# AUSTRALIAN NUCLEAR FORUM
## INFORMATION PAPER No.10

## How a Nuclear reactor Works (Adopted 17/5/07)

### 1. Introduction

Nuclear reactors are a relatively new concept being first thought of during the years just before World War II. Before this scientists had discovered that neutrons would cause fission in uranium and had determined that this process would release substantial amounts of energy. These facts provided the basis for the development of atomic bombs which are in fact just small uncontrolled fission reactors. It was realised early that nuclear technology could also be applied in the development of a new source of energy, namely nuclear power reactors. Thus after the war ended much of the nuclear research effort was redeployed toward this end. In this process specialised reactors were designed and built to test various concepts for nuclear ship propulsion, electric power production, materials testing as well as to provide high level neutron sources for more basic nuclear research.

Today much of the required research into basic nuclear physics, materials testing and power reactor concepts has been completed and the technology has matured. Nuclear power reactors are now commonplace in the industrialised world, and nuclear propulsion systems are a proven concept, albeit mainly for warships. At the same time new uses are being found for the products of nuclear reactors in the medical and industrial fields.

### 2. The Chain Reaction

As was discussed earlier, when a neutron hits the nucleus of a fissionable atom, fission - or the breaking apart of the target nucleus - can occur (see Figure 1). This process releases radiation mainly in the form of gamma rays, beta particles (electrons) and neutrons. The fragments of the original nucleus also fly apart with considerable energy which is released in the form of heat as the fragments come to rest in the surrounding materials. These fragments then form the nuclei of new atoms called fission products which usually have an imbalance of neutrons and protons and are therefore radioactive. An important feature of the fission process is that more than one neutron (on the average about 2.5) is produced. This multiplication of neutrons through fission leads to the concept of the chain reaction, whereby a single neutron can cause one fission which produces two or more neutrons, which produce more fissions and so on (see Figure 2). This whole process can take place in an extremely short time releasing increasing amounts of energy with each generation of neutrons. In fact it can be so rapid that a considerable number of fissions can occur before the heat generated is sufficient to blow the material apart. This is the principle of the atomic bomb.

The control of the chain reaction to produce a steady fissioning rate is simple in concept (see Figure 3). This can be done by keeping the neutron population constant through removing a fraction of each generation produced. This is accomplished in two ways, one by introducing neutron absorbing materials such as boron into the reactor. Another is by limiting the size of the reactor so that the neutrons flying around in the reactor. have a fair chance of leaking out ofthe surface before they encounter a fissionable nucleus. A reactor in which the neutron production and losses are balanced is called 'critical' and the amount of fuel material contained is called the 'critical mass'.

### 3. Fissionable Materials

The types of atoms that can readily undergo fission are in fact fairly limited (see Figure 4). The only one occurring to any great extent in nature is an isotope of uranium U235. This isotope is also very limited in availability being only 0.7 weight percent of natural uranium. The remainder of the uranium found in nature is U238 which is moderately fissionable but only with fast neutrons. U238 however has another property that it is a 'fertile' element meaning that if it absorbs a neutron there is a good chance that it will change into Np339 and then to Pu239. This isotope of plutonium is fairly stable but is also a fissionable material. Further, if it absorbs a neutron and does not fission, it changes into Pu240 which can absorb another neutron and turn into Pu241 (fissionable). This process can be repeated until some of the isotope Pu243 is produced, which is fissionable but also rapidly $\beta$ decays to Am243. This U238 – Pu chain of events is exploited in most reactors by using a mixture of U235 and U238 as initial fuel which on ‘burning’ produces plutonium that is also burned. In power reactors the plutonium is extracted from the spent fuel and may be reused in new fuel.

U233 is another fissionable 1sotope of 1nterest not because it occurs 1n nature but because it can be produced by neutron irradiation of Th232 which is somewhat more prevalent than uranium. The Thorium cycle however, has not been used much in the current generation of reactors and Thorium remains as an energy resource for the future.

## 4. Thermal Reactors

The cross section (probability) for fission of fissionable isotopes varies with the incident neutron energy and generally increases as the neutron velocity decreases (see Figure 5). Neutrons coming directly from a fissioned atom have energies in the million electron volt (MeV) range (speed about 5% of the speed. of light) at which energies cross sections are low. If, however, these neutrons can be slowed down to energies below 1ev without being absorbed by other reactor materials then their probability of causing a fission is enhanced. The best materials for this ‘moderation’ or ‘thermalisation’ process are the lightweight nuclei that can rapidly remove energy from a neutron through collision events (like billiard balls). The best from this point of view is ordinary hydrogen which has a nucleus of one proton having a mass nearly the same as a neutron. A collision between a neutron and hydrogen can leave the neutron with little or no energy. Figure 6 lists light materials that are potential candidates for moderators. Other criteria for choosing a moderator are that it should be reasonably inexpensive and a mild to low neutron absorber.

Of the candidates listed only ordinary water, heavy water and carbon have been used to any great extent. In fact the very first reactors built during the war for the purposes of producing plutonium for weapons were natural uranium fuelled and graphite moderated.

## 5. ‘Enriched’ Reactors

About two billion years ago in a location now known as Oklo in the country of Gabon there was formed a sedimentary deposit containing uranium minerals. At this time in the world's history the U235 content in naturally occurring uranium was above 3 weight percent. The concentration of uranium in this deposit was high enough (20 - 30%) so that when ground water percolated into the deposit a chain reaction began. This reactor is estimated to have functioned intermittently at low power levels over many thousands of years. The initial indication that this reactor had existed was a lower than normal U235 content in the uranium ore taken from the mine. Subsequent sampling showed local U235 concentrations as low as 0.44%. In addition, it is worthwhile to point out that most of the fission products and plutonium generated by the Oklo reactor remain in place to this day.

The Oklo reactor was able to exist only because the naturally occurring uranium at the time had a high content of U235. S1nce then the U235 content of natural uranium has decreased to only 0.7% by weight (the half life of U235 is about 700 million years) and at present there exists no concentration or configuration of natural uranium in ordinary water that can be critical. Thus, the first reactor designers were forced to use graphite as a moderator. However, as with Oklo, ordinary water and uranium can form a critical combination if the uranium is ‘enriched’ in its U235 content. The technology for doing this was also developed during the war years and most of the present commercial power reactors use uranium having 3.5 – 5 weight percent U235 and ordinary water as a moderator.

Another way of constructing a reactor is to utilise ‘enriched’ water as a moderator. Deuterium exists as about 0.03 weight percent in natural hydrogen. Technology exists to extract this small fraction of deuterium from natural water producing ‘heavy water’ which is over 99% pure deuterium oxide. Heavy water is an excellent moderator (although expensive) because its thermal neutron absorption cross section is about 0.5% of that of ordinary water, and its physical properties are similar to ordinary water. The commercial power reactor marketed by the Canadians is called the CANDU and operates on heavy water and natural uranium.

Other reactors for various purposes have been built over the years which have used different combinations of fuel and moderator materials. ANSTO's reactor OPAL uses light water for cooling, 20% enriched uranium fuel and heavy water as a reflector.

## 6. Reactor Cooling and Reflectors

The optimum configuration for a moderated reactor is to form the fissionable material into lumps and scatter these lumps in a regular pattern through the moderator. This has the advantage that the fast neutrons from fission can escape from the fuel lumps into the moderator where they can be slowed down without being absorbed at the resonance energies (where high peaks in the cross sections occur) in the fuel materials. Once they have been slowed down then they flow back into the fuel lumps to cause fission. The configuration used in the first man-made reactor (CP-I) consisted of natural uranium metal and oxide cylinders inserted into holes in a graphite stack (see Figure 7).

During the fission process the fuel also generates heat which must be carried away to prevent the fuel from melting. In the early plutonium production reactors this was done by forcing a flow of ordinary water down the fuel channels and over the surface of the natural uranium rods (see Figure 8).

The advent of the 'enriched' reactor materials provided an opportunity to use the ordinary water or heavy water as both a moderator and coolant. In the present light water power reactors, ordinary water is circulated through the reactor core where it provides moderation and picks up the heat from the fuel. This is then piped away to perform useful work in generating electricity.

Reactors can be made more efficient in terms of neutron economy by providing a means of returning some of the neutrons that leak out of the reactor core surface. This is done by a 'reflector' which consists of an unfuelled blanket of moderator material. This reflector captures many of the escaping fast neutrons and slows them down allowing them to flow back into the core. The best reflector materials are then just the same as the moderating materials, i.e. graphite, heavy water and light water.

## 7 Reactor Control

Although the chain reaction proceeds rapidly the process is made manageable by the fact that a small fraction (about 0.7%) of the 2.5 neutrons generated per fission are released on the average about 0.1 seconds after the event. The existence of these 'delayed' neutrons slows down the response of the system considerably, and simplifies its control. The control system of a reactor is provided to allow the chain reaction to begin, to raise power, to hold it at a steady level and to shut the system down again. This is usually done by the use of 'control rods' containing neutron absorbing material such as cadmium or boron that can be moved mechanically in and out of the reactor core as desired. The power of the reactor is usually measured by radiation detectors placed in or next to the reactor core. When these detectors show the power is too high or low, then the control rods are moved accordingly.

With some reactors control can also be achieved by introducing dissolved absorbing materials such as boron into the light water or heavy water moderator. This can then be removed by an external chemical extraction system.

In most reactors additional 'safety rods' are provided that can be inserted quickly and automatically into the core in case reactor operating limits such as high reactor power are exceeded.

## 8. Reactor Shielding, Containment and Safety

Reactors emit high levels of radiation which must be reduced to a substantial degree to allow personnel access near them. This is achieved by the use of shielding which ordinarily consists of high density materials such as concrete and steel.

Also, to provide an envelope to hold any accidental releases of radioactive material from the reactor, most reactors are enclosed in a containment building. This building is normally air tight or has sufficiently low leakage that any radioactive material released from the reactor will not escape in significant quantities to the outside (see Figure 9).

Most reactors are built with the fail safe concept in mind. Safety systems usually incorporate the ideas of redundancy (duplicate components) and diversity (different operating modes) in their design. In addition the reactors themselves incorporate self limiting features. Excessive fuel temperatures from a too high power level produce more non-fissioning absorptions in the fuel and tend to shut the reaction down. Also, reactors with light or heavy water moderation tend to shut themselves down if the water boils excessively (reduced moderation). These safety features would preclude a reactor from ever blowing up like an atom bomb even in the worst circumstances. The construction of a bomb requires the use of highly concentrated and pure fissionable materials, that must be constrained long enough for the chain reaction to reach great intensity. Such conditions cannot exist in ordinary reactors.

## 9. Radioactive Waste Disposal

As mentioned in Section 2 above, the fissioning of atomic nuclei produces fission products - radioactive atoms of a wide variety of different elements. Most of these exist for a short time before they radioactively decay to less active atoms, but some decay slowly and last much longer. Consequently the total radioactivity of the reactor fuel changes in a complex way after the spent fuel is removed from the reactor (see Figure 10). Long-term disposal of high level waste (HLW) is not a simple problem because it must be secured in a way (e.g., underground) that prevents humans and the environment from suffering the effects of excessive radiation exposure (note: humans and the environment are naturally slightly radioactive). One of the longest lived elements in spent fuel is plutonium which can last for several thousand years, however as noted in Section 3 this is also a fissionable material. Thus the ideal solution is to remove the plutonium and other heavy atoms (i.e., actinides) from the waste and reuse it as fuel. This reduces the total activity of the remaining fission product waste and shortens the time that it must be held in safe storage to about 400 years. This method of waste treatment and disposal is currently the subject of much research and development. In fact, another option being looked at is the recycle and destruction all of the fission product wastes in special purpose reactors or by neutron bombardment in special particle accelerators.

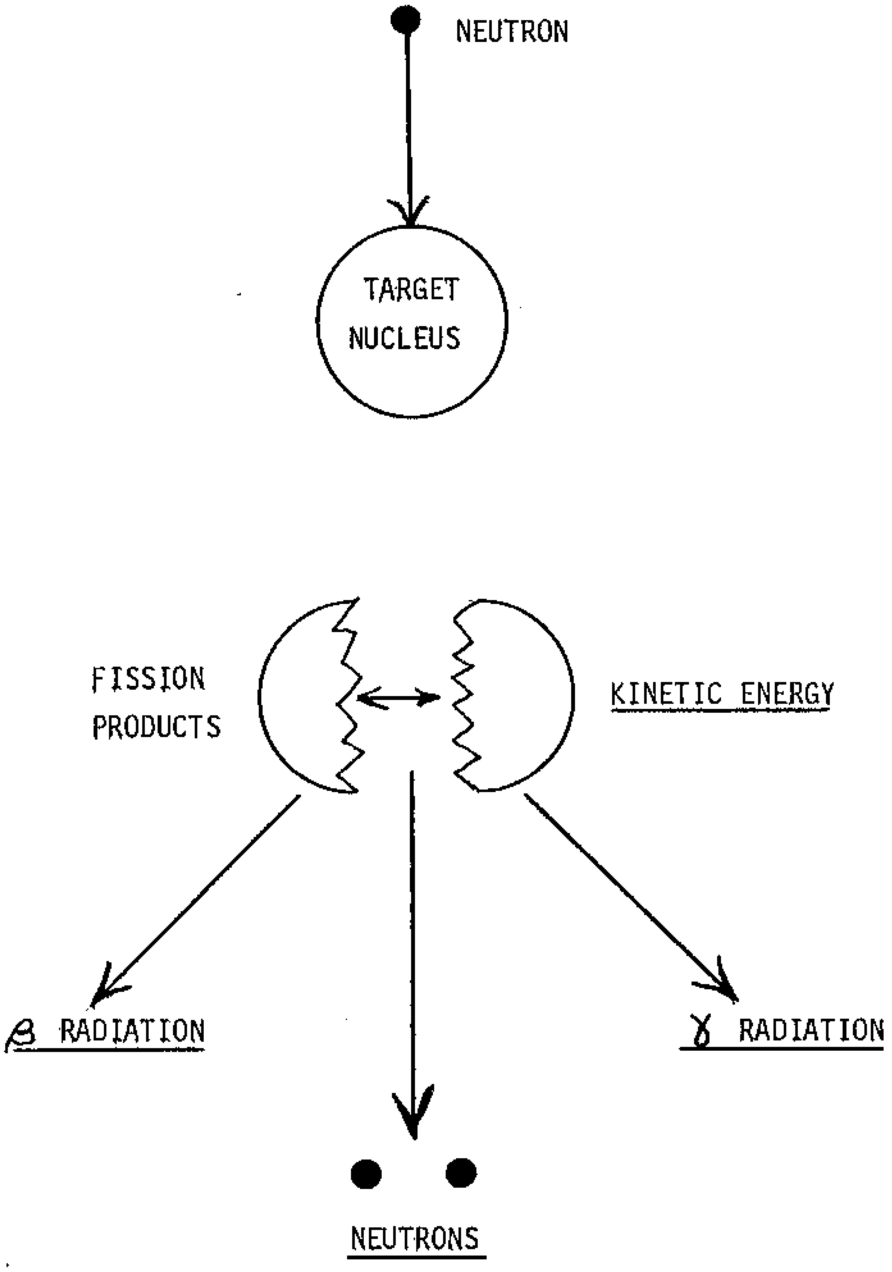


FIGURE 1: FISSION BY A NEUTRON

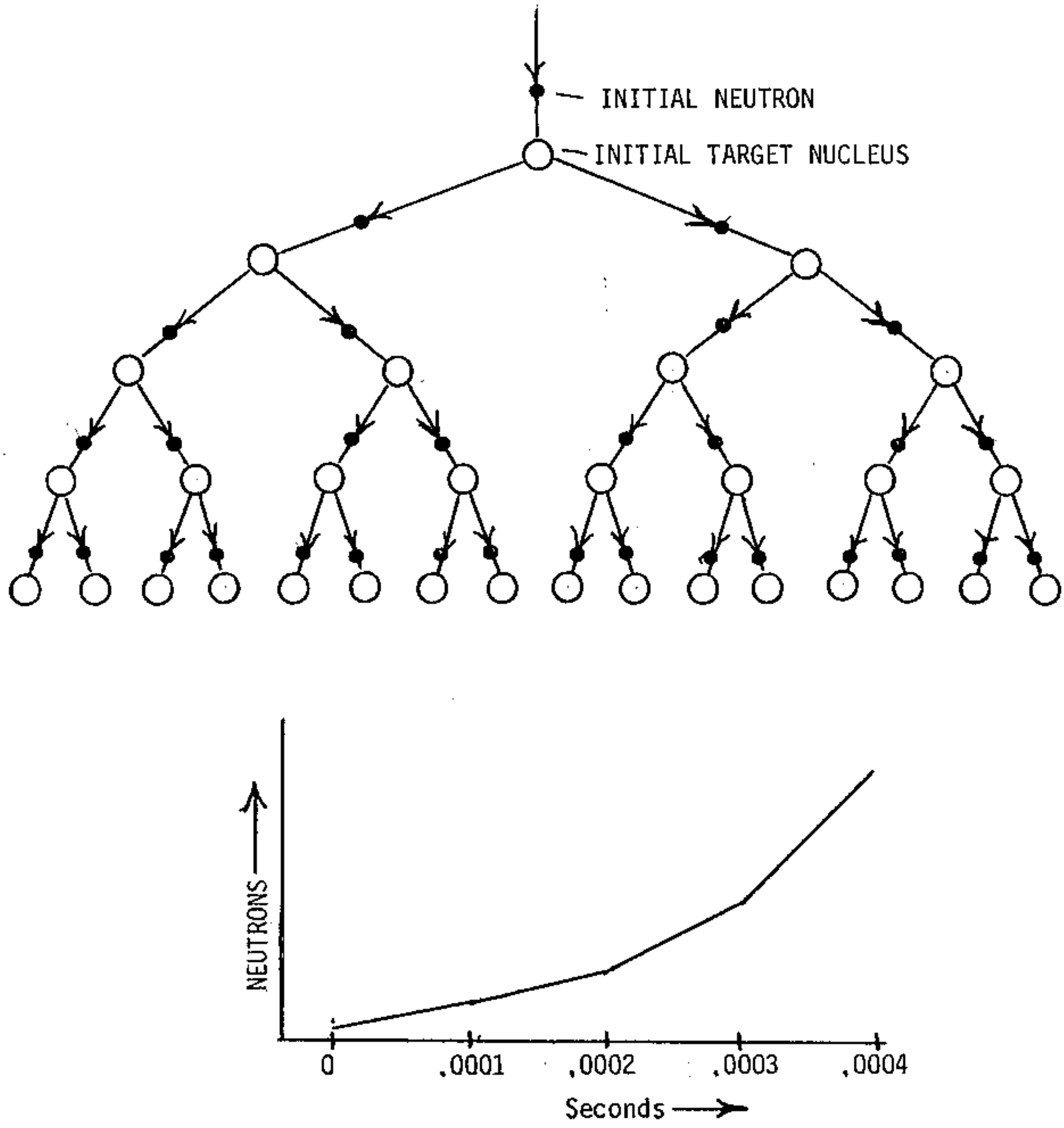


FIGURE 2: A CHAIN REACTION

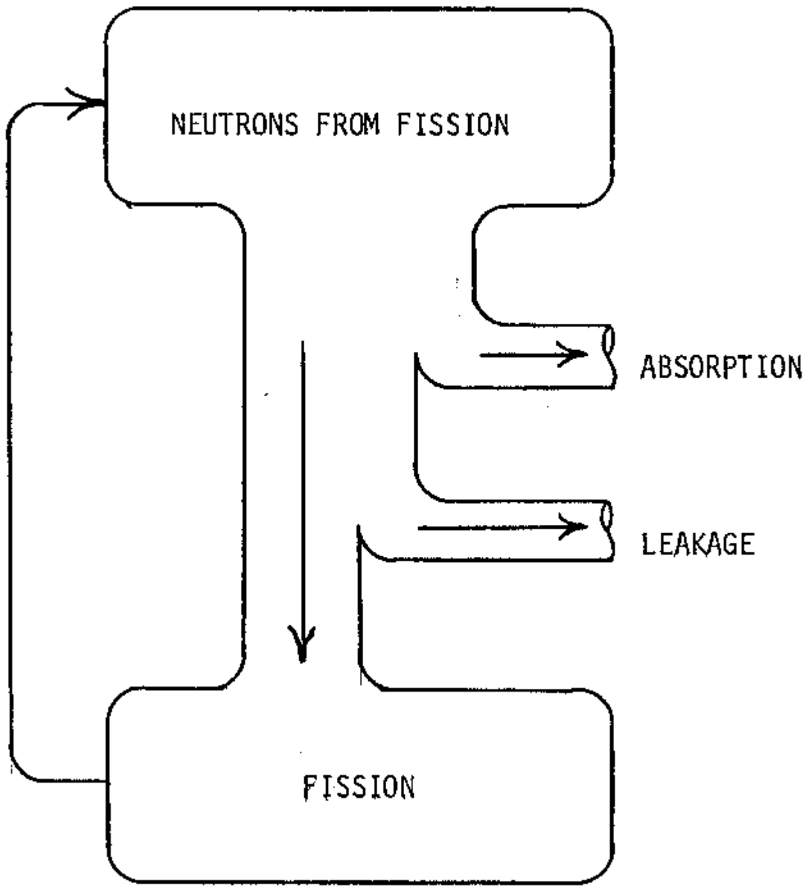


FIGURE 3: THE NEUTRON CYCLE

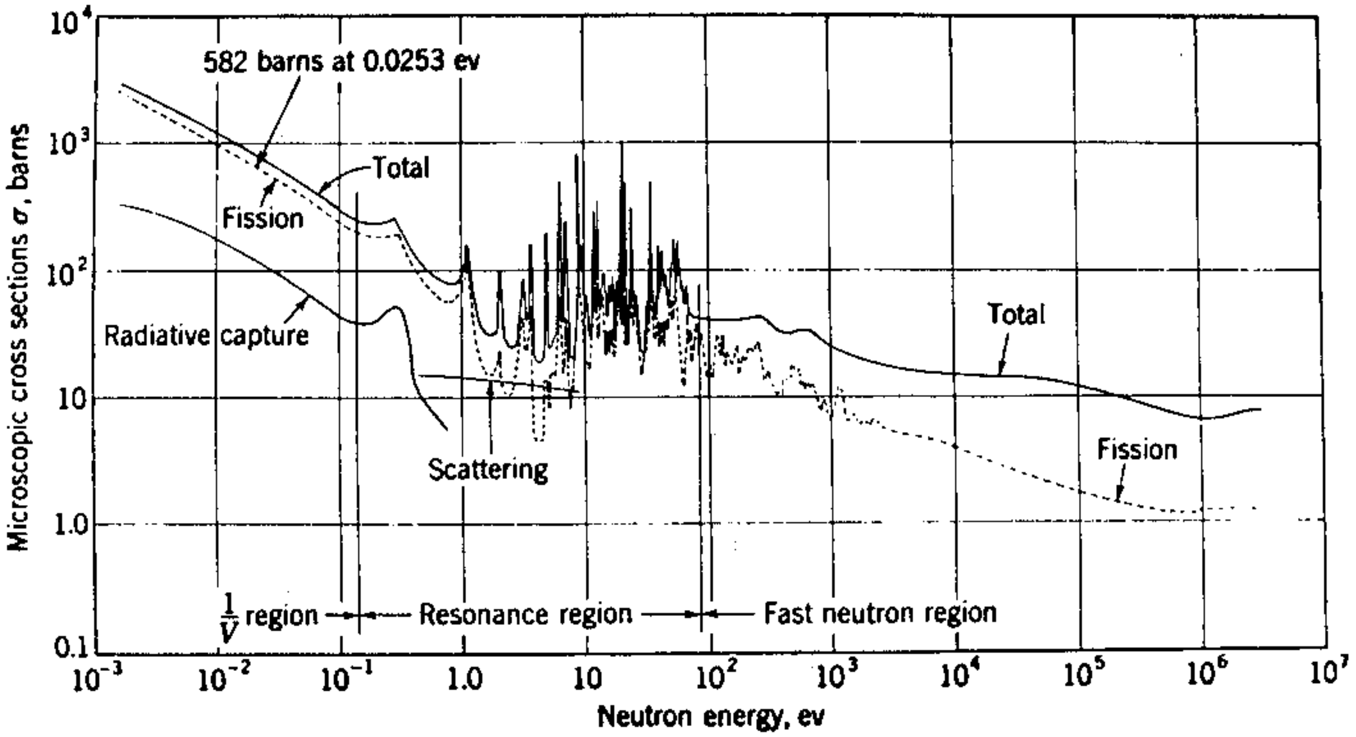
| ELEMENTS | | | | | | | | | | | PROTONS/NUCLEUS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AM | | | 237 | 238 | 239 | 240 | 241 | 242 | 243 | 244 | 95 |
| PU | 234 | 235 | 236 | 237 | 238 | 239<br>F | 240 | 241<br>F | 242 | 243 | 94 |
| NP | 233 | 234 | 235 | 236 | 237 | 238 | 239 | 240 | 241 | | 93 |
| U | 232 | 233<br>F | 234 | 235<br>0.7%<br>F | 236 | 237 | 238<br>99%<br>F<br>(FAST) | 239 | 240 | | 92 |
| PA | 231 | 232 | 233 | 234 | 235 | | | | | | 91 |
| TH | 230 | 231 | 232<br>100% | 233 | 234 | 235 | | | | | 90 |
| | 140 | 141 | 142 | 143 | 144 | 145 | 146 | 147 | 148 | 149 | |

NEUTRONS/NUCLEUS

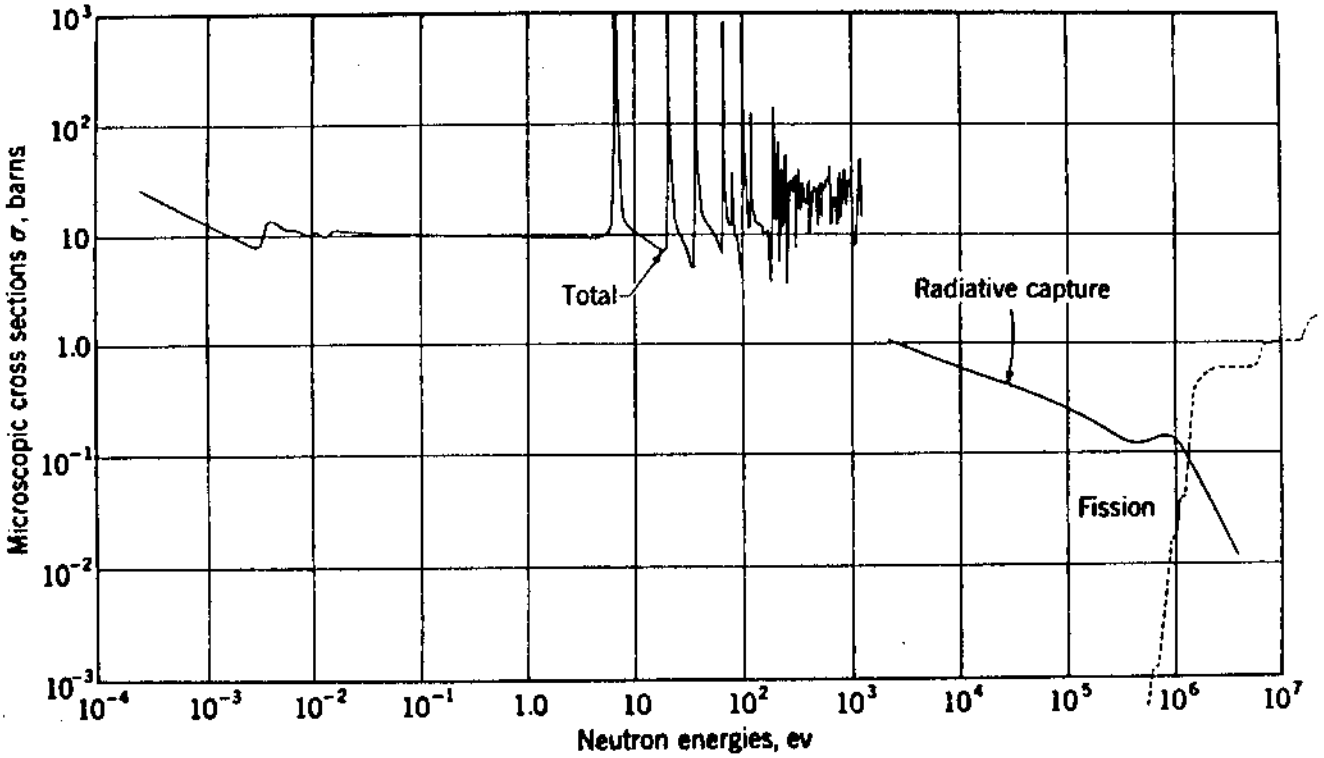
% = NATURALLY OCCURRING

F - FISSIONABLE

FIGURE 4: THE HEAVY ELEMENTS



$U^{235}$

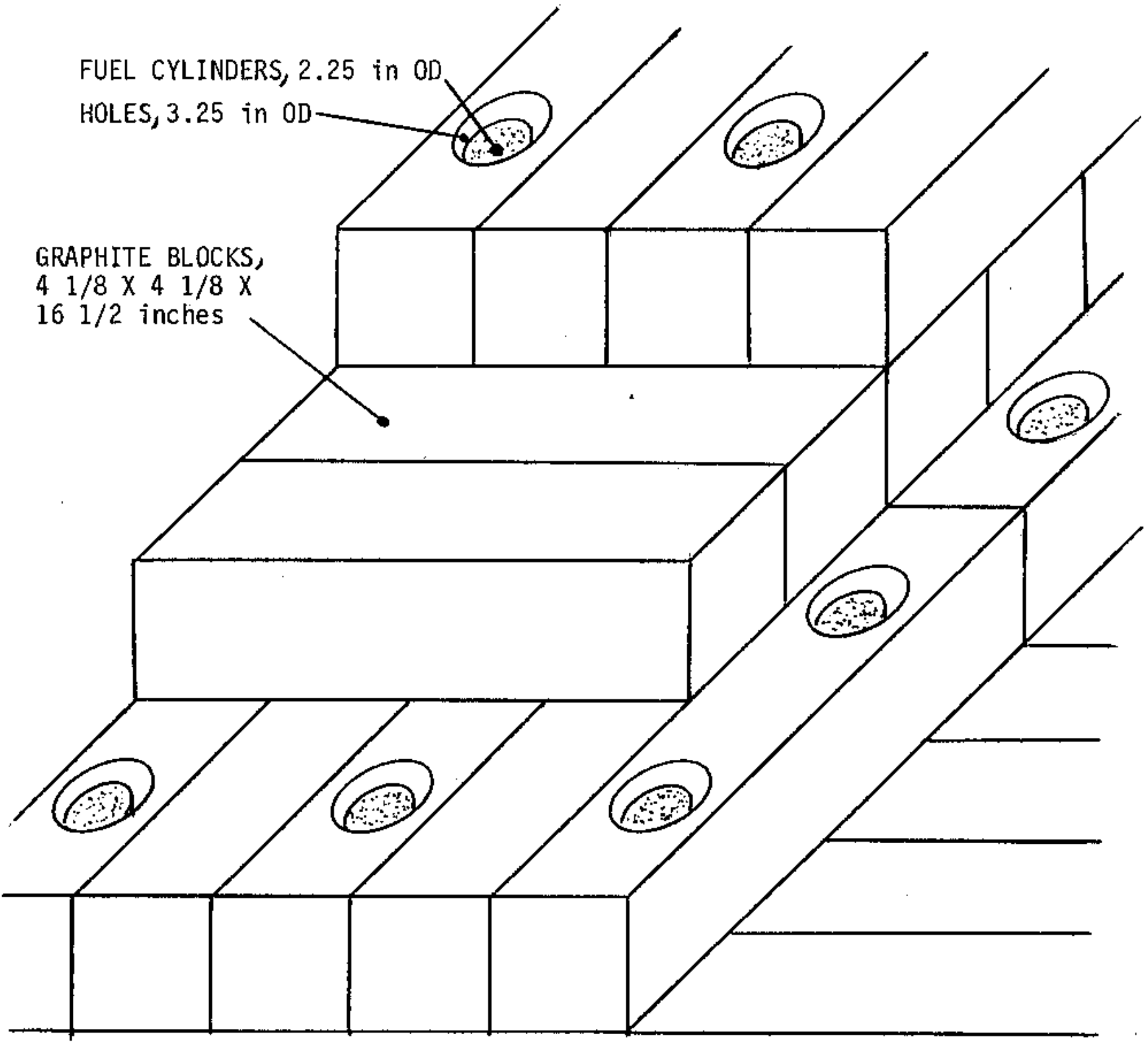


$U^{238}$

Figure 5: Neutron Cross-Sections

| SUBSTANCE | FORM | COMMENTS |
|---|---|---|
| HYDROGEN | WATER | CHEAP, BUT MILD ABSORBER |
| DEUTERIUM | HEAVY WATER | EXPENSIVE, LOW ABSORBER |
| HELIUM | GAS | NOT DENSE ENOUGH |
| LITHIUM | METAL | A HIGH ABSORBER |
| BERYLLIUM | METAL | EXPENSIVE, TOXIC |
| CARBON | GRAPHITE | CHEAP, MILD TO LOW ABSORBER |
| OXYGEN | GAS | NOT DENSE ENOUGH |

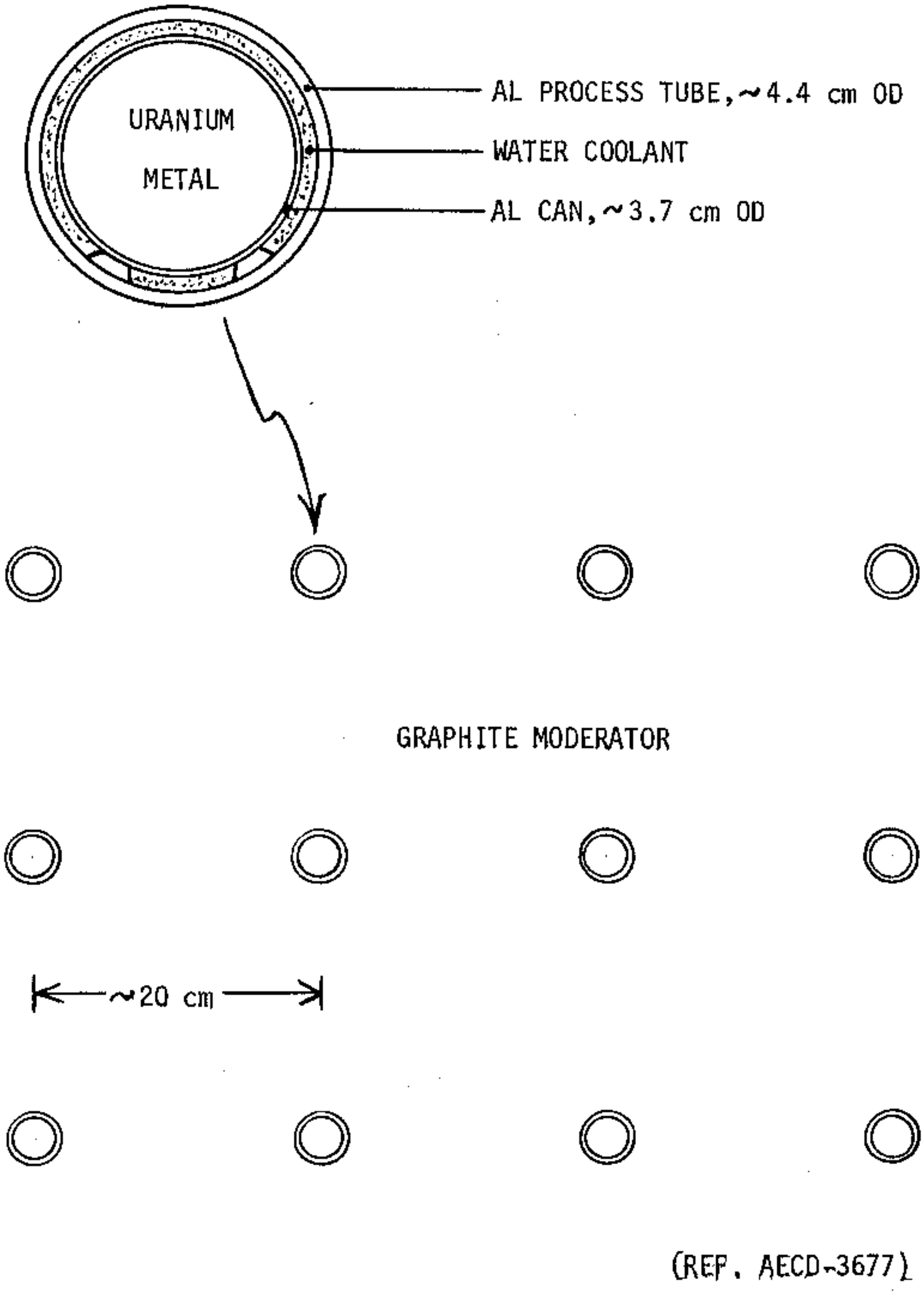
FIGURE 6: POSSIBLE MODERATING SUBSTANCES



REACTOR CONSISTED OF: 40,000 Graphite Bricks, 22,000 Fuel Locations, Fuel Cylinders; U Metal (5630 Kg), U02 (32,000Kg), U308 (8130 Kg)

FIGURE 7: CP-1 FUEL AND MODERATOR ARRANGEMENT

(THIS REACTOR ACHIEVED CRITICALITY ON DECEMBER 2, 1942)



(REF. AECD-3677)

FIGURE 8: FUEL AND MODERATOR ARRANGEMENT IN A PLUTONIUM PRODUCTION REACTOR.

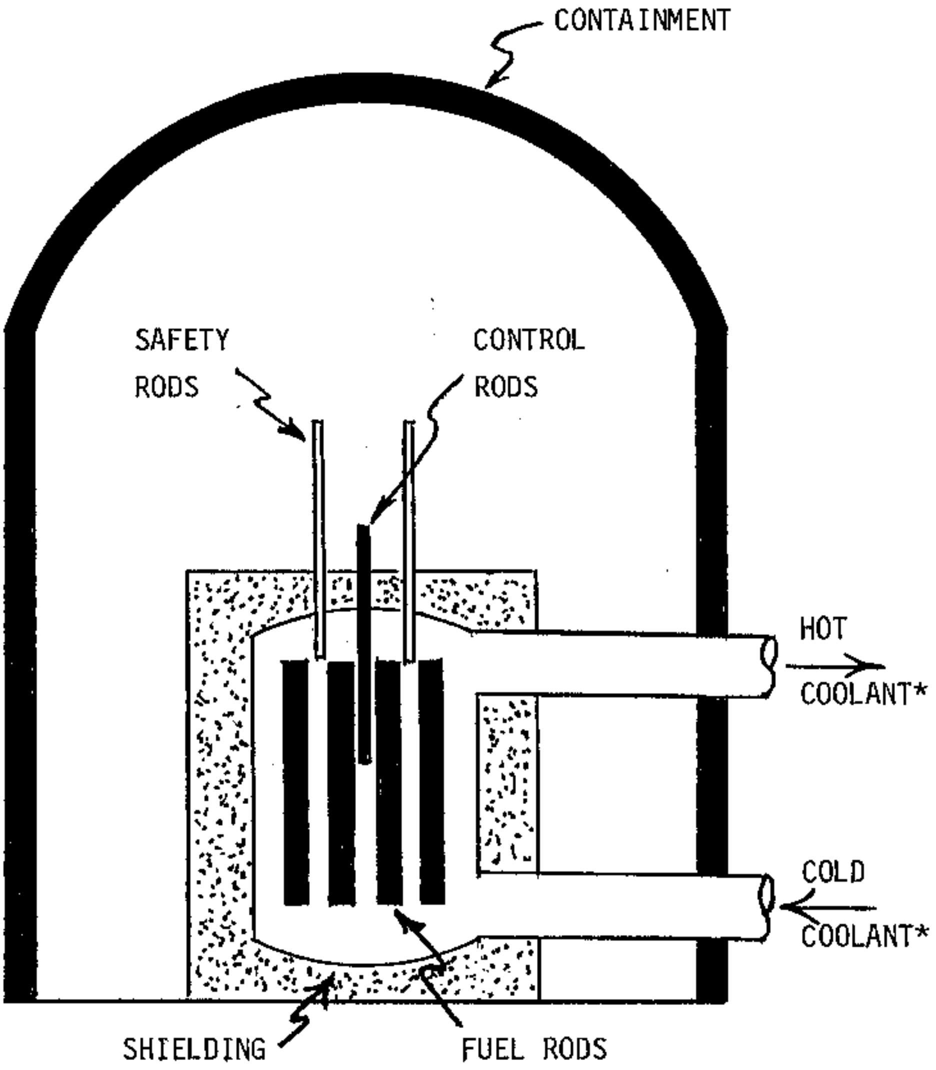
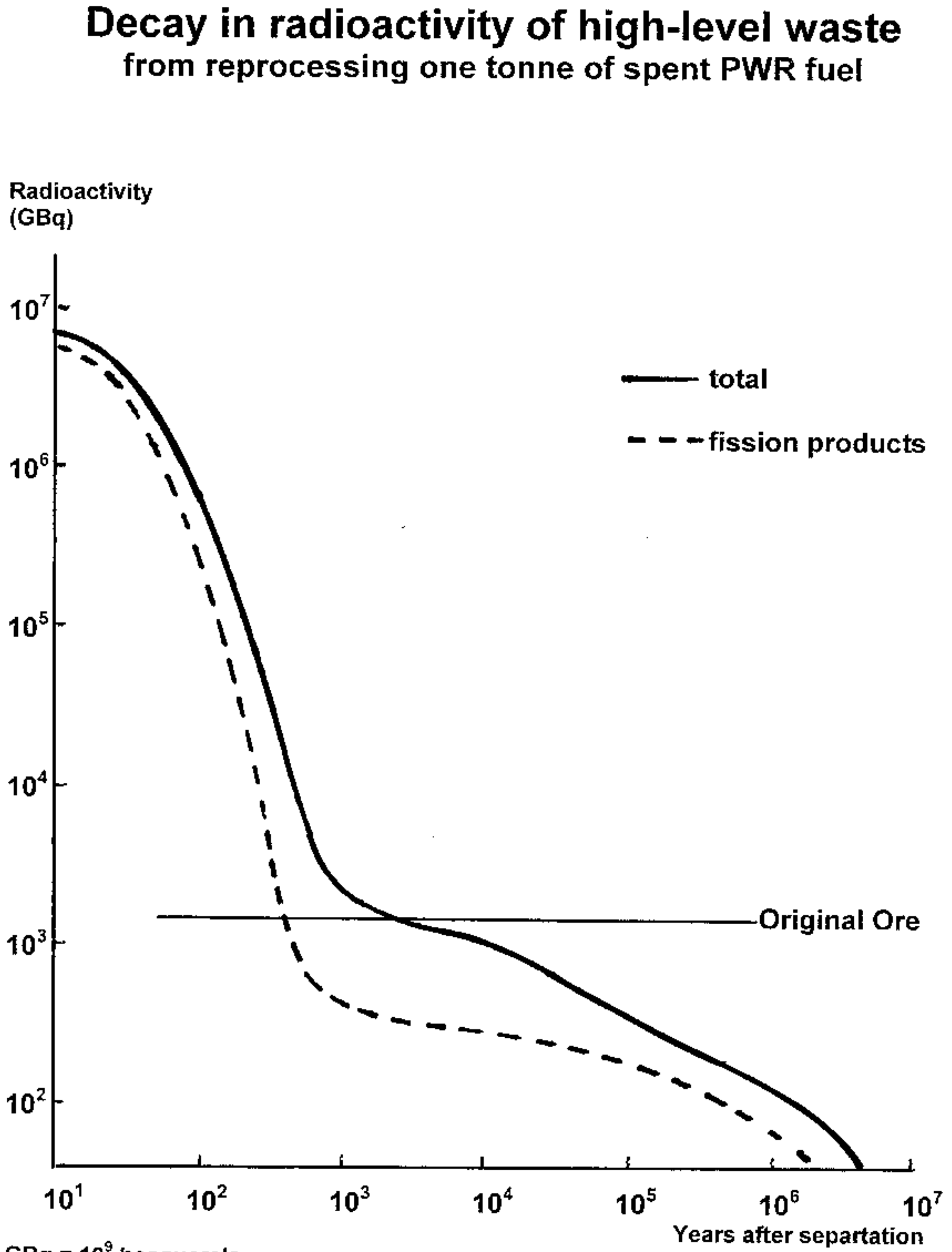


FIGURE 9: SCHEMATIC OF A REACTOR

*NOTE: Most reactors have an intermediate heat exchanger inside the containment (not shown) thereby avoiding the necessity of piping the primary coolant outside the containment.



GBq = $10^9$ becquerels
The straight line shows the radioactivity of the corresponding amount of uranium ore
Source: OECD NEA 1996, Radioactive Waste Management in Perspective

FIGURE 10: LIGHT WATER REACTOR HLW DECAY