Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 25

Nuclear Reactor Safety

Spiritual Thought

Nuclear Safety

- One MAJOR challenge
  - Nuclear heat NEVER Stops!!!!
- One MAJOR consequence – Dose to Public
- Complications:
  - Constant cooling of fuel/clad needed
  - Loss of coolant (or flow) = damage to barriers
  - Clad reacts with water at high temperature
    - Forms H2 (explosive)
    - Eliminates barrier to fuel
  - If fuel melts, (corium) could reconfigure in a MORE reactive state

What's the Worry?

- Frequency?
- Immediate Deaths?
- Radiation?
- Land Impact?
- Cost?
- Cancer?
- Public Stress?
- Nuclear power has infrequent, but SEVERE social impact due to accidents!

Annual Death rates per TW*hr		
Source	Deaths	US Electricity Percentage
Coal	161	39%
Oil	36	1%
Natural Gas	4	27%
Biofuel/Biomass	12	1.70%
Solar	0.83	0.40%
Wind	0.15	4.40%
Hydro	1.4	6%
Nuclear	0.04	20%

Purpose of Nuclear Safety Analysis

- Prevent Dose to public
  - If dose occurs, minimize it
  - Evaluate Max dose possible for DBA
- Minimize damage to core
  - Core Damage Frequency (CDF)
- Protect Investment
  - Don't want to wreck the plant (lots of lost $$$)

Design Basis Accidents (DBA)

- **Design-basis criticality**: A criticality accident that is the most severe design basis accident of that type applicable to the area under consideration.
- **design-basis earthquake** (DBE): That earthquake for which the safety systems are designed to remain functional both during and after the event, thus assuring the ability to shut down and maintain a safe configuration.
- **Design-basis event** (DBE): A postulated event used in the design to establish the acceptable performance requirements of the structures, systems, and components.
- **Design-basis explosion**: An explosion that is the most severe design basis accident of that type applicable to the area under consideration.
- **Design-basis fire:** A fire that is the most severe design basis accident of this type. In postulating such a fire, failure of automatic and manual fire suppression provisions shall be assumed except for those safety class items or systems that are specifically designed to remain available (structurally or functionally) through the event.
- **Design-basis flood**: A flood that is the most severe design basis accident of that type applicable to the area under consideration.
- **Design-basis tornado (DBT):** A tornado that is the most severe design basis accident of that type applicable to the area under consideration.
- Most Common:
  - LOCA, LOFA, Overpower

Beyond Design Basis Accidents (BDBA)

- Beyond scope of design
  - Unlikely events
  - Extreme conditions
- Extremely severe
- Station Blackout
  - Fukushima
  - Significant focus
- Have additional equipment/procedures (not safety grade) to help with these.

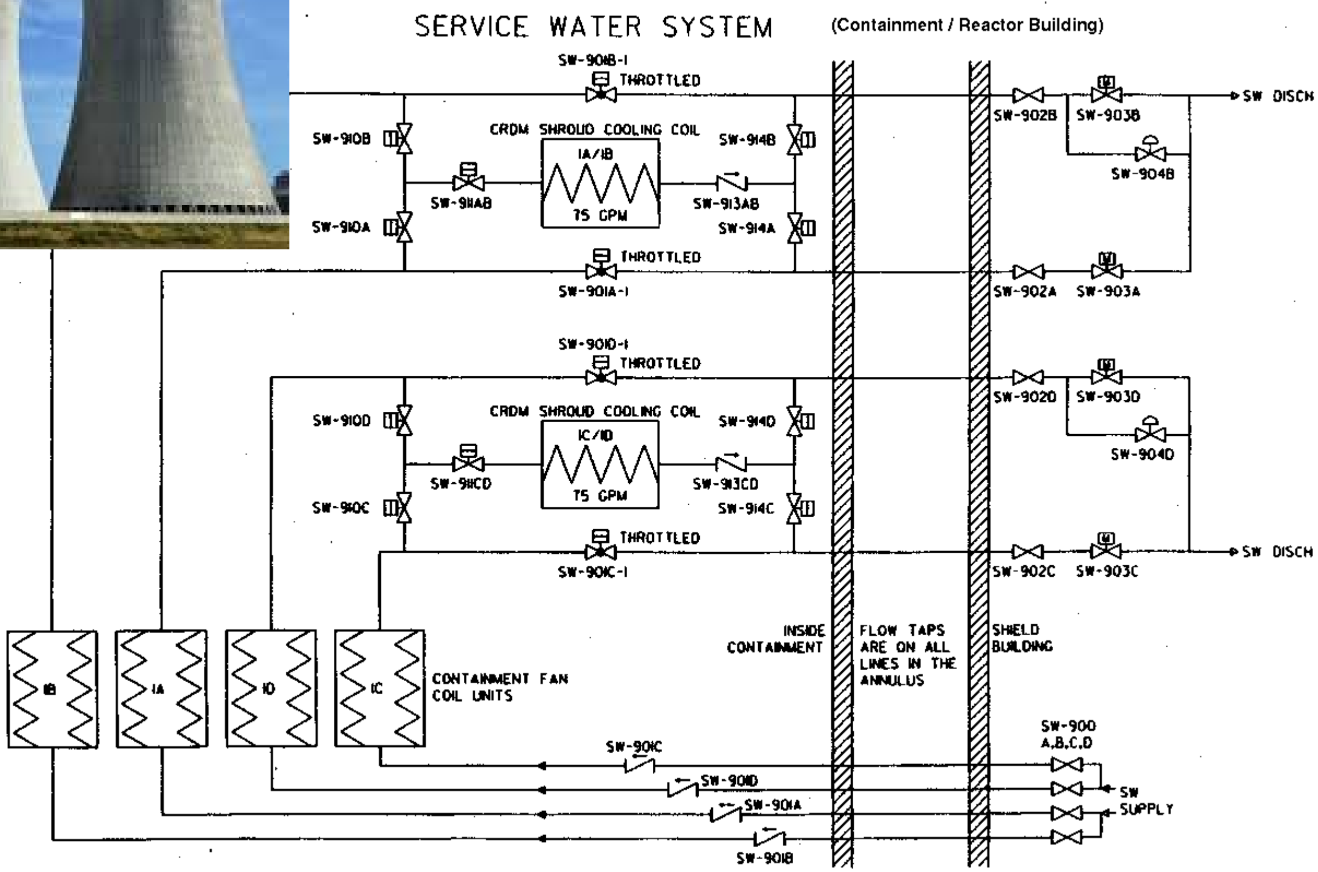
Ensuring Safety?

- Design
  - Undermoderated vs. Overmoderated
  - Negative reactivity feedback coefficients
  - CDF < 1E-6 for all Design Basis Accidents (DBA)
- Operation
  - Tech Specs – how reactor is run
    - “Control Rod movement < 20 steps per hour…”
- Margins
  - Limiting conditions of plant – SS and Transient

The Reactor Protection System (RPS)

- Control rods
- Safety Injection/Standby liquid control

Essential Service Water System (ESWS)



Emergency Core Cooling System (ECCS)

- High Pressure Safety Injection System (HPSI)
  - Initiated by:
    - Low pressurizer pressure
    - High containment pressure
    - Steam line pressure/flow anomalies
- Automatic Depressurization System
  - 7 SRVs in vessel head
  - Rapidly decrease system pressure
  - Initiated by low level + time delay

ECCS (continued)

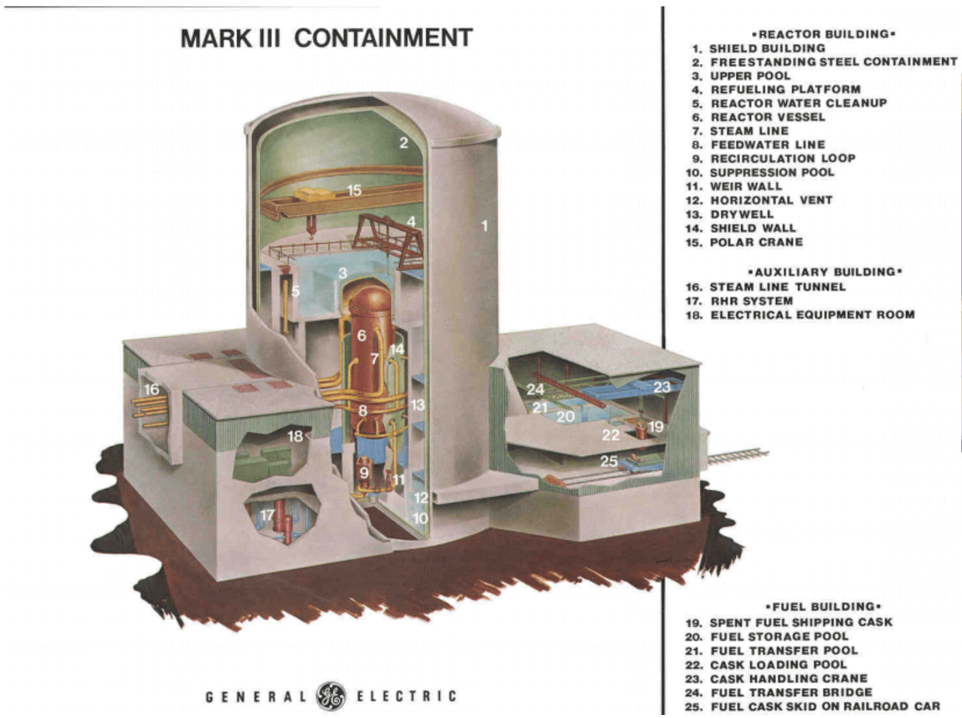
- Low Pressure Safety System (HPSI)
  - Only functions after blowdown
    - Larger supply
    - Later in accident
- Containment cooling system
  - Spray system
    - Actuated by high containment pressure/temperuture
- Core Spray System
  - (BWR only)

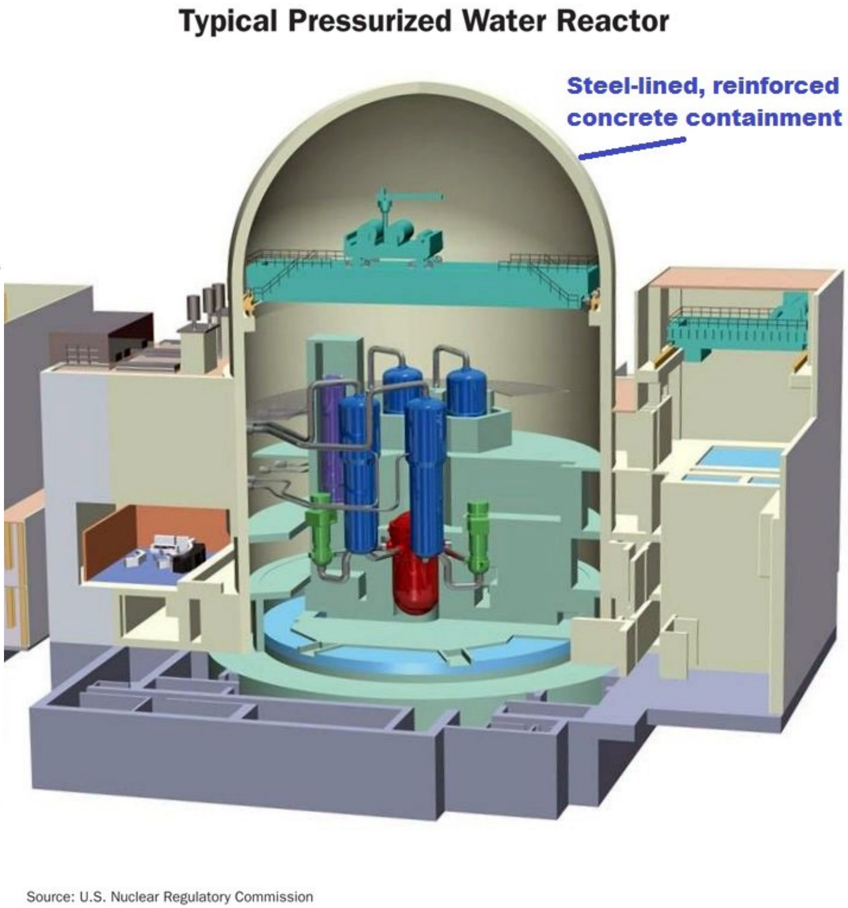
Emergency Electrical Systems (EES)

- Diesel Generators
- Flywheels
- Batteries

Containment Systems

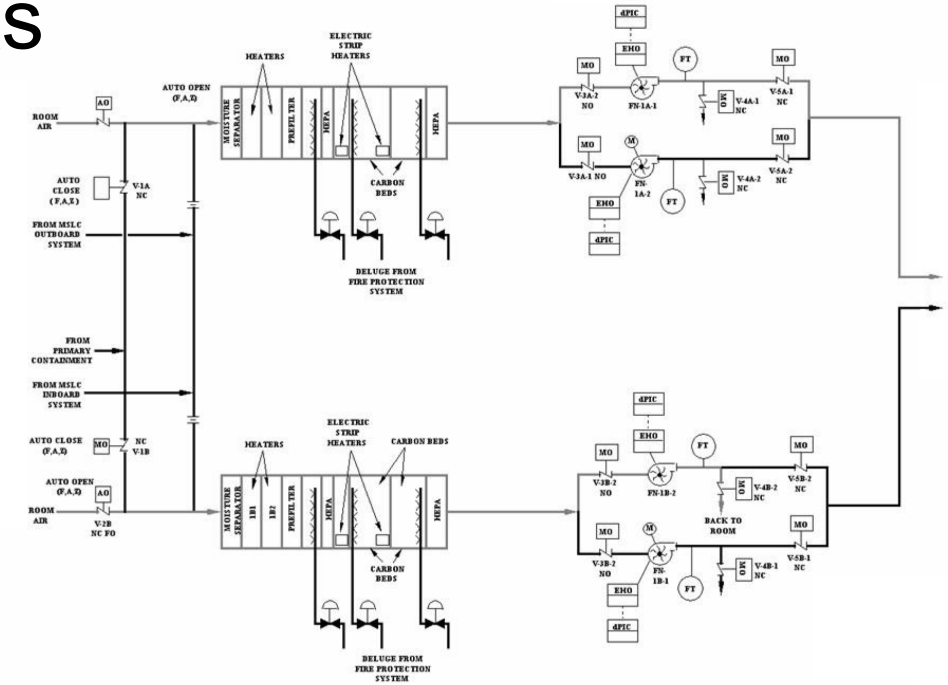
- Clad
- Containment
- Secondary Containment





Standby Gas Treatment Systems (SBGT)

- Secondary Containment
  - Maintain negative pressures
  - (pull air in, rather than release radioactivity)
- Primarily for BWRs



Ventilation and Radiation Protection Systems

- Prevention of radiation gas release
  - Auxiliary Building
  - Shield Building
  - Reactor Building
  - Turbine Building
  - Radwaste Building
  - Control Room
  - Screenhouse
- Vent, Filter, Blowers

Passive Safety Systems

- 4 levels of passivity (IAEA)
  - A. no moving working fluid
  - B. no moving mechanical part
  - C. no signal inputs of “intelligence”
  - D. no external power input or forces
- Do not yet have fully passive systems
- Increase in degree of passivity
- Many systems move to level C passivity
- Last 3-7 days depending on system

Original Safety Strategy

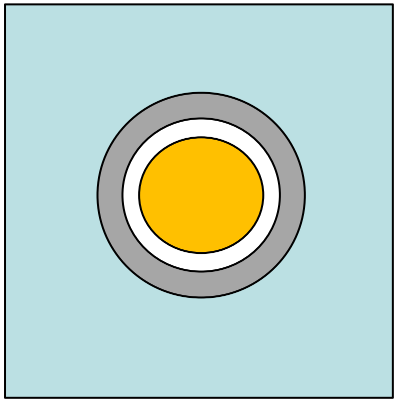
- **<u>Deterministic</u>** Approach
  - Lacked theory & computational input
  - "Empirical" approach to safety
  - Multiple Layers of protection
    - Clad
    - RPV
    - primary system
    - containment
    - etc.
  - MARGINS

Challenges with Deterministic

- More accident possibilities = more layers
- Expensive, complex and boundless
- Possible to bypass all layers (Fukushima)
- Competing effects for systems
  - Core cooling systems
    - LOHS – Loss of heat sink
    - LOCA – Loss of coolant accident
- Therefore a more scientifically, data driven approach was desired.

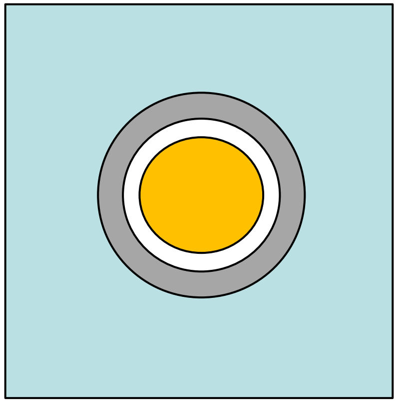
Nuclear Safety (II)

- MAJOR portion of safety is heat transfer
  - Must get heat out of fuel
  - Must eject heat to environment (months!)
- Also involves pressurized vessel
- Passive safety ideas
  - make bulk flow passive
  - Increase fuel k_c
  - Decrease fuel thickness
  - Should we decrease heat generation rate?
  - What about gap distance?



Heat Generation in Core

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



- Where: $\dot{Q}$ = core power, $\dot{q}$ = pin power

  N = number of fuel rods, L = rod length

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

  and q''' = volumetric heat rate

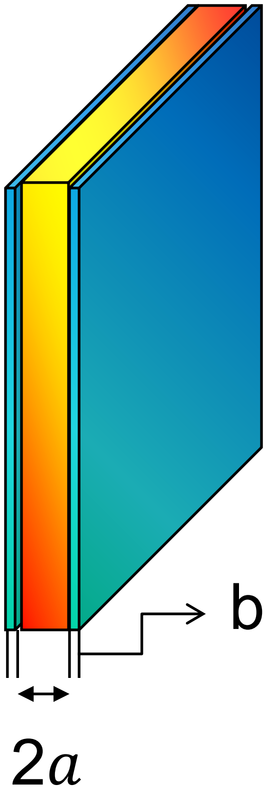
Temperature Profiles in a Plate

In fuel

$$\nabla k_f \nabla T + q''' = 0 \qquad -k_f \frac{d^2T}{dx^2} = q'''$$

BC1: $T(0) = T_{max}$

BC2: $\left.\frac{dT}{dx}\right|_{x=0} = 0$



$$\Rightarrow T = -\frac{q'''}{2k_f}x^2 + C_1 x + C_2 = T_{max} - \frac{q''' x^2}{2k_f}$$

$$T_s = T_{max} - \frac{q''' a^2}{2k_f}$$

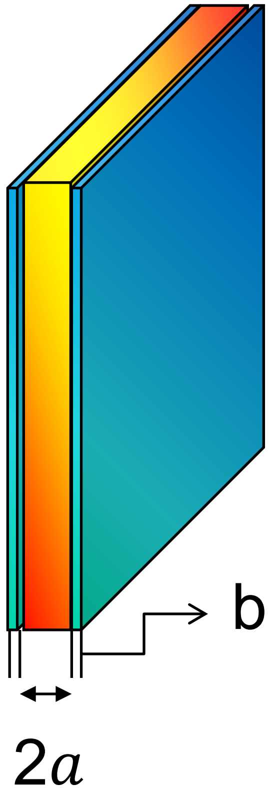
Temperature Profiles in a Plate

In cladding

$$-k_c \frac{d^2T}{dx^2} = 0$$

BC1: $T(a) = T_s$

BC2: $T(a+b) = T_c$



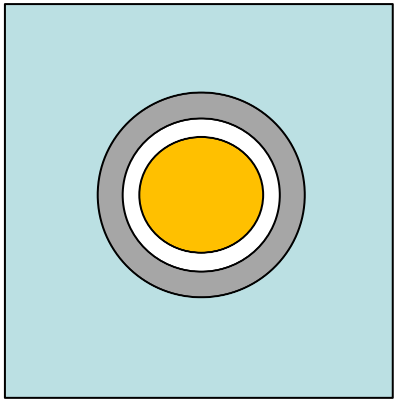
$$\Rightarrow T = C_1 x + C_2 = T_s - \frac{x-a}{b}(T_s - T_c)$$

$$q''' = \frac{T_{max} - T_c}{\frac{q}{2k_f A} + \frac{b}{k_c A}} = \frac{T_{max} - T_c}{R}$$

Temperature Profiles in Fuel Rod

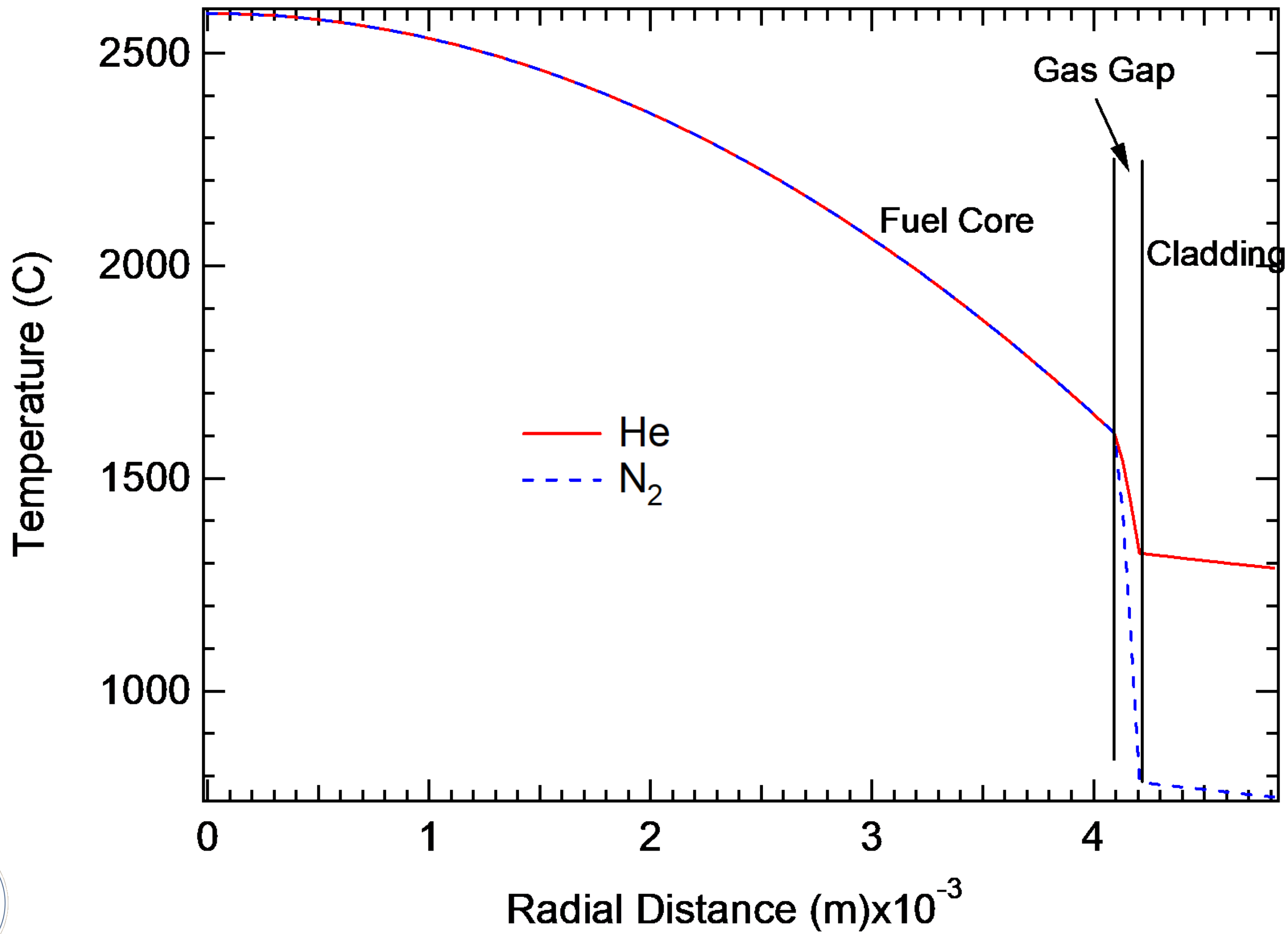
In fuel

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

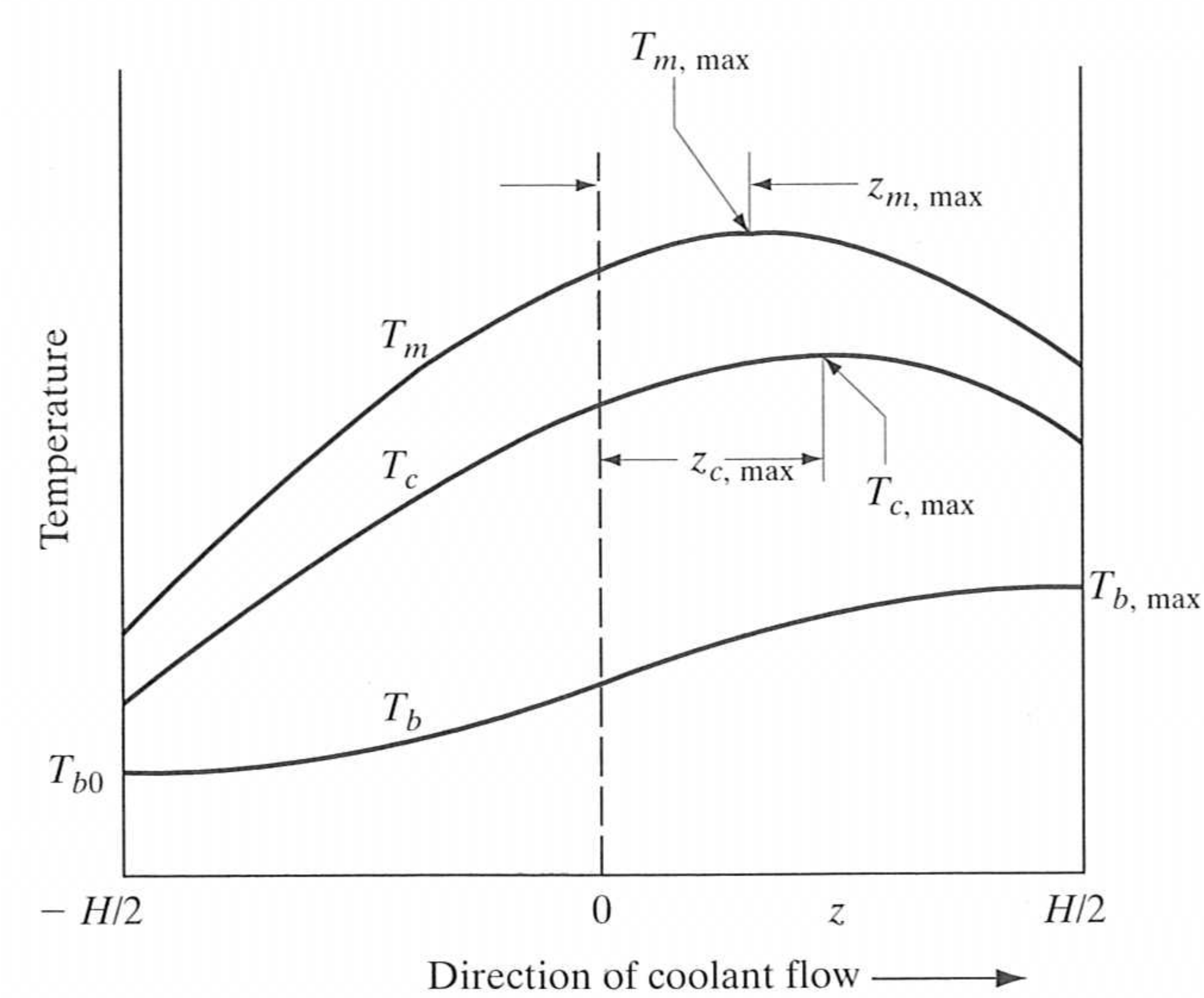


To be solved in HW, #1

Temperature Profile in Cylinder



Typical Temperature Profiles

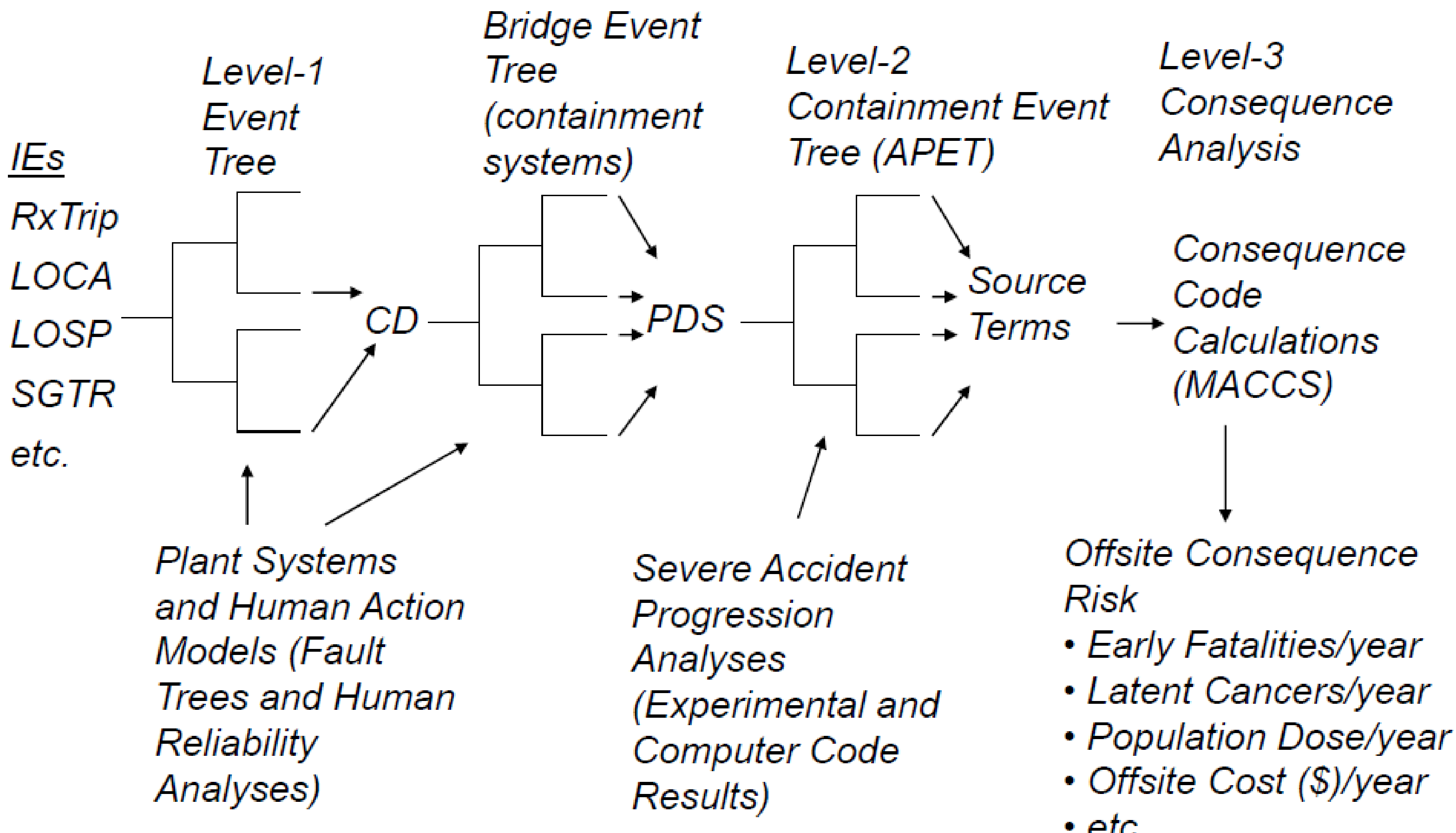


Subscripts *b*, *c*, and *m* represent bulk, cladding, and middle, respectively.

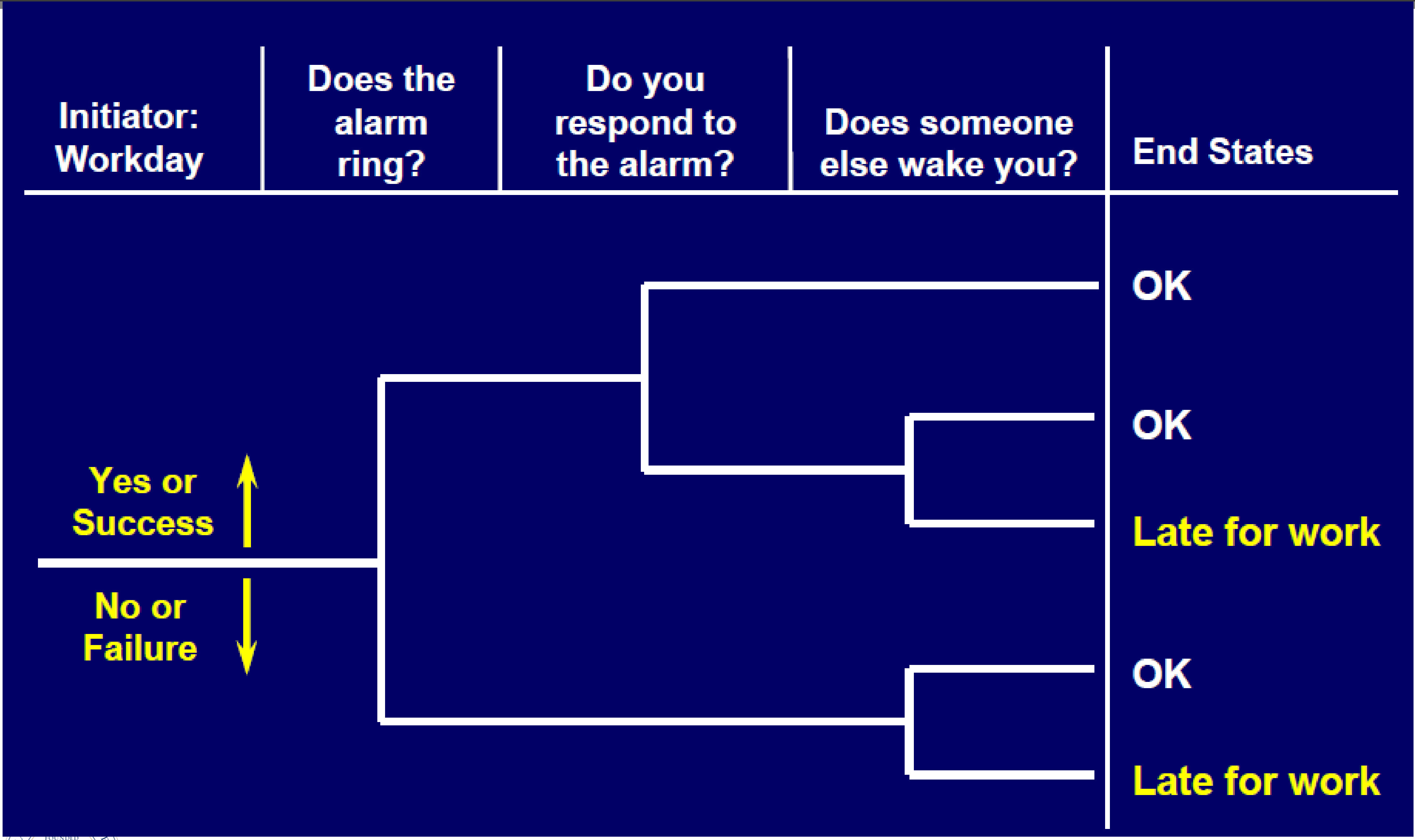
Probability Risk Assessment

$$\text{Risk}\left[\frac{\text{Consequence Magnitude}}{\text{Unit of Time}}\right] =$$

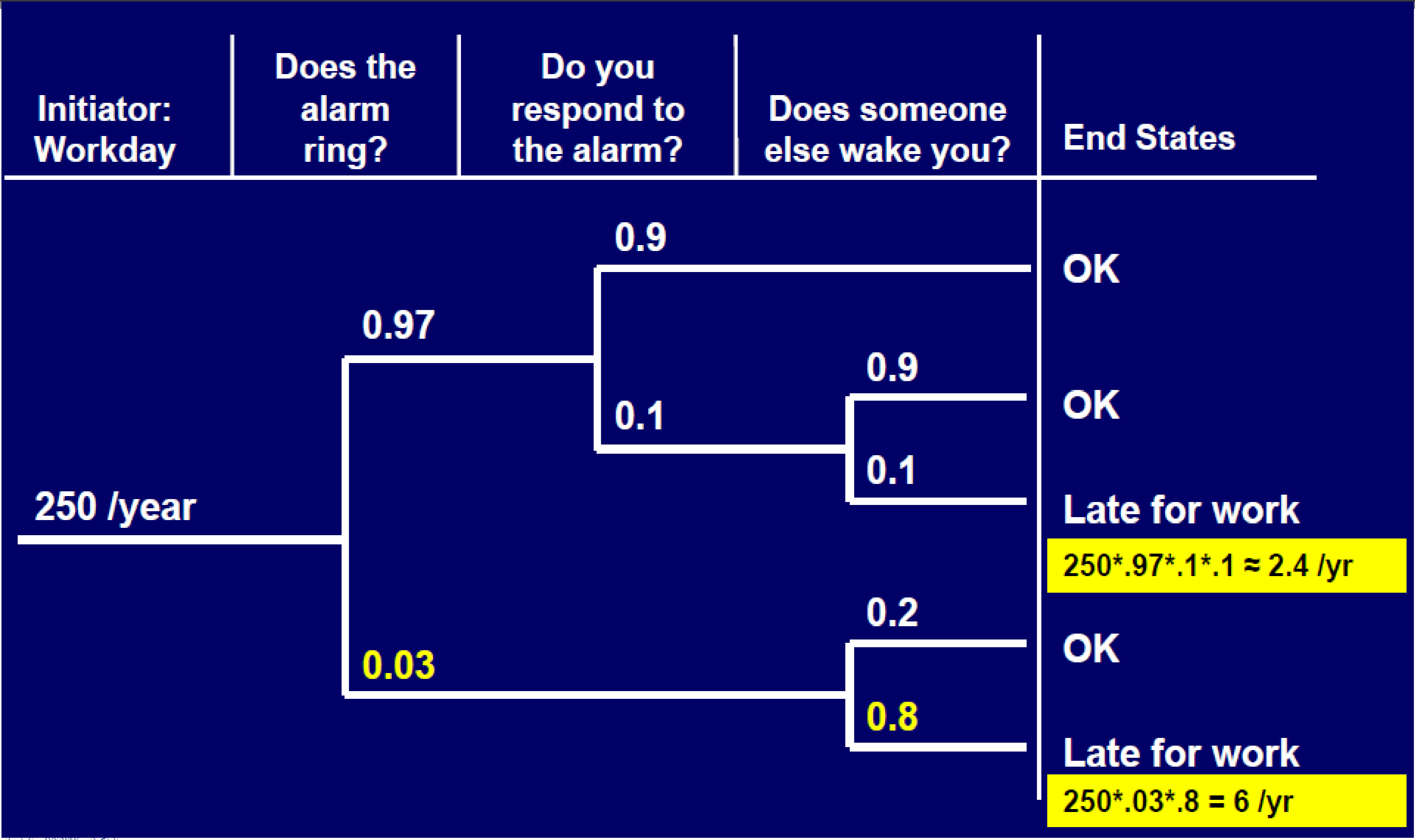
$$\text{Frequency}\left[\frac{\text{Events}}{\text{Unit of Time}}\right] \times \text{Consequences}\left[\frac{\text{Magnitude}}{\text{Event}}\right]$$



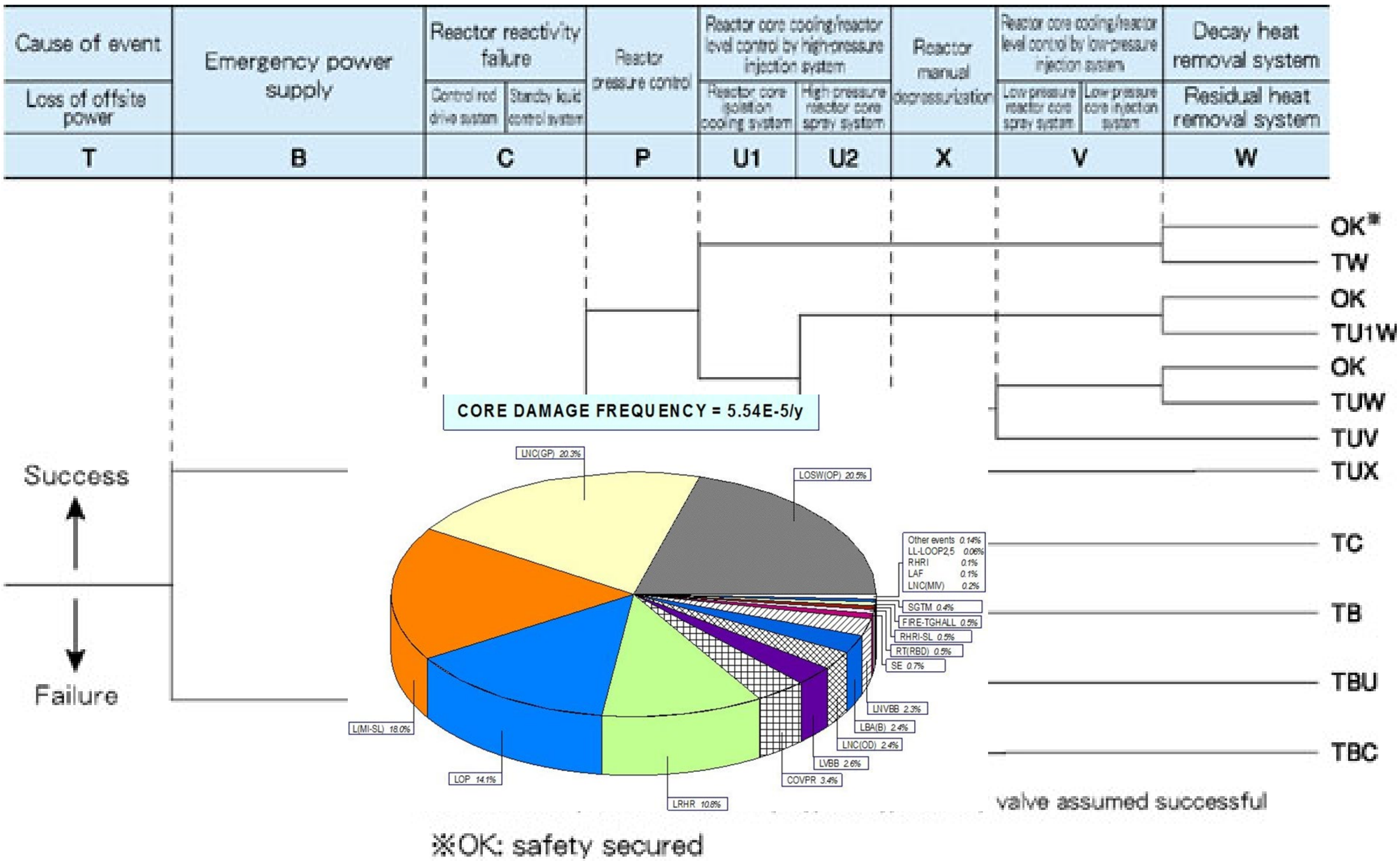
Probabilistic Example



Probabilistic Example



Sample = LOPA


Cause of event
Loss of offsite power
T
Emergency power supply
B
Reactor reactivity failure
Control rod drive system
Standby liquid control system
C
Reactor pressure control
P
Reactor core cooling/reactor level control by high-pressure injection system
Reactor core isolation cooling system
High pressure reactor core spray system
U1
U2
Reactor manual decompressurization
X
Reactor core cooling/reactor level control by low-pressure injection system
Low pressure reactor core spray system
Low pressure core injection system
V
Decay heat removal system
Residual heat removal system
W
OK※
TW
OK
TU1W
OK
TUW
TUV
TUX
TC
TB
TBU
TBC
Success
Failure
CORE DAMAGE FREQUENCY = 5.54E-5/y
LNC(GP) 20.3%
LOSW(OP) 20.5%
Other events 0.14%
LL-LOOP2,5 0.06%
RHRI 0.1%
LAF 0.1%
LNC(MIV) 0.2%
SGTM 0.4%
FIRE-TGHALL 0.5%
RHRI-SL 0.5%
RT(RBD) 0.5%
SE 0.7%
LNVBB 2.3%
LBA(B) 2.4%
LNC(OD) 2.4%
LVBB 2.6%
COVPR 3.4%
LRHR 10.8%
LOP 14.1%
L(MI-SL) 18.0%
valve assumed successful
※OK: safety secured