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THEORETICAL AND PRACTICAL ASPECTS OF 'WASTELESS' NUCLEAR ENERGY

P. Anggraita
Centre for Accelerator Technology and Material Process
National Nuclear Energy Agency (BATAN)
Jl. Babarsari, Yogyakarta 55281
pramudita@batan.go.id

ABSTRACT

THEORETICAL AND PRACTICAL ASPECTS OF 'WASTELESS' NUCLEAR ENERGY. The problem associated with the current NPP is the generation of nuclear waste and some elements in the waste have very long time of radioactivity. This paper reviews some concepts of nuclear energy generation with less nuclear waste. A concept of accelerator driven system (ADS) or energy amplifier (EA) was proposed by Carlo Rubbia, recipient of 1984 Nobel Prize in particle physics. The system is supposed to generate nuclear energy with radioactive waste of much less and shorter lifetime than those generated by present generation of nuclear power reactors. Less radioactive waste will also be generated by fusion reactions, either in hot fusion of high temperature plasma confined in a very strong magnetic field, or in cold fusion conceptually happens in muon-catalytic and lattice-trap fusions. A concept of neutronless nuclear reaction, hence activating no radioisotopes, to generate nuclear power was proposed. Present nuclear power reactors based on fission are also the source of very large number of electron neutrinos, which can be used to study neutrino oscillations.

Keywords : Nuclear waste, Accelerator driven system, Cold and hot fusion, Neutronless nuclear reactions

INTRODUCTION

The greatest use of nuclear physics is the the nuclear chain reaction proposed conceptually by Leó Sźilard in 1933. In 1939 Leó Sźilard and Enrico Fermi found out that multiplication of neutron number occurred in uranium (isotope ^{235}U, 0.7% natural abundance), making possible nuclear chain reaction induced by neutrons, generating large amount of energy. The first nuclear reactor achieving critical condition (sustained nuclear chain reaction) was built in Chicago in 1942 within the Manhattan Project. As it was developed during and for the purpose of war, the first application is for a nuclear bomb.

Application of nuclear reactor for peaceful uses is to generate electricity (nuclear power plant, NPP), which was first demonstrated at Obninsk, near Moscow in June 26, 1954, with 5 MW of electricity for 2000 homes[1]. In the world today there are 435 commercial NPPs operating in 30 countries, with a total capacity of 370 GW electricity or 16% of the world electricity, and 56 countries operate 284 research reactors (3 of which in Indonesia) and 220 power reactors in ships and submarines[2].

The problem associated with the current NPP is the generation of nuclear waste. The existing or near future NPPs work based on fission or splitting of atomic nuclei by neutrons, which generate fission products or other radioisotopes. Some of these elements have very long time of radioactivity. In NPPs these radioactive products are retained in multilayered containment (defence in depth) by fuel matrix, special cladding, neutron moderator (light or heavy water or graphite), reactor vessel, concrete shield, and reactor containment building. Hence the possibility of its release to the environment is very small.

The radioactivity of all nuclear waste diminishes with time. All radioisotopes contained in the waste have a half-life - the time it takes for any radionuclide to lose half of its radioactivity and eventually all radioactive waste decays into non-radioactive elements. Certain radioactive elements (such as plutonium-239) in “spent” fuel will remain hazardous to humans and other living beings for hundreds of thousands of years. Other radioisotopes will remain hazardous for millions of years. Thus, these wastes must be shielded for centuries and isolated from the living environment for hundreds of millennia. Some elements, such as ^{131}I, have a short half-life (around 8 days in this case) and thus they will cease to be a problem much more quickly than other, longer-lived, decay products but their activity is much greater initially.

Intermediate Level Waste (ILW) contains higher amounts of radioactivity and in some cases requires shielding. ILW includes resins, chemical sludge and metal reactor fuel cladding, as well as contaminated materials from reactor decommissioning. It may be solidified in concrete or bitumen for disposal. As a general rule, short-lived waste (mainly non-fuel materials from reactors) is buried in shallow repositories, while long-lived waste (from fuel and fuel-reprocessing) is deposited in deep underground facilities. High Level Waste (HLW) contains fission products and transuranic elements generated in the reactor core. It is highly radioactive and often thermally hot. HLW accounts for over 95% of the total radioactivity produced in the process of nuclear electricity generation.

By reprocessing some parts of the spent fuel can still be reused. Reactor with heavy water moderator (e.g. of CANDU type, Canadian Deuterium Uranium System) can directly used spent fuels from PWRs (Pressurized Water Reactor) in DUPIC (Direct Use of spent PWR fuel In CANDU) cycle. Fast nuclear reactors working at fast spectra of neutron (e.g. sodium cooled reactor) transmute long live radioisotopes into shorter live radioisotopes while generating energy (Advanced Burner Reactor). These fourth generation of reactors (Gen IV), some also gas cooled, operate at higher temperatures (HTR, High Temperature Reactor), hence the thermal efficiency double the present NPPs (Gen II and III) which is only about 30%. Better thermal efficiency means reduction in the amount of nuclear fuel and waste to generate the same amount of energy. Gen IV NPPs are expected to begin operation in 2030[3].

Fusion reactors uses deuterium (D) and tritium (T) as fuel in the form of hot plasma (hot fusion, temperature of 40 to 100 million K). To confine the hot plasma to produce nuclear fusion a very strong magnetic field is required. Since there is no fission product, the amount of nuclear waste is very much reduced (only about 5% of those generated by fission NPPs). The small amount of nuclear waste generated by fusion is the result of activation of materials used by neutrons coming out from the nuclear fusion. Fusion reactors to generate electricity do not exist yet and in the end of 2006 the construction of ITER (International Thermonuclear Experimental Reactor) was started in France and it is expected to begin operation in 2016[4].

EFFORTS TO REDUCE OR ELIMINATE NUCLEAR WASTE

To reduce or eventually eliminate nuclear waste some concepts are proposed by particle physicists.

ADS (Accelerator Driven System)

This system was proposed by Carlo Rubbia, former director of the European Nuclear Research Centre (CERN, *Centre Européenne pour la Recherche Nucléaire*), recipient of 1984 Physics Nobel Prize for his discovery of W and Z gauge bosons of weak nuclear forces. Rubbia proposed to to use $0.8 - 1$ GeV beam of proton on heavy nuclei target, such as lead or thorium, producing spallation neutron beam which can be used to sustain a chain nuclear reaction on a sub-critical system of uranium or thorium. The system will generate energy many times those needed to produce the proton beam, hence it is named energy amplifier (EA) (Figure 1)[5-7].

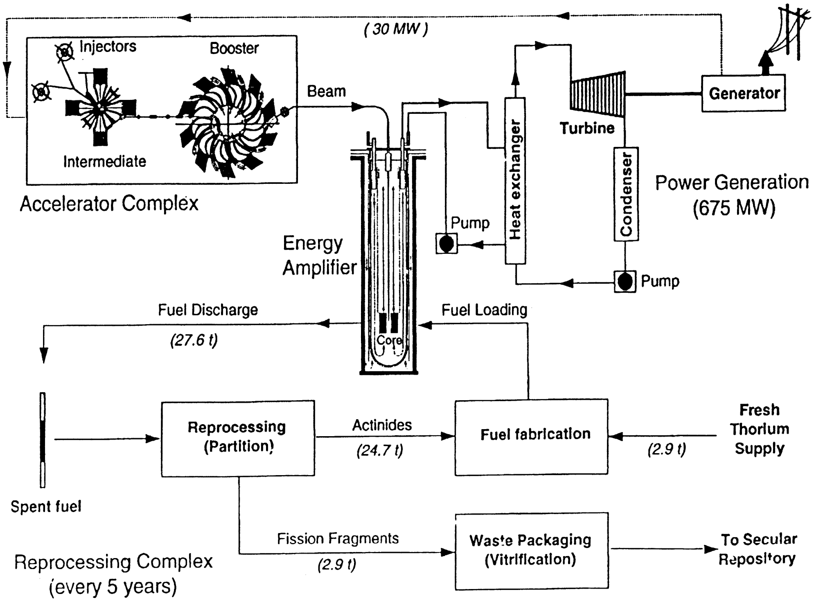

Figure 1. Energy Amplifier (EA) System[5].

The advantage of this system is in its use of a sub-critical system, which will not sustain nuclear chain reaction once the proton beam stops. The use of thorium is another advantage as it is more abundant than uranium and no isotope enrichment is required. The fast spectra of neutron used will incinerate actinides, therefore generating less long-live nuclear waste and after about 500 years the fission fragments will have the same level of radioactivity as coal ashes. The disadvantage of this system is the need of proton accelerator with high beam current (about 10 mA), which will be very costly and none has ever been built.

As the nuclear chain reaction is controlled by accelerator, the system is also called ADS (Accelerator Driven System)[8]. This system can also be used to incinerate or transmute long live actinides generated in nuclear fission reactors, such as ^{237}Np, ^{241}Am, ^{243}Am, and ^{239}Pu[9]. For ^{239}Pu, which can also be used as fast nuclear reactor fuel, can also be incinerated in EA system. Carlo Rubbia estimated by using combination of EA-PWR for power generation, all ^{239}Pu ever generated by PWR can be eliminated within 60 years (Figure 2)[10].

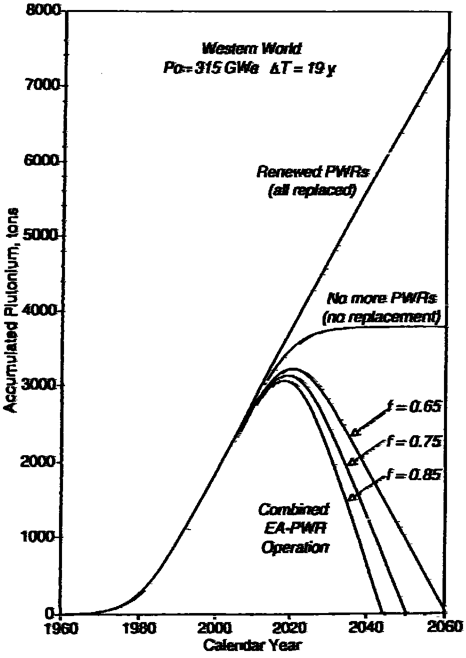

Figure 2. Elimination of ^{239}Pu by using combined EA-PWR operation[10].

Cold Fusion

Cold fusion is a nuclear fusion reaction that occurs near room temperature and normal pressure. This may happens if a positively charged deuteron (*d*), a positively charged triton (*t*), and a negatively charged muon form a positively charged muonic molecular heavy hydrogen ion $(d\text{-}\mu\text{-}t)^+$. The muon, with a rest mass about 207 times greater than the rest mass of an electron, is able to drag the more massive triton and deuteron about 207 times closer together to each other, increasing the probability of *d* and *t* to fuse. This process is called muon-catalyzed fusion (μCF), and it was theoretically predicted by Andrei Sakharov and F.C. Frank in 1947[11] and experimentally observed in 1957 by L.W. Alvarez, et al[12]. From present computation, each muon will cause as many as about 200 *d*-*t* fusion, which is not sufficient yet to reach break even point. Also economical means to generate sufficient number of muon do not exist yet.

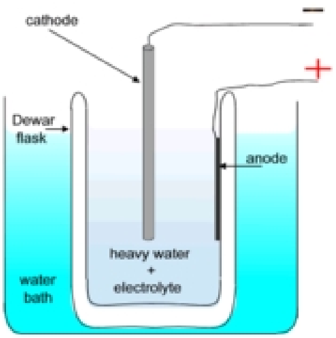

Figure 3. The electrolysis cell[13].

In March 1989 Fleischmann and Pons observed excess energy of more than 1 kW/cm^3 occurred in the electrolysis of heavy water (D_2O) using palladium (Pd) rod as a cathode (Figure 3)[13]. At room temperature palladium is known to be able to absorb hydrogen gas up to 600 times its own volume. By adding a chemical potential of several electronvolts at the electrolysis, extrapolation of quantum density formula provides a very high pressure to the deuterium (D_2) gas trapped or absorbed in Pd lattice, hence increasing the probability of deuterium fusion. A theoretical calculation to obtain the data as observed was attempted (Figure 4)[14] but so far experimental data do not yet convincingly confirmed that the cold fusion nuclear reaction has really happened.

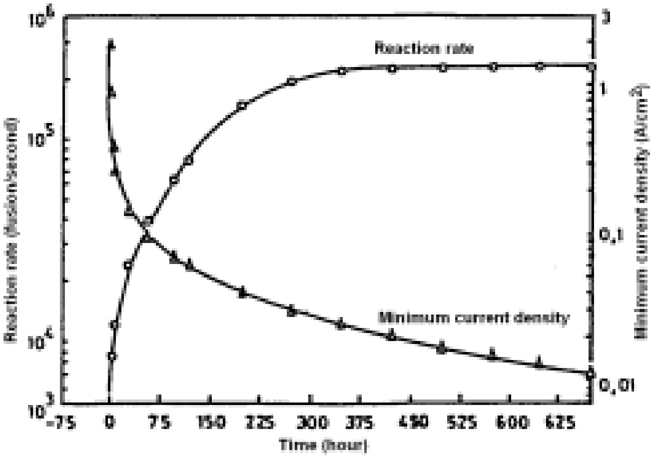

Figure 4. A calculation on cold fusion rate (s^{-1}) and minimum current density *vs* time (hours)[14].

Neutronless Nuclear Reaction

In the Scientific Forum on Nuclear Fuel Cycle at the IAEA General Conference in September 2004, Carlo Rubbia conveyed his view on the distant future to achieve nuclear energy without generating radioactive waste. Several exothermic nuclear reactions do not produce neutrons, hence no radioactive waste generated by neutron activation.

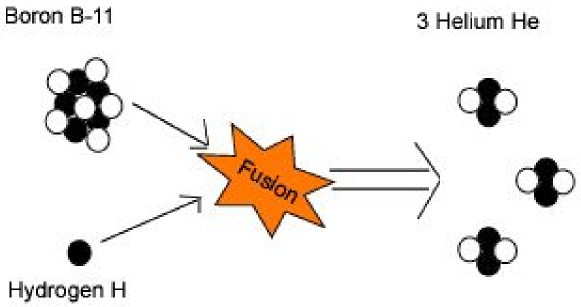

Figure 5. Neutronless nuclear fusion of a proton and a B-11 nucleus, yielding three stable He-4 nuclei.

One candidate for that nuclear reaction is the fusion of a proton (nucleus of hydrogen) and a nucleus of boron-11 (B-11, with 5 protons and 6 neutrons), yielding exactly 3 stable He-4 nuclei with no leftover neutrons (Figure 5). Hydrogen and boron are easily obtainable, with B-11 isotopic abundance of 80.1%. The challenge is the proton-boron fusion requires temperature as high as 1 billion K. This high temperature is not yet attainable in the available present D-T reaction system, but the focus fusion plasma device can[15]. A focus plasma system for D-D fusion (temperature about 100 million K) had been operated at BATAN Yogyakarta[16].

NUCLEAR REACTOR AS SOURCE OF NEUTRINOS

Beside performing nuclear fissions and activations that generate nuclear waste, most of the neutrons generated at nuclear fission reactors will decay into protons, electrons, and electron antineutrinos at very large number. According to the theory of neutrino oscillations, some of these electron antineutrinos (first generation) will oscillate into muon (second generation) and tau (third generation) antineutrinos. Therefore nuclear reactors can be used to study neutrino oscillations beside solar, atmospheric, and accelerator beam sources. The experiments will determine the three mixing angles in the Maki-Nakagawa-Sakata matrix (also called the "MNS matrix", "neutrino mixing matrix", or sometimes "PMNS matrix" to include Pontecorvo). It is the equivalent of the CKM (Cabibbo-Kobayashi-Maskawa) matrix for quarks. If this matrix were the identity matrix, then the flavor eigenstates would be the same as the mass eigenstates. However, experiment shows that it is not. The experiments also determine the estimate on the mass of neutrinos.

The observed values of oscillation parameters θ_{13} < 13°,[17] $\theta_{12} = \theta_{sol} = 33.9°\,^{+2.4°}_{-2.2°}$ ("sol" stands for solar), $\Delta m^2_{21} = \Delta m^2_{sol} = 8.0^{+0.6}_{-0.4} \times 10^{-5}$ eV^2, [18] $\theta_{23} = \theta_{atm} = 45° \pm 7°$ ("atm" stands for atmospheric), $\Delta m^2_{31} \approx \Delta m^2_{32} = \Delta m^2_{atm} = 2.4^{+0.6}_{-0.5} \times 10^{-3}$ eV^2,[19] and the phase δ that determines CP violation is still unknown. The experiments to measure the mass and mixing among neutrinos are still continued by using electron antineutrinos generated from nuclear reactions at power reactors in France (Double Chooz) and China (Daya Bay)[20] or from accelerator at Fermilab[21]. In both the Double Chooz and Daya Bay experiments, the distance to the far detector will be a kilometer or so, the length scale for oscillations of electron neutrinos into muon or tau neutrinos; θ_{13} is a parameter of the probability distribution for such oscillations. KamLAND, by contrast, watches for different oscillations, at 150 to 200 km. The best measurement to date was made at Chooz, Double Chooz's predecessor, and sets the upper limit of $\sin^2 2\theta_{13}$ at about 0.2. Double Chooz aims to explore down to 0.03, while the planned sensitivity for the Daya Bay experiment is 0.01. The upper limits of neutrino masses are $m_{\nu_e} \leq$ 2,2 eV, $m_{\nu_\mu} \leq$ 170 keV, dan $m_{\nu_\tau} \leq$ 15,5 MeV[22]. Some theoretical works on neutrino masses and oscillations are still being continued[23,24].

CONCLUSIONS

Pioneered by particle and nuclear physicists such as Enrico Fermi, Oppenheimer, Feynman, Teller and others, nuclear reactions have been utilized both for the purpose of war and peace. For the benefit of all mankind, indeed the second one that must be pursued. At present, utilization of nuclear energy still leave long-live nuclear waste. Particle physicists, along with other engineers and scientists of other fields of science and technology, keep on developing nuclear reactions to transmute these long-live nuclear wastes into shorter-live ones. Nuclear reactions for power production that generate less nuclear waste, or even without radioactive waste, are still being pursued.

Beside power and nuclear waste, present day nuclear reactors also generate electron antineutrinos which are useful for fundamental research, namely neutrino oscillation experiments that will confirm or provoke theoretical models in particle physics.

Limited by the number of available scientific resources, Indonesia must find opportunities and with strong will, to participate in these activities by seeking and nurturing cooperation and networking with other developed and developing countries. These efforts could contribute to change people view on the future negative impact of nuclear energy, and the nuclear programme as stated in Law No. 17 year 2007 on the Long Term National Development 2005-2025, can be publicly accepted and done. Even new methods can be developed to generate cleaner nuclear energy, and this will contribute significantly to the efforts to reduce the recently concerned effect of global warming, that mostly caused by the greenhouse gas generated by fossil fuel power generation.

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