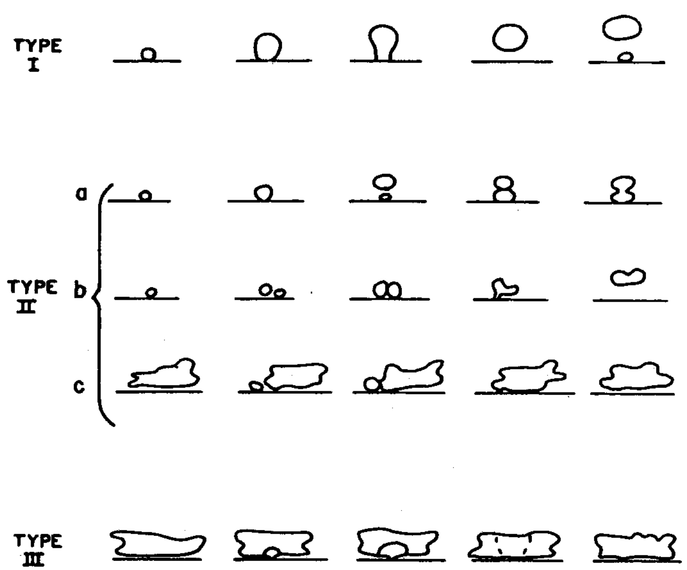
Bubble Formations

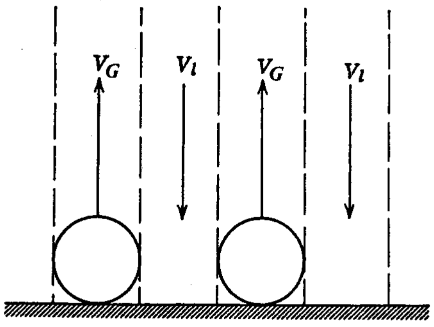
(a) Isolated bubble region

(b) Slugs & columns region (vapour jets)

(c) Film boiling region



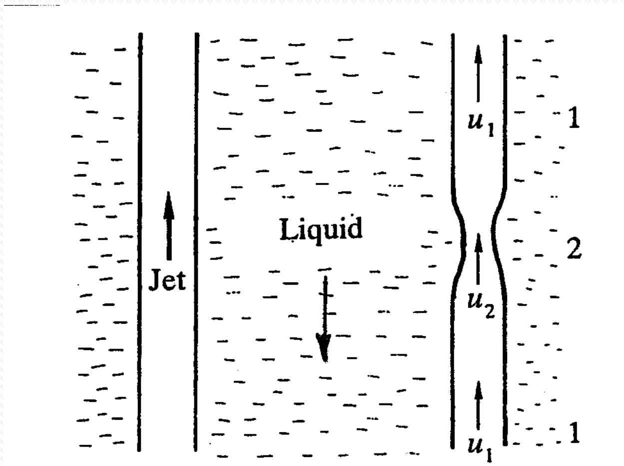


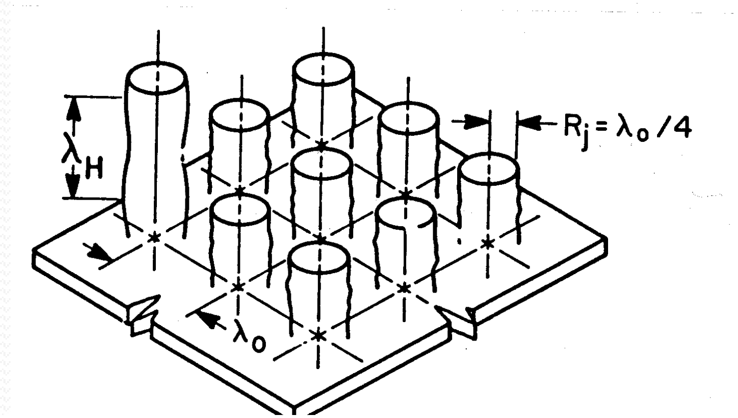


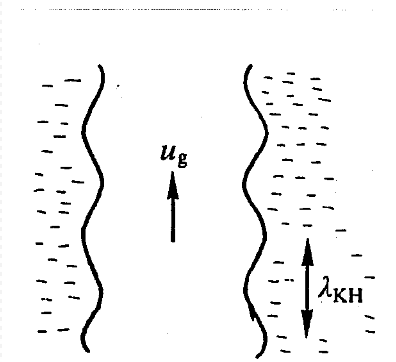
Idealized vapour jets

Boiling Crisis – Pool Boiling

Kelvin-Helmholtz instability







$$\lambda_{KH} = f(\sigma, \rho_l, \rho_g, g)$$

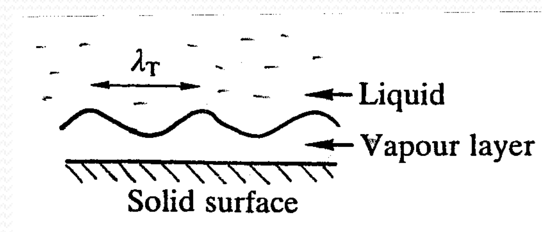
$$u_2 > u_1 \rightarrow p_2 < p_1$$

Leads to jet breakup

Boiling crisis:

$$\lambda_{KH} = \frac{\lambda_T}{\sqrt{2}}$$

Taylor instability



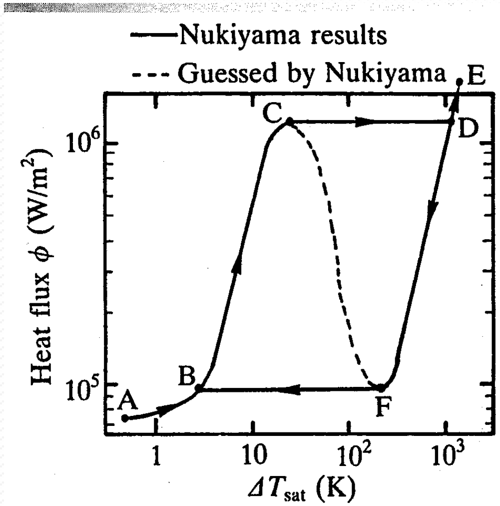
Criterion for stable film boiling

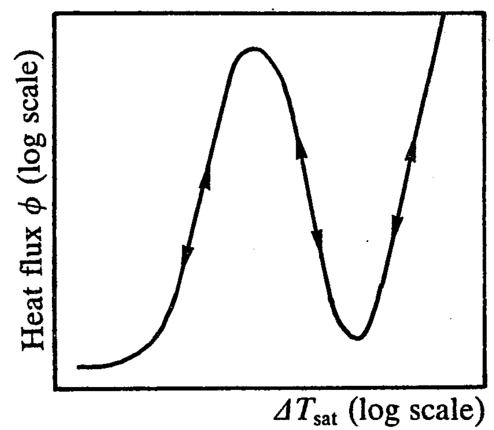
Boiling Curve – Nukiyama (1934)

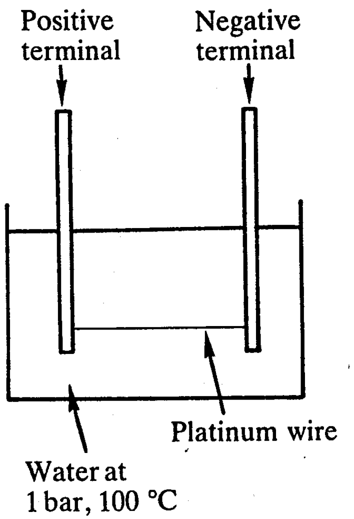
Heat-flux controlled surface

(nuclear/electric heating)

Temperature-controlled surface







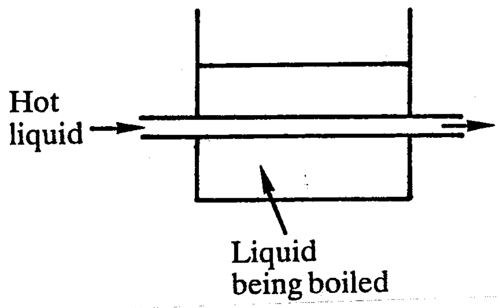
AB - SP convection

BC - Nucleate boiling

CD – boiling crisis

CF - Transition boiling

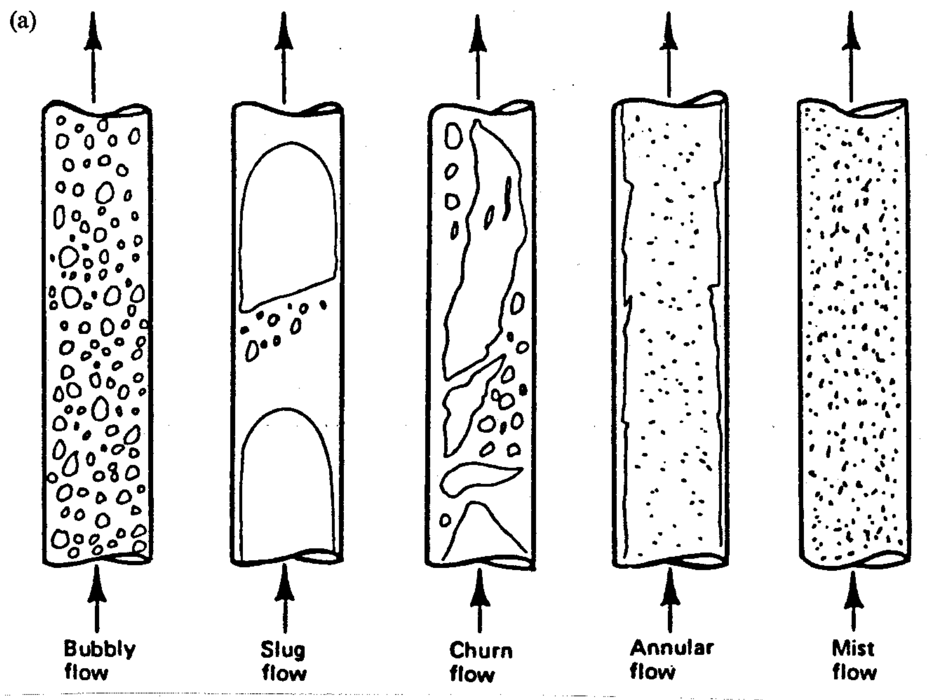
FDE - Stable film boiling



Two-phase Flow Regimes & Flow Boiling Crisis

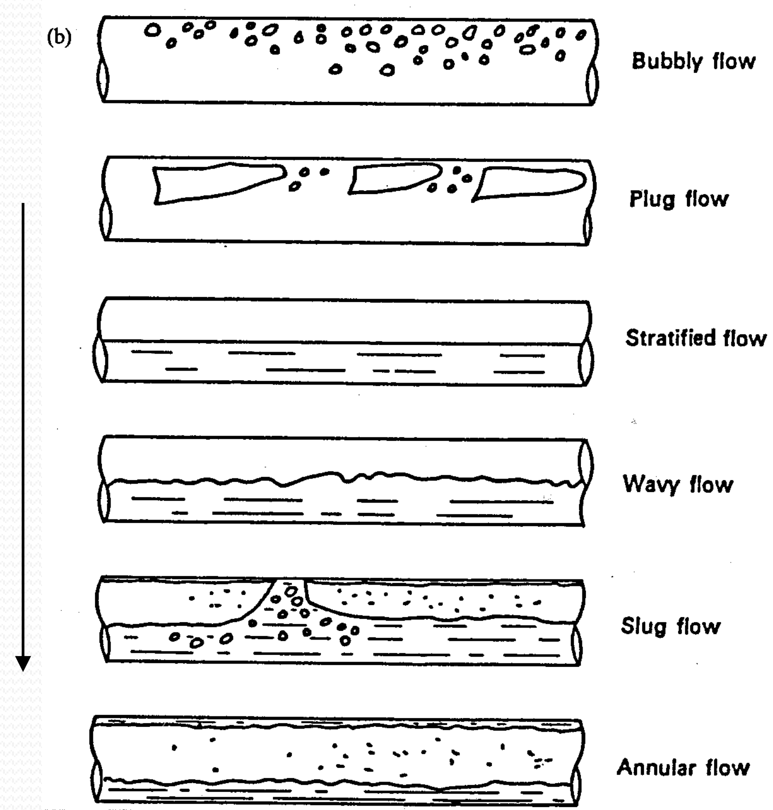
Two-phase Adiabatic Flow Regimes in Simplest Geometry - TUBE

Vertical upflow

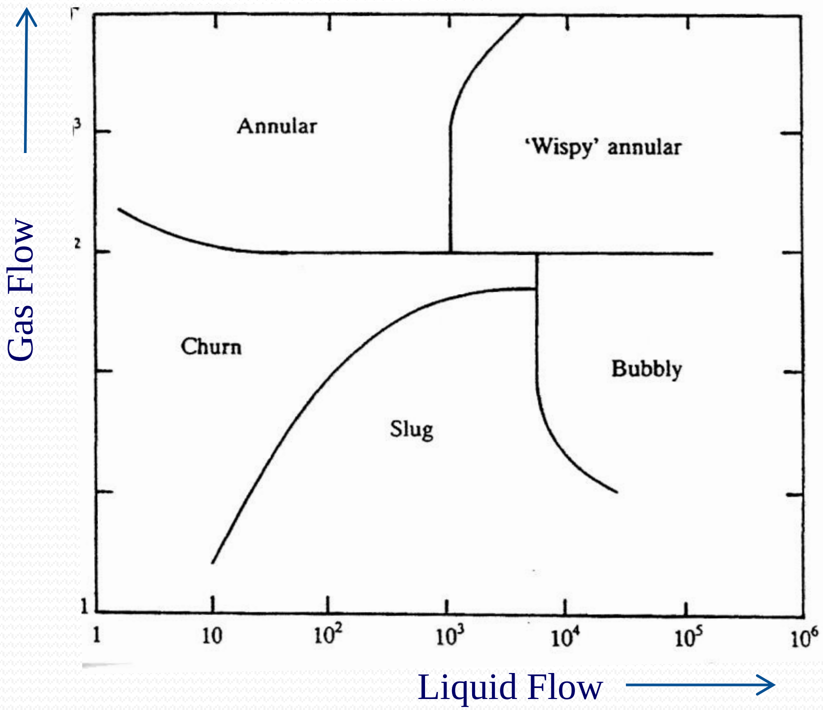


Gas flow increases

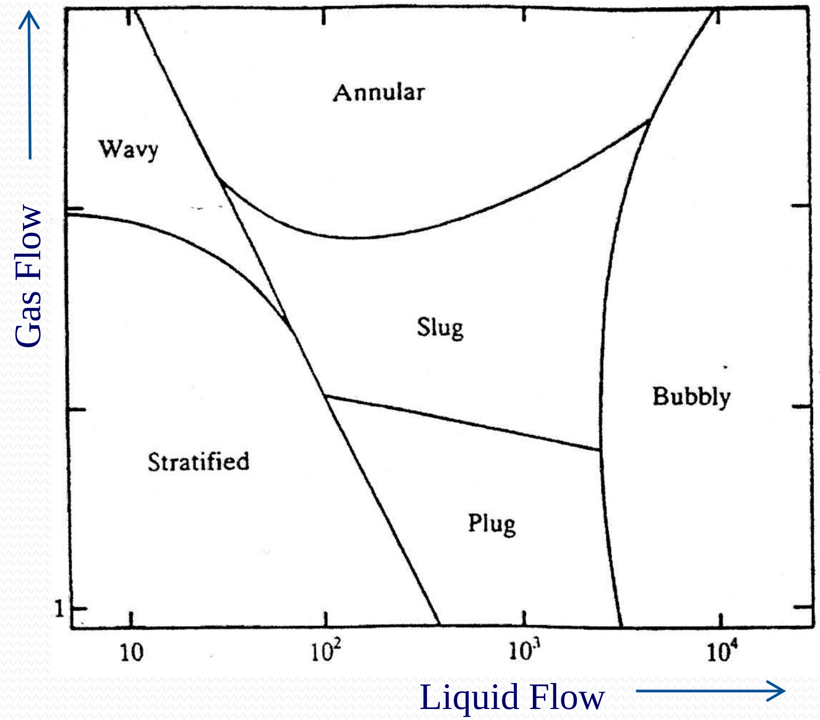
Horizontal flow



Two-phase Flow Patterns' Maps



Vertical Tube with Upflow



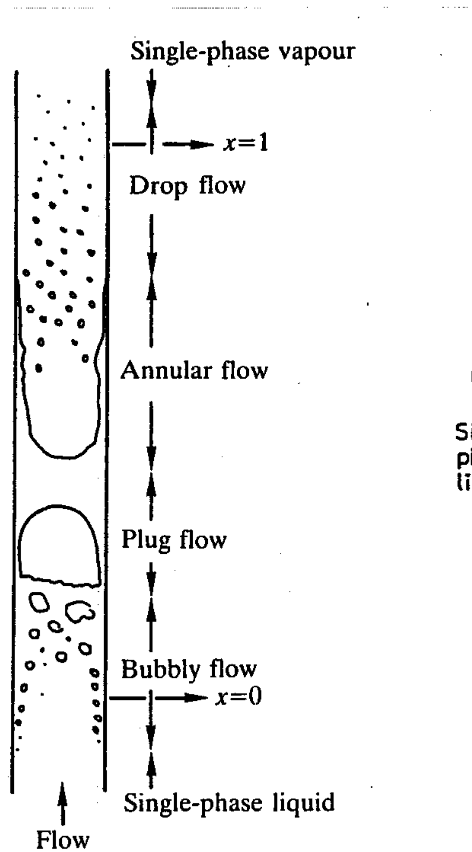
Horizontal Tube

* Such flow patterns maps are also obtained for fuel assemblies and used in TH computer codes to calculate heat transfer & pressure drop in a reactor core

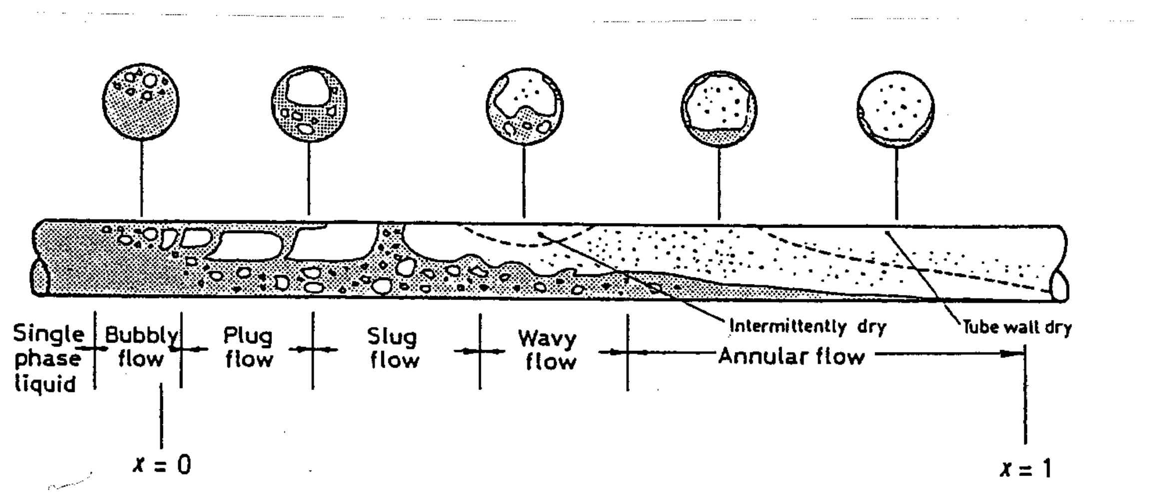
Diabatic (evaporating) Flow Regimes

Vertical upflow

Horizontal flow



Flow patterns in an evaporating flow.

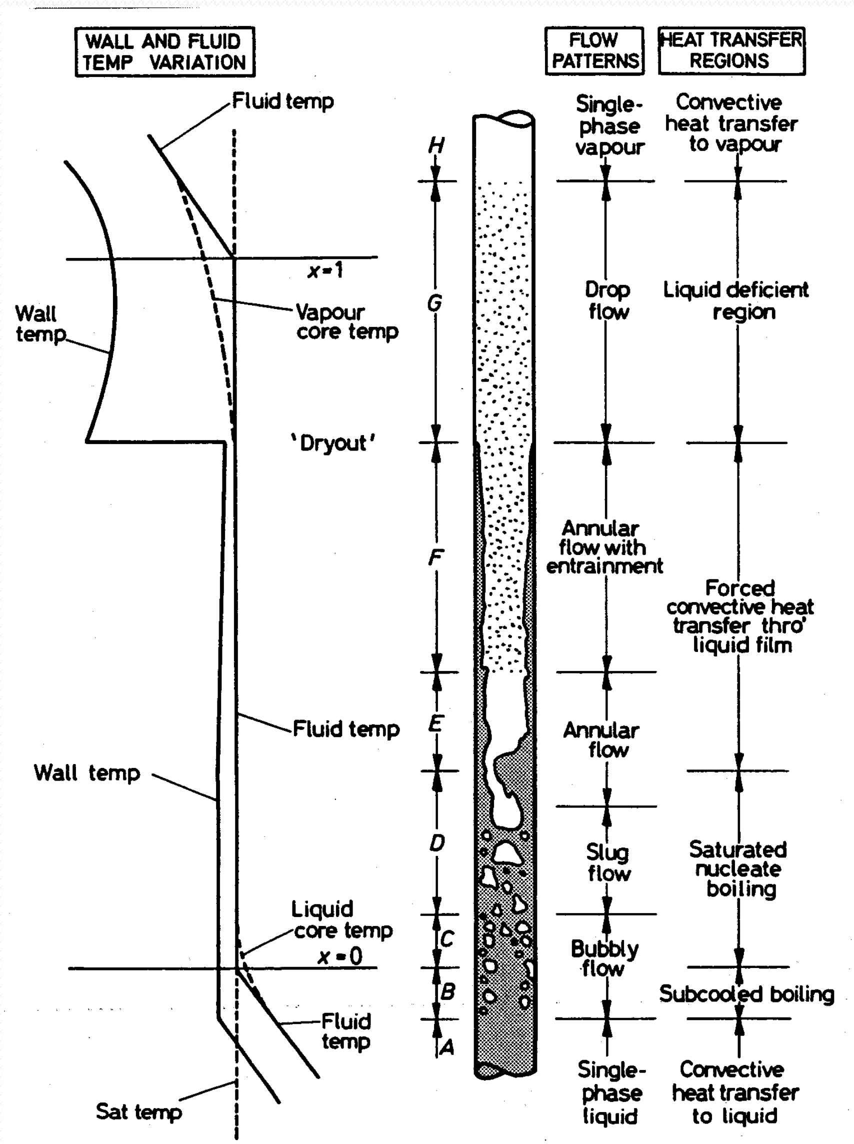


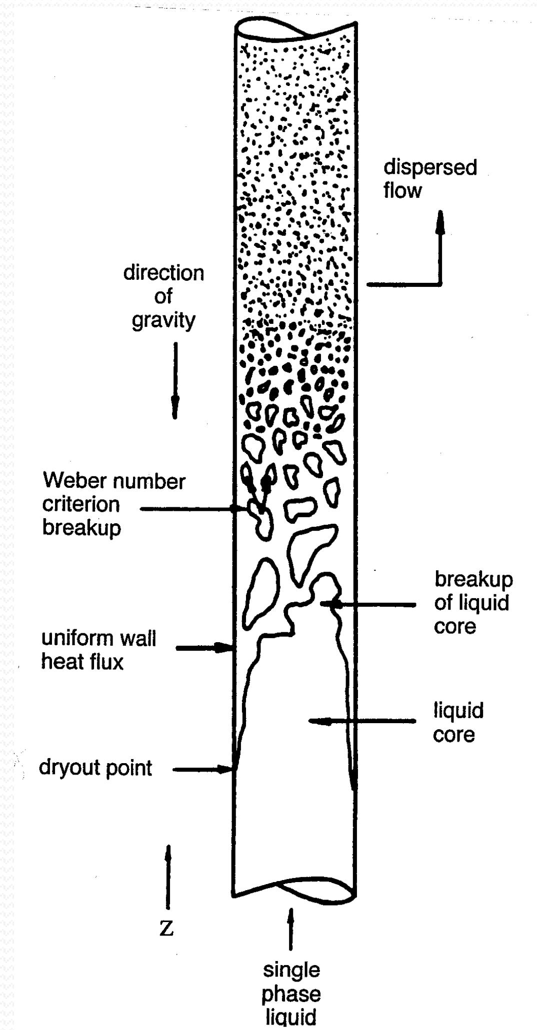
Heat generated in the wall or transferred through the wall is delivered to the coolant

Boiling Crisis – Flow Boiling

Dryout (mostly in CANDU)

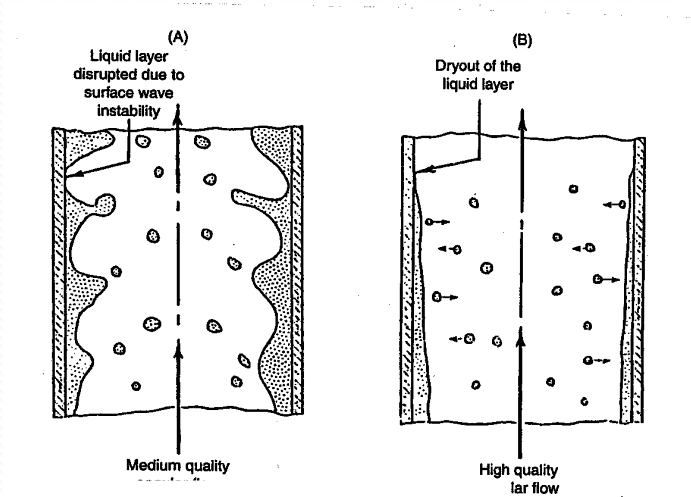
DNB (mostly in PWR)



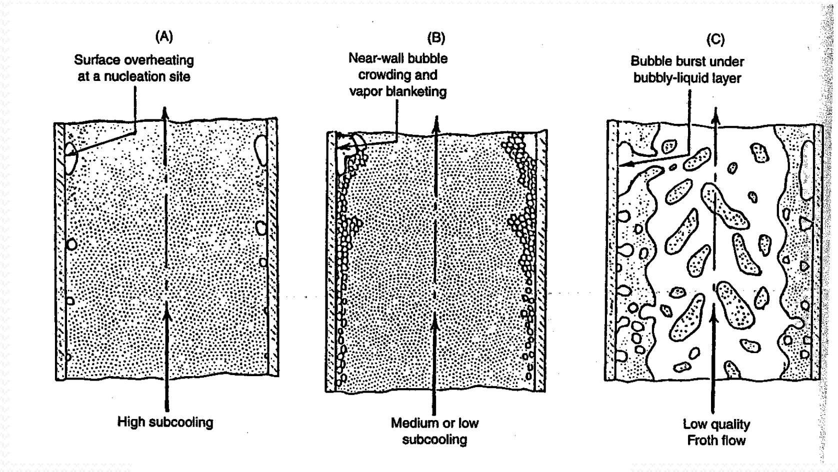


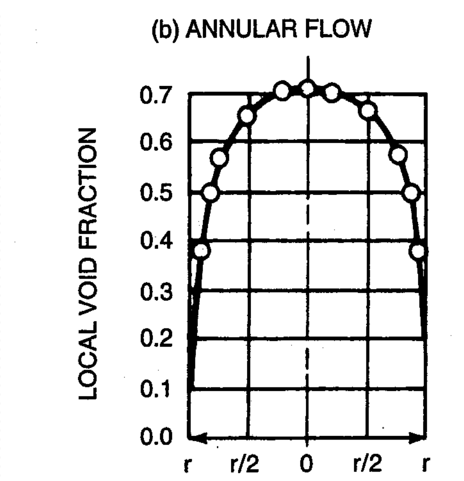
Boiling Crisis Mechanisms – Flow Boiling

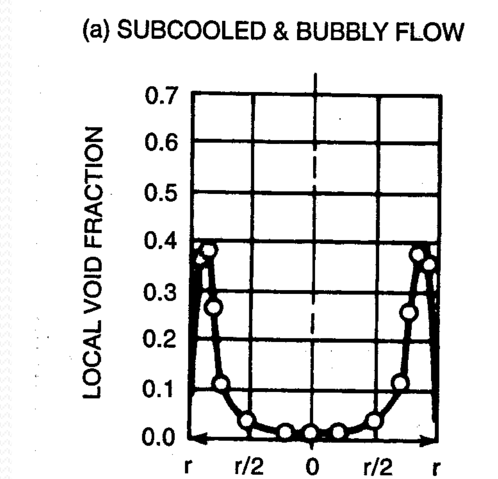
Dryout



DNB







Analytical Approach to CHF

Extreme cases of CHF in Tubes

Dryout Analytical Model

(One extreme CHF mechanism)

Based on mass balances for three phases (Whalley, 1977)

$$\frac{dG_{lf}}{dz} = \frac{4}{d}(D - E - \frac{q''}{\lambda})$$

G_{lf} – liquid film mass flux

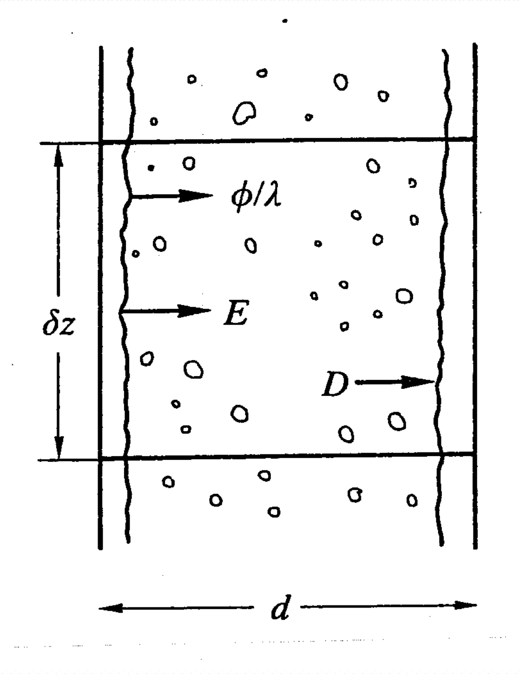
D – droplet deposition flux $\quad D = f(C, K)$

E – droplet entrainment flux $\quad E = f(\frac{\tau\delta}{\sigma})$

q''/λ - evaporation flux

C – droplet concentration

K – mass transfer coefficient



$q'' = CHF$ when $G_{lf} \rightarrow 0$

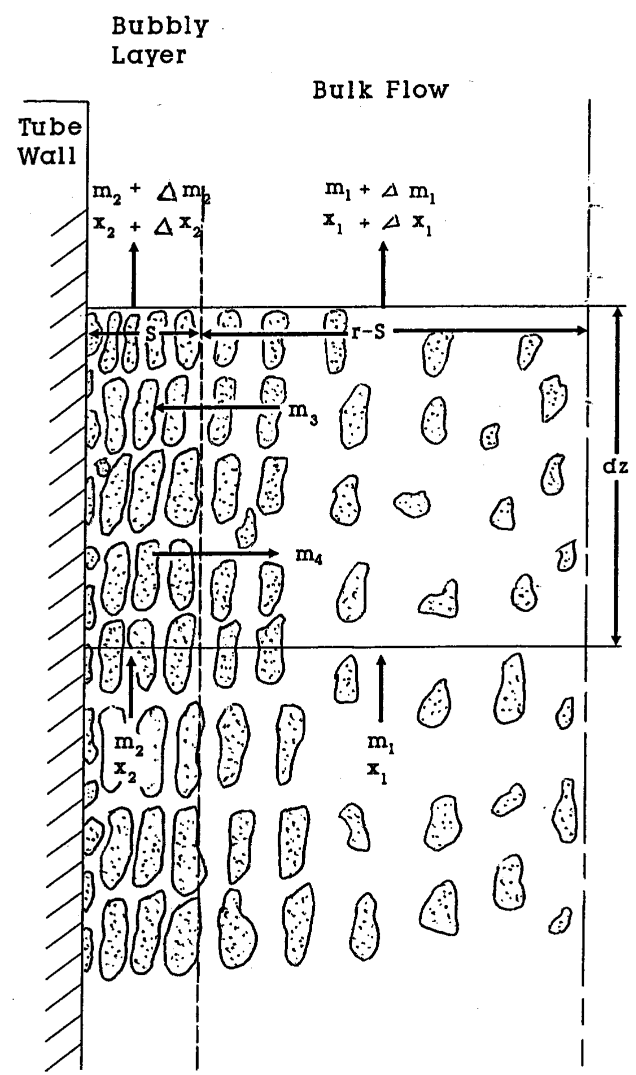
DNB Analytical Model

Based on sublayer dryout and bubble coalescence theories (Weisman & Pei, 1983)

(Another extreme CHF mechanism)

Assumptions:

- Bubbly layer builds up near-wall region preventing turbulent eddies from radial phase exchange
- CHF occurs when bubble layer reaches its max. thickness ($\alpha > 0.82$)



Verification of Analytical Methods

- Presented old CHF analytical models cover only two extremes of CHF mechanism spectrum successfully predicting CHF.
- The current analytical effort: please note the progress made by **Prof. Michael Podowski** and his coworkers at the Rensselaer Polytechnic Institute, Troy USA; still a limited range of conditions covered by their analytical/numerical models.
- To cover a wide range of conditions – **empirical CHF prediction methods are needed!**

Empirical Approach to CHF

Verification of the correctness of CHF models and to develop CHF prediction methods over a wide range of conditions

RELIABLE experimental data are needed!

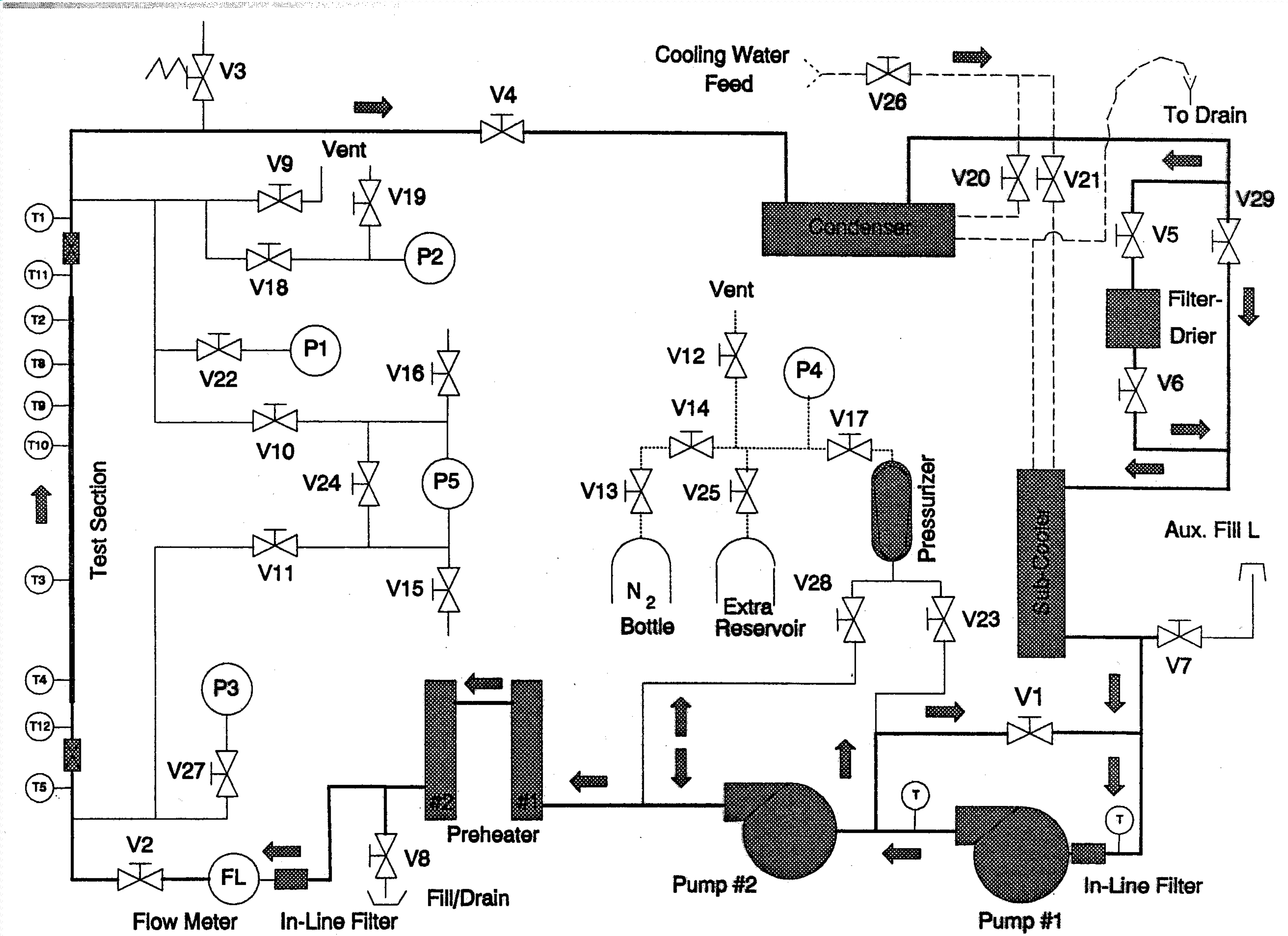
Empirical Approach

<u>As inferred from theoretical considerations CHF depends on</u>:

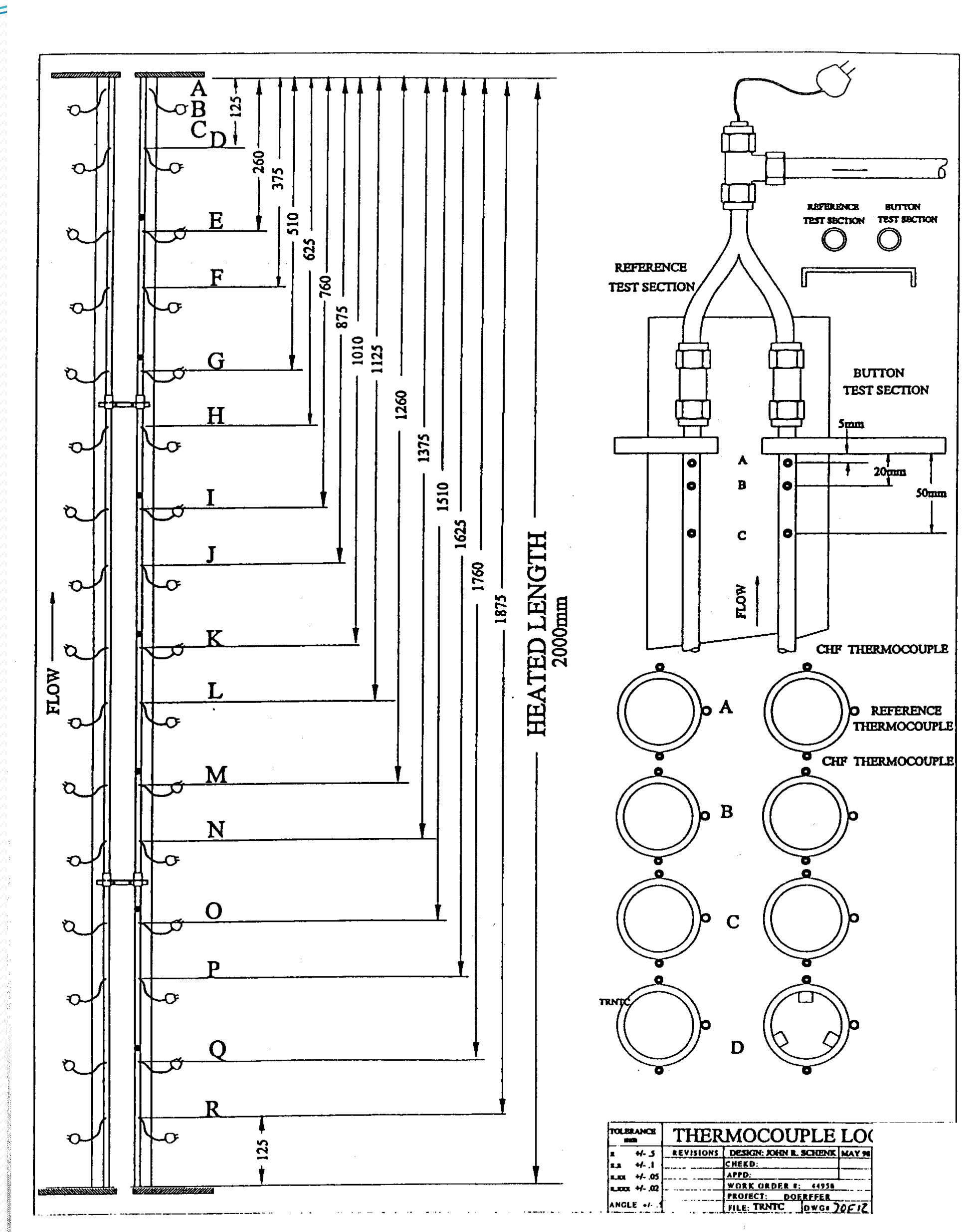
- **Flow parameters** (pressure, P, mass flux, G, local quality, x, inlet cond.),
- **Geometry** (cross section, De, heated length, L, appendages, grids),
- **Fluid properties** (latent heat, density, enthalpy, surface tension), and
- **Other** (flow orientation, heat-flux distribution, surface properties, time, etc.)

<u>These parameters define CHF value & also CHF experiment!</u>

CHF Experimental Facility



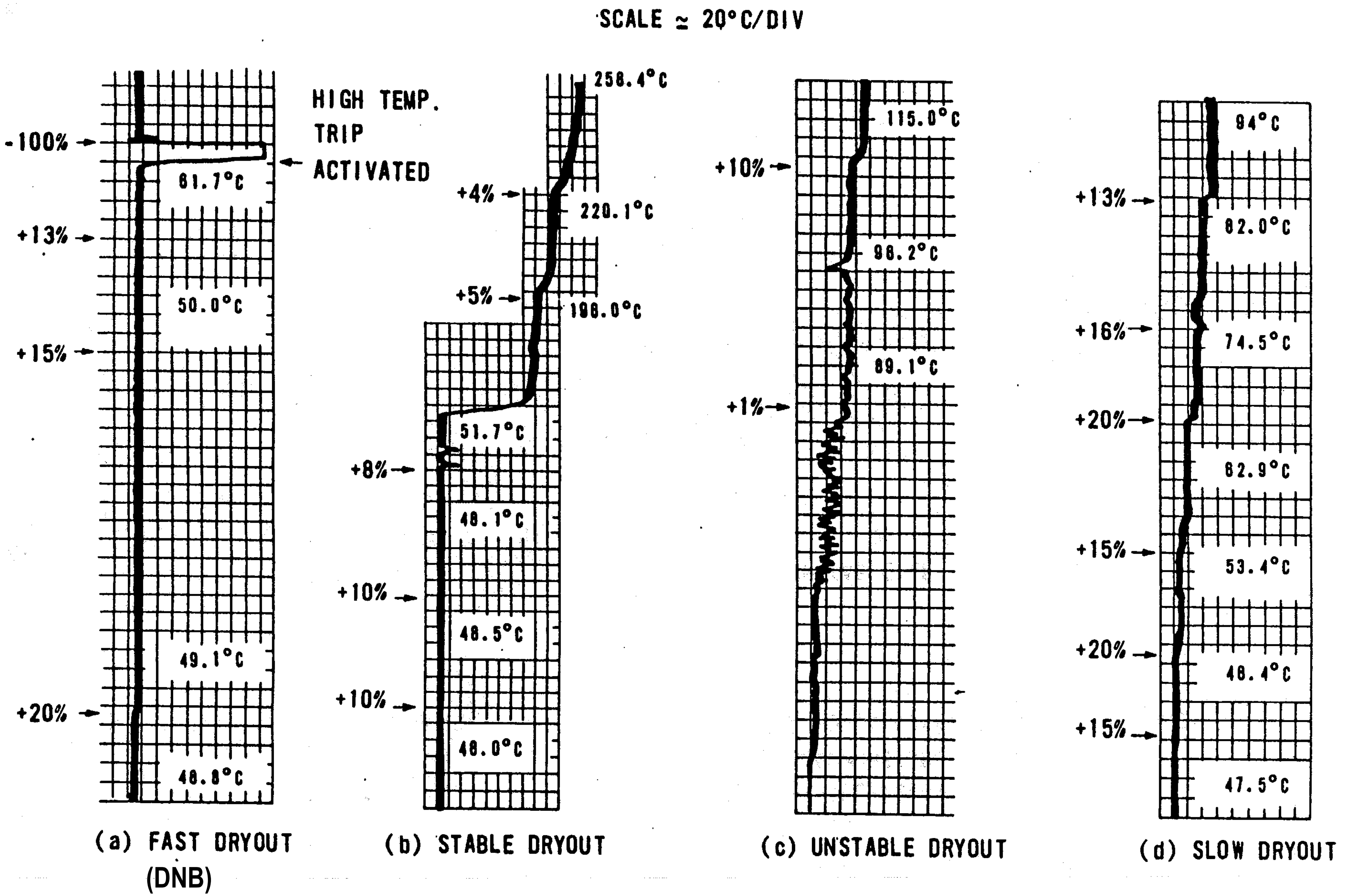
Tubular Test Sections



The CHF experiments in tubular geometry are relatively the simplest and cheapest!

That is why such setups have been extensively used in world-wide CHF research.

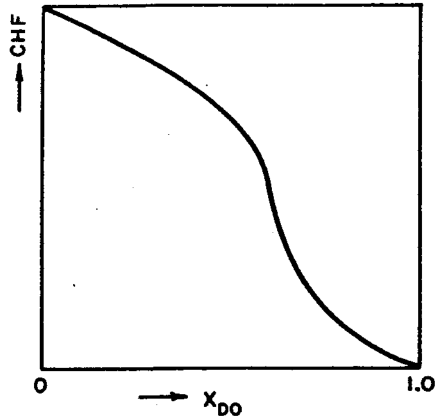
Wall Temperature Trends at CHF



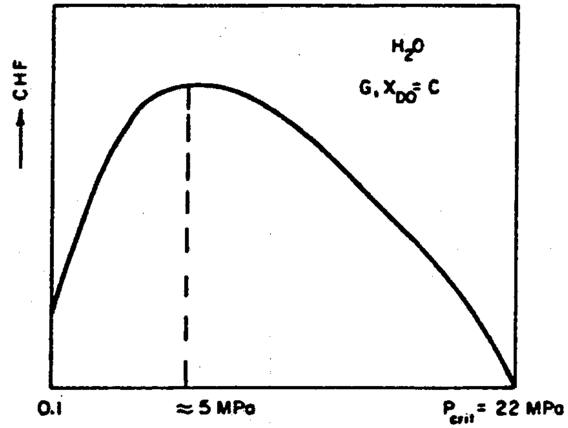
(Courtesy of AECL)

CHF Parametric Trends in Tubes

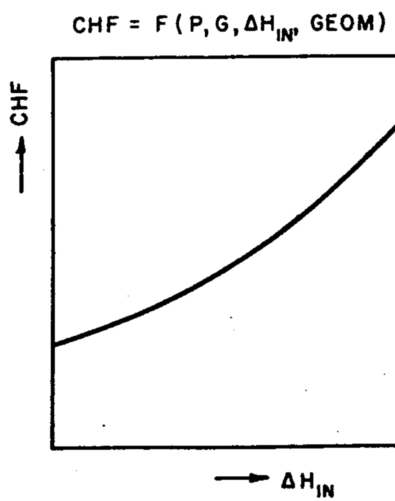
CHF Parametric Trends



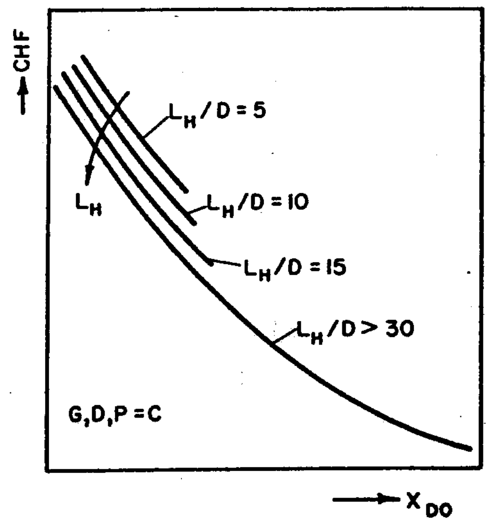
Effect of dryout quality



Effect of pressure



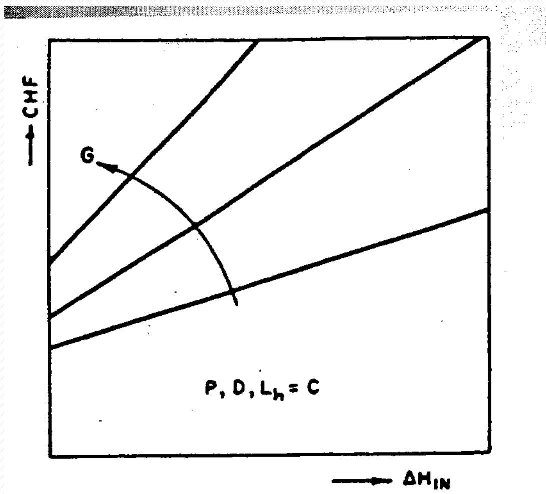
Effect of inlet subcooling



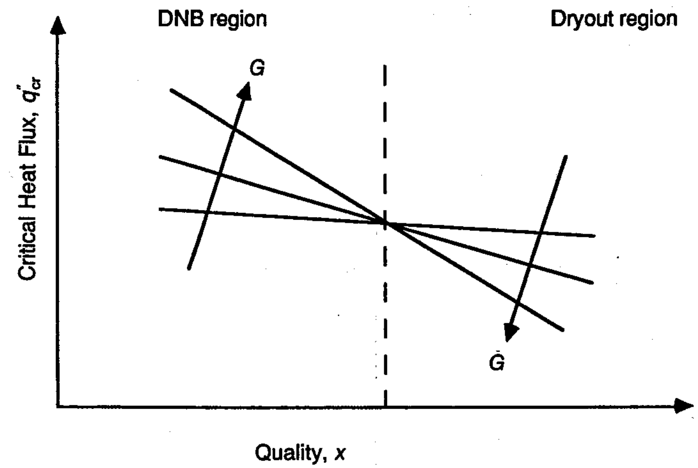
Effect of heated length

CHF Parametric Trends (cont.)

Effect of mass flux

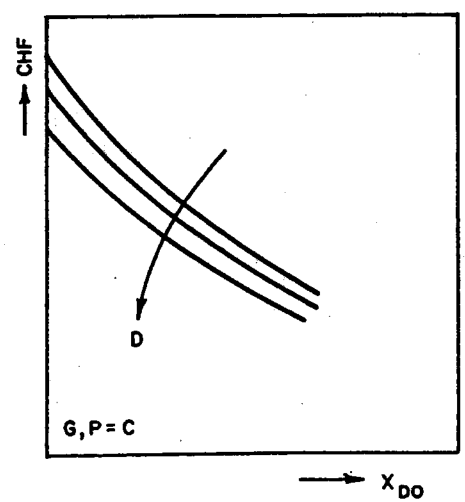


Inlet conditions



Local conditions

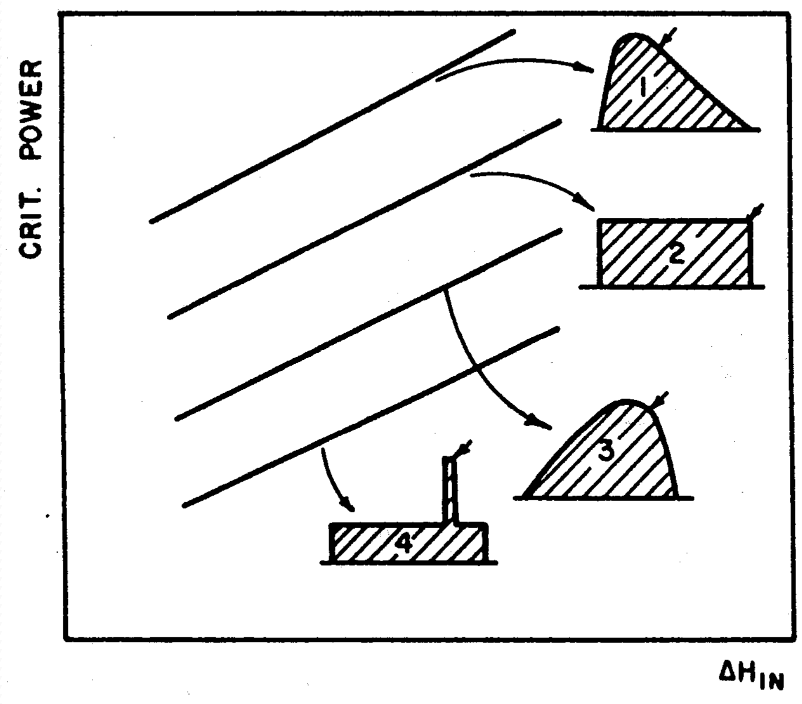
Effect of diameter

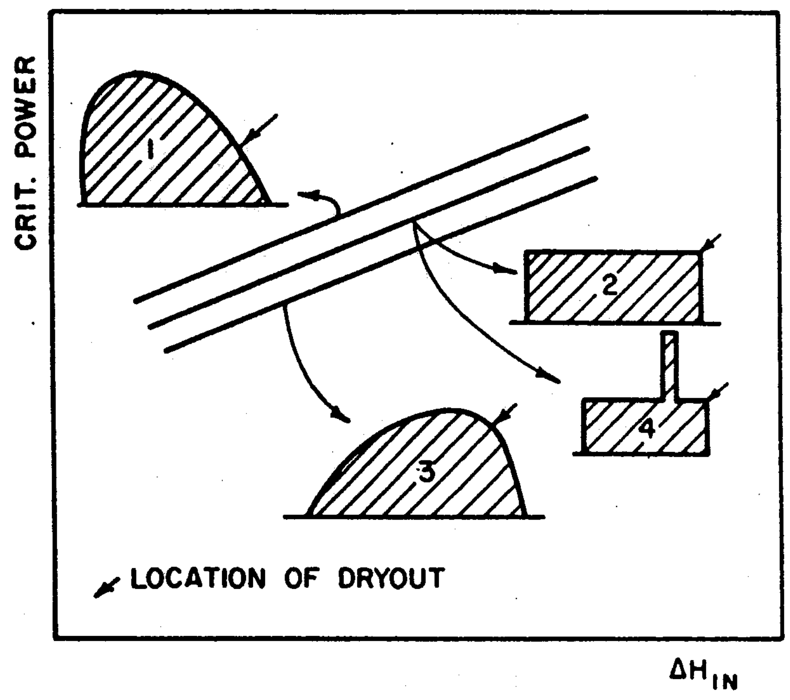


Local conditions

CHF Parametric Trends (concl'd)

Effect of axial flux distribution (AFD)





DNB (Subcooled conditions)

Dryout (of annular film)

Note: The major CHF parametric trends are similar in all geometries!

Encouragement to investigate CHF in simpler geometries!

Empirical CHF Prediction Methods

CHF Empirical Predictions

- Inlet-conditions type correlations assume overall ***Critical Power*** hypothesis ("black box" – early used correlations not satisfactorily account for separate effects such as AFD, RFD, grids etc.):

$$CP = f(P_{in}, G_{in}, T_{in}, L_H, geometry)$$

- Local-conditions type ***CHF*** correlations:

$$CHF = f(P, G, x_c, geometry)$$

(these correlations modified for separate effects are much more reliable than the inlet-conditions type)

Boiling-length Average Approach

The BLA hypothesis: exists a unique relationship between boiling length, L_B, and critical quality, x_c, which is independent of AFD for a given P, G and geometry

L_B = distance from the x = 0 to the CHF location

$$x_c = \frac{A \cdot L_B}{B + L_B} \quad \left(= \frac{4 \cdot q_{BLA} \cdot L_B}{\lambda \cdot G \cdot D}\right)$$

$$A, B = f(P, G) \qquad q_{BLA} = \frac{1}{L_b} \int_{L_{x=0}}^{L_{x=x_C}} q(l)\,dl$$

For annular flow regime (dryout) - better than local-conditions approach

Takes into account “flow history effect”

CHF Empirical Predictions for Tubes

<u>For vertical tubes over 700 CHF correlations are available!</u>

(according to the literature as of 1990)

Mysterious? A poor state-of-the-art?

A remedy?

CHF Look-up Table Method

International, normalized (to 8-mm ID) database with > 30,000 entries covering the widest ranges of parameters in water (vertical upflow):

P = 1 - 20 MPa

G = 0 - 7.5 Mg.m^{-2}.s^{-1}

X = -50% - 100%

(Groeneveld et al., 1996)

Pressure (kPa)	Mass Flux (kg.m^{-2}.s^{-1})	Quality																						
		−0.5	−0.4	−0.3	−0.2	−0.15	−0.1	−0.05	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.6	0.7	0.8	0.9	1
1000	0			5619	4685	4058	3564	2859	2175	1910	1438	1030	717	519	389	312	286	270	256	198	188	181	175	0
1000	50			6371	5523	4991	4456	3928	3323	2944	2469	2071	1752	1559	1414	1307	1230	1157	1076	876	806	804	700	0
1000	100			6981	6252	5685	5281	4851	4268	3386	2799	2631	2531	2415	2292	2184	2041	1891	1703	1312	1291	1250	732	0
1000	300			7492	7295	7089	6901	6766	6620	6215	5289	4760	4456	4120	3432	2600	2151	1924	1708	1343	1289	1215	660	0
1000	500			7577	7464	7327	7177	7110	7048	6818	5771	5094	4660	4233	3856	2754	2284	1979	1659	1035	825	767	589	0
1000	1000			7594	7466	7329	7192	7124	7022	6705	5694	5042	4634	3953	3264	2670	2035	1741	1516	958	592	452	338	0
1000	1500			7700	7468	7349	7230	7153	7013	6604	5532	4989	4422	3952	3236	2429	1557	1145	930	637	411	370	266	0
1000	2000			8187	7552	7424	7281	7192	7012	6401	5196	4720	4404	3952	3143	2259	1373	980	713	541	343	137	86	0
1000	2500			8962	7788	7544	7314	7202	6979	6100	5028	4668	4397	3924	2999	2081	1281	925	690	512	306	84	25	0
1000	3000			9731	8149	7728	7370	7206	6966	5900	4920	4647	4391	3898	2880	1955	1234	908	701	510	349	295	30	0
1000	3500			10456	8659	8005	7450	7179	6910	5800	4849	4628	4385	3865	2765	1797	1252	1059	1000	595	356	108	36	0
1000	4000			11146	9203	8342	7591	7143	6778	5752	4757	4584	4380	3794	2723	1891	1484	1292	1021	605	375	134	51	0
1000	4500			11816	9746	8754	7750	7141	6500	5537	4627	4477	4304	3715	2689	1953	1498	1327	1034	643	401	159	65	0
1000	5000			12447	10239	9182	7859	6988	5900	5107	4361	4211	3924	3338	2581	1978	1579	1363	1126	726	438	188	83	0
1000	5500			13033	10745	9599	8124	6794	5800	4822	4239	4085	3729	3112	2523	2017	1703	1469	1235	816	484	227	104	0
1000	6000			13573	11285	10064	8595	6647	5530	4654	4096	3966	3625	3050	2519	2063	1767	1555	1325	902	546	275	129	0
1000	6500			14101	11770	10479	8933	6351	5228	4460	3913	3804	3484	2973	2497	2115	1852	1633	1406	983	616	326	155	0
1000	7000			14608	12172	10857	9325	6654	4850	4232	3734	3547	3336	2867	2461	2178	1945	1707	1480	1057	681	375	180	0
1000	7500			15109	12524	11194	9725	7272	5409	4227	3683	3525	3287	2851	2478	2246	2006	1774	1548	1126	744	423	204	0
1000	8000			15629	12866	11463	9958	7773	6039	4447	3684	3536	3341	3061	2571	2306	2062	1834	1612	1190	802	470	227	0

Note: Some regions (shaded) higher uncertainties due to lack of data

From the simplest flow geometry let’s move to the most complex geometry

CHF in CANDU® Reactor Fuel Channels

(Horizontal Channels)

Experiments & Predictions

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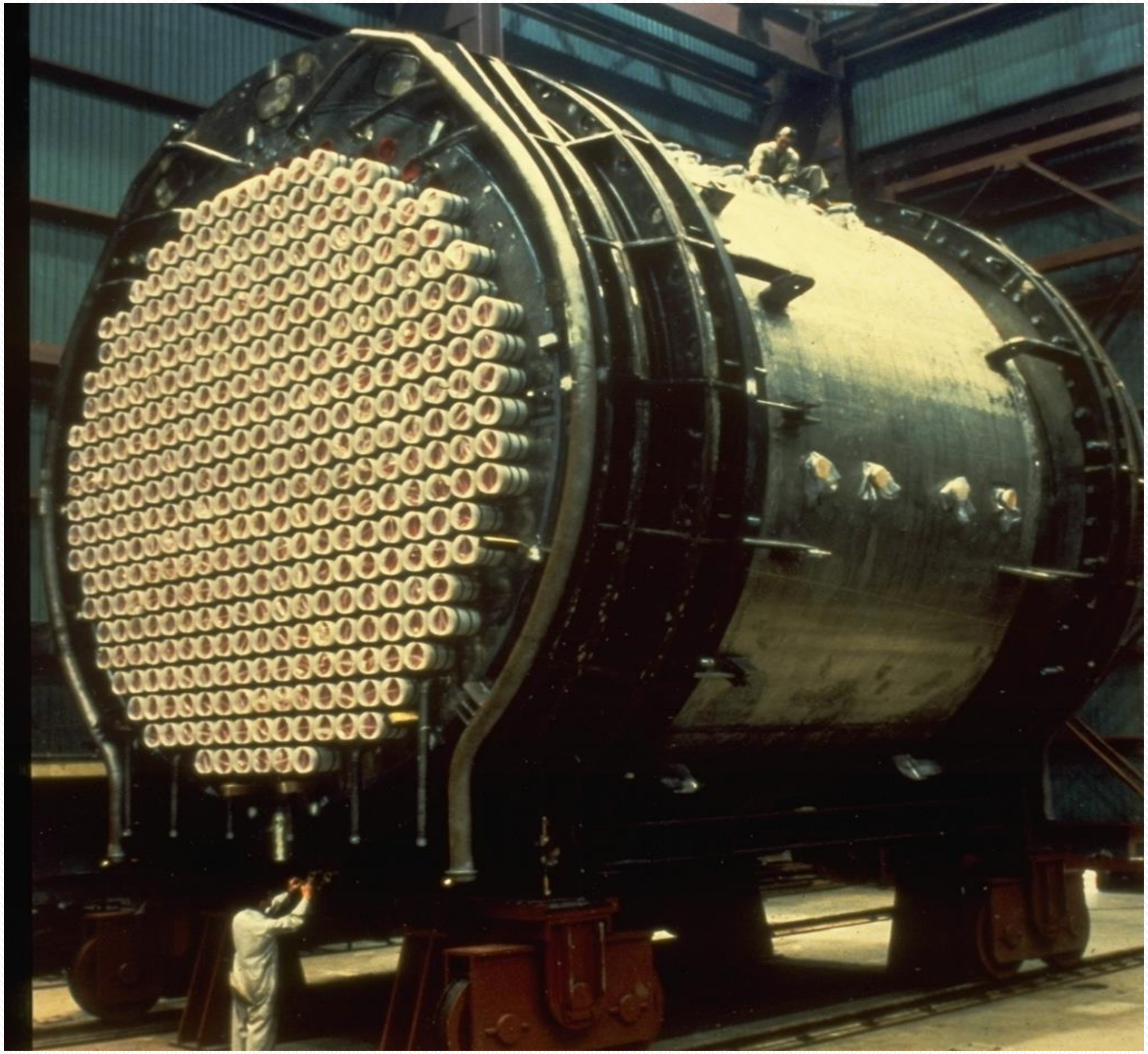
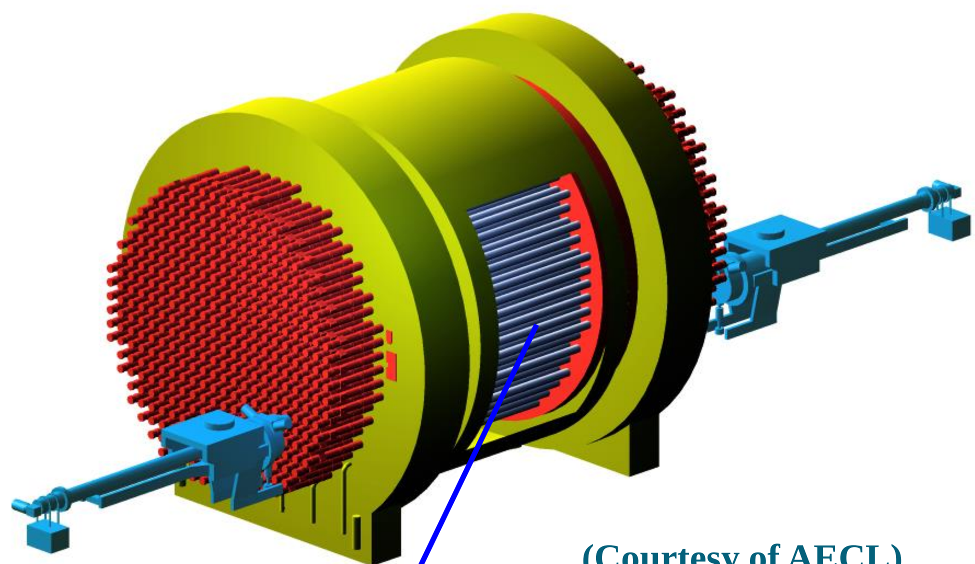
CANDU 6 Reactor



(Courtesy of AECL)

CANDU Reactor Intrinsic Features

- Channel reactor
  - Horizontal channels
  - Pressure tube as core pressure boundary
  - Heavy-water cooled
  - Heavy-water moderated
- Separate coolant and moderator
- Short fuel bundles replaceable on-line



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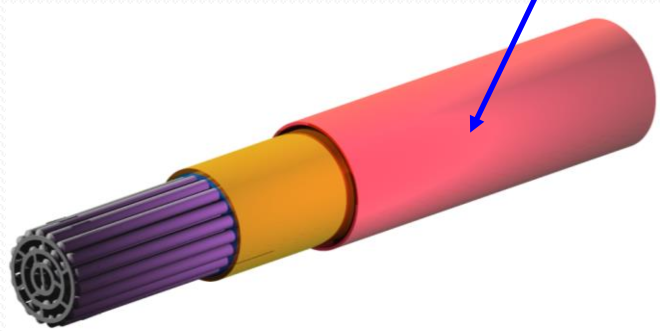


(Courtesy of AECL)

CANDU Fuel Bundle

(Courtesy of AECL)

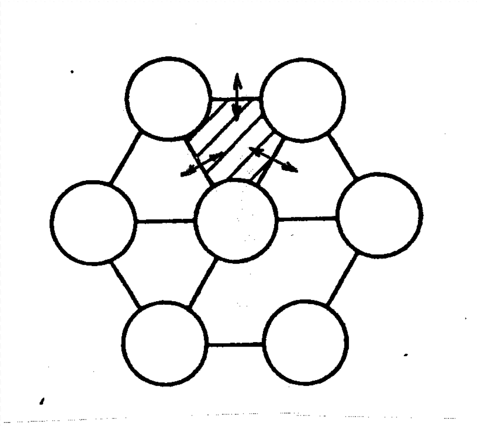
- Length ~50 cm
- Diameter ~10 cm

A questioning attitude…

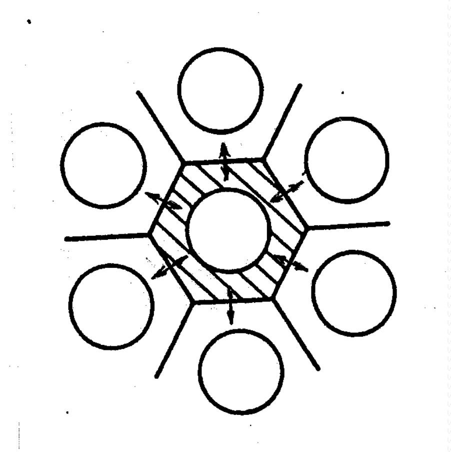
How far CHF findings in tubes can be applicable to CANDU fuel channels or any other LWR fuel assemblies?

CHF in Fuel Channels

<u>Differences between fuel-bundle and tube geometries:</u>



- External flow (convex surface) as opposed to internal flow (concave surface)
- Presence of "communicating" subchannels ("porous tubes")
- Presence of transverse flows (interchannel turbulent mixing, cross flow, void diffusion, etc.)
- Presence of bundle appendages (spacers, buttons, end plates, bundle misalignment)
- Presence of radial heat-flux distribution
- Presence of cold wall



CHF Predictions in Fuel Channels

<u>Subchannel analysis based on CHF tube data:</u>

- CHF tube prediction methods modified by several bundle-specific correction factors/functions:
  - CHF tube look-up table
  - CHF tube correlations
  - CHF tube models

$$CHF_{Bundle} = CHF_{Tube} \bullet \Pi K_i; \;\; i = 1,,,9$$

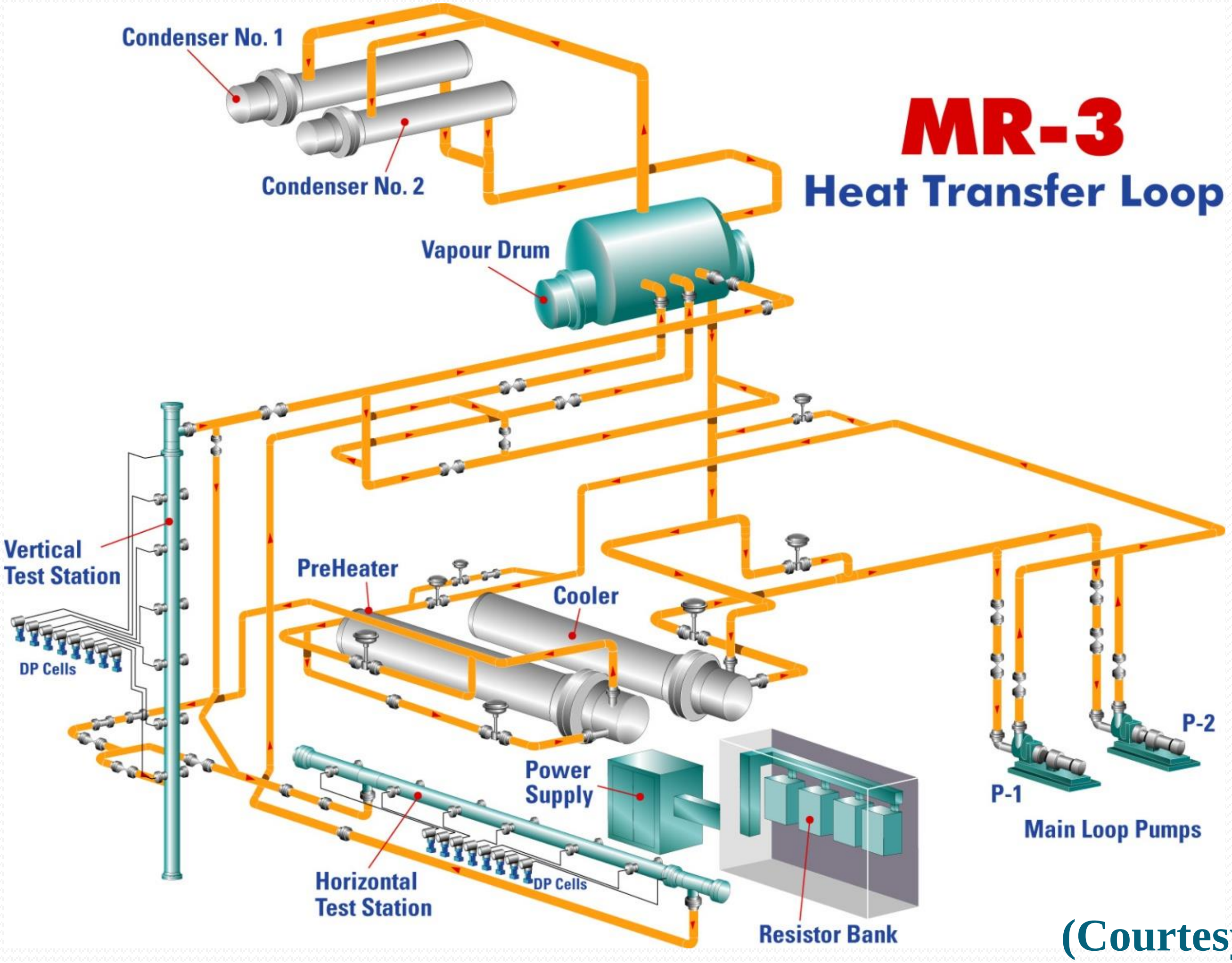
<u>The effect K</u> = 1- diameter, 2 - geometry, 3 - spacer, 4 - heated-length,
5 - AFD, 6 - RFD, 7 - orientation, 8 - low flow, 9 - transient

Note: TH codes (e.g., RELAP5-3D, PWR & CANDU codes) use a similar approach; but specific fuel assembly CHF test data are used for licensing proposes.

CHF Experimental Facilities for CANDU Reactor Fuel Bundles

- **Full-scale high-pressure steam-water loops (CRL & Stern Laboratory in Hamilton, Canada)**
  - tests at actual CANDU reactor conditions
- **Full-scale low-pressure Freon-134a loop (CRL)**
  - simulations of high-pressure steam-water conditions by Freon-134a
  - CHF fluid-to-fluid scaling applied to water-conditions conversion
- **Small-scale steam-water and Freon-134a loops (CRL)**
  - simple test sections and bundle sub-assemblies
  - fundamental & separate-effects studies

Freon Test Facility at CRL



(Courtesy of AECL)

Freon Loop Fuel Bundle Simulator

- A 6-m (20 ft) long full-scale bundle string with simulated junctions and appendages
- Non-uniform axial and radial power distributions

(Courtesy of AECL)

CHF experiments in CANDU power channels and LRW fuel assemblies are the most complex & expensive! Therefore, CHF correlations at actual geometry & conditions for licensing purposes are **proprietary**!

CHF Predictions in CANDU Channels

Empirical methods based on **CHF fuel bundle test data***

- CHF cross-section average bundle correlations
- CHF look-up tables for 37- & 43-element fuel bundles

*Developed for local as well as BLA conditions and used in the AECL's NUCIRC & CATHENA codes

For licensing purposes of water-cooled nuclear power reactors, the CHF correlations based on tests in water, at reactor conditions in a full-size fuel geometry are necessary – to be accepted by nuclear regulators!

These correlations are only valid over the tested ranges of conditions with defined uncertainties.

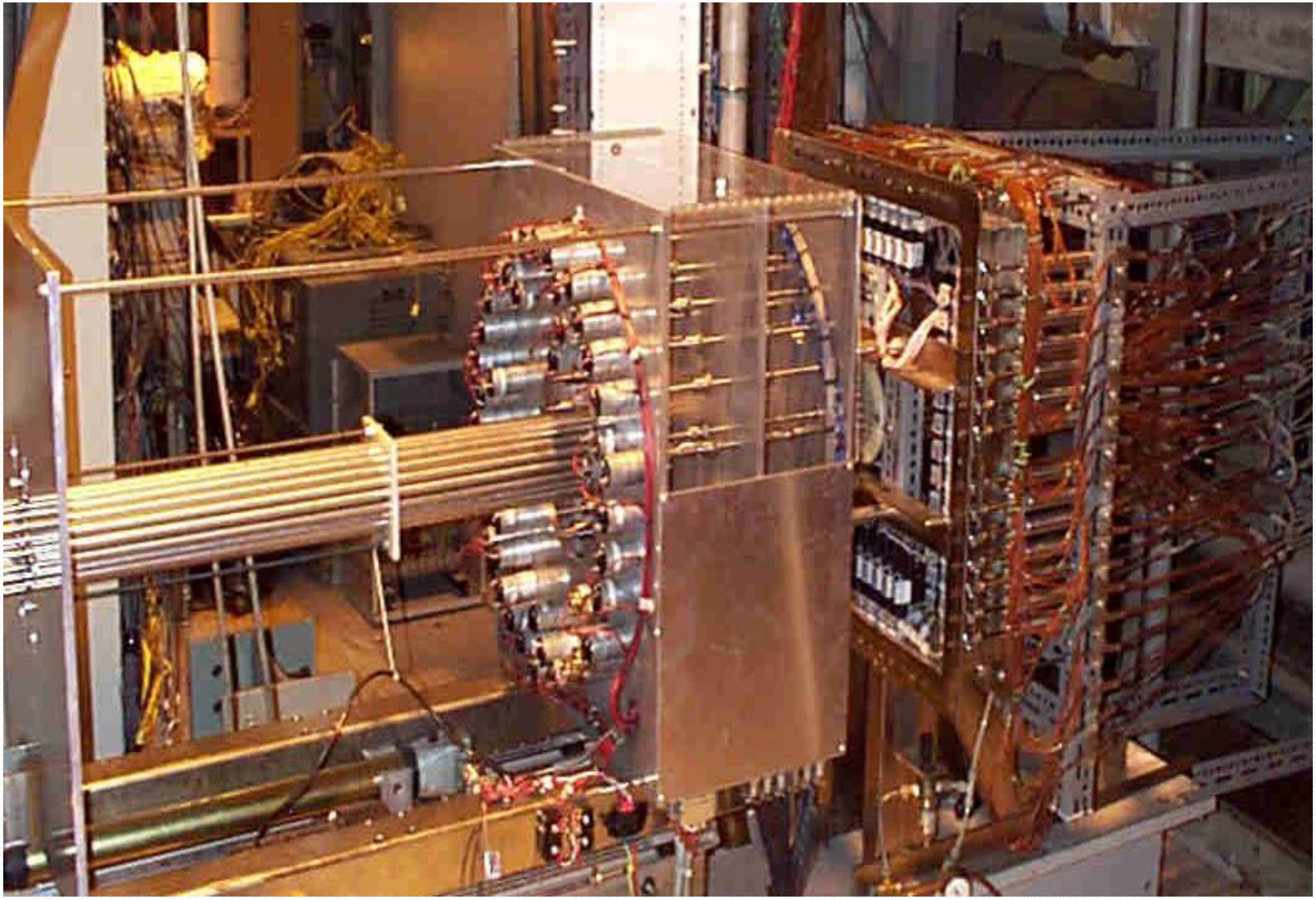
Let's see the experimental setup in a full-size CANDU fuel channel geometry & at actual CANDU reactor conditions at the Stern Laboratory in Hamilton, Ontario, Canada.

Water Test Facility at Stern Lab in Hamilton

(Courtesy of AECL)

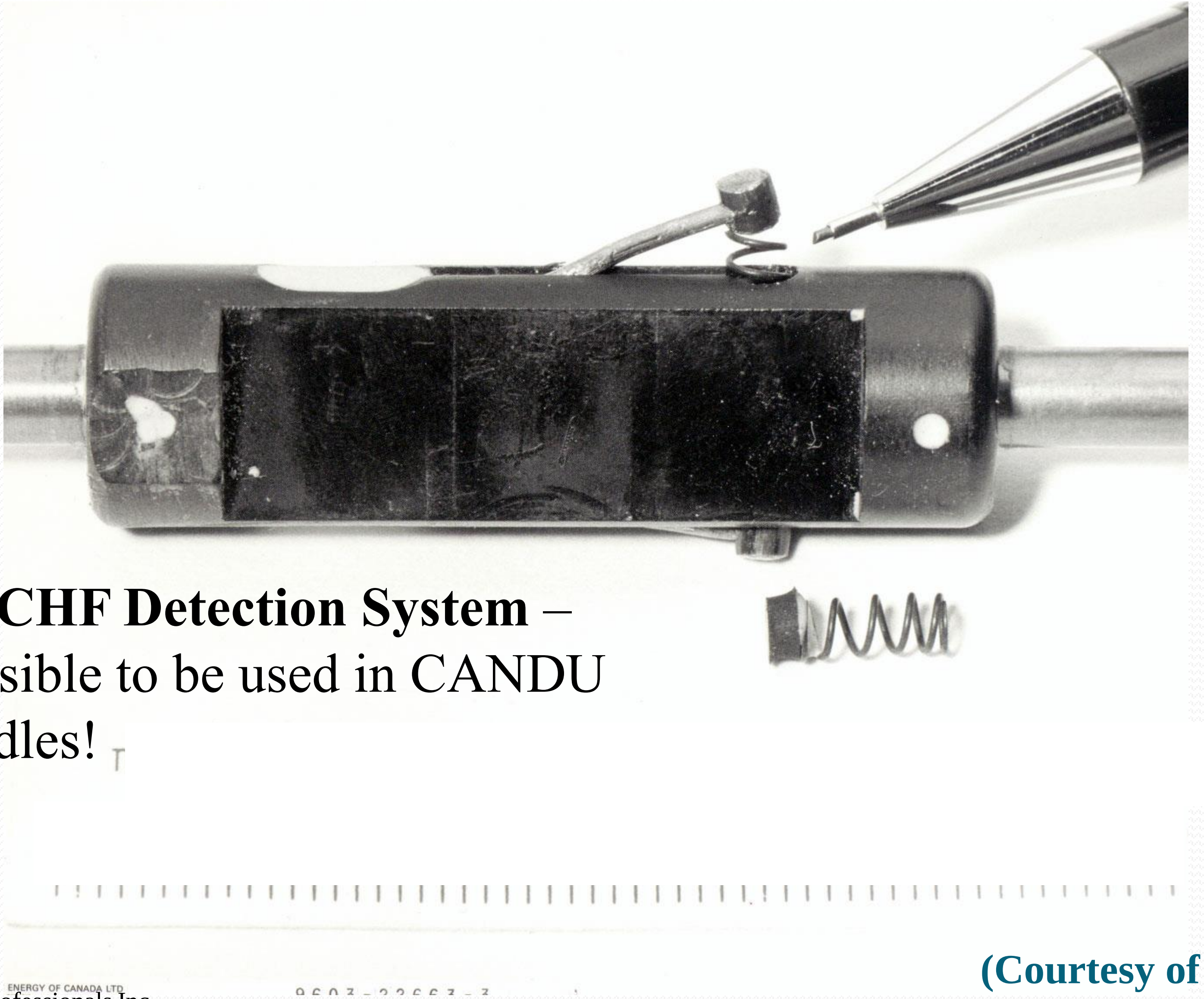
CHF tests - full-size CANDU fuel channel & at actual reactor conditions

Sliding Thermocouple Drive Unit



(Courtesy of AECL)

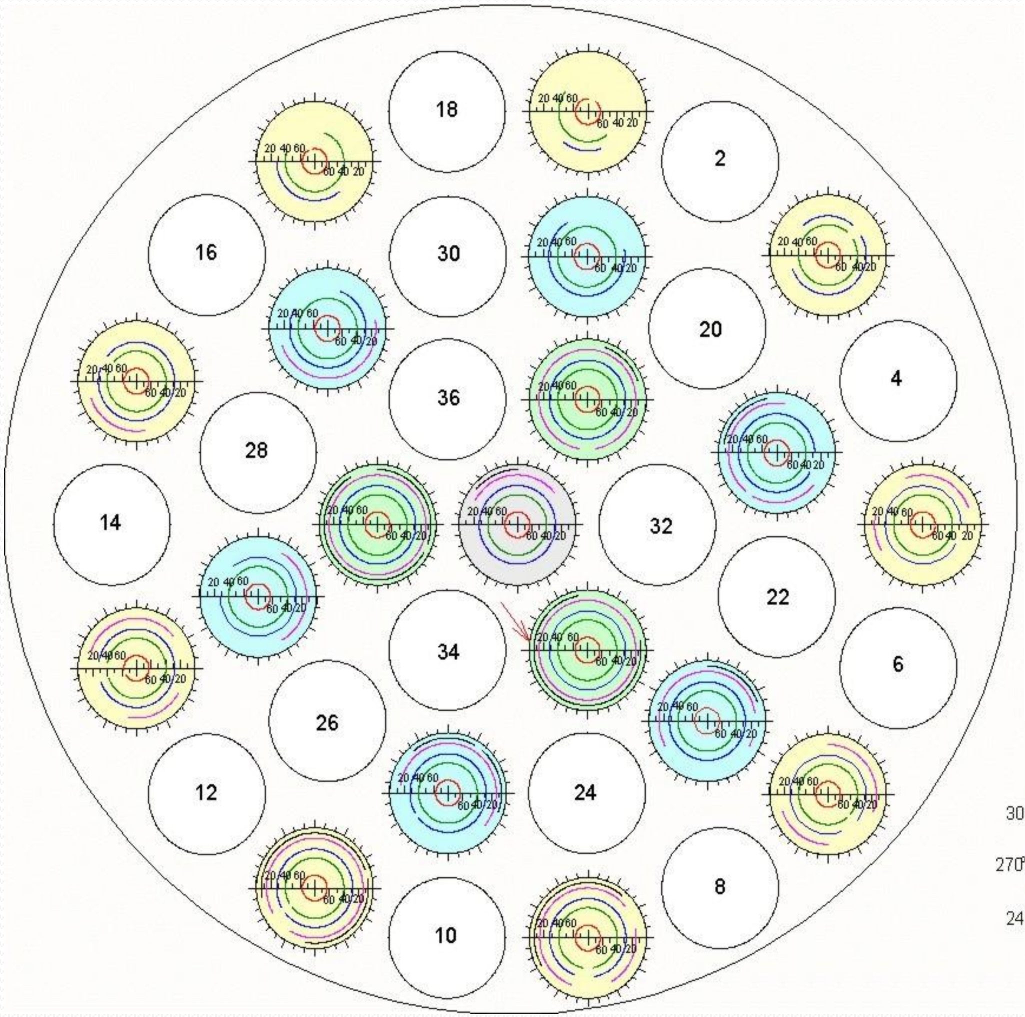
Sliding Thermocouple Assembly

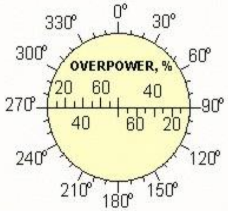


Unique CHF Detection System – only possible to be used in CANDU fuel bundles!

(Courtesy of AECL)

Circumferential Drypatch Map





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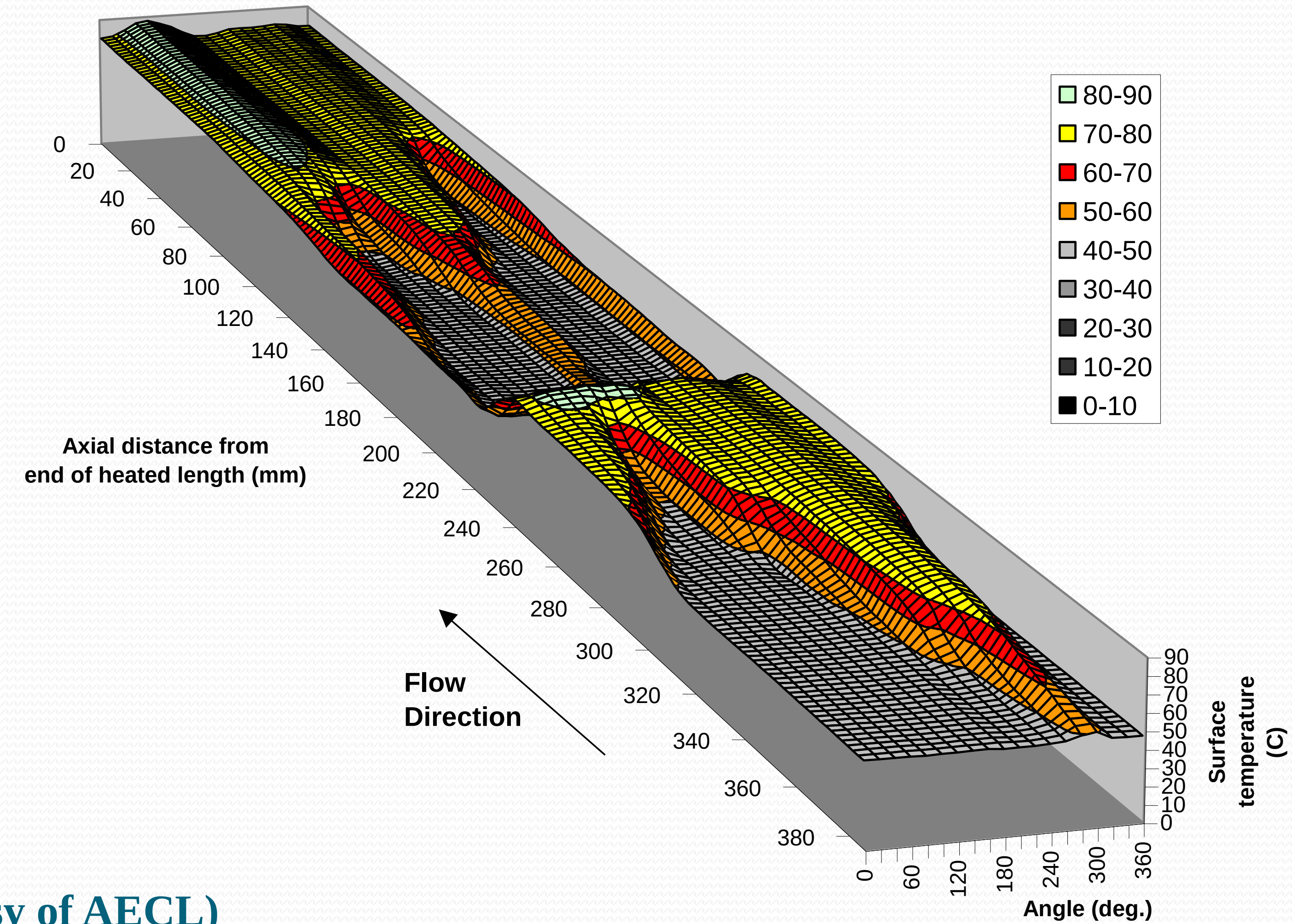
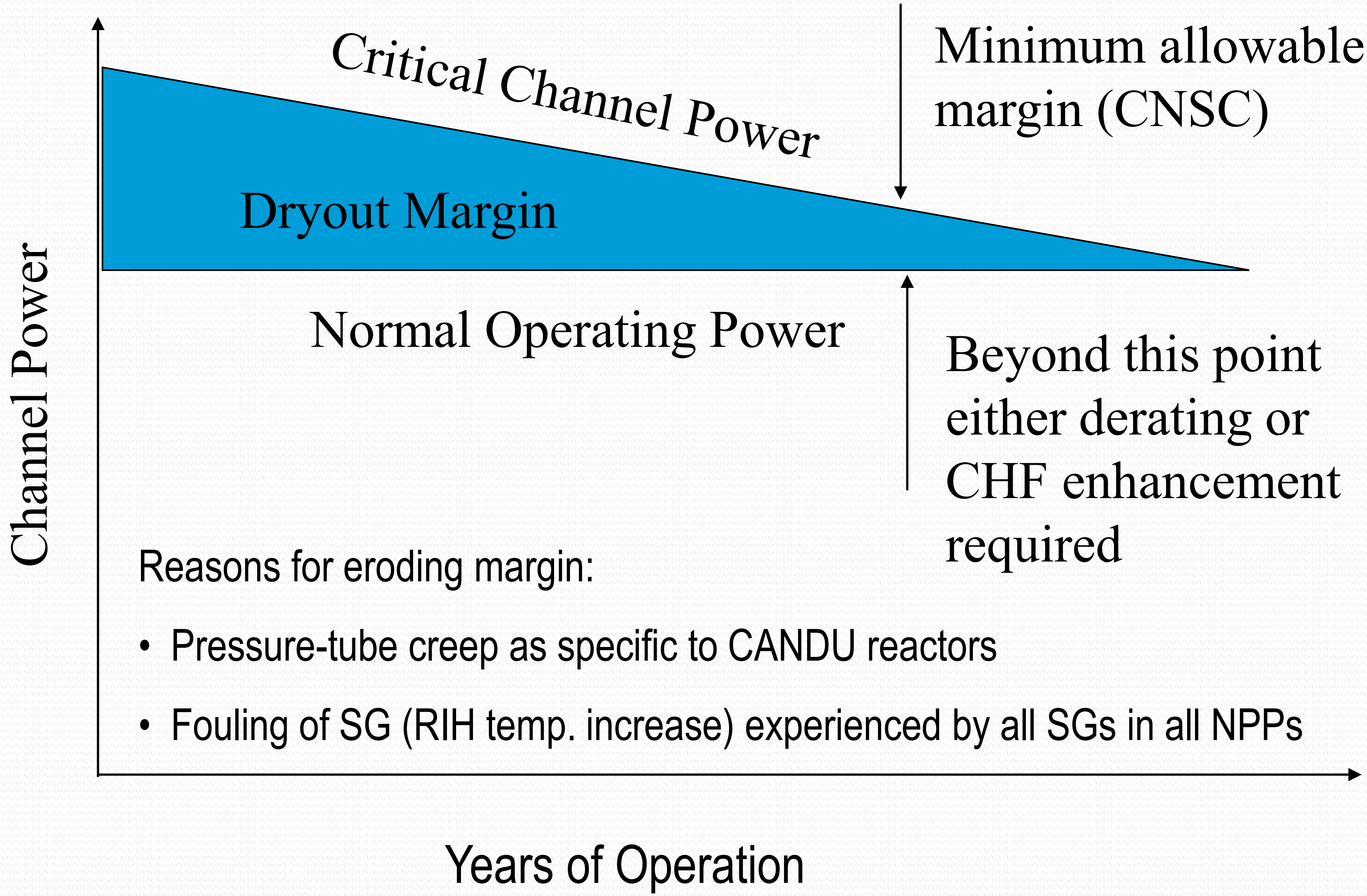
PDO Clad Temperature Profile



(Courtesy of AECL)

Operating Margin Erosion



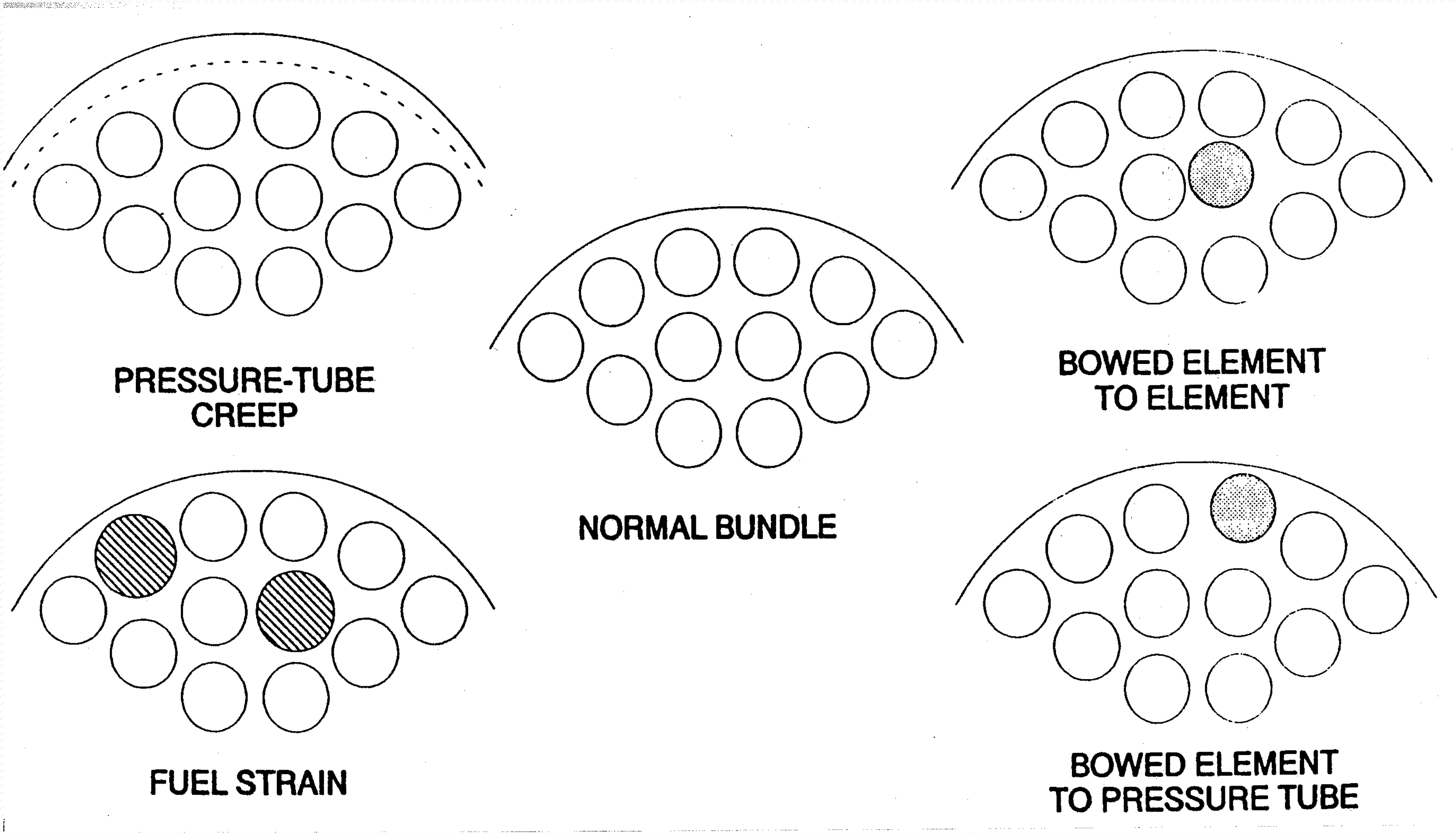
Reasons for eroding margin:

- Pressure-tube creep as specific to CANDU reactors
- Fouling of SG (RIH temp. increase) experienced by all SGs in all NPPs

All, so far, has referred to the nominal intact CANDU fuel bundle geometry.

Hypothetical geometry changes are considered in safety analysis – how to predict CHF if they do occur?

Examples of Hypothetical Geometry Changes in CANDU Fuel Bundles



Let’s focus on the pressure-tube diametral creep

To assess this problem, investigate and apply findings from:

CHF in an annular geometry - a more complex geometry than the tubular geometry

To solve this problem, investigate and apply findings from:

CHF enhancement techniques

CHF in Annular Geometries

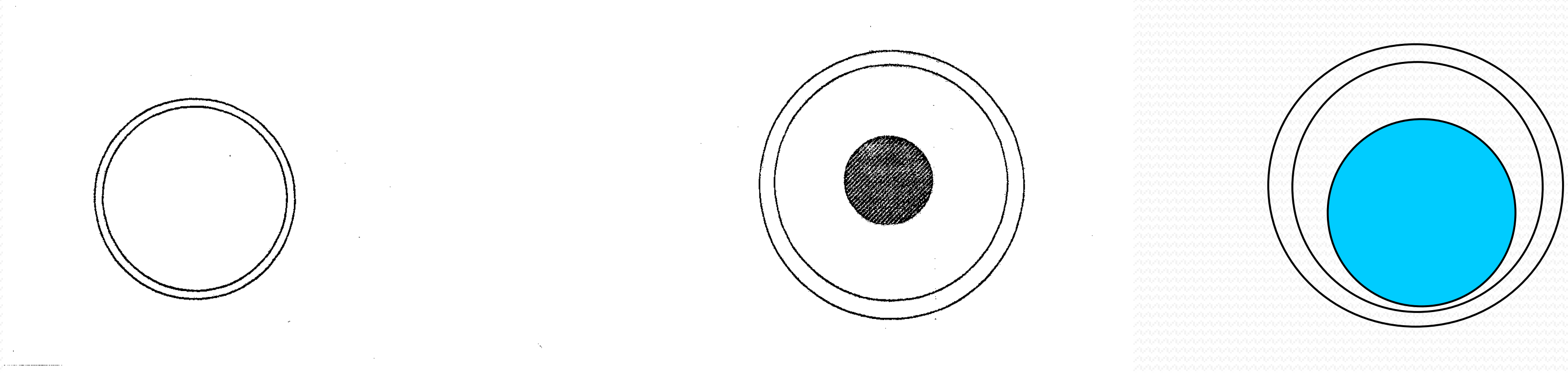
Annuli – a More Adequate Geometry?

Tubes

Annuli

Concentric

Eccentric



- diameter only

- curvature (concave only)

Note – due to complexity of CHF tests in annuli, limited CHF database exists

- diameters,

- gap size,

- curvature (concave & convex)

- concentric vs eccentric

- mode of heat supply

Physical Processes in Annuli Different from those in Tubes

- Shear stress distribution between surfaces causes:
  - Different droplet entrainment from both liquid films (dryout case)
  - Different bubbles' removal from both walls (DNB case)
- Different generation and propagation of waves on both walls (effect of surface tension)
- Droplet deposition on both walls,
- Effect of normal vapour flow from evaporating films on droplet deposition (lift force)
- Presence of cold surface in internally heated annuli

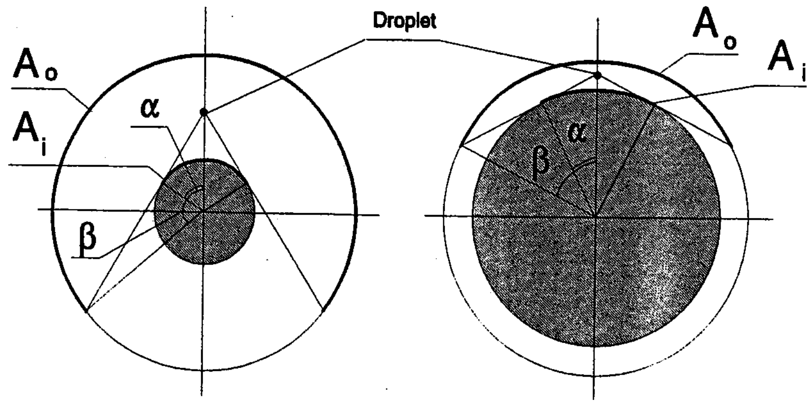
CHF Mechanisms in Annuli

- Shear Stress Distribution: $\tau_i > \tau_o$ (valid for SP laminar & turbulent flow, assumed to be true for TP flows),

- Deposition Rates: $D^* = f(C, K)$, $K = f(P, q''$, viewing factor $(\Psi))$
  at P, q" constant $K_o > K_i$ due to Ψ, hence $D^*_o > D^*_i$

$\Psi = A_o/A_i$

$\Psi = r_o/r_i$

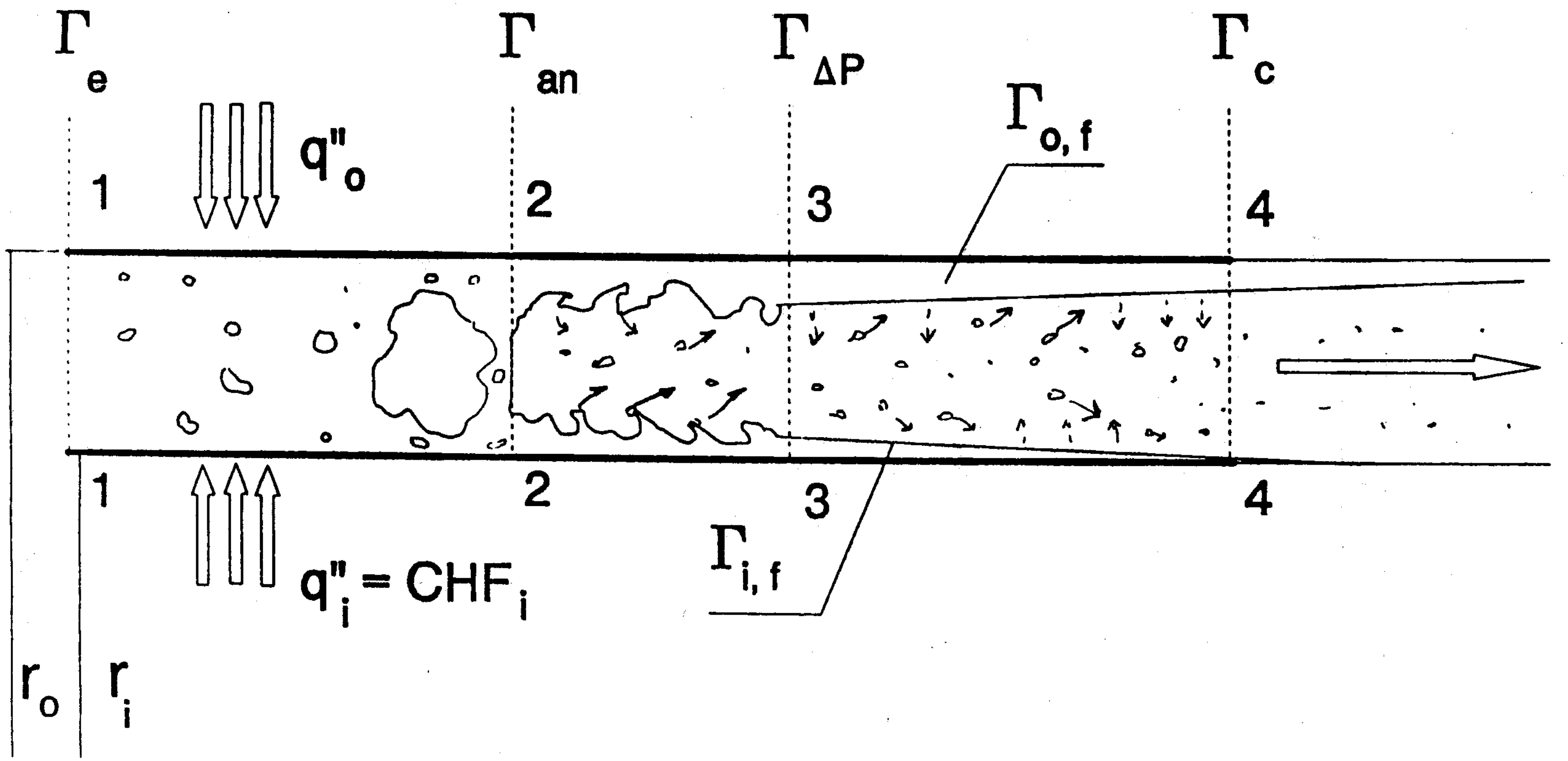


K decreases with P (Kirillov & Smogalev, 1972),

K decreases with q" due to normal vapour flow generated at the wall,

- Entrainment Rate: $E = f(\delta, \tau, q'')$, thickness of films $\delta_o > \delta_i$ due to $\tau_i > \tau_o$ and $D^*_o > D^*_i$

CHF Mechanisms in Annuli



<u>Deposition D = f(C,K), K = f(P, q", Ψ)</u> - <u>Entrainment</u> - <u>Evaporation</u>

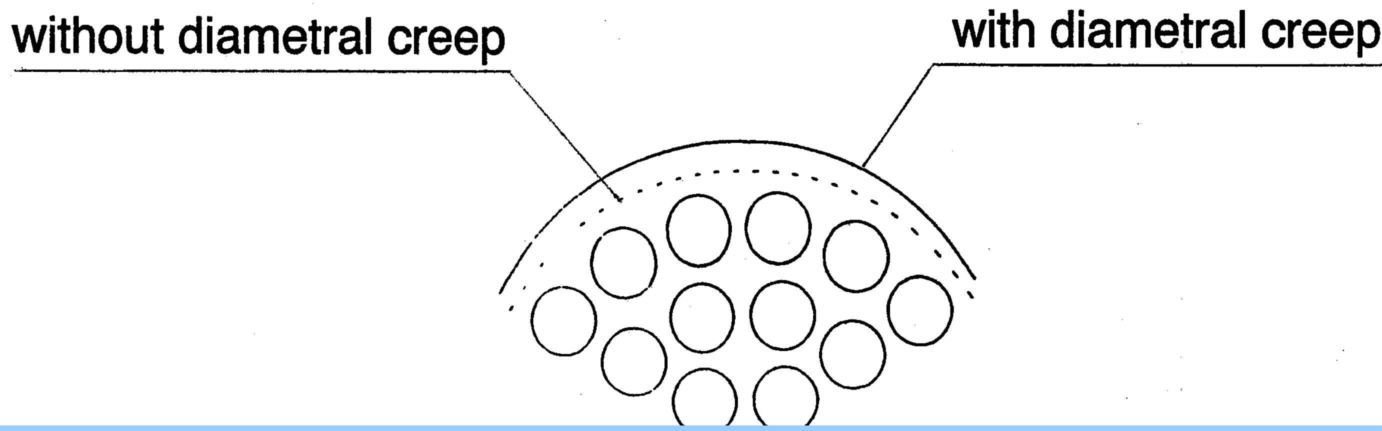
$D_{Total} \rightarrow$ CHF surface in a tube, then $CHF_{Tube} > CHF_{Annulus}$

$D_o > D_i$ & $\tau_i > \tau_o$ then $CHF_o > CHF_i$ (uni- & bilaterally heated annuli)

K $\searrow$ P & $D_o > D_i \rightarrow CHF_o \searrow$ at higher rate than CHF_i (e.g., simult. CHF)

q''_o: $\nearrow \Gamma^c$ & $K_i \rightarrow \nearrow D_i$ then $CHF_{i,q''>0} > CHF_{i,q''=0}$ (at P, G, x_c = constant)

Fuel Bundle-Pressure Tube System in CANDU Reactors



Effect of eccentricity – NURETH-6 paper (Grenoble, 1993)

Effect of bilateral heating – NURETH-7 paper (Saratoga Springs, 1995)

Relative effect on CHF the same

in bundle-pressure tube system with & without creep as in eccentric & concentric internally heated annulus

Successful approximation of a prediction method found for a simpler flow geometry to a more complex flow geometry!

CHF Enhancement

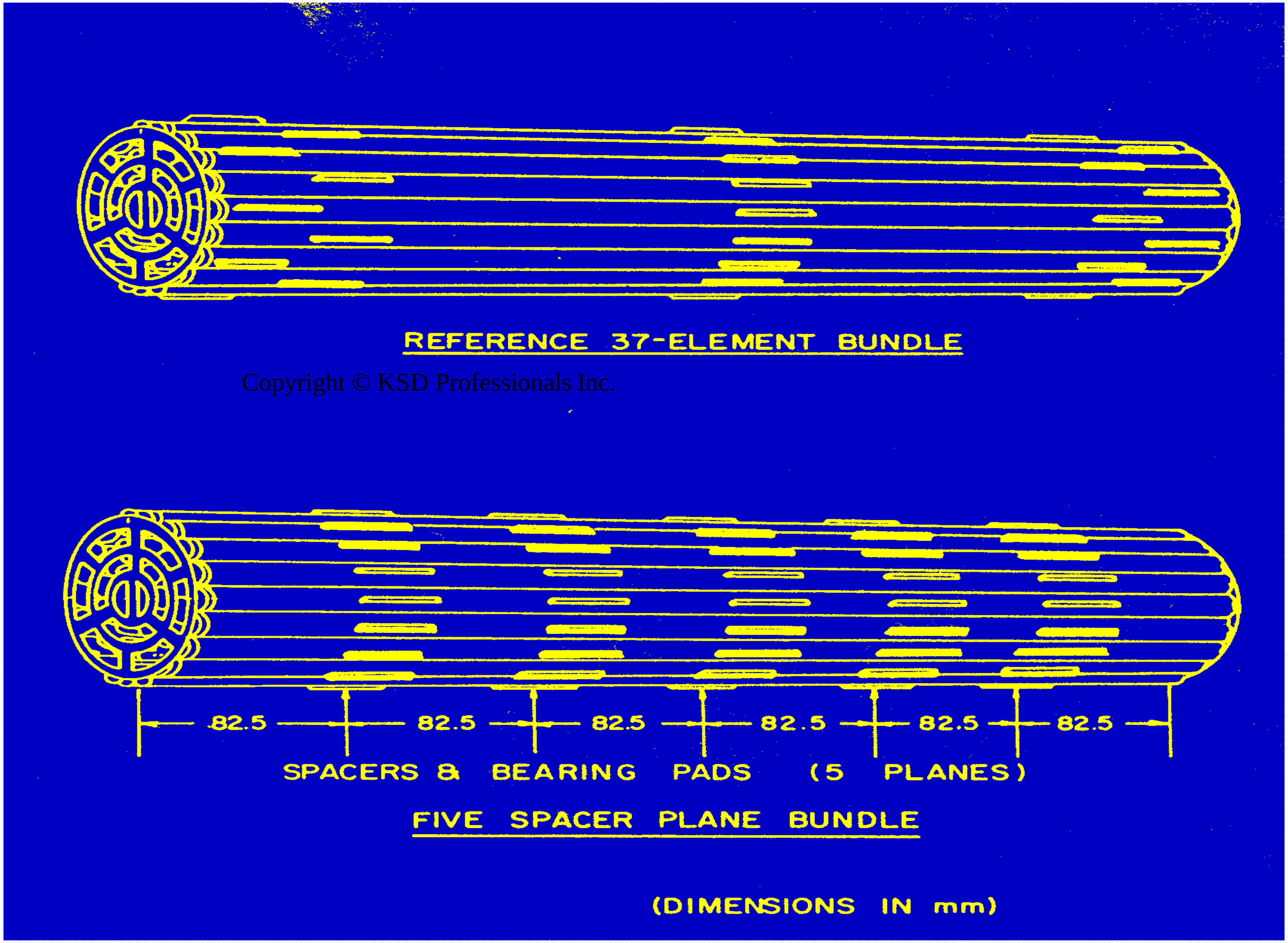
A Quest for CHF Enhancement in CANDU Fuel Channels

Observed CHF-enhancing effect of bundle junctions and spacer planes thanks to a unique temperature detecting technique led to investigation of fuel bundles with:

- One additional spacer plane,
- Two, three and four additional spacer planes,
- Installing wire wraps along fuel elements, etc.

A special CHF-enhancement program was launched to investigate the effect of “buttons” (non-loaded appendages) leading to the CANFLEX fuel bundle

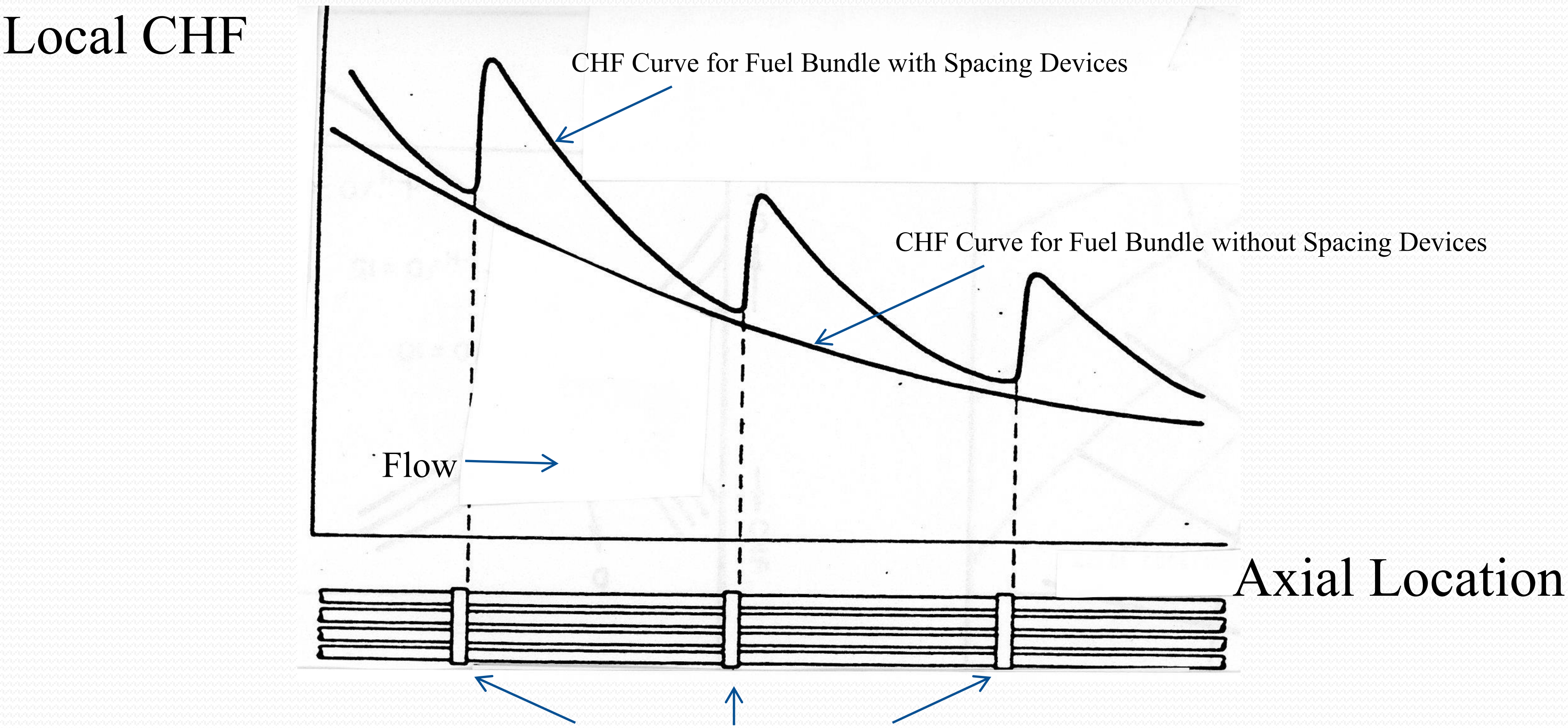
Bundles with Extra Spacer Planes



(Courtesy of AECL)

Effect of Spacing Devices on CHF

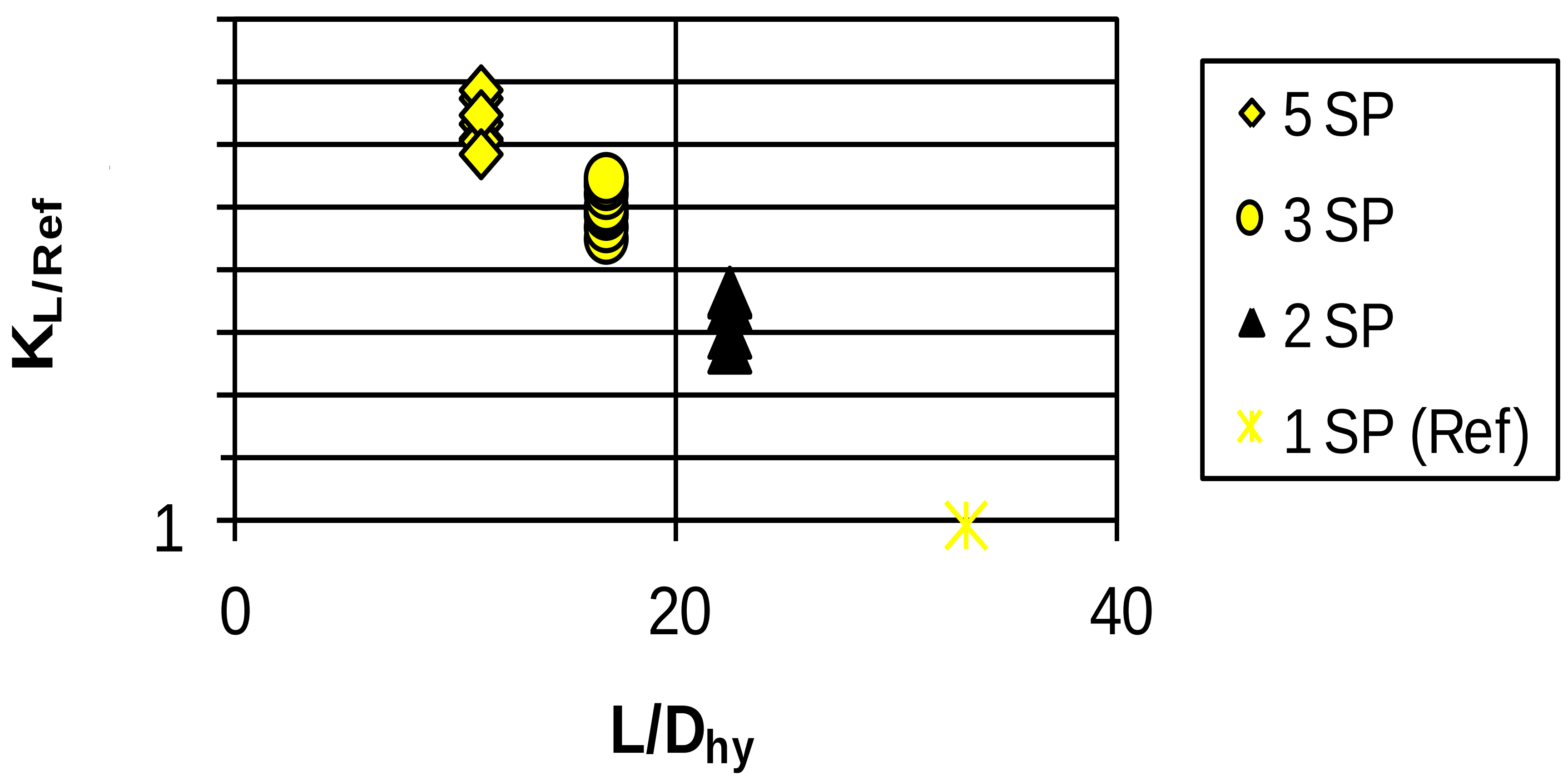
(Thanks to unique CHF detective system)



Fuel Bundle Spacing Devices (Grids, Spacer Planes, etc.)

(Courtesy of AECL)

CHF Enhancement in Fuel Bundles by Extra Spacer Planes

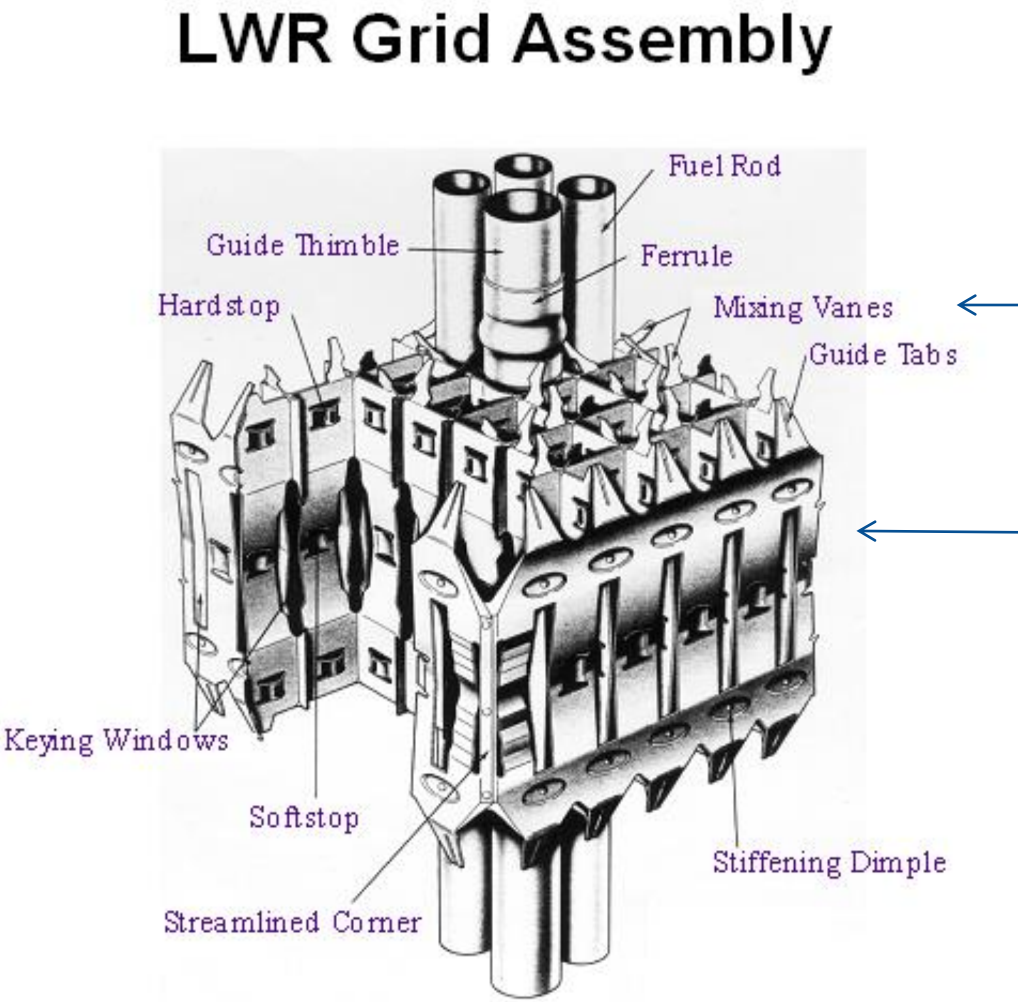


AECL New Fuel Bundle - CANFLEX

- 2 pin sizes, 43 elements
- Peak ratings reduced
- Extended burnup
- CHF-enhancing appendages

(Courtesy of AECL)

CHF Enhancement in LWR Fuel Assemblies



CHF Enhancing Mixing Vanes - in particular

CHF Enhancing Grid Structure - in general

CHF Fluid-to-fluid Modelling

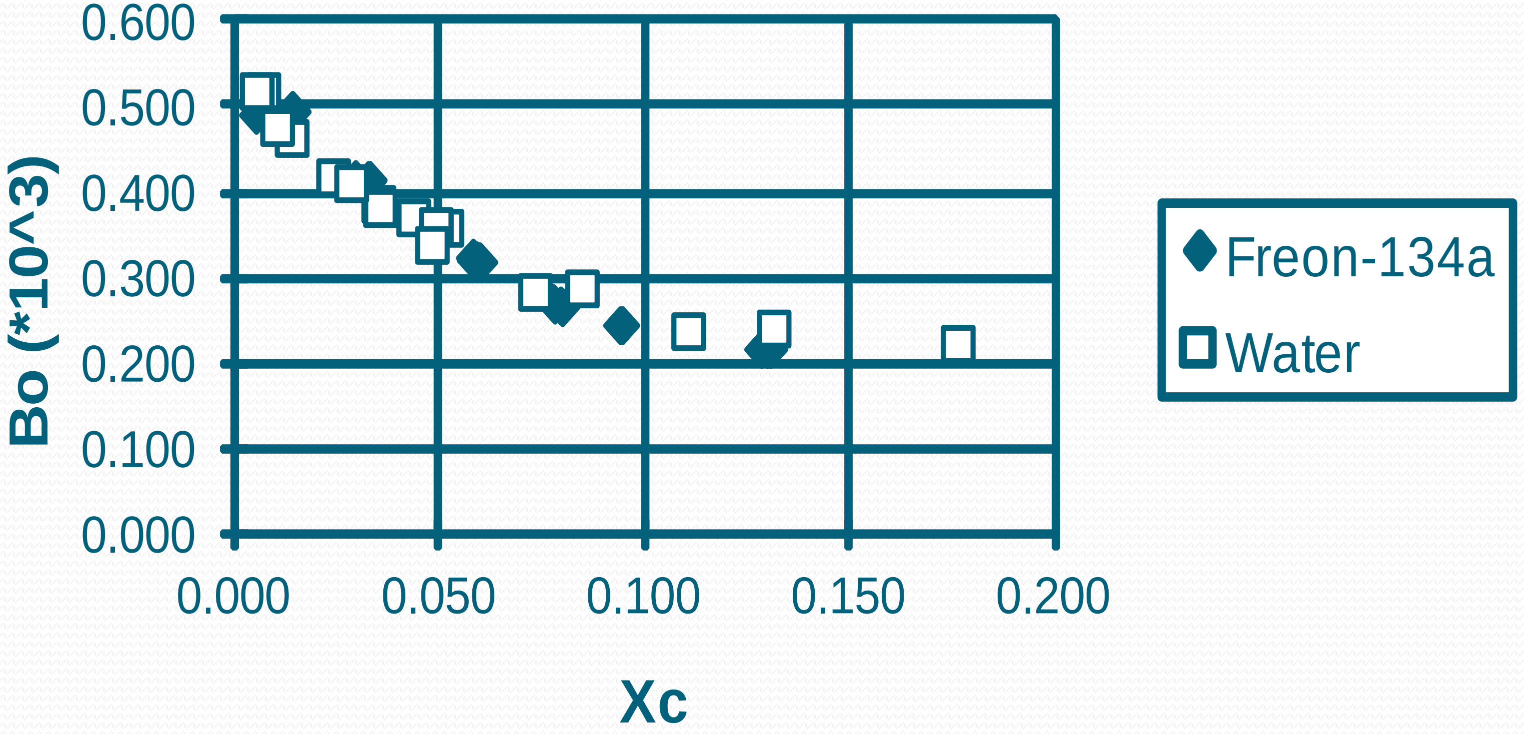
CHF Fluid-to-fluid Modelling Advantages

- Simpler & less expensive test sections & facilities
- Less severe test conditions (1.66 MPa vs 10 MPa, 59ºC vs 310ºC in Freon-134a than in water)
- Lower power requirements (0.6 MW vs 10 MW)
- Greater flexibility to use advanced instrumentation (fiber-optic void probes), and
- Increased speed of generating data

CHF Fluid-to-fluid Modelling Technique

- Identical geometry in both fluids
- The same liquid-to-vapour density ratio (to model pressure (P*))
- The same inlet and dryout qualities (to model inlet & outlet thermodynamic conditions),
- The same Weber number, We, (to model mass flux (G*)), then
- The same boiling number, Bo, is in both fluids (thus modelling CHF)

CHF Fluid-to-fluid Modelling in Tube

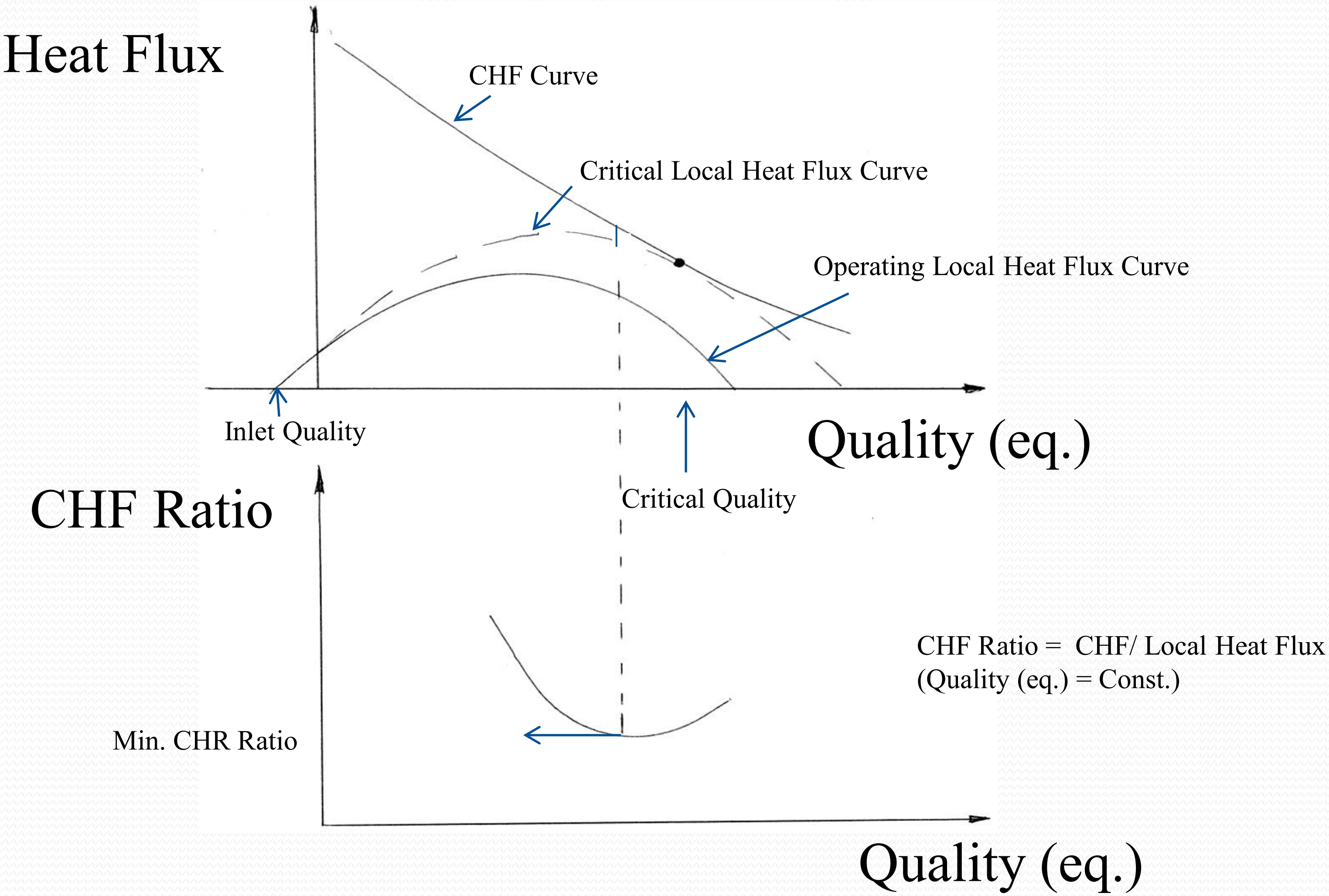


Nondimensional CHF-Reference Results in Water & Freon-134a

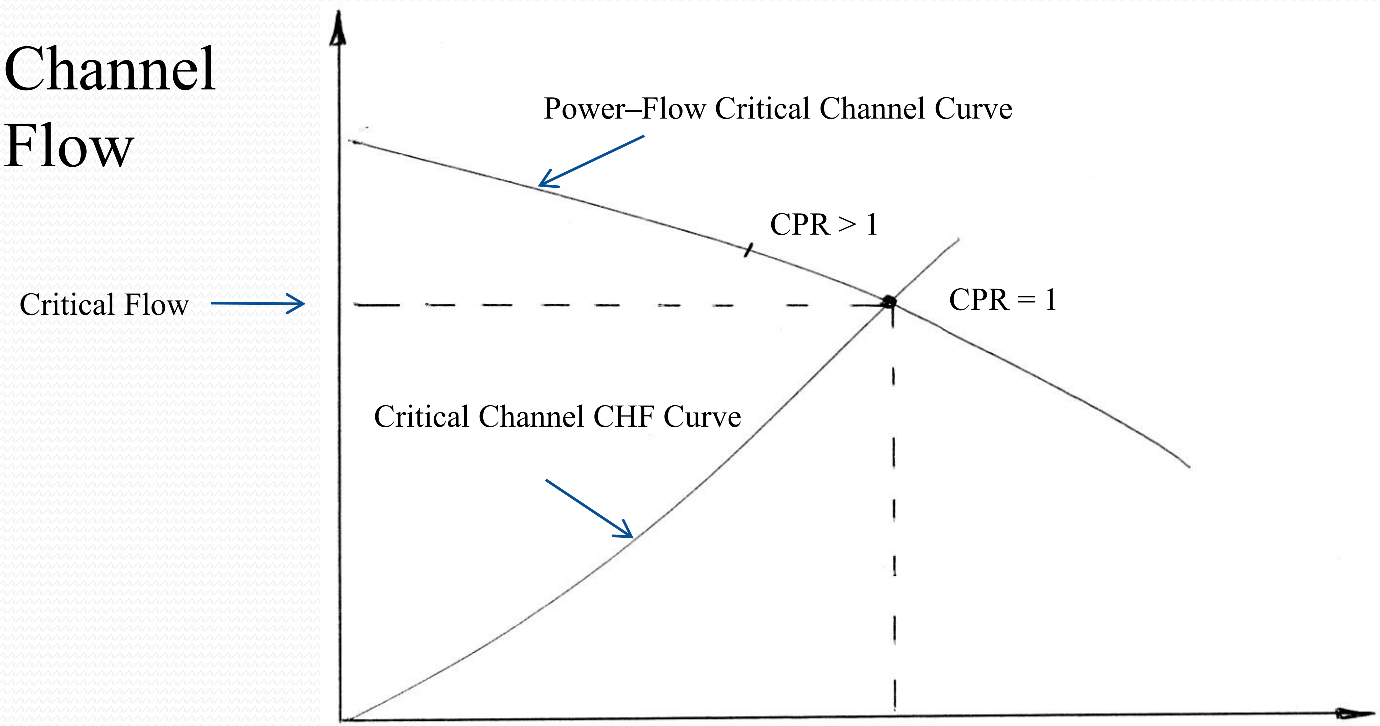
Definition of CHF and its Location Definition of CHF Ratio (CHFR) or (DNBR)

Nuclear regulators establish the minimum values of CHF ratio (CHFR or DNBR) as acceptable safety limits for normal operation and anticipated operational occurrences (AOOs) or transients so that no fuel damage is expected at this minimum CHFR (DNBR) or greater.

Definition of CHF and its Location



Definition of Critical Channel Power



CPR = Critical Power to Operating Power Ratio

Inlet Temp; Outlet Pressure = Const
Fixed Pump Characteristic

Final Remarks

- In general, CHF enhancement tests in tubes and fuel bundles can be simulated by <u>modelling fluids</u> with a high degree of certainty; however, at some conditions differences in fuel bundles occur as far as axial and transverse CHF location and CHF value are concerned.
- Modelling fluids perfectly allow for assessment of <u>relative ranking</u> of various CHF enhancing devices and other fuel bundle geometrical changes at relatively less cost and complexity of the experimental setups.
- **For licensing purposes of water-cooled nuclear power reactors, the <u>CHF correlations</u> based on tests in water, at reactor conditions in real full-size fuel assemblies are necessary!**

The End of

CHF Overview

This overview sheds light on a complexity of the CHF phenomenon!

Do you agree that still CHF is a misterious phenomenon?
Please continue the work beyond that
we have done so far!