Chem 481 Lecture Material
4/22/09

Nuclear Reactors

Poisons

The neutron population in an operating reactor is controlled by the use of "poisons" in the form of control rods. A poison is any substance that has a large cross section for neutron absorption not leading to fission such as boron, cadmium, silver, indium, gadolinium or hafnium. The reactor power level is adjusted by movement of the control rods. The control rod increases or decreases the thermal utilization factor (and hence k_{eff}) depending on whether the rod is withdrawn from or inserted into the reactor core. The effectiveness (worth) of a control rod depends largely upon the value of the neutron flux at the rod location. For a reactor which has a large amount of excess reactivity, several control rods are required. Control rods are often classified by the following designations.

Shim rods - used for coarse control and/or to remove reactivity in relatively large amounts

Regulating rods - used for fine adjustments and to maintain a specific power level

Safety rods - provide a means of a very fast shutdown in the event of an unsafe condition. The addition of a large amount of negativity by rapidly inserting the safety rods is known as a "scram".

Other poisons are present in the core as a result of fission. ^{135}Xe, with a thermal neutron absorption cross section of 2.6 x 10^6 barns and a half life of 9.10 hours, is produced directly by fission and by the decay of other fission products such as ^{135}I ($t_{½}$ = 6.57 hours). Since fuel elements are generally sealed with a cladding, fission products remain trapped in the fuel elements once they are formed. During operation of the reactor, ^{135}Xe is being formed by fission and is being removed by decay and neutron capture reactions. A steady-state level of ^{135}Xe is eventually established and depends on the reactor power level. Once the reactor is shut down, ^{135}Xe continues to be formed by decay of ^{135}I, but it is no longer being removed by neutron absorption, only by radioactive decay. Consequently, the amount of ^{135}Xe poison will increase immediately after reactor shutdown (see figure below). The peak ^{135}Xe amount is then slowly reduced as it decays. The reactivity of the ^{135}Xe poison can be quite significant if the reactor has been operating at a very high flux level (>10^{13} n/cm^2·s) before shutdown, and may prevent the reactor from being started again unless sufficient excess reactivity has been built in the reactor. At Chernobyl, operators were trying to get the reactor to recover from a too-low power level created by the presence of excessive ^{135}Xe and had removed all control rods just before the accident occurred.

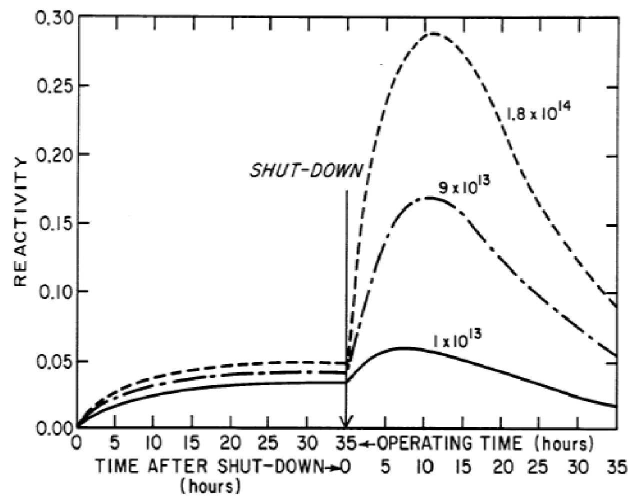


Figure 7: ^{135}Xe poisoning during operation and after shutdown.

Temperature Effects

As the amount of moderator in the core increases neutron absorption in the moderator increases and causes a decrease in the thermal utilization factor and k_{eff} (see figure below). Decreasing the moderator has the effect of increasing the slowing down time and results in a greater loss of neutrons by resonance absorption (lower escape probability and lower k_{eff}). Water-moderated reactors are designed to be under moderated so that an increase in temperature, which would decrease the moderator-to-fuel ratio due to the expansion of water, will result in a decrease in k_{eff}. When moderator temperature has an inverse relationship with reactivity, this is referred to as a negative moderator temperature coefficient.

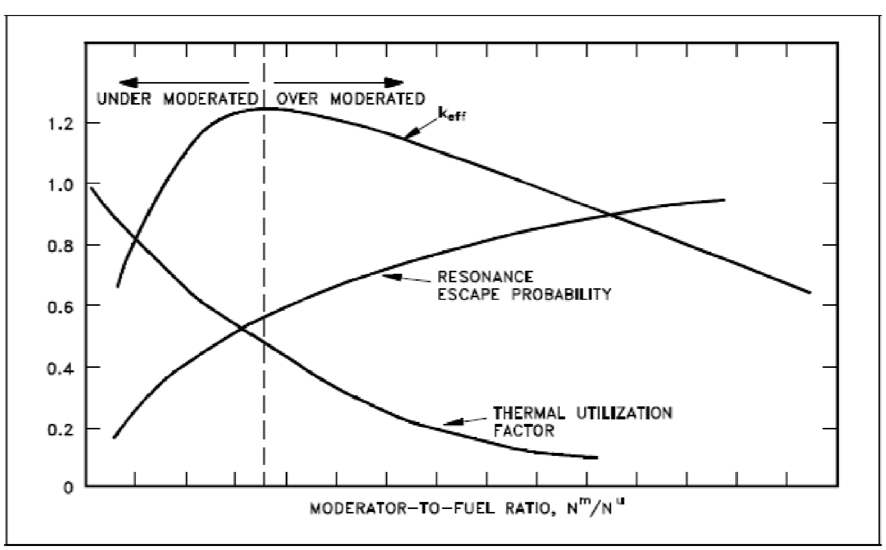


Figure 2 Effects of Over and Under Moderation on k_{eff}

Temperature has a more important effect on the fuel. Increasing the reactor power immediately increases the fuel temperature causing nuclei to vibrate more rapidly within their lattice structure. This effectively broadens the energy range of neutrons that may be resonantly absorbed in the fuel (Doppler broadening), resulting in lower escape probability and lower k_{eff} at higher temperatures. Thus, the fuel temperature coefficient is negative.

TRIGA Reactors

The TRIGA reactor (Training, Research, Isotopes, General Atomics) is the most widely used type of research reactor in the world. It is known for its inherent safety, the ability to routinely “pulse” the reactor to a very high power levels for a brief period of time and conveniently accessible positions for irradiating samples.

The reactor at UC Irvine is a Mark I TRIGA reactor licensed for steady-state operation at 250 kW (thermal) and pulsed operation to 1000 MW (see figure next page). The UCI reactor uses fuel enriched to 20% ^{235}U alloyed with zirconium hydride ($ZrH_{1.7}$). The $ZrH_{1.7}$ serves as the primary neutron moderator and it is this fuel/moderator alloy that provides an inherent safety feature. If the power level of the reactor increases rapidly, the fuel/moderator temperature promptly increases. At the higher temperature, the hydrogen in the $ZrH_{1.7}$ is not as efficient in removing energy from fission neutrons so the less moderated neutrons cause fewer fissions and escape into the surrounding water. The net result is to slow down the fission rate and return the reactor power level to a much lower and safe level within a few thousandths of a second. This blend of fuel and moderator gives the TRIGA reactor a prompt negative temperature coefficient of reactivity and is the reason TRIGA reactors can be safely pulsed to a high power level by rapidly removing almost all of the control rods from the reactor core.

The $U/ZrH_{1.7}$ alloy is chemically stable and the stainless steel cladding can withstand temperatures up to 950°C (much higher than normally operating values). Details of the construction of an individual fuel element are shown in Figure 5.4 on page 5. The graphite plug at each end of the fuel element serves to reduce neutron leakage by reflecting neutrons back into the fuel.

The entire reactor core is submerged in a swimming pool filled with continually purified (to minimize the activation of dissolved materials) water. The water serves as a coolant when the reactor is operating and as a biological shield against the intense radiation emitted by the core even when the reactor is shutdown. The water is also the medium in which the Čerenkov radiation is produced (the bluish light visible when the reactor is operating at higher power levels - see figure on p. 5 of 2/27/09 posting).

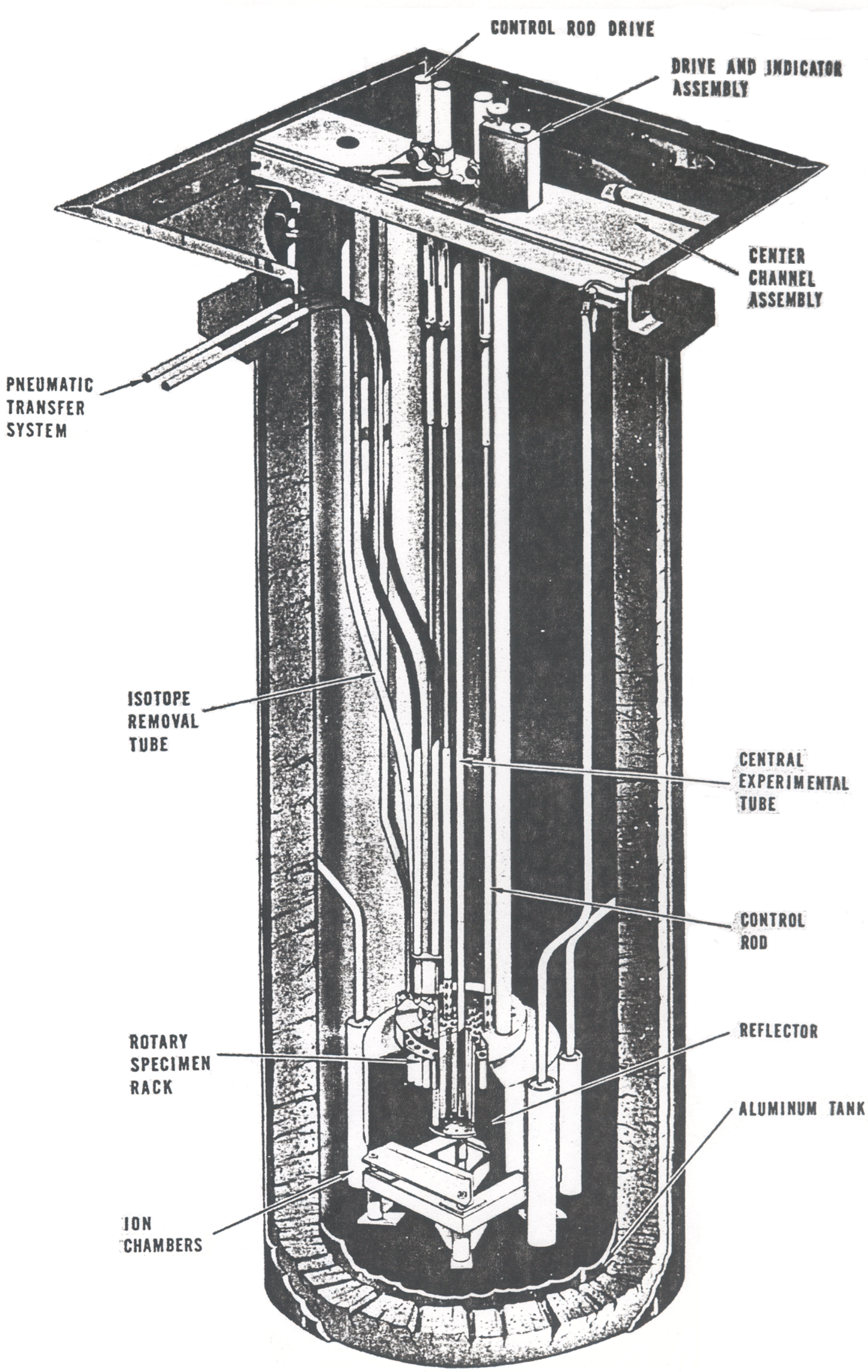


FIG. 5-1 Cross Section of TRIGA Mark I Reactor

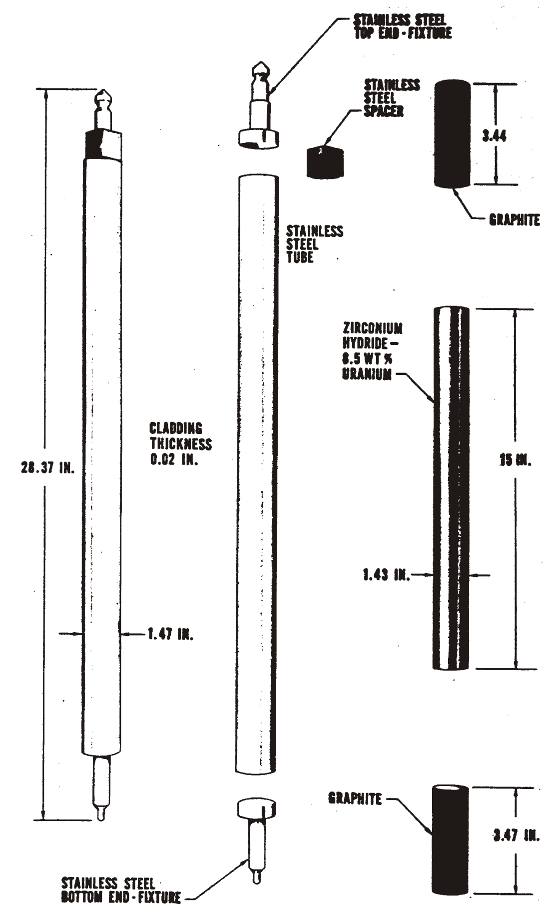
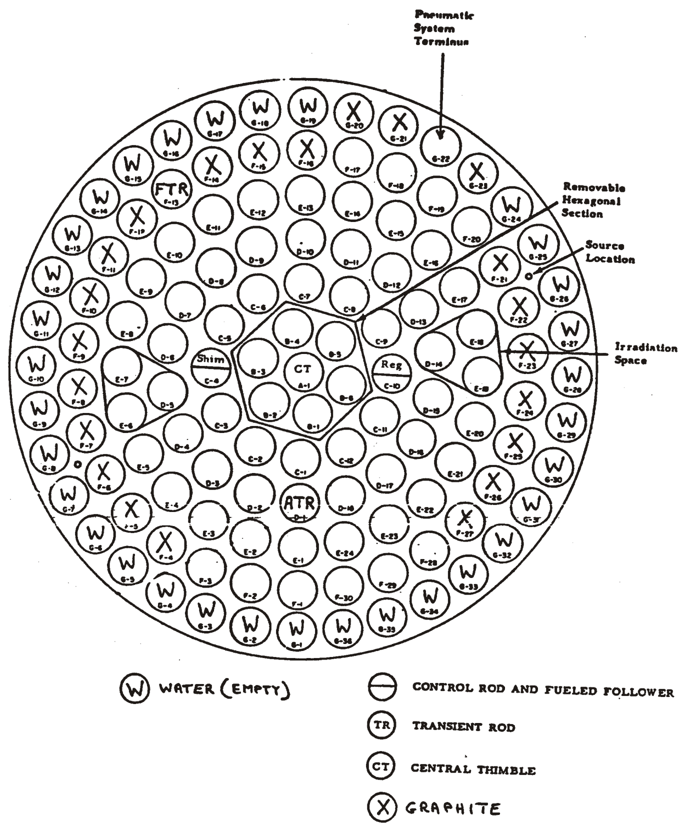


FIG. 5-4 Stainless-steel-clad Fuel-moderator Element

A diagram of an earlier arrangement of fuel elements in the core is shown on the next page. Most of the positions are occupied by fuel elements while some have graphite rods which do not absorb neutrons as readily as the empty locations filled with water. There are four control rods in the core, a SHIM rod, a REG rod and two transient control rods (ATR and FTR) that can be rapidly removed from the core by nitrogen pressure to pulse the reactor. The poison used in all of the control rods is boron in the form of borated graphite.



CORE LOADING DIAGRAM

FIG. 5-13 Grid Array

The SHIM and REG rods are the most centrally located control rods and hence are worth more than the transient rods. They are constructed with a section of borated graphite followed by a section of fuel material (see figure 5-6 below). As the control rod is removed from the core, poison is removed and replaced by fuel. This has the effect of increasing the worth of the control rod.

In steady-state operation the reactor operator usually withdraws the two transient rods completely (the reactor will still be subcritical), then partially removes the SHIM and REG rods until the reactor becomes supercritical and the power increases to the desired level.

One of the safety interlocks is a period scram. If the reactor period decreases below a preset value, the control panel circuitry automatically scrams the reactor. Shutdown is achieved by allowing all control rods to fall back into the core by the force of gravity. Prompt neutron production is dramatically reduced and the power level undergoes a "prompt drop" (see figure 3 next page) after which, because of the delayed neutrons, the power level decreases with a period of about 80 seconds.

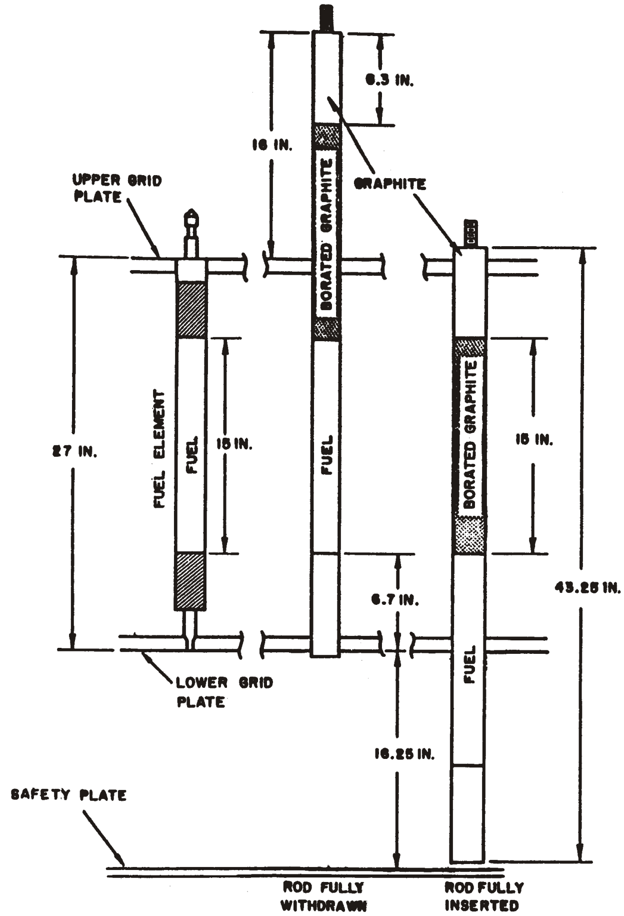


FIG. 5-6 Fueled-follower Control Rod in Core

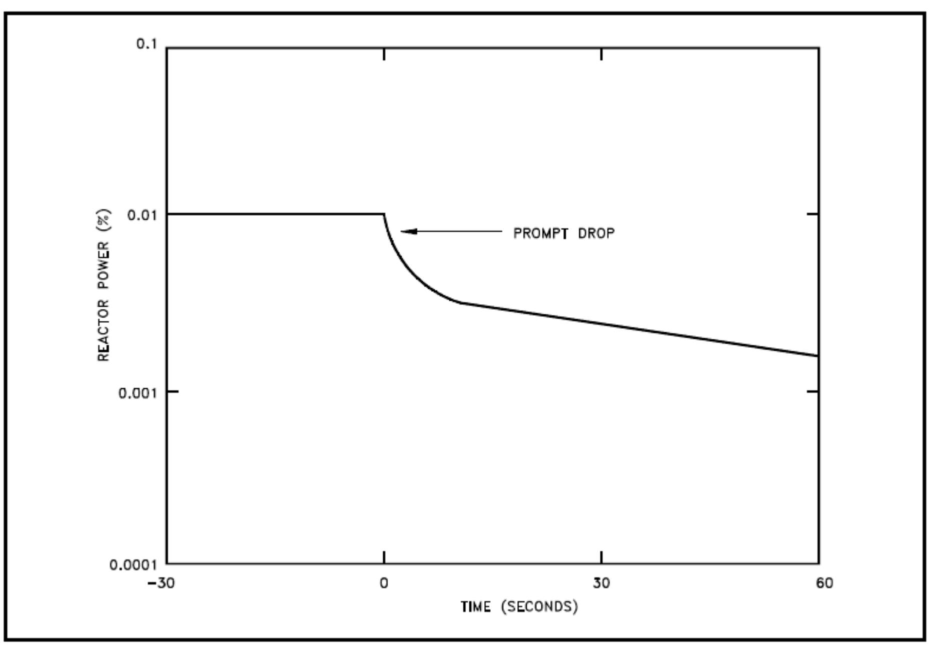


Figure 3 Reactor Power Response to Negative Reactivity Addition

Note that there is an isotopic neutron source in the core to provide a minimum neutron population at all times (note that there are fissions occurring even in a reactor that is shutdown). This ensures that the neutron population is readily detectable throughout the start-up process and decreases the time required to get the reactor critical from a shutdown condition. The neutron population in the core is monitored by a fission counter and several ion chambers positioned around the outside of the reflector.

Various irradiation positions are available in the UCI reactor depending upon experimental requirements. A maximum thermal neutron flux of about 5×10^{12} n/cm$^2\cdot$s is found in the Central Thimble (CT) position which can accommodate 1-2 samples at a time. The pneumatic transfer (PT) position allows samples to be sent into the core pneumatically from a laboratory adjacent to the reactor room. Once the reactor is operating at the desired power level, a sample in a sealed polyvial is loaded into a polethylene tube (rabbit) and propelled into the core PT position by a vacuum system. Transit time is about 3 seconds. The irradiation time can be preset, after which the sample is pneumatically transferred back to the lab. This is especially useful when activation products have short (~minutes) half lives.

Two other irradiation positions (FTS and FTS-Cd) have been installed at UCI that permit very rapid transfer (~0.5 s) from the reactor core to a terminus mounted on a semiconductor detector. This permits measurement of activation products with sub-second half lives and has been used in conjunction with reactor pulses. One of the fast transfer positions is unlined and the other is lined with Cd to allow for epi-thermal and fast neutron irradiation.

If one wishes to irradiate samples for a longer period of time, the rotary rack (Lazy Susan) facility is preferred. Up to 40 samples experiencing the same neutron flux (~1.5×10^{12} n/cm$^2\cdot$s) can be irradiated simultaneously in this rack that slowly rotates around just outside the core but inside the graphite annulus that surrounds the core. The graphite reduces neutron leakage by reflecting neutrons back into the fuel material. Sealed samples are placed in polyethylene containers (TRIGA tubes) and lowered into the Lazy Susan by a line attached to a “fission” pole. The Central Thimble position is also loaded and unloaded in this fashion. Once loaded, the Lazy Susan is set rotating and the reactor is started up. After irradiation and reactor shutdown, samples are often left in the Lazy Susan to allow for the decay of high levels of short-lived activities before further sample handling.

Reactor Fuel Burn-up

Each fission reaction produces about 200 MeV of energy, most of it recoverable as heat. In power reactors the heat is used to form steam that drives turbines connected to electrical generators to produce electricity. The conversion efficiency of thermal energy into electrical energy is about 35% for a nuclear power reactor. Since it requires approximately 3.1×10^{10} fissions/s to produce 1 watt (thermal), a 3000 MW_{th} nuclear power plant consumes about 3 kg of fuel per day.