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Decay heat of the High Temperature Engineering Test Reactor had been evaluated by the Shure Equation and/or ORIGEN code based on the LWR's data. However, to evaluate more accurately, a suitable method must be considered because of the differences neutron spectrums from the LWRs. Therefore, the decay heat and the generated nuclides for the neutron spectrums of the core with different graphite moderator amount were calculated by the ORIGEN2 code. As a result, it is clear that the calculated decay heats are similar value with LWRs for about one year after the reactor shutdown, and that the significant differences are observed on the longer period affected by the generated nuclides such as ^{90}Y, ^{134}Cs, ^{144}Pr, ^{106}Rh, ^{241}Am etc. It is also clear that the dose is affected by ^{241}Pu on the initial stage after the reactor shutdown.

Keywords: Decay Heat, HTTR Library, ORIGEN, ANSI, Shure Equation

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新しいORIGENライブラリを用いた高温工学試験研究炉の崩壊熱計算

日本原子力研究開発機構　原子力科学研究部門　大洗研究開発センター
高温工学試験研究炉部

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これまで高温工学試験研究炉の崩壊熱は、軽水炉のデータを基にしたShureの式やORIGEN計算で評価してきたが、厳密には軽水炉の中性子スペクトルと異なることから最適な評価方法を検討する必要がある。このため、黒鉛減速材量を変えた炉心の中性子スペクトルを用い、ORIGEN2コードで崩壊熱及び生成核種を計算して軽水炉の崩壊熱曲線と比較した。この結果、崩壊熱は、炉停止後1年程度であれば軽水炉と同様な値となったが、より長期になると差が顕著になり、^{90}Y、^{134}Cs、^{144}Pr、^{106}Rh、^{241}Am等が崩壊熱に大きく寄与することが明らかとなった。また、線量評価に関しては、冷却初期に^{241}Puが大きく影響することも明らかになった。

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1. Introduction

The High Temperature Engineering Test Reactor (HTTR) is the first and the only one of the High Temperature Gas-Cooled Reactor (HTGR) in Japan, which is built in Oarai Research and Development Center of the Japan Atomic Energy Agency (JAEA). The HTTR is a graphite-moderated and helium gas cooled reactor, and can achieve the outlet temperature of 950ºC with the thermal power of 30 MWt[1)]. Such high outlet temperature can be applied to the industrial applications such as the hydrogen production, the electricity generation by the gas turbine, the process heat supply, the seawater desalination, etc. The construction had completed on May 1996, and the first criticality is November 10, 1998. Overview of the reactor building is shown in Fig. 1.1.

The HTTR is a block-type of the HTGR design. This reactor consists of core components, reactor pressure vessel, replaceable and permanent reflector block, and reactivity control equipments as shown in Fig.1.2. The active core, which is 2.3 m in diameter and 2.9 m in height, consists of 30 fuel columns and 7 control rod guide blocks surrounded by the replaceable and permanent reflector blocks. The main characteristics are shown in Table 1.1.

A fuel assembly consists of the fuel rods and the hexagonal graphite block, 360 mm across flat and 580 mm in height as shown in Fig.1.3. The TRISO-coated fuel particles are dispersed in the graphite matrix and sintered to form the fuel compacts, and 14 fuel compacts inserted in the fuel rod. The coated fuel particle contains a spherical fuel kernel of low enriched UO_2 with TRISO coating. There are several layers in TRISO coating which are buffer layer, inner pyrolytic carbon (IPyC) layer, silicon carbide (SiC) layer and outer pyrolytic carbon (OPyC). The detail specifications of fuel assembly are shown in Table 1.2.

The HTTR is one of the small modular reactors and has passive safety features. The uses of helium gas cooling and graphite moderator and TRISO coated fuel particles can retain the fission product (FP) at high temperature up to 1600 ºC for a long operation period. These attributes make the spent fuel more durable than the metallic containers typically used for the final disposition. The excellent features of the HTGR make the possibility to perform the higher burnup during the operation period in comparison with

the LWRs.

In the future, the first loaded core will be replaced with the secondary core. The old fuel elements will be discharged from the core to the spent fuel storage pool. Therefore, it is necessary to manage and analyze the decay heat profile, radioactivity nuclide and nuclide composition of the spent fuels. The spent fuel composition such as Fission Products (FPs) and Minor Actinides (MAs) might be different from the LWRs due to the difference characteristic such as the burnup performance, the temperature condition in the core and the neutron spectrum.

A new library for the HTTR was developed based on ORIGEN code to analyze the characteristics and compositions of the HTTR spent fuels.

The purposes of this study are:

- To analyze the decay heat performance of the HTTR by using the new HTTR Library.
- To compare the decay heat performance of the HTTR by using the new HTTR library and LWRs library such as ANSI standard and Shure Equation.
- To investigate the important nuclides which have significant contribution for decay heat and radioactivity level during the cooling time of the HTTR.

2. Calculation of decay heat for LWRs

2.1 Calculation by ANSI/ANS-5.1-2005

Decay heat is one of the important parameters in nuclear reactor. Decay heat is the heat produced by the decay of radioactive material after a nuclear reactor has been shut down. Data from several experiments were examined in the 1960s to provide an accurate basis for predicting decay heat power. The ANSI/ANS-5.1-2005 is the latest version of the decay heat standard. This standard provides bases for determining the shutdown decay heat and its uncertainty following shutdown of the LWRs. Besides, it can be used in the performance evaluation, the design and safety evaluation of the LWRs.

The standard sets forth values for the decay heat power from the fission products and ^{239}U and ^{239}Np following shutdown of the LWRs containing ^{235}U, ^{238}U, and plutonium. Decay heat from other actinides and activation products in the structure material, and the fission power delayed neutron-induced fission, are not included in this standard. Data on the fission products decay heat power are presented in two ways: First, which represents decay heat power per fission following an instantaneous pulse of a significant number of the fission events. Second, the decay heat power from the fission products produced at a constant rate over an infinitely long operating period without the neutron absorption in the fission products. The tabular data for thermal fission of ^{235}U, ^{239}Pu, ^{241}Pu and fast fission of ^{238}U are presented in the Report of ANSI/ANS-5.1-2005[3]. In this report, the total decay heat power is given by:

$$P_d(t,T) = P'_d(t,T).\ G(t) \quad (1)$$

where

$$P'_d(t,T) = \sum_{i=1}^{4} P'_{d_i}(t,T) \quad (2)$$

$$P'_{di}(t,T) = \sum_{\alpha=1}^{N} \frac{P_{i\alpha} F_i(t_\alpha, T_\alpha)}{Q_i} \quad (3)$$

$$F_i(t_\alpha, T_\alpha) = F_i(t_\alpha, \infty) - F_i(t_\alpha + T_\alpha, \infty) \quad (4)$$

$$F(t,T) = \sum_{i=1}^{23} \frac{\alpha_i}{\lambda_i} \exp(-\lambda_i t)\,[1 - \exp(-\lambda_i T)] \quad (5)$$

$F_i(t,T)$ Decay heat power *t* seconds after an operating period of *T* seconds at constant fission rate of nuclide *i* in the absence of neutron capture in fission products [(MeV/)/(fission/s)],

G(t) The factor which accounts for neutron capture in fission products[3],

i = 1,2,3 and 4 represent of ^{235}U thermal, ^{239}Pu thermal, ^{238}U fast, and ^{241}Pu thermal,

$P'_d(t,T)$ Total fission product decay heat power corresponding to $P_d(t,T)$ but uncorrected for neutron capture in fission product (MeV/s),

$P'_{di}(t,T)$ Fission product decay heat power contribution to $P'_d(t,T)$ by *i*th fissionable nuclide, uncorrected for neutron capture in fission product (MeV/s),

$P_{i\alpha}$ Average power from fissioning of nuclide i during operating period T_α (MeV/s),

Q_i Total recoverable energy associated with one fission of nuclide i (MeV/fission),

t Time after shutdown (cooling time) (s),

T Total operating period, including intermediate period at zero power (s).

Data for equation (4) and (5) are provided by the Report of ANSI/ANS-5.1-2005[3]. The cooling time in the ANSI standard is available up to 8×10^9 seconds (about 254 years). However, in the ANSI standard, many phenomena that make the decay heat power unique to each case were ignored and assumed to be included within the appropriately large uncertainty. In this standard, by increasing the cooling time up to 10^7 seconds, the uncertainty increase to 25% [3].

2.2 Calculation by Shure equation

In principle it would be possible to calculate the fission product properties following reactor shutdown when the information such as half-life, yield and decay scheme for all nuclides were available. The Shure Equation is estimated the decay heat of FPs and MAs for LWRs.

Total decay heat by the Shure equation is given by [4]:

$$\mathrm{H(t)} = H_0\left(\frac{P_f(t)}{P_0}\times 1.135 + \frac{P_D(t)}{P_0} + \frac{P_{ACT}(t)}{P_0}\right) \quad (6)$$

Where

$$\frac{P_D(t)}{P_0} = \frac{(A.t^{-a}) - (A.(t_0+t_s)^{-a}}{200} \quad (7)$$

$$\frac{P_{ACT}(t)}{P_0} = \frac{1}{Q}\{F_{29}(t) + F_{39}(t)\} \quad (8)$$

$$F_{29}(t) = E_{29}\times \mathrm{R}\times e^{-l_1 t}$$

$$F_{39}(t) = E_{39}\times \mathrm{R}\times\left(\frac{l_1}{l_1-l_2}\times e^{-l_2 t} - \frac{l_2}{l_1-l_2}\times e^{-l_1 t}\right)$$

E_{29} Average energy from decay of one ^{239}U atom: 0.474 [MeV]

E_{39} Average energy from decay of one ^{239}Np atom: 0.419 [MeV]

$H(t)$ Heat power at t after shutdown

H_0 Heat power at steady state operation

l_1 Decay constant for ^{239}U: 4.91×10^{-4} [s^{-1}]

l_2 Decay constant for ^{239}Np: 3.41×10^{-6} [s^{-1}]

P_0 Reactor power at steady state operation

$P_f(t)$ Reactor power from delayed neutron

$P_D(t)$ Decay heat from fission element

$P_{ACT}(t)$ Decay heat from activation element

P_0 Reactor power at steady state operation

Q Energy release per fission: 200 [MeV]

R Atoms of ^{239}U produced per second per fission per second evaluated for the reactor composition at the time of shutdown: 0.5

t Time after shutdown [s]

In the Shure equation, there is a limitation for a cooling time after shutdown. As shown in equation (7) which is decay heat of fission product, data for these two constants of A and a are given in Table 2.1. It can be seen that the cooling time in the Shure equation is available up to 2×10^8 seconds (about 6 years). Based on this situation, the decay heat analysis using Shure equation is effective for short cooling period.

3. Calculation of decay heat for HTTR

The heat of reactor core still continues to be generated after the reactor shutdown by the decay of the radioactive materials, such as FPs, although the fission power would stop to be generated. The energy release by the FPs provides the main source of heating after the reactor shutdown. The decay heat becomes important issue for the safety analysis. In the LWRs, the standard decay heat such as the ANSI/ANS-5.1

and Shure Equation are used to analyze the characteristic of decay heat profile.

In the previous study, the library of LWRs was used to analyze the characteristics of the HTTR spent fuel. The different characteristics of the HTTR and LWRs could affect to the results of decay heat profile, radioactivity level and composition of nuclides of the spent fuel. To obtain the more reliable data of the HTTR, a new HTTR library was developed based on ORIGEN2 code.

3.1 ORIGEN2 code

ORIGEN2 is a computer code for the calculation of the buildup, the decay and the production of radioactive materials. This code was developed by the Oak Ridge National Laboratory (ORNL). The characteristics of ORIGEN2 are listed in Table 3.1. In ORIGEN2 data bases, three segments of nuclides: activation products, minor actinides and fission products are included. Total nuclides in ORIGEN2 code are around 1700 nuclides. For each of three segments, there are three different libraries: a radioactive decay data library, a cross-section and fission product yield data library, and a photon data library.

ORIGEN2 uses a matrix exponential method to solve the first-order ordinary differential equations with the constant coefficients. In general, the amount of nuclide i changes as a function of time (dX_i/dt) is described by a nonhomogeneous first-order ordinary differential equation:

$$\frac{dX_i}{dt} = \sum_{j=1}^{N} l_{ij}\lambda_j X_j + \phi \sum_{k=1}^{N} f_{ik}\sigma_k X_k - (\lambda_i + \phi\sigma_i + r_i)X_i + F_i \qquad (9)$$

$i = 1,..., N$

where

F_i Continuous feed rate of nuclide i

f_{ik} Fraction of neutron absorption by nuclide k which leads to formation of nuclide i

l_{ij} Fraction of radioactive disintegration by nuclide j which leads to formation of nuclide i

N Number of nuclides

r_i Continuous removal rate of nuclide i from the system

X_i Atom density of nuclide i

λ_j Radioactive decay constant

ϕ Position- and energy- averaged neutron flux

σ_k Spectrum averaged neutron absorption cross section of nuclide k

ORIGEN2 code uses several input and output unit to manage the files. These units and their functions are given in Table 3.2. For the basic uses of ORIGEN2 calculation, the only important units are unit 5, 6, 12 and 50, the rest of the units could be omitted.

3.2 Calculation method by new library for HTTR

In this study, the library was generated with unit pin cell models. There are two types of the new HTTR libraries were prepared:

HTTR-AC model: HTTR with actual fuel pin pitch (length of pitch cell is 5.15 cm)

- HTTR-AC model is to simulate the harder neutron spectrum.

HTTR-EQ model: HTTR with equivalent fuel pin pitch (length of pitch cell is 6.27 cm)

- Fuel pitch cell in this model is the average pitch cell over the fuel assembly. This model is assumed with extended fuel pitch to reserve the peripheral area of fuel assembly.

The data of HTTR-AC model was used for cell calculation before the test of the HTTR first criticality. When the test results of the first criticality of the HTTR were obtained, large discrepancy occurred between the equivalent model and the experimental result. On the other hand, the actual model successfully reproduced the test results. Therefore, the actual model was recommended for the criticality analysis.

In this study, these two models were used to analyze the spent fuel characteristics in the HTTR. Hence, the new HTGR library was generated for the HTTR-AC and HTTR-EQ models. Table 3.3 shows

the specification data to generate new libraries. To obtain averaged burnup characteristics, uranium enrichment of 5.9 wt% that is core averaged value, and representative fuel and moderator temperature are employed. The burnup calculations were performed using the MVP-BURN, and JENDL-4.0 was used as the nuclear data library. The maximum and average burnup of the HTTR are 33 GWd/t and 22 GWd/t, respectively. Therefore, the reactor specific power to generate new library was set to 33.3 MW/t to achieve average burnup of 22 GWd/t in burnup period of 660 days. The methodology[7] to generate the new HTTR library is shown in Fig 3.1.

As shown in Fig 3.1, two types of cross section were necessary to prepare for each HTTR library. The effective cross section is one energy group cross section that is obtained from the MVP-BURN calculation. Infinite dilution cross section is one energy group cross section that is obtained from the NJOY code calculation. In this study, the decay heat analysis for the HTTR-AC and HTTR-EQ models were performed using the new HTTR library by varying the period of cooling time.

4. Results and discussions

4.1 Calculation of burnup

The burnup calculations were performed for the HTTR-AC and HTTR-EQ models in a pin cell model using MVP-BURN. The difference between these two libraries is the length of fuel pin pitch. The fuel pin pitch in the HTTR-EQ model is longer than the HTTR-AC model. The burning period of 660 days was achieved to obtain average burnup of 22 GWd/t. Fig. 4.1 shows the burnup and effective multiplication factor (k_{eff}) profile of the HTTR.

It can be seen that k_{eff} of the HTTR-EQ model is higher than the HTTR-AC model, because there is more graphite in the HTTR-EQ model. It makes more neutrons from the fast region moderated to thermal region. Thus, more neutrons in the thermal region increase the number of fission in the HTTR-EQ model.

4.2 Calculation of decay heat

Decay heat analysis for the HTTR was obtained using the new HTTR library to analyze the difference of decay heat profile between the libraries of LWRs library and that of the HTTR. In this study, the decay heat profiles using the new HTTR library and LWRs library are compared in Fig. 4.2a, Fig. 4.2c and Fig. 4.2d. These figures show the time history of decay heat by increasing the period of cooling time. There are 4 decay heat profiles in each figure; the HTTR-AC and HTTR-EQ models are the decay heat profile with the new HTTR library. The ANSI and Shure are the decay heat profile with the LWRs library. It can be seen that at the beginning of cooling time, the HTTR-AC model has the highest decay heat. However, by increasing the cooling period up to 4 years, decay heat using the Shure equation shows the highest value of decay heat as can be seen in Fig. 4.2d.

The smallest discrepancy between the HTTR library and LWRs library was occurred when the cooling period is less than 12 month as presented in Fig. 4.2b due to the lowest probability of uncertainty. However, as the period of cooling time increases, the probability of uncertainty becomes larger in ANSI and Shure equation. Moreover, the difference between the HTTR library and LWRs library comes from the number of nuclides. In case of the HTTR library, it includes the nuclides which have the short and long half-life. Nevertheless, in the ANSI and Shure, only consider some nuclides such as ^{235}U, ^{239}Pu, ^{241}Pu, the fast fission of ^{238}U for fission, and ^{239}U, ^{239}Np for the minor actinide.

4.3 Important nuclides for decay heat

In this study, the decay heat analyses were performed for the HTTR using the new HTTR library. The FPs and MAs are the main contribution to decay heat profile. In the early stage, The FPs has a significant contribution to the decay heat profile. Fig. 4.3 shows the fraction of decay heat in the HTTR-AC and HTTR-EQ models. The dominant contribution of the FPs to the decay heat in the HTTR-AC and HTTR-EQ models occurred for 60 and 75 years of cooling period, respectively. Thus, the dominant contribution of MAs to the decay heat occurred for the cooling period more than 60 and 75 years for the

HTTR-AC and HTTR-EQ models, respectively.

As presented in Fig. 4.3, the decay heat fraction of FPs of the HTTR-EQ model is higher than that of the HTTR-AC model, because the neutron spectrum in the HTTR-EQ model is softer and it makes more thermal neutron. Consequently, the fraction of FPs of the HTTR-EQ model becomes higher than of the HTTR-AC model. On the other hand, the decay heat fraction of MAs in the HTTR-EQ model is smaller than that of the HTTR-AC model. Soft neutron spectrum in the HTTR-EQ model increases the fission cross section, and the neutron absorption of ^{238}U in HTTR-EQ model becomes lower consequently. Therefore, the amount of MAs in the HTTR-EQ model becomes lower than of the HTTR-AC model.

The important nuclides of the FPs and MAs are given in Table 4.1a and 4.1b, respectively. Table 4.1a shows the decay heat ranking of the FPs in HTTR for a short cooling period (10 days, 40 days, 2 years, and 5 years). In case of 10-day cooling, ^{140}La, ^{144}Pr, ^{95}Nb, and ^{95}Zr have the dominant contribution to FPs. Increasing the period of cooling time up to 5 years, the composition of FPs changed. ^{90}Y, ^{137m}Ba, ^{144}Pr and ^{106}Rh are the nuclides which have significant contribution to the FPs.

The significant contribution of MAs to decay heat can be seen in a long cooling period. The contributions of MAs are shown in Table 4.1b and Fig. 4.4. Table 4.1b shows that ^{241}Am has a dominant contribution around 77.7% to the decay heat distribution in a long cooling period. Fig. 4.4b shows the contribution of ^{241}Am ($t_{1/2}$ = 432 years) relatively stable after 60 years of the cooling period.

4.4 Important nuclides for radioactivity

Radioactivity levels of important nuclides are given in Table 4.2a and 4.2b for the FPs and MAs, respectively. Data of the radioactive levels are presented for the short and long cooling periods. Table 4.2a shows the radioactivity level of FPs. It can be seen that ^{95}Nb, ^{95}Zr, ^{144}Pr, and ^{144}Ce are dominant nuclides to the radioactivity level up to 40 days, and decrease rapidly because the most of the FPs have short half-life value. For a long cooling period up to 150 years, the radioactivity level of ^{137}Cs, ^{137m}Ba, ^{90}Sr, ^{90}Y, and ^{99}Tc become more significant. Table 4.2b shows the radioactivity level of the MAs. In case of 5 years

cooling, ^{241}Pu remain as the highest radioactivity level. Thus, for a long cooling period up to 150 years, the contributions of ^{241}Am, ^{240}Pu and ^{239}Pu to the radioactivity level become more dominant.

5. Conclusions

The calculation of decay heat for the HTTR was performed using the new HTTR Library. There are two types of library for the HTTR which are the HTTR-AC and HTTR-EQ models. The main difference between these two libraries is the fuel pin pitch. The HTTR-EQ model has a longer fuel pin pitch than the HTTR-AC model. Decay heat calculations were performed using ORIGEN2 code by varying the period of cooling time.

The calculation of decay heat for the HTTR was performed not only by using the new HTTR library but also using the LWRs data library (ANSI and Shure equation). The objective is to find out the difference between the LWRs and HTTR library. There is a limitation in the LWRs case (ANSI and Shure equation) which is the limitation of cooling period, 8×10^{9}s and 2×10^{8}s, respectively. In this study, it is clear that the calculated decay heats are similar value with LWRs for about one year after the reactor shutdown and the large discrepancies between the LWRs and HTTR libraries occurred for a long cooling period are observed, because the uncertainty in the LWRs libraries increases. Besides, the LWRs libraries only consider for the long half-life of nuclides. However, a new HTTR library considers not only long half-life but also short half-life nuclides.

In this study, the FPs have a dominant effect to the decay heat up to 60 years and 75 years for the HTTR-AC and HTTR-EQ models, respectively. Afterwards, for the cooling period more than 75 years, the MAs have a significant contribution to the decay heat distribution. In the beginning, ^{90}Y, ^{134}Cs, ^{144}Pr and ^{106}Rh have a significant contribution to decay heat. However, for a long cooling period, ^{241}Am has a dominant effect to decay heat. In case of the radioactivity level, ^{241}Pu has a contribution at the early stage and for a long cooling period, ^{241}Am, ^{240}Pu and ^{239}Pu are the dominant for the radioactivity level.

In the near future, the first loaded fuel of the HTTR will be discharged and replaced with the secondary core. The results of this study are necessary to give some information about the composition and characteristics of the HTTR spent fuels.

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Table 1.1 Major specifications of HTTR [2)]

Item	Value
Thermal power	30 MWt
Outlet coolant temperature	950 °C
Inlet coolant temperature	395 °C
Primary coolant pressure	4 MPa
Core Structure	Graphite
Equivalent core diameter	2.3 m
Effective core height	2.9 m
Average power density	2.5 W/cm^3
Fuel	UO_2
Uranium enrichment	3-10 wt % (average 6 wt %)
Type of fuel	Pin-in-block
Coolant material	Helium gas
Flow direction in core	Downward
Reflector thickness	
Top	1.16 m
Side	0.99 m
Bottom	1.16 m
Number of fuel assembly	150
Number of fuel columns	30
Number of pairs in control rods	
In core	7
In reflector	9

Table 1.2 Fuel Assembly specifications of HTTR [2)]

Item	Specification
Graphite Block	
Material	IG-110 graphite
Width across flats (cm)	36
Height (cm)	58
Density (g/cm^3)	1.75
Impurity (ppm)	< 1 (boron equivalent)
Fuel rod	
Outer diameter (cm)	3.4
Length (cm)	54.6
Number of fuel compact	14
Fuel compact	
Outer diameter (cm)	2.6
Inner diameter (cm)	1.0
Length (cm)	3.9
Packing fraction of CFPs (vol. %)	30
Coated Fuel Particle (CFP)	
Diameter of UO_2 kernel (μ m)	600
Thickness of buffer layer (μ m)	60
Thickness of IPyC layer (μ m)	30
Thickness of SiC layer (μ m)	25
Thickness of OPyC layer (μ m)	45
Diameter of CFP (μ m)	920

Table 2.1 Constant for *A* and *a* of fission product decay heat in Shure Equation [5)]

Applicable Time Interval [s]*	*A*	*a*
$10^{-1} \leq t < 10^{1}$	12.05	0.0639
$10^{1} \leq t \leq 1.5 \times 10^{2}$	15.31	0.1807
$1.5 \times 10^{2} < t < 4 \times 10^{6}$	26.02	0.2834
$4 \times 10^{6} \leq t \leq 2 \times 10^{8}$	53.18	0.3350

* The value of *A* and *a* obtained by D.J. Dudziak (private communication)

Table 3.1 Nuclear material characteristics computed by ORIGEN code [6)]

Parameter	Units
Mass	gram, gram.atom
Fractional isotopic composition (each element)	Atomic fraction, weight fraction
Radioactivity	Ci, αCi
Thermal power	Watt
Toxicity	
Radioactive and chemical ingestion	m^3 of water to dilute to acceptable levels
Radioactive inhalation	m^3 of air to dilute to acceptable levels
Neutronics	
Neutron absorption rate	n/s
Fission rate	fission/s
Neutron emission	
Spontaneous fission	n/s
(α,n)	n/s
Photon emission	
Number of photons in 18 energy groups	Photon/s, MeV of photon/W of reactor power
Total heat	W, MeV/s

Table 3.2 Description of ORIGEN2 code input/output units [6)]

Unit Number	Description
3	Substitute data for decay and cross section libraries (specified by LIB)
4	Alternate unit for reading material compositions
5	Card reader (specified in MAIN in call to LISTIT)
6	Principal output unit; usually directed to line printer (specified in BLOCK DATA, variables = IOUT, JOUT, KOUT)
7	Unit to write an output vector (used by PCH command)
9	Decay and cross section library (specified by LIB command)
10	Photon library (specified by PHO command)
11	Alternate output unit, usually directed to line printer
12	Table of contents for unit 6 above, usually directed to line printer (specified in BLOCK DATA, variables = NTOCA)
13	Table of contents for unit 11, usually directed to line printer (specified in BLOCK DATA, variables = NTOCB)
15	Print debugging information
16	Print variable cross section information
50	Data set used to temporarily store input read on unit 5 (specified in BLOCK DATA, variables = IUNIT)

Table 3.3 Specification data to obtain new HTTR library

Parameter	Value
Fuel	UO_2
Average Uranium Enrichment	5.9 wt%
Reactor Specific Power	33.3 MW/t
Fuel Temperature	1260 K
Moderator Temperature	1000 K

Table 4.1a Ratio of decay heat each fission products in HTTR

Fission Products (FAs)	Cooling time							
	10 days		40 days		2 years		5 years	
	AC	EQ	AC	EQ	AC	EQ	AC	EQ
^{85}Kr	-	-	-	-	0.3%	0.3%	0.9%	0.9%
^{89}Sr	4.0 %	4.4%	5.0%	5.5%				
^{90}Sr	-	-	-	-	1.8%	2.1%	5.9%	6.4%
^{90}Y	-	-	-	-	8.8%	9.9%	27.9%	30.7%
^{91}Y	5.5%	5.9%	7.3%	7.9%				
^{95}Nb	10.7%	11.0%	18.1%	18.7%	0.2%	0.2%	-	-
^{95}Zr	10.1%	10.5%	13.9%	14.4%	0.1%	0.1%	-	-
^{103}Ru	5.2%	4.8%	5.9%	5.3%	-	-	-	-
^{106}Ru	-	-	-	-	0.2%	0.1%	0.1%	0.1%
^{106}Rh	4.6%	3.7%	8.2%	6.6%	25.2%	21.3%	11.2%	9.3%
^{125}Sb	-	-	-	-	0.3%	0.3%	0.5%	0.5%
^{131}I	1.9%	1.9%	0.3%	0.3%	-	-	-	-
^{132}I	3.5%	3.5%	-	-	-	-	-	-
^{134}Cs	-	-	-	-	8.5%	6.4%	10.6%	7.8%
^{137}Cs	-	-	-	-	2.3%	2.4%	7.3%	7.5%
^{140}La	25.5%	25.8%	9.5%	9.6%	-	-	-	-
^{140}Ba	3.9%	3.9%	1.4%	1.5%	-	-	-	-
^{141}Ce	2.6%	2.6%	1.0%	1.1%	-	-	-	-
^{143}Pr	2.5%	2.6%	1.0%	1.1%	-	-	-	-
^{144}Pr	11.0%	11.4%	19.4%	20.0%	40.1%	43.8%	9.6%	10.3%
^{144}Ce	1.0%	1.0%	1.7%	1.8%	3.6%	3.9%	0.9%	0.9%
^{147}Nd	1.1%	1.1%	0.3%	0.3%	-	-	-	-
^{147}Pm	-	-	-	-	1.2%	1.3%	1.8%	2.0%
^{154}Eu	-	-	-	-	0.4%	0.3%	1.2%	0.8%

Table 4.1b Ratio of decay heat each minor actinides in HTTR

Minor Actinides (MAs)	Cooling Time			
	5 years		150 years	
	AC	EQ	AC	EQ
^{238}Pu	18.3%	17.2%	3.3%	3.1%
^{239}Pu	19.22%	17.9%	10.6%	10%
^{240}Pu	15.1%	21.3%	8.3%	11.8%
^{241}Pu	3.7%	3.6%	-	-
^{241}Am	39.7%	37.6%	77.7%	74.9%
^{242}Cm	0.5%	0.5%	-	-
^{244}Cm	3.2%	1.8%	-	-

Table 4.2a Ratio of radioactivity each fission products in HTTR

Fission Products (FAs)	Cooling time							
	10 days		40 days		2 years		5 years	
	AC	EQ	AC	EQ	AC	EQ	AC	EQ
^{85}Kr	-	-	-	-	0.7%	0.8%	1.6%	1.7%
^{89}Sr	4.9%	5.3%	5.6%	6.2%	-	-	-	-
^{90}Sr	-	-	-	-	5.6%	6.1%	14.5%	15.3%
^{90}Y	-	-	-	-	5.6%	6.1%	14.5%	15.3%
^{91}Y	6.4%	6.9%	7.8%	8.5%	-	-	-	-
^{95}Nb	9.4%	9.7%	14.7%	15.1%	0.1%	0.1%	-	-
^{95}Zr	8.5%	8.7%	10.7%	11.1%	0.1%	0.1%	-	-
^{103}Ru	6.6%	6.0%	6.8%	6.2%	-	-	-	-
^{103m}Rh	6.6%	6.0%	6.8%	6.2%	-	-	-	-
^{106}Ru	2.0%	1.6%	3.3%	2.7%	9.4%	7.7%	3.4%	2.7%
^{106}Rh	2.0%	1.6%	3.3%	2.7%	9.4%	7.7%	3.4%	2.7%
^{125}Sb	-	-	-	-	0.4%	0.3%	0.5%	0.4%
^{125m}Te	-	-	-	-	0.1%	0.1%	0.2%	0.2%
^{131}I	2.4%	2.3%	0.3%	0.3%	-	-	-	-
^{133}Xe	3.7%	3.6%	0.1%	0.1%	-	-	-	-
^{134}Cs	-	-	-	-	3.0%	2.1%	3.0%	2.1%
^{137}Cs	-	-	-	-	7.3%	7.4%	18.7%	18.7%
^{137m}Ba	-	-	-	-	6.9%	7.0%	17.7%	17.6%
^{140}La	6.4%	6.5%	2.2%	2.2%	-	-	-	-
^{140}Ba	5.6%	5.6%	1.9%	1.9%	-	-	-	-
^{141}Ce	7.4%	7.5%	6.8%	6.9%	-	-	-	-
^{143}Pr	5.6%	5.8%	2.1%	2.2%	-	-	-	-
^{144}Pr	6.3%	6.5%	10.3%	10.6%	19.6%	20.6%	3.8%	3.9%
^{144}Ce	6.3%	6.5%	10.3%	10.6%	19.6%	20.6%	3.8%	3.9%
^{147}Nd	1.9%	1.9%	0.5%	0.5%	-	-	-	-
^{147}Pm	1.1%	1.1%	1.8%	2.0%	14.4%	12.5%	14.3%	15.2%
^{154}Eu	-	-	-	-	0.2%	0.1%	0.4%	0.2%
^{155}Eu	-	-	-	-	0.1%	0.1%	0.2%	0.2%

Table 4.2b Ratio of radioactivity each minor actinides in HTTR

Minor Actinides (MAs)	Cooling time			
	5 years		150 years	
	AC	EQ	AC	EQ
^{238}Pu	0.4%[a]	0.4%	3.2%	3%
^{239}Pu	0.5%	0.5%	11%	10.4%
^{240}Pu	0.4%	0.6%	8.5%	12.2%
^{241}Pu	97.6%	97.5%	1.9%	1.8%
^{241}Am	1%	1%	75.1%	72.3%

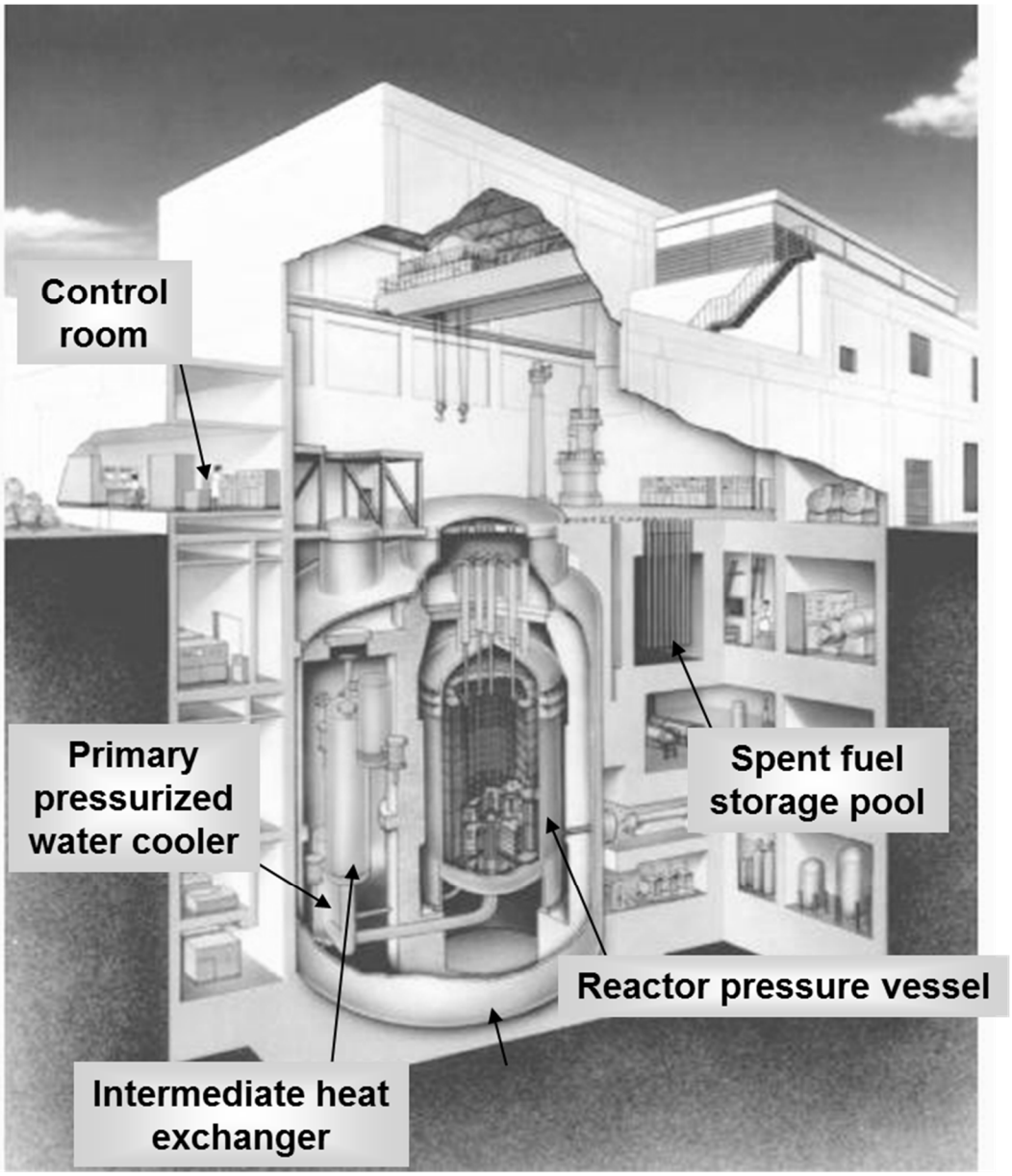

Fig. 1.1 Reactor Building of HTTR

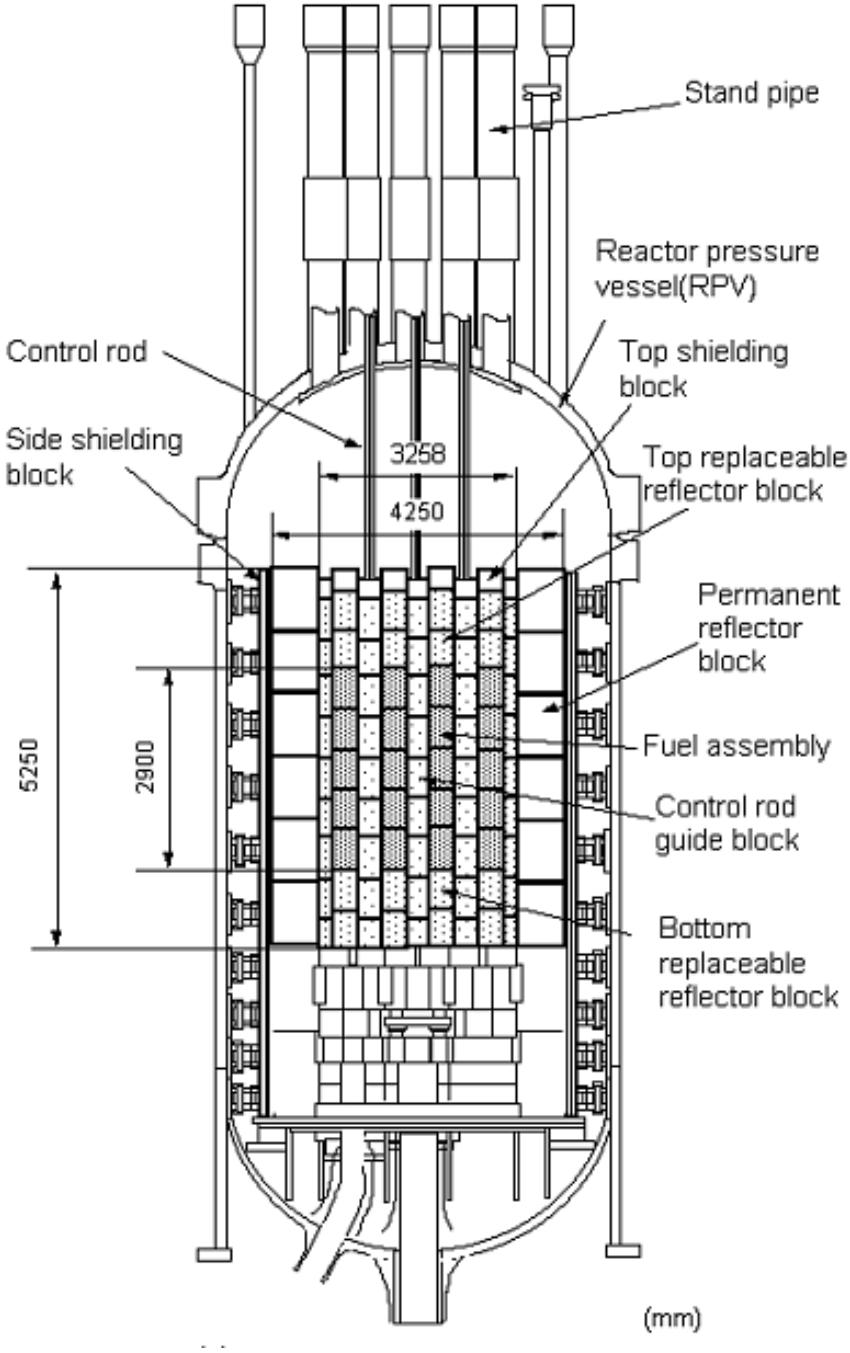

Fig. 1.2 Vertical view of HTTR [2)]

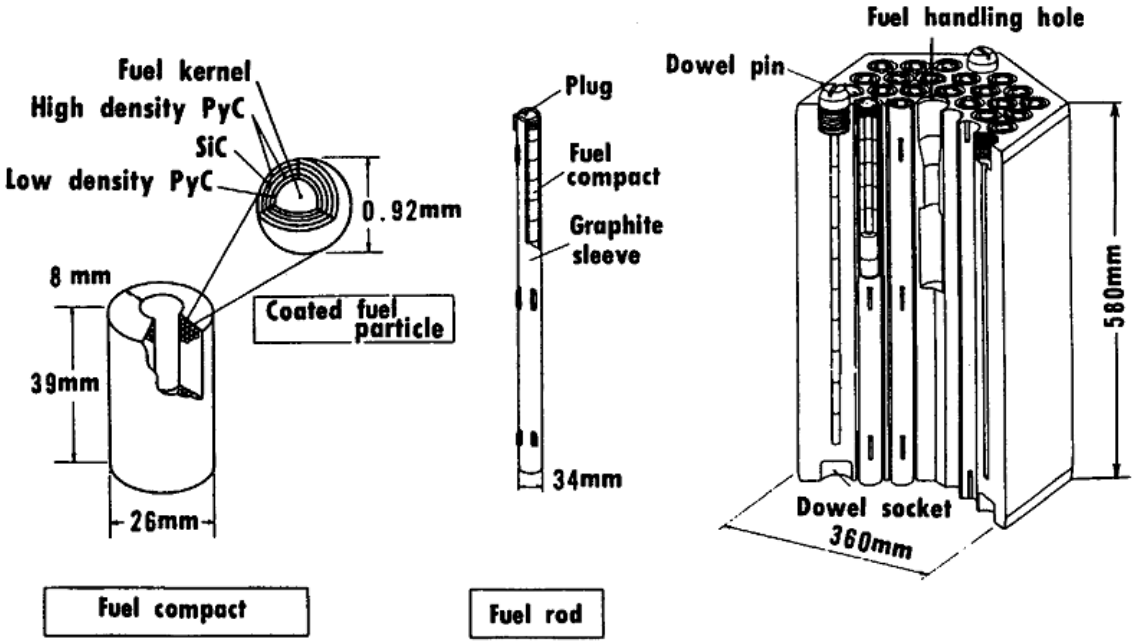

Fig. 1.3 Fuel assembly of HTTR [2)]

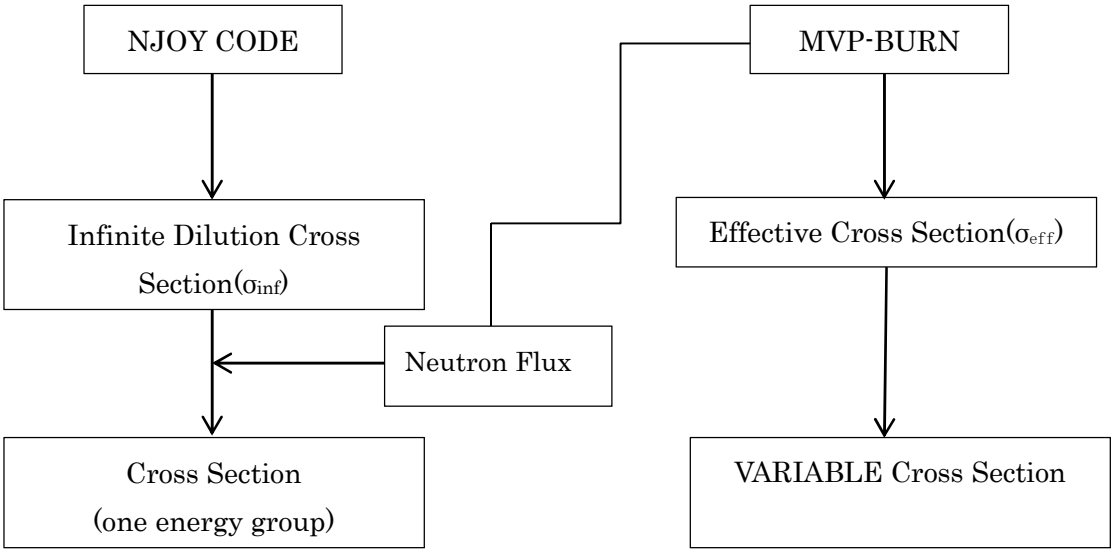

Fig 3.1 Flowchart to generate new HTTR Library

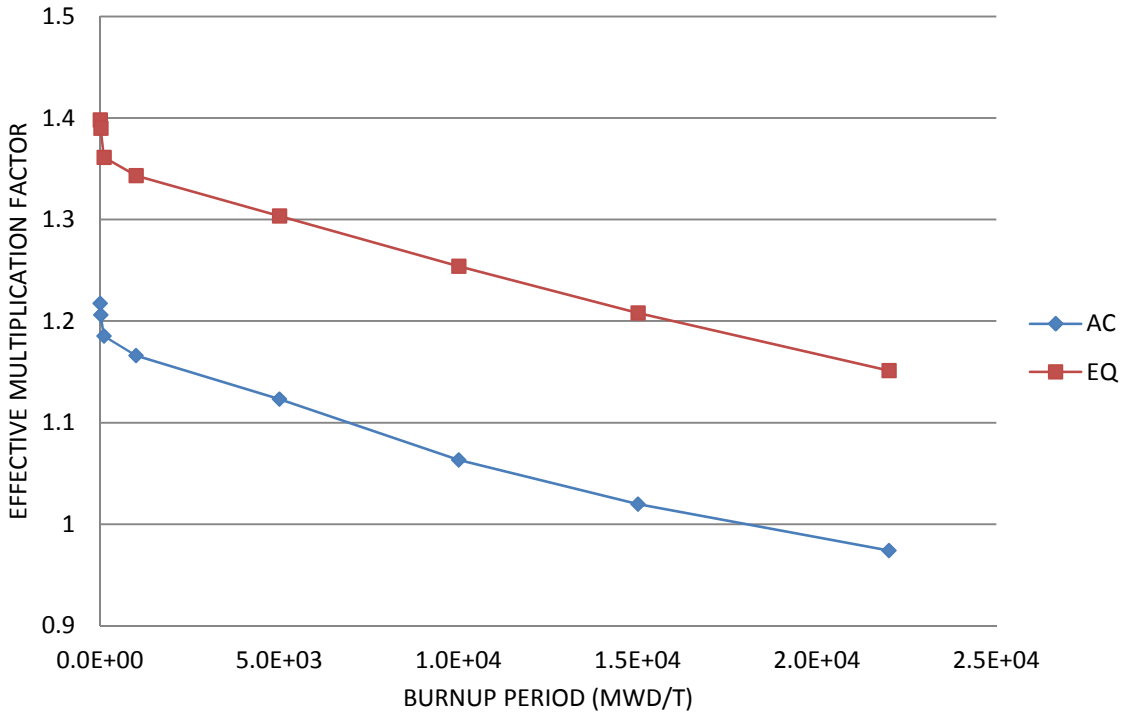

Fig. 4.1 Effective multiplication factor of HTTR-AC and HTTR-EQ

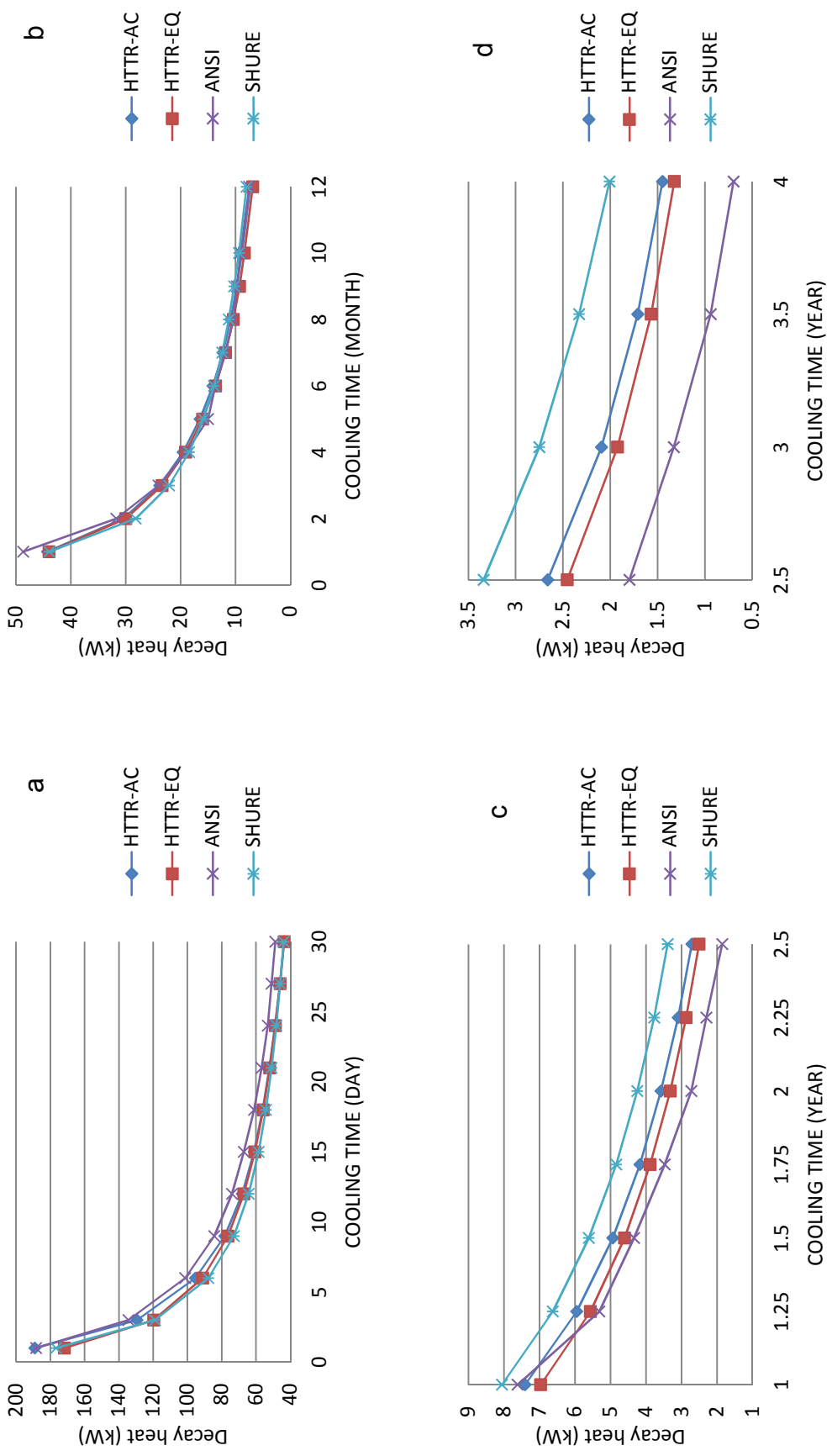

Fig. 4.2 Comparison of decay heat in HTTR by using new HTTR Library and LWRs Library

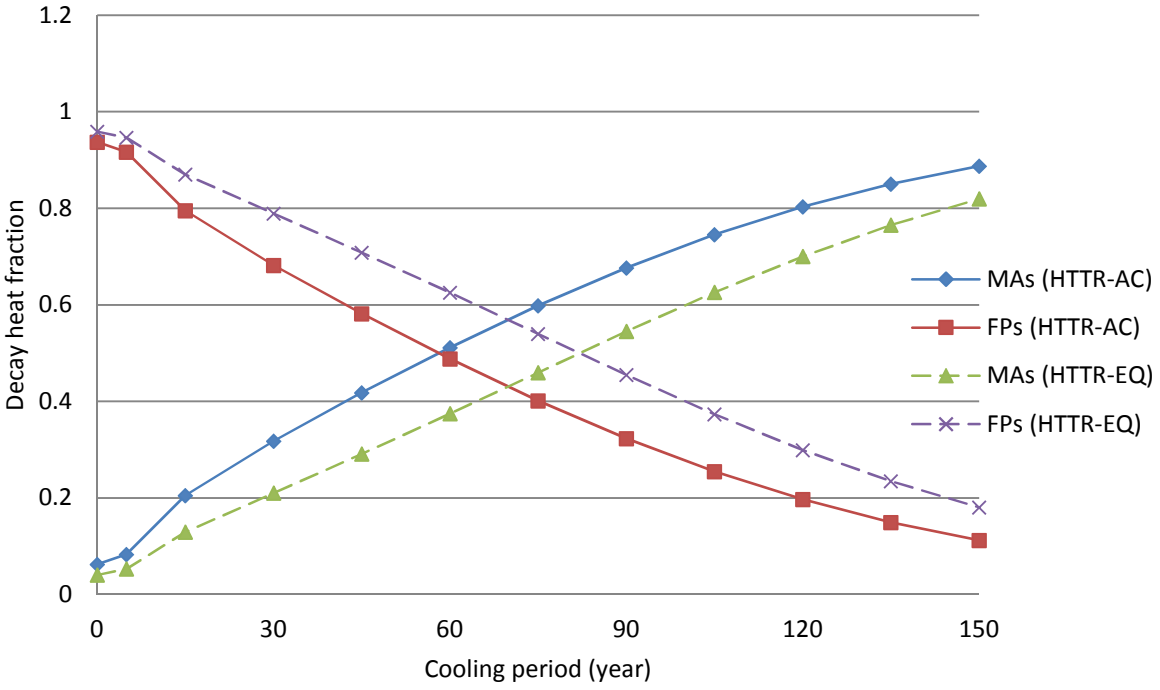

Fig. 4.3 Decay heat fraction of FPs and MAs in HTTR-AC and HTTR-EQ model

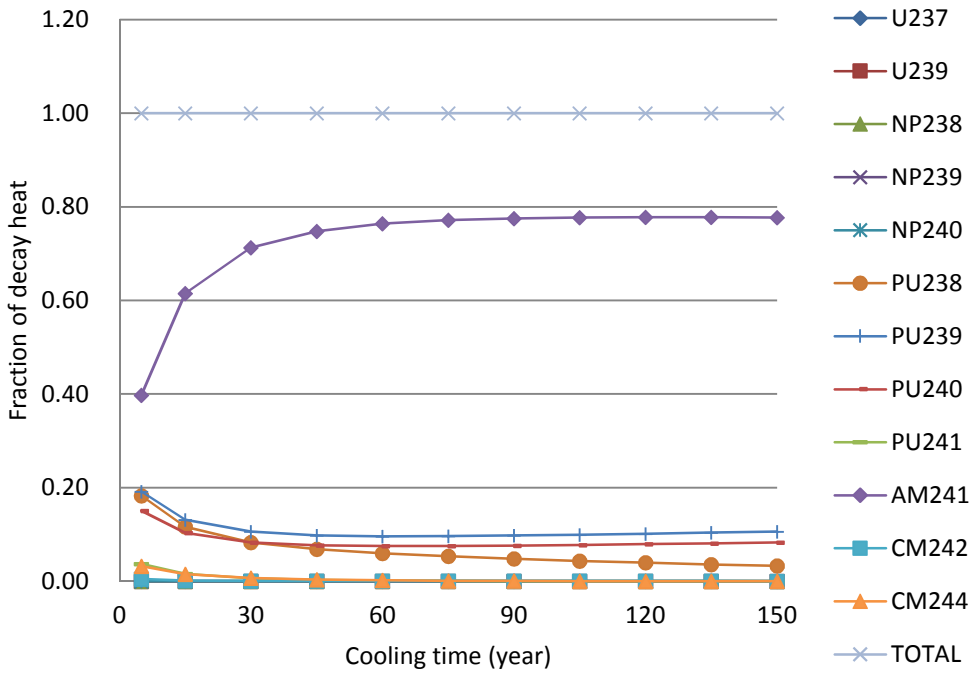

Fig. 4.4 Decay heat fraction of HTTR-AC model for a long cooling period

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の） 1	1
比透磁率(b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^2/m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		m kg s^{-2}
圧力，応力	パスカル	Pa	N/m^2	m^{-1} kg s^{-2}
エネルギー，仕事，熱量	ジュール	J	N m	m^2 kg s^{-2}
仕事率，工率，放射束	ワット	W	J/s	m^2 kg s^{-3}
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	m^2 kg s^{-3} A^{-1}
静電容量	ファラド	F	C/V	m^{-2} kg^{-1} s^4 A^2
電気抵抗	オーム	Ω	V/A	m^2 kg s^{-3} A^{-2}
コンダクタンス	ジーメンス	S	A/V	m^{-2} kg^{-1} s^3 A^2
磁束	ウエーバ	Wb	Vs	m^2 kg s^{-2} A^{-1}
磁束密度	テスラ	T	Wb/m^2	kg s^{-2} A^{-1}
インダクタンス	ヘンリー	H	Wb/A	m^2 kg s^{-2} A^{-2}
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量，比エネルギー分与，カーマ	グレイ	Gy	J/kg	m^2 s^{-2}
線量当量，周辺線量当量，方向性線量当量，個人線量当量	シーベルト(g)	Sv	J/kg	m^2 s^{-2}
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号radおよびsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	m^{-1} kg s^{-1}
力のモーメント	ニュートンメートル	N m	m^2 kg s^{-2}
表面張力	ニュートン毎メートル	N/m	kg s^{-2}
角速度	ラジアン毎秒	rad/s	m m^{-1} s^{-1}=s^{-1}
角加速度	ラジアン毎秒毎秒	rad/s^2	m m^{-1} s^{-2}=s^{-2}
熱流密度，放射照度	ワット毎平方メートル	W/m^2	kg s^{-3}
熱容量，エントロピー	ジュール毎ケルビン	J/K	m^2 kg s^{-2} K^{-1}
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	m^2 s^{-2} K^{-1}
比エネルギー	ジュール毎キログラム	J/kg	m^2 s^{-2}
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	m kg s^{-3} K^{-1}
体積エネルギー	ジュール毎立方メートル	J/m^3	m^{-1} kg s^{-2}
電界の強さ	ボルト毎メートル	V/m	m kg s^{-3} A^{-1}
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} s A
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} s A
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} s A
誘電率	ファラド毎メートル	F/m	m^{-3} kg^{-1} s^4 A^2
透磁率	ヘンリー毎メートル	H/m	m kg s^{-2} A^{-2}
モルエネルギー	ジュール毎モル	J/mol	m^2 kg s^{-2} mol^{-1}
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	m^2 kg s^{-2} K^{-1} mol^{-1}
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} s A
吸収線量率	グレイ毎秒	Gy/s	m^2 s^{-3}
放射強度	ワット毎ステラジアン	W/sr	m^4 m^{-2} kg s^{-3}=m^2 kg s^{-3}
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2$ sr)	m^2 m^{-2} kg s^{-3}=kg s^{-3}
酵素活性濃度	カタール毎立方メートル	kat/m^3	m^{-3} s^{-1} mol

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 hm^2=10^4m^2
リットル	L, l	1 L=1 l=1 dm^3=10^3cm^3=$10^{-3}m^3$
トン	t	1 t=10^3 kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1 Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^5Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^2=(10^{-12}cm)^2=$10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1cm^2 s^{-1}=$10^{-4}m^2$ s^{-1}
スチルブ	sb	1 sb =1cd cm^{-2}=10^4cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^4lx
ガル	Gal	1 Gal =1cm s^{-2}=$10^{-2}ms^{-2}$
マクスウエル	Mx	1 Mx = 1G cm^2=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(a)	Oe	1 Oe ≙ (10^3/4π)A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ=1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	μ	1 μ =1μm=10^{-6}m

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