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Power Flattening for CANDLE Fast Reactor by Adding Thorium in Inner Core

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Abstract – *CANDLE reactor shows excellent performances on the difficult problems inherent to nuclear energy concerning sustainability, safety, bomb and wastes. However, concerning economy we have still problems to be solved. Core height should be as short as possible from economy consideration. In this paper the power density profile is intended flatten for the metallic fuel CANDLE fast reactors by adding thorium uniformly in the inner core region. The total power is increased by the factor of 1.28 and 1.16 for the sodium cooled reactor and Pb-208 cooled reactor, respectively, under the constraint of maximum axially integrated power density. Though the increase rate is better for sodium cooled reactor, but the final power density is much flatter for the Pb-208 cooled reactor. The power flattening makes the axially dangling power density distribution straighter, and the core height can be made shorter.*

I. INTRODUCTION

I.A. Requirements imposed on nuclear reactors

The nuclear energy has the resource problem, if we operate only light water cooled reactors (LWR). It has also inherent difficult problems caused by radioactive materials produced in it and by employed materials and technologies tightly relating to nuclear bombs. The radioactive materials cause the problem of accident during reactor operation, and the problem of radioactive wastes after reactor operation. Reasonable price is usually an important requirement to energy. Thus the necessary and sufficient conditions for nuclear energy utilization as primary energy are considered to solve all the problems for a) resource, b) safety, c) waste, d) bomb and e) economy.[1, 2]

I.B. What is CANDLE reactor?

In conventional reactors, control rods inserted at the start-up of operation are gradually extracted along fuel burning in order to maintain the reactor critical. On the other hand, CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) reactors do not need this kind of control rods.[3,4] Their burning region moves along the direction of the core axis, at a speed proportionate to the power output, without changing the spatial distribution of the nuclide densities, neutron flux and power density as shown in Fig. 1. We can use either natural uranium or depleted uranium for the fresh fuel.

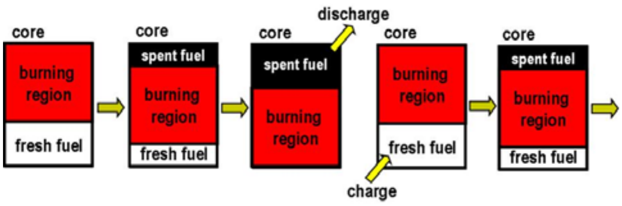


Fig. 1. CANDLE burning and fuel management

I.C. Principle of CANDLE burning

The distributions along core axis of neutron flux and number density of each nuclide are shown in Fig. 2. Here the core height is taken infinite for explaining the CANDLE burning in the most general case. Near the boundary between fresh fuel and burning regions U-238 absorbs a neutron leaking from the burning region and becomes Pu-239, and after repeating it many times this region changes to the burning region. Near the boundary between burning and spent fuel regions the density of Pu-239 saturates and fission products (FP) accumulate, and then this region changes to the spent fuel region. Therefore, the burning region shifts to the fresh fuel region.

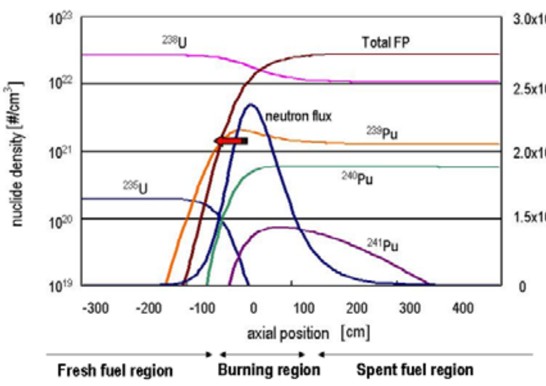


Fig. 2. Nuclide densities and neutron flux distributions along core axis

I.D. How CANDLE reactor satisfies the requirements on reactors?

Very high neutron economy is required to realize CANDLE burning for the fast reactor case. From our previous studies only very hard neutron spectrum fast reactors can realize this burning. However, once it is realized, natural or depleted uranium can be used for replacing fuels and 40% of it can burn up.

CANDLE reactor solves all the problems for a) resource, b) safety, c) waste and d) bomb as follows:[1, 2]

a) Resource

After a LWR, whose fuel enrichment is 4%, has been operated for 40 years, a CANDLE reactor can produce the energy with the same power rate for more than 2000 years by using the associated depleted uranium (enrichment of 0.1%).

b) Safety

> Reactor characteristics don't change with burning: Power peaking and reactivity coefficients don't change with burning. Orifice control along burning is not required. Estimation of core condition is very reliable at any burning stage. Reactor operation strategy remains the same for different burning stage.

> Instrument of reactivity control along burning is not required: Reactor control becomes simple and easy. Reactivity-induced accidents are avoided.

> Management of replacing fuel (depleted and natural uranium) is easy: Risk for criticality accident is small. Transportation and storage of fresh fuels become simple and safe.

> Possibility of re-criticality accidents at CDA is considerably reduced: Reasons: the control rods are not inserted in the core under usual operation, and coolant amount in the core is small.

c) Waste

The amount of spent fuel per produced energy from CANDLE reactor is one tenth of the amount from LWR and one quarter from a typical fast reactor. The amount of minor actinides is considerably reduced compared with these reactors. The amount of secondary wastes associating to fuel cycle is drastically reduced.

d) Bomb

The enrichment and reprocessing are the most important key technologies for bomb-making. CANDLE reactor can be operated without enrichment or reprocessing forever, once it starts, if only natural or depleted uranium is available. Therefore, CANDLE reactor shows excellent features on physical protection and non-proliferation.

For e) Economy, we can expect low operation and maintenance cost, since CANDLE reactor is simple. We can also expect low fuel cycle cost, since separation of elements of discharged fuel is not required. However, coolant channel space is smaller than conventional reactors, and core height may be longer. Therefore the core cooling performance may be inferior. It may result in lower average power density.

Low average power density deteriorates strongly its economical performance. In the present paper we try to increase the average power density by flattening the power shape. If the power density profile becomes flat, it is expected that the axial position of burning region is aligned at the same height for each radial position. It makes core height shorter and raises the average power density farther. The shorter core has usually more merits such as smaller loss of coolant pressure obtained during passing fuel channel and more negative coolant void coefficient.

II. HOW TO MAKE POWER DENSITY FLAT?

We can consider many methods to make the power density profile flat. In the present paper for this purpose some amount of the uranium fuel in the inner core is replace by thorium. Thorium which produces U-233 has less performance ability of neutron production than U-238 which produces Pu-239. If we choose the amount of thorium proper, net radial current of neutrons in the inner core becomes zero in the inner core and at the boundary between inner and outer core (boundary between thorium-uranium region and uranium region), enough neutrons leak from the uranium region and the net radial current is still zero at this point. In the outer region the neutrons leak outward. By this way we can make the power density distribution flat in the inner core.

III. DEMONSTRATION FOR A SAMPLE PROBLEM

III.A. Core design

We treat both sodium cooled fast reactor and Pb-208 cooled fast reactor, where the fuel is only metallic. The metallic fuel shows much better performance than the oxide fuel.[5] The sodium cooled fast reactor has been studied for many years in several countries, and we have almost enough experience for this type of reactor. On the other hand, though we have no experience for Pb-208 cooled fast reactor, it is expected more neutrons available in the core and much less positive void coefficient expected.

Since the purpose of this study is to investigate the performance of our method on power flattening, we will consider only reactor physics. The total power of these reactors is 1980 MWth and core diameter is 4.0 m. The core height is 2.0 m. The radial reflector of stainless steel of the thickness of 50cm is introduced to the sodium cooled reactor, but the lead coolant outside of the core works as the reflector. Some basic fuel cell design parameters are shown in Table I. We choose the same design conditions for these reactors, though they may be changed in the future more practical designs.

TABLE I
Fuel Cell Design Parameters

Fuel	Natural uranium metallic
Cladding	ODS steel
Coolant	Na or Pb-208
Pin diameter [mm]	12.2
Cladding thickness [mm]	0.5
Pin pitch [mm]	14.4

III.B. Calculation Method

The steady state CANDLE burning can be described by the following equations:[3,4)]

$$V\frac{\partial}{\partial z}N_n(\vec{r}) = -N_n(\vec{r})\left(\lambda_n + \int_0^\infty dE'\sigma_{A,n}(E')\int_{4\pi}\phi(\vec{r},\vec{\Omega}',E')d\vec{\Omega}'\right) + \sum_{n'}N_{n'}(\vec{r})\lambda_{n'\to n} + \sum_{n'}N_{n'}(\vec{r})\int_0^\infty dE'\sigma_{n'\to n}(E')\int_{4\pi}\phi(\vec{r},\vec{\Omega}',E')d\vec{\Omega}' \quad (1)$$

$$\vec{\Omega}\cdot\nabla\phi(\vec{r},\vec{\Omega},E) + \sum_n N_n(\vec{r})\sigma_{T,n}(E)\phi(\vec{r},\vec{\Omega},E) = \int_0^\infty dE'\int_{4\pi}d\vec{\Omega}'\sum_n N_n(\vec{r})\sigma_{S,n}(\vec{\Omega}'\cdot\vec{\Omega},E'\to E)\phi(\vec{r},\vec{\Omega}',E') + \frac{1}{4\pi k_{eff}}\int_0^\infty dE'\int_{4\pi}d\vec{\Omega}'\sum_n N_n(\vec{r})\chi_n(E)\nu_n\sigma_{F,n}(E')\phi(\vec{r},\vec{\Omega}',E') \quad (2)$$

and

$$\int_V d\vec{r}\int_0^\infty dE'\int_{4\pi}d\vec{\Omega}'\sum_n N_n(\vec{r})\sigma_{F,n}(E')\phi(\vec{r},\vec{\Omega}',E') = P \quad (3)$$

where V and P is the speed of burning region and the total fission rate in the core, respectively, and the notations of the other variables are conventional. These equations are solved by using a code system including SRAC-CITATION part for solving Eqs. (2) and (3) and our original part for Eq. (1). Fine 107-energy-group microscopic cross section set was obtained using SRAC with JENDL-3.3 nuclear data library.[6] It was collapsed to coarse 21 group microscopic cross section set and used for neutron diffusion calculation by CITATION. The details of calculation method including the method for obtaining the speed of burning region V are shown in the reference [4)].

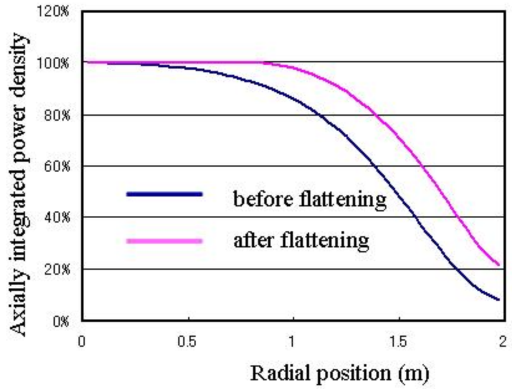
III.C. Calculation results

The replacement rate of uranium by thorium in the inner core and boundary position between inner and outer core are adjusted to make the power density distribution flat in the inner core, and the uranium density in the outer core also adjusted at the same time to make the power density distribution continuous at the boundary. The obtained values of these parameters for each reactor are shown in Table II. The amount of thorium addition is smaller for the sodium cooled reactor, since its original effective neutron multiplication factor (k-eff) is smaller (See Table III). The thickness of outer core for the sodium cooled reactor is much larger than the lead cooled reactor, since the neutron mean free path is larger.

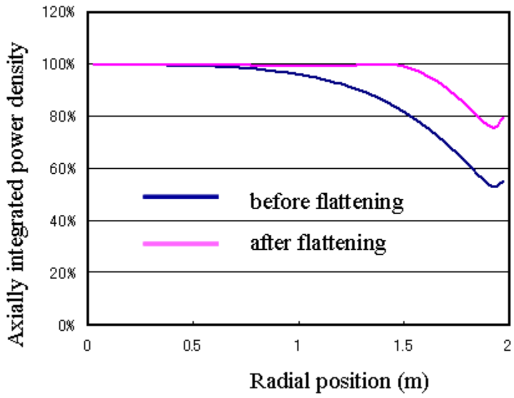
TABLE II
Replacement Rate of Uranium by Thorium in Inner Core and Boundary between Inner and Outer Core

	Na cooled reactor	Pb-208 cooled reactor
Replacement rate of uranium by thorium	22%	37%
Boundary between inner and outer core	80cm	140cm

The obtained radial power distributions for both reactors are shown in the Fig. 3 in which ones before flattening are also shown for comparison. The effective neutron multiplication factor (k-eff) and the maximum to average ratio of axially integrated power density are shown in Table III for before and after flattening for each reactor. The core conditions including each nuclide density are adjusted for each reactor in order to make it just critical for flat power case. Therefore, the value of k-eff is much higher than unity before flattening. The radial power peaking factor is shown in the same figure. From these values it is found that, for the given maximum axially integrated power density constraint, the total power can be increased by the factor of 1.28 and 1.16 for the sodium cooled reactor and Pb-208 cooled reactor, respectively. Though the improvement is larger for the sodium cooled reactor, the final power shape is much better for Pb-208 cooled reactor, whose radial peaking factor is near unity. It is attributed to the outer radial position of boundary between inner and outer core inner core, since the mean neutron free path is smaller for the Pb-208 cooled reactor.



(a) Sodium cooled fast reactor



(b) Pb-208 cooled fast reactor

Fig. 3. Axially integrated power density normalized by the maximum value

TABLE III
Obtained Effective Neutron Multiplication Factor and Radial Power Peaking Factor

	Na cooled reactor		Pb-208 cooled reactor	
	before flattening	after flattening	before flattening	after flattening
k-eff	1.015	1.000	1.043	1.002
radial power peaking factor	1.815	1.416	1.231	1.063

The r-z two-dimensional power density distributions for these two reactors before and after flattening are shown in Fig. 4. The power flattening makes the axially dangling power density distribution straighter. This effect is stronger for the Pb-208 cooled reactor, and its core height can be made shorter.

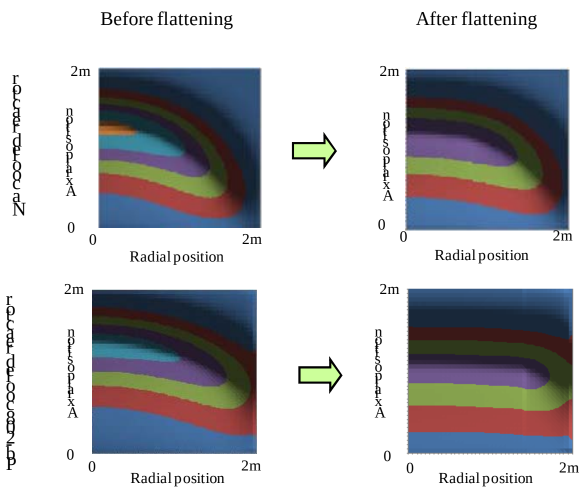


Fig. 4. Two-dimensional power density distributions for Na and Pb-208 cooled reactors before and after flattening

IV. CONCLUSIONS

The power density profile is intended flatten for the metallic fuel CANDLE fast reactors by adding thorium uniformly in the inner core region. The total power is increased by the factor of 1.28 and 1.16 for the sodium cooled reactor and Pb-208 cooled reactor, respectively, under the constraint of maximum axially integrated power density. Though the increase rate is better for sodium cooled reactor, but the final power density is much flatter for the Pb-208 cooled reactor. The power flattening makes the axially dangling power density distribution straighter, and the core height can be made shorter.

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