DEEP UNDERGROUND TRANSMUTOR (PASSIVE HEAT REMOVAL OF LWR WITH HARD NEUTRON ENERGY SPECTRUM)

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Abstract

To run a high conversion reactor with Pu-Th fuelled tight fuelled assembly, which has a long burn-up of a fuel, the reactor should be sited deep underground. By putting the reactor deep underground heat can be removed passively not only during a steady-state run and also in an emergency case of loss of coolant and loss of on-site power; hence the safety of the reactor can be much improved. Also, the evacuation area around the reactor can be minimised, and the reactor placed near the consumer area. This approach reduces the cost of generating electricity by eliminating the container building and shortening transmission lines.

1. Introduction

The concept of a high conversion light water reactor using a high concentration of Pu-fuel tight-lattice has been proposed [1]. This reactor has a hard neutron energy spectrum close to that of an Na-cooled fast reactor, and high burn-up of fuel can be obtained. A reactor with uranium fertile material has a positive water-coolant void coefficient, so, to get a negative void-coefficient, it is required a pancake-type flat core configuration or a fuel assembly with a neutron-streaming void section which reduces neutron economy. The use of thorium fertile material [2], however, provides a negative void-coefficient without having neutron-leaky core configuration; the neutron economy accordingly is improved and a higher burn-up of fuel can be obtained compared with a reactor with uranium fertile materials. However, the pumping power of water coolant has to be substantially increased to remove the high-density heat from a tight latticed-fuelled core. During steady operation, coolant flow can be maintained by increasing pumping power several times above that of the regular LWR. But during emergencies, such as an outage of on-site power or loss of coolant, heat removal becomes serious problem. This accident scenario has been studied analysed in detail and an experimental study for heat removal from a tight lattice has been planned in the Japanese research programme.

Due to the hard neutron energy spectrum from the high concentration of the Pu-fuel tight lattice and the good neutron economy, this reactor can be used for transmuting minor actinide (MA) and long lived fission product (LLFP). MA has a similar neutronics properties as the fertile material of thorium. By capturing the neutrons, MA will be converted into fissile material, and thereby contribute to long burn-up of fuel. To transmute the LLFP of Tc, which has low neutron-capture cross-section, a moderator such as zirconium hydride is used in the transmutor cooled by Na or Pb-Bi; however, the neutrons can be effectively moderated by light water, so that the configuration of the light-water-cooled transmutor becomes simple.

2. Passive heat removal

To withstand an emergency case of loss of pumping power, a passive cooling system, such as heat removal using the natural circulation of the coolant, has been studied. I propose here using a tight-latticed water reactor embedded in a deep underground location, so that it is cooled by the natural circulation of the water. The high pressure difference between the inlet and outlet in the narrow water channel of the tight lattice is generated by the difference in gravity force between the low density of boiled water and the high density water condensed after the steam passes through steam turbine. To obtain such a high-pressure difference, the vacuum condenser must be located far above the boiling point of the water. The pumping-pressure difference needed to circulate water in a regular BWR and PWR are, respectively, 2 atm and 1.5 atm which is equivalent to a 20-15 meter difference in water height. But for our high conversion (HC) LWR with a tight lattice, the difference in pumping power is increase several times; a water height of more than 80-60 meters is needed to naturally circulate coolant water. By putting the reactor deep underground, we can provide enough space to get such a high pressure difference between the inlet and outlet using the density difference between the steam section and the water which is condensed after passing through the steam turbine and steam condenser which in our configuration are located far above the reactor vessel.

By locating the reactor even deeper, the pressure imposed on the pressure vessel is increased by the gravitational force of the surrounding earth. A water pressure of 100 atm and 150 atm for a BWR and a PWR can be provided, respectively, by the earth's pressure at a depth of 400- and 600-meters.

The passive cooling system using natural circulation which is conventionally proposed, is operated in an environment wherein there is not enough pressure, so that the steam -water state is not well defined and some instability is created; hence this is not necessarily a safe operation, even in the passive state. By operating at a high enough pressure, these non-linear effects can be eliminated, and we can obtain safe operation of the reactor deeper underground. From this point of view, there are many advantages to the concept of a deep underground reactor. Due to the pressure of earth's gravity, the pressure vessel can be quite thin, thus the reactor would be much lighter than that of a regular LWR operated on the earth surface. A huge heavy crane would not be required to move this reactor and it could be constructed with a modular-type design.

It has been proposed to use super-critical steam for gaining high efficiency of electric generation [3], this reactor requires 250 atm water pressure, this can be achieved by the earth pressure in the 1 000 meter deep under ground: 260 atm. The more high water pressure can be obtained by providing thick pressure vessel.

3. A deep underground facility

Deep underground geological storage of high level waste has been studied. The depth of the Yucca Mountain Repository is about 300 meters depth, so that a tunnel more than tens of kilometers long is planned.

To measure neutrino oscillation, a super-kamiokande detector with a 50-meter high and 40-meter diameter water-tank is installed 1 000 meters deep in a mountain in Kamioka mine in Japan. Many other high-energy facilities such as the Grand Sasso (Italy) have been used for such high-energy experiments.

The cost of the digging a large hall underground is not as expensive as digging above ground. I was informed that the cost of a 10×20 meter tunnel is about 10 000 dollars per 1 meter depth in Japan, although this depends on geological features. Nevertheless, the cost of the digging in hard rock deep underground is cheaper than excavating in shallow but fractured rock [4].

Figures 1 and 2 respectively show the conceptual layout of the installation of a BWR and a PWR in deep underground. The emergency cooling can be installed high above the reactor, to provide the high pressure needed to cool the decay heat. In the PWR version, the heat exchanger with primary boiling water is used to obtain the high-pressure difference between the inlet and outlet of narrow water channel.

To get a high gravitational force, deep tunnelling such as in the case in Yucca Mountain programme can be utilised instead of making a deep vertical hole, the reactor can be embedded in the tunneling's wall. By putting the steam turbine and vacuum condenser far above level of the reactor we can get high pressure difference between inlet and outlet in the narrow cooling water channel so that heat can be removed by the natural circulation of water. In a light reactor without a thick pressure vessel, when the fuel must be exchanged (which is infrequent due to long burn-up of fuel in Pu-fuel with thorium fertile with a tight latticed reactor), the reactor can be taken out of the wall of the tunnel, and fuel can be exchanged in the space adjacent the tunnelling wall. Although the tubes of steam and condensed water must be disconnected and connected again to do this, it can be done without difficulty.

4. Economy of the deep underground reactor, transmission lines, container building's emergency cooling system and evacuation

To protect the public from radiation hazards in the fall out from radioactive releases from regular nuclear power plants, a container building for the reactor is provided. By putting the reactor deep underground, the radiation field generated from any release would be very small, and we could minimise the number of people who would have to be evacuated.

Thus, we could build a NP near a consumer area and thereby shorted the transmission lines. This would entail substantial reduction in the cost of electricity generation. Generally the cost of transmission lines is very substantial, especially establishing lines in densely populated areas where the cost of land is high; it was estimated that the construction of a transmission line of more than 400 km is greater than the cost of building the power plant itself.

Although installing many facilities, such as the steam turbine and vacuum condenser is more expensive than building on the earth's surface, by not having to construct long transmission lines and a double-walled container building and other facilities associated with having a seismically strong building structure, lowers the overall cost of the constructing the reactor deep underground. However, a detailed cost evaluation is still required.

To remove decay heat after an accident, emergency-cooling borated water is stored in the container building; in the case of the tight-lattice reactor, the height of the cooling water must be considerable to get the needed high pressure; also it is very vulnerable for seismic protection.

When the reactor is deep underground the emergency borated water also can be stored underground where the movements of an earthquake is smaller than at shallower depths. Also there is enough room to store a huge amount of water high above the reactor and so water under high pressure can be provided to cool the reactor.

Also to protect against re-criticality of the core due to its melting, a large pool of water can be provided under an underground reactor without difficulty.

Installing a nuclear facility in under deep underground ensures that public are well protected. We can eliminate containment building and reduce the seismic hazards avoiding the strong earth motions at the surface. The area of emergency evacuation, which closed down the Shoreham NP near BNL in the last decade, also be minimised, thus there is possibility of constructing the NP near a consumer area, and the expensive construction of high voltage electricity transmission lines can be lessened. Therefore, building a deep underground reactor might be more economical than building the nuclear power plant on the above ground. Although it might be very difficult to obtain public acceptance in the present political climate, it might be wise to built future reactor deep underground.

5. The accelerator driven reactor

I have discussed a power-generating reactor so far, but this reactor with its hard-neutron energy spectrum, can also be used for transmuting the minor actinides and LLFP. As the neutron energy spectrum becomes harder, neutron economy increased, but the negative void-coefficient might be small and so the delayed neutron portion also becomes small. To run this type of reactor in a safer mode, it is desirable to run it in a sub-critical condition.

For transmuting minor actinides (MAs) and long-lived fission products (LLFPs), several kinds of nuclear reactor concepts were proposed, such as the Na, Pb, Pb-Bi cooled fast reactor in critical operation, and in sub-critical operation driven by spallation neutrons. For a transmutor of Tc, which has a low neutron-capture cross-section at intermediate energy, to a get high transmutation rate, the high-energy neutron is thermalized by moderator such as Zr hydride. In this water-cooled reactor the excellent moderator of water is in the core and so it is not necessary to install another moderator.

I have proposed using an accelerator driven reactor [5], run sub-critical condition by providing spallation neutrons created by medium energy proton. When the spallation target is equipped with a beam window, it should be protected from radiation damage by expanding the proton beam. By locating the reactor deep underground, there is enough space to install the beam expansion section.

6. Conclusion

The construction of a nuclear power plant underground was proposed by A. Sakharov and E. Teller [6] for protection against radiation hazard, and Russian Pu and Electric Generation nuclear power plant is operated in Enisei river [7]. However, my proposal for a deep underground reactor uses earth's gravity force to provide passive heat removal using natural circulation of the reactor coolant, such a nuclear power plant can be operated more safely. The high pressure required for heat removal from the coolant can be supplemented by use of earth's gravity. Also it provides the pressure difference required removing fission heat from the nuclear fuel with natural circulation of gravity force. This natural-water-coolant circulation can eliminate concerns about an on-site electricity blackout. The storage facility for the emergency coolant system can be built far above the reactor because there is enough space available in a deep underground installation.

Also for defence purposes in protecting people from nuclear hazards created by nuclear plants smart bombing, future reactor should be built in deep underground.

Here, I have discussed mainly the light water reactor, but this concept equally can be applied to gas-cooled reactors, which require high pressure, and it will apply many other types of rectors.

The capability of removing heat, not only during steady-state operation but also in accidents involving a loss of coolant or an outage in on-site power is essential especially for the HC reactor with tight latticed fuel assembly. By putting the reactor deep underground and removing heat passively, public safety is ensured.

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REFERENCES

[1] T. Iwamura *et al.*, *Resarch on Reduced-moderation Water Reactor (RMWR)*, JAERI_research Report, 99-058 (In Japanese).

[2] Hiroshi Takahashi, Upendra Rohatgi, *A Proliferation Resistant Hexagonal Tight Lattice LWR Fuelled Core for Increased Burn-up and Reduced Fuel Storage Requirements*, Progress report of NERI: Aug. 1999 to May 2000.

[3] Y. Oka, *Physics of Supercritical Pressure Light Water Cooled Reactors*, 1998 Frederic Joliot Summer school, Aug. 17-Aug. 26 1998, Cadarache, France.

[4] K. Higuchi, Ikuta, Private Communication, Nov. 2000.

[5] H. Takahashi, *Safe, Economical Operation of a Slightly Sub-critical Fast Reactor and Transmutor with a Small Proton Accelerator*, Proc. Int. Conf. on Reactor Physics and Reactor Computation, p. 79, Y. Ronen and E. Elias (Eds.), Tel-Aviv, Jan. 23-26, 1994, Ben-Gurion Univ. of the Negev Press (1994).

[6] Edward Teller, Muriel Ishikawa, Lowell Wood, Roderick Hyde and John Nukolls, *Completely Automated Nuclear Reactors for Long Term Operation II*, ICENES 96.

[7] Informal meeting between US and Russia for Pu reduction at BNL, Sept. 2000.

Figure 1. **Layout of deep underground BWR**

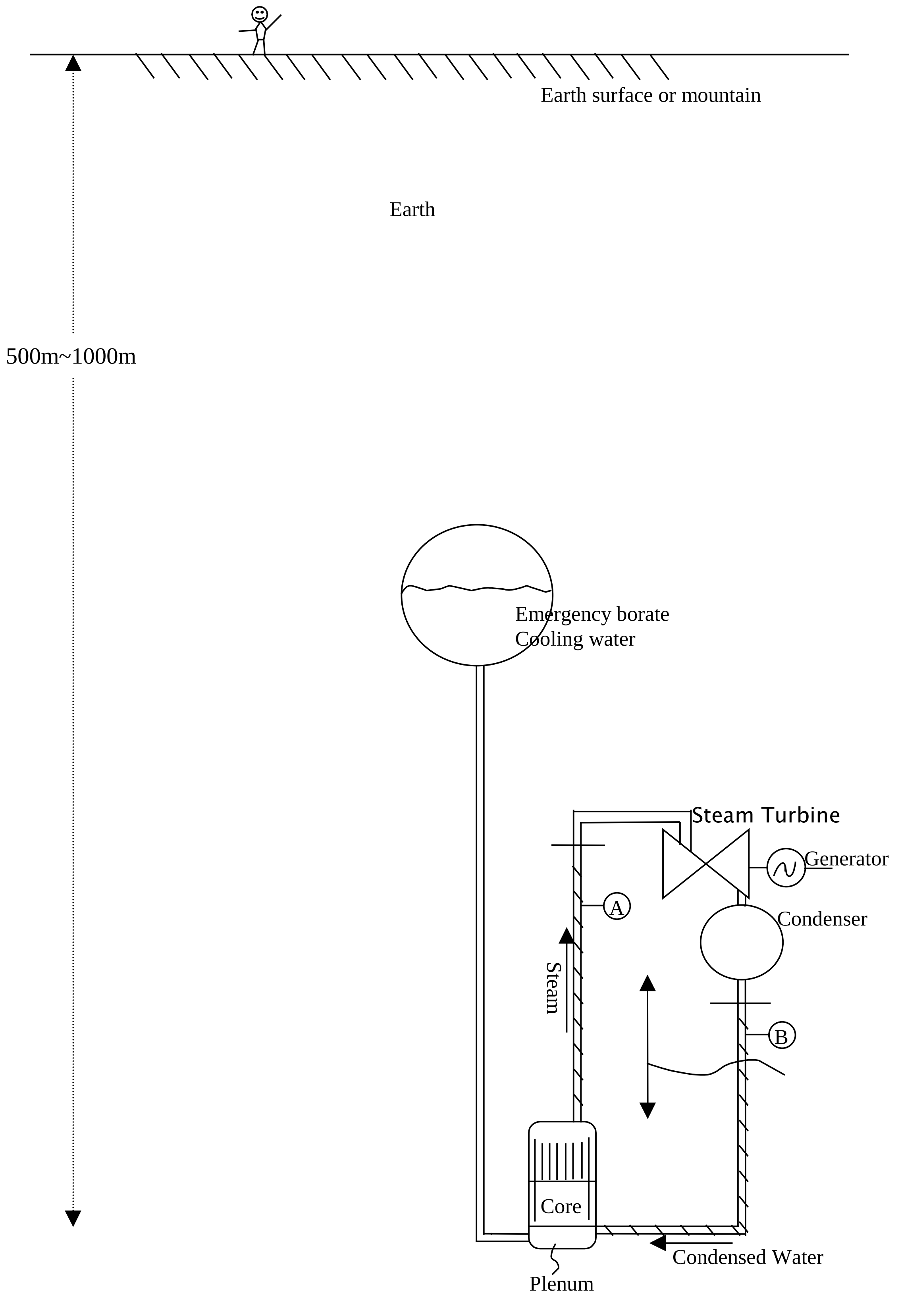

Figure 2. **Layout of deep underground PWR**