# Lecture 11 – Technology of Accident Analysis

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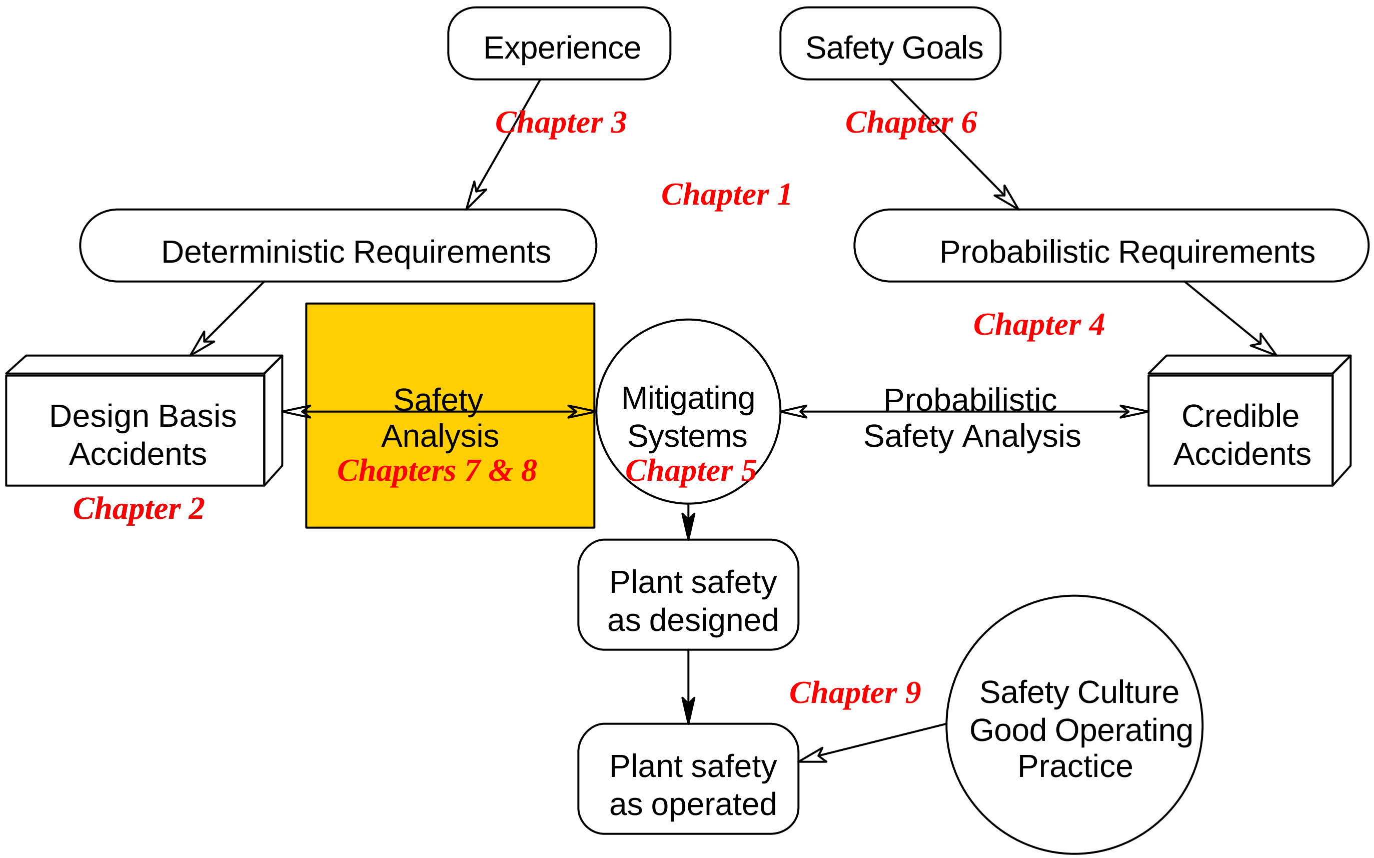
# Where We Are



Experience
Safety Goals
Chapter 3
Chapter 6
Chapter 1
Deterministic Requirements
Probabilistic Requirements
Chapter 4
Design Basis Accidents
Safety Analysis
Chapters 7 & 8
Mitigating Systems
Chapter 5
Probabilistic Safety Analysis
Credible Accidents
Chapter 2
Plant safety as designed
Chapter 9
Safety Culture Good Operating Practice
Plant safety as operated

# Reactor Physics - Revisited

- Recall for a point reactor:

$$\frac{dN_f(t)}{dt} = \frac{k_\infty(r - b)}{l_p} N_f(t) + \sum_{i=1}^{6} l_i C_i$$

$$\frac{dC_i}{dt} = \frac{b_i N_f(t)}{l_p(1 - r)} - l_i C_i$$

# CANDU is Not a Point Reactor

- Flux tilts from movement of adjusters, varying zones, fuelling, xenon
- Flux tilt in accidents from half-core void, insertion of shutoff rods from top
- 3-D diffusion + point kinetics
  - Neutrons are like flow through medium

# Continuity Equation - Production

Let $n(\mathbf{r},t)$ be neutron density at point $\boldsymbol{r}$ and time $t$

- assume all at same speed

$$\frac{d}{dt}\int_V n(\mathbf{r},t)dV = production - absorption - leakage$$

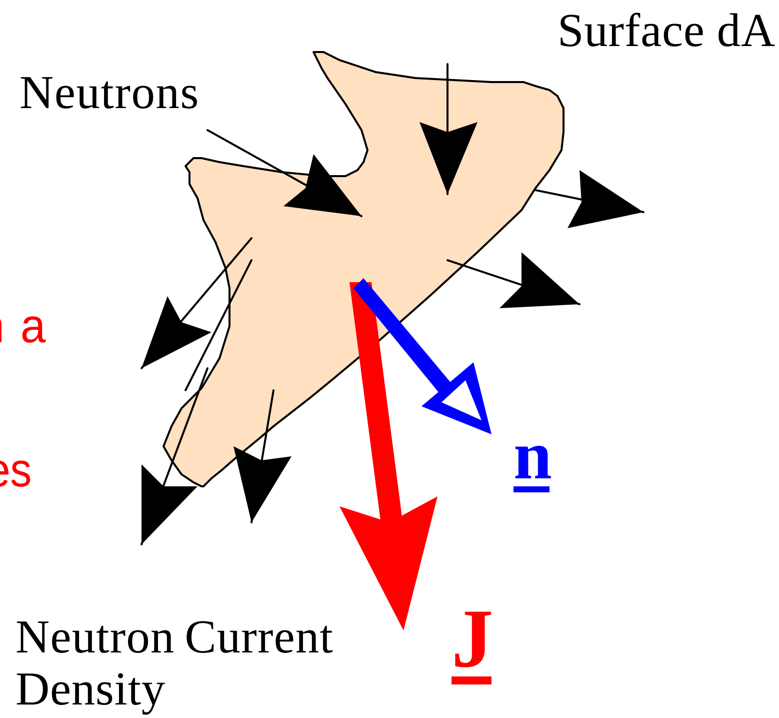
Let $s(\mathbf{r},t)$ be # of neutrons/vol/time emitted at point $\boldsymbol{r}$ and time $t$

$$production = \int_V s(\mathbf{r},t)dV$$

# Continuity Equation – Absorption

Similarly

$$absorption = \int_V \Sigma_a(\mathbf{r}) f(\mathbf{r},t)\, dV$$




$f(\mathbf{r},t)$ is flux

- Total rate at which neutrons pass through a given area, regardless of orientation
- Useful for describing neutron reaction rates

$\Sigma_a(\mathbf{r})$ is the absorption cross section

# Continuity Equation – Leakage

Let ***J****(r,t)* =neutron current density vector

- measures the net flow of neutrons across a unit area in any given direction

Let ***n*** be a unit normal vector pointing outward from the surface ***A*** around ***V***

$$leakage = \int_A \mathbf{J}(\mathbf{r},t) \bullet \mathbf{n} dA$$

# Continuity Equation

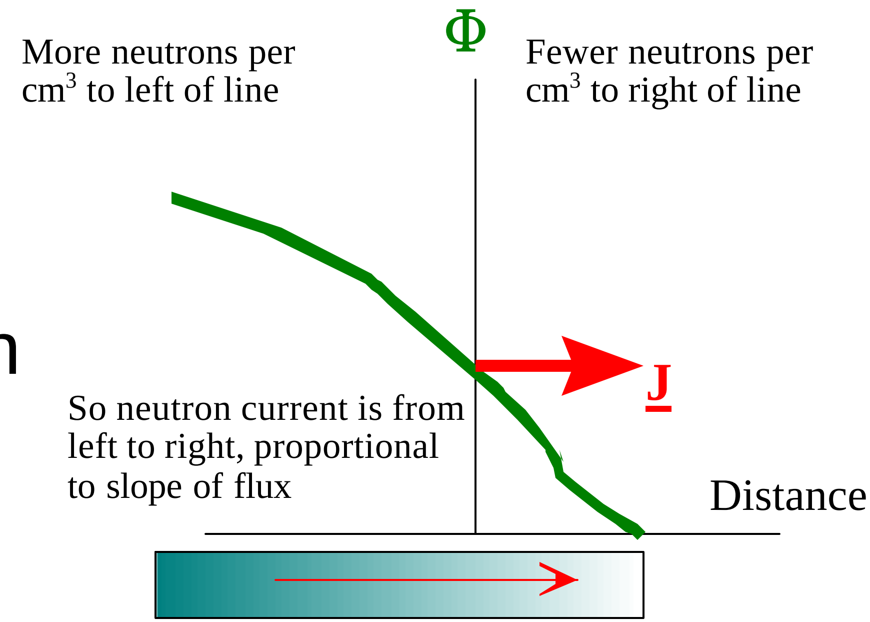
$$\frac{d}{dt}\int_V n(\mathbf{r},t)dV = \int_V s(\mathbf{r},t)dV - \int_V \Sigma_a(\mathbf{r}) f(\mathbf{r},t)dV - \int_V \nabla \bullet \mathbf{J}(\mathbf{r},t)dV$$

$$\frac{\P n(\mathbf{r},t)}{\P t} = s(\mathbf{r},t) - \Sigma_a(\mathbf{r}) f(\mathbf{r},t) - \nabla \bullet \mathbf{J}(\mathbf{r},t)$$

# Fick's Law

- Current density vector ∝ negative gradient of the flux
- Proportionality constant is diffusion coefficient, D

$$\mathbf{J} = -D\vec{\nabla} f$$



# Neutron Diffusion Equation

- For single energy

$$D\nabla^2\phi - \Sigma_a\phi + s = \frac{1}{v}\frac{\partial \phi}{\partial t}$$

- Compare heat conduction

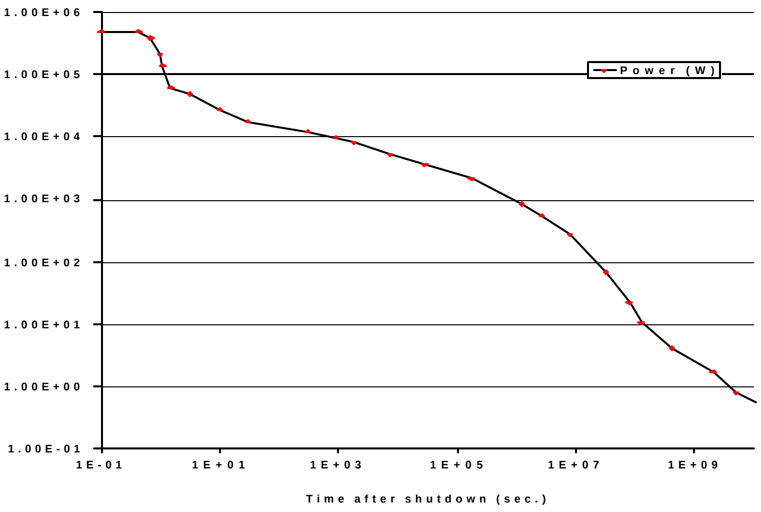
$$\rho c\frac{\partial T}{\partial t} = H + k\nabla^2 T$$

# Decay Heat

$$P_d(t) = \sum_i n_i(t) E_i$$

- $P_d(t)$ - power produced by all decaying fission products at time $t$
- $n_i(t)$ - number of atoms decaying per unit time of fission product $i$ at time $t$
- $E_i$ - average energy produced by the decay of each atom of fission product $i$

CANDU Bundle Power after Shutdown



# Fuel

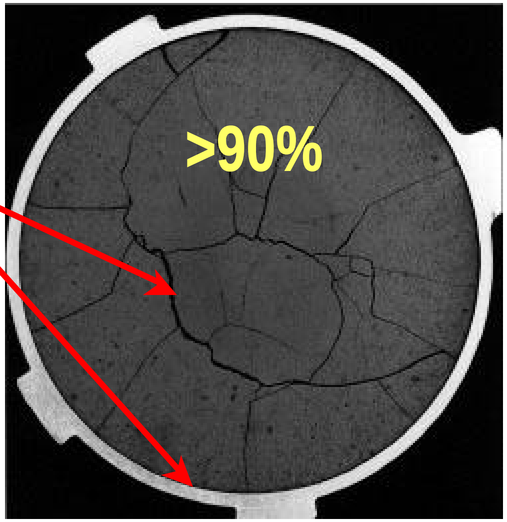
- Key safety parameters
  - Fuel temperature
    - Drives fission product transport
    - Drives pressure tube deformation
    - Potential sheath failure
    - Potential pressure-tube failure
    - Limited effect on physics
  - Fuel sheath integrity
  - Fission product inventory & release

# Location of Fission Products

- Fission products formed within fuel grains
- Diffuse
  - Bound inventory – in grains
  - Grain boundary inventory
  - Gap inventory

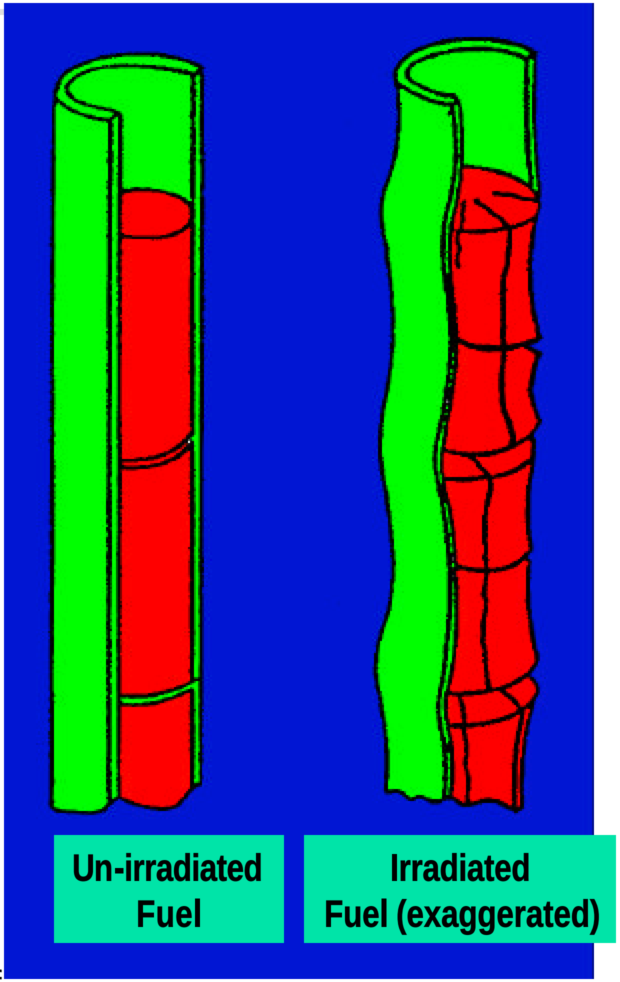
**Fission products move this way with increasing temperature & burnup**

<10%



# Behaviour With Irradiation

- Cracking
- Swelling
- Dishing/ridging
- Gas pressure increase
- Pellet-clad interaction



# Fuel Heat Conduction

**One dimension**

$$Q = -kA\frac{dT}{dx}$$

**Three dimensions**

(Rate of change of internal energy) =
(rate of energy release) - (rate of energy loss from conduction)

$$\rho c\frac{\partial T}{\partial t} = H + k\nabla^{2}T$$

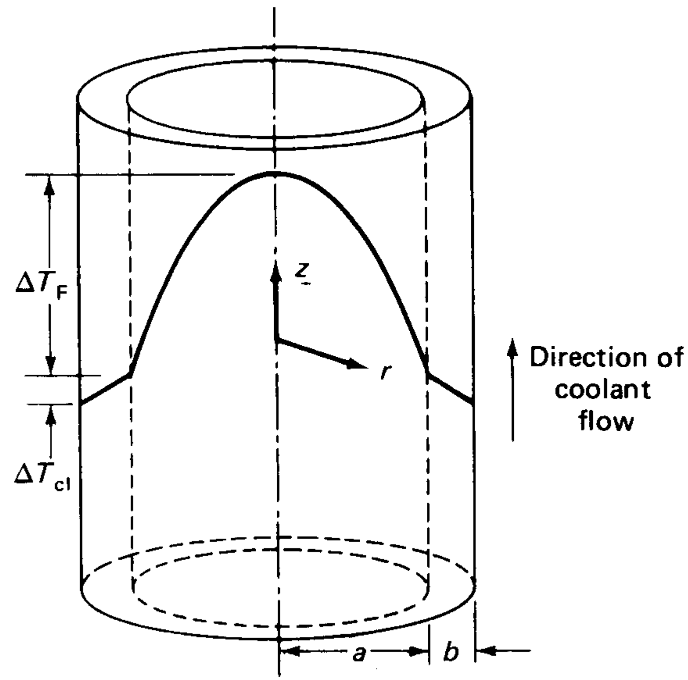
# Cylindrical Fuel Pin

**Steady state heat conduction**

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = -\frac{H}{k_F}$$

**Integrate (let** $u = r\dfrac{dT}{dr}$ **)**

$$T(r) = T(0) - \frac{Hr^2}{4k_F}$$



# Sheath and Gap

**Apply same equation to sheath**

$$\Delta T_S = T_{Si} - T_{So} = \frac{Ha^2 \log[(a+b)/a]}{2k_S}$$

**And gap**

$$q = h_g(T_F - T_{Si})$$

**And coolant**

$$q = h(T_{So} - T_C)$$

# Sheath-to-Coolant ΔT

**Steady State –**

**All heat produced in fuel is transferred to coolant, so for length *l* :**

$$q = \frac{Hp\,a^2\ell}{2p\,(a+b)\ell}$$

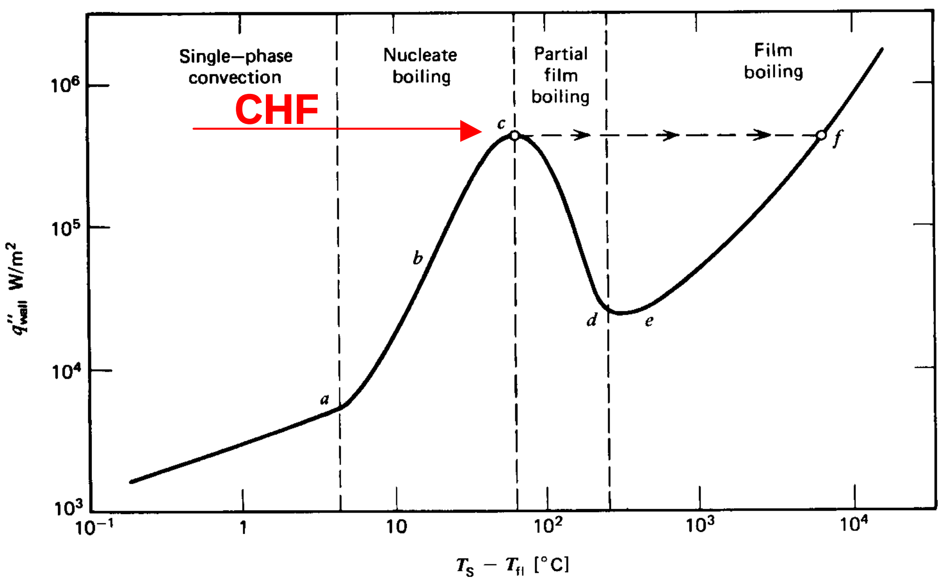
$$T_C - T_{So} = \frac{Ha^2}{2h(a+b)}$$

# Safety Importance

| Characteristic | $UO_2$ Fuel | Metal Fuel |
|---|---|---|
| Thermal Conductivity | Low | High |
| Melting Point | High | Low |
| Heat Capacity | High | Low |

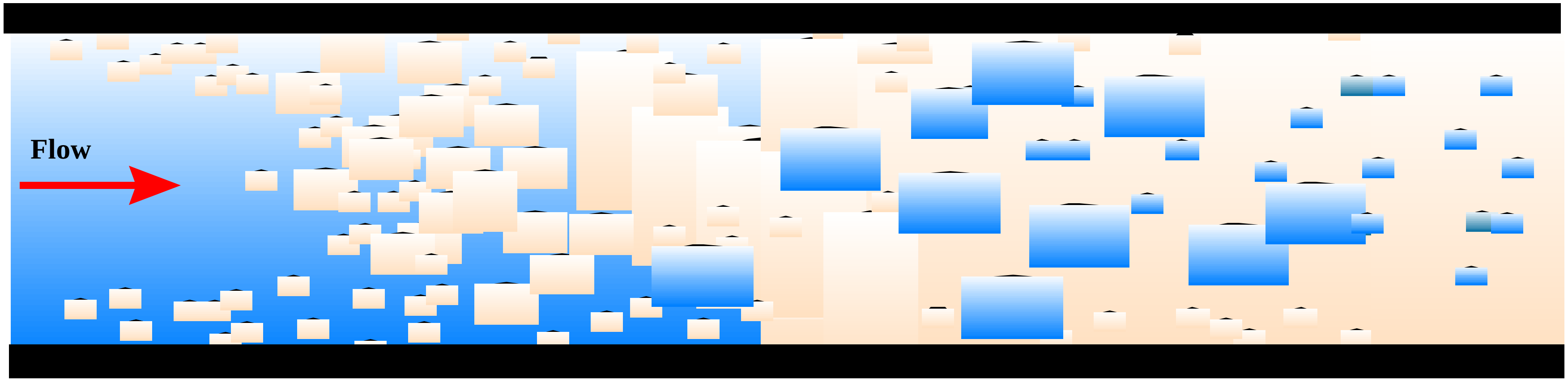
# Dryout

- Sudden drop in sheath-to-coolant heat transfer when “Critical Heat Flux” is reached
- Temperature jump strongly dependent on subcooling




Heat flux versus temperature difference for pool-boiling heat transfer.

# Flow Regimes in Horizontal Heated Channel (High Flow)




**Subcooled Boiling**

**Saturated Nucleate Bioling**

**Forced Convective Evaporation**

**Film Boiling**

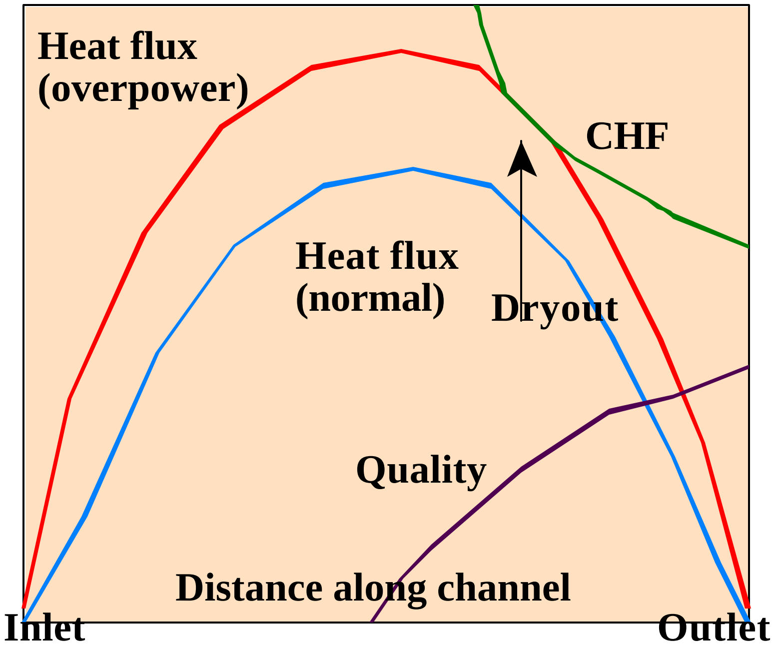
**Forced Convection toVapour**

# Progressive Effects of Overpower

- Dryout
- Sheath temperature rise
- Zircaloy annealing
- Oxidation embrittlement of sheath
- Braze melting and attack on Zircaloy
- Zirconium-water reaction (exothermic)
- Bundle collapse
- Sheath melting
- Fuel melting (extremely unlikely)
- Pressure tube balloon or burst
- Heat transfer to moderator

# CHF in a CANDU Channel

- CHF determined experimentally
  - no reliable theory for needed accuracy
- Local flux shape means dryout is not at the end
- How can we change the flux shape to improve margins?



# Gas Pressure

- Driving force for sheath strain in accidents
- Affects sheath liftoff
  - Therefore fuel-to-sheath heat transfer
  - Therefore fuel temperature
- Model via ideal gas law

# Strain

- Relevant to large LOCA
- Transverse stress:

$$s = \frac{Pr}{w}$$

  - *P* is the pressure differential across the tube
  - *r* is the tube radius
  - *w* is the tube thickness

# Strain Rate Equations

$$\dot{e} = \frac{de}{dt} = As^{n}e^{-k/T} + Bs^{m}e^{-\ell/T}$$

All parameters determined from experiment

Sheath may fail by ballooning if ε > 5%

What is fission product release?

- fraction of gap inventory
- small % of grain-boundary & bound inventory
  - at high temperatures only

# Fission Product Release

**Release is a strong function of temperature, atmosphere**