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CAI 335 : SOLAR AND WIND ENERGY SYSTEMS

UNIT 5

ALTERNATE ENERGY SOURCES

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Nuclear Energy: Reactions, Fusion, and Fission

Nuclear energy is the energy that is released during nuclear reactions, either through **fission** or **fusion**. This energy is produced from the nucleus (core) of atoms, which contain a large amount of energy due to the forces binding protons and neutrons together. Nuclear reactions involve changes in the nucleus of an atom, and these reactions release energy far greater than chemical reactions.

There are two primary types of nuclear reactions that harness nuclear energy:

1. **Nuclear Fission**
2. **Nuclear Fusion**

Let's explore both in detail.

1. Nuclear Fission

Overview:

Nuclear fission is the process by which the nucleus of an atom is split into two smaller nuclei, accompanied by the release of a large amount of energy. Fission occurs when a heavy nucleus, such as uranium-235 or plutonium-239, absorbs a neutron and becomes unstable, causing it to split into smaller nuclei (called fission products).

How It Works:

- When a **nucleus of a heavy isotope** (such as uranium-235 or plutonium-239) absorbs a **neutron**, it becomes highly unstable.
- This instability causes the nucleus to split, resulting in the formation of **two smaller nuclei** (fission fragments), **several free neutrons**, and a release of **energy**.
- The energy released comes in the form of **kinetic energy** of the fission fragments, **gamma radiation**, and **neutrinos**.
- The **free neutrons** released can go on to initiate further fission reactions in a process known as a **chain reaction**.
- This chain reaction is what makes fission useful for both energy generation and nuclear weapons.

Fission Products:

- The products of nuclear fission are typically smaller nuclei known as **fission fragments**. These fragments are often radioactive and decay over time, emitting radiation.
- Common fission products include isotopes such as **cesium-137** and **strontium-90**, which are highly radioactive and need to be managed carefully.

Energy Release:

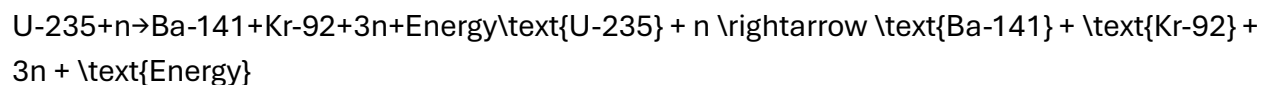
- The energy released in fission comes primarily from the **conversion of mass into energy** (as described by Einstein's famous equation $E=mc^2$).
- Even though the mass of the fission products is slightly less than the original mass of the nucleus and neutron, this mass difference is converted into energy, which is released as heat.
- A single fission event of uranium-235 releases about **200 million electron volts (MeV)** of energy, most of which is in the form of heat, which can be used to produce steam and drive turbines in nuclear power plants.

Applications:

- **Nuclear Power Plants:** Fission is used in nuclear reactors to generate electricity. The heat produced from fission reactions is used to produce steam, which drives turbines to generate electrical power.
- **Nuclear Weapons:** Fission is also used in the design of nuclear weapons, where an uncontrolled chain reaction leads to an explosive release of energy.
- **Research and Medicine:** Some medical devices, such as cancer treatments, also rely on nuclear fission for producing certain radioactive isotopes.

Example of Fission Reaction:

A typical fission reaction involving uranium-235 might look like this:



Where:

- U-235 (uranium-235) absorbs a neutron (n) and splits into two smaller nuclei (Ba-141 and Kr-92).
- This reaction releases 3 more neutrons and a significant amount of energy in the form of heat and radiation.

2. Nuclear Fusion

Overview:

Nuclear fusion is the process by which two light atomic nuclei, typically isotopes of hydrogen, combine to form a heavier nucleus, releasing a tremendous amount of energy. Fusion is the process that powers the sun and other stars, and it has the potential to provide a nearly unlimited and clean source of energy.

How It Works:

- In fusion reactions, two **light atomic nuclei**, usually isotopes of hydrogen such as **deuterium (D)** and **tritium (T)**, collide under extreme temperature and pressure, overcoming their natural repulsion (due to the positive charge of their protons).
- When the nuclei fuse, they form a heavier nucleus, such as **helium-4 (He-4)**, and release a significant amount of energy.
- The energy comes from the **mass difference** between the reactants and products, which is converted into energy as per Einstein's equation $E=mc^2$.

Fusion Reaction:

The most common fusion reaction for energy production is:

$D + T \rightarrow He-4 + n + 17.6 \text{ MeV of energy}$

Where:

- **D** is deuterium (hydrogen-2) and **T** is tritium (hydrogen-3).
- The products are a **helium nucleus (He-4)**, a **neutron (n)**, and the release of **17.6 MeV** (million electron volts) of energy.

Challenges in Achieving Fusion:

- **High Temperature:** To overcome the electrostatic repulsion between the positively charged nuclei, the fuel must be heated to extremely high temperatures (millions of degrees Celsius). This is known as the **plasma state**, where electrons are stripped from atoms, and only ions and free electrons exist.
- **Pressure:** High pressure is required to force the nuclei close enough to fuse. In stars, the immense gravitational pressure provides this, but on Earth, it is challenging to replicate these conditions.
- **Containment:** At such high temperatures, the plasma cannot touch the walls of the containment vessel because it would cool down and stop fusing. Magnetic confinement (using a device like a **tokamak**) or inertial confinement (using lasers) is required to keep the plasma stable and contained.

Advantages of Fusion:

- **Clean Energy:** Fusion does not produce harmful greenhouse gases or long-lived radioactive waste. The primary byproducts are **helium** (an inert, non-toxic gas) and **neutrons**, which are far less hazardous than fission products.
- **Abundant Fuel Supply:** The fuel for fusion (deuterium and tritium) is abundant. Deuterium can be extracted from water, and tritium can be produced from lithium, making fusion fuel widely available.

- **Safety:** Fusion reactions do not pose the same risks as fission reactors, such as meltdowns or the spread of radioactive materials. The reaction is self-limiting; if containment is lost, the reaction simply stops.

Current Fusion Research:

Fusion power has not yet been fully achieved in a commercial setting due to the extreme conditions required to sustain the reaction. However, projects like **ITER** (International Thermonuclear Experimental Reactor) in France are working toward creating a controlled and sustained fusion reaction.

- **Tokamaks** and **Stellarators** are the two main types of magnetic confinement fusion devices being developed.

Comparing Nuclear Fission and Fusion

Aspect	Nuclear Fission	Nuclear Fusion
Reaction	Splitting of heavy nuclei (e.g., uranium-235)	Combining of light nuclei (e.g., hydrogen isotopes)
Energy Released	Large amounts of energy, but much less than fusion	Tremendous amounts of energy (greater than fission)
Byproducts	Radioactive fission products (e.g., cesium-137)	Primarily helium (non-radioactive) and neutrons
Fuel	Uranium-235, Plutonium-239	Deuterium (from water) and Tritium (from lithium)
Environmental Impact	Radioactive waste and potential for accidents (e.g., Chernobyl, Fukushima)	No greenhouse gases, less radioactive waste, but challenges in containment
Technology Readiness	Commercially viable (e.g., nuclear power plants)	Still in experimental stage (e.g., ITER, Tokamak)
Safety	Risk of meltdown, nuclear weapons proliferation	No risk of meltdown, reaction self-limiting if containment is lost

Aspect	Nuclear Fission	Nuclear Fusion
Sustainability	Requires careful management of radioactive waste	Very sustainable, as fuel is abundant and clean

Conclusion

Nuclear energy, through **fission** and **fusion**, offers vast potential for generating electricity. **Fission** is currently used in commercial nuclear reactors worldwide, though it comes with significant challenges such as radioactive waste and safety concerns. **Fusion**, on the other hand, promises a cleaner, safer, and virtually limitless source of energy, but it remains an experimental technology due to the extreme conditions required to sustain the reaction. As research continues, particularly in fusion technologies, the future of nuclear energy may shift towards fusion, offering a sustainable and environmentally friendly alternative to current energy production methods.

Hybrid Reactors: Overview and Concept

Hybrid reactors are a class of nuclear reactors that combine traditional nuclear fission with other types of energy generation or fusion. The term "hybrid" generally refers to a reactor system where nuclear fission and another energy source (like fusion, neutron sources, or advanced fuel cycles) work together to enhance the reactor's efficiency, safety, and sustainability.

The most commonly discussed form of hybrid reactors in the context of nuclear energy is the combination of **fission reactors** with **fusion** or **neutron sources** to enhance the performance and reduce the challenges of conventional nuclear energy. However, hybrid reactors can also refer to **nuclear fission reactors** that use advanced fuel cycles or **accelerator-driven reactors** (where particle accelerators drive fission reactions).

Hybrid reactors are primarily seen as a potential solution for future energy systems, aiming to address some of the long-standing issues with nuclear energy, such as nuclear waste, safety, and fuel scarcity. They are an exciting concept because they could potentially utilize fusion's clean energy while benefiting from fission's existing technological infrastructure.

Let's break down hybrid reactors into different categories:

1. Fusion-Fission Hybrid Reactors

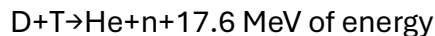
Overview:

A **fusion-fission hybrid reactor** is a concept that combines nuclear fusion and nuclear fission. In these systems, fusion reactions (typically involving deuterium and tritium) are used to generate high-energy neutrons, which then drive fission reactions in a surrounding blanket of fissionable material, like uranium or thorium.

Working Principle:

- **Fusion Reaction:** The core of a fusion-fission hybrid reactor is a **fusion reactor** that generates **high-energy neutrons** by fusing light isotopes like deuterium (D) and tritium (T). These neutrons are produced at an extremely high rate in fusion reactions.

The fusion reaction typically looks like this:



where deuterium (D) and tritium (T) combine to produce helium (He), a neutron (n), and a large amount of energy.

- **Fission Reaction:** The high-energy neutrons produced by the fusion process are used to **initiate fission reactions** in a blanket of fissionable material, such as uranium-238 or thorium. These fission reactions release additional energy and produce more neutrons, which further sustain the fusion-fission cycle.
- **Energy Production:** The fission reactions produce both thermal energy, which can be used to generate electricity, and more neutrons, which can be used to keep the fusion process going. The net effect is a system that produces more energy than the energy needed to initiate the fusion process.

Advantages of Fusion-Fission Hybrid Reactors:

1. **Efficient Energy Production:** Fusion reactions produce large numbers of high-energy neutrons, which can initiate fission reactions in materials that are less efficient in traditional fission reactors (such as uranium-238).
2. **Breeding Fuel:** Fusion-fission reactors could potentially "breed" more fuel than they consume. For example, neutrons from fusion reactions can convert fertile materials (like uranium-238 or thorium-232) into fissile materials (such as plutonium-239 or uranium-233). This process is called **breeding**.
3. **Cleaner Energy:** Fusion produces much less nuclear waste compared to fission alone, and fusion byproducts (mainly helium) are not radioactive.
4. **Reduction in Nuclear Waste:** The fission component could help transmute radioactive isotopes into less harmful ones, reducing the long-term risks associated with nuclear waste disposal.

Challenges:

1. **Fusion Technology:** The most significant hurdle for fusion-fission hybrid reactors is that fusion technology is still in the experimental stage. Achieving the necessary conditions for sustained fusion reactions (extremely high temperature and pressure) remains a huge technical challenge.
2. **Material Durability:** The high-energy neutrons generated in fusion reactions can damage the structural materials used in reactors, leading to wear and tear and making the design of fusion reactors particularly challenging.
3. **Cost:** The cost of developing and maintaining fusion reactors is currently prohibitively high, especially when compared to conventional fission reactors.

Example:

- **IFMIF-DONES** (International Fusion Materials Irradiation Facility and Demonstration of Neutron Source) is an experimental project that investigates fusion-fission hybrid technologies, particularly focused on testing materials for fusion reactors.

2. Accelerator-Driven Reactors (ADR)

Overview:

Accelerator-driven reactors (ADR) are another form of hybrid reactors that combine nuclear fission with an accelerator-based particle source, such as a proton accelerator, to produce neutrons for fission reactions. These reactors use an accelerator to generate high-energy particles, which interact with a target (usually a heavy metal) to produce neutrons. These neutrons then initiate fission reactions in a surrounding fuel.

How ADR Works:

- **Proton Accelerator:** In an ADR, a proton accelerator generates protons that are accelerated to high energies.
- **Neutron Production:** These high-energy protons then strike a **target material** (typically **bismuth- or mercury-based liquid targets**), producing neutrons through a process called **spallation**.
- **Fission Fuel:** The neutrons generated by the accelerator then induce fission reactions in a **nuclear fuel** like uranium-235 or thorium-232, thereby producing energy. The fission process is similar to that in conventional nuclear reactors.

Advantages of Accelerator-Driven Reactors:

1. **Waste Transmutation:** ADRs can potentially be used for **nuclear waste transmutation**, where the neutrons produced can be used to reduce the long-lived isotopes in nuclear waste, transforming them into more stable, shorter-lived isotopes.

2. **Enhanced Safety:** Accelerator-driven reactors are often considered to be **safer** than conventional reactors because the neutron source (accelerator) can be turned off, halting the fission process immediately. This is a significant safety advantage.
3. **Reduced Risk of Proliferation:** Because the fission reactions are initiated by an external source of neutrons rather than a chain reaction, there is less risk of nuclear proliferation, which involves the use of fissile materials like uranium-235 or plutonium-239.

Challenges of ADR:

1. **Technical Complexity:** Accelerator-driven reactors are more technically complex compared to conventional reactors, and the technology is still in the experimental stage.
2. **High Cost:** Particle accelerators require substantial energy to operate, and this makes the cost of running an accelerator-driven reactor higher than that of conventional reactors.

Example:

- **The MYRRHA Project** in Belgium is a leading example of an accelerator-driven system under development. It is intended to be a flexible irradiation facility that can be used for research and the development of nuclear waste transmutation technologies.

3. Hybrid Reactors with Advanced Fuel Cycles

Overview:

Some hybrid reactors use advanced **fuel cycles** to improve the efficiency and sustainability of nuclear fission. For example, a **thorium-fuelled hybrid reactor** can combine thorium fuel (which is fertile) with a small amount of fissile material (like uranium-235 or plutonium-239) to initiate fission reactions.

These reactors can potentially be used to breed fuel in addition to producing energy. The thorium-232 isotope absorbs a neutron and transforms into uranium-233, which is fissile and can sustain further reactions. This system could be used to reduce nuclear waste and provide more efficient energy production.

Advantages of Advanced Fuel Cycles in Hybrid Reactors:

1. **Breeding Fuel:** The use of thorium or other fertile materials can "breed" more fuel than is consumed, offering a more sustainable fuel cycle.
2. **Reduced Radioactive Waste:** Some advanced fuel cycles, such as those using thorium, can produce less long-lived nuclear waste compared to uranium-based reactors.
3. **Safety:** Thorium-based reactors are inherently safer because they are less likely to experience a meltdown compared to uranium-based reactors.

Challenges:

1. **Fuel Availability:** Although thorium is more abundant than uranium, there are still challenges in developing the infrastructure for large-scale thorium utilization.
 2. **Technology Development:** The full potential of advanced fuel cycles, particularly thorium reactors, is still being explored and developed.
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Conclusion

Hybrid reactors represent an exciting frontier in nuclear energy technology, combining the strengths of **fusion and fission**, **accelerator-driven** systems, and **advanced fuel cycles** to create a safer, more sustainable, and efficient nuclear energy system. While fusion-fission hybrid reactors and accelerator-driven reactors offer significant potential in terms of safety, waste reduction, and fuel sustainability, the technology is still in the experimental and development stages.

As fusion technology advances, the prospect of hybrid reactors that combine fusion with fission could revolutionize the energy landscape by providing a **clean, abundant**, and **safe** source of energy. However, challenges in terms of cost, technical complexity, and materials need to be overcome before these hybrid systems can become commercially viable. Hybrid reactors could play a major role in addressing some of the challenges of conventional nuclear reactors, such as waste disposal, fuel scarcity, and safety risks.