INNOVATIVE NUCLEAR ENERGY SYSTEM AND RELATED FUEL CYCLE FOR PEACEFUL USE OF NUCLEAR ENERGY

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ABSTRACT

It is considered that the nuclear science and technology will grow up to constitute a fundamental pillar supporting human civilization. The science and technology which supports the civilization has the long history to unveil the unforeseeable world though it is too small to look into, too big to catch whole sight or hidden in the veil. Upon this understanding, nuclear science and technology treats the interaction between radiation and material which starts from the microscopic quantum world and then extends to big world like cosmos which is governed mainly by quantum energy fundamentally. With the interactions, it has possibility to contribute to the civilization through 1) energy production 2) material conversion, 3) new technology development and 4) latent information and the laws of physics.

As equipment to facilitate these interactions, we have 1) nuclear fission reactors and nuclear fusion reactors, and 2) particle accelerators and lasers. This would be an essential view to broadly understand the whole picture of nuclear development from the aspect of a comprehensive nuclear science and technology. If we confine our discussion on the nuclear energy system, it is highly recommended to develop nuclear energy system which fulfills the conditions of long lasting resources and environmental protection simultaneously utilizing the assets of nuclear fission reaction. For future energy system supplied by nuclear fission reaction, the following five functions are required to be satisfied. 1) Energy production, 2) fuel production, 3) system safety, 4) conversion of long-lived radioisotopes into short-lived ones or non-radioactive materials and 5) proliferation resistance.

1. SCIENCE AND TECHNOLOGY SUPPORTS THE CIVILIZATION

Mankind has cultivated the civilization. The civilization has its basis on the science and technology from the beginning of human history. The fundamental fields and areas in the science and technology are four elements such as energy, information, material and technology. This feature has not changed through the history fundamentally, though we find big difference and improvement in quality and quantity. A comparison is made for the four elements in the past and present. (Fig.1)

For instance, concerning technology or in other word tool, the change is so big between the boat rowed by people and Queen Elizabeth, more with the space rocket and jet airplane. Time necessary for transportation by plane is governed by sound velocity at present.

Fig. 1 What has Civilization required to Science and Technology?

Concerning to material, age and era in the history can often be expressed by the material mainly used in that age such as: Stone Age, Clay Age and Bronze or Copper Age since the production of gold was too small to represent an age. People in Mesopotamia attempted to create gold by alchemy, but it failed in vain. The alchemy was realized when Ernest Rutherford created an artificial element by a nuclear reaction around 1930 using the Cockcroft- Walton accelerator.

The Iron Age came a few hundred years ago and initiated and supported the industrial revolution. Now, we are in the era of ceramics. We use ceramics in many areas of science and technology such as; semiconductor, artificial tooth and even nuclear fuel of light water reactor.

Concerning information, we have sensitivity on light, sound, smell, taste and feeling. Some are saying in Japan, the sixth sensitivity which can not be made clear, is more important to create new idea in science.

On the first day of the world creation but not Big Bang, God introduced light and separated day and night, as is described in the Old Testament. It clearly shows the light as the main information method. Nowadays information is transferred with light velocity with e-mail and other methods.
Language with literature enables us to memorize the history to the descending generations.
Energy, the most important one of the four is energy. The other three should be energized before and during operation.
The main energy source on the earth changes from physical to chemical and now, on the way to nuclear. The former two are originally supplied from the sun, in the form of sunshine, solar energy. What can nuclear energy play in the 21st century to supply plenty of energy and to preserve the environment? In other words, the recycling based civilization.

2. TO LEARN AND ASSIMILATE THE NATURE

Look at the sky, not in the daytime but at night. We can have many images concerning to the nuclear science and technology. Several phenomena in the cosmos beginning from the big bang, followed by creation of elements and radiation, birth and death of fixed stars, especially supernova are matters of interest. The phenomena in the sun and the earth are of course of major interest.

Big bang initiated the formation of the cosmos 14 billion years ago. (Fig.2) George Gamov, a Russian physicist, imagined the origin of the cosmos in the fireball of atomic bomb test at Manhattan Project. Big Bang was an expanding ball filled with soup of radiation and particles. It is the origins of time, space, energy or mass. We can see some high energy particles and mechanism of particle acceleration in the cosmos.

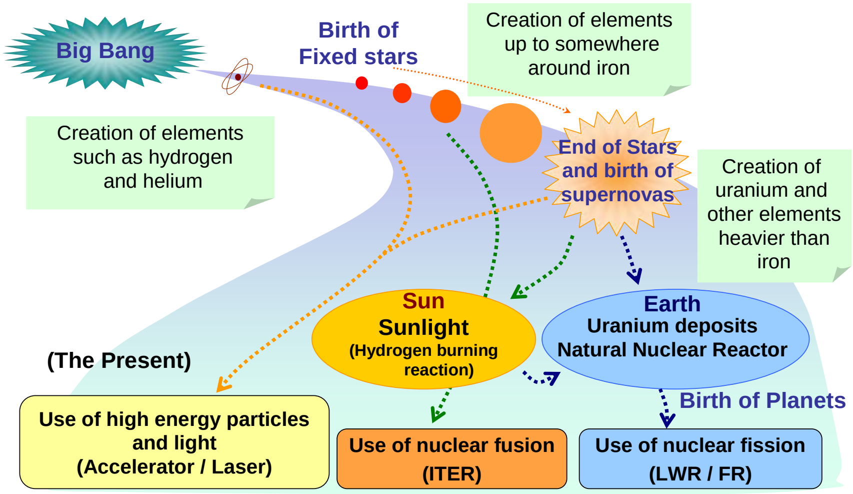


Fig. 2 Creation of the Cosmos

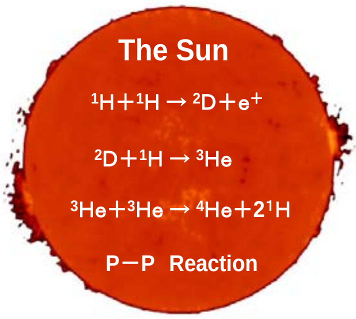
In fixed stars nuclear fusion reaction occurs and releases energy and creates elementary particles. Elements, not heavier than iron, are created in the fixed stars. But when a fixed star burns out its nuclear fuel, it sometimes become unstable and gravitational collapse happens to lead to supernova explosion. In the process of supernova, it is considered that gravitational energy is transformed to create heavy particles like uranium and trans-uranium (TRU). In Heian era a Japanese poet, Fujiwarano Teika described in his book “Meigetuki” the occurrence of supernova about 1000 years ago, a millennium ago. In the supernova, elements heavier than iron were created and distributed into the space. Sun and earth have also accumulated such heavy elements. We have uranium in the earth. It led to the natural fission reactors about two billion years ago at the Oklo uranium mine in the Republic of Gabon. And the sun makes a fusion reaction from hydrogen to helium and delivers so-dense energy into the space. George Gamov also proposed and analyzed the energy source in the sun due to the nuclear fusion from hydrogen to helium.

Laser as well as particle accelerator plays mainly for nuclear transmutation and change of material properties. It is also important to ask them to join for completion of nuclear fuel cycle and radiation application. These facilities will open the new era of nuclear science and technology in the coming civilization.

The nuclear science and technology treats the microscopic quantum world. However, the quantum world reveals its ability in the macroscopic world, that is stars in the cosmos. Really, energy in the cosmos is supplied by the nuclear reaction in the microscopic world. We find several important phenomena to apply for the nuclear science and technology as mentioned already. The facilities which bring the microscopic quantum world to the human society are nuclear fusion as well as nuclear fission reactor mainly for energy supply and particle accelerator as well as laser.

The sun has long been both an object of faith and a subject of study. Despite of our non-stop dependence on the sun, we only succeeded in proper understanding how it generates its energy midway through last century. The belief that the sun burns petroleum can be immediately rejected through detailed observation, as a chemical reaction could not produce the estimated temperature of 6,000°C observed on the surface of the sun. Furthermore, if chemical reactions among hydrogen, carbon, and oxygen were responsible, the sun would have burned out within 100 million years.

It was also Gamov who proposed that the sun generates its energy from nuclear fusion reaction. (Fig.3) In this reaction known as the hydrogen burning reaction, four hydrogen atoms come together to form helium-4. This reaction can take place in either of two ways; through a hydrogen chain reaction or a carbon–nitrogen cyclical reaction.



Solar Data as a Nuclear Energy System

- Core Temperature: 1.58 x 10^7 degree C.
- Core Pressure: 2.40 x 10^{11} atm
- Core Density: 1.56 x 10^5 kg/m^3, (14 times higher than lead)
- Total Emission Energy: equivalent to 1 x 10^{17} units of 1000MWe nuclear power plants

Fig. 3 Nuclear Fusion Reactions in the Sun and the Solar Data as a Nuclear Energy System

The energy density of the fusion reaction occurring in the sun is actually quite small, around 1.0 W/m^3. The sun is able to sustain a nuclear fusion chain reaction, namely because of its large size, which enables gravity to easily confine the nearby plasma.

Natural fission reactors are found on the earth. (Fig.4) These natural fission reactors are really light-water reactors whose enrichment of U-235 was about 3.7%. If we calculate back to 2 billion years ago, it is U-235 content in natural uranium at that time. We use the enriched uranium from 3 to 5% for the light-water reactor nowadays. It is astonishing to see that the light water reactor existed about 2 billion years ago. But, we cannot find yet a fast neutron reactor on the earth or some other planets or stars though we find fast neutron from supernova, however no chain reaction with fast neutron.
The history of natural reactor will tell us the way to treat the radioactive wastes both underground disposal and annihilation of radioactivity.

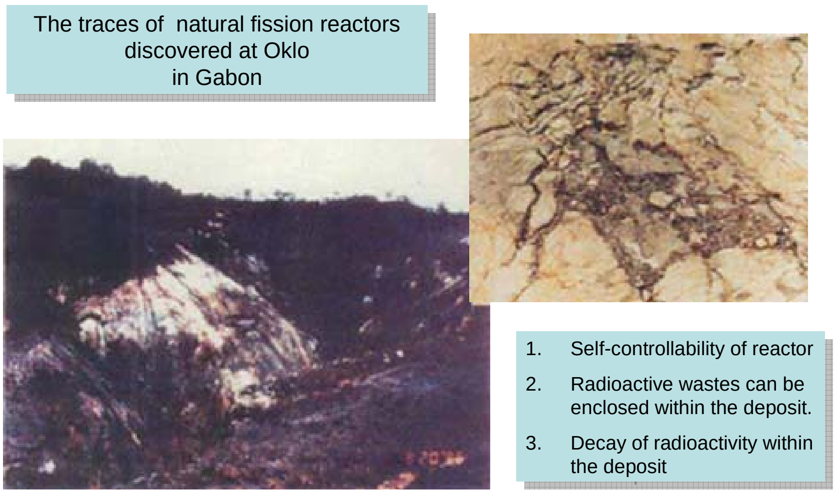


Fig. 4 Lessons learnt from Natural Fission Reactors

Ecological energy system on the earth

Bio-sphere appeared on the earth as the joint work between the sun and the earth to enable the photo-synthesis of plant. (Fg.5) Bio-sphere is the important natural phenomena, especially to find out the goal of the recycling based nuclear energy system. One of the important phenomena is the formation of a biosphere, the ecological system on the earth. There existed sea with mild environment for the birth and growth of plants. Synthesis of organic material out of carbon-dioxide, water and nitrogen by absorbing solar energy is the starting point of bio-sphere on the earth.

After coming to the land from the sea the plant grew up by photo-synthesis as to be fed to animal which dissolves glucose, amino acid and protein to carbon dioxide, water and nitric acid. Here carbon, hydrogen, oxygen and nitrogen play main roles in the biosphere.

The co-existence of plant and animal has had the possibility to keep the equilibrium state between formation of organic material and the dissolution of them in the biosphere; the closed system in which energy comes in and out, an open energy flow, however, materials or elements are kept inside the biosphere. It's really an energy system with closed material flow.

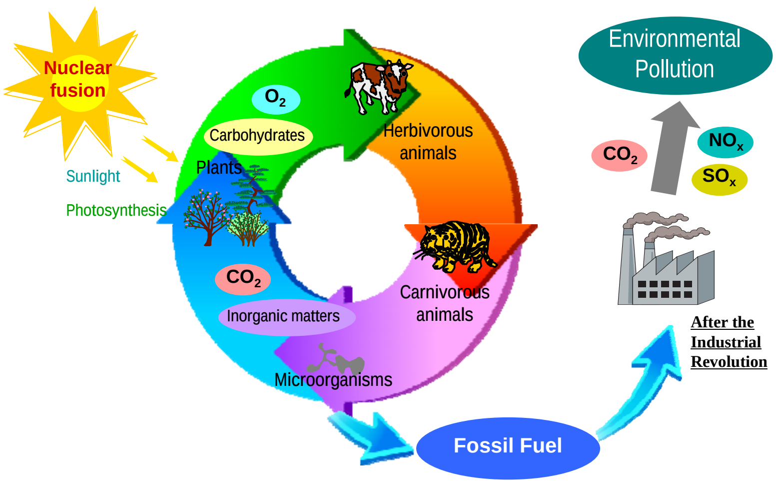


Fig. 5 Bounty from the Sun and Ecological System

But in reality the plant surpasses the animal in magnitude therefore the earth had a history in which carbon-dioxide contained in the air decreased. However when the mankind came into this biosphere, it reversed this trend by touching to the fossil fuel underground.

3. LONG TERM PERSPECTIVE OF NUCLEAR SCIENCE AND TECHNOLOGY

The nuclear science and technology can be understood as the utilization of the "interaction between material and radiation based on nuclear reactions." With this interaction, 1) energy is produced, 2) material is converted and new one is created, 3) new technology can be brought to civilization and 4) latent information and the laws of physics can be learned. As equipment to facilitate these interactions, we have 1) energy-related nuclear fission and fusion reactors, and 2) non-energy-related accelerators and lasers. This is the essential view to broadly understand the whole picture of nuclear development from the aspect of a comprehensive nuclear science and technology. (Fig.6)

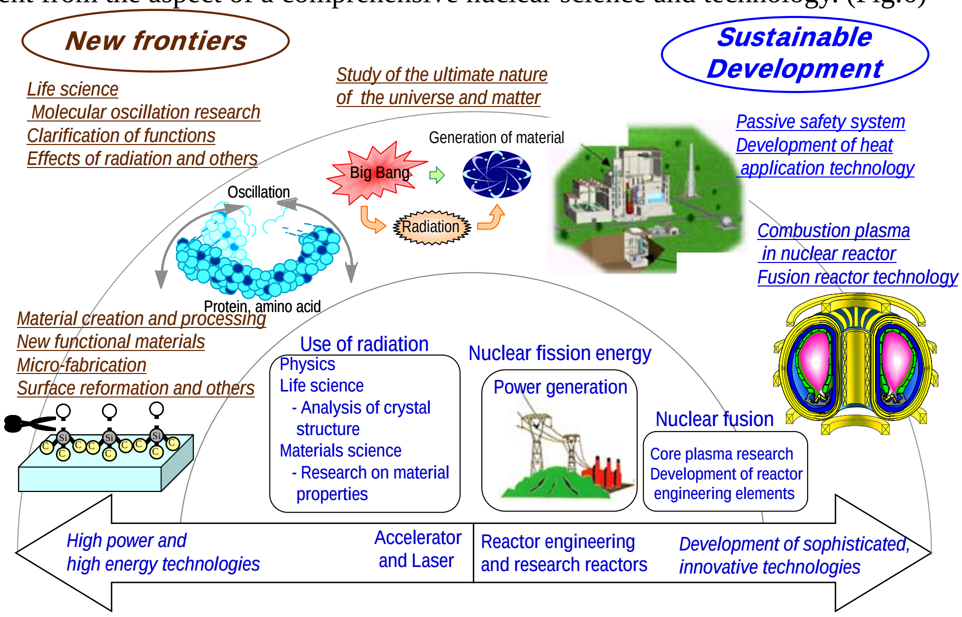


Fig. 6 Future of Nuclear Science and Technology

Therefore, the aims of nuclear development are:
(1) Energy supply as well as environmental preservation to support a resource-recycling civilization,
(2) Conversion and generation of material,
(3) Creation of knowledge opening the potential for new cutting-edge applications.
Besides the conventional view of nuclear energy, it is also a measure to investigate the physical phenomena of the big bang of space, stars or interstellar-molecules. I regard it as a measure to create knowledge; that is a field in which new science and technology are created.

At the end of 19th century, X-rays, radiation, radioactive material and electron were discovered successively. (Fig.7) After the discovery of radioactivity, we came up to the skirt of the mountain through Chicago Pile No.1 in 1942 to the present position.
Might it be one-tenth of our roadmap to the summit? We realized the commercialization of light-water reactor and radiation application in the various fields and also new information we got from the cosmos and the quantum world. If we look at the summit, we can see the summit in the cloud from time to time. It is not clear, however we can see the summit where we find the horizon of nuclear science and technology which contributes to the coming civilization, that is recycling-based civilization. To the summit there are several routes, here three main routes are shown. One is for the fast reactor and fuel cycle. We have already commercialized light-water reactors and now on the stage for commercialization to close the light-water reactor fuel cycle with usage of reprocessing of spent fuel and MOX loading in the light water reactor. The second step is to materialize fast reactor system with its fuel cycle. In this way, the first route to the summit can be cultivated.

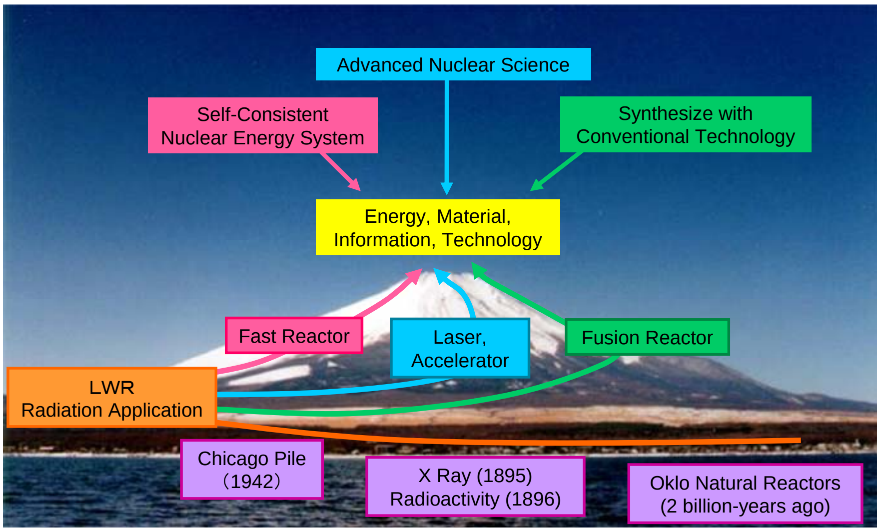


Fig. 7 Various Routes to Summit of Nuclear Science and Technology

The route for the nuclear fusion is not shown explicitly in the view graph. However, it is also a very hopeful to contribute to the future human civilization.
And in the middle the route for laser and particle accelerator is shown, so called hi-tech. route.
Through these routes we provide energy, material, technology and information to the civilization. It can be used firstly to synthesize the conventional technology. We should keep the progress of the conventional technology we have now. Then, we should make advance of nuclear science and technology, as mentioned already. And finally, a self-consistent nuclear energy system will be realized. It can be constructed, both for nuclear fission and nuclear fusion system. This is a whole view, or a whole roadmap to the future.

4. CHALLENGE TO FUTURE NUCLEAR ENERGY SYSTEM

The first step in the broader perspective of nuclear science and technology is energy conversion and utilization, and the second step is the material conversion and management. A future nuclear energy system consists of two parts; one performs nuclear reaction for energy as well as fuel production and also make nuclear transmutation for deactivation of radioactive fission products. The other part is really fuel cycle to treat separation of material, element and nuclide to prepare recycled fuel and stable fission products for next use if possible.
For the future prospect of a nuclear fission energy system, it is requested to make full use of the assets of nuclear fission reaction. The assets of the fission reaction are 3 neutrons and 200 MeV energy released by a fission reaction.

Future Nuclear Energy System SCNES

In order to contribute to civilization, the most important point we should first consider is to supply high quality energy solving the resource as well as environmental problems simultaneously. For this aim a scientific feasibility should be better discussed before entering to a technological one with discrete technologies and facilities where efficiency plays main roles rather than scientific discussion.

A nuclear energy system should have five functions to be realized to contribute for the future civilization. (Fig.8)

They are:

(1) energy production,
(2) fuel production,
(3) transmutation of radioactive substance, mainly fission products,
(4) safety and
(5) non-proliferation.

Any nuclear energy system developed so far satisfies these functions partially even insufficiently.

Light water reactor for example has played a role in generating electric power with a satisfactory safety record. However, production of new nuclear fuel (plutonium) can meet only half of the uranium consumption at present, and deactivation of radioactive wastes has not been realized.

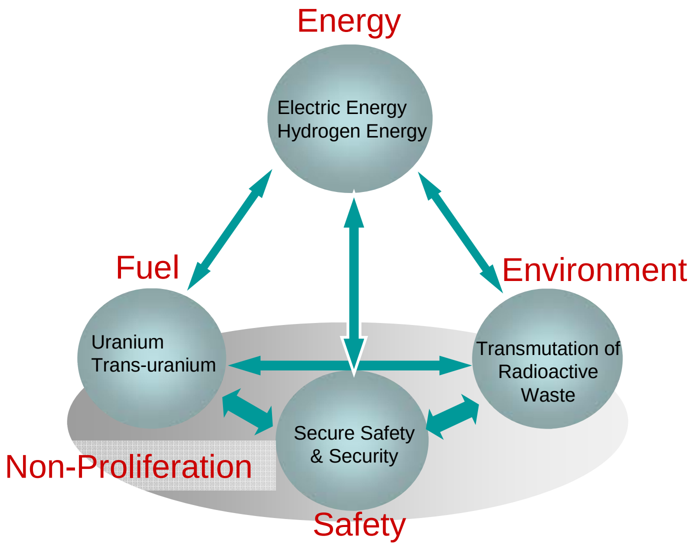


Fig. 8 Self-Consistent Nuclear Energy System (SCNES) with Non-Proliferation Objectives

Study of SCNES aims to show scientifically the possible extent to which the assets of nuclear fission can achieve these five functions.

Neutron Balance in SCNES

In Table 1 both requirements for a self-supporting energy supply (fuel production) and deactivation by nuclear transmutation of radioactive materials are discussed.

The requirements cannot be realized in principle by light water reactors or high temperature gas-cooled reactors using thermal neutrons but are only feasible theoretically by employing fast neutron nuclear energy system. This is just the scientific possibility for effective use of resources and zero-release of radioactive wastes as a real vision of nuclear energy.

Table 1 Neutron Balances in SCNES

number of neutrons per fission	oxide fuel core	metal fuel core
Consumption		
1. Chain reaction		
fissile fission	0.8	0.72
fertile fission	0.2	0.28
2. Breeding (fertile capture) (BR=1.0)	1	0.85
3. FP transumutaion (with isotope separation)	0.24	0.24
4. Parasitic capture		
fissile capture	0.2	0.13
others	0.25	0.2
5. Parent nuclide capture for non-proliferation	0.2 (available)	0.5 (available)
Fission yield	2.9	2.9

It is required to achieve non-proliferation by the addition of Pu239, Pu241, Np237, Am241 and Am243 to fuel under the condition of the available neutrons.

Hereafter discussions are made on the two items, safety and non-proliferation. Though they need treatment of space dependent material allocation, no big consumption of assets as to kill the consistency of SCNES is found at this moment.

SCNES with Non-Proliferation Objectives

From the scientific view, non-proliferation problem can be categorized to two aspects, one is the space allocation of the nuclear material, and the other is the characteristic of the nuclear material itself. That is the adaptability to a nuclear explosion or a nuclear weapon. Given the place of fuel material usage, it is better to deal with this problem by the material composition of nuclear fuel.
To enhance the proliferation resistance by the change of material characteristic, the most important physical point in SCNES is the "neutron balance", since the multi-recycled TRU fuel burning and the isotopic denaturing of plutonium require more neutrons in addition to fission, fuel production, and waste transmutation.
In order to reconsider the neutron balance in SCNES with the non-proliferation sense, neutrons required for the denaturing of plutonium by even-mass-number plutonium isotopes are evaluated (Table 2). The results show that in the fuel cycle within SCNES, plutonium fissile is always together with even-mass-number plutonium isotopes and plutonium isotopes composition always satisfies the level of reactor grade plutonium.
With isotope separation of fission products, there is a clear perspective of neutron balance with oxide and metal fueled fast reactors with multi-recycling of TRU.
Conclusively the scientific approach to non-proliferation can be treated within SCNES framework.

Table 2 Neutron Balance in SCNES with Proliferation Resistance(1)
-Pu Grade Target: Reactor Grade Pu-

Case1: Pu Grade Target: Reactor Grade(^{240}Pu>18%)

Required Neutrons	MOX Fuel Core	Metal Fuel Core	Requirement
1. For Chain Reaction	**1.00**	**1.00**	$N_{fis1}+N_{fis2}$ =1.0
Pu Fissile Fission (N_{fis1})	0.80	0.72	
Others Fission (N_{fis2})	0.20	0.28	
2. For Fuel Production (Pu Fissile Productio	**1.00**	**0.88**	Breeding Ratio = $N_b/(N_{fis1}+N_{p1})$
^{238}U, ^{238}Pu, ^{240}Pu capture (N_b)	1.00	0.88	≧1.0
3. For Pu Protection (Taget: Rea. Grade Pu)	**0.18**	**0.16**	N_{p1}/N_b =0.18
Pu Fisslie,^{239,241}Pu, capture (N_{p1})	0.18	0.16	≧Reactor Grade Pu
4. For LLFP Transmutation	**0.24**	**0.24**	$T_{1/2}$ > 1 year FP Transmutation
LLFP capture (N_{fp})	0.24	0.24	with isotpe sepalation
5. Others	**0.27**	**0.20**	
total	**2.69**	**2.48**	
Generated Neutron by Fission	**2.90**	**2.90**	

(1) Fundamental Data derived from the paper, Yoichi Fujiie', Masao Suzuki, "Nuclear Energy System for a Sustainable Development Perspective -Self-Consistent Nuclear Energy System-," Progress in Nuclear Energy, Vol. 40, No. 3-4, pp. 265-283, 2002
Re-composed by H. Sagara

Safety of SCNES with Re-criticality Free Reactor Core

The safety aspects of a nuclear energy system are discussed sometimes from its inherent safety characteristics. In other words stop, cool and contain. The essential safety measure is to avoid that the radioactive material should have mobility to move outside the system to the environment during the core disruptive accident.
Especially in fast reactor system, since the criticality issues for both normal and abnormal operation conditions are related to the principal safety characteristics of fast reactor core configuration. It means that the core does not show the maximum reactivity configuration related to the material relocation.
On the contrary, concerning to the cooling ability of the system it is possible to apply a system with high heat transport material with low pressure operation like sodium-cooled system.
Treatment of hypothetical core disruptive accident (HCDA) issues like unprotected transient overpower (UTOP) and unprotected loss of flow (ULOF) have been made for the safety assessment of

fast reactors in the world even the occurrence probability is negligibly small like 10^{-7}/(reactor x year). In SCNES we also put our focus on the re-criticality problem.
If we consider the low occurrence probability, it is not possible to equip such a system with active elements as a safety circuit. We decided to introduce a safety system to make use of physical properties like a melting point and relocation due to phase change in the existence of gravity.
After 20 years of joint work among academia both national and international, governmental organization, manufacturers and utilities, a research program for re-criticality-free core was fixed and tested in pile of test reactor IGR (Impulse graphite reactor) in the collaboration between Japan Atomic Energy Agency (JAEA) and National Nuclear Center (NNC) in the Republic of Kazakhstan.
We are convinced now that our efforts bring delicious fruits for safety assurance of a fast reactor system.

Nuclear Energy System for SCNES

Ultimate nuclear energy system corresponding to SCNES can be shown as a system where the entrance is natural uranium and the exit is stabilized fission products. (Fig.9)
Put simply, this would mean producing nuclear energy using a nuclear energy system incorporating uranium-238, and as a result only releasing stable fission products outside the system.
Is there a nuclear energy system that can succeed in completely recycling the nuclear fuel, which is suitable for a recycling-oriented civilization and releases zero radioactive materials at the same time?
In a scientific sense, the ultimate target is to construct the ultimate nuclear energy system SCNES within the confines of the assets of nuclear fission reactions. The scientific pursuit is to provide that this is possible using the assets. SCNES shows that this is possible, at least in the sense of scientific feasibility. The concept of SCNES that I presented in 1992 had this purpose, namely, discussing whether it would be scientifically possible to make the full use of resources and discharge no radioactive materials. In other words, it presented the question of whether it would be possible to achieve recycling and zero release (zero emission).

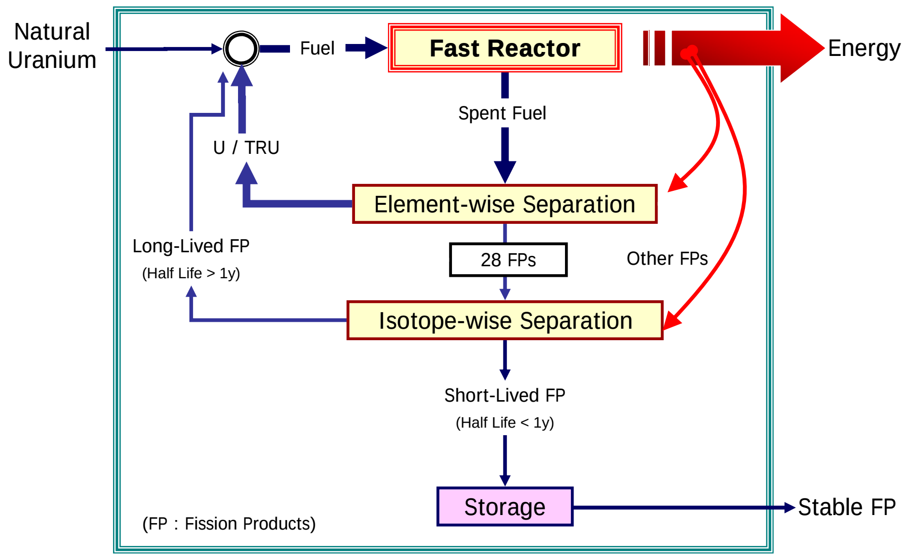


Fig.9 Fuel Cycle of SCNES