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DESIGN STUDY ON POWER FLATTENING TO SODIUM COOLED LARGE-SCALE CANDLE BURNING REACTOR WITH USING THORIUM FUEL

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ABSTRACT

The CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) burnup strategy is a new burnup concept. The CANDLE reactors generate energy by using only natural or depleted uranium as make up fuel and achieve about 40% burnup without fuel recycling of the conventional nuclear energy concept. So far the CANDLE cores feature a relatively large peak-to-average power density and discharge burnup distribution. Peaked power and burnup distribution are undesirable as they deteriorate economical performance. The objective of this paper is to study the feasibility of power flattening of sodium cooled large scale CANDLE reactor toward commercial use by using thorium fuel loading into the inner core zone. When 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. For this purpose, thorium is added uniformly to the uranium fuel in the inner core. 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 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. In the present work, the power density profile is intended flatten for the metallic fuel CANDLE reactors by adding thorium uniformly in the inner core region. The maximum axially integrated power density (radial peaking factor) decreases from 1.87 with only uranium fuel to 1.44 with uranium and thorium fuels. We can expect increasing average discharge burnup and decreasing fuel inventory and pressure drop.

INTRODUCTION

The liquid metal cooled CANDLE cores[1–2] feature a relatively large peak-to-average power density and discharge burnup distribution as shown in Fig. 1. The power distribution is tilted backward than at the inner radial position. This is due to the fact that the flux level at the outer radial position is less than at the inner radial position and plutonium-239 production from uranium-238 at the outer radial position is less and is produced slowly. Peaked power and burnup distribution are undesirable as they deteriorate economical performance. The burning speed in the inner core zone is faster than in the outer core zone. Hence longer core height is defined by the shape of burning region and shift of the region along burn-up. In order to flatten the radial power density distribution, we need to adjust inserted fuel composition at each radial position.

Thorium is 3 to 4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. During the 1950s to 1970s[3-4], there was considerable interest worldwide to develop thorium fuels and fuel cycles. Now thorium cycle begin to come under the spotlight in India and so on due to international competition for energy resources. Transmutation of thorium-232 into uranium-233 is analogous to that of uranium-238 into plutonium as

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below.

$$^{232}\mathrm{Th} \xrightarrow{(n,\gamma)} {}^{233}\mathrm{Th} \xrightarrow[23.4m]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27d]{\beta^-} {}^{233}\mathrm{U}$$

ThO_2 has also been successfully used as blanket material in liquid metal cooled fast breeder reactor (LMFBR) and for neutron flux flattening of the initial core of pressurized heavy water reactor (PHWR) in India during startup. In this paper, we will apply thorium fuel to power flattening as a transmutation material in the inner core zone for increasing discharge burnup, and reducing fuel inventory and coolant pressure drop.

Several kinds of coolant can be applied to the above mentioned CANDLE cores[5], but in the present study sodium cooled metallic fuel fast reactor is investigated, since Generation IV program[6] is especially focused on developing sodium-cooled fast reactor (SFR) with spent nuclear fuel cycle in the Global Nuclear Energy Partnership (GNEP).

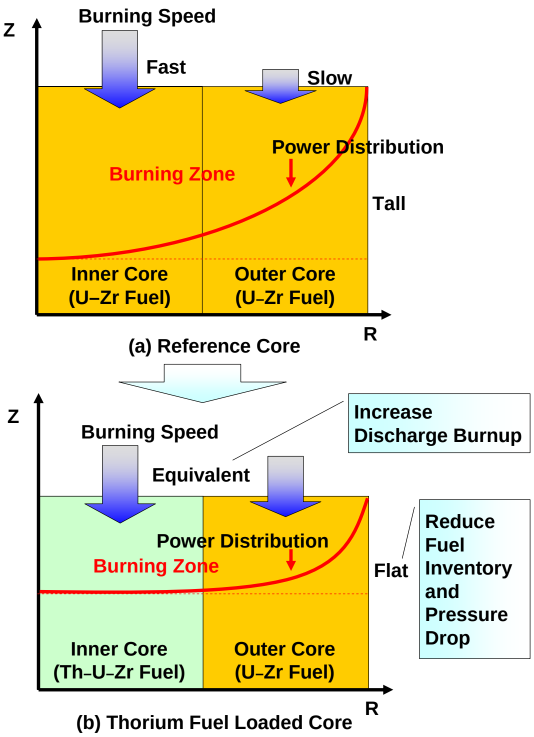

Fig. 1. Comparing axial position of burning region and power shape between references only (a) U–10wt% Zr fuel loaded core and (b) Th–U–10wt% Zr fuel loaded core for power flattening.

CANDLE BURNING CONCEPT

Principle of CANDLE Burning

The CANDLE burnup strategy is proposed that does not require a burnup reactivity control instrument such as a control rod, chemical control and so on. For this burnup strategy, distributions of fuel nuclide densities, neutron flux, and power density move with the same constant speed and without any change in their shapes, as shown in Fig. 2, and its neutron multiplication factor remains constant along burnup. This burnup strategy is applied to a fast reactor capable of excellent neutron economy. In this case, only natural uranium is required as its fuel except for the burning region of the initial core. The burnup of spent fuel is considerably high.

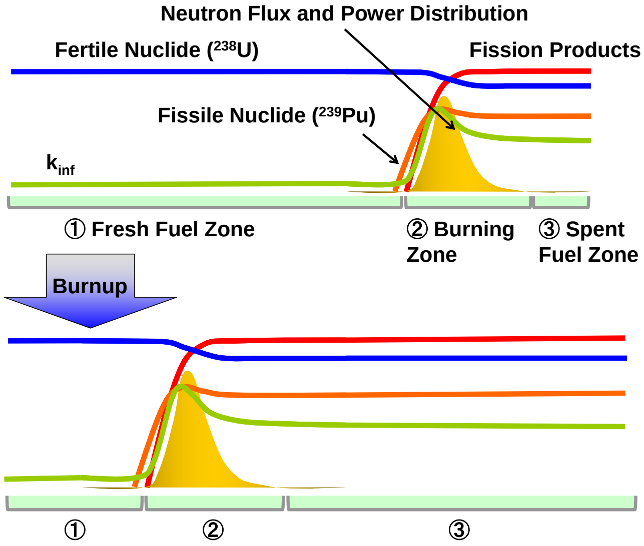

Fig. 2. CANDLE burnup strategy.

CANDLE Burning Characteristics and Advantages

CANDLE fast reactors have the following four distinctive features:

- Simple and safe: Control rod withdrawal accident never happens during normal reactor operation, since burn-up excess reactivity is zero. The power profile and reactor characteristics such as power feedback coefficients do not change during burn-up. The reactor operation is simple and reliable. Recritcality accidents can be avoided easily since the coolant volume fraction of core is small in addition to no burn-up excess reactivity.
- Highly resistant to nuclear proliferation: CANDLE requires neither enriched uranium nor plutonium as fresh fuel at the normal operation.
- Small volume of waste: The volume of spent fuel is 1/10 of LWR per produced energy, since CANDLE fuel is burned up about ten times as LWR fuel. The amount of minor actinides is also considerably small.
- Efficient fuel utilization: Natural and/or depleted uranium is used as replacing fuels, and 40% of charged fuel can be burned by fission.

Recladding Concept with CANDLE Burning Strategy

The CANDLE reactors are possible to attain very high burnup ~40% utilization of natural uranium without reprocessing and enrichment processes. Hence the discharged fuel clad is exposed and affected by high fast neutron fluence.

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In the current proven art, HT-9 of ferritic-martensitic stainless steel used for EBR-II in U.S[7]. is the most promising cladding material which is limited only fluence of 4×10^{23} neutrons of 0.1 MeV and higher energies per cm^2. The CANDLE cores need about several times higher fluence resistance for fast neutron.

We proposed a procedure called “Recladding”[8–9] as shown in Fig. 3, where the claddings of the fuel pins are removed from the core and were replaced by new cladding.

The recladding procedure is carried out during cooling period, the fuels are removed from core and the entire old cladding of the fuel slugs is replaced by new cladding. Further, gaseous fission products in these fuels are also removed. Hence we will not require consideration of a neutron exposure limitation for obtaining high discharge burnup to efficient fuel utilization.

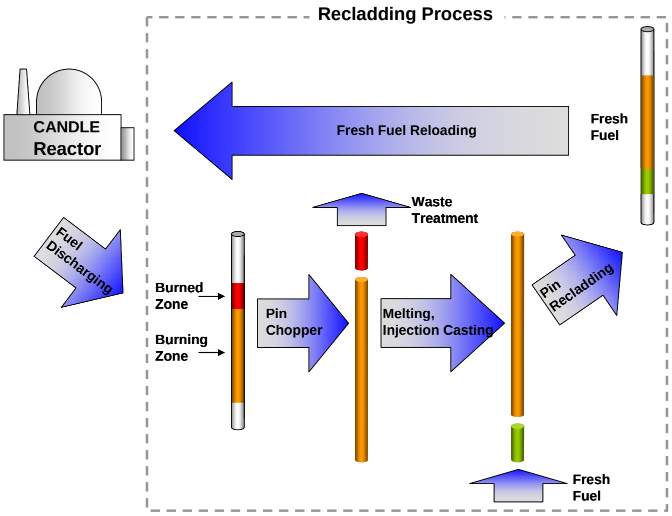


Fig. 3. Diagram of recladding process

OPTIMIZATION METHOD OF POWER FLATTENING

When 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 enough neutrons leak from the uranium region and the net radial current is still zero at this point. By this way we can make the power density distribution flat in the inner core. On the other hand, this arrangement will pose reducing of effective multiplication factor due to loading thorium fuel. The optimization flow of this method is as follows:

Step-1 Optimization of Th–U–10wt% Zr Fuel Zone Radius and thorium content

Firstly, Th–U–10wt%Zr fuel zone radius and thorium content are adjusted to obtain criticality and flat power shape in the inner Th–U–10wt% Zr fuel core zone.

Step-2 Optimization of U–10wt% Zr Fuel Density

Secondary, when Th–U–10wt% Zr fuel zone radius is optimized, there is another issue that is large power density change at the boundary between the inner and outer core zones. To reduce this change, we will reduce the U–10wt% Zr fuel number density in the outer core zone. The U–10wt% Zr number density is multiplied by $P_{Th-U-Zr}/P_{U-Zr}$ up to the following condition

$$\left|\frac{P_{Th-U-Zr}}{P_{U-Zr}}-1.0\right|\le 0.1\%, \qquad (1)$$

where

$P_{Th-U-Zr}$=power density in the boundary of the inner Th–U–10wt% Zr fuel zone,

P_{U-Zr}= power density in the boundary of the outer U–10wt% Zr fuel zone.

CORE MODEL AND COMPUTATIONAL METHOD

Neutron group constants are obtained using SRAC code system[10] with JENDL 3.3 nuclear data library[11]. A broad 107 energy group microscopic cross section set generated by SRAC is collapsed to a coarse 21 group microscopic cross section set for this study. For the thermal calculation, the one-dimensional heat conduction equation is used for the temperature distribution calculation in fuel, cladding, and coolant[12–13]. Table I shows design parameters and constraints for neutronic and thermal hydraulic calculation.

The peak cladding temperature is used as a temperature criterion of 650°C based upon HT-9. The fuel melting point imposes a limit on the maximum fuel temperature. In this study, the limits are set to 1000°C for Th–U–10wt% Zr[14] of the inner core fuel and 1360°C for U–10wt% Zr[15] for the outer core fuel. At present, the Th–U–10wt% Zr data is very limited, hence the fuel temperature limit is based on 8wt% U–59wt% Th–18wt% Pu–5wt% MA–10wt% Zr fuel applied for MIT-actinide burning reactor. This assumption may be too conservative since CANDLE core will not be loaded a large amount minor actinides.

From previous sodium cooled FBRs or FRs design, the primary coolant delta-T and coolant velocity are to be limitted 150°C and ~12 m/sec[16] to reduce cladding erosion and to prevent flow vibration respectively. Fig. 4. shows the calculation RZ model of the reference core and fuel pin. In this study, we assume only demonstrated materials to apply the CANDLE reactor to near future.

TABLE I Reference and Power flattening Cores Design Parameters

Design parameters and constraints	Values
Design parameters	
Thermal power rate	3570MWt
Fuel type	U–10wt% Zr Th–U–10wt% Zr
Cladding	HT-9
Coolant	Sodium
Bonding material	Sodium
Reflector	Sodium
Primary coolant outlet temperature	550°C
Primary coolant inlet temperature	400°C
Cladding outer diameter	13.2mm
Cladding thickness	0.5mm
Pitch to Diameter (P/D)	1.09
Smear density	75%TD
Pin array	Triangular array
Core diameter	400cm
Core height	200cm
Gas plenum height	100cm
Design constraints	
Maximum primary coolant delta-T	150°C
Maximum cladding temperature	650°C
Maximum fuel temperature	1000 °C for Th–U–10wt% Zr 1360°C for U–10wt%Zr
Maximum coolant velocity	~12 m/sec

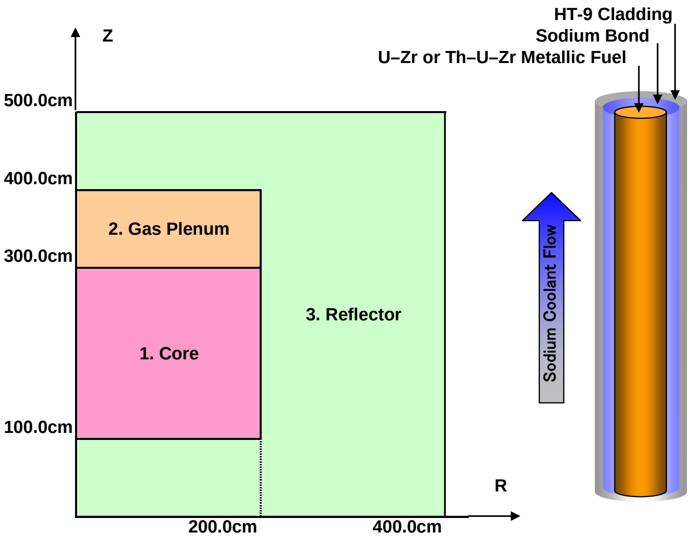


Fig. 4. Schematic layout of reference core and fuel.

CORE DESIGN AND PERFORMANCE

Neutronic Calculation Results

As shown in Table II, an effective multiplication factor of the power flattening core, keff=1.00001 is adjusted to that of the reference core. To decrease a radial peaking factor, a thorium weight fraction in the inner core zone is optimized and thorium fraction and radius in the inner core zone are set 23.4wt% and 115cm respectively.

Fig. 5 compares the power distribution of the two cores at an equilibrium state. A maximum power density of 622.3 W/cm^3 of the reference core is significantly high and it is required high coolant velocity to heat removal from fuel pins. In case of the power flattening core, the axially integrated radial peaking factor is remarkably reduced from that of the reference core by 0.43. There is no marked difference for axial peaking factor between those cores.

The burning zone area of the power flattening core is smaller than that of the reference as shown in Fig. 5. A burning speed of the reference core, 5.64 cm/year is faster than the power flattening core (5.44 cm/year), because thorium works like a blanket fuel of conventional fast breeder reactors. For above reason, it is possible to reduce core height and fuel inventory or to increase fuel discharge burn-up with using thorium loading uniformly in the inner core zone.

Thermal Hydraulic Calculation Results

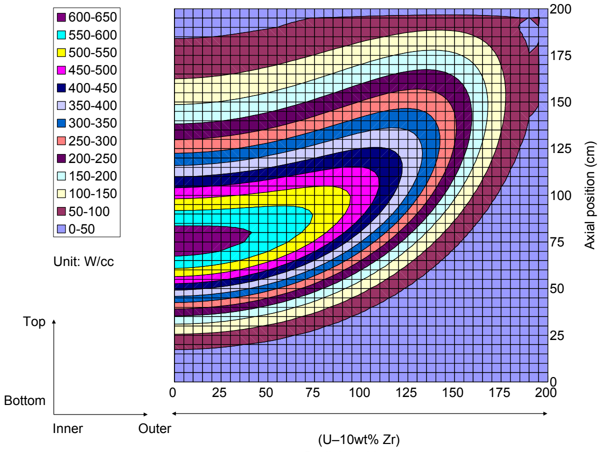
From thermal hydraulic calculation, the reference coolant velocity exceeds the 12 m/s design criterion; on the other hand, the flattening core is capable to heat removal. The maximum cladding and fuel temperature are 587°C and 802°C respectively and these temperatures satisfy the design criteria.

CONCLUSION

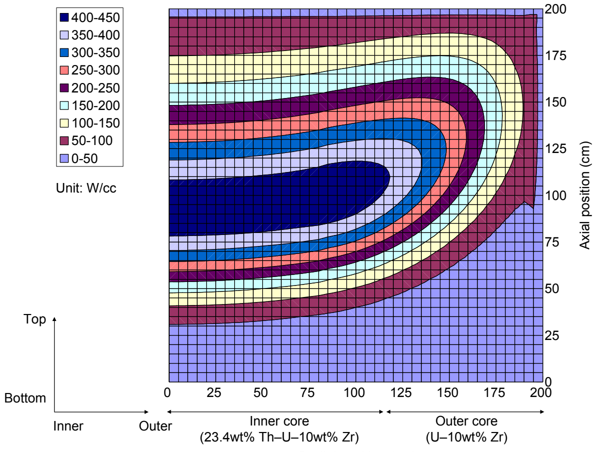
In this study, we demonstrate a large scale CANDLE burning reactor capability toward actual application for future energy resource with using verified technology and widely used materials, sodium coolant, HT-9 cladding and metallic fuel. Thorium fuel in the inner core zone works on excellent power flattening. In the future work, we will design and study on optimization of the CANDLE cores for commercial power plant and also an implementation plan to the real world including an experimental and a demonstration reactors.

TABLE II Comparison of Calculation Results between Reference Core and Power Flattening Core

Design parameters	Reference core	Power flattening core
Neutronic results		
keff	1.01922	1.00001
Burning speed	5.64 cm/year	5.44 cm/year
Thorium weight fraction in the inner core zone	-	23.4wt%
Inner core zone radius	-	115 cm
Maximum power density	622.3 W/cm^3	440.7 W/cm^3
Radial peaking factor (Axially integrated)	1.87	1.44
Axial peaking factor	2.34	2.13
Thermal hydraulic results		
Maximum coolant velocity	15.8 m/s	12.5 m/s
Maximum cladding temperature	-	587^{o}C
Maximum fuel temperature	-	802^{o}C



(a) Reference CANDLE core



(b) Power flattening CANDLE core

Fig. 5. Power distribution of (a) reference and (b) power flattening CANDLE at an equilibrium state.

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