COE-INES

Tokyo Institute of Technology

Light a CANDLE

An Innovative Burnup Strategy of Nuclear Reactors

Hiroshi Sekimoto

與其詛咒黑暗
不如點亮蠟燭
中國諺語

CANDLE

Better to light a candle than curse the darkness

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An Innovative Burnup Strategy of Nuclear Reactors

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Preface

This world is created in an orderly fashion. With the advancement of science, it is becoming increasingly clear what the purpose behind this order is. It almost appears as if the world is created in an orderly fashion for the benefit of humankind. Nuclear fission provides a good example of this. The neutrons generated in the process of nuclear fission can be used to trigger succeeding nuclear fissions or to create further fissile material. Very few neutrons are left over in this process. How should we use these remaining neutrons? The Creator of this world has presented us with this very interesting question and seems to be wondering what solutions we come up with. CANDLE burnup is one solution.

CANDLE is a new burnup strategy for nuclear reactors. The acronym stands for Constant Axial Shape of Neutron Flux, Nuclide Densities and Power Shape During Life of Energy Production, but also represents the candle-like burnup. When this burnup strategy is adopted, although the fuel is fixed in a reactor core, the burning region moves, at a speed proportionate to the power output, along the direction of the core axis without changing the spatial distribution of the number density of the nuclides, neutron flux, and power density. The reactivity and reactor characteristics do not change. Most significantly, when using this strategy it is not necessary to use control rods for the control of the burnup. A CANDLE nuclear reactor is hence safer, and just as importantly, makes us feel safer.

CANDLE burnup has various other ground-breaking merits. When this burnup is used in a fast reactor that has excellent neutron economy, excellent performance is obtained. It is possible to use natural uranium or depleted uranium as fuel and about 40% of the fuel will burn. A large amount of depleted uranium is already available, and hence if we are able to use it as fuel, we can continue to use nuclear energy for almost a millennium without further uranium mining, enrichment, and reprocessing. In addition, the amount of spent fuel is greatly reduced.

While there are great advantages in using CANDLE burnup, numerous technological developments are necessary before it can be used. However, for block-fuel high-temperature gas-cooled reactors, currently under development in several countries, CANDLE burnup can be applied without additional technological development. In this booklet, the specific application of CANDLE burnup to a high-temperature gas-cooled reactor and a fast reactor with excellent neutron economy are described.

When the former Nuclear Regulatory Commission Chairman Dr. Meserve lectured on the current status of nuclear energy, he cited a Chinese proverb to brighten the present dark status. I remember he said, “Better to light a candle than curse the darkness”. Thus, I have given the booklet the title: “Light a CANDLE”. I hope that this booklet will contribute to the bright future of nuclear energy.

I have avoided rigorous discussions in this booklet so that it can be read in a relaxed manner. If this makes it difficult for experts to understand, then please forgive me. I recommend that interested experts should read the references. Even though numerous papers concerning CANDLE burnup have been published, they are not targeted to the general audience, and therefore I have not listed many references. Although I tried not to use equations, I had no option in the explanation of the analysis method, and differential equations had to be included, though I used only the most basic equations from nuclear reactor theory. Those who have studied the subject will easily understand these equations, however, those readers who are not good at mathematics can skip that chapter. This booklet is written so that even those readers can understand the rest of the chapters.

I have received encouragement from numerous people in preparing this booklet. Professor Thomas H. Pigford, my Ph.D. thesis adviser, is chief amongst them. He has an interest in the important role of the combination of neutron transport and burnup, which was the topic of my Ph.D. thesis, and gave me great encouragement in my research. Professor Ehud Greenspan assisted with considerable discussions concerning CANDLE burnup. It was he who informed me of similar research conducted by Dr. Edward Teller. I am also grateful to the numerous other researchers for giving me advice and encouragement.

Although I do not know Dr. Alvin M. Weinberg personally, I once sent him a

paper, as he had been promoting the development of inherently safe reactors and I thought that he would be interested in CANDLE burnup. Dr. Weinberg showed an interest in the paper and sent me a letter of encouragement. I heard that he contacted Dr. Teller. Some time later I saw Dr. Teller's obituary in the newspaper. I would have liked to have known what he thought of CANDLE burnup.

The Japanese Minister of Education, Culture, Sports, Science and Technology began "21st Century COE (Center of Excellence) Program" in fiscal 2002 for selecting excellent research institutes of universities and forming internationally competitive research bases. Academic disciplines from humanities and social sciences to natural sciences are divided into ten categories. A proposal from Tokyo Institute of Technology "Innovative Nuclear Energy Systems for Sustainable Development of the World (COE-INES)" was adopted in the category of "Mechanical, civil, architectural and other fields of engineering." It is the only one COE in the nuclear engineering field. CANDLE burnup is one of the most important research topics in COE-INES.

The research described in this booklet was conducted by Dr. Kouichi Ryu, Mr. Kentaro Tanaka, Mr. Takashi Takada, Dr. Yasunori Ohoka, Mr. Yutaka Udagawa, Mr. Ken Tomita, and Mr. Makoto Yamasaki, graduate students of my research laboratory. I am very grateful to them, and also grateful to Associate Professor Tohru Obara for his fruitful discussions.

Tokyo Hiroshi Sekimoto

November 2005

Contents

1. Excess Neutrons

1.1. Does Instability Mean More Stability?

When I was a student, I believed that a neutral state was more stable than a state in which positive and negative charges were separated. Therefore, when I learned that the neutron is unstable and the proton stable, I thought it was very strange. However, I was impressed with the mechanism of nature after I realized that the instability of the neutron is absolutely necessary for our existence in the universe. A neutron in isolation can exist for only a short time, and breaks down to a heavy, positively charged proton and a light, negatively charged electron by the process known as β-decay. However, a neutron can be stable when it is bonded to a proton. A suitable number of protons and neutrons bonded together form a positively charged nucleus. The traditional image of an atom is of a nucleus circled by negatively charged light electrons. Interestingly, the state in which electrons circle around only one nucleus is not necessarily the most stable state. This instability leads to the formation of molecules, with further integration leading to polymers, making possible living matter, and eventually leading, as the degree of complexity increases, to human beings.

Most interesting is the fact that the mass of a neutron is only 0.08% larger than the sum of the masses of a proton and an electron. As a result of this, the half-life of a neutron is 10.4 minutes. It is assumed that when the universe was created with the Big Bang, approximately the same number of protons and neutrons were created. However, these neutrons began converting into protons. Yet, the half-life of a neutron was sufficient for deuteron to be formed by the bonding of neutrons to protons before the neutrons disappeared, and subsequently for helium to be formed. If the half-life of a neutron was any shorter, very little helium would have been formed and heavier atoms would not have been created. Accordingly, intelligent life constructed from complicated molecules would have never been created. On the other hand, if the half-life was longer, neutrons would be more stable and neutron stars would have been easily created. In this case, shining stars would not have been created, making conditions for the creation of intelligent life very difficult.

The allowable instability range of the neutron is extremely narrow for the birth of intelligent life. It may be possible to explain the mechanism by which this value was selected based on more basic laws and constants. However, this leads into an endless cycle of searching for the origin of the basic laws and constants. One might almost be inclined to concede that God himself selected the exact instability of the neutron. Whatever its origin, the instability of the neutron is thus exquisite.

1.2. Nuclear Fission

As described above, a nucleus consists of protons and neutrons. Therefore, protons and neutrons are called nucleons. Light atomic nuclei have good symmetry and consist of approximately the same number of protons and neutrons. However, as the size of the nucleus increases, the electric repulsion due to the positive charges of the protons makes the nucleus unstable. However, atomic nuclei with a larger number of neutrons than protons become stable again. The largest atomic nucleus existent on the earth is uranium-238 (^{238}U), which has 146 neutrons compared to 92 protons.

Nuclear reactions between atomic nuclei are very difficult to achieve because the strong electric repulsion due to the positive charge of nuclei hinders their approach to each other. However, since neutrons have no charge, they can easily cause nuclear reactions. A neutron with low energy is more likely to cause a nuclear reaction because of the quantum effect. When a neutron with low energy hits a nucleus, neutron absorption usually takes place. When a neutron is absorbed by a nucleus, the newly created nucleus usually gains excess energy. The excess energy increases the internal kinetic energy of the nucleus and it becomes unstable. In most cases the excess energy is eventually released as high energy electromagnetic waves (γ rays) and the nucleus becomes stable. However, when a neutron hits uranium-235 (^{235}U), the nucleus gains a large amount of excess energy, and since it consists of many nucleons, it starts vibrating like a liquid drop, eventually breaking into two nuclei of a similar size with very high probability. This nuclear reaction is called nuclear fission and the two generated nuclei are called fission products.

In nuclear reactors, fast-traveling neutrons collide with light nuclei, lowering the energy of the neutrons. By repeated collisions the neutrons are rapidly moderated and reach a final energy equivalent to the kinetic energy of the collision target, namely, the thermal energy of the medium. Hence, moderated neutrons are called thermal neutrons. If a thermal neutron is absorbed by ^{235}U, nuclear fission takes place. Uranium-238 (^{238}U) on the other hand does not undergo nuclear fission by neutron absorption, due to the fact that a nucleus with an even number of neutrons and of protons is more stable than one with an odd number of neutrons or protons. That is, the neutron number of ^{235}U is 143, which is odd, but becomes 144, which is even, after absorbing a neutron. The neutron number of ^{238}U however becomes odd after absorbing a neutron. Because of this difference, the excess energy gained by neutron absorption is larger for ^{235}U than ^{238}U, and accordingly, nuclear fission takes place for ^{235}U but does not for ^{238}U. A nuclide that fissions after absorbing a thermal neutron is called a fissile material, and a nuclide that does not fission but becomes a fissile material is called a fertile material.

As mentioned above, a heavy nucleus has more neutrons relative to the number of protons than a light nucleus. In nuclear fission, a heavy nucleus is converted into two nuclei each of approximately half the weight of the parent nucleus. As a result, the number of neutrons is in excess of that required for nuclear stability, and hence two to three neutrons are usually released per nuclear fission. This number of emitted neutrons, averaging around 2.5, will be very important in the rest of this booklet. It is less than the number of neutrons expected from the excess neutrons of the two daughter nuclei. Not all the excess neutrons are released; the majority of them are retained in the fission products. These nuclei are unstable, but are gradually stabilized by the decay of the excess neutrons into protons. It should be noted though that a small fraction of nuclei are stabilized by releasing neutrons. Neutrons released in this way are called delayed neutrons. Delayed neutrons play an important role in the operation of a nuclear reactor; however, the explanation of this role will be omitted here.

Even for stable nuclei, some nuclei have high stability and some have low stability. The peak of stability is located around iron; nuclei heavier and lighter than iron are less stable than iron. Uranium is located at the heaviest end. It is intrinsically unstable and changes very slowly into a lighter nucleus by successively releasing α- and β- particles. Through nuclear fission a very unstable nucleus is converted into stable nuclei in one reaction. Energy is released when an unstable state changes to a stable state. The energy released per nuclear fission is about 200 MeV (200×10^6 eV). In contrast, the burning of fossil fuel is a chemical reaction, where the heat value per chemical reaction is measured in eV. From the comparison we can see that the heat value of nuclear fission is extremely large.

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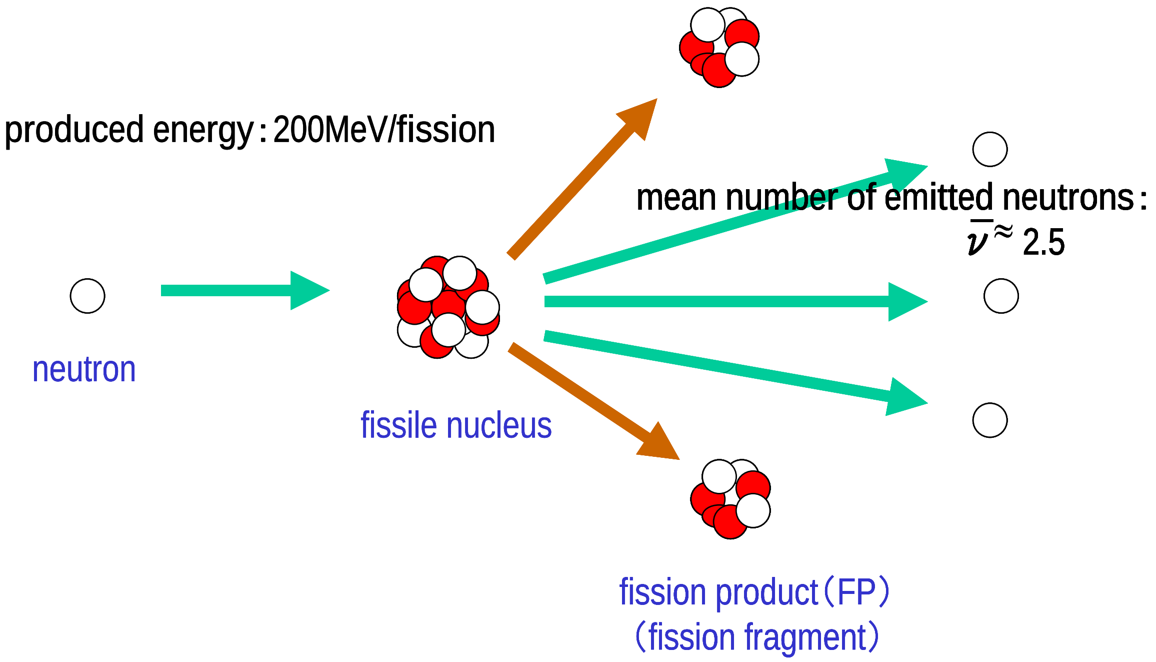


Figure 1　Characteristics of nuclear fission.

The characteristics of nuclear fission are summarized in Figure 1.

1.3 Chain Reaction and Control of Criticality

As mentioned, if a fissile material absorbs a neutron, nuclear fission takes place at a high probability and two to three neutrons are released. This leads to the possibility of the newly generated neutrons inducing successive nuclear fissions. A string of such succeeding nuclear fissions induced by the generated neutrons is called a chain reaction, shown in Figure 2.

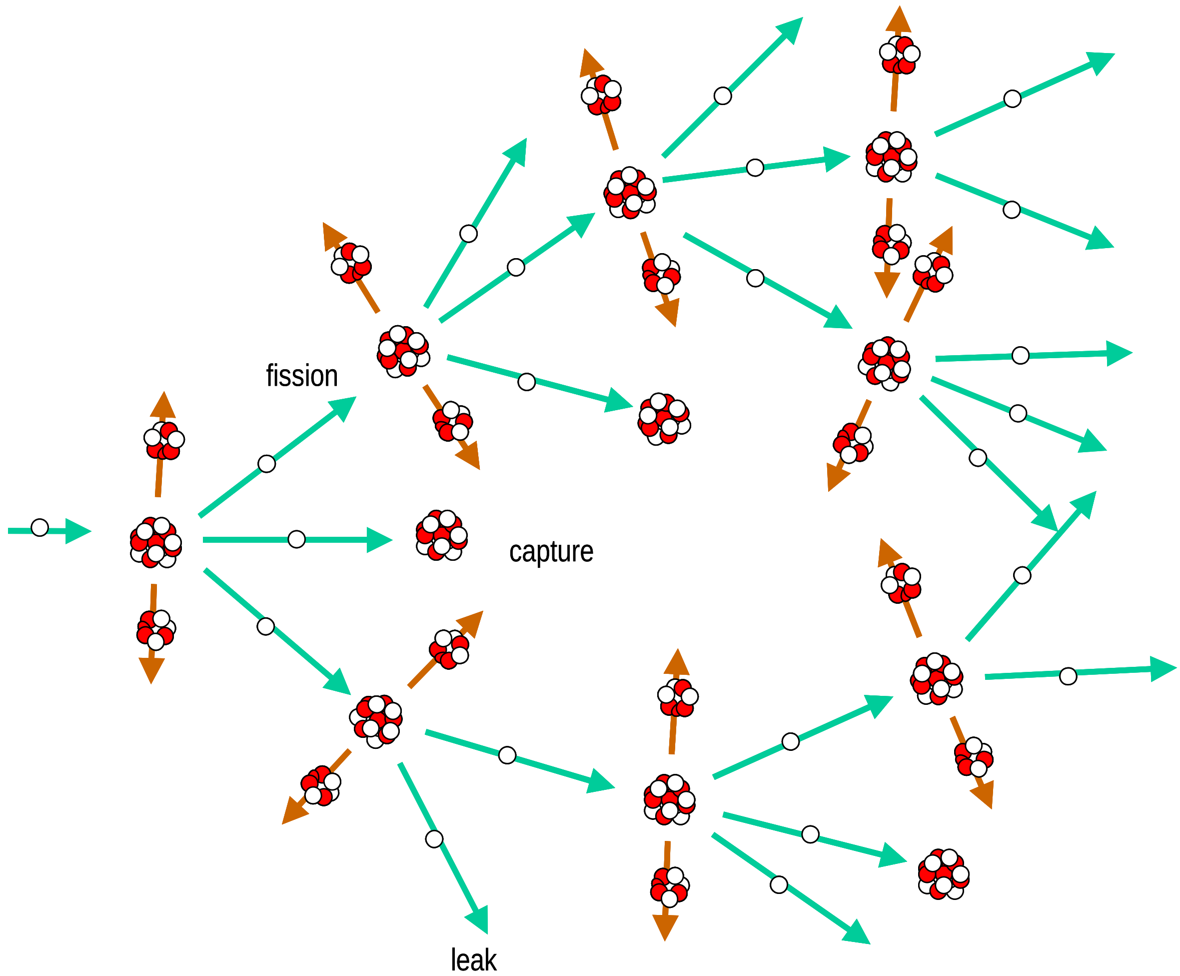


Figure 2　Nuclear fission chain reaction.

The number of neutrons in the system may increase or decrease with time, or it may stay the same. This is very important for nuclear reactors and is encapsulated by the neutron multiplication factor. A nuclear fission chain reaction progresses from one generation of nuclear fission to the succeeding generation of nuclear fission. The neutron multiplication factor is defined as the ratio of the number of neutrons in one generation divided by the number of neutrons in the preceding generation:

$$\text{Neutron multiplication factor} = \frac{\text{Number of neutrons in one generation}}{\text{Number of neutrons in the preceding generation}}$$

When this value is equal to unity, the number of neutrons does not change with time and the system is in what we call a critical state. When the value is larger than unity, the number of neutrons increases with time, giving a supercritical state. When the value is smaller than unity, the number of neutrons decreases with time, giving a subcritical state.

In a nuclear reactor operating at constant power, the number of neutrons is constant and the neutron multiplication factor is unity. In order to stop the operation of the reactor, we make the neutron multiplication factor sufficiently smaller than unity. This is accomplished by inserting a neutron absorber into the core (the fuel region of the nuclear reactor). In this way, neutrons generated by nuclear fission are absorbed by the neutron absorber by the time of the succeeding generation of nuclear fission. Thus, the neutron multiplication factor becomes less than unity. A neutron absorber is usually formed into a rod shape and therefore is called a control rod. The neutron multiplication factor will also change depending upon operational circumstances. For example, a change of core temperature alters the multiplication factor. It is a serious problem if the neutron multiplication factor increases with an increase in temperature. In this case, even if the initial state is critical (i.e., the neutron multiplication factor is unity), as the nuclear fission causes an increase in temperature, the number of nuclear fissions increases (i.e., the neutron multiplication factor increases to greater than unity). This causes the temperature to increase further, resulting in a further increase in the number of nuclear fissions. In this way, the nuclear reactor will enter a vicious cycle leading to a runaway reaction. Hence, it is necessary to design a nuclear reactor so that the neutron multiplication factor decreases with an increase in temperature. In a reactor designed in this way, when the temperature increases as a result of an increase in nuclear fission (i.e., when the neutron multiplication factor is greater than unity), the neutron multiplication factor decreases and eventually converges to unity. That is, the nuclear reactor responds to external disturbances due to temperature change, eliminating the effect and stabilizing the operation.

1.4. Burnup and Burnup Control

Nuclear reactors differ from fossil fuel reactors in the way the fuel is used. In a fossil fuel reactor, a large amount of fuel must be continuously supplied to the furnace. In a nuclear reactor, however, once fuel has been put into the nuclear reactor, it can be kept in the reactor for years. Hence it is said that a nuclear reactor has high energy security. It can continue to operate even when the supply of fuel is suspended. Both reactors however consume their fuel, and by analogy with fossil fuel power generation, the consumption of fuel by a nuclear reactor is called ‘burnup’.

What happens in a nuclear reactor in a critical state when burnup progresses? In widely operated light-water reactors, fissile material decreases and fission products accumulate. The reactor is initially put in a critical state by adjusting the neutron multiplication factor to be unity. However, the multiplication factor becomes less than unity after the progression of burnup, and if nothing is done, the reactor will become subcritical. In order to solve this problem, the following method is generally adopted. An excess of neutron absorber is initially placed in the reactor. As the neutron multiplication factor decreases, due to the change of the fuel components with burnup, the amount of neutron absorber in the reactor is decreased so that the multiplication factor returns to unity. As a method for decreasing the neutron absorber, a neutron absorber that changes due to burnup can be used, in addition to a method in which an operator withdraws the neutron absorber, as described in the preceding section. In this case, a neutron absorber is selected that is converted to a material with smaller neutron absorption as it absorbs neutrons. The adjustment of the conversion rate, however, is an important design challenge. A neutron absorber used in this way is called burnable poison. It is difficult to maintain a nuclear reactor in an exact critical state with only burnable poison and it is necessary to include a human-operated control mechanism. Nevertheless, the load of the human-operated control mechanism can be considerably decreased by the use of burnable poison.

1.5. Use of Excess Neutrons

The only fissile material existent in nature is ^{235}U, and its half life is shorter than that of ^{238}U. Both have been present in the earth from its creation, but ^{235}U decays faster than ^{238}U and hence natural uranium contains at present only 0.7% ^{235}U, with the rest being ^{238}U. Thus, many of the neutrons generated by nuclear fission in natural uranium are absorbed by ^{238}U, and a chain reaction cannot be maintained. However, the reactivity of ^{235}U with thermal neutrons is much larger than that of ^{238}U. By applying the characteristics of nuclear fission, Fermi succeeded in making the first nuclear reactor. In order to moderate the neutrons, he mixed natural uranium with pure graphite in a heterogeneous structure. In order to lessen the leak of neutrons, the assembly had to be huge. This need for size demonstrates how difficult it is to achieve criticality and how few neutrons are available for our use.

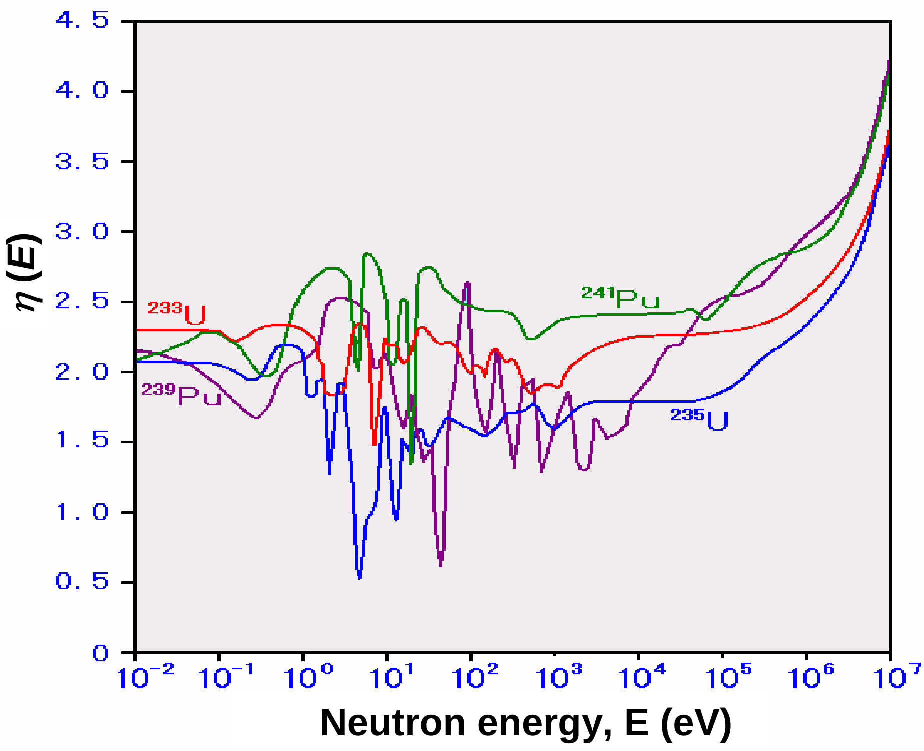


Figure 3 Value of η for typical fissile materials.

Recall that the number of neutrons generated by nuclear fission is two to three. However, a fissile nuclide does not always fission after the absorption of neutrons; it may remain a heavy nucleus after absorbing a neutron. Therefore, in the discussion of criticality and the effective use of neutrons, the number of generated neutrons per neutron absorption is more pertinent than the number of generated neutrons per nuclear fission. This value is called η (the Greek letter, read "eta"). As shown in Figure 3, the value of η changes depending upon the nuclide and the energy of the absorbed neutrons. Plutonium-239 (^{239}Pu) shows larger values of η than ^{235}U, and the value increases drastically with an increase in neutron energy from around 10 keV.

If we allow ^{238}U to absorb a neutron, it can convert into the fissile material ^{239}Pu. This is why ^{238}U is called a fertile material. In the nuclear fission of ^{239}Pu induced by a neutron, more neutrons are generated than for ^{235}U, especially for high energy incident neutrons. Thus, ^{239}Pu can be generated by allowing ^{238}U to absorb excess neutrons, and criticality of a nuclear reactor can then be achieved by a chain reaction of nuclear fission of mainly ^{239}Pu. In this way, more ^{239}Pu can be generated than is lost. If this can be achieved, natural uranium can be used in nuclear fission. (Of course, not all natural uranium can be used since some plutonium may be mixed into the waste at the time of plutonium recovery from the spent fuel. It is reasonable to say that about 70% can be utilized. Even in this case, we can use 100 times more than in the present method in which only about 0.7% of natural uranium is usable.)

In a nuclear reactor, a large amount of radioactive material is produced. If there are excess neutrons, it is possible to convert the radioactive waste into harmless stable material by nuclear reactions. If the neutrons are used for nuclear fission and the generation of fissile nuclides, the number of excess neutrons available for this purpose will be less than one. In reality, the amount of excess neutrons available is marginal when we take into account wasteful neutron absorption and leakage. However, realizing the application of stabilizing the radioactive waste of nuclear power is potentially epoch-making. Thus, the very interesting challenge of "How will it be done?" has been presented to us. One solution is CANDLE burnup.

2. What is the CANDLE Burnup Strategy?

2.1. Concept of the Burnup Strategy

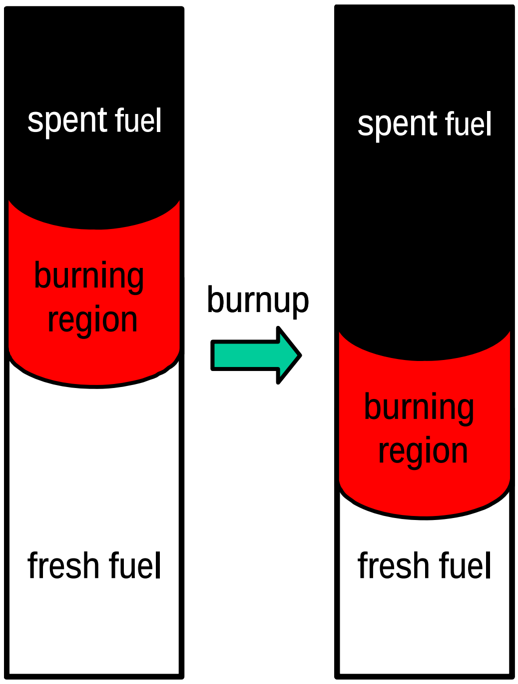


Figure 4 CANDLE burnup strategy. (Note that the moving direction can be the opposite of that illustrated. The core height is illustrated here to be extremely long to make the explanation easy.)

CANDLE stands for Constant Axial Shape of Neutron Flux, Nuclide Densities and Power Shape During Life of Energy Production [1]. The abbreviation also represents the candle-like burnup. As shown in Figure 4, when this burnup strategy is used, the burning region moves at a speed proportionate to the power output along the direction of the core axis without changing the spatial distributions of the nuclide densities, neutron flux, or power density. What is significant is that even though the fuel is fixed in the core, it is not necessary to use movable devices to control the burnup, such as control rods and reflector control, as is the case in conventional reactor design. Note that the core height has been illustrated as being extremely long to make it easy to show the characteristics of the burnup strategy. In a normal core however, the combined length of the spent fuel and fresh fuel regions is much shorter than that of the burning region. Figure 7, presented later, better illustrates an actual reactor; though even in Figure 7, the moving distance is shown as being long. Note also that although in Figure 4 the burning region is shown as moving from the top to the bottom, it is possible to have the region move from the bottom to the top.

CANDLE burnup is possible in a core designed so that the infinite medium neutron multiplication factor k_∞ (the neutron multiplication factor considering the reactor to be of infinite size) of the fuel changes with burnup specifically as shown in Figure 5. In the figure, the neutron fluence is plotted on the abscissa, which is obtained by integrating the neutron flux with respect to time. This value is considered to be proportional to the burnup. The infinite medium neutron multiplication factor k_∞ of fresh CANDLE fuel is less than unity. However, it increases with the burnup and eventually becomes greater than unity. After reaching a maximum, k_∞ decreases and becomes less than unity.

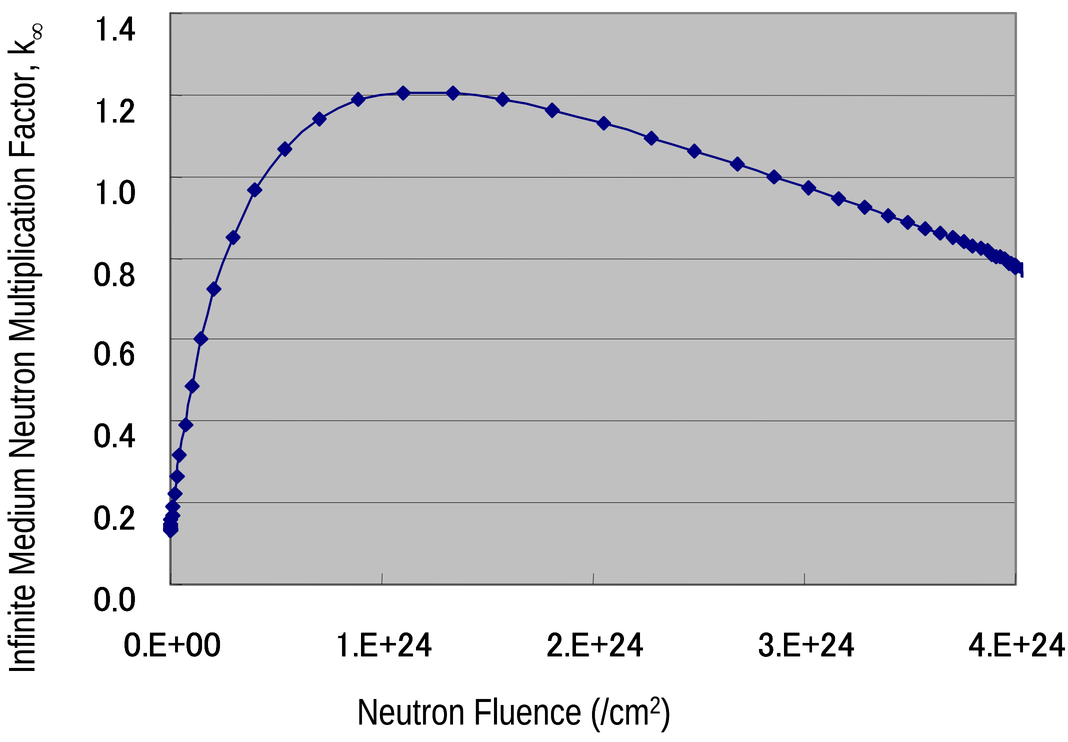


Figure 5 Infinite medium neutron multiplication factor k_∞ of fuel, with neutron fluence plotted on the abscissa.

Figure 6 shows the same data as Figure 5 with the core axis (Z axis) plotted on the abscissa. On the left is the fresh fuel side and on the right is the spent fuel side. On the left side of the peak, k_∞ increases with burnup, and on the right side it decreases. Accordingly, the peak shifts to the left side, namely, to the fresh fuel side. The peak of the neutron flux is located in the vicinity of the k_∞ peak. At locations away from the peak, k_∞ takes smaller values and is less than unity and the neutron flux approaches zero. As a result, burnup does not take place and k_∞ shows a constant value at the left and right ends. In an equilibrium state, the spatial distribution of k_∞ does not change with time, it only shifts to the fresh fuel side. It is not difficult to generate the k_∞ change shown in Figure 5. The specific methods vary depending upon the nuclear reactor and will be explained later.

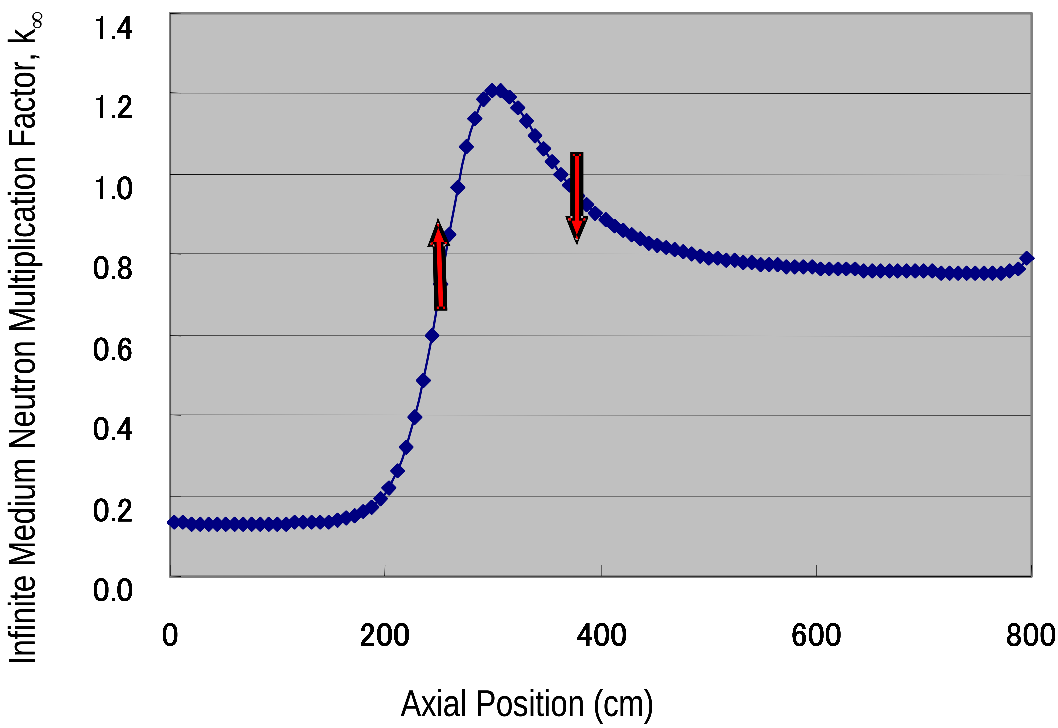


Figure 6 Infinite medium neutron multiplication factor of fuel plotted against the central axis (Z axis). Arrows indicate the directions of change with burnup.

I will add here the following points. Even if the power level is changed, the relative shape of the power distribution does not change and only the absolute values of the power distribution change. The moving speed of the burning region is proportional to the power level, the principle of which I will explain in Section 3, “Mathematical Explanation and Analysis Method”.

In reality, the core height is finite. When the burning region reaches the end of the core, the fuel should be changed, as shown in Figure 7. When the burning region reaches the end of the core, the spent fuel region is removed and fresh fuel is added in the direction of burnup. In this way CANDLE burnup can be continued.

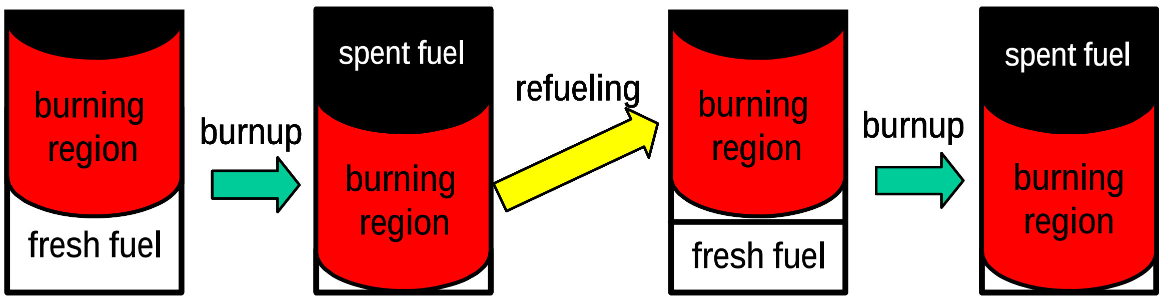


Figure 7 Refueling in the CANDLE burnup strategy.

Once the initial core is successfully prepared, the second and later cores are easily prepared. However, short life radioactive materials located in the burning region in the steady state cannot be used in the initial core preparation process, and hence it might be difficult to fabricate the burning region of the initial core using only easily obtained materials. Control rods might be necessary in the case where an ideal initial core could not be prepared and a large variation in excess reactivity is caused with burnup. If this happens, it may be more appropriate to build a special reactor only for the first several cores, with control rods installed to control the excess burnup reactivity. When the first several cores are burned, fuel for the remaining core is produced with a composition close to that of an ideal CANDLE core. This new core is then transferred to a normal CANDLE reactor, which has no mechanism of controlling the excess burnup reactivity. Thus, many initial CANDLE cores can be produced using the one nuclear reactor.

Presently, research into the makeup of the burning region of the initial core is in progress. With current technology it is possible to prepare an initial core that has little change in excess reactivity, using only enriched uranium and natural elements. An example is given Section 6.1. We are gaining confidence that a nuclear reactor dedicated for preparing the initial core will not be necessary.

2.2. Advantages and Issues in the Burnup Strategy

I should explain how the k_∞ change shown in Figure 5 can be accomplished and leads to CANDLE burnup. However, the specific methods vary depending upon the nuclear reactor type. Therefore, I will explain this later when I detail the different reactors. Instead I will first explain what advantages are generally expected when this type of burnup becomes possible. From general considerations, the following advantages are expected.

1) No control mechanism is required for the burnup.

   In presently used general nuclear reactors, operation is continued for a fixed period between refuelings. As the operation is continued with fuel in the core, fissile material is consumed and fission products, which waste neutrons, accumulate. As a result, the characteristics of criticality deteriorate. To make the interval between refuelings long enough, it is necessary to make the reactivity (defined as $(1-k)/k$ where k is the neutron multiplication factor of the core) sufficiently positive after the refueling. This causes the reactor to become supercritical, and it must be adjusted so that it becomes critical by the insertion of control rods. However, this leads to a big waste of neutrons, and in addition the malfunction of control rods and operational error may lead to serious accidents. In CANDLE burnup, control rods for the adjustment of burnup reactivity are not necessary, and hence the following advantages are expected.

   - There is no waste of neutrons. This is highly desirable since the number of excess neutrons is few, as mentioned in Chapter 1.
   - The operation is simple and easy since burnup control is not necessary.
   - The insertion of control rods into the core causes considerable distortion to the power distribution, which varies greatly with the burnup. This effect suppresses the average power density and deteriorates the economy. This does not take place in CANDLE burnup.
   - Accidents due to withdrawal errors of control rods cannot take place.
   - Control rods kept continuously in a nuclear reactor lose their neutron absorption capability. In CANDLE burnup it is not necessary to have a

countermeasure for this situation.

2) There is no change in the core characteristics during the progress of burnup.

In a conventional nuclear reactor, the power density peaking factor and the power coefficient of reactivity change during the progress of burnup. Therefore, these effects should be fully taken into account in the control method. In CANDLE burnup, these parameters are constant throughout the burnup. As a result, the operation does not change, and it is very simple and reliable.

The calculation precision in reactor physics (of the criticality characteristics, power distribution, power coefficient of reactivity, etc.) is high. This is due not only to the precision of the data and calculation methods used, but is also the result of numerous criticality experiments. However, calculations in reactor physics are difficult to verify experimentally when burnup has progressed, and errors are large compared with calculations for fresh fuel. Therefore, it has been necessary in conventional reactors to include large safety margins in the power density peaking factors and power coefficient of reactivity due to burnup. This type of consideration is less important for CANDLE burnup.

3) It is not necessary to adjust the flow rate with orifices during the progress of burnup.

In ordinary nuclear reactors, the power distribution changes with the progress of burnup in a plane perpendicular to the axis. Therefore, even if the flow rate of coolant is adjusted at the start of the burnup, so that the exit temperature of the coolant is constant (for flow parallel to the core axis), the flow rate changes with the progress of burnup. If the change is too big, it is necessary to readjust the flow rate through the coolant channel of the core. For example, a long life reactor using the out-in burnup strategy has been proposed, where the power peak moves from the outside to the center. In order to optimize its cooling, the outside of the orifice is initially kept open and then later narrowed. At the center, it is initially narrowed and then opened. In CANDLE burnup, the axial integrated power distribution in the plane perpendicular to the axis does not change during the progress of burnup. Therefore, it is not necessary to adjust the flow rate during burnup. As a result, the operation is easy and operational errors can be reduced.

4) High-level optimization of the radial power distribution is possible.

As described above, in conventional reactors, the power distribution exhibits complicated change during the progress of burnup. An optimum distribution at one time point may change to a considerably deviated distribution at another time point. Therefore, it is necessary to optimize the distribution as a whole, considering the total lifetime of the core. In CANDLE burnup, once the power distribution is optimized, it can be maintained throughout the lifetime of the core, and high-level assured optimization is possible.

5) The lifetime of a nuclear reactor can be easily lengthened by increasing the height of the core.

In the case of a light-water reactor, the core lifetime is lengthened by increasing the enrichment of fresh fuel and increasing the burnup. The lifetime is simply determined by the material integrity and allowable excess reactivity. If we want to lengthen the lifetime more than allowed by this process, we have to decrease the power density. Thus, even for the same burnup, the number of years of operation can be lengthened. In this case, if we want to increase the lifetime of the core by a factor of M without changing the total power, the volume should be made M times larger. If we want to extend the lifetime of a CANDLE core, the core height should be lengthened, increasing the volume. If the distance the burning region moves in the original design is D, then a length $(M-1) \times D$ should be added to the core height in order to increase the lifetime by a factor of M. In the case of the power density strategy the volume must be increased by a multiplicative factor, whereas in case of the CANDLE strategy, the volume must be increased by an additive factor. Thus, the required increase in volume is generally smaller in the CANDLE strategy than in the power density strategy. The larger M is, the larger the difference between the two strategies. However, even in the CANDLE strategy, if D is large, the required change in volume is expected to be large, though D is generally extremely small. The advantages of CANDLE burnup because of this assumption are listed below.

- The moving speed of the burning region is generally very slow. As a result, it is easy to design a super long-life reactor.

- The core life can be easily altered by changing the core height.
- Once a small long-life reactor is realized, a nuclear reactor can be produced at a factory, transferred and installed at the site, operated for a long time without changing fuel, and transferred back to the factory (for replacement with a new nuclear reactor). Thus, the following additional advantages are expected:
  - Refueling is the most difficult of the normal operations for a nuclear reactor. Hence, when a reactor is operated at a location where high-level technology may not be available, not requiring refueling is a big advantage.
  - A nuclear reactor that has fuel semi-permanently enclosed in the core has high nuclear proliferation resistance.

6) k_∞ of fresh fuel in an exchanged core is less than unity.

As shown in Figure 5, an important feature of CANDLE burnup is that k_∞ of fresh fuel is less than unity (though depending upon its design, it can slightly exceed unity). From the viewpoint of safety, it is highly desirable that k_∞ of fresh fuel be less than unity. Even when a large amount of fresh fuel is gathered together, the possibility of it becoming critical is very small. Thus, the transportation and storage of fresh fuel is simple and safe.

On the other hand, CANDLE burnup has the following issues.

1) The core tends to be axially long and the pressure loss of coolant tends to become large.

If a long-life reactor is desired, an axially long core should be prepared, which requires that the channel length of the coolant also becomes long. As a result, the pressure loss becomes large, and it is necessary to use a powerful pump.

However, as long as the core is not extremely long, this is not a problem. If the moving speed of the burning region is very slow, a long lifetime can be achieved without using a very long core. For example, the moving speed in a large fast reactor is typically about 4 cm/year, or 40 cm in 10 years and 80 cm in

20 years. These lengths are in a range that even a normal pump will not be affected by an increase in pressure loss.

2) The adjustment freedom in the axial power density distribution is small.
   An axial power distribution is inherent to CANDLE burnup. However, the radial power distribution can be greatly optimized, as mentioned above in advantage 4. On the whole, the total power distribution is considered to be quite good.
3) The preparation of the initial core is difficult.
   The preparation of exchange fuel is simple. However, for the initial core, fuel that can stimulate the burning region effectively must be prepared. Since there is considerable radioactive material in the burning region, it is difficult to stimulate it with easily available materials. The requirements are as follows.
   - The effective neutron multiplication factor of the core in an equilibrium state should be unity.
   - The change of the effective neutron multiplication factor should be small until an equilibrium state of the core is reached.
   - The CANDLE core should be swiftly brought to equilibrium.

   It may be necessary to install control equipment if the change of the effective neutron multiplication factor of the initial core is large. In this case, as mentioned in Section 2.1, one solution is to make a special nuclear reactor for the preparation of the fuel of the equilibrium core.

Various solutions have been proposed to address these issues. I will not go into further detail here, though I will describe one example in Section 6.1.

Hopefully the above explanation has shown you that CANDLE burnup is an excellent burnup strategy. There are notable advantages for each type of reactor employing CANDLE burnup, as will be explained later as each reactor type is analyzed. In the following sections, calculation results will be presented for the application of the burnup strategy in a block-fuel high-temperature gas-cooled reactor and a lead-bismuth-eutectic (LBE) cooled metallic fuel fast reactor. Before that, however, I will briefly touch on an analysis method for CANDLE burnup.

3. Mathematical Explanation and Analysis Method

Some principles of CANDLE burnup are easy to understand if they are mathematically explained. In fact, the explanation of the analysis method is difficult without using some equations. Here the mathematical explanation and analysis method for CANDLE burnup are described. Readers who do not like mathematics can skip this chapter since the other chapters can be understood without reading this chapter.

It is not easy to directly solve the equations for a CANDLE burnup reactor. It is also difficult to confirm if the core is in an equilibrium state in the true sense. Since the power distribution shifts with time, a long coordinate axis is necessary and the determination of convergence is difficult. A detailed explanation of these is omitted and only the principles of how to solve the problem of equilibrium will be explained. See reference [1] for further details.

First, the neutron transport equation and nuclide transformation equation must be solved. For the degree of precision presently under consideration, the neutron diffusion equation is sufficient instead of the neutron transport equation. In order to simplify the equation, cylindrical coordinates are used for the equation. Note that this does not mean that the diffusion equation is suitable for CANDLE burnup reactor analysis, though the strict transport equation can be transformed in a similar way. Even when space is treated three-dimensionally, a similar expansion is possible.

$$\frac{1}{r}\frac{\partial}{\partial r}rD_g\frac{\partial}{\partial r}\phi_g+\frac{\partial}{\partial z}D_g\frac{\partial}{\partial z}\phi_g-\sum_n N_n\sigma_{R,n,g}\phi_g+\sum_n N_n\sigma_{n,g-1\to g}\phi_{g-1}$$
$$+\frac{\chi_g}{k_{eff}}\sum_{g'}\sum_n N_n\nu\sigma_{F,n,g'}\phi_{g'}=0 \qquad \text{--- (1)}$$

Here the terms for short time transients such as the time derivative of the neutron flux and delayed neutron contributions are omitted.

The nuclide transformation equation is expressed in the next equation.

$$\frac{\partial N_n}{\partial t} = -N_n\left(\lambda_n + \sum_g \sigma_{A,n,g}\phi_g\right) + \sum_{n'} N_{n'}\lambda_{n'\to n} + \sum_{n'} N_{n'}\sum_g \sigma_{n'\to n,g}\phi_g \qquad \text{--- (2)}$$

These equations are the most basic in nuclear reactor theory. The symbols used for the variables are those generally used, and therefore an explanation of them is omitted. Unfamiliar readers should consult textbooks on nuclear reactor theory. The solution is obtained by solving these equations simultaneously.

This analysis is much the same as conventional nuclear reactor analysis. However, there are very different characteristics, which I will describe. In ordinary nuclear reactor analysis, the nuclide density distribution in the nuclear reactor is given as a calculation condition, and the power density and criticality are solved for this given nuclide density distribution. In the case of a CANDLE reactor, the situation is different and the location of the burning region is not certain. Under ideal conditions given for the infinite-length core, the burning region moves from infinity in one direction, to infinity in the other direction. The burning region has a spread, but it is difficult to determine. The power distribution, which is usually constrained by boundary conditions (and neutron source conditions in some other cases) in ordinary nuclear reactor analysis, cannot be fixed with coordinates in the analysis of a CANDLE reactor. Nevertheless, the power distribution undeniably exists.

The difficulty in calculation is related to the uncertainty in the position of the burning region and because of the movement of the burning region. In order to address this difficulty, we can consider a coordinate system that moves along with the burning region. In this case, even as burnup progresses, the burning region does not move. The transformation to this type of coordinate system is the Galilean transformation. Under this transformation, the neutron diffusion equation and nuclide transformation equation become as follows.

$$\frac{1}{r}\frac{\partial}{\partial r} rD_g \frac{\partial}{\partial r}\phi_g + \frac{\partial}{\partial z} D_g \frac{\partial}{\partial z}\phi_g - \sum_n N_n \sigma_{R,n,g}\phi_g + \sum_n N_n \sigma_{n,g-1\to g}\phi_{g-1}$$

$$+ \frac{\chi_g}{k_{eff}}\sum_{g'}\sum_n N_n \nu\sigma_{F,n,g'}\phi_{g'} = 0 \qquad \text{--- (3)}$$

$$-V\frac{\partial N_n}{\partial z'}-N_n\left(\lambda_n+\sum_g \sigma_{A,n,g}\phi_g\right)+\sum_{n'} N_{n'}\lambda_{n'\to n}+\sum_{n'} N_{n'}\sum_g \sigma_{n'\to n,g}\phi_g=0 \qquad \text{--- (4)}$$

Here V stands for the moving speed of the burning region. Since V is an unknown, it is necessary to determine it.

These equations are solved by iteration, but the details will be omitted. Please see reference [1]. Equation (3) does not change under the Galilean transformation, and is the same as equation (1). The important fact is that the time variable has disappeared in equations (3) and (4). Thus, the calculation becomes very simple and convergence becomes certain. The neutron transport equation corresponding to equation (3) would also not change under the Galilean transformation even if the strict transport equation was considered instead of the diffusion equation.

Several characteristics can be derived from the obtained equations and here a few of the most important aspects are described. In equation (4), there are two kinds of nuclear transformation, neutron induced reaction and radioactive decay; however, radioactive decay can be generally ignored. If $\Phi_g=\phi_g/V$ is used instead of ϕ_g, V is removed from equations (3) and (4).

$$\frac{1}{r}\frac{\partial}{\partial r}rD_g\frac{\partial}{\partial r}\Phi_g+\frac{\partial}{\partial z}D_g\frac{\partial}{\partial z}\Phi_g-\sum_n N_n\sigma_{R,n,g}\Phi_g+\sum_n N_n\sigma_{n,g-1\to g}\Phi_{g-1}$$

$$+\frac{\chi_g}{k_{eff}}\sum_{g'}\sum_n N_n\nu\sigma_{F,n,g'}\Phi_{g'}=0$$

$$-\frac{\partial N_n}{\partial z}-N_n\left(\sum_g \sigma_{A,n,g}\Phi_g\right)+\sum_{n'} N_{n'}\sum_g \sigma_{n'\to n,g}\Phi_g=0$$

This indicates the following. If the neutron flux, namely the power, is increased by a factor of m, the moving speed of the burning region also increases by m. Even the absolute value of the power becomes m times greater, though the relative shape does not change. That is, when the power is changed, the moving speed of the burning region and the absolute value of the power density change, however, the power density distribution does not change. These results, however, do not hold when radioactive decay cannot be ignored. In this case, a change in the neutron multiplication factor poses a bigger problem than a change in the power distribution.

The relationship between the moving speed of the burning region, burnup of spent fuel, and total power is more directly expressed by the following equation, which has no approximation.

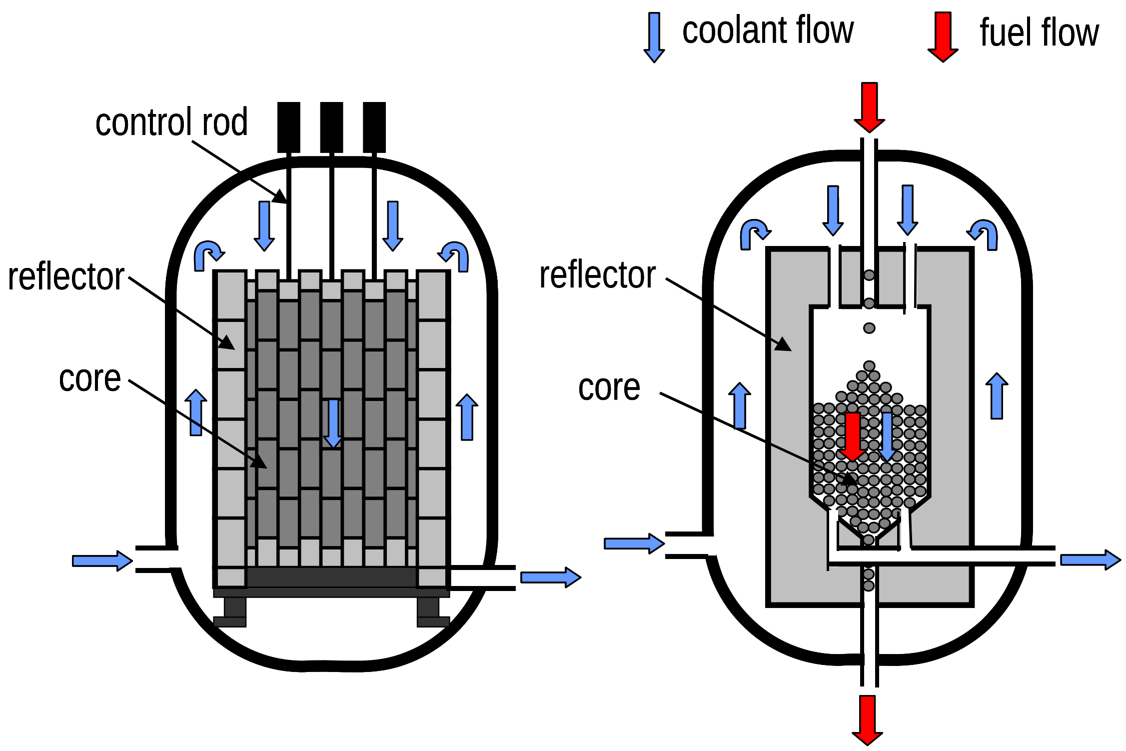
$$\int_{-\infty}^{\infty}\sum_{g'}\sum_{n}N_n\sigma_{F,n,g'}\phi_{g'}dz = V\int_{-\infty}^{\infty}\sum_{g'}\sum_{n}N_n\sigma_{F,n,g'}\phi_{g'}dt$$

Here the left side is the total number of nuclear fissions integrated along the axis at a certain radial position. The integral on the right side is proportional to the burnup of the spent fuel at the same radial position.

4. Block-fuel High-temperature Gas-cooled Reactor

4.1. Principle

The high-temperature gas-cooled reactor [2] has attracted a growing interest and various applications based on its use of high temperature gas are envisioned. Lately, the high safety of the reactor has attracted attention and its excellent economy has been recognized. As a result, the construction of commercial reactors is planned. A further advantage of this reactor is that the integrity of coated fuel particles in the reactor can be maintained up to high burnup, and thus the reactor has attracted attention as a suitable reactor for the elimination of plutonium and minor actinides. For details see the explanation in reference [2].



(a) Block-fuel type (b) Pebble-bed type

Figure 8 Schematic diagrams of high-temperature gas-cooled reactors.

High-temperature gas-cooled reactors can be mainly classified into the block-fuel type and pebble-bed type. Schematic diagrams of the two types are shown in Figure 8.

Keep in mind however that the length ratios in these illustrations are very different from the actual length ratios; for example, the pebbles (fuel spheres) in the pebble-bed reactor are of tennis ball size. The size of the pressure vessel in these nuclear reactors is not very different from that of a large light-water reactor. The driving mechanism for the control rods is illustrated only for the block-fuel reactor. For the pebble-bed reactor, only a control rod driving mechanism for start-and-stop control is necessary; control rods are not necessary for burnup control. Although the pebble-bed reactor has an advantage in that refueling is possible during operation, it has some technological complications.

For the application of CANDLE burnup, the block-fuel high-temperature gas-cooled reactor is the most suitable nuclear reactor amongst presently operated nuclear reactors since no drastic design changes are necessary.[3] Burnup and refueling in this reactor are shown in Figure 9. In this figure, changes in nuclide density of important nuclides and neutron flux (speed weighted average number density of neutrons) along the core axis are shown.

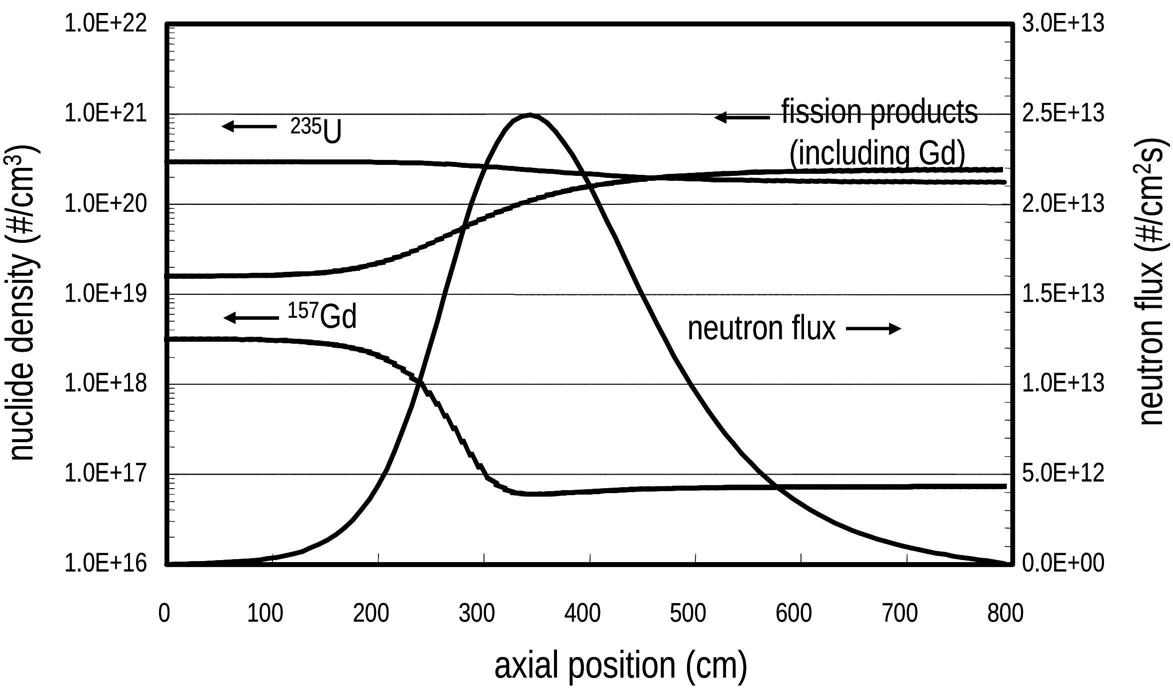


Figure 9 CANDLE burnup in a block-fuel high-temperature gas-cooled reactor.

In a thermal reactor, CANDLE burnup is realized by adding burnable poison to the fuel. In Figure 9 gadolinium (Gd) is employed. When the microscopic absorption cross section of the burnable poison is sufficiently larger than that of the fissile material, the burnable poison will absorb neutrons leaking from the burning region to the fresh fuel region and will quickly disappear, as shown in Figure 9. In the figure it does not decrease to zero because it is replenished by fissions. Thus, fissile material remains in the fresh fuel region and the burning region can move into this region, realizing CANDLE burnup. Burnable poison is presently used in ordinary nuclear reactors for suppressing excess reactivity during burnup. Thus, the self-shielding effect, which adjusts the neutron absorption rate, is conveniently utilized. However, in CANDLE burnup, the burnable poison ideally disappears as soon as possible. Thus, it is thinly mixed into a graphite matrix to decrease self-shielding.

As is clear from Figure 7, CANDLE-type refueling is possible for block fuel without drastic design change, unlike pin-type fuel in light-water reactors. Note that in this figure, to emphasize the characteristics of CANDLE, the moving distance of the burning region is shown to be long. Hence, the figure is quite different from the actual design as it shows the exchange section as being large. In reality, one block of spent fuel is removed and one block of fresh fuel loaded. Even in this case, the lifetime of an operation cycle is usually a few years.

4.2. Advantages

Applying CANDLE burnup to a block-fuel high-temperature gas-cooled reactor has the following advantages.

1) It shares the major advantages of the pebble-bed reactor.
   - Control rods for burnup control are not necessary.
     This is very important from a safety viewpoint, so I will explain it further. In a high-temperature gas-cooled reactor, the coolant helium pressure is high, around 70 atmospheres. Therefore, there is a possibility that the driving mechanism of the control rods, which runs through the pressure vessel, may jump out. If this happens, the reactivity of the nuclear reactor

suddenly increases greatly and the power may run out of control. In a CANDLE reactor, there are no control rods for burnup control. Other control rods used in the reactor do not cause big reactivity increases and the danger of reactivity accidents converges even if they should jump out.

- The characteristics of the nuclear reactor do not change with time.
- Operation is simple and highly reliable. 2) It has more advantages than the pebble-bed reactor.
- Complicated equipment used for on-power refueling is not necessary.
- In the pebble-bed reactor, the burnup history of each pebble is randomly different; thus, it is uncontrollable and unpredictable. In a CANDLE core, the burnup of each element of fuel is controllable and predictable.
- In the pebble-bed reactor, the fuel pebbles pile up and move. Therefore, they may get damaged. This does not occur in a block fuel reactor. 3) The maximum fuel temperature can be lowered by channeling the coolant in the opposite direction of the movement of the burning region.

The power distribution shifts in the direction of the movement of the burning region and exponentially decreases in the opposite direction. For such a power distribution, the maximum fuel temperature can be lowered by channeling the coolant in the opposite direction of the movement of the burning region.

The other advantages described in Section 2.2 can also be achieved.

4.3. Analysis Results

The design parameters for an example_block-fuel high-temperature gas-cooled reactor are shown in Table 1. As burnable poison, natural gadolinium is used. For the thermal output and core shape, the values for the High Temperature Engineering Test Reactor (HTTR), operated at JAERI, were mostly adopted. HTTR is an experimental reactor and the thermal output is extremely small. Thus, the design is not suitable for a commercial reactor. However, the values for this reactor were adopted since the design data are easily available.

For the calculation, a four-group diffusion equation, which is often used for the analysis of high-temperature gas-cooled reactors, was used. The group constants were obtained using the SRAC code system with the JENDL-3.2 library. Because of the restriction of the code, there was no option other than mixing the burnable poison with the fuel kernel. This causes the microscopic cross section of the burnable poison to become small because of the neutron shielding effect, and the CANDLE characteristics deteriorate.

Table 1 Design parameters for a block-fuel high-temperature gas-cooled reactor.

reactor	thermal output	30MWt
	core radius	115cm
	radial reflector thickness	100cm
fuel	^{235}U enrichment	15%
	fuel kernel	UO2
	burnable poison	natural Gd (3.0%)
	cladding	TRISO
	kernel diameter	0.608mm
	coated fuel particle diameter	0.940mm
	particle packing factor	30%

Table 2 Calculation results for a block-fuel high-temperature gas-cooled reactor.

effective neutron multiplication factor		1.008
moving speed of burning region		29.2cm/y
axial half width of power density		154cm
burnup	maximum	12.3%(115.2GWd/t)
	average	10.7%(100.3GWd/t)

The calculations confirmed that CANDLE burnup is realized for this design. The results are shown in Table 2. The burnup was small, though much larger than the HTTR value, and it cannot be claimed that the results were good. However, this is due to the fact that the burnable poison had to be put into the fuel kernel. In the future, the burnable poison will be mixed with graphite, which will drastically improve the results. Thus, there is no technological problem to solve.

We have investigated the elimination of surplus plutonium by this method.[4] The higher the burnup, the better CANDLE burnup is achieved. It was shown that about 90% of ^{239}Pu can be eliminated. If the burnup is increased in an ordinary reactor, the power distribution will show larger distortion. In addition, characteristics such as the reactivity coefficient change drastically with the burnup. On the other hand, a CANDLE reactor shows an unchanged smooth distribution and unchanged reactivity coefficients even for very high burnup.

5. Natural Uranium (or Depleted Uranium) Loaded Fast Reactor

5.1. Principle

Since a fast reactor has excellent neutron economy, CANDLE burnup was tried with natural uranium or depleted uranium used as fresh fuel [5]. The principle behind this is that the ^{238}U in the fresh fuel region absorbs neutrons leaking from the burning region and changes into ^{239}Pu. Burnup and fuel change in this reactor are shown in Figure 10. In this figure, changes in nuclide densities of important nuclides and neutron flux (speed weighted average number density of neutrons) along the core axis are shown.

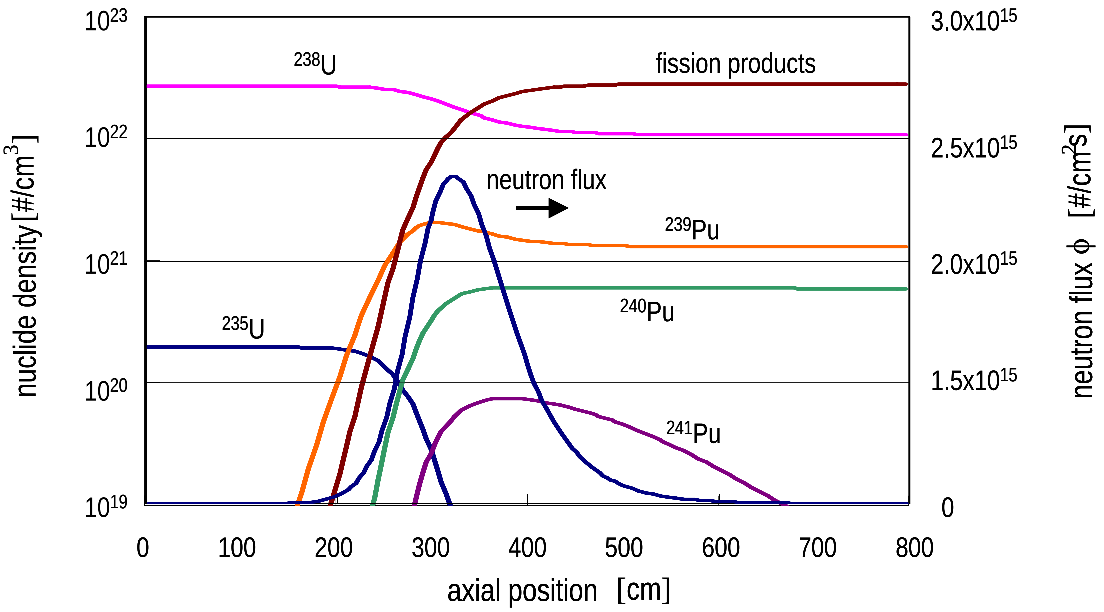


Figure 10 CANDLE burnup in a fast reactor.

Since natural uranium is highly sub-critical, many neutrons must be absorbed by ^{238}U to bring the system to a critical state. Thus, it is important to have a nuclear reactor with excellent neutron economy. For this purpose, the neutron spectrum should be extremely hard (i.e., the effective neutron energy should be extremely high.).

The burnup of fuel is increased by supplying many neutrons to the fresh fuel region. This also results in a reduction in the moving speed of the burning region.

Edward Teller proposed a similar idea [6], using thorium. However, it has been confirmed that CANDLE burnup cannot be achieved in the truest sense when thorium is used.*

5.2. Analysis Results

The basic design parameters for an example natural uranium loaded fast reactor are shown in Table 3 using lead-bismuth-eutectic (LBE) coolant and metallic fuel. Calculations were also carried out for other coolants and fuel [5], but the basic values were not changed. Natural uranium was used as fresh fuel for this investigation, however the same design is possible for depleted uranium.

Table 3 Design parameters for a natural uranium loaded fast reactor

reactor	thermal output	3000MWt
	core radius	200cm
	radial reflector thickness	50cm
fuel pin	fuel form	U-10w%Zr
	fuel pellet diameter	0.8 cm
	cladding tube material	HT-9
	cladding tube thickness	0.035cm
coolant		Pb-Bi (44.5%,55.5%)
fuel volume fraction		50%

To increase the neutron economy with a hard neutron spectrum, the percentage of fuel volume was set to 50%, which is larger than used in current reactors. In this case, the cooling capability of the coolant decreases. However, we plan to adopt a tube-in-shell design [7] for the actual reactor. In this design, the fuel has a similar

* In the proposal of Edward Teller, a neutron source—only necessary at the start of the operation—is located at the center of the core, surrounded by thorium on both sides. The thorium is thus converted into the fissile material ^{233}U and the burning region spontaneously moves from the center to both sides. This method is similar to CANDLE burnup [6], however CANDLE burnup has not been achieved with thorium. Teller's proposal is not CANDLE burnup in a strictly geometric sense; with the progress of burnup, the shape of the burning region changes so that the leakage of neutrons decreases, and also lithium is used to control the burnup reactivity.

structure to the fuel block employed in the high-temperature gas-cooled reactor and the coolant flows through holes in the block. In this way, a high cooling capability can be obtained with a small amount of coolant. This structure is also suitable for CANDLE burnup from a viewpoint of refueling.

For the calculation, 21-group diffusion equations were used. The group constants were obtained using the SRAC code system with the JENDL-3.2 library.

It was confirmed that CANDLE burnup can be established for this design. The results are shown in Table 4.

It is clearly difficult to realize CANDLE burnup with oxide fuel. In the case of nitride, however, it may be possible with a little effort. There is some difference also in the efficacy of different coolants, however, the differences are not significant and it can be seen that CANDLE burnup is possible for any coolant when a metallic fuel is used.

Table 4 Calculation results for a fast reactor loaded with natural uranium.

(a) Results for various fuels in a lead-bismuth-eutectic (LBE) cooled system.

fuel	oxide	nitride	metal
effective neutron multiplication factor	0.926	0.990	1.015
moving speed of burning region	4.7cm/year	3.5cm/year	3.8cm/year
average burnup of spent fuel	452GWd/t	445GWd/t	426GWd/t

(b) Results for various coolants when metallic fuel is used.

fuel	sodium	lead bismuth	lead	helium
effective neutron multiplication factor	1.006	1.015	1.012	1.035
moving speed of burning region	3.8cm/year	3.8cm/year	4.1cm/year	3.8cm/year
average burnup of spent fuel	415GWd/t	426GWd/t	427GWd/t	413GWd/t

The moving speed of the burning region was very slow, at about 4 cm/year for all cases. The average burnup of spent fuel was extremely high, at about 400 GWd/t. This indicates that about 40% of the loaded fuel burnt. The values were similar for all cases.

5.3. Advantages and Issues

Based on the above results, the advantages are summarized for the use of

CANDLE burnup in a fast reactor with excellent neutron economy. These results reveal the following advantages, which defy the common wisdom regarding conventional nuclear reactors.

1) It is possible to design a reactor in which fissile fuel is not necessary except for the initial core.

   Accordingly, natural uranium or depleted uranium suffices as fuel for all the cores following the initial core. That is, if we have enough fissile material for the initial core, no enrichment or reprocessing facilities are necessary. Needless to say, there will not be any waste from these facilities.

2) The average burnup of spent fuel in this reactor is about 40%.

- 40% of natural uranium (or depleted uranium) fissions to produce energy without enrichment and reprocessing.
- This value corresponds to that of a currently planned, typical fast reactor/reprocessing system (with 70% utilization of natural uranium).
- Even in the case of a simple once-through cycle, fuel resources will be 60 times greater and the waste for geological disposal will be 1/10 that of presently used light-water reactors (with a burnup rate of 4%, corresponding to 0.7% of the original natural uranium). Miscellaneous waste, especially associating to reprocessing of the fuel, will also be extremely small.
- It may be important to explain in some detail the use of depleted uranium presently stored at enrichment facilities. Until now enriched uranium fuel has been prepared for use in light-water reactors. As a result, a large amount of depleted uranium is in storage. 82% of the original natural uranium is made into depleted uranium. If 40% of this can be burnt, then 33% of the original natural uranium can be utilized through CANDLE burnup. The use of enriched uranium (18% of the original natural uranium) in a light-water reactor with 4% burnup means that 0.7% of the original natural uranium is used. In other words, using depleted uranium in a CANDLE reactor can generate 45 times more energy than has been produced until now.

3) The speed of the movement of the burning region with burnup is about 4 cm/year; thus the design of a long-life reactor is easy.

If we want to increase the core life by 20 years or 30 years, all we have to do is lengthen the core height by 0.8 m or 1.2 m.

4) Even when a core disruptive accident occurs, it is less likely to become a recriticality accident.

There is no need for a neutron absorber or reflector for the control of excess reactivity. There is also no excess fissile material in the core to produce excess reactivity. Therefore, even if the core is disrupted and fuel rearrangement takes place, it is less likely to lead to a recriticality accident.

However, there are the following potential issues.

1) A reactor design with excellent neutron economy is necessary.

This is an important issue, but I have already introduced some design examples where these designs are considered to be currently possible. For a fast reactor with excellent neutron economy, a design with a negative power reactivity coefficient is generally difficult. It is hence important that this issue be further investigated. It is necessary to ensure material integrity under more than 40% burnup.

At present we do not have any material of fuel element standing for such a high burnup. This is discussed in Section 6.2. The volume of accumulated fission products becomes large with high burnup. Under this state, the pressure will become too high, and thus it is necessary to release gas from the fuel element. This necessitates a big design change. Since the volume of solid components of the fission products will also become high, it is necessary to deal with this by decreasing the density of fresh fuel.

Considerable research is required for material development. However, even though the presently attainable burnup of cladding is much less than 50%, employing simple reprocessing such as DUPIC fuel-handling technique[8] can realize the CANDLE burnup as shown in Fig. 11. DUPIC is a dry process without separating actinides and fission products, where the volatile fission products are released from the fuel and the cladding is replaced by new one.

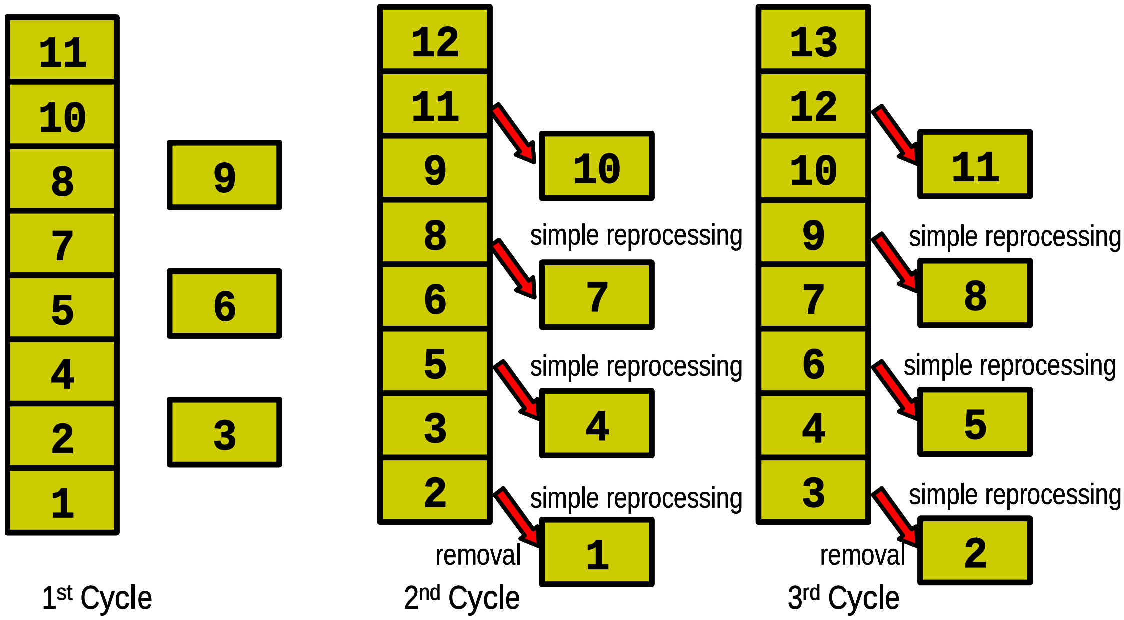


Fig. 11 An example of CANDLE fuel cycle: At the 1st cycle, the fuel element 1 is a fresh fuel and the fuel elements 3, 6 and 9 are under simple reprocessing. At the 2nd cycle the fuel element 1 is removed from the core and the fuel element 2 is moved down to this place. The fuel elements 3, 6 and 9 are charged to the positions previously occupied by the fuel elements 2, 5 and 8, respectively. The fuel element 12 is charged to the core. At the 3rd cycle the fuel element 2 is removed, and the similar refueling is repeated.

6. Supplementary Issues

Up to this point, only the basics of CANDLE burnup have been explained. If the full details were to be presented, this booklet would be too long and would deviate too much from the main discussion. Thus, some explanations have been omitted. However, I will here add explanations to some important questions: “The equilibrium state came out nicely. But how is it achieved? Can we assemble the initial core?” “It was found that a burnup of 40% could be achieved by a fast reactor with excellent neutron economy. How is research and developments on the materials withstanding these conditions?”

6.1. Issues Concerning the Initial Core

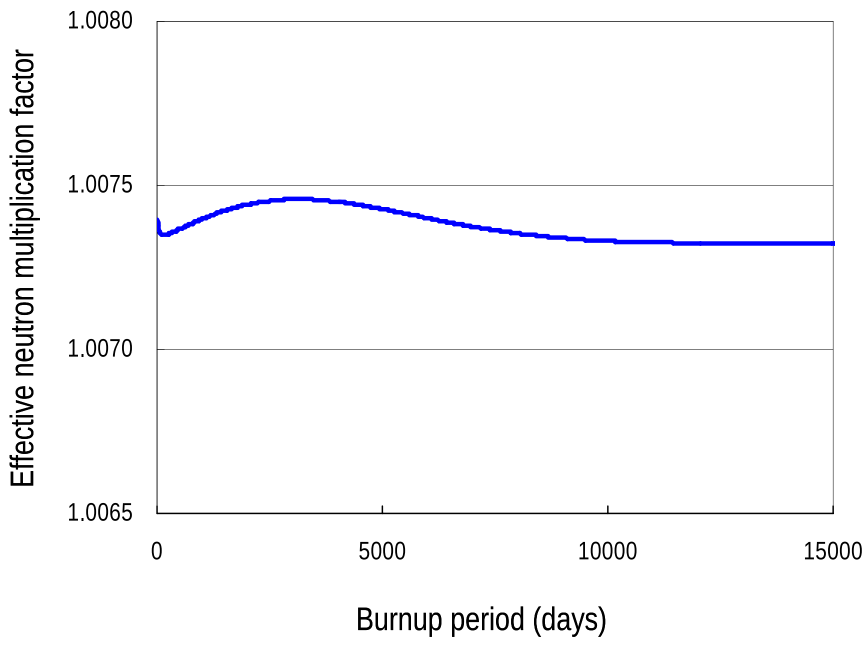


Figure 12 Change in effective neutron multiplication factor with time, obtained by simulation starting from a stationary solution.

In Chapter 3, I presented a method to directly solve the equilibrium state. The analysis results shown in the preceding section were obtained using this method. To study issues concerning the initial core, it was necessary that a simulation code be formulated so that equations (1) and (2) could be solved easily in the same way as with conventional code.

An equilibrium solution of nuclide densities was first obtained and used as the initial values and the newly prepared simulation code was run. The results shown in Figure 12 were obtained. A minor change in the effective neutron multiplication factor is observed due to misalignment between the time mesh and space mesh, arising in the calculation. The simulation code had been verified in advance and the results indicate that the equilibrium calculation code was appropriate.

In the next step an initial core is constructed with effectively stable and easily obtainable materials. In the present trial, actinides are simulated by enriched uranium with changing enrichment and fission products are simulated by niobium. Simulation was carried out from this initial core. [9] The results are shown in Figure 13. The figure shows that the effective neutron multiplication factor oscillates with time, but the maximum change with time is only 0.0008, which is fully acceptable.

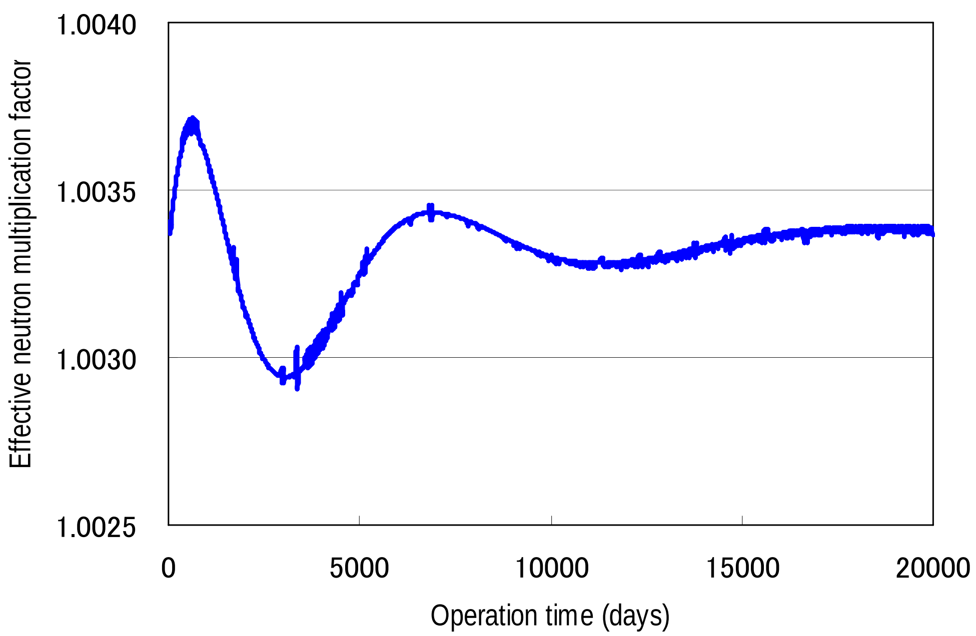


Figure 13 Change in effective neutron multiplication factor with time, obtained by simulation starting from an initial core prepared with easily obtainable materials.

6.2. Issues in High Burnup

Presently there are no data for material integrity under a condition of 40% burnup. Since the beginning of the 1970s, the maximum burnup has steadily increased in verification tests of oxide fuel used in fast reactors. At the beginning of the 1990s, data for 20% burnup has been reported. However, data suddenly stopped appearing in 1994 and there has been none published since then. I heard that this is because the fast reactor program in the United States had been abolished. Though material integrity may be sound up to pretty high burnup, it may be difficult to maintain material integrity up to a burnup as high as 40%. We simply do not know, as the experiments have not been carried out. However, it is known that resistance to radiation damage can be improved by heat treatment, which could be used on the reactor material. At any rate, such a material may not be realized in the near future. At any rate, as mentioned in Section 5. 3 the issue could be resolved by simple reprocessing of fuel elements after a certain burnup is reached, where the volatile fission products are released from the fuel and only the cladding is renewed.

7. Summary

A new burnup strategy called CANDLE is proposed. Unlike ordinary nuclear reactors, in a CANDLE burnup reactor excess reactivity is not necessary for burnup. In addition, the shape of the power distribution and core characteristics do not change with the progress of burnup. Consequently, there are numerous advantages in safety and economy of this burnup strategy.

If this burnup strategy is applied to a large fast reactor that has excellent neutron economy, it is possible to design a nuclear reactor in which depleted uranium or natural uranium can be used as exchange fuel. It was also found that 40% of the fuel can be utilized. The present once-through fuel cycle of LWR utilize 0.7% of natural uranium. For this case 87% of the original natural uranium is left as depleted uranium. If this depleted uranium is utilized as the fuel for CANDLE reactor, 35% (=0.87×0.4) of the original natural uranium is utilized. Therefore, if the LWR has already produced energy of X Joules, the CANDLE reactor can produce 50(=35/0.7)X Joules from the depleted uranium stored at the enrichment facility for the LWR fuel. Let us assume that the total energy generated so far with light-water reactors corresponds to enough nuclear power energy for the world's use for about 20 years. With this burnup system, it is then possible to continue supplying energy for 1000 years without further mining and without enrichment and reprocessing.

It may take a long time to solve material and other issues for such a reactor. However, it is possible to deal at a much earlier stage by employing simple reprocessing. On the other hand, it may be dangerous to hastily make a large CANDLE burnup fast reactor and it may be a good idea to make a small long-life reactor that uses CANDLE burnup. Various uses of small long-life reactors are possible, and such small reactors are suitable for exporting to developing countries. Small reactors are generally safe and have little economic risk. However, for a small reactor, there will be more neutron leakage and it will become difficult to make the reactor critical. It is possible to make the reactor critical by adding plutonium. However, if too much plutonium is added, it will become critical only by using fresh exchange fuel. In such a case it is no longer CANDLE burnup. Compared with these problems, the application of

CANDLE burnup to block-fuel high-temperature gas-cooled reactors is simple and certain.

The first practical experiment of CANDLE burnup may be to use it in a block-fuel high-temperature gas-cooled reactor. In this system, we can confirm its merits, gain experience of its operation, and discover any possible problems. We can then shift from it to a small long-life fast reactor. Eventually a large fast reactor may be developed in which only depleted uranium is used as fuel. We have learned that we can use just depleted uranium, which remains after the production of enriched uranium for light-water reactors, for the production of energy for a millennium. This period can be further lengthened by uranium mining and extracting uranium from sea water. In reality, however, the usage period will be determined with the volume of waste. If we consider a once-through fuel cycle, the volume of fuel waste will be 1/10 that of conventional reactors, since the burnup of CANDLE is 10 times that of the present nuclear reactors. If we assume that the size of usable waste disposal sites is similar to the presently planned size, a couple of hundred years may be a reasonable period. We hope that within this period the era of zero waste will come after realizing complete separation technology for radioactive wastes [10].

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Technical Terms

These technical terms have been compiled only to assist in reading this booklet. Hence, the explanations of the terms may not necessarily be entirely precise.

Note on expression of atomic nucleus: To fully express an atomic nucleus, the atomic symbol is written with the atomic number (number of protons) written as subscript on the left and the mass number (total number of protons and neutrons) written as superscript also on the left side. Once the atomic symbol is determined, the atomic number can be uniquely determined, and thus the atomic number is often omitted. For example, ^{235}U is written for uranium-235.

Burnable poison: Neutron absorber that is inserted into the core. The neutron absorber with large microscopic absorption cross section is converted, with the progress of burnup, into a material with a small neutron absorption cross section. It is used to lessen the reduction of the effective neutron multiplication factor in the early stage of burnup.

Burnup: It has two meaning in this booklet. One is the change of fissile material into fission products through nuclear fission in a reactor core. The other is the unit of burnup: generated energy per unit of spent fuel. The unit GWd/t is usually used. This expresses generated energy in GWd (giga-Watt days), per weight of uranium and plutonium in t (tons) contained in fresh fuel. Sometimes the expression is given in %.

Burnup reactivity: The same as excess reactivity. (See excess reactivity.)

Cladding tube: A tube that covers fuel pellets to prevent a leak of radioactive material from the fuel into the coolant and other elements of the reactor.

Coated fuel particles: Fuel particles of about 1 mm diameter used in a high-temperature gas-cooled reactor. Fuel kernels are coated with graphite and silicon carbide.

Control rods: The criticality of a nuclear reactor is adjusted with these rods, which are made of neutron absorber. The power level and shape can also be adjusted. They are also effective in stopping the operation of a nuclear reactor.

Core: Region where fuel is located in a nuclear reactor.

Criticality: A state in which neutrons stays under the balance of generated neutrons and consumed (absorbed or leaked) neutrons. If the number of generated neutrons is larger than the number of consumed neutrons, the state is called supercritical. If the number of consumed neutrons is larger, it is called subcritical.

Criticality experiment: An experiment to verify the precision of calculations by assembling fuel, achieving criticality, and comparing the critical amount of fuel and other measurements with the calculated values.

Cross section: The probability that a nuclear reaction takes place. The larger the cross section, the more likely that a nuclear reaction will take place. (See microscopic absorption cross section.)

Decay: See radioactive decay.

Depleted uranium: When natural uranium is enriched to obtain enriched uranium, a large amount of uranium containing less ^{235}U than natural uranium is generated. This is called depleted uranium.

Effective neutron multiplication factor: Neutron multiplication factor for an actual core under consideration. If the core in consideration is critical, the factor is exactly unity. If it is subcritical, the factor is less than unity, and if supercritical, it is more than unity. (See neutron multiplication factor.)

Excess reactivity: In a normal nuclear reactor, the reactivity at the start of burnup is positive. However, the reactivity becomes smaller with the progress of burnup. When the reactivity becomes zero, the operation is stopped and refueling is required to continue the operation. The reactivity is suppressed with control rods to attain criticality. The reactivity described above is called excess reactivity.

Fast reactor: A nuclear reactor in which neutrons are not moderated and the nuclear fissions are caused by fast neutrons. Water, which moderates neutrons, cannot be used as a coolant. Thus, sodium, lead (or lead bismuth alloy), or gas is used as a coolant.

Fertile material: Material that does not undergo nuclear fission when a thermal neutron is absorbed, but instead becomes fissile material.

Fissile material: Material that fissions by the absorption of a thermal neutron. Fissile material does not necessarily fission after absorbing a neutron and to distinguish the absorption of a neutron without nuclear fission, it is called capture.

Fission products: When fissile material undergoes nuclear fission, two fission products are generated in most cases. Nuclear fission does not take place when a neutron is absorbed by a fission product.

Fuel cycle: Fuel cycle is generally a stream of fuel in a nuclear energy utilization system with nuclear reactors, but in this booklet it means the following specific fuel cycle. Fuel from a nuclear reactor is reprocessed, fissile material is separated and processed into fuel, and is then returned to the nuclear reactor. This is the cycle of fuel. Nowadays, however, the fuel cycle includes the mining of uranium to the final disposal of waste.

Fuel kernel: Fuel sphere located at the center of coated fuel particle. (See coated fuel particles.)

Galilean transformation: Transformation from one coordinate system to another coordinate system that is moving at a different speed. In the case considered in this book, the two coordinate systems are one at rest and one traveling at a speed *V*.

Half life: Time necessary for a radioactive material to decay to half of its original amount.

High-temperature gas-cooled reactor: A reactor in which graphite is used for to moderate neutrons and high temperature helium is used for cooling. Fuel is prepared by mixing coated fuel particles into graphite.

Infinite medium neutron multiplication factor: The neutron multiplication factor where the size of the core is assumed to be infinite. This is expressed in k_∞. (See neutron multiplication factor.)

Light-water reactor: A reactor in which light water (normal water, as distinguished from heavy water) is used to moderate neutrons and to cool the core. Presently, most extensively operated reactors are light-water reactors. In a boiling-water reactor (BWR), water boils in the core, and in a pressurized-water reactor (PWR), water does not boil in the core.

Microscopic absorption cross section: Neutron absorption cross section per nucleus. (See cross section.)

Neutron fluence: Time-integrated neutron flux of particles per unit area. (See neutron flux.)

Neutron flux: A quantity obtained by multiplying the neutron density and the neutron speed. The reaction rate is obtained by multiplying the neutron flux and the cross section.

Neutron spectrum: Energy distribution of neutrons.

Neutron multiplication factor: The rate of change of the average number of neutrons during one cycle. Here, one cycle is from one nuclear fission to the succeeding nuclear fission. In a critical state it is exactly unity, in a subcritical state it is less than unity, and in a supercritical state it is more than unity. (See effective neutron multiplication factor and infinite medium neutron multiplication factor.)

Nuclear proliferation: The spread of nuclear weapons to countries or organizations whose possession of the weapons is not approved.

Nuclear proliferation resistance: Deterrence of nuclear proliferation.

Nucleons: Particles that constitute a nucleus, namely, protons and neutrons.

Nuclide: Species of atomic nuclei. A nuclide can be uniquely determined once the number of protons and the number of neutrons in the nucleus are determined.

Once-through: Spent fuel is permanently disposed of as is.

Peaking factor: Ratio between the maximum value and the average value of power density.

Power/thermal power: Power of a nuclear reactor. The unit used is watt. Since the values are big, MW (mega-watt; mega means 10^6) is used. When burnup is expressed, GW (giga-watt; giga means 10^9) is often used. Power may be thermal or electric. If the efficiency of power generation is known, the electric power can be calculated from the thermal power.

Power coefficient of reactivity: The change in reactivity due to a change in power. In a normal nuclear reactor, the value should be negative so that the nuclear reactor can be stably controlled. If the value is positive, there is a possibility that the power will go out of control because of control instability. (See reactivity.)

Radioactive decay: A change into another nuclide through radiation. Typical decays are α-decay, which releases a nucleus of helium (α-ray), β-decay, which releases an electron (β-ray), and γ-decay, which releases high energy electromagnetic waves (γ-ray).

Reactivity: A value that indicates how far away the effective neutron multiplication factor is from criticality. If the effective neutron multiplication factor is expressed by k, the reactivity is defined as $(1-k)/k$. (See effective neutron multiplication factor.)

Reactor physics: The study that deals with neutron behavior in a nuclear reactor, where the criticality characteristics, power distribution, power coefficient of reactivity, etc. are analyzed.

Reflector: A component that returns leaking neutrons from the core back to the core. (See core.)

Reprocessing: Extraction of fissile materials, especially plutonium, from spent fuel, and associating processes.

Thermal neutron: Neutrons generated by nuclear fission have high energy. Thermal neutrons are obtained by moderating these neutrons and decreasing their energy to the same level as the temperature of the medium. Generally the probability of nuclear reaction with thermal neutrons is much higher than with fast neutrons.