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INTRODUCTION OF "MOTTO" CYCLE TO CANDLE FAST REACTOR

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ABSTRACT

CANDLE reactor shows excellent performances on the inherent difficult problems concerning sustainability, safety, bomb and wastes. However, concerning feasibility and economy we have still problems to be solved. Cladding integrity should be considered from feasibility and core height should be as short as possible from economy consideration. In this paper the cladding integrity problem is solved by recladding, and the core height is tried to be short by making the axial power centroid position to the same height at any radial position by introducing MOTTO cycle. As a result, the core height becomes 1.6 m, where the reactivity swing during operation is 0.0007.

Key Words: CANDLE, MOTTO, fast reactor, power density distribution, core height

1. INTRODUCTION

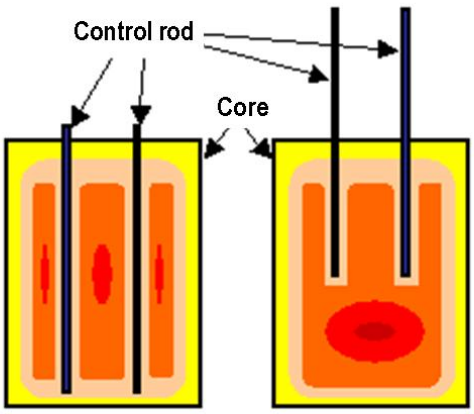
1.1. Requirements Imposed on Nuclear Reactors

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].

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 as shown in Fig. 1.

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 reg ion 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. 2, where each region in the core is shown for different burning stage. We can use either natural uranium or depleted uranium for the fresh fuel.



(a) early stage (b) middle stage

Figure 1. Burn control of conventional reactors (Contour shows power density)

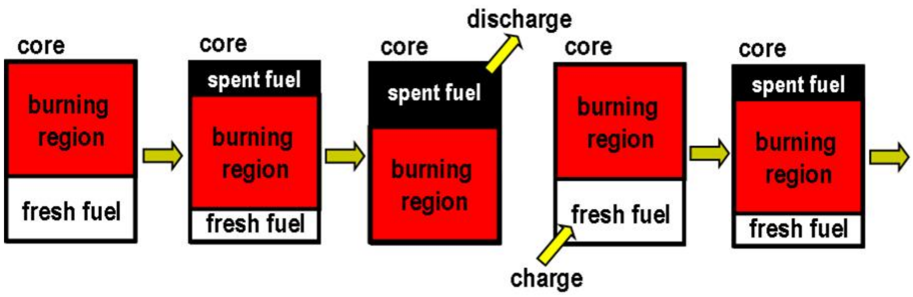


Figure 2. CANDLE burning and fuel management

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.

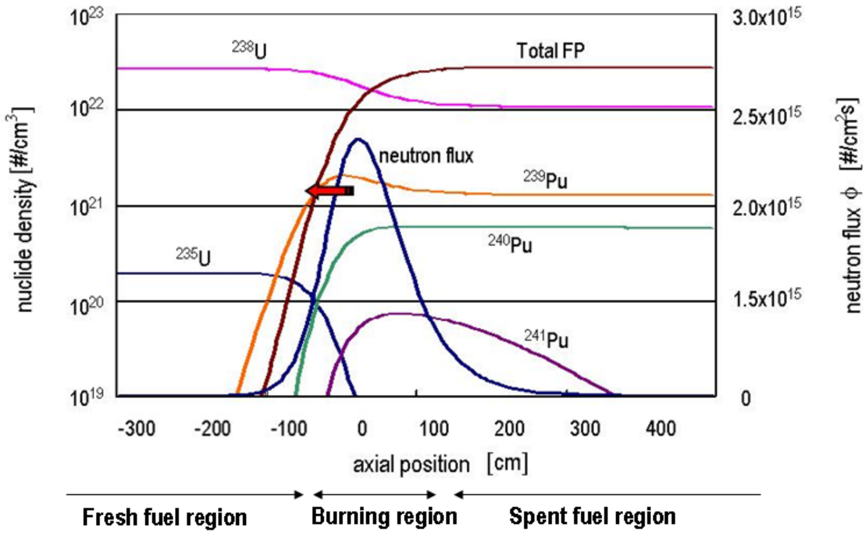


Figure 3. Nuclide densities and neutron flux distributions along core axis

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]:

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
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. On the other hand, 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 worse economy. However, radial power flattening may be performed better than the conventional reactors. The burnup of discharged fuel from CANDLE reactor is very high, and the cladding material integrity and increased gas pressure of accumulated fission products should be considered. In order to solve these problems we try to employ recladding. It requires a special fuel management for this reactor. We introduce MOTTO (Multi-channel Once Through Then Out) cycle for it. This cycle makes the axial power peak position straight radially and the core height shorter.

2. RECLADDING AND "MOTTO" CYCLE

When we use conventional cladding materials, the burnup of 40% is too much and we should employ recladding [4]. Once we employ recladding, frequency of it becomes an optional parameter. The cost of recladding is much cheaper than reprocessing including chemical processes. If the burnup for one-cycle is small enough, the recladding becomes very easy and the separation of cladding from meat becomes more perfect. However, the best value of burnup for recladding is not clear at this moment, and we choose the maximum permissible fast neutron fluence for it. Smaller value can be used without any big violation.

To improve the economic performance, the core height shortening is important, since it increases power d ensity and decreases coolant pressure drop in the core. The typical steady state *r-z* power density distribut ion in a uniform core of CANDLE burnup is shown in Fig. 4. The position of burning region near periphe ral region is higher than in the central region. It causes the necessary core height longer.

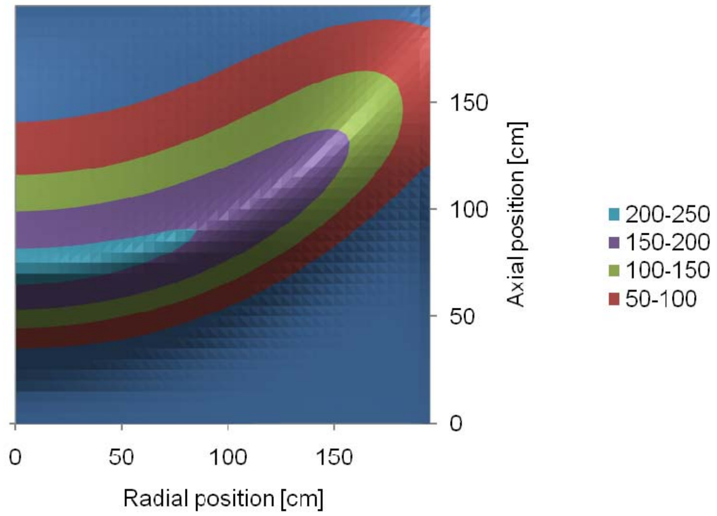


Figure 4. Steady state power density distribution in a uniform core of CANDLE burnup

We consider a similar core configuration to the conventional fast reactors, where many fuel pins stand in the core. In MOTTO fuel cycle, the discharged fuel amount from each fuel pin changes for different position [5]. By adjusting the discharged fuel amount for each fuel pin we try to make the axial position of burning region at each radial position to the same height.

2. DEMONSTRATION FOR A SAMPLE PROBLEM

3.1. Core Design

Total power is 1980 MWth, and core diameter is 4.0 m. The core height is changed from 1.5 m to 1.7 m. Other basic core design parameters are shown in Table 1.

This is only an example for this study. Especially the cladding material should be considered. If we can reduce the burnup, we can change to another cheaper material and easy to be pealed out after irradiation.

Table I. Core design parameters

Fuel	Natural uranium nitride (81%TD)
Cladding	ODS steel [6]
Coolant	Lead Bismuth Eutectic
Pin diameter [mm]	13.2
Cladding thickness [mm]	0.5
Pin pitch [mm]	14.5

3.2. Calculation Method

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

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

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

and

$$\int_V d\vec{r}\int_0^\infty dE'\int_{4\pi}d\vec{\Omega}'\sum_n N_n(\vec{r})\sigma_{F,n}(E')\phi(\vec{r},\vec{\Omega}',E') = P_0 \cdot \quad (3)$$

where V and P_0 is the speed of burning region and the total fission rate in the core, respectively, and the n otations 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 calculation by CITATION. The details of calculation method including the method for obtaining the speed of burning region V are shown in the reference [3].

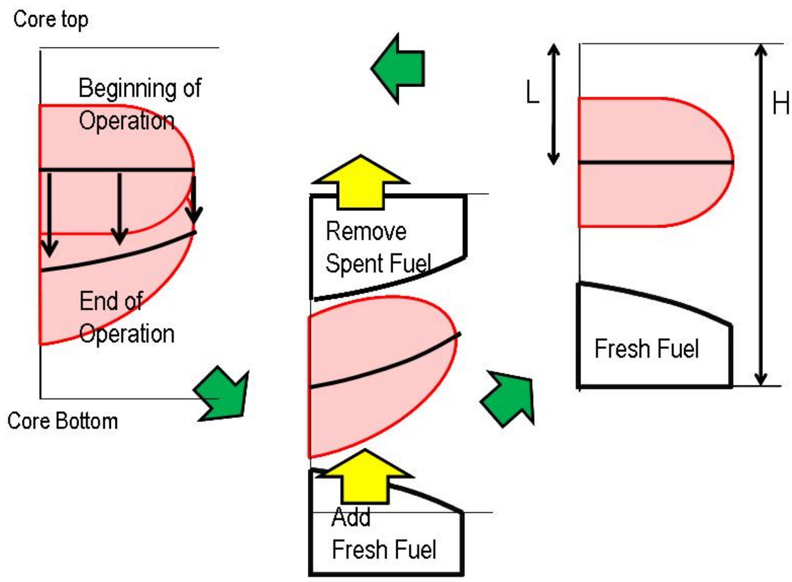


Figure 5. Centroid line of power density distribution for different fuel management stages

The steady state power density distribution of CANDLE burnup is already shown in Fig. 4. Figure 5 shows how this distribution is changed by MOTTO cycle. Here the centroid position is defined as

$$z_c(r) = \frac{\int_{core-bottom}^{core-top} zP(r,z)dz}{\int_{core-bottom}^{core-top} P(r,z)dz}$$

where $P(r,z)$ is the power density at the position (r,z). In this figure H is the core height and L is the di stance of the centroid position from the core top boundary.

At the beginning of power operation, the cetroid line is levelized by adjusting the amount of removed spent fuel at each radial position. The amount of added fresh fuel is the same to the amount of removed spent fuel at each radial position. Along burning of fuel the burning region shifts downward. The speed of downward motion is higher in the central region than the peripheral region, since the power density in the central region is higher. Therefore, at the end of operation the cetroid line is not levelized but lower in the central region than the peripheral region. This line is again levelized by adjunsting the amount of discharged fuel at each radial position in MOTTO cycle.

3.3. Selection of *L*

The criticality for different L is investigated for an enough length of core height of 4.0 m. Here we can ignore the neutron leakage from the core lower boundary in this analysis.

Figure 6 shows the effective neutron multiplication factor (k_{eff}) for different L. It increases with increasing L, and becomes more than 1.0 at L=55 cm. The change of value becomes smaller for L>80 cm. From this calculation result, L=50, 60, 70, and 80 cm are selected, for which the exploratory analysis is performed.

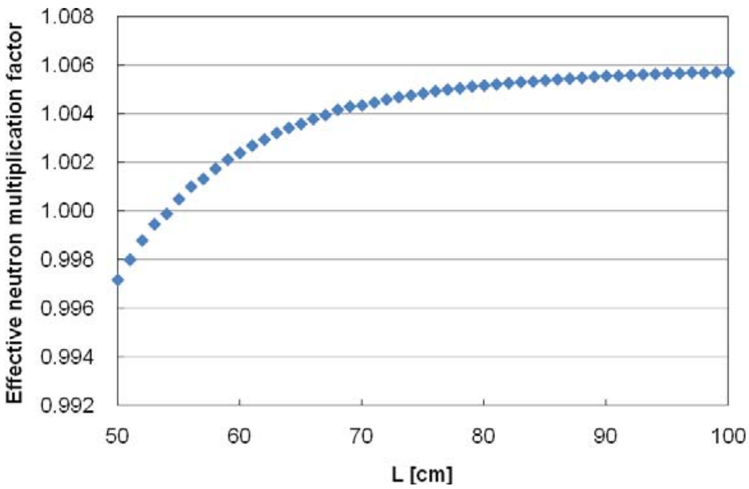
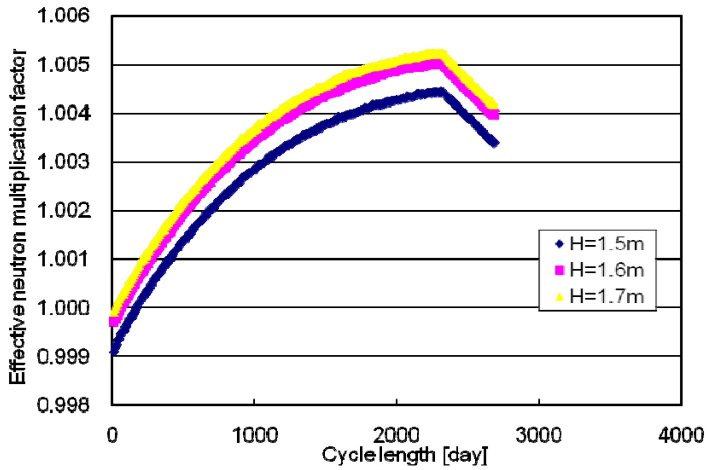


Figure 6. Effective neutron multiplication factor for different *L*

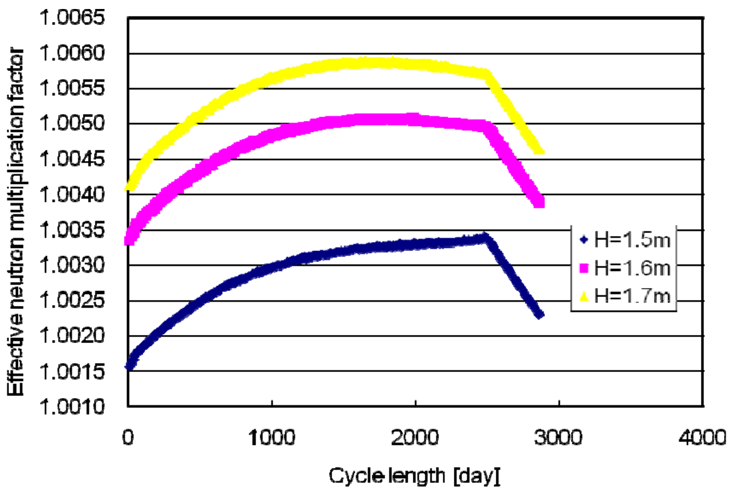
3.4. Calculation Results

For four *L* selected in the previous section, calculation is performed for core height *H* of 1.5, 1.6, and 1.7 m.

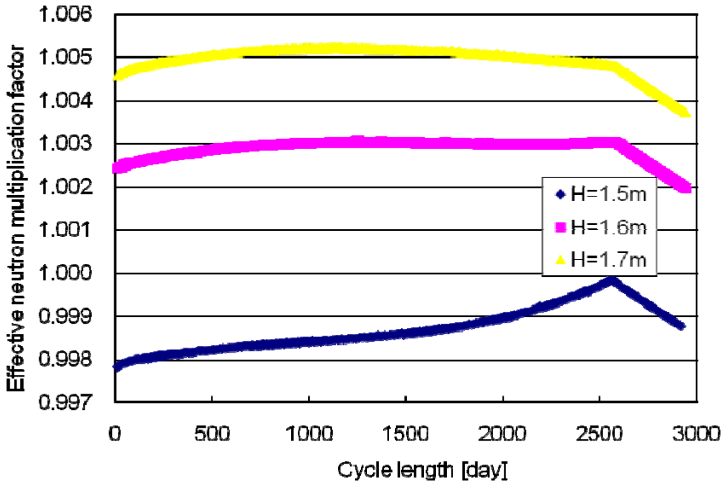
A fuel cycle consists of the period of burning in the core and the period of cooling and recladding. Any length of burning period can be selected if it is less than fast neutron (>0.1 MeV) fluence limit of 5.0×10^{23} /cm^2 [7]. However, in this paper this limit value is used as the most severe case, though a less value may be better for recladding. The cooling and recladding period is taken to be 1 year. Its optimum value should also be determined in the future from consideration of total system of fuel cycle and economy.



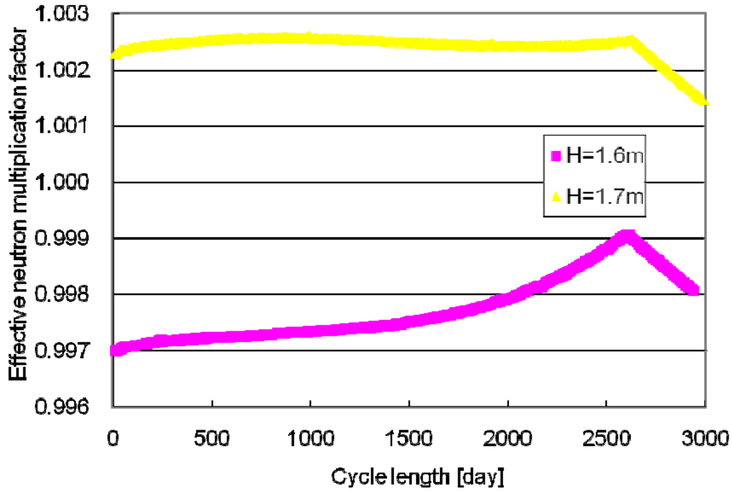
a) *L*=50 cm



b) *L*=60 cm



c) *L*=70 cm



d) *L*=80 cm

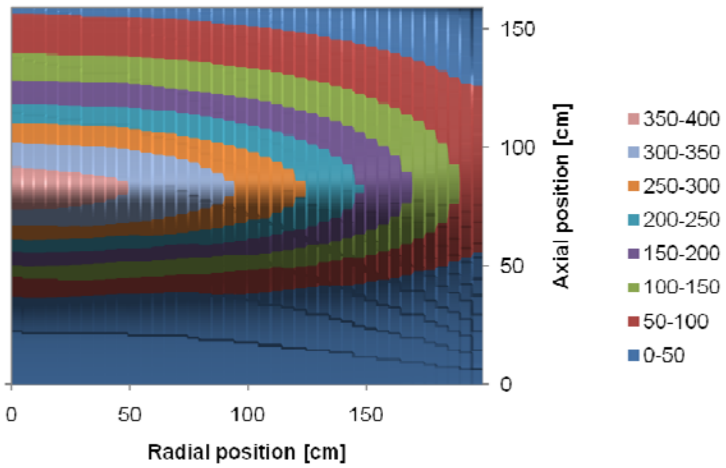
Figure 7. Change of effective neutron multiplication factor for different *L* and *H*

Figure 7 shows change of k_{eff} along the time after start up of burning for different *H* and *L*. Linear decrement of k_{eff} in final phase corresponds to the cooling period. For a fixed *L*, the higher *H* gives the higher k_{eff}. It is attributed to the fact that the amount of neutron leakage from the core bottom decreases for larger *H*. After start up, k_{eff} increases along burning because ^{241}Pu increases from a decayed level to the equilibrium value and the neutron leakage from core top decreases. Here, the larger *L* makes k_{eff} increment speed smaller, since contribution of the neutron leakage from core top becomes larger for smaller *L*.

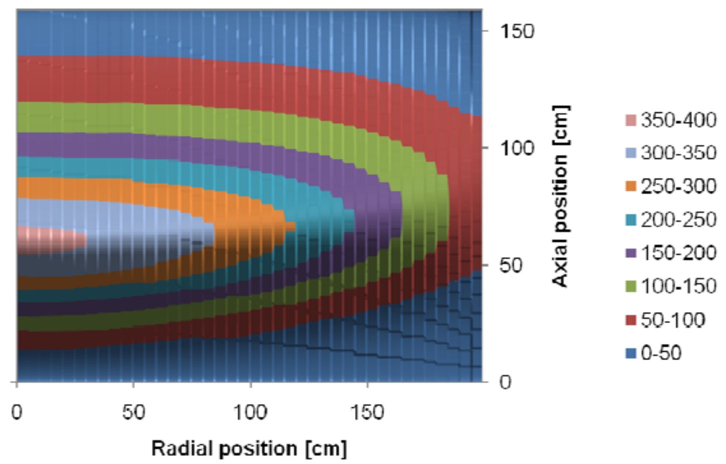
Table II shows the reactivity swing for these cases. The reactivity swing for cases of (*H*=1.6 m: *L*=70) and (*H*=1.7 m: *L*=70, 80 cm) is less than 0.001. Although the case of (*H*=1.7 m: *L*=80cm) gives minimum reactivity swing, the core height for the case (*H*=1.6 m: *L*=70 cm) is 10 cm shorter. In the present study, the case (*H*=1.6 m: *L*=70 cm) is selected for the farther investigation.

Table II. Reactivity swing of each *H* and *L*

Core height: *H* (m)	1.5	1.6		1.7		
Distance between distribution centroid and SCB *L* (cm)	60	60	70	60	70	80
Reactivity swing	0.0018	0.0017	0.0007	0.0018	0.0007	0.0003



a) at the beginning of burning



b) at the end of burning

Figure 8. Power density distribution for the case (*H*=1.6 m, *L*=70 cm)

For the selected case (*H*=1.6 m: *L*=70 cm) the power density distribution is shown in Fig. 8. The centroid line curve shows the change between the beginning and end of burning as we expected.

4. CONCLUSIONS

The cladding integrity problem is solved by recladding, and the core height is tried to be short by making the axial power centroid position to the same height at any radial position by introducing MOTTO cycle. As a result, the core height becomes 1.6 m, where the reactivity swing during operation is 0.0007.

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