

Small High Temperature Gas-Cooled Reactors with Innovative Nuclear Burning

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ABSTRACT

Since the innovative concept of CANDLE (Constant Axial shape of Neutron Flux, nuclide densities and power shape During Life of Energy producing reactor) burning strategy was proposed, intensive research works have been continuously conducted to evaluate the feasibility and the performance of the burning strategy on both fast and thermal reactors. We learned that one potential application of the burning strategy for thermal reactors is for the High Temperature Gas-Cooled Reactors (HTGR) with prismatic/block-type fuel elements. Several characteristics of CANDLE burning strategy such as constant reactor characteristics during burn-up, no need for burn-up reactivity control mechanism, proportionality of core height with core lifetime, sub-criticality of fresh fuel elements, etc. enable us to design small sized HTGR with a high degree of safety, easiness of operation and maintenance, and long core lifetime which are required for introducing the reactors into remote areas or developing countries with limited infrastructures and resources. In the present work, we report our evaluation results on small sized block-type HTGR designs with CANDLE burning strategy and compared with other existing small HTGR designs including the ones with pebble fuel elements, under both uranium and thorium fuel cycles.

KEYWORDS

Small sized HTGR, innovative nuclear burning, CANDLE,
remote area, uranium fuel, thorium fuel

1. Introduction

The needs for small sized (including very small-size or mini) and medium sized reactors (SMR) have been identified both by the user countries and the vendor countries (IAEA 1985; IAEA 1996; IAEA 2000; Kuznetsov 2005). As for the user countries which are dominated by developing countries facing a large growth of its domestic energy demand, there are many regions and applications where this increased demand will be best met by power plants in the above mentioned range, due to a small grid system or for application in a remote area or for a special purpose. As for the vendor countries in responding the needs, various reactor designs have been proposed where their designs can be classified as light water reactors (LWR), heavy water reactors (HWR), gas-cooled reactors (GCR) and liquid metal reactors (LMR). Furthermore, since half of the world primary energy consumption is used as hot water, steam and heat, but only a few nuclear power plants are used for heat applications, small sized reactors which can provide both electricity and heat could play a major and important role in the future.

High temperature gas-cooled reactors (HTGR) have been considered to be a potential candidate of SMR since they can provide both electricity and heat with a relatively higher efficiency and have leading safety characteristics. The coated particle fuel and reactor technologies as well as safety characteristics of HTGR have been proven in the past through the Peach Bottom 1 (General Atomic, Peach Bottom, Pa., United States), Fort St. Vrain (General Atomic, Platteville, Co., United States), AVR and THTR-300 (BBC/HRB, Hamm-Uentrop, Germany). In addition, the recently reported results of the safety demonstration experiments conducted in the block-type HTTR (Japan) and pebble-type HTR-10 (China) reconfirmed the inherent safety characteristics of HTGR.

The innovative designs of small sized or medium sized HTGR proposed by vendor countries such as PBMR (110 MWe, ESCOM, South Africa), HTR-PM (160 MWe, Tsinghua University, China), GT-MHR (600 MWth, GA, United States), GTHTR300 (600 MWth, JAERI-TEPCO, Japan) have relatively large power levels which may not be suitable for applications in a small remote island with a low number of population. This situation can be readily found for example in the eastern region of Indonesia, where it consists of a large number of dispersed less-developed small islands yet with a great potential to be developed as an industrial center based on marine resources, as well as agro-business and agro-industry (Arbie 1998). The design requirements for such region include:

1. Siting which determines the reactor power level needed. The rather high seismic condition of the eastern region of Indonesia (e.g. the horizontal ground acceleration is between 0.05 g to 0.25 g) also favors for small sized or very small sized reactors.
2. Licensibility in the country of origin; The adoption of passive safety concept, non-active components, and other improvement of engineered safety features as well as very low power level and power density should be taken into account to simplify the licensing process.
3. Economic criteria; Although small sized and very small sized reactors tend to lose their economies of scale, the following factors must be considered in assessing the generation cost: (a) large social gain, (b) zero or the least government subsidy, (c) smaller than the cost to upgrade the infrastructure and transportation means in order to remove the “remoteness” qualification. In addition, as stated in point (2),

simplification of design and licensing process, modularization etc. will lead to shorter construction times and savings in interest during construction. The reduced capital requirements compared with large plants are also an important factor for developing countries.

4. Domestic participation, and research and development cooperation for technology transfer.

To respond those requirements, in our previous work (Liem, 1995a), along with the development of analytical codes (Liem, 1994 and Liem 1995b), we have proposed design procedures for small sized pebble-bed high temperature reactors based on the established design of 200 MWth HTR-Module (Reutler and Lohnert, 1983). In the work, the multipass, Once-Through-Then-Out (OTTO) and Peu A Peu (PAP) burning schemes using either uranium or thorium fuel were considered and reviewed. Under the proposed design procedures, very small sized HTGRs (25 MWth) with multipass and OTTO burning schemes may have fuel burn-up performance competitive to the 200 MWth HTR-Module and meet the safety constraints satisfactorily. On the other hand, the burn-up performance of small PAP HTGRs was in general inferior to the HTR-Module design. However, since the PAP fueling scheme requires the simplest refueling mechanism and devices, it may be the best option of pebble-type HTGR for a remote or isolated island where minimum maintenance and surveillance are required. Another important finding was that the thorium fuel for all three fueling schemes showed superior burn-up performance than the uranium fuel.

Recently, a simpler burning scheme than PAP, **CANDLE** (Constant Axial shape of Neutron flux, nuclide densities and power shape **D**uring **L**ife of **E**nergy producing reactor) burning scheme was proposed by Sekimoto (Sekimoto 2001) originally for fast reactor design. Under CANDLE burning scheme, relative distribution shapes of neutron flux, nuclide densities and power density are constant but move autonomously in the axial direction with a constant velocity during the whole life of reactor operation. The excess reactivity is constant (and can be set very low) during burn-up and no control mechanism for burn-up is required. Small HTGRs can take the advantages of this innovative burning scheme, and works are being conducted to apply the burning scheme to block-type HTGRs.

In this paper, we report our latest evaluation results on small sized block-type HTGR designs with CANDLE burning scheme and compared with other existing small sized HTGR designs including the ones with pebble-type fuel elements, utilizing either uranium or thorium fuel.

2. The Innovative CANDLE Burning Scheme

The **CANDLE** (Constant Axial shape of Neutron flux, nuclide densities and power shape **D**uring **L**ife of **E**nergy producing reactor) burning scheme was proposed by Sekimoto *et al.*, (2001) originally aimed for fast reactors. Under this burning scheme, the burning region moves autonomously with a constant velocity along the core axis from bottom to top (or from top to bottom) as shown in Fig. 1 (left). As shown in the figure, the core can be roughly divided into three regions: (1) fresh fuel region ($k_{inf} < 1$), (2) burning region ($k_{inf} > 1$) and (3) spent fuel region ($k_{inf} < 1$). When the burning scheme is applied to a block-type HTGR, burnable poison (for e.g. gadolinium) is used to adjust the k_{inf} of the fresh fuel to be sub-critical. The CANDLE burn-up process is as follows (cf. Fig. 1 right). Neutrons leaked from the burning region into the fresh fuel region will

be absorbed by the burnable poison and the burning region will move slowly into the fresh fuel region with depleted burnable poison. In the burning region, depletion of fissile material for energy production is accompanied by conversion of fertile material into fissile material. The spent fuel region is the region left by the burning region which contains mainly fission products and depleted fuel.

For a unique combination of core geometry and fresh fuel composition, one can find an equilibrium critical condition where CANDLE burning scheme is realized. Under the equilibrium condition, the moving (axial) velocity of the burning region is constant. Analytical codes for obtaining either the equilibrium condition or for simulating the reactor start-up have been developed. The details of the computational procedures are not given here and readers should consult other references (Ohoka 2004; Ohoka 2005).

3. Advantages of Small Sized HTGR with CANDLE Burning Scheme

Small sized prismatic/block-type HTGRs adopting CANDLE burning scheme can take full advantages of CANDLE properties:

1. Constant reactor parameters (e.g. power peaking, reactivity coefficients etc.) during reactor operation. This will simplify not only the reactor design itself and its licensing process but also simplify its reactor operation and maintenance.
2. No requirement for burn-up reactivity control mechanism. Besides simplifying the reactor design, a control rod ejection accident during full power operation (under nominal pressure) can be avoided.
3. No requirement for fuel loading mechanism during reactor operation. Compared to pebble-bed reactors, even for the simplest PAP burning scheme a mechanism for inserting pebble fuel into the core during operation is needed.
4. Favorable axial power distribution for obtaining higher gas outlet temperature. This axial power distribution is similar to the ones of OTTO and PAP.
5. Relatively higher axial peaking factor of CANDLE burning scheme will not be a problem for small sized HTGRs when considering the consequence of a depressurization accident.
6. Proportionality of core height to reactor core life. A long-life core can be easily designed by adjusting the core height.
7. Sub-criticality of fresh fuel. No criticality accident will occur during transportation and storage of fresh fuels.

In addition, application of CANDLE burning scheme to small sized HTGRs can be realized by the present coated particle fuel and HTGR reactor technologies. Nevertheless, the output temperature of small sized HTGRs for heat application on agro-industries in the above-mentioned remote islands is expected not to exceed 850 degree Celsius, so that considerable effort of R & D on heat resistant materials is not needed.

Table 1 shows the comparison of the innovative CANDLE burning scheme with the other existing burning schemes, i.e. the multipass, OTTO and PAP. No complex mechanism is needed for CANDLE burning scheme. However, as will be shown in the next section, the use of burnable poison (BP) in the fresh fuel of CANDLE makes it difficult to compete with other scheme which requires no BP in term of discharge fuel burn-up level. Furthermore, a relatively higher power peaking factor, which is natural for CANDLE, is observed, but still comparable with the one of PAP.

4. Burn-up Performance of Small Sized CANDLE HTGRs

One example of our analytical results for small sized HTGRs with various burning schemes will be discussed. The calculation conditions and results are shown in Table 2. We assume that several small sized reactors, with thermal output of 25 MWth and a long core life of 10 years, would be suitable for a small, remote island in the eastern region of Indonesia. TRISO coated particle fuel is used for all cases. Under 6 MPa He pressure, the core inlet and outlet temperatures are set to 250 and 700 degree Celsius.

For the block-type CANDLE cases, the fuel element resembles the one of the JAERI HTTR fuel element with packing fraction of 0.25 and 8 % fissile enrichment for its fuel compact. A proper concentration of gadolinium BP mixed in the fuel kernel is calculated iteratively to establish an equilibrium critical condition of CANDLE scheme (4.2 % and 1.2 % for uranium and thorium fuels, respectively). As depicted in the figure inside Table 1, in the real CANDLE reactor, besides the effective core height which determines the core life time, the unused regions in the core upper and lower sides have to be added (around 0.5 m). For the present work, since we assume a core life time of 10 years then the required (effective) core height are 4.1 m and 2.9 m for uranium and thorium fuels, respectively (the core radius is 1.5 m, and the corresponding effective core volumes are about 42 m³ and 35 m³, respectively). The axial distributions of main nuclides and power density for uranium and thorium fuels are shown in Figure 2 and 3, respectively. In the figures, the burning region is moving over the half height of the core.

On the other hand, for the pebble-type cases, a pebble fuel element contains 7 g heavy metal with 8 % fissile enrichment. A proper pebble flow velocity is iteratively found to establish an equilibrium critical condition for both multipass (pebble fuel elements are reloaded into the core 15 times) and OTTO schemes, while the loading speed is continuously adjusted to keep the PAP core critical during its operation (Liem, 1995a). The core radius and height for the multipass and OTTO cases are 1.5 m and 4.5 m, respectively (correspond to core volume of around 32 m³), while for the PAP cases, the same core radius is used but the final (EOC) core height depends on the fuel cycle. Since we assume a core life time of 10 years, then the required core height are 6.9 m and 4.0 m for uranium and thorium fuel, respectively (correspond to core volumes of around 49 m³ and 28 m³, respectively).

The core volumes (or heights) of CANDLE HTGR for 10 years core life time are as compact as the ones of multipass and OTTO, and smaller than the one of PAP. The CANDLE burning region moving velocities are about 40 cm/year and 30 cm/year for uranium and thorium fuels, respectively. Under these conditions, the discharge fuel burn-up levels of 52 and 76 GWD/t can be achieved for uranium and thorium fuels, respectively. These values are approximately 33 % lower than those of the multipass, approximately 22 % lower than those of the OTTO, but slightly better than those of PAP. Lower achieved burn-up levels compared with the multipass and OTTO are also reflected in higher fissile loading values. These are attributed partly by the fact that some neutrons are absorbed by burnable poisons in the fresh fuel region to convert the region into the burning region.

The PAP burn-up performance is in general inferior to the others. This is due to the relatively larger neutron leakage, especially at BOC when the core dimension is

small. The multipass scheme seems to be the best available method to burn fuel in a pebble bed reactor. The low neutron leakage combined with the effect of reloading the old pebble fuel elements yields a better burn-up performance and fuel utilization.

To increase the burn-up level of CANDLE with the same initial fissile content, redesigning the BP (e.g. placing the BP outside fuel kernel) and increasing the fuel packing fraction will be considered in the future.

For all schemes, the thorium fuel shows more than 40 % higher burn-up level than the uranium fuel. For CANDLE and PAP schemes, this also results in a shorter core height for the same core life time.

The maximum power densities of CANDLE are relatively higher than those of the multipass and OTTO but are significantly smaller than the ones of PAP. For much larger reactor power levels, better design of BP is required to improve the axial power peaking to anticipate the maximum fuel temperature attained during a depressurization accident. Nevertheless, it is well known that the core effective conductivity of block-type fuel elements adopted by CANDLE is much larger than the one of the pebble-type fuel elements. Furthermore, radial peaking factor is easier controlled in a block-type core. Unlike the PAP, the core pressure drop of CANDLE, multipass and OTTO schemes is constant since the core height is constant.

5. Concluding Remarks and Future Works

We have shown that the innovative CANDLE burning scheme is very potential to be adopted for small sized HTGRs which are expected to be deployed in remote areas or less-developed regions where only minimum infrastructures and resources are available. More works are still required for improving its burn-up performance and assessing the possibility to be adopted for medium sized or large sized HTGRs.

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Table 1. Comparison of HTGR burning schemes

Fuel Element Type and Burning Scheme	Fuel element	Pebble-type			Block-type
	Burning scheme	Multipass	OTTO	Peu A Peu	CANDLE
Illustration C: fresh fuel charging mechanism D: burnt fuel discharging mechanism B: burnt fuel burn-up measuring mechanism R: burnt fuel reloading mechanism Q: axial power distribution BOC: beginning of cycle EOC: end of cycle					
	Fresh fuel loading mech.	Yes	Yes	Yes	No
	Burn-up measuring mech.	Yes	No	No	No
	Fuel reloading mech.	Yes	No	No	No
	Fuel discharging mech.	Yes	Yes	No	No
	Core life (theoretical)	Infinite	Infinite	Prop. to core height	Prop. to core height
	Burnable poison	No	No	Yes or No	Yes
	Neutron economy (burn-up level, conversion ratio)	Best	Better	Good (some neutrons leak, especially at BOC)	Good (some neutrons absorbed by burnable poison)
Thermal/ Safety	Power peaking (axial)	Low	Moderate	High (esp. at BOC)	High
	Core pressure drop	Constant	Constant	Change considerably	Constant

Table 2. Small sized HTGR performance for several innovative burning schemes ¹⁾

BURNING SCHEME	Multipass	OTTO	Peu-a-Peu	CANDLE
Fuel Element Type	Pebble-type			Block-type
Fresh Fuel Loading Method	On-line, Continuous			Off-line, Batch
Thermal Power (MWth)	25.0			
Core Diameter (m)	3.0			
CFP and Fissile Enrichment	TRISO, 8.0 % ²⁾			
Core Height and Volume (m, m ³)	4.5 / 31.8	4.5 / 31.8	6.9 / 48.8	4.1 / 29.0
	4.5 / 31.8	4.5 / 31.8	4.0 / 28.3	2.9 / 20.5
Core Life Time (year) or Residence Time (year)	11.0	9.4	10.0	10.0
	16.5	14.0	10.0	10.0
Velocity (cm/day) or Fueling Rate (ball/month)	1.8	0.14	1774.0	0.113
	1.2	0.09	703.0	0.080
Fissile Loading (kg/GWD)	1.03	1.20	1.61	1.53
	0.68	0.81	1.13	1.05
Ave. Burnup (GWD/t)	78.5	67.2	49.8	52.3
	117.0	99.4	71.1	76.3
Conversion Ratio (CR) or Fissile Inventory Ratio (FIR) ³⁾	0.486	0.468	0.471	0.492
	0.549	0.490	0.488	0.271
Max. Power Density (W/cm ³)	0.99	1.53	4.78	3.55
	1.02	2.10	7.33	4.96

¹⁾ First and second rows indicate uranium and thorium fuels, respectively.

²⁾ CANDLE scheme uses gadolinium BP mixed in its fuel kernels (1.2 and 4.0 w/o for uranium and thorium fuels, respectively).

³⁾ CR is evaluated for Multipass, OTTO and PAP and FIR is for CANDLE

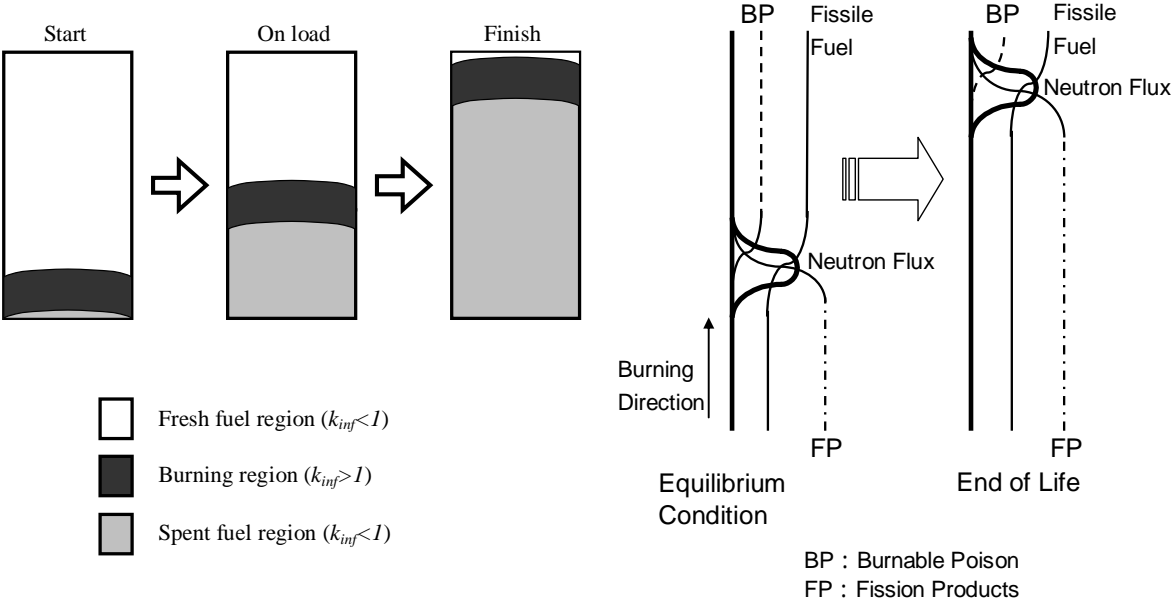


Figure 1. CANDLE burning concept (left) and its application to HTGR (right)

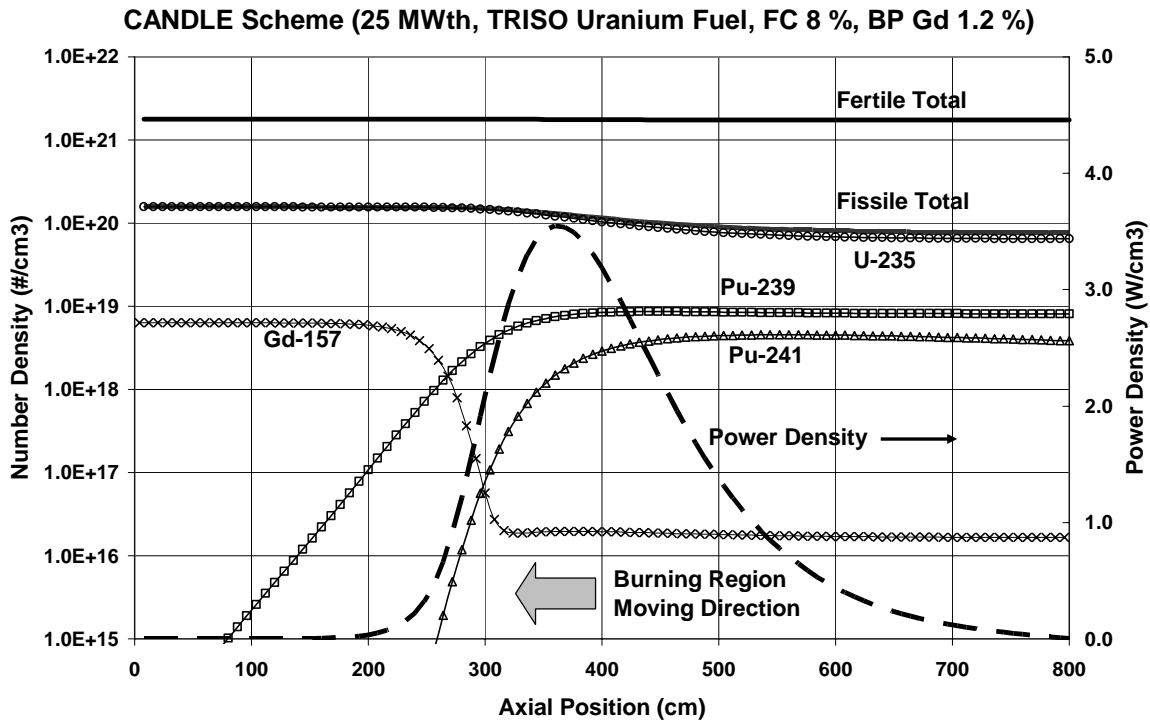


Figure 2. Nuclide densities and power axial distributions of a small sized CANDLE HTGR with uranium fuel.

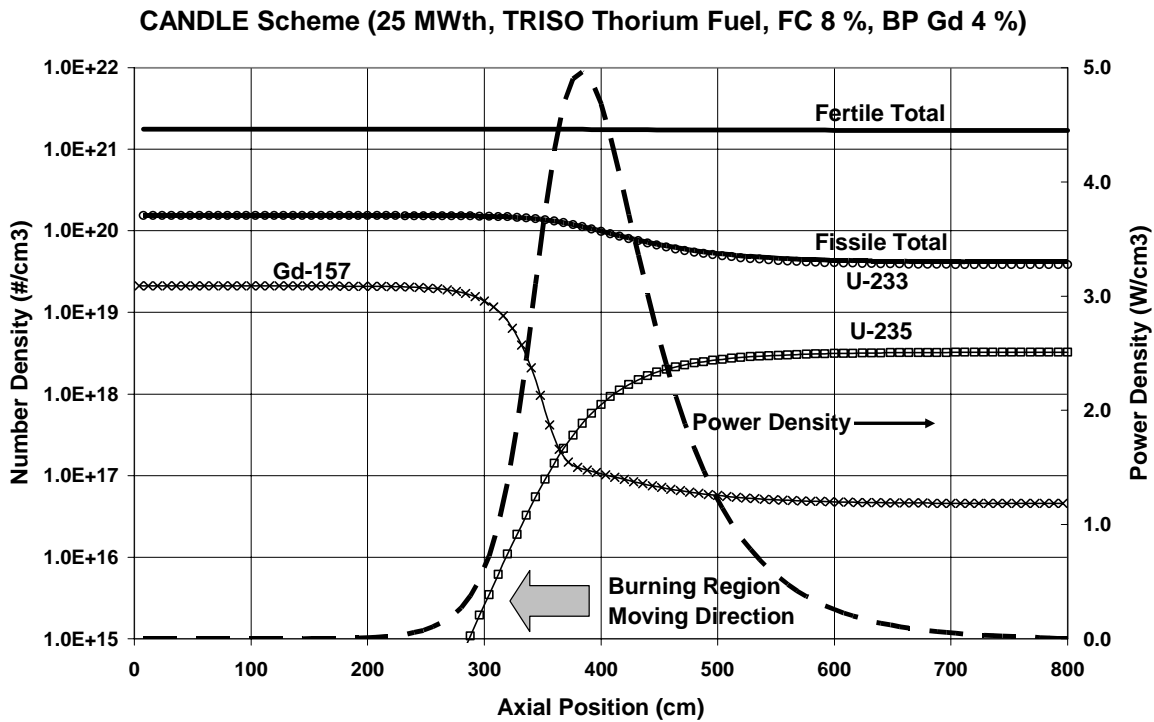


Figure 3. Nuclide densities and power axial distributions of a small sized CANDLE HTGR with thorium fuel.