

SIX REQUIREMENTS FOR NUCLEAR ENERGY SYSTEM AND CANDLE REACTOR

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ABSTRACT

Future nuclear energy system should satisfy the six requirements for safety, wastes, A-bomb, resource, technical feasibility, and economy. CANDLE fast reactors, where shapes of neutron flux, nuclide densities and power density distributions remain constant but move to an axial direction, satisfy these requirements as follows:

1) Simple and safe: Control rod withdrawal accident never happens during normal operation. The power profile and reactor characteristics such as power feedback coefficients do not change during burn-up. Transportation and storage of fresh replacing fuels are safe and simple. Therefore, the reactor operation and maintenance are simple and reliable, and the frequency of undesired events is considerably reduced. The effect and possibility of CDF accidents (considered the most severe accident) becomes very small.

2) Waste: The volume (or weight) of spent fuel is 1/10 of LWR per produced energy. The amount of minor actinides is considerably small.

3) Nuclear proliferation and safeguards: CANDLE requires neither enriched uranium nor plutonium as replacing fuel at the normal operation.

4) Efficient fuel use: Only natural and/or depleted uranium is used as replacing fuels, and 40% of charged fuel can be burned by fission. This is more than fifty times the fission efficiency of LWR. The depleted uranium produced by 40 years of LWR operation can operate CANDLE reactors for more than 2000 years.

5) Technical feasibility: Measures for high fast neutron fluence are discussed. A start-up scenario of the first core is also presented.

6) Economy: Fuel cycle cost and O&M cost are smaller than the conventional reactors. The capital cost is discussed.

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. Any proposed reactors should satisfy technical feasibility, of course. Finally reasonable price is usually an important requirement to energy. Thus the necessary and sufficient conditions for nuclear energy utilization as primary energy in the future are considered to satisfy six requirements for 1) resource, 2) safety, 3) waste, 4) bomb, 5) technical feasibility, and 6) economy (1).

1.2 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 (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. The same idea is employed in Travelling Wave Reactor, whose design study was started recently by the support of Bill Gates. (4)

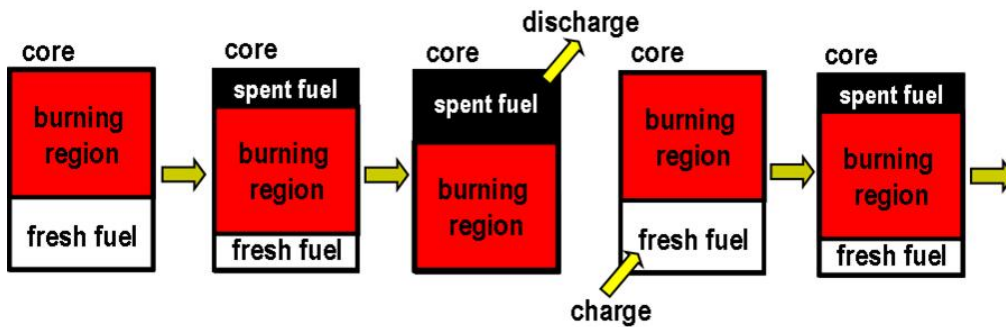


Fig. 1. CANDLE burning and fuel management

1.3 Principle of CANDLE burning

The distributions along core axis of neutron flux and number density of each nuclide are shown in Fig. 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 accumulation of Pu-239 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.

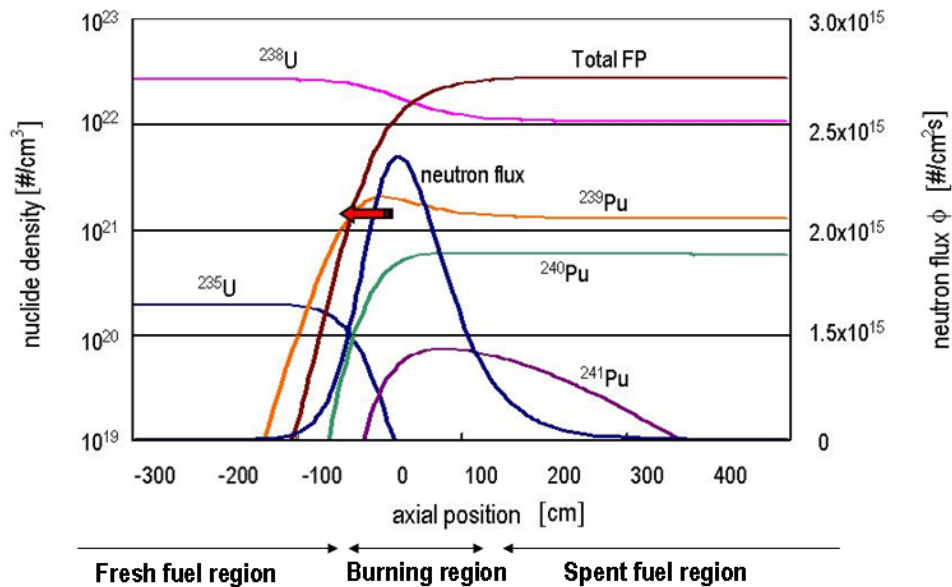


Fig. 2. Nuclide densities and neutron flux distributions along core axis

2. 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 fast reactors with metallic fuel and some others with very hard neutron spectrum 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.

In this chapter it is shown how CANDLE reactor to satisfy six requirements 1) resource, 2) safety, 3) waste, 4) bomb, 5) technical feasibility, and 6) economy shown in Sec. 1.1 on nuclear energy utilization as primary energy in the future.

2.1 Resource

The burn-up of the spent fuel is about 40% (400 MWd/tHM). 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.

The present once-through fuel cycle of 4% enriched uranium in LWR performs the burn-up of about 4% of the inserted fuel, and it corresponds to the utilization of about 0.7% of natural uranium depending on the enrichment of depleted uranium. For this case about 87% of the original natural uranium is left as depleted uranium. If this depleted uranium is utilized as the fuel for CANDLE reactor, 35% ($=0.87 \times 0.4$) of the original natural uranium is utilized. Therefore, if the LWR has already produced energy of X Joules, the CANDLE reactor can produce about 50X Joules from the depleted uranium stored at the enrichment facility for the LWR fuel.

If LWRs have already produced energy sufficient for full 40 years and the nuclear energy production rate will not change in the future, we can produce the energy for 2000 years by using the CANDLE reactors as shown in Fig. 6. We need not mine any uranium ore, and do not need reprocessing facility.

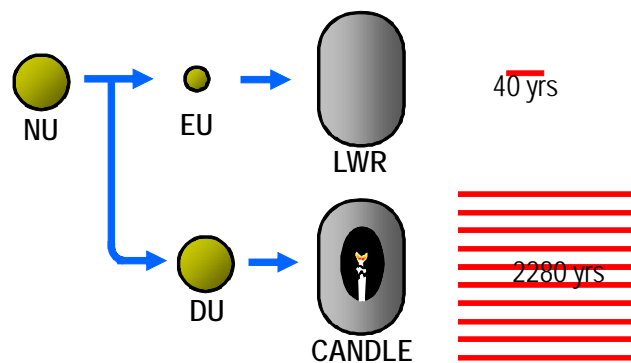


Fig. 3. CANDLE reactor operation after LWR operation

2.2 Safety

There are so many kinds of events and accidents for nuclear reactor that the best way for increasing safety features of nuclear reactor is considered to reduce both frequency of undesired events and consequence of the most severe accident.

The frequency of undesired events for CANDLE reactor is reduced by many ways as follows. Firstly the burn-up reactivity control mechanism is not required for CANDLE burning. The reactor control becomes simple and easy. The excess burn-up reactivity becomes zero, and the reactor becomes free from reactivity-induced accidents at operating condition. Secondly the number density distribution of each nuclide does not change with burning in the burning region. Therefore, the reactor characteristics such as power peaking and power coefficient of reactivity do not change with burning. The estimation of core condition becomes very reliable. The reactor operation strategy remains un-changed for different burning stage. Thirdly since the radial power profile does not change with burning, the required flow rate for each coolant channel does not change. Therefore, the orifice control along burning is not required. The operational mistakes are avoided. Furthermore, fresh fuel charged after the second cycle is

depleted uranium or natural uranium. The transportation and storage of fresh fuels become easy for criticality and physical protection problems. They become simple and safe.

The most severe accident of fast reactors is considered CDA accident. The consequences and possibility of re-criticality accidents at CDA is considerably reduced, since the control rods are not inserted in the core under operating condition, and coolant amount in the core is small.

2.3 Waste

The present LWR performs the burn-up of about 4% of the inserted fuel of 4% enriched uranium. On the other hand the burn-up of the spent fuel for CANDLE reactor is about 40%. It is ten times as high as for LWR. Therefore, the spent fuel amount per produced energy is reduced to be one-tenth of once-through cycle of LWR.

Separation of spent fuel and vitrification may reduce the volume of high level wastes, but the total volume of radioactive wastes increases. The once-through fuel cycle of CANDLE reactor system reduces the total volume of radioactive wastes.

The amount of actinides is decreased since they are stored in the core much longer than conventional reactors and fissioned in a considerable amount during this period.

We can use the depleted uranium. The wastes from uranium mining do not appear.

2.4 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.

2.5 Technical feasibility

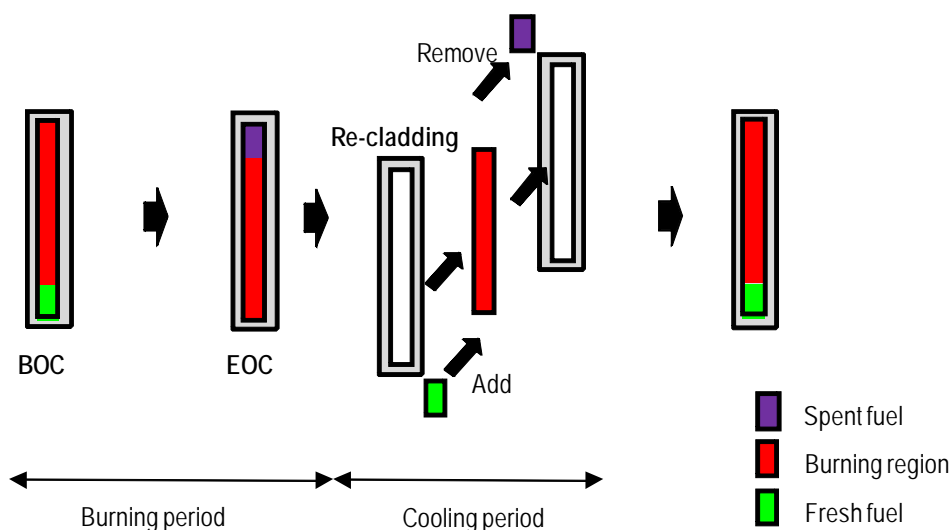


Fig. 4. Recladding process of fuel element

When we use conventional cladding materials, the burnup of 40% is too much and we should employ re-cladding as shown in Fig. 4. Once we employ this process, frequency of it becomes an optional parameter. The re-cladding process is a purely dry process and its cost is much

cheaper than conventional reprocessing. If the burnup for one-cycle is small enough, the recladding becomes very easy and the separation of cladding from meat becomes rigid.

The start-up of the initial core can be easily performed by enriched uranium as demonstrated in the reference (5).

Now we do not have any severe technical difficulties.

2.6 Economy

The cost of nuclear reactor consists of capital, fuel, and O& M (operation and maintenance).

We can expect low O&M cost, since CANDLE reactor is simple.

We can also expect low fuel cycle cost, since the reprocessing of discharged fuel is not required.

Since coolant channel space is smaller than conventional reactors, the core cooling performance is poor. It may result in lower average power density. Low average power density deteriorates strongly its economical performance. However, this deterioration may be reduced considerably by the designs without blanket, short core height and radially flat power distribution. The short core and radially flat power distribution can be realized by employing radially multi-region core and MOTTO fuel cycle (6, 7).

3. References

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