PHYSOR 2010 – Advances in Reactor Physics to Power the Nuclear Renaissance
Pittsburgh, Pennsylvania, USA, May 9-14, 2010, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2010)

POWER FLATTENING FOR SODIUM COOLED METALLIC FUEL "CANDLE" 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 a sodium-cooled metallic-fuel CANDLE fast reactor by adding thorium uniformly in the inner core region. The total power is increased by the factor of 1.28 under the constraint of maximum axially integrated power density. The core height can be also decreased.

Key Words: CANDLE, thorium, fast reactor, power flattening, core height

1. INTRODUCTION

1.1. 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 cost is usually an important requirement to energy. Thus the necessary and sufficient requirements are considered to solve all the problems for a) resource, b) safety, c) waste, d) bomb and e) economy [1, 2].

1.2. What is CANDLE Reactor?

In conventional reactors, control rods inserted at the start-up of operation are gradually extracted along burning of fuel 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 [2, 3]. 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.

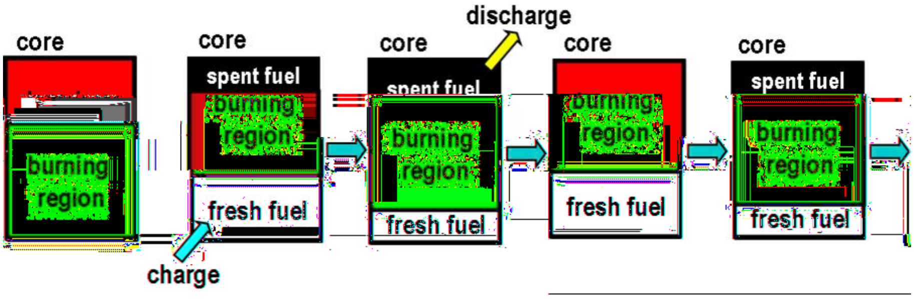


Figure 1. CANDLE burning and fuel management

1.3. Principle of CANDLE Burning

The distributions along core axis of neutron flux and number density of each nuclide are shown in Fig. 3. 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 then 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.

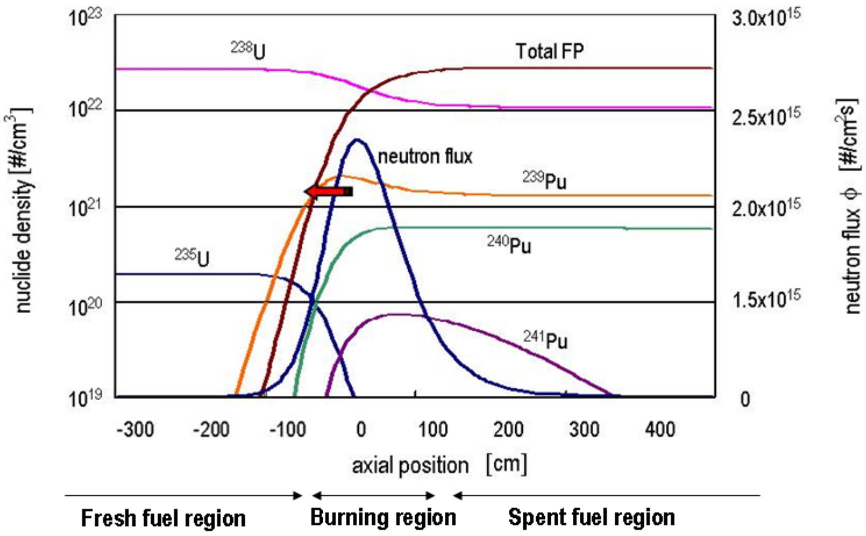


Figure 2. Nuclide densities and neutron flux distributions along core axis

1.4. 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
When a LWR, whose fuel enrichment is 4%, is operated for 40 years, a CANDLE reactor with the same power will use the associated depleted uranium (enrichment of 0.1%) and can produce the same amount of energy for more than 2000 years (See Fig. 3).

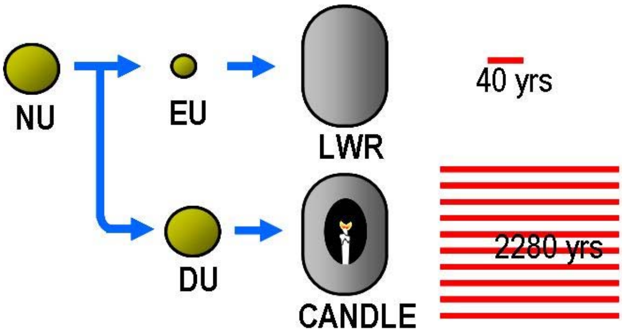


Figure 3. CANDLE reactor operation after LWR operation

b) Safety
The safety can be improved by both reducing frequency of expected incidences including human error and reducing the maximum magnitude of expected consequences.

b-1) Reducing frequency of expected incidences
- 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.
- Mechanism of reactivity control along burning is not required:
    - Reactor control becomes simple and easy.
- 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.

b-2) Reducing the maximum magnitude of expected consequences
- Possibility of re-criticality accidents at CDA is considerably reduced:
    - Reasons:
        - The control rods are not inserted in the core under usual operation.
        - Coolant amount in the core is small.

c) Waste
The amount of spent fuel per produced energy for CANDLE reactor is one tenth of the amount for LWR and one quarter for 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 plant or reprocessing plant for ever, 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.

2. 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 thorium is added uniformly to the uranium fuel in the inner core. 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.

3. DEMONSTRATION FOR A SAMPLE PROBLEM

3.1. Core Design

Table I. Fuel cell design parameters

Fuel	Natural uranium metallic (75%TD)
Cladding	ODS steel [6)]
Coolant	Na
Pin diameter	12.2mm
Cladding thickness	0.5mm
Pin pitch	14.4mm

We treat sodium cooled metallic fuel fast reactor. Since the purpose of the present 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. Some basic fuel cell design parameters are shown in Table I.

3.2. Calculation Results

The steady state CANDLE burnup is solved by the method we have developed [3, 4] with JENDL-3.3 nuclear data library [5].

The amount of thorium addition rate in the inner core and boundary position between inner and outer core are adjusted to make the power density distribution 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 are shown in Table II and the obtained radial power density distributions are shown in the Fig. 4.

Table II. Rate of thorium addition in the inner core and boundary between inner and outer core

Thorium addition rate in the inner core	22%
Boundary between inner and outer core	80cm

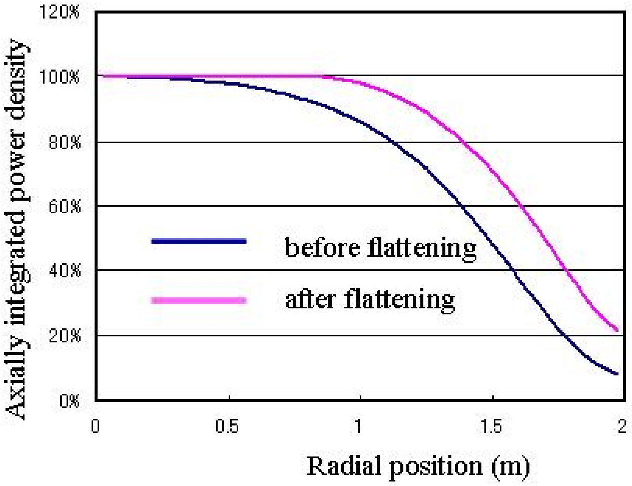


Figure 4. Axially integrated power density normalized by the maximum value

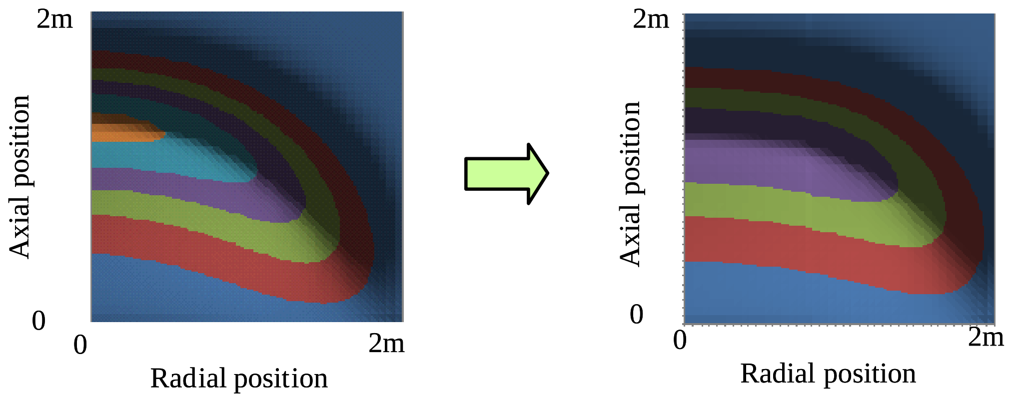
The effective neutron multiplication factor (k-eff) and the maximum to average ratio of axially integrated power density before and after power flattening are shown in Table III. The core condition including each nuclide density is adjusted in order to make it critical for flatten power case. Therefore, k-eff is much higher than unity before flattening.

Table III. Obtained effective neutron multiplication factor and radial power peaking factor

	before flattening	after flattening
k-eff	1.015	1.000
Radial power peaking factor	1.815	1.416

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.

The r-z two-dimensional power density distributions before and after power flattening are shown in Fig. 5. From these figures we can conclude the core height shortening is possible.



(a) before flattening

(b) after flattening

Figure 5. Two-dimensional power density distributions before and after power flattening

4. CONCLUSION

The power density profile is intended flatten for the sodium cooled 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 under the constraint of maximum axially integrated power density. The core height shortening is possible by this method.

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