A Short Course in Energy Conversion
Session 7

Jim Rauf
• Radiation
• Light
• Incandescent light
• Fluorescent light
• LED light
• Radioactivity
• Nuclear Fission
• Nuclear Fusion
Radiation

- **Radiation** is a process in which energetic particles or waves travel through a medium or space.
- The particles or waves radiate i.e., travel outward in all directions, from a source.
- Two types of radiation are: **ionizing** and **non-ionizing** radiation.
- Ionizing radiation is far more harmful to living organisms per unit of energy deposited than non-ionizing radiation, since the ions that are produced by ionizing radiation, even at low radiation powers, have the potential to cause DNA damage.
- Most non-ionizing radiation is harmful to organisms only in proportion to the thermal energy deposited.
- **Ultraviolet** radiation in some aspects occupies a middle ground, in having some features of both ionizing and non-ionizing radiation.
- It is non-ionizing but it can do damage to many molecules in biological systems than is accounted for by heating effects (e.g. sunburn).
- Ultraviolet radiation’s power to alter chemical bonds, even without having quite enough energy to ionize atoms is the reason...
Radiation

• **Electromagnetic radiation** is created when an atom absorbs energy
• The absorbed energy causes one or more electrons to change their locale within the atom—move to a higher energy state
• When the electron returns to its original energy state, an electromagnetic wave is produced
• Depending on the kind of atom and the amount of energy, this electromagnetic radiation can take the form of heat (infrared radiation), light, ultraviolet, or other electromagnetic waves

• There are several ways of causing atoms to absorb energy
• One way is to excite the atoms with electrical energy
  – Heating filaments in incandescent bulbs
  – Fluorescent lights
Radiation

How Atoms Emit Light

1. A collision with a moving particle excites the atom.
2. This causes an electron to jump to a higher energy level.
3. The electron falls back to its original energy level, releasing the extra energy in the form of a light photon.
Radiation-- Maxwell’s Equations

**Gauss’s law**
- There are two types of charge, positive and negative, just as there are two types of real numbers, positive and negative
- Electric field lines diverge from positive charge and converge on negative charge

**No one’s law**
- There is no magnetic monopole
- Magnetic field lines neither converge nor diverge (have no beginning or end)

**Faraday’s law**
- Electric field lines don’t curl
- … except when the magnetic field changes

**Ampère’s law**
- Magnetic field lines curl around electric current
- … and also curl when the electric field changes.

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]

\[ \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} \]
Thermal Radiation

- **Thermal radiation** is electromagnetic radiation generated by the thermal motion of charged particles in matter.
- All matter with a temperature above absolute zero emits thermal radiation.
- The atoms or molecules have kinetic energies which are changing, and these changes result in charge-accelerations.
- This motion of charges produces electromagnetic radiation.
- The spectrum of the radiation reflects the wide range of energies and accelerations of the charges in any piece of matter at even a single temperature.

- Examples of thermal radiation:
  - Visible light and infrared light emitted by incandescent light bulbs.
  - Infrared radiation emitted by animals.
  - Cosmic microwave background radiation.
- Sunlight is thermal radiation generated by the sun’s fusion reactions.
- The earth emits thermal radiation, but at a much lower intensity and at a different part of the spectrum –infrared rather than visible- because it is much cooler.
- The Earth's absorption of solar radiation, followed by its outgoing thermal radiation are the two most important processes that determine the temperature and climate of the Earth.
- In engineering, thermal radiation is considered one of the fundamental methods of heat transfer.
Radiation

\[ P = \sigma A e T^4 \]

- \( P \)—power radiated in watts
- \( \sigma \)—Stephan-Boltzmann constant
- \( A \)—surface area
- \( e \)—Emissivity of surface
- \( T \)—Temperature of surface

\[ I = \frac{P}{A} \]
Radio waves

• **Radio waves** are a type of electromagnetic radiation with wavelengths longer than infrared light

• Radio waves have frequencies from 300 GHz to as low as 3 Hz, and corresponding wavelengths from 1 millimeter to 100 kilometers

• Like all electromagnetic radiation, they travel at the speed of light

• Naturally occurring radio waves are made by lightning and by astronomical objects-radio telescopes observe

• Different frequencies of radio waves have different propagation characteristics in the Earth's atmosphere:
  
  – Long waves may cover a part of the Earth very consistently
  
  – Shorter waves can reflect off the ionosphere and travel around the world
  
  – Much shorter wavelengths bend or reflect very little and travel on a line of sight

• Radio waves are generated by varying motion of electrical charges
Radio waves

- **Amplitude Modulation** - Both AM radio stations and the picture part of a TV signal use amplitude modulation to encode information.
  - In amplitude modulation, the amplitude of the sine wave (its peak-to-peak voltage) changes. So, for example, the sine wave produced by a person's voice is overlaid onto the transmitter's sine wave to vary its amplitude.

- **Frequency Modulation** - FM radio stations and hundreds of other wireless technologies (including the sound portion of a TV signal, cordless phones, cell phones, etc.) use frequency modulation.
  - The advantage to FM is that it is largely immune to static. In FM, the transmitter's sine wave frequency changes very slightly based on the information signal.

- Once you modulate a sine wave with information, you can transmit the information
Visible light is electromagnetic radiation that is visible to the human eye.

Visible light has a wavelength in a range from about 380 nanometers to about 740 nm.

Speed of light (and other forms of EMR) in a vacuum is about 300,000,000 meters per second or 186,000 miles per second.

- A fundamental constant of nature, \( c \)

Light and all types of EMR is emitted and absorbed in tiny "packets" called photons, and exhibits properties of both waves and particles.

\[ \lambda f = c \]

- \( \lambda \) = Wavelength of light (centimeters)
- \( f \) = Frequency of light (Hertz=cycles/sec)
- \( c \) = Speed of light (3\( \times \)10\(^{10} \)) centimeters/second)

This energy is carried in smalll packs called photons. The energy per photon of an electromagnetic wave can be calculated from the Planck–Einstein equation:

\[ E = hf \]

where \( E \) is the energy, \( h \) is Planck’s constant, and \( f \) is frequency.

\[ h = 6.626 \times 10^{-34} \text{ joule-second} \]
Electromagnetic Spectrum
Incandescent Light Bulb

- The **incandescent light bulb** produces light by heating a filament wire to a high temperature until it glows.
- The heat energy goes into electrons of the filament’s tungsten atoms.
- The energy pushes the electrons farther away from the nucleus of the atoms.
- As the electrons fall back, they give off **photons**, little bits of light.
- The hot filament is protected from oxidation in the air with a glass enclosure that is filled with inert gas or evacuated.

- Incandescent lamps are nearly pure **resistive** loads.
- Incandescent light bulbs are sold based on the electrical power consumed in watts.
- The **power** depends mainly on the **resistance** of the filament, which in turn depends mainly on the filament's length, thickness, and material.

\[ P = VI \quad P = I^2R \]

- The light output is measured in **lumens**
  - A measure of the total "amount" of visible light emitted by a source.
Incandescent Light Bulb

1-Outline of Glass bulb
2-Low pressure inert gas (argon, nitrogen, krypton, xenon)
3-Tungsten filament
4-Contact wire (goes out of stem)
5-Contact wire (goes into stem)
6-Support wires (one end embedded in stem; conduct no current)
7-Stem (glass mount)
8-Contact wire (goes out of stem)
9-Cap (sleeve)
10-Insulation
11-Electrical contact
Fluorescent Light

• A **fluorescent lamp** is a gas discharge lamp that uses electricity to excite mercury vapor

• The excited mercury atoms produce short-wave ultra violet light that then causes a phosphor in the lamp tube to fluoresce, producing visible light

• The electrons in the mercury vapor are displaced by electrical energy directly not be thermal energy so fluorescent lamps operate at lower temperatures than do incandescent bulbs

• A fluorescent lamp converts electrical power into useful light more efficiently than an incandescent lamp

• Fluorescence occurs when an atom (or molecule) absorbs energy from some source (like a photon of light, or a collision with another atom) and then releases that energy in the form of light in two or more consecutive steps

• In the fluorescent bulb, high-energy ultraviolet light from within the tube is absorbed by the phosphor, which then re-radiates the energy by emitting two or three lower-energy light waves

• Since the visible spectrum to which our eye is sensitive is at a lower energy than is ultraviolet (uv) radiation, we can use the fluorescing phosphor as a light source
Fluorescent Light

- Fluorescent lighting has a considerable advantage in energy efficiency over incandescent lighting.
- Fluorescent lights can produce 50-100 lumens/watt compared to about 15 lumens/watt for incandescent bulbs.
LED Light

- **A light-emitting diode (LED)** is a *semiconductor* light source
- Introduced in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible, UV and IR spectrum
- When an LED is switched on, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons
- This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor

- LEDs present many advantages over incandescent light sources:
  - Lower energy consumption
  - Longer operating lifetimes
  - Improved robustness
  - Smaller size

- Failure is often due to overheating
  - Inadequate heat sink
  - Loose contact allows arcing-current surges
Atoms

- An atom a fundamental piece of matter
- All the elements in the universe are made of atoms
- An atom itself is made up of three particles called subatomic particles: protons, neutrons, and electrons
- The protons and the neutrons make up the center of the atom called the nucleus and the electrons "orbit" around the nucleus in a small “cloud”
- The electrons carry a negative charge and the protons carry a positive charge

- In a normal (neutral) atom the number of protons and the number of electrons are equal
- Often, but not always, the number of neutrons is the same, too
- The negative electrons are attracted to the positive nucleus by the electromagnetic force
Atoms

Atoms are mostly empty space
Nucleus

- The **nucleus** is the very dense region consisting of protons and neutrons at the center of an atom.
- The protons and neutrons are bound together by the **strong nuclear force**.
- The number of protons is called the **atomic number** and determines the chemical element.
- **Nuclei** of a given element (same atomic number) may have different numbers of neutrons and are then said to be different **isotopes** of the element.
  - Isotopes have same chemical properties.

- The diameter of the nucleus is about 23,000 (uranium) to about 145,000 (hydrogen) smaller than the diameter of the atom.

- Almost all of the mass of an atom is located in the nucleus, with a very small contribution from the electrons.
Radioactivity

- **Radioactivity** refers to the particles which are emitted from nuclei as a result of nuclear instability.
- Because the nucleus experiences the two strongest forces in nature, the *strong nuclear force* and the *weak nuclear force* it should not be surprising that there are many nuclear isotopes which are unstable and emit some kind of radiation.
- The most common types of radiation are:
  - **Alpha**- alpha particle is a nucleus of the element helium
  - **Beta**- high-energy, high-speed electrons or positrons
  - **Gamma**- electromagnetic radiation of high frequency and therefore energy
- **Radioactive decay** rates are normally stated in terms of their half lives, and the half-life of a given nuclear species is related to its radiation risk.
- The different types of radioactivity lead to different decay paths which transmute the nuclei into other chemical elements.
- Examining the amounts of the decay products makes possible radioactive dating –
  - C14
  - K40
  - Ar40
Radioactivity

- Products of radioactivity called **alpha**, **beta**, and **gamma** behave differently when subjected to electrical and magnetic fields.
Nuclear Fission

• If a massive nucleus like uranium-235 breaks apart (fissions), then there will be a net yield of energy because the sum of the masses of the fragments will be less than the mass of the uranium nucleus

$$E = mc^2$$

• The fission of U-235 in reactors is triggered by the absorption of a low energy neutron, often termed a "slow neutron" or a "thermal neutron"

• Higher energy neutrons must be slowed by a *moderator* in order to produce fission

• Each absorbed thermal neutron releases ~ 2.4 neutrons

• A single fission event can yield over 200 million times the energy of the neutron which triggered it

• Other fissionable elements which can be induced to fission by slow neutrons are plutonium-239, uranium-233, and thorium-232

• Plutonium-239 can be produced by “breeding” it from uranium-238
Uranium Fuel

• Natural uranium is composed of:
  – 0.72% U-235 (fissionable isotope)
  – 99.27% U-238
  – 0.0055% U-234.

• The 0.72% U-235 is not sufficient to produce a self-sustaining critical chain reaction in U.S. style light water reactors.

• For light-water reactors, the fuel must be enriched to 2.5-3.5% U-235.

• Uranium is found as uranium oxide which when purified has a rich yellow color and is called “yellowcake.”

• After reduction, the uranium must go through an isotope enrichment process.

• Even with the necessity of enrichment, it still takes only about 3 kg of natural uranium to supply the energy needs of one American for a year.
Fission Reactor

- **Fuel** - fissile material
  - U235, P239, U233, Th232
- **Moderator** - slows neutrons to thermal neutrons
  - Water
- **Control rods** - absorbs neutrons
  - Control nuclear reaction by absorbing neutrons
- **Thermal medium** - carry away heat from reaction
  - Water
  - Direct steam generation - BWR
  - Heat exchanger to steam generator - PWR
- **Steam turbine** - convert thermal energy of stem to mechanical energy
  - Drives generator
- **Generator** - convert mechanical energy to electrical energy
- **The nuclear reactor takes the place of the boiler in a gas or coal fired powerplant**
- **It generates the thermal energy used to create steam**
Fission Reactor

- **Boiling Water Reactor (BWR)** - only one coolant loop is present
- The water is allowed to boil in the reactor
- The steam is generated as it heads out of the reactor and then flows through the steam turbine
- One major disadvantage of a BWR is that, the coolant water comes in direct contact with fuel rods as well as the turbine
- So, there is a possibility that radioactive material could be placed on the turbine
Fission Reactor

- **Pressurized Water Reactor (PWR)** - uses regular water as coolant
- The coolant (water) is kept at very high pressure so that it does not boil
- The heated water is transferred through heat exchanger where water from secondary coolant loop is converted into steam
- Thus the secondary loop is completely free from radioactive stuff
- In a PWR, the coolant water itself acts as a moderator
- Due to these advantages, pressurized water reactors are most commonly used
### U.S Electric Power

- **Total Generation 2018**: 4178 Terrawatt Hours (TWH)

<table>
<thead>
<tr>
<th>Source</th>
<th>TWH</th>
<th>Percentage</th>
</tr>
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<tbody>
<tr>
<td>Gas fired</td>
<td>1468</td>
<td>35%</td>
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<tr>
<td>Coal Fired</td>
<td>1146</td>
<td>27%</td>
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<tr>
<td>Nuclear</td>
<td>807</td>
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<tr>
<td>Hydroelectric</td>
<td>292</td>
<td>6.9%</td>
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<td>Wind</td>
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<td>Solar</td>
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<td>Biomass</td>
<td>63</td>
<td>1.5%</td>
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<tr>
<td>Geothermal+Other</td>
<td>60</td>
<td>1.4%</td>
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Energy According To Einstein

• Mass can be converted into energy with a yield governed by:

\[ E = mc^2 \]

where \( c \) = the speed of light.

• The yield from converting one kilogram is:

\[ E = (1 \text{ kg})(3 \times 10^8 \text{ m/s})^2 = 9 \times 10^{16} \text{ Joules} \]

• The energy consumption for one U.S. citizen for one year is about

\[ 1 \text{ US Year}^* = 5 \times 10^{11} \text{ Joules} \]

• One kilogram of mass conversion could supply the needs of about 180,000 U.S. citizens for one year, or the needs of a city of one million for over two months.
Fusion

• In fusion reactions two light atomic nuclei fuse together to form a heavier nucleus
• In doing so they release a large amount of energy arising from the binding energy due to the strong nuclear force which is manifested as an increase in temperature of the reactants
• Basis for sun’s energy release

Diagram of the Deuterium -Tritium reaction
Fusion

- The leading designs for controlled fusion research:
  - Magnetic confinement (tokamak design) of plasma
  - The Joint European Torus (JET) produced a peak of 16.1 megawatts of fusion power (65% of input power), with fusion power of over 10 MW sustained for over 0.5 sec
  - Inertial (laser) confinement of plasma
- Heat from the fusion reactions would be used to operate a steam turbine to drive electrical generator
- Controlled fusion has proven to be extremely difficult
- The “pay off” is really great
### Relative Energy Releases

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<th>Chemical</th>
<th>Fission</th>
<th>Fusion</th>
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<tbody>
<tr>
<td><strong>Sample Reaction</strong></td>
<td>C + O₂ -&gt; CO₂</td>
<td>n + U-235 -&gt; Ba-143 + Kr-91 + 2 n</td>
<td>H-2 + H-3 -&gt; He-4 + n</td>
</tr>
<tr>
<td><strong>Typical Inputs</strong></td>
<td>Bituminous Coal</td>
<td>UO₂ (3% U-235 + 97% U-238)</td>
<td>Deuterium &amp; Lithium</td>
</tr>
<tr>
<td><strong>(to Power Plant)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Typical Reaction</strong></td>
<td>700</td>
<td>1000</td>
<td>10⁸</td>
</tr>
<tr>
<td><strong>Temperature (K)</strong></td>
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<tr>
<td><strong>Energy Released</strong></td>
<td>3.3 x 10⁷</td>
<td>2.1 x 10¹²</td>
<td>3.4 x 10¹⁴</td>
</tr>
<tr>
<td><strong>per kg of Fuel</strong></td>
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"Here's where you made your mistake."
Next Session

- Telephone
- Sound
- Microphone
- Speaker
- Television
- Radio
- Microwave oven
- Refrigeration/Air conditioning/Heat Pump
- Review/Summary
- Everyday energy conversion