Plan for Lecture 26 (Chapter 45):

Some topics in nuclear physics

1. Nuclear reactions
2. Fusion reactors
3. Fission reactors

Link to NCSU Professor Wesley Henderson's course materials on "Engineering Challenges at the Energy Frontier“ (includes fission reactors)  http://www.che.ncsu.edu/ILEET/CHE596web_Fall2011/index.html
<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Sections</th>
<th>Sections</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>03/08/2012</td>
<td>Faraday's law</td>
<td>31.1-31.5</td>
<td>31.12, 31.23, 31.40</td>
<td>03/20/2012</td>
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<td>03/13/2012</td>
<td>No class (Spring Break)</td>
<td></td>
<td></td>
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<td>03/15/2012</td>
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<td>03/20/2012</td>
<td>Induction and AC circuits</td>
<td>32.1-32.6</td>
<td>32.4, 32.20, 32.43</td>
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<td>03/22/2012</td>
<td>AC circuits</td>
<td>33.1-33.9</td>
<td>33.8, 33.24, 33.71</td>
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<td>Electromagnetic waves</td>
<td>34.1-34.3</td>
<td>34.3, 34.10, 34.13</td>
<td>03/29/2012</td>
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<tr>
<td>03/29/2012</td>
<td>Electromagnetic waves</td>
<td>34.4-34.7</td>
<td>34.22, 34.46, 34.57</td>
<td>04/03/2012</td>
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<tr>
<td>04/03/2012</td>
<td>Ray optics</td>
<td>35.1-35.8</td>
<td>35.20, 35.27, 35.35</td>
<td>04/10/2012</td>
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<tr>
<td>04/05/2012</td>
<td>Image formation</td>
<td>36.1-36.4</td>
<td>36.8, 36.31, 36.42</td>
<td>04/10/2012</td>
</tr>
<tr>
<td>04/10/2012</td>
<td>Image formation</td>
<td>36.5-36.10</td>
<td>36.52, 36.54, 36.64</td>
<td>04/12/2012</td>
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<tr>
<td>04/12/2012</td>
<td>Wave interference</td>
<td>37.1-37.6</td>
<td>37.2, 37.19, 37.29</td>
<td>04/17/2012</td>
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<td>04/17/2012</td>
<td>Diffraction</td>
<td>38.1-38.6</td>
<td>38.24, 38.30, 38.37</td>
<td>04/19/2012</td>
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<tr>
<td>04/19/2012</td>
<td>Quantum Physics</td>
<td>40.1-42.10</td>
<td>40.41, 41.12, 42.10</td>
<td>04/24/2012</td>
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<tr>
<td>04/24/2012</td>
<td>Molecules and solids</td>
<td>43.1-43.8</td>
<td>43.2, 43.40, 43.43</td>
<td>05/01/2012</td>
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<tr>
<td>04/26/2012</td>
<td>Nuclear reactions</td>
<td>45.1-45.4</td>
<td>45.6, 45.20, 45.30</td>
<td>05/01/2012</td>
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<tr>
<td>05/01/2012</td>
<td>Nuclear radiation</td>
<td>45.5-45.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>05/08/2012</td>
<td>Final exam 9 AM</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
General comments on final exam:
• It will be comprehensive
• May bring up to 4 equation sheets (turned in with exam papers)
• Need calculator; must not use cell phone, computer, etc.
• May pick up final exams from my office after they are graded

A PHY 114 review session has tentatively been scheduled for Thursday 5/3/2012 at 11 AM in Olin 107

A. I plan to come
B. I do not plan to come
C. Other suggestions?
NOTE: Students should have no more than two exams in a 24-hour period. They should be allowed to reschedule exams in excess of two in a 24-hour period.
How many of you need to reschedule the final exam time:
A. Happy to take the exam as scheduled (May 8)
B. Entitled to reschedule according to WFU policy
C. Not entitled, but would prefer to reschedule

For those of you who need/would like to reschedule – which time is likely to be preferable

A. Prefer rescheduled time earlier than May 8
B. Prefer rescheduled time later than May 8
Webassign comments:

1. **−0.334 points**

The following fission reaction is typical of those occurring in a nuclear electric generating station:

\[ ^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3(^{1}_{0}n) \]

(a) Find the energy released in the reaction. The masses of the products are 140.914 411 u for \(^{141}_{56}Ba\) and 91.926 156 u for \(^{92}_{36}Kr\).

\[
\text{MeV}
\]

(b) What fraction of the initial rest energy of the system is transformed to other forms?

\[
\%
\]

**Need Help?**  Read It  Chat About It

2. **−0.333 points**

For the fusion reaction shown below, find the amount of energy (Q) released.

\[ ^{1}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma \]

\[
\text{MeV}
\]
Typical reaction:
(Reactants) → (Products) + excess energy

excess energy = \begin{cases} 
\text{kinetic energy (eg. neutron production)} \\
\text{photon energy} 
\end{cases}

Assume that any available mass can be converted to energy according to $E=mc^2$.

\begin{align*}
1\text{ u} &= 1.660539 \times 10^{-27} \text{ kg} \\
E_u &= m_u c^2 = 1.660539 \times 10^{-27} \text{ kg} \cdot \left(2.99792 \times 10^8 \text{ m/s}\right)^2 \\
&= 931.494 \text{ MeV}
\end{align*}

Need table of atomic mass numbers: 
http://www.nist.gov/pml/data/comp.cfm
# Atomic Weights and Isotopic Compositions for All Elements

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Relative Atomic Mass</th>
<th>Isotopic Composition</th>
<th>Standard Atomic Weight</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H 1</td>
<td>1.007 825 032 07(10)</td>
<td>0.999 885(70)</td>
<td>1.007 94(7) g,m,r,b,w</td>
</tr>
<tr>
<td></td>
<td>D 2</td>
<td>2.014 101 777 8(4)</td>
<td>0.000 115(70)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T 3</td>
<td>3.016 049 2777(25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>He 3</td>
<td>3.016 029 3191(26)</td>
<td>0.000 001 34(3)</td>
<td>4.002 602(2) g,r,a</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.002 603 254 15(6)</td>
<td>0.999 998 66(3)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Li 6</td>
<td>6.015 122 795(16)</td>
<td>0.0759(4)</td>
<td>6.941(2) g,m,r,c,i</td>
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<tr>
<td></td>
<td>7</td>
<td>7.016 004 55(8)</td>
<td>0.9241(4)</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>U 233</td>
<td>233.039 6352(29)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>234</td>
<td>234.040 9521(20)</td>
<td>0.000 054(5)</td>
<td>238.028 91(3) g,m,c</td>
</tr>
<tr>
<td></td>
<td>235</td>
<td>235.043 9299(20)</td>
<td>0.007 204(6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>236</td>
<td>236.045 5680(20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>238</td>
<td>238.050 7882(20)</td>
<td>0.992 742(10)</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>Np 236</td>
<td>236.046 570(50)</td>
<td></td>
<td>[237]</td>
</tr>
<tr>
<td></td>
<td>237</td>
<td>237.048 1734(20)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Neutron

1.008655 u
Example:

\[ _1^1\text{H} + _1^2\text{H} \rightarrow _2^3\text{He} + \gamma \]

Energy available to \( \gamma \) ray:

\[
\left[ m(_1^1\text{H}) + m(_1^2\text{H}) - m(_2^3\text{He}) \right] c^2 = \left[ 1.007825 + 2.014102 - 3.016029 \right] \cdot 931.494 \text{MeV}
\]

\[
= 0.005878 \cdot 931.494 \text{MeV} = 5.475 \text{ MeV}
\]

In principle, nuclear energy is available in both fission and fusion reactions.
Fusion reactions

Summary of reactions in the sun:

\[ {^1\text{H}} + {^1\text{H}} \rightarrow {^2\text{H}} + e^+ + \nu \quad (Q = 0.42 \text{ MeV}) \]
\[ e^+ + e^- \rightarrow \gamma + \gamma \quad (Q = 1.02 \text{ MeV}) \]

\[ {^2\text{H}} + {^1\text{H}} \rightarrow {^3\text{He}} + \gamma \quad (Q = 5.49 \text{ MeV}) \]

Total energy release for each event: 26.7 MeV

This process has been occurring for \( \approx 5 \times 10^9 \) years and is expected to last for \( 10^9 \) more years.
Fusion reactions which might be possible on earth:

\[ {^2}_1\text{H} + {^2}_1\text{H} \rightarrow {^3}_2\text{He} + \text{n} \quad (Q=3.27 \text{ MeV}) \]

\[ {^2}_1\text{H} + {^2}_1\text{H} \rightarrow {^3}_2\text{He} + {^1}_1\text{H} \quad (Q=4.03 \text{ MeV}) \]

\[ {^2}_1\text{H} + {^3}_1\text{H} \rightarrow {^4}_2\text{He} + \text{n} \quad (Q=17.59 \text{ MeV}) \]

\[ \text{n} + {^6}_3\text{Li} \rightarrow {^4}_2\text{He} + {^3}_1\text{H} \quad (Q=4.78 \text{ MeV}) \]

Technological challenge: How to control the energetic reactants to effect net energy gain???

- Magnetic confinement – “tokamak” design
- Laser confinement – high powered lasers focused on fuel put into solid form
Energy enters the reactor by means of a laser pulse or other method.

Energy is carried to the heat exchanger by means of a mixture of molten lithium and tritium.
<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission</td>
<td>Technology has been demonstrated</td>
<td>Nuclear waste</td>
</tr>
<tr>
<td>Fusion</td>
<td>Less dangerous nuclear waste</td>
<td>Technology has not yet been demonstrated</td>
</tr>
</tbody>
</table>
Nuclear power plant in France (photo from textbook)
Fission: Some history –

1932 James Chadwick (England) discovered neutron

Enrico Fermi (Italy) discovered that neutrons could be absorbed by nuclei to form new elements

Lise Meitner, Otto Hahn, Fritz Strassmann, Otto Frisch (Germany) discovered fission of U

Example:

\[ n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2n \]

\[ ^{140}_{54}Xe \rightarrow ^{140}_{55}Cs \rightarrow ^{140}_{56}Ba \rightarrow ^{140}_{57}La \rightarrow ^{140}_{58}Ce \]

\((14s) \quad (64s) \quad (13d) \quad (40h) \quad (\text{stable})\)

\[ ^{94}_{38}Sr \rightarrow ^{94}_{39}Y \rightarrow ^{94}_{40}Zr \]

\((75s) \quad (19\text{min}) \quad (\text{stable})\)

Q\approx200 \text{ MeV}
Other decay products for $n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$
Mechanism for power plant

Heat $\rightarrow$ mechanical energy $\rightarrow$ generator $\rightarrow$ electricity

Heat sources:

Chemical burning: oxygen + coal, oil, etc.

Nuclear burning: $n + _{92}^{235}U$

Neutrons generated in the reaction are also used to fuel the reaction
One incoming neutron causes a fission event in a $^{235}\text{U}$ nucleus.

Several neutrons from the initial fission event cause fission in additional $^{235}\text{U}$ nuclei.

The number of neutrons and the number of fission events grow rapidly.
Model for nuclear reactor – accounting for 1000 neutrons

Thermal neutron leakage
1050 thermal neutrons
1170 thermal neutrons
1300 fast neutrons

Thermal captures
Resonance captures

(water)

Moderator

1000 thermal neutrons

Fast neutron leakage

1370 fast neutrons

235U fuel

1330 fast neutrons

238U

Fast fissions

Thermal fissions
Simplified model of nuclear power plant

- Reactor core
- Reactor pressure vessel
- Water (cool)
- Pump
- Steam (high pressure)
- Steam generator
- Water (hot)
- Primary loop
- Secondary loop
- Electric power
- Turbine
- Electric generator
- Steam (low pressure)
- Steam condenser
- Coolant in
- Coolant out
Thermal power release by radioactive wastes from one year’s operation of a typical large nuclear power plant
Generations of Nuclear Energy

Generation I
- Early Prototypes
  - Shippingport
  - Dresden
  - Magnox

Generation II
- Commercial Power
  - PWRs
  - BWRs
  - CANDU

Generation III
- Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600

Generation III+
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV
- Revolutionary Designs
  - Safe
  - Sustainable
  - Economical
  - Proliferation Resistant and Physically Secure

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

http://www.gen-4.org/Technology/evolution.htm
# Overview of the Generation IV Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Neutron Spectrum</th>
<th>Fuel Cycle</th>
<th>Size (MWe)</th>
<th>Applications</th>
<th>R&amp;D Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercritical-Water Reactor (SCWR)</td>
<td>Thermal, Fast</td>
<td>Open, Closed</td>
<td>1500</td>
<td>Electricity</td>
<td>Materials, Thermal-hydraulics</td>
</tr>
<tr>
<td>Gas-Cooled Fast Reactor (GFR)</td>
<td>Fast</td>
<td>Closed</td>
<td>200-1200</td>
<td>Electricity, Hydrogen, Actinide Management</td>
<td>Fuels, Materials, Thermal-hydraulics</td>
</tr>
<tr>
<td>Lead-Cooled Fast Reactor (LFR)</td>
<td>Fast</td>
<td>Closed</td>
<td>50-150, 300-600, 1200</td>
<td>Electricity, Hydrogen Production</td>
<td>Fuels, Materials</td>
</tr>
<tr>
<td>Sodium Cooled Fast Reactor (SFR)</td>
<td>Fast</td>
<td>Closed</td>
<td>300-1500</td>
<td>Electricity, Actinide Management</td>
<td>Advanced recycle options, Fuels</td>
</tr>
<tr>
<td>Molten Salt Reactor (MSR)</td>
<td>Epithermal</td>
<td>Closed</td>
<td>1000</td>
<td>Electricity, Hydrogen Production, Actinide Management</td>
<td>Fuel treatment, Materials, Reliability</td>
</tr>
</tbody>
</table>

http://www.gen-4.org/Technology/systems/index.htm
Molten Salt Reactor (MSR)

Characteristics
- Fuel is liquid fluorides of U and Pu with Li, Be, Na and other fluorides
- 700–800°C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

Benefits
- Waste minimization
- Avoids fuel development
- Proliferation resistance through low fissile material inventory

http://www.gen-4.org/Technology/systems/index.htm
Other uses of nuclear radiation

- Food irradiation:

http://www.epa.gov/rpdweb00/sources/food_irrad.html

Food irradiation is a technology for controlling spoilage and eliminating food-borne pathogens, such as salmonella. The result is similar to conventional pasteurization and is often called "cold pasteurization" or "irradiation pasteurization." Like pasteurization, irradiation kills bacteria and other pathogens, that could otherwise result in spoilage or food poisoning. The fundamental difference between the two methods is the source of the energy they rely on to destroy the microbes. While conventional pasteurization relies on heat, irradiation relies on the energy of ionizing radiation. The FDA emphasizes that no preservation method is a substitute for safe food handling procedures.
http://www.epa.gov/rpdweb00/sources/food_irrad.html

What is the radiation dose to the food?

Radiation doses vary for different foodstuffs. For the vast majority of foods, the limit is less than 10 kiloGray. The U.S. Food and Drug Administration (FDA) sets radiation dose limits for specific food types:

<table>
<thead>
<tr>
<th>Food Type</th>
<th>Dose (kiloGrays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fruit</td>
<td>1</td>
</tr>
<tr>
<td>poultry</td>
<td>3</td>
</tr>
<tr>
<td>spices, seasonings</td>
<td>30</td>
</tr>
</tbody>
</table>

The dose limit for spices and seasonings is higher, because they are consumed in very small quantities.

How does irradiation kill bacteria?

When ionizing radiation strikes bacteria and other microbes, its high energy breaks chemical bonds in molecules that are vital for cell growth and integrity. As a result, the microbes die, or can no longer multiply causing illness or spoilage.

Breaking chemical bonds with radiation is known as radiolysis.
Measures of radiation:

**TABLE 45.1**  \(*RBE\) Factors for Several Types of Radiation

<table>
<thead>
<tr>
<th>Radiation</th>
<th>RBE Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays and gamma rays</td>
<td>1.0</td>
</tr>
<tr>
<td>Beta particles</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Alpha particles</td>
<td>10–20</td>
</tr>
<tr>
<td>Thermal neutrons</td>
<td>4–5</td>
</tr>
<tr>
<td>Fast neutrons and protons</td>
<td>10</td>
</tr>
<tr>
<td>Heavy ions</td>
<td>20</td>
</tr>
</tbody>
</table>

*Note:* RBE = relative biological effectiveness.

**TABLE 45.2**  Units for Radiation Dosage

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI Unit</th>
<th>Symbol</th>
<th>Relations to Other SI Units</th>
<th>Older Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed dose</td>
<td>gray</td>
<td>Gy</td>
<td>= 1 J/kg</td>
<td>rad</td>
<td>1 Gy = 100 rad</td>
</tr>
<tr>
<td>Dose equivalent</td>
<td>sievert</td>
<td>Sv</td>
<td>= 1 J/kg</td>
<td>rem</td>
<td>1 Sv = 100 rem</td>
</tr>
</tbody>
</table>
Fundamental processes of radiation

- Nuclear reactions
- Move nuclei of atoms in materials (Ex: neutrons can cause crystal defects)
- Produce many electronic excitations → excited and/or charged species undergo uncontrolled chemical reactions (Ex. Electrons and γ-rays are examples of effective “ionizing” radiation); the greater the energy the greater the potential radiation damage
- The least massive reaction products carry the most energy and are responsible for the most radiation effects
Energy analysis of a simple reaction:
\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_{2}\text{He} \]

Before decay:
- \( K_{\text{Ra}} = 0 \)
- \( \vec{p}_{\text{Ra}} = 0 \)

Q = 4.87 MeV

After decay:
- \( K_{\text{Rn}} \)
- \( \vec{p}_{\text{Rn}} \)
- \( K_{\alpha} \)
- \( \vec{p}_{\alpha} \)
Energy analysis of a simple reaction:

\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_{2}\text{He} \]

\[ Q = 4.87 \text{ MeV} \]

\[ \mathbf{p}_{\text{Rn}} = -\mathbf{p}_{\text{He}} = \mathbf{p} \]

\[ Q = \frac{p_{\text{Rn}}^2}{2m_{\text{Rn}}} + \frac{p_{\text{He}}^2}{2m_{\text{He}}} \approx \frac{p^2}{2m_u} \left( \frac{1}{222} + \frac{1}{4} \right) \]

\[ E_{\text{He}} = \frac{p_{\text{He}}^2}{2m_{\text{He}}} = \frac{1/4}{1/222 + 1/4} Q = 0.98 \cdot Q = 4.8 \text{ MeV} \]
Other uses of nuclear radiation
  • Carbon dating

Living organisms have a ratio of $^{14}\text{C} / ^{12}\text{C}$ of $1.3 \times 10^{-12}$ reflecting normal atmospheric processes. When an organism dies, the ratio is reduced due to the 5730 yr half-life of $^{14}\text{C}$.

Example from your textbook: A piece of charcoal containing 25 g of carbon is found to have an activity of 4.167 decays/s. How long ago did the tree live that produced this charcoal?

Decay rate when tree was alive for 25 g of C:

$$\frac{dN}{dt} = \lambda N_0$$
$$\lambda = \frac{\ln(2)}{5730 \text{ yr} \cdot 3.1556 \times 10^7 \text{ s/yr}} = 3.83 \times 10^{-12} \text{ /s}$$

$$N_0 = \frac{25}{12} \cdot 6.022 \times 10^{23} \cdot 1.3 \times 10^{-12} = 1.631 \times 10^{12} \quad \lambda N_0 = 6.25 \text{ decays/s}$$
Other uses of nuclear radiation

- Carbon dating -- continued

Decay rate when tree was alive for 25 g of C:

\[ \frac{dN}{dt} \bigg|_0 = \lambda N_0 \quad \lambda = \frac{\ln 2}{5730 \text{ yr} \cdot 3.1556 \times 10^7 \text{ s/yr}} = 3.83 \times 10^{-12} /\text{s} \]

\[ N_0 = \frac{25}{12} \cdot 6.022 \times 10^{23} \cdot 1.3 \times 10^{-12} = 1.631 \times 10^{12} \quad \lambda N_0 = 6.25 \text{ decays/s} \]

Current decay rate:

\[ \frac{dN}{dt} = \lambda N_0 \ e^{-\lambda t} = 4.1667 \text{ decays/s} \]

\[ \frac{dN}{dt} \bigg|_0 = e^{\lambda t} \quad \Rightarrow \quad t = \frac{1}{3.83 \times 10^{-12} /\text{s}} \ln \left( \frac{6.25}{4.17} \right) = 1.06 \times 10^{11} \text{ s} = 3400 \text{ yr} \]