NE 591 Final Exam

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1.(a)

```
(*fission gas diffusion coefficient*)

In[17]:= Fdot = 2.0 * 10^14 (*fissions/cm^3-s*);
T = 1200 (*K*);
D1 = 7.6 * 10^(-6) * Exp[-3.03 / ((8.617 * 10^(-5)) * T)];
D2 = 1.41 * 10^(-18) * Exp[-1.19 / ((8.617 * 10^(-5)) * T)] * Fdot^0.5;
D3 = 2.0 * 10^(-30) * Fdot;
Print["D1", "=", D1, " cm^2/s"];
Print["D2", "=", D2, " cm^2/s"];
Print["D3", "=", D3, " cm^2/s"];
Print["D", "=", D1 + D2 + D3, " cm^2/s"];
```

Ans:

$D1 = 1.4285 \times 10^{-18}$ cm^2/s

$D2 = 2.00337 \times 10^{-16}$ cm^2/s

$D3 = 4. \times 10^{-16}$ cm^2/s

$D = 6.01765 \times 10^{-16}$ cm^2/s

1.(b)

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(*gas released from the fuel*)

In[22]:= t = 2 * 365 * 24 * 60 * 60 (*sec*);
a = 8 * 10^-4 (*cm*);
Dtot = 6.02*^-16 (*cm^2/s*);
Print["τ", "=", Dtot * t / a];
```

τ=0.0000474617

```
τ < Pi^-2;

(*use equation for in-pile fission gas release*)

In[21]:= t = 2 * 365 * 24 * 60 * 60 (*sec*);
a = 8 * 10^-4 (*cm*);
Fdot = 2.0 * 10^14 (*fission/cm^3-sec*);
Dtot = 6.02*^-16 (*cm^2/s*);
Nfg = 0.3017 * Fdot * t (*generation of fission gas (atoms/cm^3)*);
f = 4 * (Dtot * t / (Pi * a^2))^0.5 - 3 / 2 * Dtot * t / (a^2) (*fission gas release,
assume in-pile fission gas release*);
Print["gas released from the fuel", " = f*0.3017*Fdot*t = ", f * Nfg,
 " atoms/cm^3"];
```

Ans: gas released from the fuel = f*0.3017*Fdot*t = 1.75328×10^{21} atoms/cm^3

1.(c)

```
(*How long before fraction of the gas trapped in the pellet is released*)

In[39]:= Fdot = 2.0 * 10^14 (*fission/cm^3-s*);
T = 2000 (*K*);
a = 8 * 10^-4 (*cm*);
D1 = 7.6 * 10^(-6) * Exp[-3.03 / ((8.617 * 10^(-5)) * T)];
D2 = 1.41 * 10^(-18) * Exp[-1.19 / ((8.617 * 10^(-5)) * T)] * Fdot^0.5;
D3 = 2.0 * 10^(-30) * Fdot;
Dtot = D1 + D2 + D3;
Print["Dtot", "=", D1 + D2 + D3, " cm^2/s"];
fraction = 0.3;
Print["assume τ>Pi^-2 for post-annealing case"];
Print["t", "=(Log[(1-fraction)*Pi^2/6])*(-a^2/Dtot/Pi^2) = ",
 (Log[(1 - fraction) * Pi^2 / 6]) * (-a^2 / (Dtot * Pi^2)), " s"];

Dtot=1.96292×10^-13 cm^2/s
assume τ>Pi^-2 for post-annealing case
```

Ans:

```
t=(Log[(1-fraction)*Pi^2/6])*(-a^2/Dtot/Pi^2) = -46588.2 s
```

2. (a)

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(*Oxide thickness on ZIRLO caldding*)

In[4]:= T = 600 (*K*); t = 1 * 365 (*day*); t' = 6.62 * 10^(-7) * Exp[11949 / T]

Out[4]= 295.007

(*t'<365 days=>gone through transition*)

In[6]:= T = 600 (*K*);
t = 1 * 365 (*day*);
t' = 6.62 * 10^(-7) * Exp[11949 / T];
δ' = 5.1 * Exp[-550 / T];
k = 7.48 * 10^6 * Exp[-12500 / T];
Print["δ", "=", δ' + k * (t - t'), " um"]
```

Ans:

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δ=2.50821 um
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2.(b)

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(*Zirconium cladding creep under irradiation*)

In[8]:= σm = 300 (*MPa*);
T = 600 (*K*);
t = 1 (*yr*);
LHR = 350 (*W/cm*);
C0 = 2.846 * 10^(-24) (*ZIRLO type cladding*);
C1 = 0.85 (*ZIRLO type cladding*);
C2 = 1 (*ZIRLO type cladding*);
ϵirr = C0 * (LHR * 3 * 10^11)^C1 * σm^C2;
Print["d/(ϵirr)/dt", " = C0*(LHR*3*10^11)^C1*σm^C2 = ", ϵirr];
Print["ϵirr", " = d/(ϵirr)/dt*t*365*24*3600 = ", ϵirr * t * 365 * 24 * 3600]
```

Ans: d/(ϵirr)/dt = C0*(LHR*3*10^11)^C1*σm^C2 = 7.06915×10^{-10}

Irradiation creep ϵirr = d/(ϵirr)/dt*t*365*24*3600 = 0.0222933 //

3.

```
In[2]:= T = 1800 (*K*);
(*if T>750, Cd=1*);
Tref = 300 (*K*);
deltaρ = 0.01;
Bd = 7 (*MWD/kgU*);
d = 10.97 (*g/cc*);
α = 11 * 10^-6;
B = 0.0195 (*FIMA*);
ϵth = α * (T - Tref);
ϵD = deltaρ * (Exp[B * Log[0.01] / (Bd / 950)] - 1);
ϵSFP = 5.5577 * (10^(-2)) * d * B;
ϵGFP = 1.96 * (10^(-28)) * d * B * ((2800 - T)^11.73) * Exp[-0.0162 * (2800 - T)] *
   Exp[-17.8 * d * B];
Print["ϵth", " = α*(T-Tref) = ", α * (T - Tref)];
Print["ϵD", " = deltaρ*(Exp[B*Log[0.01]/(Bd/950)]-1) = ", ϵD];
Print["ϵSFP", " = 5.5577*(10^(-2))*d*B = ", 5.5577 * (10^(-2)) * d * B];
Print["ϵGFP",
 " = 1.96*(10^(-28))*d*B*((2800-T)^11.73)*Exp[-0.0162*(2800-T)]*Exp[-17.8*d*B] = ",
 1.96 * (10^(-28)) * d * B * ((2800 - T)^11.73) * Exp[-0.0162 * (2800 - T)] *
   Exp[-17.8 * d * B]];
Print["ϵtot", " = ϵth+ϵD+ϵSFD+ϵGFD = ", ϵth + ϵD + ϵSFP + ϵGFP];
```

Ans: ϵth = α*(T-Tref) = $\frac{33}{2000}$ = 0.0165

ϵD = deltaρ*(Exp[B*Log[0.01]/(Bd/950)]-1) = -0.00999995

ϵSFP = 5.5577*(10^(-2))*d*B = 0.0118888

ϵGFP = 1.96*(10^(-28))*d*B*((2800-T)^11.73)*Exp[-0.0162*(2800-T)]*Exp[-17.8*d*B] = 0.0132822

ϵtot = ϵth+ϵD+ϵSFD+ϵGFD = 0.031671

4.

Types of fission products

① Soluble oxides

② Insoluble oxides

③ Metals

④ Volatiles

⑤ Noble gases

5. Stages of fission gas release

① Gas atoms produced in the fuel diffuse to grain boundaries.

② Gas bubbles nucleate on grain boundaries, growing and interconnecting.

③ Gas travels through interconnected bubbles to a free surface.

6. Types of creep :

General creep equation : $\dot{\epsilon} = \frac{C\sigma^m}{D_{gr}^b} e^{-\frac{Q}{k_b T}}$

① Nabarro-Herring creep $\longrightarrow$ $Q = Q$ (self-diffusion), $m=1$, $b=2$

② Coble creep $\longrightarrow$ $Q = Q$ (grain boundary diffusion), $m=1$, $b=3$

③ Dislocation creep (climb and glide) $\longrightarrow$ $Q = Q$ (self-diffusion), $m = 4 \sim 6$, $b=0$

Nabarro-Herring creep is based on bulk diffusion.

9. Microstructure-based fuel performance modeling

Fuel performance codes used to rely on materials models correlated to temperature and burn-up. However, development has begun on models based on microstructure rather than burn-up.

mechanistic models ⇒ base on microstructure

empirical models ⇒ " " burn-up

10. A reactivity initiated accident (RIA) is a nuclear reactor accident that an unwanted increase in fission rate and reactor power.

RIA can lead to:

① a fast rise in fuel power and temperature

② failure of fuel rods due to the power ramp and release of radioactive material into coolant.

③ rapid steam generation and pressure pulses, damaging other core internals due to release of hot fuel.

④ long-term cooling of the core impaired by damaging the fuel or other core internals and breaking the reactor coolant pressure boundary due to coolant pressure pulse.

8. Benefits of Zirconium alloys

① Low neutron cross section

② Corrosion resistance in 300°C water

③ Resistance to void swelling

④ Adequate mechanical properties

⑤ Good thermal conductivity

⑥ Affordable cost

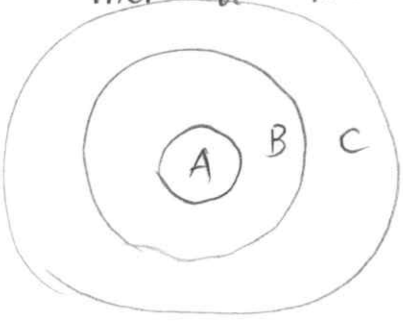
⑦ Avaiable in large quantities

9. Fuel redistribution of U-Zr

Zr diffuses via Soret diffusion up the temperature gradient.
Zr possesses different solubilities in each phase of U.
Therefore, these lead to distinct zones of Zr content in radial rings.

Microstructure of U-Zr fuel

There are multiphases in the fuel.



A: gamma phase (high Zr content)

B: beta phase (low Zr content)
↳ means lower melting temperature

C: alpha/delta phase (as-fabrication Zr content)

Besides, each phase and each Zr content has different elastic and thermal properties.

11.

Hydrogen tends to move toward low temperature due to soret effect. It also moves to areas with tensile stress.

Hydride concentrations are not uniform, because they respond to temperature and stress gradients.