Chemical Engineering 612

Introductory Nuclear Engineering

Lecture 12

Core Thermal Analysis II

Spiritual Thought

"There is another way to look at your problem of crowded time. You can see it as an opportunity to test your faith. The lord loves you and watches over you. He is all-powerful, and He promised you this: 'But seek ye first the kingdom of God, and his righteousness; and all these things shall be added unto you.' This is a true promise. When we put God's purposes first, He will give us miracles. If we pray to know what He would have us do next, He will multiply the effects of what we do in such a way that time seems expanded. He may do it in different ways for each individual, but I know from long experience that He is faithful to His word."

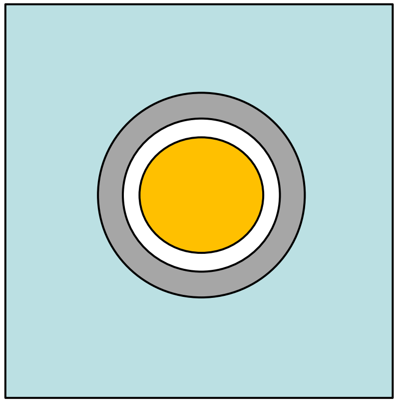
President Russel M. Nelson

Thermal Parameters

- Thermal Evaluation of Core:
  - heat generation
    - Neutron Flux – Hard!
    - Fuel – Type, Number Density
    - Poisons, shim – Directly affects flux
    - $q''' = N\sigma_f \Phi_{avg} E_f = \sum_f N\Phi_{avg} E_f = \frac{W}{cm^3}$
  - pump power requirements
    - $P = \Delta P \dot{V} = \Delta P \frac{\dot{m}}{\rho}$
  - heat removal
    - $Q = \dot{m} C_p \Delta T$

Heat Generation in Core

- Heat in core vs. heat per rod:
  - $\dot{Q} = N\langle\dot{q}\rangle$
  - $=NL\langle q'\rangle$
  - $=NL\pi D_{co}\langle q''\rangle$
  - $= NL\pi R_{fo}^{2}\langle q'''\rangle$



- Also need sufficient cooling!
  - Pump Power = $\Delta P \cdot A \cdot v$ = $\Delta P \cdot \dot{V}$
- Where: $\dot{Q}$ = core power, $\dot{q}$ = pin power, A = flow area, v = coolant velocity, $\dot{V}$ = coolant volumetric flow rate,

  N = number of fuel rods, L = rod length

  q' = linear heat rate, q'' = heat flux

  and q''' = volumetric heat rate

6 Basic Reactor Characteristics I

Characteristic	BWR	PWR(W)	PHWR	HTGR	AGR	LMFBR[a]
Reference design						
Manufacturer	General Electric	Westinghouse	Atomic Energy of Canada, Ltd.	General Atomic	National Nuclear Corp.	Novatome
System (reactor station)	BWR/6	(Sequoyah)	CANDU-600	(Fulton)	HEYSHAM 2	(Superphenix)
Moderator	H_2O	H_2O	D_2O	Graphite	Graphite	—
Neutron energy	Thermal	Thermal	Thermal	Thermal	Thermal	Fast
Fuel production	Converter	Converter	Converter	Converter	Converter	Breeder
Fuel[b]						
Particles						
Geometry	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Coated microspheres	Cylindrical pellet	Annular pellet
Dimensions (mm)	10.4*D* × 10.4*H*	8.2*D* × 13.5*H*	12.2*D* × 16.4*H*	400–800 μm *D*	14.51*D* × 14.51*H*	7.0 *D*
Chemical form	UO_2	UO_2	UO_2	UC/ThO_2	UO_2	PuO_2/UO_2
Fissile (wt% 1st core ave.)	1.7 ^{235}U	2.6 ^{235}U	0.711 ^{235}U	93 ^{235}U	2.2 ^{235}U	15–18 ^{239}Pu
Fertile	^{238}U	^{238}U	^{238}U	Th	^{238}U	Depleted U
Pins						
Geometry	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Cylindrical fuel stack	Pellet stack in clad tube	Pellet stack in clad tube
Dimensions (mm)	12.27*D* × 4.1 m*H*	9.5*D* × 4 m*H*	13.1*D* × 490*L*	15.7*D* × 62*L*	14.89*D* × 987*H*	8.65*D* × 2.7 m*H*(C) 15.8*D* × 1.95 m*H*(BR)
Clad material	Zircaloy-2	Zircaloy-4	Zircaloy-4	Graphite	Stainless steel	Stainless steel
Clad thickness (mm)	0.813	0.57	0.42	—	0.38	0.7
Assembly						
Geometry[c]	8 × 8 square rod array	17 × 17 square rod array	Concentric circles	Hexagonal graphite block	Concentric circles	Hexagonal rod array
Rod pitch (mm)	16.2	12.6	14.6	—	25.7	9.7 (C)/17.0 (BR)
No. rod locations	64	289	37	132 (SA)/76 (CA)[d]	37	271 (C)/91 (BR)
No. fuel rods	62	264	37	132 (SA)/76 (CA)[d]	36	271 (C)/91 (BR)
Outer dimensions (mm)	139	214	102*D* × 495*L*	360*F* × 793*H*	190.4 (inner)	173*F*
Channel	Yes	No	No	No	Yes	Yes
Total weight (kg)	273	—	—	—	342	—

6 Basic Reactor Characteristics II

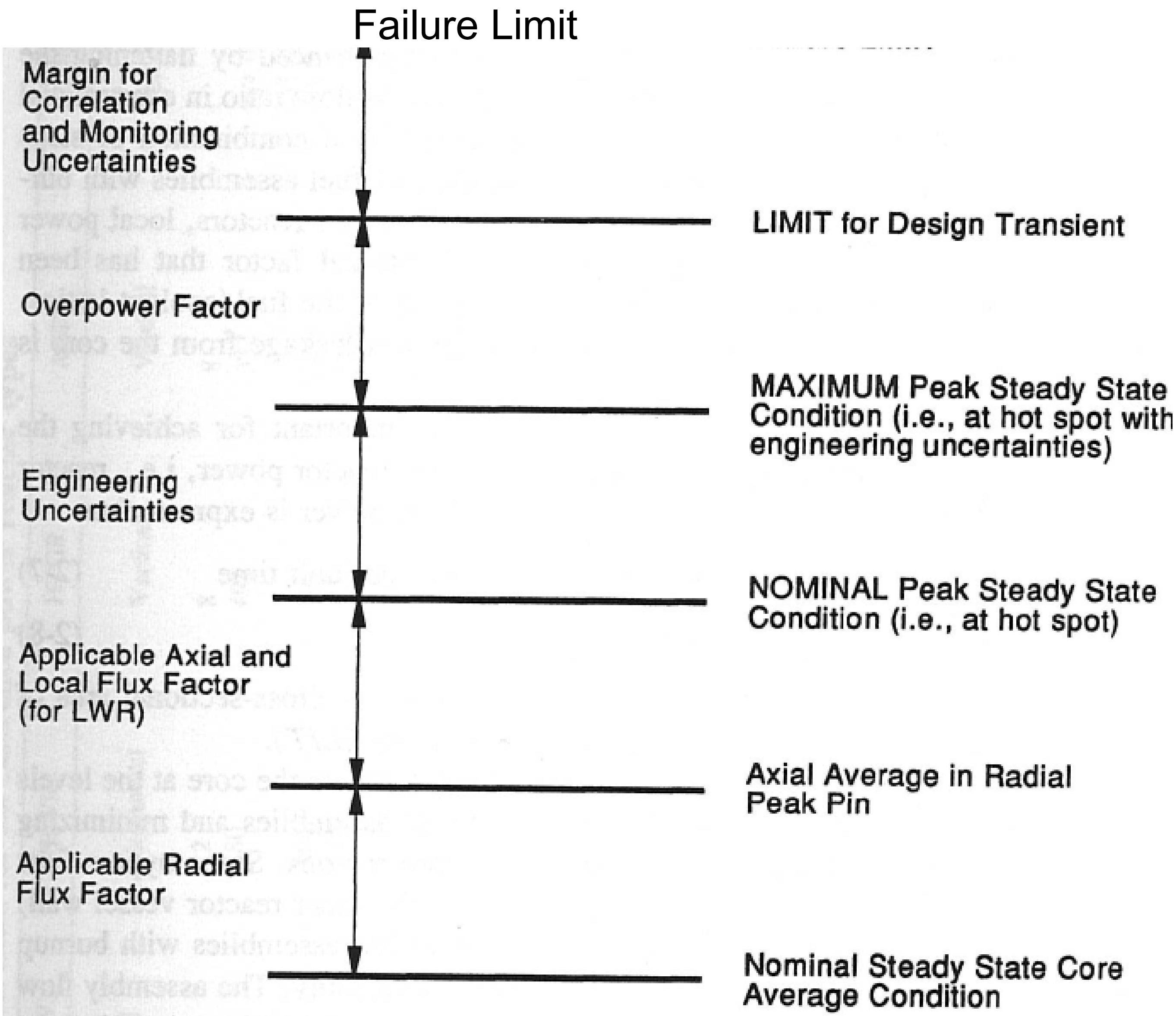
Characteristic	BWR	PWR(W)	PHWR	HTGR	AGR	LMFB
Core						
Axis	Vertical	Vertical	Horizontal	Vertical	Vertical	Vertica
No. of assemblies						
Axial	1	1	12	8	8	1
Radial	748	193	380	493	332	364 (C 233 (B
Assembly pitch (mm)	152	215	286	361	460	179
Active fuel height (m)	3.81	3.66	5.94	6.30	8.296	1.0 (C 1.6 (C
Equivalent diameter (m)	4.70	3.37	6.29	8.41	9.458	3.66
Total fuel weight (ton)	156 UO_2	101 UO_2	98.4 UO_2	1.72 U 37.5 Th	113.5 UO_2	32 MC
Reactor vessel						
Inside dimensions (m)	6.05*D* × 21.6*H*	4.83*D* × 13.4*H*	7.6*D* × 4*L*	11.3*D* × 14.4*H*	20.25*D* × 21.87*H*	21*D* ×
Wall thickness (mm)	152	224	28.6	4.72 m min	5.8 m	25
Material[b]	SS-clad carbon steel	SS-clad carbon steel	Stainless steel	Prestressed concrete	Concrete helical prestressed	Stainle
Other features			Pressure tubes	Steel liners	Steel lined	Pool ty
Power density core average (kW/L)	54.1	105	12	8.4	2.66	280
Linear heat rate						
Core average (kW/m)	19.0	17.8	25.7	7.87	17.0	29
Core maximum (kW/m)	44.0	42.7	44.1	23.0	29.8	45
Performance						
Equilibrium burnup (MWD/T)	27,500	27,500	7500	95,000	18,000	100,00
Average assembly residence (full-power days)			470	1170	1320	
Refueling						
Sequence	$\frac{1}{4}$ per yr	$\frac{1}{3}$ per yr	Continuous on-line	$\frac{1}{4}$ per yr	Continuous on-line	Variab
Outage time (days)	30	30		14–20		32

Source: Knief [3], except AGR data are from Alderson [1] and Debenham [2].
[a]LMFBR: core (C), radial blanket (BR), axial blanket (BA).
[b]SS = stainless steel.

Best Estimate and Uncertainties

- Best Estimate
  - Most likely value
  - Do we know this?
  - Are we sure of all dependent values?
- Propagation of Uncertainties
  - (UO Lab) designed to give range of possible values
- Once distribution given, used to develop margin

Thermal Design Margins



Heat Transport

$$\nabla k_f \nabla T + q''' = 0$$

- Convection
  - Fluid to surface/surface to fluid
  - $\dot{Q} = hA(T_1 - T_2)$
- Conduction
  - Transport through solid material
  - $\dot{Q} = A\nabla kT = kA\frac{dT}{dr}$
- Radiation
  - Electromagnetic heat transport →two surfaces
  - $\dot{Q}_{1\to 2} = \sigma A_1 F_{1\to 2}(T_1^4 - T_2^4)$

Fuel Thermal Properties

Property	U	UO_2	UC	UN
Theoretical density at room temp (kg/m^3)	19.04×10^3	10.97×10^3	13.63×10^3	14.32×10^3
Metal density* (kg/m^3)	19.04×10^3	9.67×10^3	12.97×10^3	13.60×10^3
Melting point (°C)	1133	2800	2390	2800
Stability range	Up to 665°C†	Up to m.p.	Up to m.p.	Up to m.p.
Thermal conductivity average 200–1000°C (W/m°C)	32	3.6	23 ($UC_{1.1}$)	21
Specific heat, at 100°C (J/kg °C)	116	247	146	—
Linear coefficient of expansion (/°C)		10.1×10^{-6} (400–1400°C)	11.1×10^{-6} (20–1600°C)	9.4×10^{-6} (1000°C)
Crystal structure	Below 655°C: α, orthorhombic Above 770°C: γ, body-centered cubic	Face-centered cubic	Face-centered cubic	Face-centered cubic
Tensile strength, (MPa)	344–1380‡	110	62	Not well defined

*Uranium metal density in the compound at its theoretical density.
†Addition of a small amount of Mo, Nb, Ti, or Zr extends stability up to the melting point.
‡The higher values apply to cold-worked metal.

From Nuclear Systems I

UO2 thermal conductivity (I)

- $\bar{\bar{k}}$ is tensor
- However, typically assume isotropic $\bar{\bar{k}}$ → k
- K dependencies:
  - Temperature
    - k(T) decreases with T initially to 1750˚C
    - k(T) increases slightly with T after 1750˚C
  - Porosity (P):
    - P = $1 - \frac{\rho}{\rho_{TD}}$
    - Biancharia approximation
    - $k = \frac{(1-P)}{1+(\alpha_2 - 1)P} k_{TD}$, α_2 = 1.5 for spherical, larger for asymmetric

UO2 thermal conductivity (II)

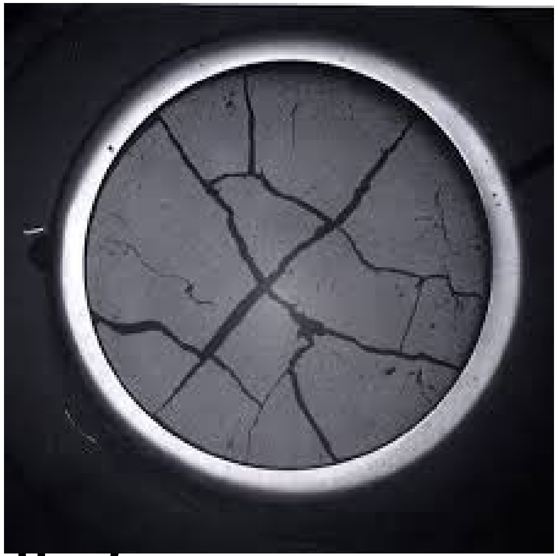
- Oxygen to metal atomic ratio
  - Theoretical (stoichiometric) = 2
  - Departure from theoretical occurs during burnup, both +/- decrease k
- Plutonium content
  - Increased Pu content decreases k
- Pellet cracking
  - INL developed relationship for k (given later)
- Burnup
  - Changes porosity, composition, stoichiometry, fission product introduction, sintering, etc.
  - Small → 3% in LWRs, larger in Fast Reactors
  - For MSR, this can be controlled by U233 addition

Other UO_2 Fuel Properties

- Fission Gas Release
  - Plenum included in fuel rod
  - Initially in pellet, released to plenum based on temperature (see Nuclear Systems I)
- Melting Point
  - 2840˚C, starts at solidus temperature moves up to liquidus temperature. (see text)
- Specific Heat
  - Varies greatly over temperature
  - Plays key role in accident behavior

Fuel Irradiation

- Changes k dramatically
- $k_e = k_{UO_2} - (0.0002189 - 0.050867X + 5.6578X^2)$
- $X = (\delta_{hot} - 0.014 - 0.014\delta_{cold})\left(\frac{0.0545}{\delta_{cold}}\right)\left(\frac{\rho}{\rho_{TD}}\right)^8$



- Where
- δ_{hot} = calculated hot gap witdh for uncracked fuel (mm)
- δ_{cold} = calculated cold gap width (mm)