University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Thermal-Hydraulics Applied to Nuclear Reactors

Module 8.2

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Module Objectives

- Decay Heat
- Plant Parameters
- Reactor Design Considerations

Decay Heat Generation

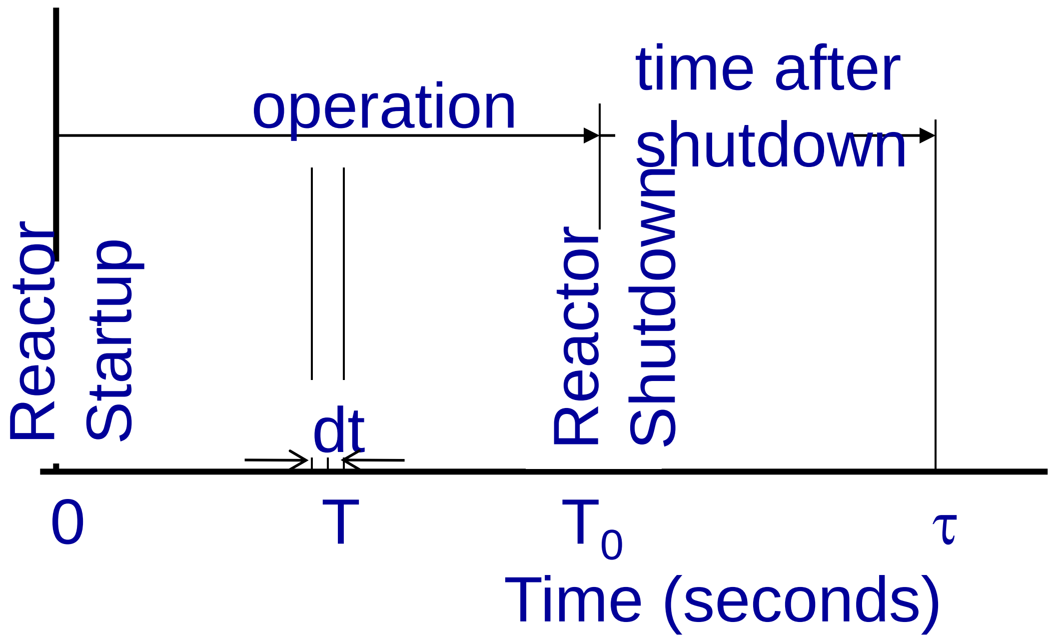
Decay Heat

- Following shutdown of the reactor, power does not immediately drop to zero
  - Falls off rapidly following shutdown
    - Rate determined by the half-life of the longest lived delayed neutron (neutrons emitted by neutron decay of fission products) group
  - Power is still produced by the decay of fission products
    - Beta and gamma decays are major contributors

Decay Heat

- Amount of decay heat is dependent upon the operating history of the reactor
  - Longer operation builds up more fission products to decay and produces more decay heat
  - Larger power levels yield the same effect
- Because of the large amount of decay heat produced following shutdown, cooling is still essential to prevent fuel damage
  - Residual Heat Removal (RHR) systems incorporated to provide shutdown cooling
- Has decay heat caused major problems in the nuclear industry?

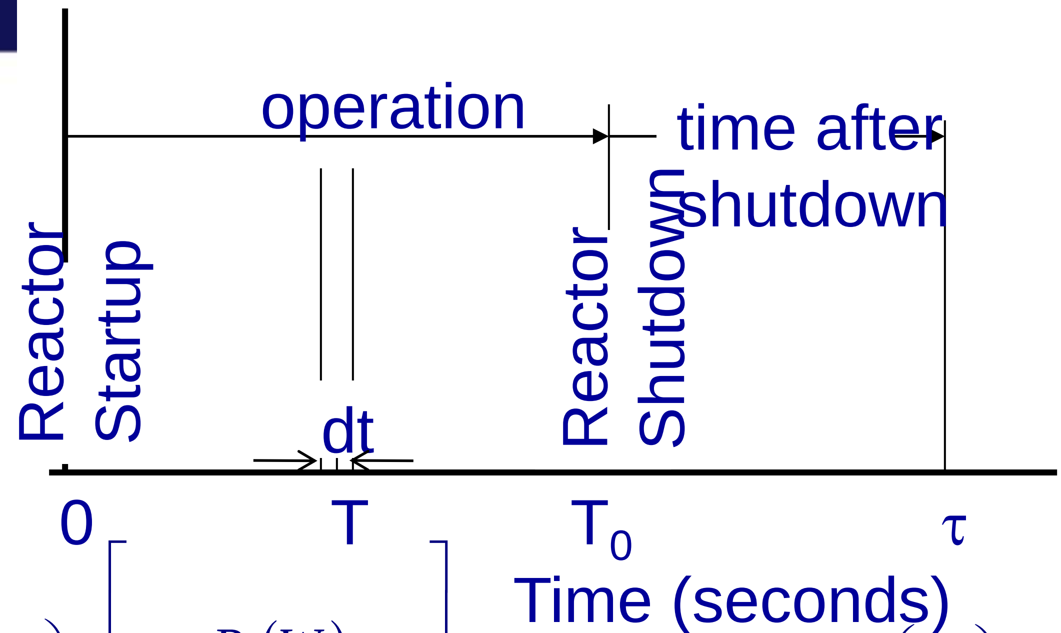
Decay Heat



Empirical formulas (where $t = \tau - T_0$ in seconds)

Beta-particle	~0.4 MeV/β	$3.5 \times t^{-1.2}$ β/s-fission	$1.4 \times t^{-1.2}$ MeV/s-fission
Gamma	~0.7 MeV/γ	$1.8 \times t^{-1.2}$ γ/s-fission	$1.26 \times t^{-1.2}$ MeV/s-fission
Total Energy			$2.66 \times t^{-1.2}$ MeV/s-fission

Decay Heat



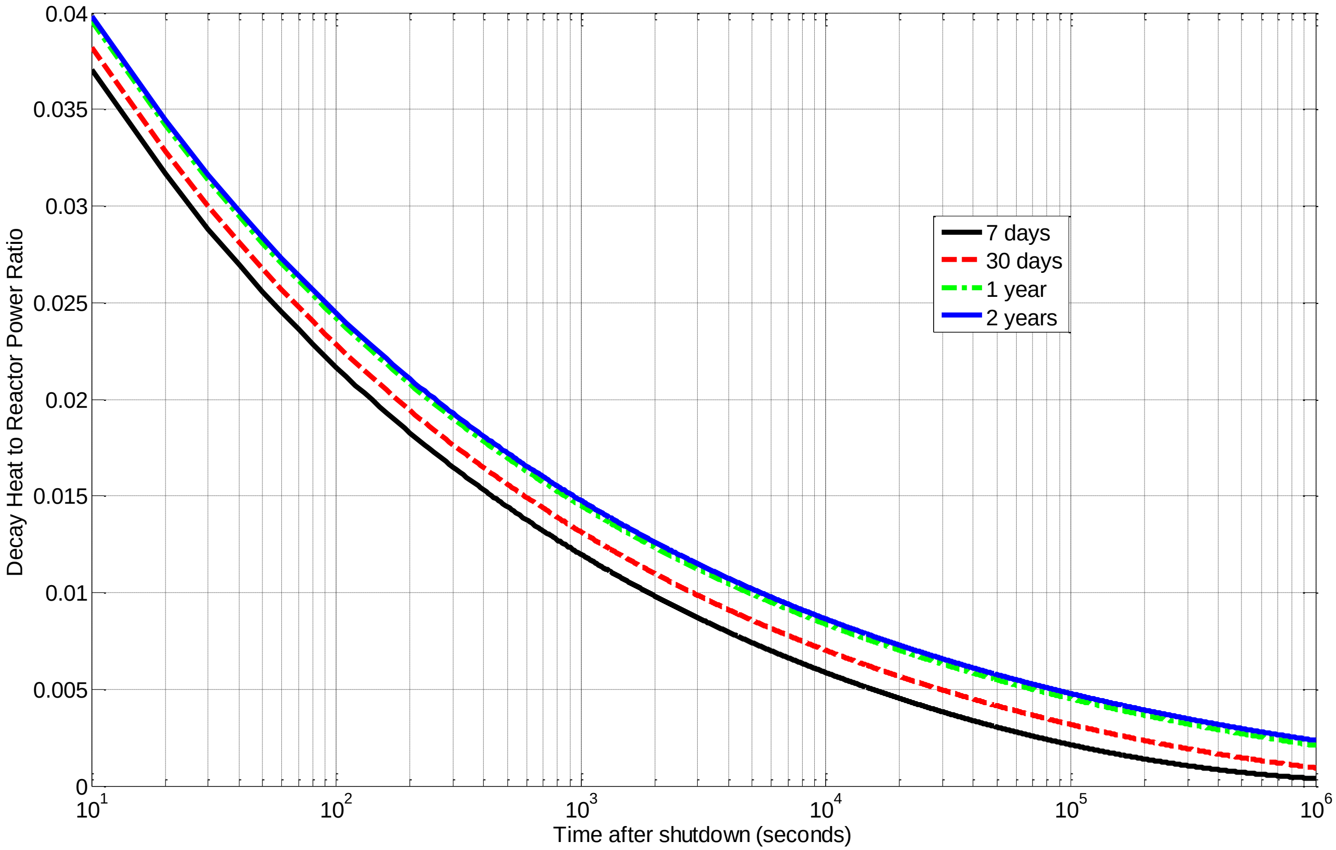
$$2.66(\tau - T)^{-1.2}\left(\frac{MeV}{\sec\cdot fission}\right)\times\left[\frac{P_0(W)}{200\left(\frac{MeV}{fission}\right)}\right] = 0.0133P_0(\tau-T)^{-1.2}\left(\frac{W}{s}\right)$$

$$P_{decay} = \int_0^{T_0} 0.0133P_0(\tau-T)^{-1.2}\,dT = 0.066P_0\left[(\tau-T_0)^{-0.2}-\tau^{-0.2}\right]$$

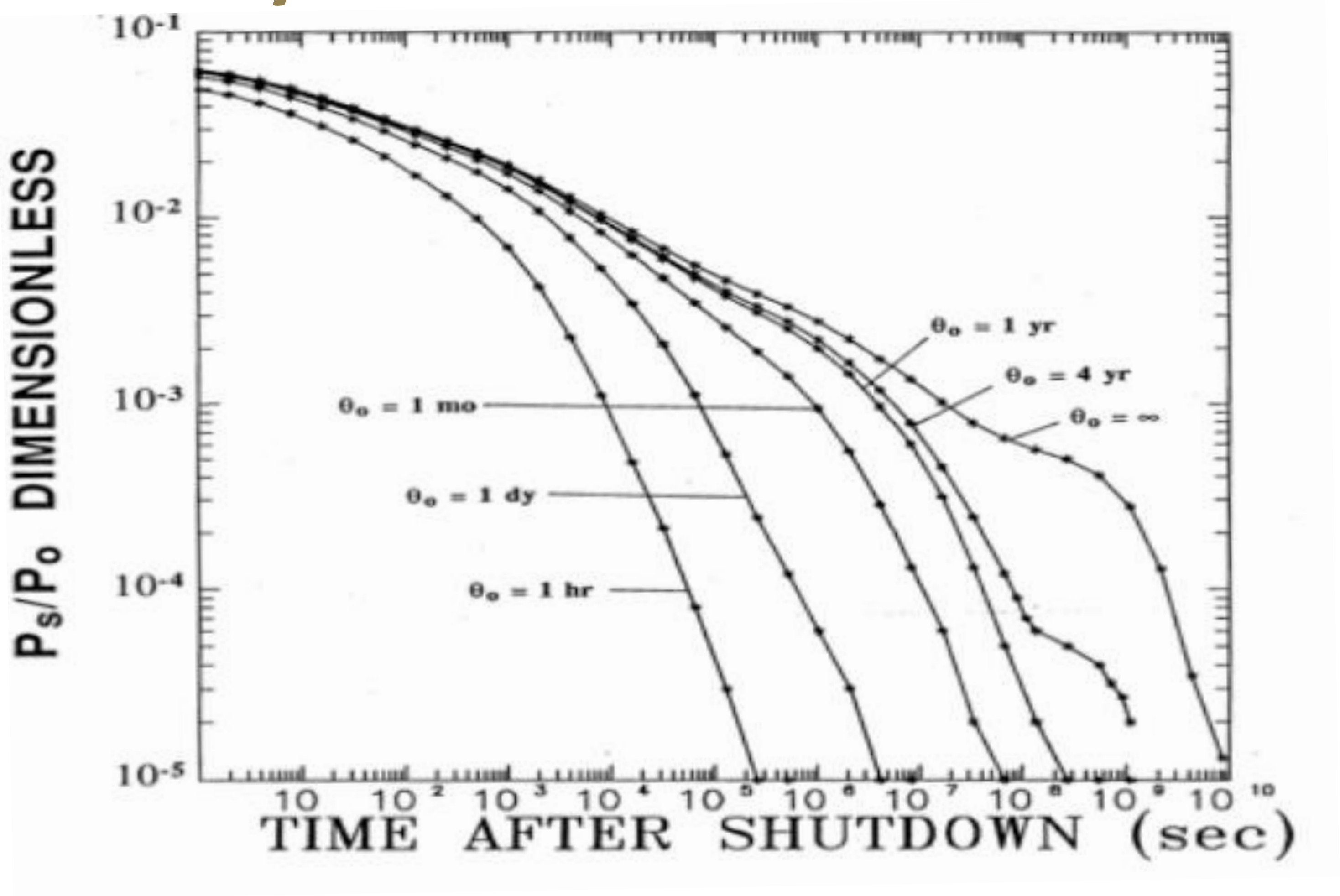
$$\frac{P_{decay}(\tau)}{P_0} = 0.066\left[(\tau-T_0)^{-0.2}-\tau^{-0.2}\right]$$

$$\frac{P_{decay}(\tau)}{P_0} = 0.066\left[(t_{\text{after shutdown}})^{-0.2}-\left(t_{\text{operation}}+t_{\text{after shutdown}}\right)^{-0.2}\right]$$

Decay Heat


0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Decay Heat to Reactor Power Ratio
7 days
30 days
1 year
2 years
10^1
10^2
10^3
10^4
10^5
10^6
Time after shutdown (seconds)

ANS Decay Heat Standard



Plant Parameters

Important Parameters

(1) Reactor thermal power [MW_t]: The total heat produced in the reactor core.

(2) Plant electrical output [MW_e]: Net electrical power generated by the plant.

(3) Net plant efficiency [%]:

$$\frac{\text{Plant Electrical Output}}{\text{Reactor Thermal Power}}$$

(4) Plant capacity factor [%]:

$$\frac{\text{Total Energy Generated Over Time Period}}{\text{Plant Rating x Time}}$$

(5) Plant load factor [%]:

$$\frac{\text{Average Plant Electrical Power Level}}{\text{Peak Power Level}}$$

Important Parameters

(6) Plant availability factor [%]: $\frac{\text{Integrated Electrical Energy Output Capacity}}{\text{Total Rated Energy Capacity for Period}}$

(7) Core power density [kW/liter]: $\frac{\text{Reactor Thermal Power}}{\text{Total Core Volume}}$

(8) Linear power [kW/ft]: $\frac{\text{Thermal Heat Generated}}{\text{Unit Length of Fuel}}$

(9) Fuel loading [kg]: Total mass of fuel (i.e., fissionable material)

(10) Specific power [kW/kg]: $\frac{\text{Reactor Thermal Power}}{\text{Fuel Loading}}$

Important Parameters

(11) Fuel burnup [MW-days/metric ton uranium = MWD/TU]:

$$\frac{\text{Energy Generated in Fuel During Core Residence}}{\text{Fuel Loading}}$$

(12) Fuel residence time:

$$\frac{\text{Fuel Burnup}}{\text{(Specific Power) * (Capacity Factor)}}$$

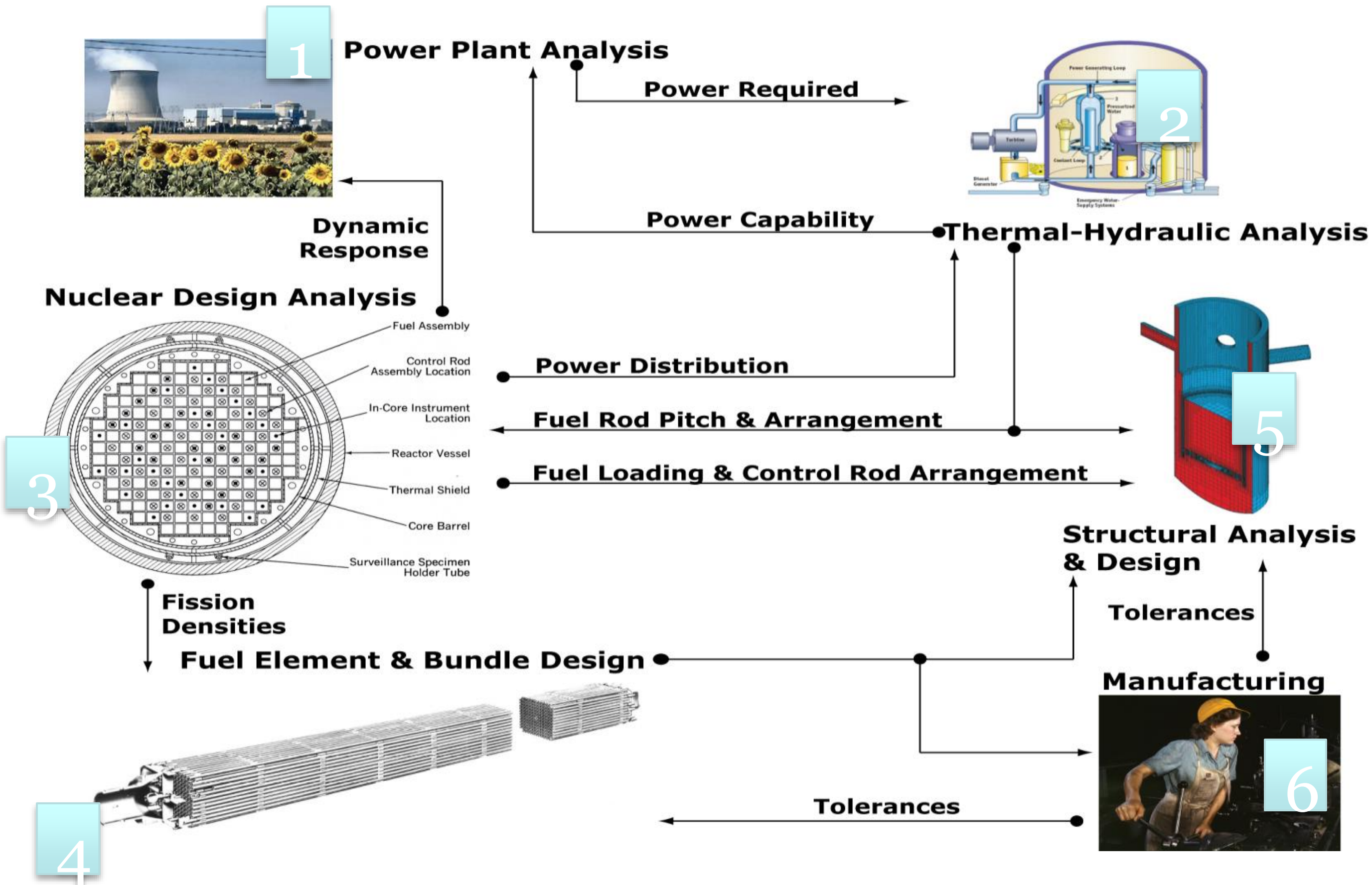
(13) Heat Rate:

$$\frac{\text{Amount of Heat Supplied}}{\text{Needed to Generate 1 kWh of Electricity}}$$

Nuclear Reactor Design Considerations

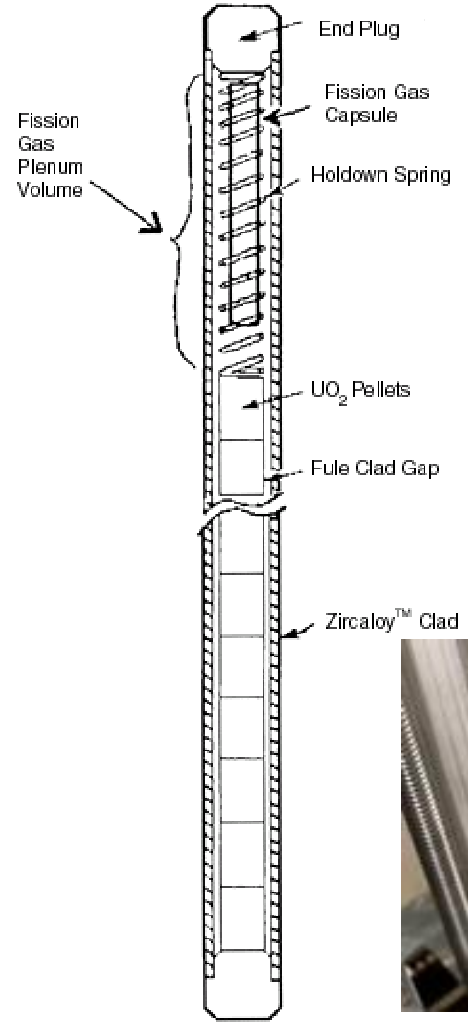
Nuclear Reactor Design

An Iterative Process



An Approach to Reactor Thermal-Hydraulic Analysis

- Basic fuel rod dimensions:
  - active fuel rod length
  - fuel pellet diameter
  - cladding thickness
  - gap size



- Avg. power per rod:

$$\langle \dot{q}_{rod} \rangle = \langle \dot{q}''' \rangle \times V_{fuel}$$

- Total number of rods:

$$\frac{P_{th}}{\langle \dot{q}_{rod} \rangle} \approx \# rods$$

An Approach to Reactor Thermal-Hydraulic Analysis

- Reactor thermal power represents the amount of heat that must be removed at steady-state
  - Energy balance to determine axial fluid temperature distribution
  - Work inwards using:
    - Newton’s Law of Cooling – convection HT
    - Fourier’s Law – conduction HT
  - Ultimately estimate the fuel centerline temperature
    - Acceptable design?

Core Thermal-Hydraulic Design

- The ability to transfer heat from the fuel element to coolant determines:
  - Power density
  - Determines the "size" of the fuel element and reactor
    - Must be balanced with criticality implications
  - Operating temperatures and coolant flow rates.

- The reactor T-H designer must assure that the integrity of the fuel cladding is never violated:
  - Prevent the release of fission products into the coolant
  - Ensures the safe operation of the reactor

Where does the heat go?

- Nuclear Heat Transfer (focus on PWR's)
  - A nuclear reactor represents a heat source necessary to drive a thermodynamic power system
  - We will investigate the following:
    - The thermodynamic cycle that converts heat into work.

      → electricity or other useful form
    - The waste heat rejection to the environment
    - The heat transfer from the fuel element to the primary coolant