22.06 ENGINEERING OF NUCLEAR SYSTEMS

QUIZ 1 (solutions) 1.5 HOURS

CLOSED BOOK QUESTIONS (20%)

For each of the following drawings, identify the components indicated by the red arrows and describe (in one sentence!) their function.

PWR

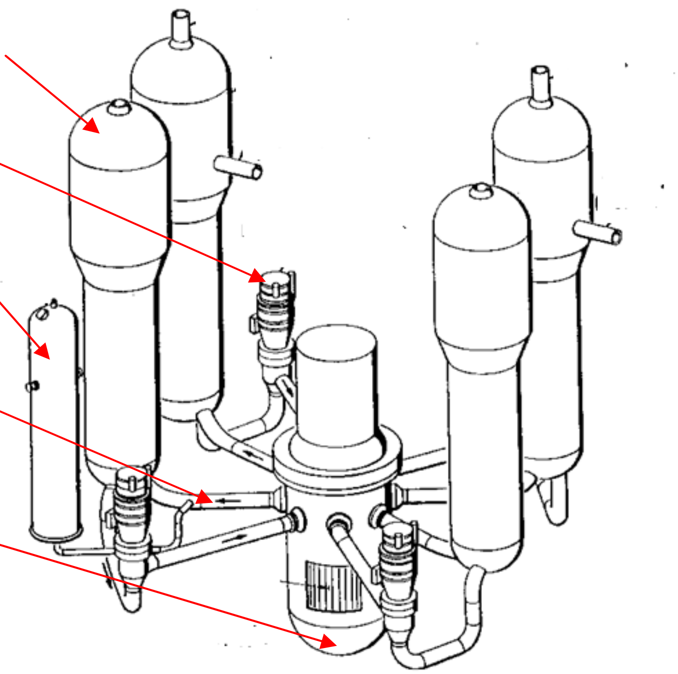
What is it? What is its function?
Steam generator transfers heat from primary to secondary coolant

What is it? What is its function?
Reactor coolant pump drives primary coolant flow through the core

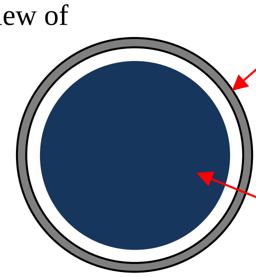
What is it? What is its function?
Pressurizer controls pressure in primary system

What is it? What is its function?
Hot leg directs hot primary coolant to steam generator

What is it? What is its function?
Reactor pressure vessel houses core and reactor internals

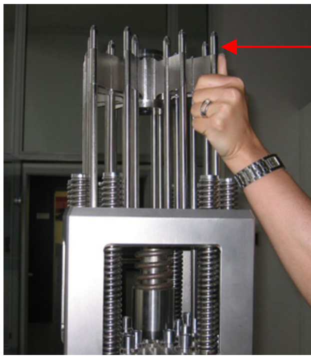


Cross-sectional view of a PWR fuel pin



What is it ? What is its funtion? What material is it made of?
Fuel cladding encapsulates fuel pellets. It is made of Zircaloy.

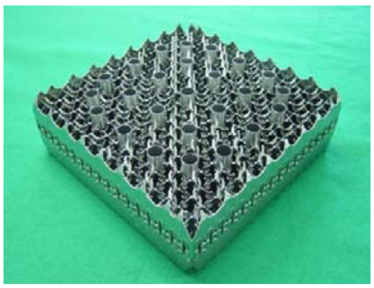
What is it ? What is its function? What material is it made of?
Fuel pellet, reactor fuel. It is made of uranium dioxide.



What is it? What is its function? What material is it made of?

Control rod cluster (or spider) can be used to control power and shutdown reactor

It is made of neutron absorbers (B, Cd, In, Ag…)

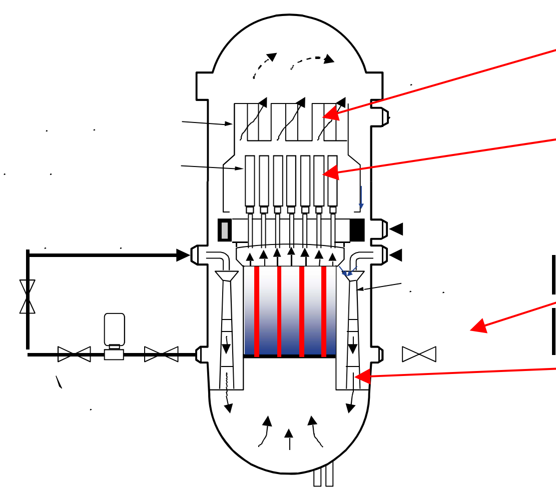


What is it? What is its function? What material is it made of?

Spacer grid prevents fuel rod vibration, promotes heat transfer.

It is made of Zircaloy.

BWR



What is it? What is its function?

Steam dryer removes droplets from steam

What is it? What is its function?

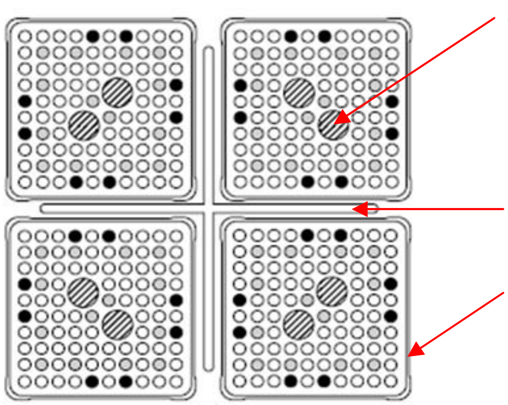
Steam separators separates steam from liquid

What is it? What is its function?

Recirculation pump drives flow through the core

What is it? What is its function?

Jet pump boosts flow through the core



What is it? What is its function?

Water rod enhances moderation in center of fuel assembly

What is it? What is its function? What material is it made of?

Cruciform control blade used to control power and shutdown reactor

It is made of neutron absorbers

What is it? What is its function? What material is it made of?

Fuel assembly duct prevent steam drifting from one fuel assembly to the next. It is made of Zircaloy.

22.06 **ENGINEERING OF NUCLEAR SYSTEMS**

OPEN BOOK QUIZ 1 (solutions)

Short Questions (10% each) (adapted from Shultis & Faw textbook)

a)
The duration of the trip is 60,000/(20×1.852) ≈ 1620 hr or 5.83×10^6 s. The total electric energy needed for the trip is $18\times10^6\times5.83\times10^6 \approx 1.05\times10^{14}$ J, which requires $1.05\times10^{14}/0.25 \approx 4.20\times10^{14}$ J of thermal energy or $4.20\times10^{14}/(200\times10^6\times1.6\times10^{-19}) \approx 1.312\times10^{25}$ fissions. Therefore, the total consumption of U-235 (including fissions and parasitic captures) is $1.312\times10^{25}\times(678/577) \approx 1.54\times10^{25}$ atoms of U-235, which is $1.54\times10^{25}/(6.022\times10^{23})\times0.235 \approx 6$ kg of U-235.

b)
The decay power for a reactor that had operated for infinitely long time prior to shutdown is:
$\dot{Q}_{decay}/\dot{Q}_0 = 0.066t^{-0.2}$
Setting the LHS equal to 0.005 and solving for *t*, we get t=4.007×10^5 s or 4.6 days.

c)
The total number of target nuclei in the sample is $N_{av}\, m/A$, where N_{av} is the Avogadro's number. The total reaction rate (scatterings per second) within the sample is ($N_{av}\, m/A\ \sigma_s\ \phi$). Therefore, the time it takes all target nuclei on average to scatter at least once is $(N_{av}\, m/A)/(N_{av}\, m/A\ \sigma_s\ \phi) = 1/(\sigma_s\ \phi)$. The implicit assumption made is that the absorption cross-section of the material is negligible, so that the total number of target nuclei does not change with time.

Problem 1 (50%) – Temperature distribution within a fuel pellet with non-uniform heat generation (adapted from Duderstadt & Hamilton textbook)

i)
The linear power can be obtained from the following integration:

$$q' = \int_0^R q'''(r)2\pi r dr = \int_0^R q_0'''[1+a(r/R)^2]2\pi r dr = \therefore\ q_0'''\pi R^2(1+a/2) \qquad (1)$$

ii)
The heat equation in the pellet (for constant thermal conductivity) is:

$$k_f \frac{1}{r}\frac{d}{dr}[r\frac{dT}{dr}] + q''(r) = 0 \qquad \Rightarrow \qquad \frac{d}{dr}[r\frac{dT}{dr}] = -\frac{rq_0'''}{k_f}[1+a(r/R)^2] \qquad (2)$$

The boundary conditions are as follows:

$T=T_{fo}$ at $r=R$

$\frac{dT}{dr}=0$ at $r=0$

Integrate Eq 2 from r=0 and a generic location r, to get:

$$r\frac{dT}{dr}-r\frac{dT}{dr}\bigg|_{r=0}=-\frac{q_0'''}{k_f}\left[\frac{r^2}{2}+a\frac{r^4}{4R^2}\right] \quad \Rightarrow \quad \frac{dT}{dr}=-\frac{q_0'''}{2k_f}\left[r+a\frac{r^3}{2R^2}\right] \tag{3}$$

where the second boundary condition was imposed. Integrating Eq 3 from r=R and a generic location r, we get:

$$T(r)-T_{fo}=-\frac{q_0'''}{2k_f}\left[\frac{r^2}{2}+a\frac{r^4}{8R^2}\right]+\frac{q_0'''}{2k_f}\left[\frac{R^2}{2}+a\frac{R^4}{8R^2}\right] \tag{4}$$

Where the first boundary condition was imposed. The centerline temperature is found by setting r=0 in Eq 4:

$$T_{\max}-T_{fo}=\frac{q'}{4\pi k_f}\frac{4+a}{4+2a} \tag{5}$$

where Eq 1 was used to substitute q_0''' with q'.

iii)

Substituting the numerical values into Eq 5, we get $T_{\max}\approx 1044$°C.

iv)

As derived in class, the centerline temperature for the case of uniform heat generation and constant thermal conductivity is:

$$T_{\max}-T_{fo}=\frac{q'}{4\pi k_f}\approx 1063\text{°C}$$

The temperature in the non-uniform case is lower because, on average, the energy (heat) has a shorter distance to ‘travel’ to the heat sink (coolant) than in the uniform heat generation case.

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