# APPLICATION OF “CANDLE” BURNUP TO SMALL FAST REACTOR

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## ABSTRACT

A new reactor burnup strategy CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) was proposed [1], where shapes of neutron flux, nuclide densities and power density distributions remain constant but move to an axial direction. An equilibrium state was obtained for a large fast reactor (core radius is 2m) successfully by using a newly developed direct analysis code. However, it is difficult to apply this burnup strategy to small reactors (core radius is 0.8m), since its neturon leakage becomes large and neutorn economy becomes worse. In the present paper, the long-life small fast reactor with nitride fuel and LBE coolant is investigated. The 5% enrichment of plutonium makes possible to perform CANDLE burnup. The simulation is performed. The core height of 2 to 3 m can realize the operation period of 9 to 28 years with a very small excess reactivity change of less than 0.2% during whole operation period.

## 1 INTRODUCTION

## 1.1 CANDLE Burnup Strategy

### *1.1.1 What is CANDLE burnup?*

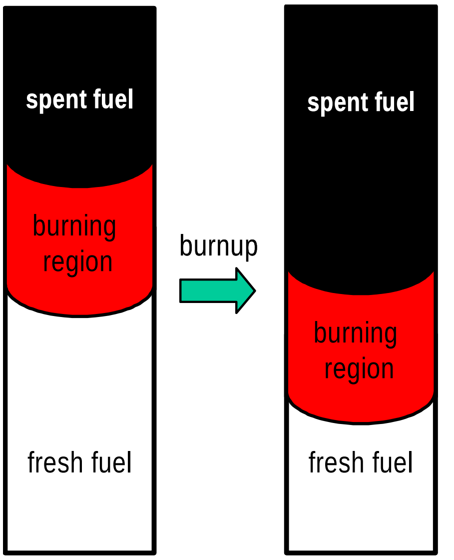

*Figure 1.* Concept of CANDLE burnup strategy

A new reactor burnup strategy CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) is proposed [1, 2], where neutron flux, nuclide densities and power density do not change their shapes along burnup but move in the axial direction of a core with a constant velocity under a constant power operation as shown in Fig. 1. The moving direction can be chosen either upward or downward, but in the present paper only the downward direction is considered for making description of the paper simple.

The CANDLE burnup strategy can be applied to several reactors, for which the infinite neutron multiplication factor of fuel element changes along burnup in a proper way, such as it changes from less than or nearly unity to considerably more than unity, and then to less than or nearly unity. When this condition is satisfied, in the lower part of the burning region the infinite neutron multiplication factor increases along burnup, and in the upper part of the burning region it decreases along burnup. Therefore, the burning region shifts downward. Both natural uranium and depleted uranium show this behavior of their infinite neutron multiplication factor in fast neutron field with hard neutron spectrum. In the present paper only fast reactor cases are studied, even though a thermal reactor can offer interesting examples of CANDLE burnup by introducing highly enriched fuel and burnable poisons with high microscopic absorption cross section.

The axial distribution of each nuclide density in the fresh fuel region is uniform, but they are complicated in the burning region. It may be difficult to construct the ignition region for this burnup strategy. However, the setup of the succeeding core configuration is very easy. The burning region at the end of reactor life can be used as the ignition region of the succeeding core as shown in Fig. 2.

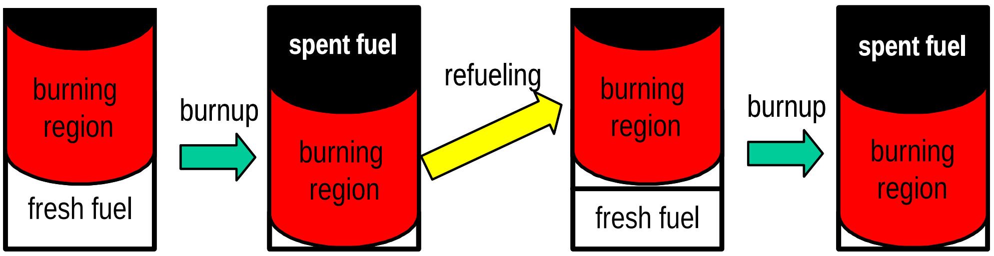

*Figure 2.* Concept of CANDLE burnup and refueling strategy

### *1.1.2 General merits and demerits*

The CANDLE burnup may be considered to have the following many general merits:
(a) Burnup reactivity control mechanism is not required:

It derives the following merits: The reactor control becomes simpler and easier. The excess burnup reactivity becomes zero, and the reactor becomes free from reactivity-induced accidents. The burnup of control rod becomes negligible. Neutrons are not absorbed by control absorber but efficiently utilized.

(b) Reactor characteristics do not change with burnup:

The reactor characteristics such as power peaking, reactivity coefficients do not change with burnup. It derives the following merits: The expectation of core condition becomes very reliable. The reactor operation strategy remains same for different burnup stage. Therefore the reactor operation becomes simple and easy.

(c) Orifice control along burnup is not required:

Since the radial power profile does not change with burnup, the required flow rate for each coolant channel does not change. Therefore, the orifice control along burnup is not required. The operational mistakes are avoided.

(d) Radial power distribution can be optimized more thoroughly:

Since the radial power distribution does not change with time, it can be optimized more thoroughly. The optimization method is much simpler. By choosing properly the radial fresh fuel distribution, the discharged fuel burnup can be equalized for every discharged fuel. This fuel distribution at the same time equalizes the integral power output for each radial position. It also equalizes the coolant output temperature from the core for each coolant channel for equal coolant flow.

(e) By simply increasing the core height, the reactor life can be elongated:

Therefore, design of long-life reactor becomes easier.

(f) Recriticality accident caused by CDA is avoided:

Since the reactor is just critical without any absorbers and contains no surplus fissile materials in its core, Recriticality accident caused by CDA hardly happens.

(g) Infinite neutron multiplication factor of fresh fuel is less than unity:

Therefore, the risk for criticality accident is small. The transportation and storage of fresh fuels become simple and safe.The CANDLE burnup may be considered to have the following demerits at the same time:
(a) Coolant pressure drop becomes larger, since the core becomes higher.

(b) Freedom of optimization of axial power distribution becomes smaller.

However, these demerits are not important by the following reasons: 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. Some examples will be given in the following calculation results. Therefore, the demerit (a) is not important. The demerit (b) should be considered with the radial power distribution optimization. The total power distribution can be optimized to the higher level for this burnup strategy, since the radial power distribution is optimized thoroughly.

### *1.1.3 Application to fast reactors*

In the present paper the applications of CANDLE burnup strategy to fast reactors are discussed. The infinite neutron multiplication factor of natural uranium satisfies the required condition mentioned above in a fast neutron spectrum. However, the excess reactivity is marginal. Though a hard spectrum large fast reactor can realize CANDLE burnup strategy, most small fast reactor cannot realize it with only natural uranium because of the large neutron leakage from the core.

The above-mentioned characteristics are general characteristics of CANDLE. The followings are the outstandingly good characteristics obtained when it is applied to fast reactors with excellent neutron economy [1, 2]:

(a) Enriched fuels are not required after the second core.

Only natural or depleted uranium is enough to be charged to the core after the second core. Namely, if the fuel for the first core is available, neither enrichment nor reprocessing plant is required.

(b) The burnup of the spent fuel is about 40%.

This value is competitive to the value of the presently expected fast reactor system with reprocessing plant. The 40% of natural uranium burns up without enrichment or reprocessing.

(c) Long-life reactor can be designed easily, since the burning region drift speed is only about 4cm/year for the conventional power density level.

Even the reactor with 30 years life can be designed simply by adding 1.2m to the initial core height.

The problems for this case are as follows:
(a) The reactor is required to pertain very high neutron economy.

However, we can present many designs satisfying this requirement.

(b) The fuel material should pertain integrity performance for very high burnup.

Though we have some experimental results for such a high burnup, the number of results is not enough.
The merits for this case is outstanding, but the problem seems very difficult. The criticality requirement can be satisfied by adding some plutonium to the fresh fuel even for the small reactors. However, the requirement for the fresh fuel, that its infinite neutron multiplication factor should be less than or nearly unity, becomes difficult to be satisfied. The rigid performance of CANDLE burnup is not required for these

reactors, if several characteristics are attained such as long-life, simple and safe. In the present paper the application of CANDLE burnup strategy is tried to be investigated for the small fast reactor with plutonium-mixed natural uranium as fresh fuel.

In the present paper the natural uranium is treated, but depleted uranium can be also utilized for the same role. At present we have so large amount of depleted uranium storage. However, to make the story simple, only the natural uranium is discussed in this paper.

The long-life small reactor is considered very important to solve present global energy and environmental problems. Before descussig the application of CANDLE to the long-life samll reactor, discussion on the long-life small reactors will be presented in the next section.

## 1.2 Long-Life Small Reactor

### *1.2.1 Problems for Past Trend of Power Nuclear Reactors and Small reactors [3]*

The size of conventional nuclear power reactors has reached at almost its maximum limit, after pursuing their economy by exploiting scale merit. It is difficult to find a future way for them to be conducted. Soon it becomes almost impossible to find any new site for them in the developed countries. They also have a large economical risk unbearable even for large companies or government.

Small reactors can be built on a less graded land such as a small land and less stable land. Therefore, it is much easier to find their site.

Nuclear reactors can also be utilized several purposes other than electricity production, such as heat generation, desalination, hydrogen production, etc. Since the transportation of heat, portable water and hydrogen for long distance requires high cost and meets energy and material loss, the amount of production is expected small and small reactors are prferable.

Present power-plant owners hesitate to build a larger reactor as the reason of its large economical risk. Even a delay of construction may cause a considerable economical damage. They may prefer to build a smaller reactor, if it is economically feasible.

The scale demerit is a considerable factor to degrade the economical performance of the small reactors. However, there are many items pertaining to small reactors for improving the economical performance. Some of small reactors can be built in a factory as a completed form. It can reduce the reactor cost considerably. Since the number of required reactors for a given power rate becomes larger for the small reactor than large one, we can obtain more experiences for the small reactor. The term required for licensing and construction becomes shorter for the small reactor, and the amount of interest on investments becomes also smaller. Modular system is expected to work efficiently with excellent economical performance even for large station.

### *1.2.2 Small Reactors for Developing Countries*

It is well known that the smaller reactor is safer than the larger reactor, since its system is simpler and the total amount of contained radioactive materials is smaller. Furthermore, certain small reactors possesses inherent safety characteristics, where safety function relies more on natural phenomena and less on human action or mechanical devices.

If a reactor is transportable and has a long life, it can be built in a factory and shipped to a site and installed there and operated in a certain period without refueling and replaced with a new reactor after producing full of energy and finishing its operation and shipped back to the factory. When the vessel of this reactor is designed to be sealed, this reactor possesses an excellent performance of proliferation resistance.

In the 21st century global warming caused by the carbon dioxide emission becomes an inevitable problem. Especially the carbon dioxide emission from developing countries is 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 small reactor is easy for operation and maintenance. It is also inherently safe and proliferation resistant. Therefore, small reactors have large potential to solve global worming problem.

The target reactor for this purpose should satisfy all of small-size, portableness, long-life, safety, simplicity (easy maintenance and operation), and proliferation-resistance. However, some of these characteristics are tightly related each other. By investigating these characteristics, it appears that only long-life and small-size are basic characteristics and the other characteristics can be derived from these two.

### *1.2.3 LBE Cooled Fast Reactor*

In the above discussion it appears that the long-life and small-size are basic for realizing long-life safe simple small portable proliferation-resistant reactor. However, the lastly left items long-life and small-size are in conflict, because a small-sized reactor usually shows poor neutron economy, hence higher burnup can not be expected. The neutron economy, namely reactor criticality, limits both size and life of the reactor. Our discussion leads to the conclusion that the long-life safe simple small portable proliferation-resistant reactor requires excellent neutron economy. It is well known that fast reactors show much better neutron economy compared to thermal or epithermal reactors.

The above discussion suggests that we should investigate small fast reactors. At present sodium is considered as the best coolant for fast reactors. The main reason is its superior cooling ability. It realizes high power density and makes its doubling time shorter. The short doubling time was an indispensable requirement at early time of fast breeder reactor history. It is reported that from a safety viewpoint lead-bismuth-eutectic (LBE) was originally considered [4].

As previously mentioned the neutron economy is very important for realizing long-life small reactor. For the small fast reactor, it is expected that LBE coolant shows much better performance on the neutron economy than sodium coolant because of its large scattering cross section and heavy nuclide mass. It is reported that the LBE-cooled long-life small fast reactor shows better performances for neutron economy, burnup reactivity swing and void coefficient [3, 5]. However, in the western world it has been considered for long time that LBE cannot be used as a reactor coolant from negative experimental results on corrosion problem. But in Russia this problem was solved by oxygen concentration control, and LBE was employed as submarine reactor coolant. It is reported that 8 nuclear submarines with LBE coolant were constructed and operated for about 80 reactor-years [4]. After the Russian research results were opened, many researches especially for corrosion experiment are started worldwide. The corrosion problem is considered to be solved by choosing proper material, temperature, fluid velocity and oxygen concentration.

In the present paper we study on LBE cooled fast reactors.

### *1.2.4 Characteristics of LBE*

In the last of this section, some description about LBE coolant is added. The most important merit of LBE compared to sodium is chemical inertness. LBE does not react violently with water or air.

The boiling temperature of sodium is 1156K, and it is not easy to protect boiling at some severe accidents. If the void coefficient is positive, the accident may lead to core destructive accident. The boiling temperature of LBE is 1943K, and the possibility of boiling seems negligible. Furthermore, the void coefficient is more negative than sodium as mentioned before.

The density of LBE is about 12 times of sodium density. The viscosity of LBE is large and pressure drop is expected to be large. The Prandtl number is about 3 times of sodium value. These characteristics lead to the poor cooling ability of LBE. Then the power density of LBE-cooled reactor should be lower. Anyway from corrosion protection, the flow speed has to be set lower.

For small power reactor, since its power density is usually restricted from the minimum size of core determined by criticality conditions, power density of some very small fast reactor even with sodium coolant becomes very low. Therefore, the poor cooling ability of LBE is not so important for long-life small reactors.

For natural circulation capability, LBE-cooled reactors can offer better potential provided by larger core equivalent hydraulic diameter. It improves the response of the reactor at accidents.

As mentioned before the LBE-cooled long-life small fast reactor shows better performances for neutron economy, burnup reactivity swing and void coefficient from large scattering cross section. The LBE shows also large shielding effects for neutrons and gamma-rays. Then the size of the reactor can be reduced.

The radioactive materials produced in the coolant during operation are also important. For sodium $^{24}$Na should be considered. Its half-life is 15 hrs and emits high-energy gamma-rays (2.8MeV and 1.4MeV).

Therefore, the primary loop of sodium cooled reactor shows very high dose rate. On the other hand, LBE does not produce so much gamma-ray emitters, though Polonium is produced, which is an alpha-ray emitter. Then the dose-rate around the primary loop of LBE is expected much lower than the sodium case.

## 2 CALCULATION METHOD

The present work is the first trial of the CANDLE burnup strategy to the small fast reactor. At the first stage the equilibrium state satisfying the CANDLE burnup requirements is tried to be obtained by using the steady state code [2]. Once shape is obtained as a realistic value for a given reactor design, then as the next and final stage, simulation will be performed.

For calculating the steady state CANDLE burnup, Galilean transformation is employed in order to make the burning region at rest in the transformed coordinate system. Otherwise, the necessary calculation region is expanding, since the burning region moves steadily with repeating iteration of calculation. The convergence judgment becomes also easy for this coordinate system. The actual mathematical treatment and calculation method are shown in the reference [2].

The simulation calculation is the same as conventional calculation method composing of neutorn transport and nuclide burnup equations.

## 3 CALCULATION CONDITIONS

Though the subject of the present paper is the application of CANDLE burnup to small fast reactor, typical applicatin to the large fast reactor with natural uranium fuel is also presented as a reference. Design parameters for these reactors are shown in Table 1.

*Table 1.* Design parameters for large and small fast reactors

| thermal output | | 3000MWth | 300MWth |
|---|---|---|---|
| core radius | | 2.0 m | 0.8 m |
| core height | | 8 m (infinity) | 2.0, 2.5, 3.0 m |
| radial refrector thickness | | 0.5 m | 0.5 m |
| material | fuel | $U_{0.77}Zr_{0.23}$ | (U, Pu)N |
| | cladding | HT-9 | HT-9 |
| | coolant | Pb-Bi (44.5, 55.5%) | Pb-Bi (44.5, 55.5%) |
| cell type | | fuel pin | tube in shell |
| fuel pin diameter | | 0.8 cm | |
| coolant channel diameter | | | 0.668 cm |
| cladding thikness | | 0.035 cm | 0.035 cm |
| fuel | theoretical density | 15.90 g/cm$^3$ | 14.32 g/cm$^3$ |
| | fuel smear density | 75% | 80% |
| fuel volume ratio | | 50% | 61% |

The small reactor is difficult to keep its criticality, since its neturon leakage becomes large and neutorn economy becomes worse. In the present work it is satisfied by adding some plutonium to the fresh fuel. However, this method makes the requirement for the fresh fuel, that its infinite neutron multiplication factor should be less than or nearly unity, difficult to be satisfied. The rigid performance of CANDLE burnup is not necessarily satisfied for the present long-life small reacotor, if several characteristics are attained such as long core life, small core size and small excess reactivity change.

As the fuel material, metallic fuel, which shows an excellent neutron economy, is chosen for the large reactor, but for the small reactor a more practical nitride fuel is employed, whose nuclide compositions are shown in Table 2. For the small reactor, in order to increase the neutron economy, the fuel volume ratio is increased by employing the tube in shell type fuel cell. For the large reactor typical pin type fuel is employed.

The reactor is cylindrically symmetric. The core height of the large reactor is set 8m, which is equivlent to infinity for our case. On the other hand, the height of the small reactor is set practical values, 2.0. 2.5 and 3.0 cm. The core height should be determined by considering the axial power distribution and burning region speed determined by CANDLE bunup. The average power density of large reactor is expected 1.6 times higher than the small reactor, if the core height is the same for each reactor. Since inherently safe performance is generally employed for the small reactor, the power density of small reactor is usually set lower.

*Table 2.* Nuclide number densities in the small reactor fuel

| nuclide | number density [/cm3] |
|---|---|
| U235 | 1.87372×1020 |
| U238 | 2.58004×1022 |
| Pu238 | 2.73556×1019 |
| Pu239 | 8.61701×1020 |
| Pu240 | 2.59878×1020 |
| Pu241 | 1.64134×1020 |
| Pu242 | 5.47112×1019 |
| N14 | 2.75166×1020 |
| N15 | 2.72415×1022 |

The neutron transport is treated by 21-group diffusion equation, where the group constants and their changes with respect to temperature and atomic density are calculated using a part of SRAC code system [6] with JENDL-3.2 nuclear data library [7]. In the present calculation 20 actinides and 66 fission products are employed. The capture cross section of the nuclides produced by neutron capture of the nuclide at the end of the nuclide chain is assumed to be the same as the cross section of the nuclide at the end of the chain. It is equivalent to that the nuclide at the end of the chain remains the same nuclide even after capturing neutrons.

## 4 CALCULATION RESULTS

The obtained results for the above calculation conditions by employing the steady state calculation method are shown in Table 3.

*Table 3.* Calculation results

| thermal output | 3000MWth | 300MWth | | |
|---|---|---|---|---|
| fuel material | metal | nitride | | |
| Pu enrichment | 0 % | 5.0 % | | |
| core height | infinity | 3.0 m | 2.5 m | 2.0 m |
| $k_{eff}$ | 1.003 | 1.010 | 1.009 | 1.004 |
| shift speed of burning region | 4.25 cm/year | 2.67 cm/year | 2.71 cm/year | 2.73 cm/year |
| average burnup of discharged fuel | 38.20% | 31.30% | 30.90% | 30.30% |

The value of effective neutron multiplication factor, $k_{eff}$, should be set unity, since this calculation is performed for the equilibrium condition at operation temperature. However, since this design is at a preliminary stage, it is set to be more than unity with small uncertain margin. As already mentioned, the obtained average burnup of discharged fuel is very large. It presents not only a very good fuel cycle performance mentioned before, but also problmens associating to the materials. The spent fuel burnup for the small reactor is lower then the large reactor, but it is still much higher than the conventional reactor.

The shift speed of burning region is small enough for long-life reactor. The powr shape is important for small reactor design. The reactor with poor neutron economy usually shows a wide power shape, which is not good for desigining small reactor. The power shapes obtained by steady state caluculation code are shown in Fig. 3 for small reacotors, whose core height is 3.0 and 2.0 cm. The power shape near power peak does not change for different core heights. However, the shpe near core axial boundary changes drastically for different core heights.

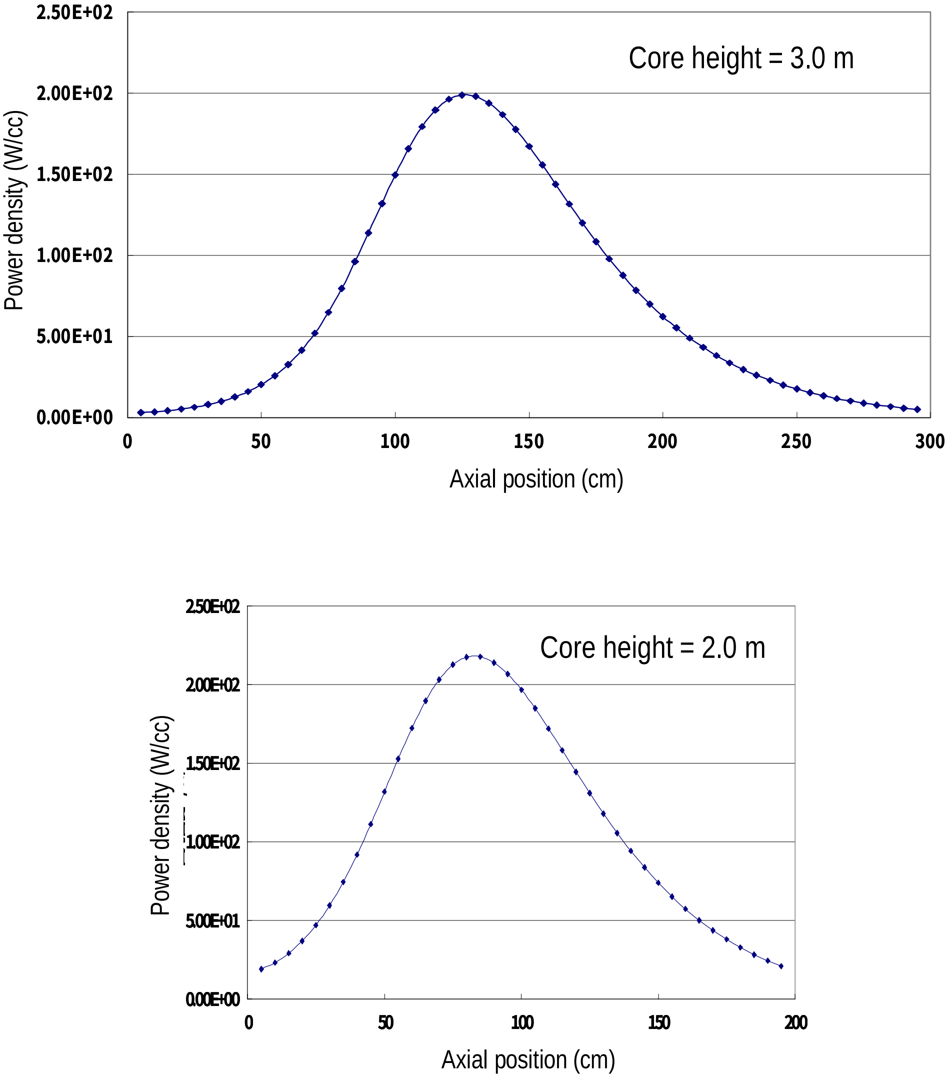

*Figure 3.* Power shapes obtaind by steady state code for limitied core height

From these obtainted results from steady state calculation, it may be cxpected that a long-life small reactor can be designed for its core height more than 2m. Simulation study of CANDLE burnup are performed for these core haight. Obtained results are shown in Table 4. The operation period is increasing along increasing the core height within an acceptable value of excess reactivity change during cycle. Figure

4 shows more vividly the relation between core heignt and operation period. The operation period is long enough for long-life reactor. For given core life, the core height can be estimated in good accuracy by (power shape width) + (shift speed of burning region) x (core life). It is much effective than the method of increasing core life by reducing power density, for which case the core height can be estimated by (standard core height) x (design core life) / (standard core life).

*Table 4.* Simulation results for small reactors

| core height | 3.0 m | 2,5 m | 2.0 m |
|---|---|---|---|
| operation period | 28 years | 18 years | 9 years |
| maximaum change of excess reactivity during cycle (dk/k) | 0.16% | 0.14% | 0.14% |

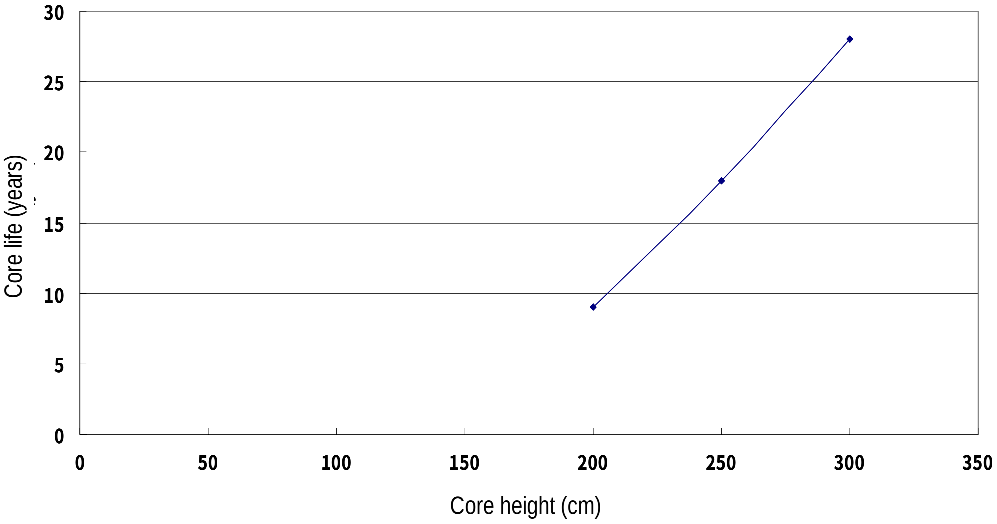

*Figure 4.* Relation between core height and core life for CANDLE burnup

## 5 CONCLUSIONS

A new reactor burnup strategy CANDLE was proposed where relative distribution shapes of neutron flux, nuclide densities and power density are constant but move to an axial direction with a velocity proportional to the power rate during whole life of reactor operation. It requires a special change of infinite neutron multiplication factor along burnup, and can be applied to neutron economical fast reactor.

In the present paper, the long-life small fast reactor with nitride fuel and LBE coolant is investigated. The 5% enrichment of plutonium makes possible to perform CANDLE burnup. The simulation is performed. The core height of 2 to 3 m can realize the operation period of 9 to 28 years with a very small excess reactivity change of less than 0.2% during whole operation period.

## ACKNOWLEDGMENTS

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