Proc. International Conference on Design and Safety
of Advanced Nuclear Power Plants (ANP '92)
October 25-29, 1992, Tokyo Japan
Atomic Energy Society of Japan

AN APPROACH TO SELF-CONSISTENT NUCLEAR ENERGY SYSTEM
- POTENTIAL OF FAST REACTORS -

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ABSTRACT

This paper discusses the feasibility of a self-consistent nuclear energy system which satisfies the requirements of energy production, fuel production, radionuclide burning, and also inherent safety characteristics, mainly from the role assignment of fission neutrons. A rough estimation shows that fast neutron plays main role for the requirements in such a nuclear system.

The discussion concentrates on facilitation of the inherent tolerance against the threats of criticality-related safety issues. Some proposals are made to materialize an inherent tolerance to recriticality, considering an integrated system of material selection and spatial location.

1. DEFINITION OF SELF-CONSISTENT NUCLEAR ENERGY SYSTEM (SCNES)

1-1. Definition and objectives of SCNES

It is convinced in the nuclear community that nuclear energy shall be one of the main energy sources for the human race in the next century. However, people in well-cultivated societies are generally nervous in opposition to the development of a nuclear energy system if contradictions exist or matters are left unexplained. The discrepancies between experts on nuclear energy and the public can be minimized by showing the ultimate goal of nuclear energy and the way to attain that goal using only simple logic.

The ultimate goal of nuclear energy is to realize a stable supply of energy without endangering the environment or humans. The following four objectives should be realized simultaneously in the nuclear energy system at least.

a. Energy generation
b. Fuel production
c. Burning of radionuclides
d. System safety

a. Energy Generation

Fission chain reaction generates high quality energy, about 200MeV per fission. It can be utilized by controlling fission neutrons. The energy generation is the fundamental objective of the system.

b. Fuel Production

To obtain a really inexhaustible energy source for mankind, the breeding of fissile material is inevitable, especially while demand for energy is increasing. In addition, Fission energy should be derived by utilizing not only uranium but also transuranium (plutonium, neptunium, americium, curium, etc.) as nuclear fuel from the viewpoint of effective utilization of world energy resources.

c. Burning of Radionuclides

The radionuclides born in the nuclear system need to be burnt by neutron reaction through recycling, so as not to leave a radiological burden in the future. The radionuclides to be burnt are minor actinides (MA; neptunium, americium, curium, etc.) and long-lived fission products (technetium-99, iodine-129, etc.). MA can be burnt by utilizing them as nuclear fuel as described above.

d. System Safety

To minimize the discrepancy between the perception of reactor safety by the experts and the public, the criticality-related safety issues, which are intrinsic for a fission chain reactor, need to be eliminated using inherent safety characteristics and simple logic. If this can be done, main safety issue is then only cooling or decay heat removal as in the existing Light Water Reactor, and the cooling problem can be more easily solved. The specific goals are a negative power reactivity coefficient, passive shutdown capability for unprotected events, subcritical state for a fully-voided core, and the elimination of recriticality for material relocation (i.e., fuel melting).

A self-consistent nuclear energy system (SCNES) is defined as a system that satisfies the four objectives simultaneously[1].

1-2. Assumptions for energy needs in the future

When we consider the energy demand in the future, the trend for nuclear energy capacity is separated into two phases. In the first phase, the demand for nuclear energy would increase in order to meet the increasing energy consumption and the replacement of fossil energy by nuclear energy to solve the environmental problem. In the second phase, since the eternal increase of energy consumption can not be allowed on the earth, an equilibrium state of energy demand is envisaged.

Based on the above consideration, the transitions of the capacity of nuclear energy, the amount of fuel, and the long-lived radionuclides in SCNES are conceptually shown in Fig.1 on an extremely long time scale. In the first phase, the breeding of fissile material is inevitable. In the second phase, there is theoretically no need to breed. Although long-lived radionuclides can be burnt by neutron reaction in the system, the amount of them increases at least equal to the equilibrium material (i.e., fuel) composition in the first phase, as the capacity of nuclear energy increases. However, in the second phase, the amount can be kept constant at the equilibrium level which is determined by the balance of the production rate and the burning rate under a certain neutron spectrum.

Thus, a really inexhaustible energy source can be obtained and the successive accumulation of radionuclides can be prevented in SCNES, without endangering the environment or humans.

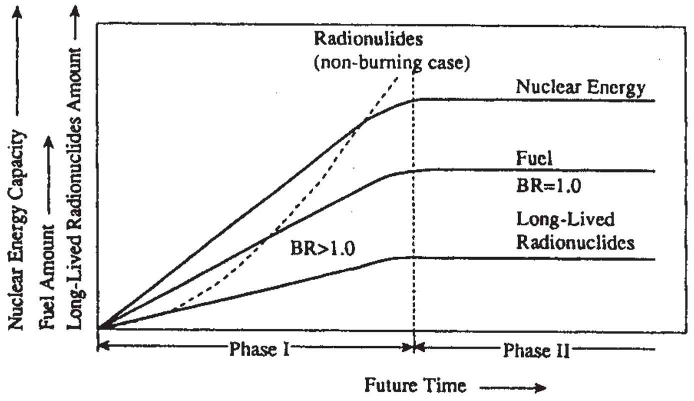


Fig. 1. Nuclear energy growth and material (fuel and radionuclides) balance in the self-consistent nuclear enegy system

1-3. Role of fission neutrons

It is more difficult to overcome the first phase than the second phase from the viewpoint of neutron utilization, since both the breeding and the burning require fission neutron. Simultaneous realization of the objectives can be proven by role assignment of fission neutrons. Only a nuclear system using fast neutron such as FBR has the potential to burn radionuclides and to breed nuclear fuel simultaneously, due to the large neutron yield per fission and its hard neutron spectrum. Moreover, since a hard neutron spectrum also reduces the α-value (capture-to-fission ratio) of MA, FBR can utilize MA as a fuel and produce fewer high-mass-number MA. Therefore, FBR should play a major role of SCNES.

This paper mainly discusses the facilitation of the inherent tolerance to recriticality, and proposes some possible solutions.

2. SAFETY CONSIDERATION FROM THE VIEWPOINT OF LEAKAGE STRUCTURE

2-1. Safety goal and leakage structure

In general, the goal of safety for a nuclear system is to contain the radioactive materials inside the system itself and to isolate them from the environment as completely as reasonably possible. To realize this goal, it is necessary to keep the integrity of system boundaries and to suppress the mobility of the radioactive materials in the core fuels.

Thus, the safety characteristics of the existing nuclear system can be characterized in the frame of the leakage structure of radioactive materials from the concentrated region in the system to the environment. From the viewpoint of the "leakage structure", which is defined as the mass transfer processes of the source term along its transportation paths in the accident, the discharge state of the radioactive materials (R), which is a function of the amount and rate of the source term, is described by direct multiplication between the leakage path state (L) and the mobility of the radioactive materials (Q). These quantities are essentially a function of the potential energy (E) released during the abnormal state of the nuclear system, and they are symbolically written by the equation:

$$R(E)= L(E) \times Q(E) \qquad (1)$$

Based on the simple relationship between R(E), Q(E), and L(E), some important safety characteristics can be commonly deduced for different types of nuclear reactor system such as LWRs, HTGRs, and FBRs:

a. In normal operation, there is no abnormal release of energy. Thus no radiological consequence (R(E)=0) would be realized through the boundary integrity (L(E)=0) and the immobility of radioactive materials (Q(E)=0).

b. In an abnormal state, where the abnormal energy E is generated, the radiological consequence R(E) would occur only when the formation of the leakage paths ($L(E)\neq0$) and the mobility of the radioactive materials ($Q(E)\neq0$) were simultaneously generated in the system.

c. To achieve the safety goal of the nuclear system, it is thus necessary to keep the integrity of the system boundaries and to suppress the mobility of radioactive materials remained mainly in core fuels.

2-2. Abnormal energy release challenging of the boundary integrity, and the immobility of radioactive materials

Since the nuclear fission system can be characterized as "a centralized system" in which the main functions, the fission reaction and the heat production, are concentrated in the core regions as well as the radioactive materials, the system has a multi-tiered structure against leakage of radioactive materials. The mobility of the radioactive materials Q(E) is surrounded by the multi-tiered structures in which leakage paths L(E) might form under abnormal conditions.

Thus, the threat to the containment of radioactive materials in fuel can occur due to an abnormal energy release from either outside or inside the system. Due to the multi-tiered structure of the fission system, various events could lead to an abnormal energy release and then the leakage of the radioactive materials.

A leading event, which is defined as the representative events inherently dependent on the type of the fission reactor system introducing the radiological consequence $R\neq0$, is the mismatch phenomena between the reactor power and cooling due to either an abnormal power increase or the loss of coolability. The radiological consequence R(E) also occurs through simultaneous occurrence of the $L(E)\neq0$ and $Q(E)\neq0$ in Eq.(1) caused by the external events such as fire and missile. In the safety design of the nuclear fission system, the initiating processes of the leading events which could lead to an abnormal energy release, are developed and treated as design basis events (DBEs) or beyond design basis events (BDBEs).

Abnormal energy releases, which eventually challenge the boundary integrity and activate the mobility of radioactive materials during the extended or final stage of the leading events, can be classified by the location of the energy source, physical mechanism of energy generation, and the type of hazard potential. They are summarized in Table 1.

Table 1. Abnormal energy release in leading events

location of energy source	physical basis of abnormal energy release	type of hazard potential
inside of nucler system (internal events)	neutronic reaction	• mechanical energy release due to power excursion
		• thermal energy release due to power excursion
	thermal-hydraulic reaction	• mechanical energy release due to - steam explosion - fuel-coolant interaction
		• thermal energy release due to - loss of DHR
	chemical reaction	• mechanical energy release due to - hydrogen burning - sodium-water reaction
		• thermal energy release due to - sodium burning - sodium-concreat reaction - graphite burning
outside of nuclear system (external events)	geological event	• mechanical energy release due to - earthquake
	missile impact	• mechanical energy release due to - fall of air craft - turbine missile

This Table shows that the abnormal energy released in the internal events challenges both the boundary integrity L(E) and the mobility of the radioactive materials Q(E) via the mechanical and thermal energies as well as the external events. In order to establish safety goal, it should be emphasized that the protection against external events and limiting the propagation of the chemical reactions induced by the internal event are important, in addition to the shutdown of the neutronic reaction, decay heat removal, and containing the source term.

3. ACCIDENT SCENARIO INHERENT TO SAFETY CHARACTERISTICS OF THE EXISTING NUCLEAR REACTORS BASED ON LEAKAGE STRUCTURE

The safety characteristics of the existing typical nuclear reactors, such as LWRs, HTGRs, and FBRs, can be characterized by the leakage structure under an abnormal energy release identified in the previous section.

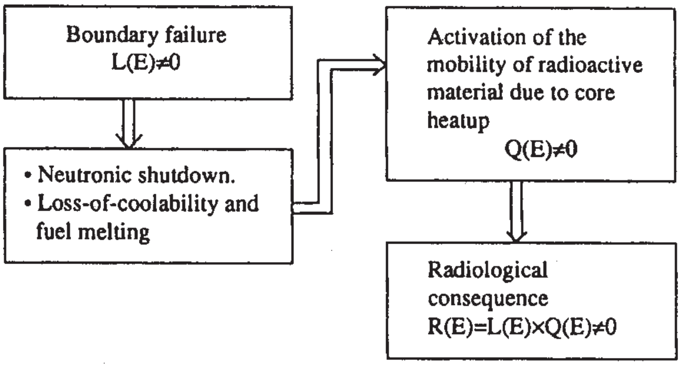
Based on the relationship between the radiological consequence R, leakage paths L, and mobility of radioactive materials Q, the event sequences of the leading events have been investigated for the existing nuclear reactors.

3-1. Safety characteristics of LWRs

In LWRs, negative reactivity feedback can be introduced by material relocation in the reactor core, especially fuel displacement from the configuration of the core material at a normal operation. The reactor core cannot enter into a recritical state even if the coolant is discharged from the core. The recriticality problem is thus not an issue with typical LWRs. In-pile experiments with TREAT, BORAX and also the neutronic behavior during the TMI accident clarified the inherent safety of LWRs concerning recriticality. Therefore, only the coolability of the fuel elements is of concern.

A typical safety characteristics of LWRs is, of course, the high pressure operation of the coolant. Highly compressed water and its two phase mixture may easily be discharged outside the pressure vessel if there is loss of boundary integrity. In such a situation, thermal-hydraulic phenomena will govern how the event progresses, which could lead to the activation of the source term through the loss of core coolability.

The schematic expression for the sequence of leading events and radiological consequences for LWRs is described based on the leakage structure:



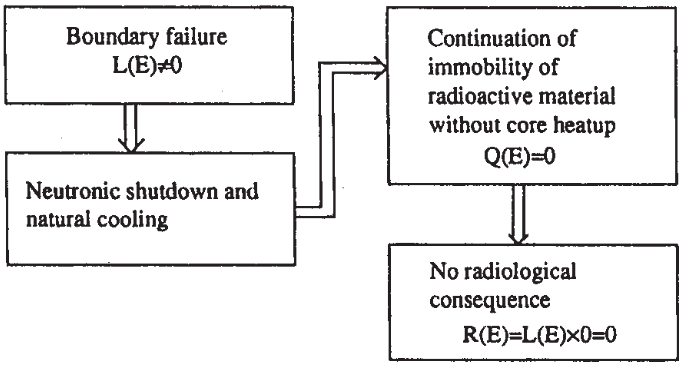
It should be noted that the radiological consequence of the leading events in LWRs is initially induced by the formation of a leakage path L followed by the activation of the mobility of radioactive material Q. This is the representative phenomena or the leading event which identifies the safety characteristics of LWRs and is treated as a DBA named as loss-of-coolant-accident (LOCA).

3-2. Safety characteristics of HTGRs

The safety characteristics of the HTGRs are the low power density of the fuel, the large heat capacity of the primary system, and the high sublimation temperature of graphite and coated particle fuel.

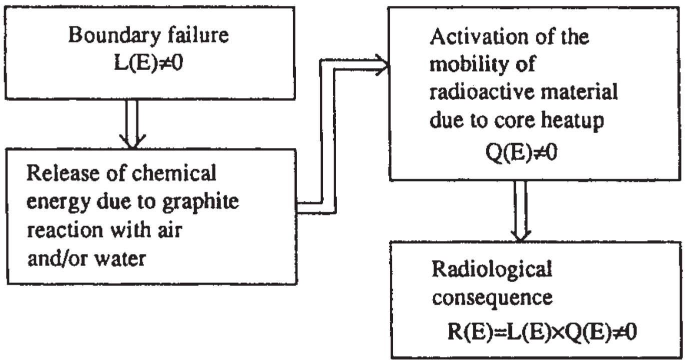
However the high pressure of the primary system may lead to the release of thermal-hydraulic potential (E) in the event of the boundary failure as in LWRs. In the primary boundary failure ($L(E)\neq0$), however, the reactor power inherently decreases due to negative feedback, and cooling occurs by natural circulation even for unscrammed events. Such passive safety characteristics were confirmed in AVR.

The symbolic expression for the event sequence in HTGRs is as follows:



This shows the inherent safety characteristics due to the large reactivity margin against temperature increase and the self-regulation of the system. As with LWRs, it is meaningless to consider direct causes of a nuclear excursion leading to activation of source term.

On the other hand, chemical reactions between graphite and air or water ought to be considered if boundary fails or vapor ingresses due to piping rupture in the steam generator. These events lead to activation of the source term and loss of boundary integrity, and therefore leakage of radioactive materials. In such a case, the event sequence in the frame of the leakage structure is written as:

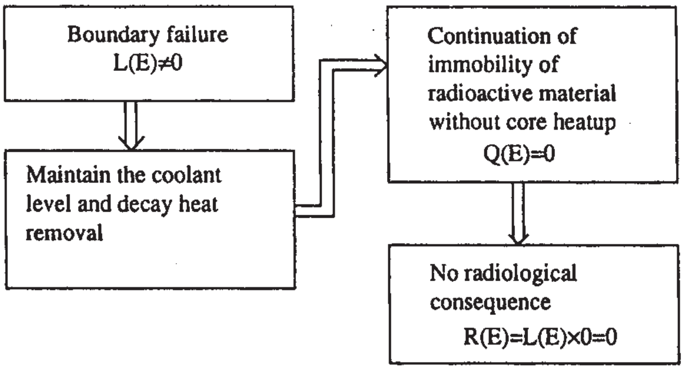


As can be seen from this figure, this event represents the safety characteristics of HTGRs.

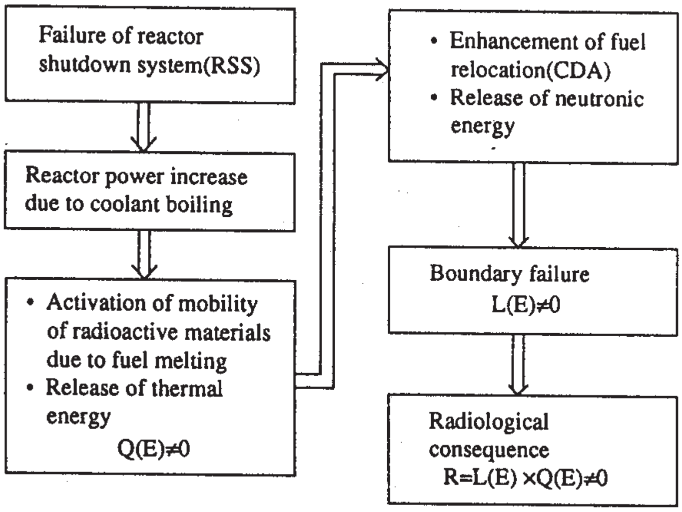
3-3. Safety characteristics of LMFBRs

LMFBRs also reveal the safety characteristics such as low system pressure during operation, high boiling temperature, high power density, and high nuclear potential concerning to the breeding of the plutonium.

Due to the low pressure operation in an LMFBR, the sequence of event is not similar to that of LWRs and HTGRs. In the case of the boundary failure of an LMFBR, the event sequence will develop as follows:



For LMFBRs, it should be noted that another type of event sequence develops for unscrammed events such as unprotected-transient-over-power (UTOP), unprotected-loss-of-flow (ULOF), and unprotected-loss-of-heat-sink (ULOHS). The transient behavior of these unscrammed events is characterized by reactor power increase due to the positive reactivity insertion. This insertion is driven by the power-to-cooling mismatch phenomena such as the coolant boiling and the succeeding molten fuel relocation, which would complicate both the neutronic and thermal hydraulic behaviors. This is primarily due to the fact that the core is designed with non-maximum reactivity configuration. They are named as core disruptive accident (CDA) and be expressed symbolically as follows:



Although unscrammed events, in general, have been treated as a BDBE due to the low probability of occurring, some initiators such as ULOF was the representative phenomena which identify the safety characteristics of LMFBRs.

3-4. Key safety characteristics for existing reactors

Based on the discussion above, the key safety characteristics for the existing reactors (LWRs, HTGRs, and LMFBRs) can be summarized as follows:

a. The recriticality problem, which is intrinsic for a nuclear fission reaction, shall be treated in the reactor core design as safe that the problem should not be realized. The nuclear excursion shall be suppressed by the inherent tolerance of the nuclear system.

b. As is clear in the accident scenario of the existing reactors, there is no problem in principle concerned directly with nuclear excursion. Thus, attention should be directed to the problem of cooling or decay heat removal for LWRs, and to chemical reactions upon boundary failure for HTGRs.

c. For LMFBRs, however, the recriticality problem has not yet been completely treated in an extensively degraded core geometry. This indicates that a nuclear reactor system which utilize fast neutrons is not yet a "recriticality-free" reactor system.

4. REQUIREMENT ON THE SAFETY CHARACTERISTICS OF SCNES

Based on a comparison of the safety characteristics of existing nuclear reactors, the general safety requirements can be introduced for SCNES, in which fast neutrons play the major role for the production of nuclear fuel and the burning of radioactive materials.

Due to high nuclear potential of the nuclear reactor system utilizing fast neutrons, the event progression of the leading event would be faster than the typical events in LWRs and HTGRs. Thus, SCNES should have the inherent capability to prevent or suppress on a neutronic abnormal energy release. In order to achieve the inherent tolerance to the abnormal release of nuclear energy, the following four basic requirements would be claimed in the safety characteristics of SCNES.

a. Negative power coefficient during normal operation:

During normal operation, the safety characteristics of SCNES to small disturbances are ensured by the negative power coefficient due mainly to the neutronic kinetics and the negative reactivity feedback as with existing reactors.

b. Passive shutdown capability for the initiating phase of the leading event:

The SCNES should inherently give the event progression to neutronic shutdown with an intact core geometry during the initiating phase of the leading event. Neutronic shutdown should be achieved by negative reactivity feedback due to the power-to-cooling mismatch.

c. Subcritical state for a fully-voided core:

Even in a fully-voided core state, SCNES should remain in the subcritical state without any possibility to introduce directly the power excursion.

d. Elimination of recriticality during fuel relocation phase:

SCNES would ultimately be required to eliminate the recriticality by inherent tolerance with simple logic during material relocation.

By satisfying these requirements, the nuclear potential of SCNES would not be activated in an abnormal state, and thus the only cooling problem becomes dominant safety issues as in LWRs.

In the current stage of the safety research, much effort has been concentrated on the former three requirements in the field of LMFBRs which is applicable to SCNES. The negative power coefficient of the fast neutron system was confirmed due primary to Doppler effect and the thermal expansion of the reactor core structure[2]. The passive shutdown capability of the fast neutron system was also principally confirmed based on the experiments simulating the unscrammed events by using RAPSODIE[3], EBR-II[4], and FFTF[5]. The results of these experiments on the unscrammed event such as ULOF and ULOHS reveal the existence of the negative reactivity feedback effects to decrease the reactor power into the level in which the core coolability could be achieved by the natural circulation. The neutronic characteristics to achieve the subcritical state for a voided core were also widely investigated from the viewpoint of the core configurations with low void reactivity by taking into account the enhancement of the neutron leakage[6,7].

5. PROPOSAL FOR THE ELIMINATION OF THE RECRITICALITY

The elimination of the recriticality during material relocation does not have been investigated so much up to the present. It is difficult to solve the recriticality problem because of large positive reactivity due to spectrum hardening and ambiguity of degraded core geometry during material relocation. However, the elimination of the recriticality would be possible by employing the basic considerations below.

Fig.2 schematically indicates the change of the effective multiplication factor k-eff for a usual core system with fast neutrons as a function of the core state. The effective multiplication factor, which is unity in the normal operation state as shown by point A in Fig.2, increases with the enhancement of the fuel density due to the in-place compaction of the relocated fuel.

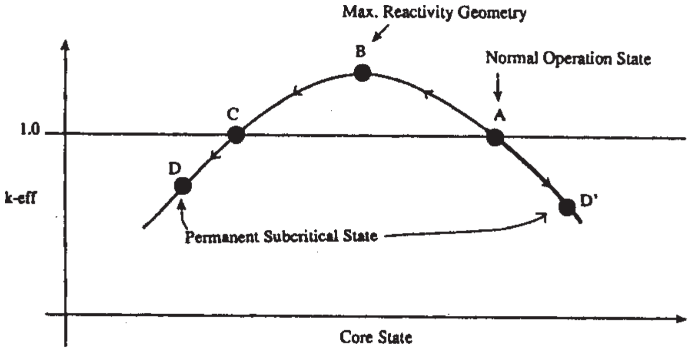


Fig. 2. Effective multiplication factor, k-eff for various core states

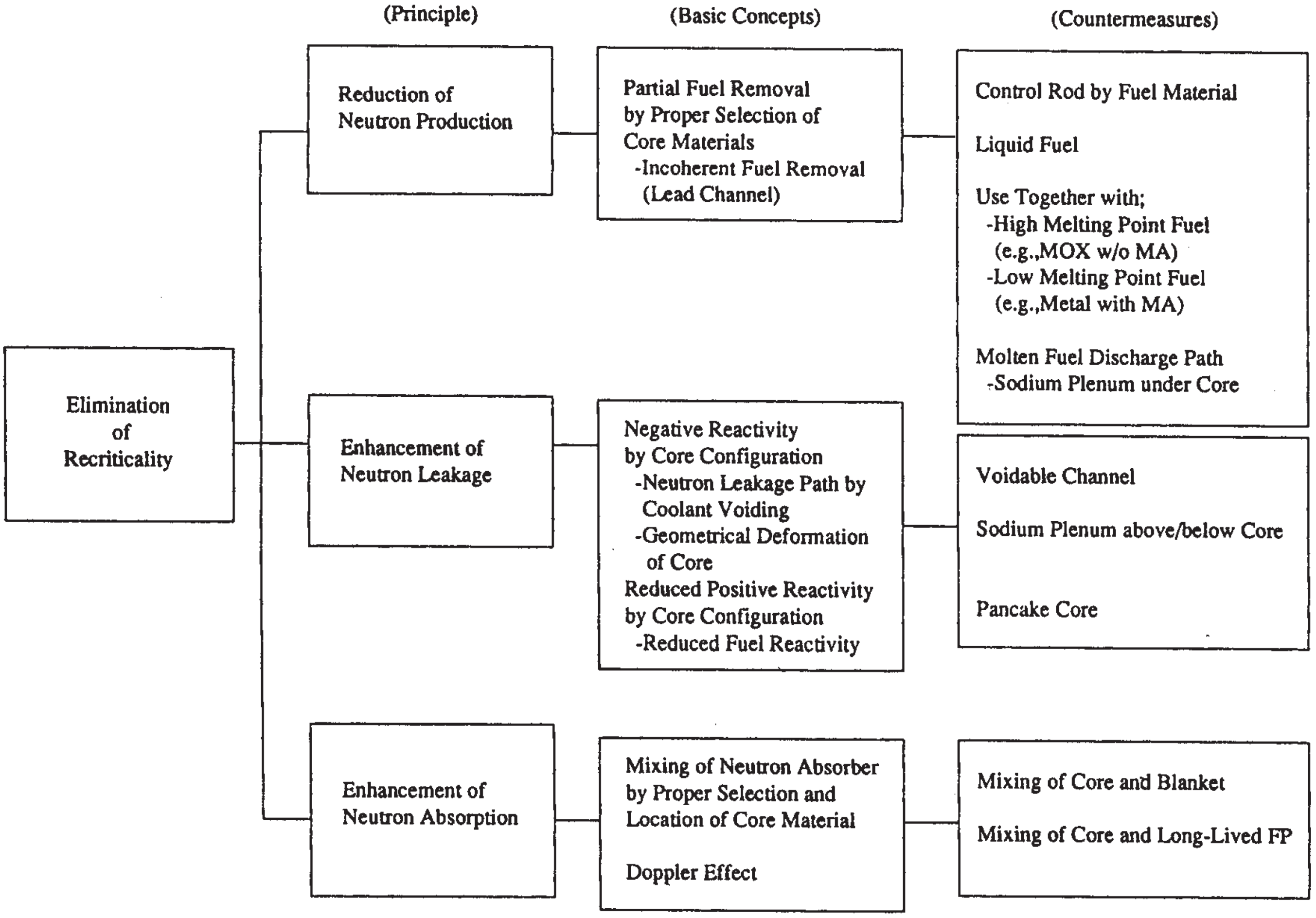


Fig. 3. Principle, basic concepts and countermeasures for subcriticality during material relocation

According to the extension of the fuel relocation, the value of the k-eff reaches to the peak point B at the maximum critical geometry and again decreases to the subcritical state D through the critical point C due to the increased neutron leakage from the degraded core. In such a system, the neutronic power excursion would be possible to occur for the range of the core state between point A and point C.

It should be noted, however, that the subcritical state D or D' could be reached not passing through point B by taking account of the following measures. Fig.3 summarizes the principal and dominant mechanism to achieve the subcritical state, and also indicates the actual countermeasures.

a. Reduction of Neutron Production

The subcritical state can be achieved by the negative reactivity insertion due to the particular partial fuel removal keeping intact geometry under the controlled and enhanced incoherent relocation condition. It is important to select the combination of the core materials, such as a normal fuel and the particular removal elements called as Lead Channel, and their configuration. Control rod by fuel material and Liquid Metallic Fuelled Core[8] are effective as the actual countermeasures.

b. Enhancement of Neutron Leakage

The subcritical state can be also obtained by the negative reactivity insertion to cancel the positive reactivity caused by fuel compaction. In this concept, enhancement of negative reactivity and reduction of positive reactivity are simultaneously required. The negative reactivity can be enhanced by the rearrangement of the core materials which increases the neutron leakage, e.g., production of the neutron leakage path due to coolant voiding, geometrical deformation of the core, etc. The positive reactivity caused by fuel compaction can be reduced by pancake core geometry, lower fissile enrichment, etc.

c. Enhancement of Neutron Absorption

The subcritical state can also be achieved by the enhancement of the neutron absorption during material relocation. The intermixing of fissile with fertile and/or neutron absorption material would be effective. And Doppler feedback may play an important role in increasing neutron absorption during material relocation.

In SCNES, it is important to actualize the above basic concepts based on the simple logic or the simple mechanism by considering the proper selection of core materials and their spatial configurations.

6. POSSIBILITY OF SCNES WITH FAST NEUTRONS

6-1. Neutron assignment for SCNES

It should be noted that the full utilization of fission neutrons is important to achieve the objectives of energy generation, fuel production, and radionuclide burning simultaneously.

The reactor characteristics related to the three objectives are dominated by the role assignment of neutrons in the steady state. The components of role assignment are fission, core-region neutron capture (i.e., in-core capture), and outside-of-core capture (i.e., ex-core capture).

Although fuel production is done either in the in-core region or in the ex-core region, the core region should be surrounded by fertile material to achieve breeding capability. The in-core capture consists of fertile capture, fissile capture, and parasitic capture (FP, structural material, and coolant). For the in-core capture, small parasitic capture and large fertile capture are desired to give a high internal conversion ratio. As for radionuclides burning, MA prefers burning in the in-core region, since MA loading in the in-core region reduces the burnup reactivity swing by increasing fertile capture. The long-lived FP prefers burning in the ex-core region, since FP loading in the in-core region has a negative effect on core performance by increasing parasitic capture.

Therefore, MA should be located in the in-core region, and blanket and long-lived FP should be located in the ex-core region.

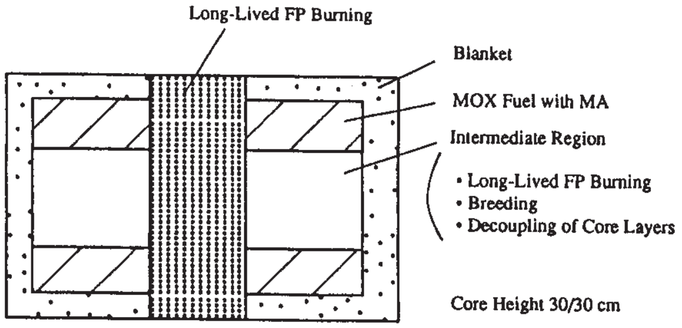
Concerning safety, a negative power reactivity coefficient is normally obtained and passive shutdown capability can be achieved by using high thermal conductivity fuel, or lowering the linear heat rating. Therefore much attention is focused on the elimination of the criticality problem for a fully-voided core and material relocation below. The criticality in the abnormal state is dominated mainly by excess neutron shift from the in-core capture to fission during transients. The criticality problem can be eliminated by 1) preventing the shift from the in-core capture to fission, and 2) enhancing the shift from fission to the ex-core capture (i.e., neutron leakage) or the in-core capture. In the former approach, reduction of the in-core capture in the steady state is effective, since the in-core capture is the neutron source of the shift during transients. This means reducing the positive reactivity due to neutron spectrum hardening. Although the latter approach seems to relate only to controlling neutron shift during the abnormal state, it is also desired to reduce the in-core capture (i.e., to increase neutron leakage) in the steady state to some extent, in order to leak neutrons more effectively through leakage paths during transients.

These simple approaches can solve the criticality problem for a fully-voided core as described below. However, since the recriticality during material relocation could not be eliminated only by neutron assignments in the steady state, countermeasures such as those described in Section 5 are required.

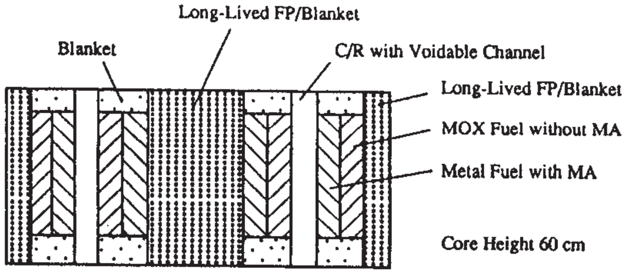
Two types of neutron assignment for SCNES are considered as follows.

Type 1: Assigning a large amount of excess neutrons to the ex-core region in the steady state from the viewpoint of the subcritical state for a fully-voided core, and utilizing the excess neutrons at the ex-core region for breeding and long-lived FP burning.

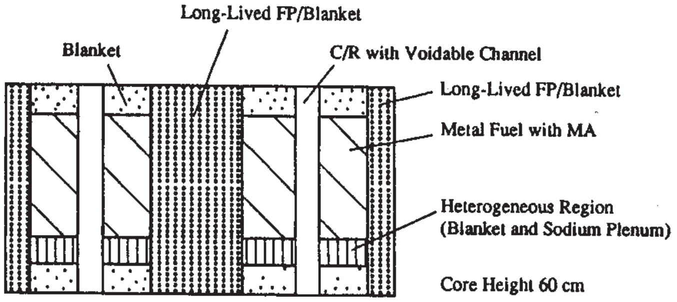
Type 2: Assigning a moderate amount of excess neutrons to the fertile capture in the in-core region in the steady state for high internal conversion ratio, and enhancing neutron leakage during an abnormal state from the viewpoint of the elimination of the criticality for a fully-voided core.



(1) Annular type Axially Parfait Core



(2) Annular type MOX/Metal Radially Parfait Core with Voidable Channel



(3) Annular type Metal Core with Voidable Channel

Fig. 4. Core concepts for self-consistent nuclear energy system

6-2. Core concepts

Based on the above neutron assignment, three core concepts for SCNES are shown in Fig.4. The neutron assignment of the cores is shown in Table 2. Since the annular type axially parfait core is based on Type 1 neutron assignment, fertile capture in the ex-core capture is increased in order to achieve breeding capability. On the other hand, fertile capture in the in-core capture is kept relatively high level in the other two cores, since the countermeasure to enhance neutron leakage for a fully-voided core is adopted based on Type 2 neutron assignment. The main features of the cores are shown in Table 3.

Table 2. Neutron Assignment of the Core Concepts for SCNES

Neutron Assignment per Fission at a Normal Operation*	Annular type Axially Parfait Core	Annular type MOX/Metal Radially Parfait Core	Annular type Metal Core
Fission			
Fissile (U, Pu)	0.85	0.78	0.74
Fertile (U, Pu, MA)	0.15	0.22	0.26
Subtotal	1.00	1.00	1.00
In-Core Capture			
Fertile (U, Pu, MA)	0.58	0.81	0.79
Fissile (U, Pu)	0.22	0.17	0.14
Parasitic	0.11	0.17	0.15
Subtotal	0.91	1.15	1.08
Ex-Core Capture			
Fertile (U)	0.62	0.35	0.33
Long-Lived FP	0.18	0.24	0.32
Parasitic	0.09	0.06	0.07
Subtotal	0.89	0.65	0.72

* Neutron yield per fission is assumed as 2.8.

Table 3. Main Features of the Core Concepts for SCNES

Items	Annular type Axially Parfait Core	Annular type MOX/Metal Radially Parfait Core	Annular type Metal Core
Breeding Ratio *1	1.05	1.15	1.20
Net MA Burning Rate *2	>0	>0	>0
Net Long-Lived FP Burning Rate *3	>0	>0	>0
Power Reactivity Coefficient	Negative	Negative	Negative
Passive Shutdown for ATWS	Possible by Reduced Linear Heat Rate	Possible by Reduced Linear Heat Rate	Possible by Metal Fuel
Sodium Void Reactivity	0$ (30cm Core Height)	0$ (Voidable Channel)	0$ (Voidable Channel)
Considerations for Material Relocation	Mixing of Molten Fuel and Intermediate Material	Incoherency of Fuel Melting (MOX without MA/ Metal with MA)	Partial Molten Fuel Removal (Sodium Plenum under Core)

*1. (Fissile Nuclides Production Rate)/(Fissile Nuclides Consumption Rate) at MOC
*2. (MA Inventory at BOC) - (MA Inventory at EOC)
*3. (Long-Lived FP Inventory at BOC) - (Long-Lived FP Inventory at EOC)

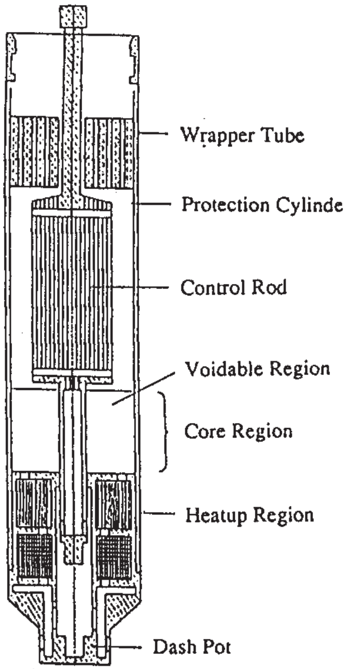


Fig. 5. Voidable channel structure with C/R

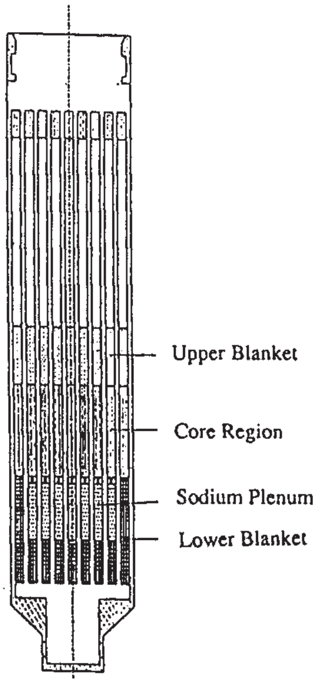


Fig. 6. Fuel subassembly structure for a heterogeneous region concept

In the annular type axially parfait core, the core height is substantially reduced to 30cm and the core geometry is annular in order to assign excess neutrons to the ex-core region in the steady state. The two pancaked core layers are piled up to reduce the core diameter. The central cylindrical region and the intermediate region between the two layers are suitable for effective utilization of excess neutrons, especially for long-lived FP burning. Zero sodium void reactivity and passive shutdown capability are achieved with a breeding ratio of 1.05. In addition, more MA and long-lived FP are burnt than is produced. In this core geometry, large area penetration of the molten fuel through the intermediate region should be prevented by the introduction of the molten fuel blockage structure in the intermediate region.

In the second example, i.e., the annular type MOX/metal radially parfait core, voidable channels are provided to increase neutron leakage during an abnormal state (e.g., a fully-voided state). The example of a voidable channel structure is shown in Fig.5. It is designed to produce a neutron leakage path during an abnormal state by heating up the coolant at the control rod channel to boiling. Zero sodium void reactivity is achieved with a core height of 60cm by the voidable channel. To secure incoherency of fuel melting during material relocation, MOX fuel without MA and metal fuel with MA are used due to melting point difference between them. Passive shutdown capability and a breeding ratio of 1.15 are also achieved. In addition, more MA and long-lived FP are burnt than is produced.

In the third example, i.e., the annular type metal core, a heterogeneous region under the core region is provided to maintain negative reactivity during material relocation. The fuel subassembly consists of fuel pins which have sodium plenum between core fuel and lower axial blanket, and fuel pins which have no sodium plenum as shown in Fig.6. During material relocation, molten core fuel above the sodium plenum is likely to drop into the sodium plenum. Thus the core during material relocation has negative reactivity because of partial fuel removal and neutronic spoiled geometry. This core also has the voidable channel to achieved zero sodium void reactivity. Passive shutdown capability and a breeding ratio of 1.20 are also achieved. In addition, more MA and long-lived FP are burnt than is produced.

Therefore, FBR has the potential to achieve the four objectives of SCNES simultaneously by controlling neutron assignment.

7. SUMMARY AND CONCLUSION

An approach to SCNES has been investigated focusing on the safety issues, and some countermeasures to eliminate the recriticality problem have been proposed. It has been found possible to achieve the four objectives of SCNES simultaneously and FBR lies on the way to the goal.

This study is based on the joint work between Tokyo Institute of Technology (TIT) and Toshiba Corporation. The members who contribute to this study, are A.Shimizu, K.Aizawa, H.Sekimoto (TIT), K.Arie, H.Endo, M.Suzuki, and H.Kawakami (Toshiba).

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