PDHonline Course E256 (2 PDH)

Understanding Nuclear Power

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Nuclear Force

The first concept to introduce is the concept of a nuclear force. It is one of the basic forces in nature but often not discussed until nuclear energy is studied. Anyone with a technical background has some understanding of the force of gravity or electromagnetic force. What is the nuclear force?

Let us first review our understanding of the atom. The center of the atom is the nucleus which contains protons and neutrons. In orbit circling around the nucleus are electrons. Protons carry a positive charge, neutrons have no charge, and electrons a negative charge. As long as the number of protons and electrons is the same, the atom is neutral or has no charge. Everything seems to be in balance.
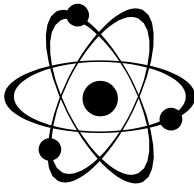
We further remember that like charges repel and opposite charges attract. With the case of an atom with the same number of protons and electrons there is no charge for the atom. The electrons circle the nucleus and the effect of charges seem to cancel out. At this point the discussion generally ends.
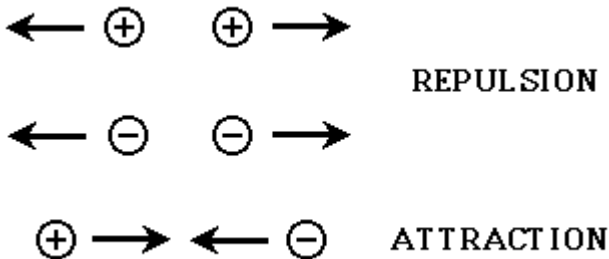
However, let us take a closer look at the nucleus. In the nucleus there are all the positively charged protons and neutral neutrons. If like charges repel then how did all the positive charged protons get compacted into the nucleus of the atom?

Now we can discuss the nuclear force. It seems that is must be very strong compared to the positive charges because it overcomes the repulsive like charge of the protons. Since all the neutrons are in the nucleus, it does not appear to be charge dependent. Since, all the electrons are not effected it does seem to be very short ranged. Also, we know that particles can be emitted from the nucleus or atoms split apart that do not spring back to the nucleus. In summary, the nuclear force has three properties:

    Very Strong
    Short Range
    Charge Independent

Next, how does one determine how strong the nuclear force is? This will be discussed in the next section.

Binding Energy

If we could overcome the nuclear force and separate the protons and neutrons apart, we would know about the strength of the nuclear force. The energy required to do this is called binding energy or separation energy.

Since the nuclear force is very strong then it would be expected that the binding energy would be large. This leads to the introduction of Einstein's theory of relativity concerning that mass and energy are equivalent and convertible.

    $E = mc^2$
   E is energy
    m is mass
    c is the speed of light

If we would measure the mass of the atom before separation and the mass of the individual parts after separation, there would be a change in mass. Part of the mass of the atom is converted into energy.

How much energy would we get if we applied this to an atom of uranium used in a nuclear power plant?

Uranium Atom Separation

First let us take a look at Uranium, chemical element symbol "U", which is used to fuel nuclear reactors. The atomic number of U is 92 which is the number of protons in the nucleus. The atomic mass number is the number of protons and neutrons in the nucleus. A chemical element can have atoms with different number of neutrons and these are called isotopes. The two isotopes of Uranium of interest are U-235 and U-238. U-235 is the isotope that will more readily separate by fission. Fission is the breaking apart of the atom into two or more parts when bombarded by a particle such as a neutron. More neutrons are produced when the atom separates and the process or chain reaction continues.
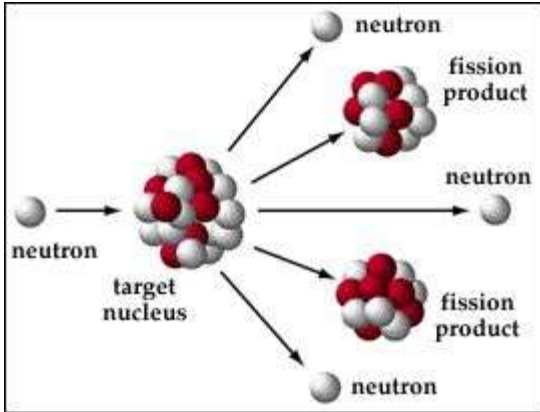
U-238 is naturally occurring in nature but only contains less than one percent U-235. Nuclear reactors operated in the United States use U-238 that has the percentage of U-235 increased to 2-4%, called enrichment. Enrichment is a difficult process requiring a physical (not chemical) separation of U-235 from U-238. Centrifuges or gaseous diffusion techniques are used for enrichment.

How much energy is released when a U-235 atom undergoes fission? The unit of energy used in nuclear engineering is electron volt, ev. This is the increase in kinetic energy of an electron as it falls through a potential of one volt. This is the charge of an electron times the potential drop. The fundamental physical charge of an electron is 1.62×10^{-19} coulomb.

$$1eV = 1.62 \times 10^{-19} \text{ coulomb} \times 1 \text{ volt} = 1.62 \times 10^{-19} \text{ joule (j)}$$

Since we will be discussing large units of energy, MeV (10^6 eV) is often used. $1MeV = 1.62 \times 10^{-13}$ j. Also, one joule is equivalent to one watt- sec.

A U-235 atom on average will release 200 MeV of energy during fission.

Knowing the energy released per fission, a calculation can be performed to determine how much U-235 will be required to produce a certain power level. First, we will calculate the fission (F) rate (R) at a power level (P_{mw}) in megawatts (MW) of the reactor. The number of fissions has the symbol #F. Also, one joule is equivalent to one watt-sec.

$FR = P_{mw} \times 10^6$ j/MW-sec $\times$ #F/200MeV $\times$ MeV/1.62×10^{-13} j $\times$ 86400sec/day

$FR = P_{mw}$/MW $\times$ 2.7×10^{21} #F/day

To convert to grams per day we use Avogadro's number. Recalling from chemistry, the number of atoms in the gram atomic weight of an element is Avogadro's number (6.02×10^{23} atoms / gram atomic weight). For U-235, 235 grams contains Avogadro's number of atoms. The amount for one megawatt is calculated.

$FR = 1 \times 2.7 \times 10^{21}$ #F /day $\times$ (235 gram/ 6.02×10^{23} atoms) $\times$ 1 atom/fission

Grams/day for 1 Megawatt thermal energy is 1.05g/day.

This is called the burnup rate.

Some atoms of U-235 do not undergo fission so the actual rate or consumption rate is 1.23g/day.

We have tied the energy released in fission to grams of U-235 used per day for a power rate. Thus, given this information, we can build and size the reactor for the appropriate energy level.

Nuclear Reactor

Reactors built in the United States typically use fuel assemblies that are 12 feet long. Each assembly might consist of a 12 by 12 arrangement of fuel rods. Each fuel rod has a diameter of a thick pencil or pen and is 12 feet long. There would be 144 fuel rods in one fuel assembly. Each reactor may have several hundred fuel assemblies supported in a reactor vessel. Cooling water is pumped through the reactor to dissipate the heat produced in the fuel caused by fission.
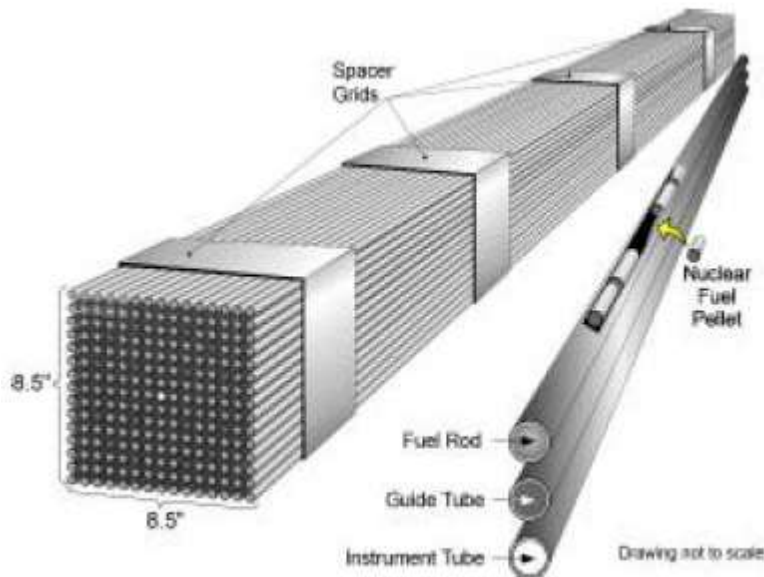
Fuel rod assembly

Commercial power reactors in the United States are of two types – boiling water reactor (BWR) and pressurized water reactor (PWR). There are advantages and disadvantages to each type. In the PWR boiling does not occur and the heated water passes through another heat exchanger termed a steam generator where steam is produced. An advantage is the radioactive water passing through the reactor never comes in contact with the steam side of the power plant. A disadvantage is that it operates at higher pressures and the steam generator is required. The BWR allows some boiling of the water in the reactor and steam passes out of the reactor

directly to a turbine. This requires additional shielding from radiation during operation and the steam cycle gets contaminated. No steam generator is required and operation can occur at lower pressures. Both reactor types are termed commercial power reactors. These are not the only reactors in the United States. Research reactors are located at many universities. Test reactors like the Advanced Test Reactor are located at the Idaho National Laboratory.   The U.S. Navy uses reactors in nuclear submarines and surface ships.

There are 104 operating commercial power reactors located in the United States. These reactors produce about 20% of the nation's energy production. A list of these can be found at several websites.

http://www.nrc.gov/reactors.html

or

http://www.nuclearstreet.com

The list on nuclear street shows the plants arranged by regions. The regions correspond to the U.S. Nuclear Regulatory Commission's (NRC) regional offices.

Recently, four plants have stopped operation (Crystal River, San Onofre 2 and 3, and Kewaunee) bringing the total number in operation to 100. Five units are under construction – Watts Bar 2, Vogtle 3 & 4, and Summer 2 & 3.

Light Water Reactor

The commercial power reactors operating in the United States are termed light water reactors. They use ordinary water as the coolant and moderator. The coolant is what cools the reactor and transports the heat generated in the fuel. Neutrons born from fission are prompt neutrons and to successfully interact with U-235 to cause fission must be slowed down by a moderator. The hydrogen atom in water is about the same size as a neutron and interacts with neutrons is an excellent way, similar to billiard balls striking each other, to slow them down to thermal neutrons. Thermal neutrons are in thermal equilibrium with their surroundings. These thermal neutrons can interact with the U-235 to cause fission. These reactors are said to be inherently stable. This is because as power is increased the water heats up and becomes less dense. Therefore, there is less interaction with the neutrons and some may escape the reactor. This provides a negative feedback to decrease power.

These concepts are important to understand about different types of reactors. Our focus in this course will be commercial power reactors in the United States. However, to discuss some of the issues with the fuel cycle and proliferation of nuclear materials it is necessary to introduce some other reactor types. Different reactor types, for the fission process, depend on neutrons that are at different energy levels after they leave the fission process as prompt. Fast Breeder Reactors use Plutonium, "P", for fuel. This reactor type captures neutrons at a higher speed

than the ones used in a thermal reactor. Also, they do not use water for the coolant because it is effective at slowing down the neutrons. Some use liquid sodium.

In Canada, the Candu reactors use heavy water or deuterium which is an isotope of hydrogen with an additional neutron in the nucleus. They can use U-238 without enrichment (0.7 % U-235) as a fuel. Heavy water will not adsorb another neutron since the hydrogen atom already has two instead on the normal one. Therefore, not many neutrons are lost as they are slowed down therefore effectively using all the neutrons produced for fission.   However, these reactors do not have the inherently stable properties of US reactors. They are not licensed in the US.

Fuel Cycle and Storage

As previously stated in the section, Nuclear Reactor, each reactor is loaded with hundreds of fuel assemblies with U-238 enriched to 2-4 % of U-235. A typical operating cycle is 18 months or 24 months. Nuclear plants are considered base loaded power plants. They typically operate at full power (100%). As demand changes during the day a utility will change power on other fossil fuel plants to meet the changing load.

The power demand is the lowest in the fall or spring time. This is the time for scheduling a refueling outage. During a refueling outage lasting several weeks the reactor head is unbolted and removed so the fuel assemblies can be lifted out of the reactor vessel. At this time about one third of the fuel assemblies are replaced with new assemblies. The assemblies that have been in the reactor for three operating cycles are taken out and placed in a spent fuel pool. The spent fuel assemblies are stored under 30 to 40 feet of water as they are highly radioactive.

As many of the older reactors have been operating a number of years, the storage capacity of the spent fuel pool is about to be exceeded. Some of the plants were designed assuming that the spent fuel assemblies would be transported to a national storage facility. Plans are to take the spent fuel to Yucca Mountain in Nevada. However, the state of Nevada and others are strongly opposed to licensing of Yucca Mountain as a national storage facility where fuel from all over the United Stated will be transported to it. Yucca Mountain was undergoing licensee review by the NRC until it was suspended several years ago. The suspension was challenged in court. In August 2013, the court determined the NRC had acted improperly and ordered the NRC to resume licensing of Yucca Mountain. The final outcome is uncertain.

Yucca Mountain

Dry Cask Storage

The current alternative for fuel storage is onsite dry cask storage to make room until a national storage location is operating. Dry cask storage is also licensed and reviewed by the NRC. At a location next to the plant, concrete pads have been built for placing heavily shielded spent fuel storage casks. As many as 16 or more fuel assemblies are placed in a storage cask in the spent fuel pool. The storage cask is sealed and transported from the spent fuel pool to the storage pad. Usually, the fuel that is placed in the storage casks has been sitting in a fuel pool for a number of years and has cooled considerably since being removed from the reactor. Plants can continue to operate this way indefinitely until a permanent storage resolution is reached.

But what about all the used fuel assemblies … are they good for anything? The answer is in the next section.

Chemical Reprocessing

What happens to all the U-238 in the used fuel assemblies? Some of it is converted to P-239 by absorbing a neutron in U-238 and decaying to P-239.

U-238 + Neutron-1 = P-239

P-239 does not occur in nature and is only produced in a nuclear reactor. At one time in the United States a chemical processing plant was to be built and the P-239 used in a Fast Breeder Reactor. Since Plutonium is a different chemical element the separation process is chemical rather then a physical one. Isotopes of the same chemical element must be separated by physical means. However, due to concerns about proliferation of nuclear materials for nuclear weapons, these programs were stopped.

The concern about nuclear material for a nuclear bomb is that it takes about 50 kilograms of highly enriched Uranium (around 90% enriched in U-235) or 10 kilograms of P-239 to make a nuclear weapon. The fuel is assembled in certain configuration and a carefully timed explosion drives the material together for a nuclear explosion.

Therefore, it should be realized that having a nuclear reactor does not mean one can make a nuclear weapon. However, having a uranium enrichment facility, which may be many centrifuges, can generate highly enriched uranium. Likewise, the used fuel from a reactor can be taken to a chemical processing facility and the plutonium separated.

The other point to realize regardless about how one feels about nuclear proliferation is that there is a enormous amount of fuel that could be used to provide power in future reactors. This raises the question about the life expectancy of present reactors.

Life of Present Reactors

Power reactors licensed by the NRC in the United States are licensed for 40 years. Some of the initial licenses were in the 1960s. Therefore, it would seem that many of the older plants would have exceeded their life expectancy. However, a formal process was developed for license renewal for an additional 20 years. Extension must be approved by the NRC. This requires both a safety review and an environmental review. There is public involvement in the process with public meetings. The NRC conducts inspections as part of the formal approval process. Licensees must establish an aging management program to deal with equipment aging issues.

Additionally, there is no limit on the number of extensions that can be obtained. It is somewhat of an economic decision for plants to seek license renewal. About half of the operating plants have received 20 year extensions on their operating lifespan. Many more are expected to apply for a license extension.

Regulation of Nuclear Power

Reactors in the United States are licensed and regulated by the NRC. The NRC was formed in 1974 from the Atomic Energy Commission (AEC). One of the criticisms of the AEC was that it had a dual role of promoting nuclear energy and regulating safety. The authority for the NRC comes from the Atomic Energy Act of 1954. The NRC was formed by the Energy Reorganization Act of 1974. The NRC regulates the civilian uses of nuclear material and facilities.

The NRC headquarters in is Washington, DC. Their offices are in Rockville Pike, Maryland. There are four regional offices located as follows:

    Region I – King of Prussia, PA
    Region II – Atlanta, GA
    Region III – Lisle, IL
    Region IV – Arlington, TX

Besides the headquarters and regional offices the NRC has at each nuclear facility one or more resident inspectors. They act as first responders in the event of a problem. In addition, they are the day to day interface with the facility.

Both the US House and Senate have judiciary oversight of the NRC. In the Senate, it is the Committee on Environment and Public Works. In the House, it is the Committee on Energy and Commerce. The NRC makes routine reports to Congress. It also responds to inquires from the Congress.

Many of the regulations covering the NRC are found in the Code of Federal Regulations, Title 10, NRC Regulations.

Safety, Risk, and Regulation

Safety

The question about nuclear reactor safety has been asked many times since the beginning of nuclear power. In the early years, the focus was on discussing the design of barriers to prevent a release of radioactive material. Three principal barriers were the fuel cladding, reactor vessel and piping system, and containment.   Fuel cladding is a metal barrier around the fuel rod which contains the fuel pellets. The fuel cladding is not breached during normal operation. The reactor vessel is made of several inches of steel and manufactured to rigorous codes and standards. Likewise, the piping systems connected to the reactor vessel are carefully made to insure a second layer of defense. However, if the first two barriers are breached, a large thick steel reinforced concrete containment building encloses the reactor and systems to prevent a release to the environment. These systems are said to provide defense in depth.   This discussion is often termed the deterministic process.

Risk

After the Three Mile Island in 1979, many attempts were made to assess the risk of nuclear power. In other words, attempts were made to give the risk of an accident a number. The NRC issued a policy statement in 1986 and later clarified this in 1990.   It was stated that the benchmark for accidents should be 10^{-4} accident per year. This was expresses as core damage frequency (CDF). Another way of thinking about this is indicated below:

> 100 reactors for 10 years of operation and only one in ten chance of an accident

> $1/10 \; X \; 1/100 \; X \; 1/10 = 1/10,000 = 10^{-4}$

Likewise, for a release from containment the number was 10^{-5} which was called large early release frequency (LERF). These numbers set a baseline or reference point.

The use of risk in accident analysis is termed probabilistic risk assessment (PRA). Two factors in risk determination are how often an event can occur and how much harm is likely to occur. For example, consider a large pipe break. This event is not expected to happen but if it does the potential for damage is great. Next, consider the failure of a large safety pump designed to pump water into the reactor in the unlikely event of a pipe failure. We can add all this together and come up with an event tree or model for a pipe break with a safety pump failure. If all the events trees are considered for a plant, this is called the plant specific PRA. Plant PRAs give numbers for CDF that range from 10^{-5} to 10^{-6} depending on the plant design. Many plants have improved their numbers by making design changes to systems that PRA have shown to be big contributors to accidents. How does risk tie to regulation of nuclear plants?

Regulation

The NRC in 2000 changed its oversight program to include risk insights. The part dealing with reactor safety was made up of four cornerstones. These were initiating events, mitigating systems, barrier integrity, and emergency preparedness. An initiating event could be something to cause a pipe failure. The failure of the pipe would be barrier integrity. The large safety pump to pump water would be the mitigating system. Next, given a failure has occurred, the emergency plan would be used to deal with the situation. Each of the cornerstones was given specific criteria for assessment. A color coded system was developed using Green, White, Yellow, and Red. Green would mean a problem was not very safety significant. The NRC response for a Green issue would not require any additional action than normal. However, safety significance and NRC action or response increases moving from Green to Red.

Summary

The topics presented in this course are to give an overall perspective on the Unites States commercial power industry. Many of the discussions and terms are ones that would be encountered working in the industry. NRC, PRA, license renewal, dry cask storage, White issue, are everyday terms.