DESIGN STUDY ON SMALL CANDLE REACTOR

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ABSTRACT

A new reactor burn-up strategy CANDLE was proposed, where shapes of neutron flux, nuclide densities and power density distributions remain constant but move to an axial direction. Here important points are that the solid fuel is fixed at each position and that any movable burn-up reactivity control mechanisms such as control rods are not required. This burn-up strategy can derive many merits. The change of excess reactivity along burn-up is theoretically zero, and shim rods will not be required for this reactor. The reactor becomes free from accidents induced by unexpected control rods withdrawal during power operation. The core characteristics, such as power feedback coefficients and power peaking factor, are not changed along burn-up. Therefore, the operation of the reactor becomes much easier than the conventional reactors especially high burn-up reactors. The transportation and storage of replacing fuels become easy and safe, since they are free from criticality accidents.

In our previous works it appeared that application of this burn-up strategy to neutron rich fast reactors makes excellent performances. Only natural or depleted uranium is required for the replacing fuels. The average burn-up of the spent fuel is about 40 % of total charged fuel. It is equivalent to 40 % utilization of the natural uranium without the reprocessing and enrichment. This reactor can be realized for large reactor, since the neutron leakage becomes small and its neutron economy becomes improved.

In the present paper we try to design small CANDLE reactor, whose performance is similar to the large reactor, by increasing its fuel volume ratio of the core, since its performance is strongly required for local area usage. Small long life reactor is required for some local areas. Such a characteristic that only natural uranium is required after second core is also strong merit for this case.

The core with 1.0m radius, 2.0m height can realize CANDLE burn-up with nitride (enriched N-15) natural uranium as fresh fuel. Lead-Bismuth is used as a coolant.

From equilibrium analysis, we obtained the burning region velocity, power density distribution, core temperature distribution, etc. The burning region velocity is less than 1.0cm/year that enables a long life design easily. The core averaged discharged fuel burn-up is about 40%. For more understanding about the effect of the coolant to fuel volume ratio, the comparison between five cases is made. The coolant channel radius is different from each other, while fuel pin pitch is fixed. Further, the comparison is made with fixed coolant channel radius and different fuel pin pitches.

Key Words: CANDLE, fast reactor, small reactor, high burn-up, natural uranium.

1 INTRODUCTION

1.1 Small Long-life Reactor

Conventional nuclear power reactors have been developed to obtain better economical performance by making full use of scale merits in their history. However, at present further deployment of large nuclear reactors seems difficult, and meets large economical risks. Small reactors are good from investment protection. However, they are considered more expensive per unit power output, though many factors can be expected for reducing expense, such as removal of safety equipments, mass production, reduced regulatory cost, increased experience, reduced construction period, increased operation efficiency. They can be built on a less graded land such as a small land and less stable land. Therefore they usually can be built in more diversified sites. They are also suitable for more diversified purposes. The transportation of heat and potable water for long distance requires high cost and meets energy and material loss. For such a purpose, a local reactor is proper. Then the required power is small, and the reactor should be small. In the second half of this century, hydrogen production may be requested from nuclear reactors. For such cases small reactors seem suitable. The nuclear reactor can be utilized for other than energy production such as neutron unitization and medical uses. For such cases small reactors can be better applicable. For solving future problems such as global warming, environmental problems, energy resource shortage, etc., purely innovative nuclear reactors are expected to be developed. For developing such reactors we should start from a small reactor.

In the 21st century global warming caused by the carbon dioxide emission becomes an inevitable problem. Especially the carbon dioxide emission from developing countries becomes important. The nuclear reactors are free from these problems. However, in developing countries infrastructure is not sufficient and enough number of technicians cannot be obtained. Furthermore, some developing countries are politically unstable. The energy demand in these cases is usually local and small. As already mentioned, the long-life small reactor is simple and easy for operation and maintenance, inherently safe and proliferation resistant. Therefore, the long-life small reactors have large potential to solve global worming problem. If a reactor is small enough to be transportable and has a long life, it can be built in a factory and shipped to an operation site. When this reactor is designed to be sealed in order to make discharge of any fuel impossible outside the factory, it can show an excellent performance of proliferation resistance.

However, both smallness and long-life require a lot of excess neutrons for the reactor criticality condition and high fissile-nuclide conversion ratio, respectively. Fast reactors show a good conversion ratio, and lead bismuth eutectic (LBE) is a good coolant to perform better criticality performance from hard spectrum (caused by large nuclear mass) and better neutron confinement performance (due to large scattering cross section). [1] LBE is good not only for neutron economy but for chemical inertness, high boiling point and low gamma activity under neutron irradiation, which may realize a much safer reactor than conventional sodium-cooled reactor. However, it has some problems such as large specific mass, corrosiveness, polonium production, and small resource amount. They are now intensively investigated and may be considered solvable.

1.2 CANDLE Burn-up

1.1.1 Principles

A new reactor burn-up strategy CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) was proposed [2], where shapes of neutron flux, nuclide densities and power density distributions remain constant but move to an axial direction as shown in Fig. 1. The refueling strategy is also shown in Fig. 2. Here important points are that the solid fuel is fixed at each position and that any movable burn-up reactivity control mechanisms such as control rods are not required. Namely the above-mentioned motion of the distribution is autonomous.

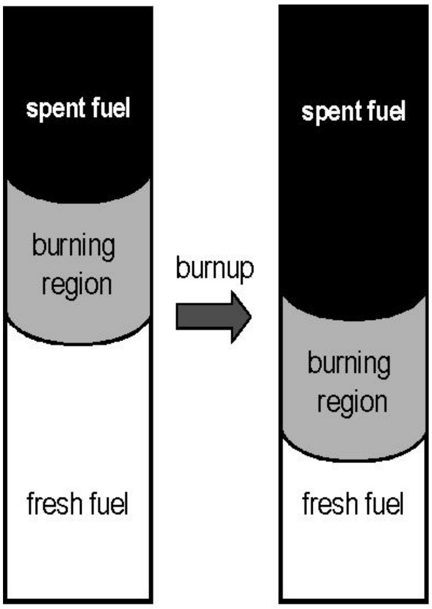

Fig.1. CANDLE burn-up strategy

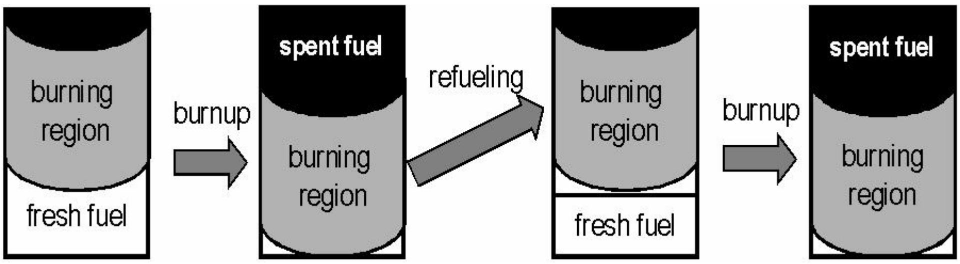

Fig. 2. CANDLE burn-up and refueling scheme.

CANDLE burn-up strategy can be realized, when the infinite-medium neutron multiplication factor, k_{inf}, satisfies some characteristics. A typical change of k_{inf} along core axis is shown in Fig. 3. Here the left side corresponds to fresher fuel, and the right side corresponds to burned-up fuel. The k_{inf} value for fresh fuel should be less than unity. Otherwise, the power profile will extend so much to the fresh fuel region or the reactor becomes super-critical. After a certain amount of burn-up k_{inf} takes more than unity to keep the reactor critical. Finally it becomes again less than unity caused by the accumulation of fission products (FPs) and consumption of fissile materials. The same k_{inf} change is shown along the core axis in Fig. 4. The left side of the core is the fresh fuel region. In the area where the fresh fuel region changes to the burning region, k_{inf} increases with time. On the other hand in the area where the burning region changes to the spent fuel region, it decreases with time. Therefore, as the bunup succeeds, the burning region moves to the fresh fuel region. At the equilibrium state, the shape of power density does not change with time.

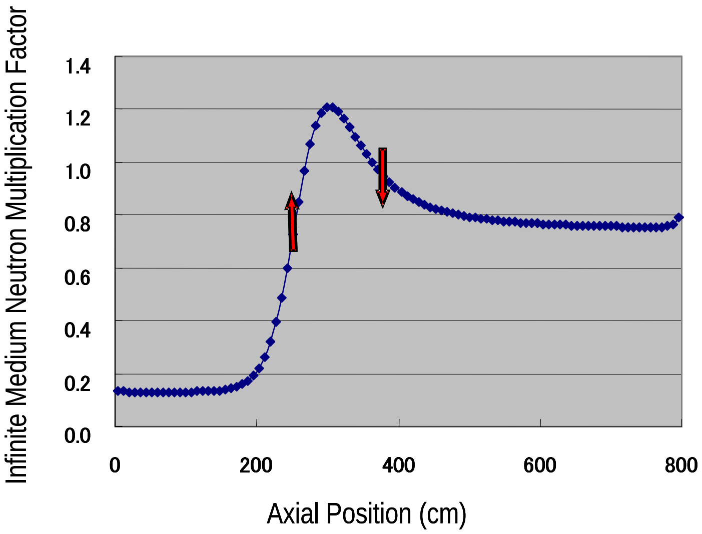

Fig. 3. Change of k_{inf} along core axis.

Numerical analysis of CANDLE burn-up is more sophisticated than conventional methods. The steady state of CANDLE burn-up is obtained by solving a Galilee transformed system of neutron diffusion (or transport) and nuclide burn-up equations. The description about calculation method is omitted in the present paper. It is written in the reference [2, 3].

The computing program system is our original, but group constants preparations are performed by using SRAC code system [4] with JENDL-3.2 nuclear data library [5].

1.1.2 General merits and demerits of CANDLE burn-up

CANDLE burn-up strategy has the following general merits:

1) Burnup reactivity control mechanism is not required: The reactor control becomes simpler and easier. The excess burn-up reactivity becomes zero, and the reactor becomes free from reactivity-induced accidents. Neutrons are efficiently utilized.

2) Reactor characteristics do not change with burn-up: The reactor characteristics such as power peaking and power coefficient of reactivity do not change with burn-up. The estimation of core condition becomes very reliable. The reactor operation strategy remains unchanged for different burn-up stage. The inaccuracy of present burn-up calculation is much less important for this reactor compared with for conventional reactors.

3) Orifice control along burn-up is not required: Since the radial power profile does not change with burn-up, the required flow rate for each coolant channel does not change. Therefore, the orifice control along burn-up is not required. The operational mistakes are avoided.

4) Radial power distribution can be optimized more thoroughly: Since the radial power distribution does not change with time, it can be optimized more thoroughly than conventional reactors. The optimization method is much simpler.

5) By simply increasing the core height, the reactor life can be elongated: Design of long-life reactor becomes easier. Even a very long-life reactor does not require refueling during its life. Such a reactor is well suited to the case that high infrastructures cannot be expected.

6) k_{inf} of fresh fuel after the second cycle is less than unity: The risk for criticality accident is small. The transportation and storage of fresh fuels become simple and safe.

Some general demerits of this burning strategy may be considered. Coolant pressure drop becomes larger, since the core becomes higher. However, the core height is a function of axial power profile and drift speed of burning region. Both of these values become small for many designs. Therefore, the pressure drop is usually manageable. Freedom of optimization of axial power distribution becomes smaller. However, the total power distribution is optimized to a high level, since the radial power distribution is optimized thoroughly. Therefore, CANDLE burn-up does not show any fatal demerits, even though it shows many considerable merits.

1.1.3 Outstandingly excellent merits of CANDLE burn-up

When CANDLE burn-up strategy is applied to neutron rich fast reactors (FRs), outstandingly excellent merits will be expected as follows:

The merits of CANDLE burn-up applied to neutron rich FRs are summarized as follows:

1) Enriched fuels are not required after the second cycle: Only natural or depleted uranium is enough to be charged to the core after the second cycle. Namely, if the fuel for the first cycle is available, neither enrichment nor reprocessing plant is required. It is an excellent feature from the physical protection point of view.

2) The burn-up of the spent fuel is about 40% (400 MWd/tHM): This value is competitive to the value of the presently expected FR system with reprocessing plant. The 40% of natural uranium burns up without enrichment or reprocessing.

3) Long-life reactor can be designed easily, since the burning region drift speed is only about 3cm/y: Even the reactor with 30 years life can be designed simply by adding 0.9m to the initial core height.

The present once-through fuel cycle of 4% enriched uranium in light water reactor (LWR) performs the burn-up of about 4% of the inserted fuel, and it corresponds to the utilization of 0.7% of natural uranium. For this case 87% of the original natural uranium is left as depleted uranium. If this depleted uranium is utilized as the fuel for CANDLE reactor, 35% (=0.87x0.4) of the original natural uranium is utilized. Therefore, if the LWR has already produced energy of X Joules, the CANDLE reactor can produce 50X Joules from the depleted uranium stored at the enrichment facility for the LWR fuel.

If LWRs have already produced energy sufficient for full 20 years and the nuclear energy production rate will not change in the future, we can produce the energy for 1000 years by using the CANDLE reactors. We need not mine any uranium ore, and do not need reprocessing facility. The burn-up of spent fuel becomes 10 times. Therefore, the spent fuel amount per produced energy is also reduced to be one-tenth.

They are outstandingly good characteristics. However, for this case it meets the following severe problems:

1) The fuel material should show integrity performance for very high burn-up.

2) The equilibrium state should be realized from initial core, which can employ only easily available material.

For the first problem, development of fuel cladding, which wears well for 50% burn-up, is required but it may take too much time for research and developments. However, even though the presently attainable burn-up of cladding is much less than 50%, employing simple reprocessing, where only the cladding is replaced by new one, can realize the CANDLE burn-up.

For the second problem, we found a good initial core by constructing enriched uranium. [6]

2 SMALL CANDLE REACTOR

2.1 Core Design

Table I shows the reactor design for the present study. The tube-in-shell type is chosen for fuel pin type in order to obtain higher value of fuel to coolant volume ratio. The core size is almost smallest limit for performing CANDLE burn-up.

Table I. Core design parameters

Total thermal power [MWth]	200
Core height [cm]	200
Core radius [cm]	100
Reflector Thickness [cm]	50
Coolant Channel diameter [cm]	0.453
Cladding Thickness [cm]	0.035
Fuel pin thickness [cm]	1.132
Fuel material [-]	Nitride (N-15) enriched natural uranium
Cladding material[-]	HT-9
Coolant material [-]	Pb-Bi(44.5%-55.5%)
Core inlet coolant temperature [K]	600
Core outlet coolant temperature[K]	800

2.2 Calculation Results

Table II shows the calculation results. The present small reactor shows a similar value of discharged fuel burn-up to large reactors. However, the burning region velocity is much smaller than the previous results since the power density is smaller. By this small burning region velocity, long core life is easy to be obtained.

Table II. Calculation results

k_{eff}		1.0001
Burning region velocity [cm/year]		0.7
Core averaged discharged fuel burn-up [%]		40.2
	[GWd/tU]	374.2
Peak fuel temperature [K]		824
Peak cladding temperature [K]		801

Figure 4 shows the radially averaged nuclides number density for each important nuclide along the core axis. They are similar to the large fast reactor case. It is consistent with the already mentioned agreement of discharged fuel burn-up between small and large reactors. The number density of Pu239 takes a peak, and decrease with the same curve to the U238. It means the density of Pu239 becomes equilibrium to U238 density.

The obtained power density distribution is shown in Fig. 5. It is also similar to the large reactor. The peak is sharp, and the corresponding axial fuel temperature distribution takes its peak as shown in Fig. 6, where the temperature at the center of fuel pin is shown. However, the overshoot is only about 20K and it is not so big demerit. Cladding maximum temperature is 801K and fuel maximum temperature is 824K. Both have large margin to the temperature limits.

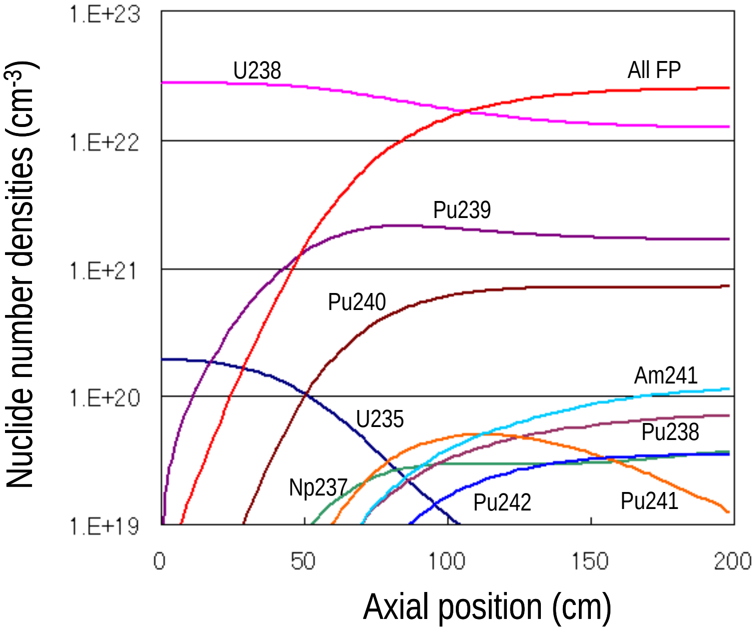

Fig. 4 Number densities of important nuclides along core axis

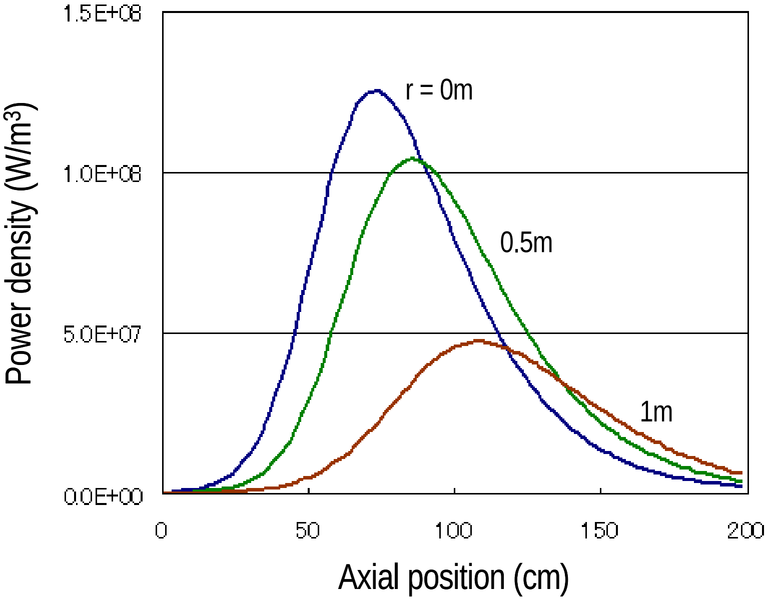

Fig. 5 Power density distribution in the core

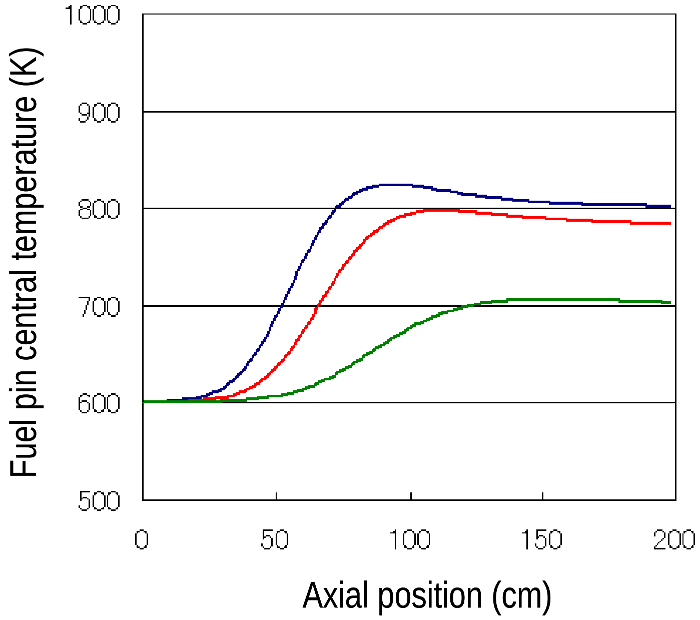

Fig. 5 Fuel pin temperature distribution in the core

3 CONCLUSION

We have tried to design a small long life CANDLE fast reactor, and investigated its characteristics in steady state, where nitride (enriched N-15) fuel and lead-bismuth coolant are employed. CANDLE burn-up can be established successfully in a core with a radius of 1.0m and a height of 2.0m. Total thermal power output is 200MW. Mining, enrichment plants and reprocessing plants are not necessary, once it starts operation. Very long core life without refueling can be realized by taking advantage of very slow burn-up velocity (0.7cm/year). It shows the possibility to design a sealed and maintenance free reactor, which can prevent nuclear proliferation. Deep burn-up is also realized. The core averaged burn-up is as high as 40%. It means the 40% of original natural uranium is utilized as energy source without reprocessing. Coolant velocity is controlled in a reasonably slow range (less than 2.0m/s) which can help core structure to keep integrity. Cladding maximum temperature is 801K and fuel maximum temperature is 824K. Both have large margin to the temperature limits. The reactor characteristics do not change with burn-up, and the operation of this reactor is simple and easy.

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