DECAY HEAT CONDITIONS OF CURRENT AND NEXT GENERATION REACTORS

A Senior Scholars Thesis

by

JONGSOO L. CHOE

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Nuclear Engineering

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Approved by:

Research Advisor:	Pavel V. Tsvetkov
Associate Director, Honors and Undergraduate Research:	Duncan MacKenzie

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ABSTRACT

Decay Heat Conditions of Current and Next Generation Reactors. (May 2012)

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Decay heat is an important parameter in reactor design. Fission products generate heat in the reactor core even when the reactor has shut down. This heat has potential to melt the core if heat removal is not sufficient, and it is what caused the accident in Japan last year. Thus, decay heat must be considered in reactor design for safety. The research focused on decay heat conditions of current and next generation reactors. US-APWR, ABWR, VHTR, and ABR were modeled and simulated using the program SCALE. When the reactors were simulated to operate for two years and cool down for one year, the ABR produced the most decay heat power during operation and cooling time, and the US-APWR, VHTR, and ABWR followed respectfully. Therefore, the ABR requires more coolant and cooling time than other reactors, and the ABWR requires the least.

ACKNOWLEDGMENTS

I thank Dr. Tsvetkov for advising me on this research and teaching me program SCALE through the class last semester. I also thank Pedro and Jonathan for correcting grammar.

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CHAPTER I

INTRODUCTION

Since the Fukushima nuclear disaster in Japan, the safety of nuclear reactors has come into question now more than ever. When the earthquake occurred, the power plants were shut down immediately (SCRAM), and emergency diesel generators began to power the plant's cooling and control systems. However, the earthquake was followed by a tsunami, inundating the generators causing them to fail, and this led to a meltdown (Fukushima Daiichi nuclear disaster, 2011).

Decay heat

Decay heat energy is unavoidable in nuclear reactors. Nuclear reactors generate electricity from fission of heavy nuclides which produce fission fragments. These fission fragments are highly unstable; therefore they decay releasing alpha and beta particles, and gamma rays. These fission products remain in the fuel and increase the temperature of the reactor core even after the reactor has been shut down. This decay heat caused the accident in Fukushima, and thus this must be understood well for safety.

This thesis follows the style of Journal of Progress in Nuclear Energy.

Reactors

This research analyzes decay heat conditions of current and Next Generation Reactors. The reactors the research focused on were the US-APWR, ABWR, VHTR and SFR. Each was compared with respect to decay heat conditions and coolant required. Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) are currently the only commercialized reactors in the United States. Generation IV nuclear plants (VHTR, SFR, LFR, MSR, etc) will provide future nuclear energy in a few decades. The Advanced Pressurized Water Reactor (APWR) is a generation III nuclear reactor developed by Mitsubishi Heavy Industries based on the older PWR design. The US-APWR is a modified APWR to comply with US regulations. Texas Utilities (TXU) decided to build the US-APWR for Comanche Peak units 3 and 4 (Comanche Peak Nuclear Power Plant, 2011). Similarly, the Advanced Boiling Water Reactor (ABWR) is a generation III nuclear reactor developed by GE Hitachi Nuclear Energy (GEH) and Toshiba based on the older BWR design. South Texas Project (STP) selected the ABWR for its units 3 and 4, but the project was recently canceled (Advanced boiling water reactor, 2011). Very High Temperature Reactors (VHTR) are a thermal neutron spectrum reactor. Its high coolant outlet temperatures enable high efficiency and hydrogen production. Its fuel design is inherently safe with no possibility of core melting. It has advantages of higher efficiency, potential for lower waste inventories, and process heat application. The United States Department of Energy (DOE) has determined that the VHTR will be the Next Generation Nuclear Plant (NGNP). The DOE expects to operate the VHTR by 2021 (NGNP, A Report to Congress, 2008). Advanced Burner

Reactors (ABR) are Sodium-Cooled Fast Reactors (SFR) which are fast neutron spectrum and closed fuel cycle system reactors. Its management of actinides and conversion of fertile uranium is efficient. It is strong in sustainability with lower waste (INL: SFR, 2012).

CHAPTER II

METHODS

Design parameters such as active fuel height, number of fuel and control rods, rod and assembly pitches, compositions, and component dimensions for four types of reactors were collected from databases hosted by the U.S. Nuclear Regulatory Commission (NRC), International Atomic Energy Agency (IAEA), DOE, and open internet sources. Then the reactor models were developed by using the SCALE program.

Scale

"The scale code system is a comprehensive modeling and simulation suite for nuclear safety analysis and design that is developed, maintained, tested, and managed by the Reactor and Nuclear Systems Division (RNSD) of Oak Ridge National Laboratory (ORNL)." Scale has 89 computational modules including 3 deterministic and 3 Monte Carlo radiation transport solvers. These modules are selected based on the user's desired solution strategy. "Scale includes current nuclear data libraries and problem-dependent processing tools for continuous-energy and multigroup neutronics calculations, multigroup coupled neutron-gamma calculations, as well as activation and decay calculations." Scale provides graphical user interfaces to make it easy to use, and also it can plot three-dimensions of the model which helps the user acquire desired results (ORNL, 2011).

Analysis

In order to simulate the reactor models, Scale requires user inputs including averaged power, irradiation time, and the time after the reactor shutdown. The output file of scale contains change of compositions of the fuel and criticality during reactor operations. The compositions of the fuel in the reactors are changed due to fission, neutron capture, and decay. Scale provides the compositions in terms of how much power was produced. These powers indicate the production of the decay heat. The nuclides of interest were selected from decay heat study by NRC (Gauld et al., 2000).

Design parameters

The operation power of the US-APWR is 4451 MWth. Its core diameter is 3.88 m and has a height of 4.2 m. It has a square pitch with 17 x 17 arrays. Each assembly has 264 fuel rods, and there are 257 assemblies in the core. It uses enriched uranium dioxide(UO_2) less than 5 wt% and gadolinia-uranium dioxide(Gd,UO_2). The cladding material is ZIRLO which is a zirconium based alloy for improved corrosion resistance (US-APWR, 2011).

The operation power of the ABWR is 3926 MWth. Its core diameter is 5.16 m and has a height of 3.71 m. It has a square pitch with 10 x 10 arrays. Each assembly has 92 fuel rods, and there are 872 assemblies in the core. It uses three different levels of enriched uranium dioxide(UO_2) which are 3.18, 2.18, and 1.23 wt%. For simplicity, only 3.18 wt% was used in this study. The cladding material is Zircaloy-2 which is also a zirconium based alloy for improved corrosion resistance (ABWR Plant General Description, 2006).

Unlike light water reactors, the VHTR uses Helium as a coolant. Its high outlet temperature, 1000 ^{o}C, is favorable for the production of hydrogen. The reactor produces 600 MWth, and its core diameter is 4.82 m and has a height of 7.93 m. It has 102 fuel columns and 10 blocks per column. Each column has 216 fuel holes (Very High temperature Gas Reactor, 2009). VHTR uses two types of TRISO fuels. Both fuels are spherical pellets. One contains fissile particles made of 19.9 % enriched uranium oxycarbide (UCO) and the other is made of fertile particles containing natural uranium oxycarbide ($U_{nat}CO$). Only fissile fuel was used in this study for simplicity. The fuel kernel has UCO at the center. That core is then surrounded by a 35 μm layer of PyC. Then it is covered again by a 35 μm layer of SiC. Finally it is covered again with a 40 μm layer of PyC (IAEA, 2012).

The ABR's operation power is 250 MWth. Sodium is used for its coolant. The core diameter is 2.27 m and has a height of 2.6 m. It has 210 fuel rods per assembly and there are 54 assemblies. Inner and outer core fuel enrichments (^{239}Pu) are 16.5 and 20.7% respectively. ^{239}Pu was used for fissile materials and ^{238}U for fertile which becomes ^{239}Pu during operation. A material called HT9, 12% Cr ferritic-martensitic steel, was used for cladding (Cahalan et al., 2006).

Collected reactor design parameters are summarized in Table 1.

Table 1

Reactor Core design parameters.

	US-APWR	ABWR	VHTR	ABR
Power (MW)	4451	3926	600	250
Core Diameter (m)	3.88	5.16	4.82	2.27
Core Height (m)	4.2	3.71	7.93	2.6
Number of fuel assemblies	257	872		54
rod array	17 x 17	10 x 10		
rods per assembly	264	92	216	210
Number of fuel columns			102	
Number of fuel blocks per column			10	
rod pitch (cm)	1.259	1.63	1.836	0.908
pitch	square	square	triangular	triangular
fuel rod diameter (cm)	0.949	1.23	1.27	0.603
Cladding material	ZIRCO	Zircaloy-2	Graphite	HT9
Cladding Thickness (cm)	0.0569	0.086	0.165	0.052
Fuel enrichment	MAX 5 wt%	3.18 wt %	19.9 wt%	^{239}Pu 16.5 wt%, 20.7 wt%
Coolant	H_2O	H_2O	He	Na

CHAPTER III

RESULTS

US-APWR core design

The US-APWR was modeled using Table 1, and its fuel assembly is shown in Fig. 1.

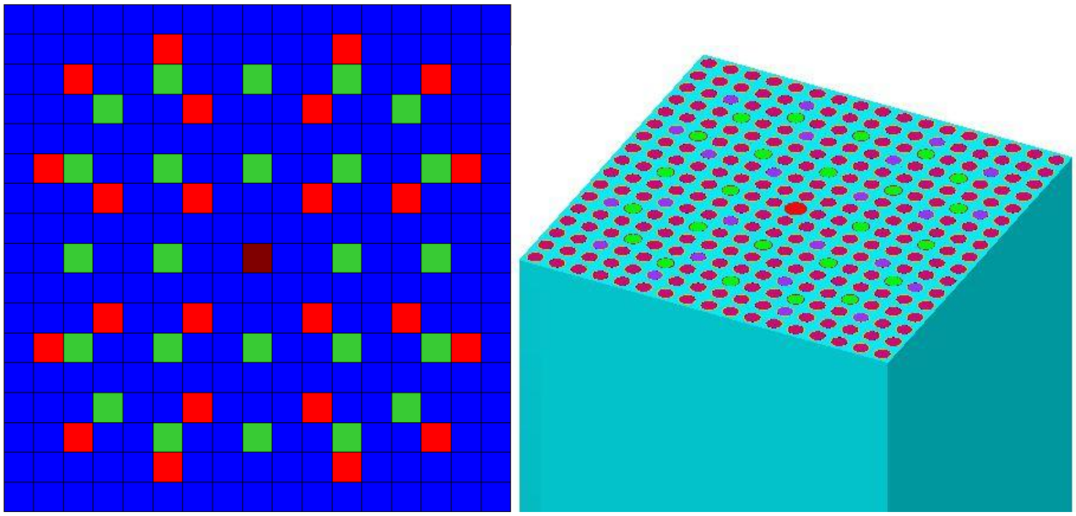

Fig. 1. US-APWR fuel assembly with integral fuel rods.

The blue square boxes represent regular fuel rods, and the red square boxes are the integral fuel rods. The green and brown colors are control rods and instrumentation tubes respectively. This assembly was used to construct the US-APWR core as shown in Fig. 2.

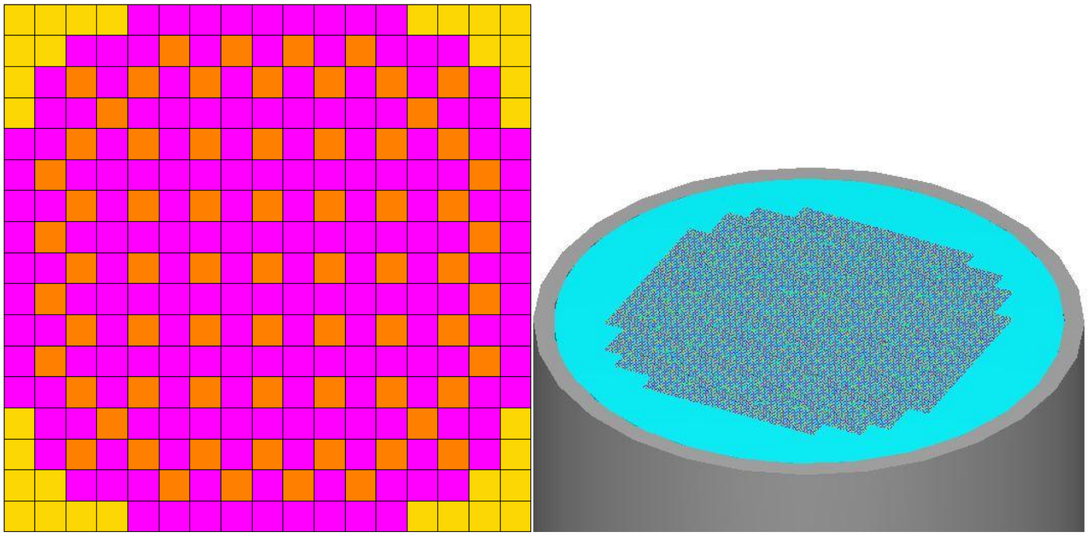

Fig. 2. US-APWR core layout.

The pink squares are fuel assembly without integral fuel rods, and the orange squares are fuel assembly with integral fuel rods. The yellow squares are water surrounding the core.

US-APWR decay heat

The US-APWR model was simulated assuming 730 days of operation and cooled for 365 days. These operation and cooling dates were applied to the other reactors. Fig. 3 shows how the decay heat power changes during operation and cooling.

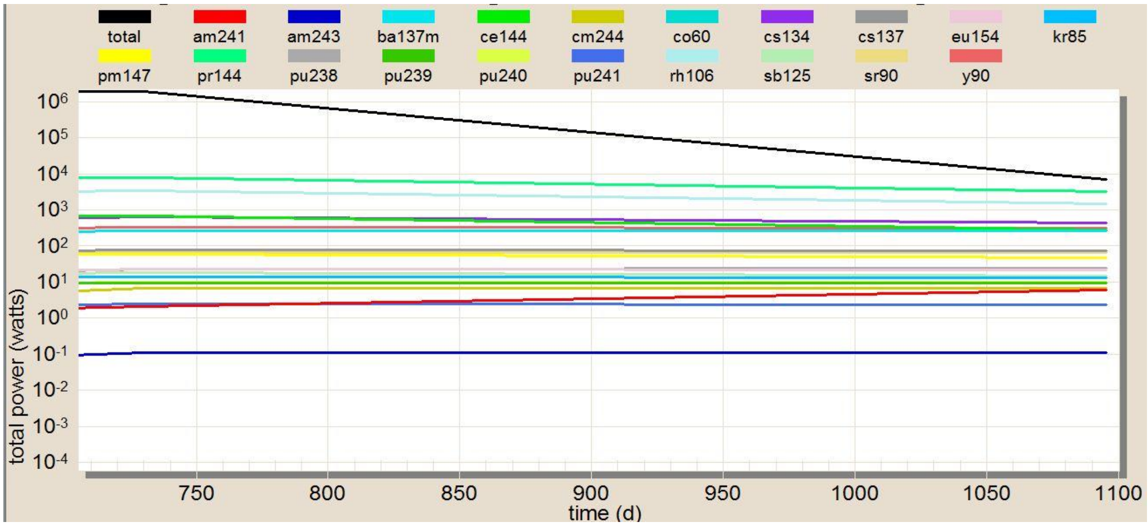

Fig. 3. US-APWR Opus decay heat power for 730 days operation and 365 days cooling.

The total power was increased very quickly as the operation started, then it stabilized and remained at nearly the same decay heat power during operation. After 730 days the reactor was shut down and the decay heat production was decreased. After the reactor was shut down, it is clear that the total power decreased more compared to the other nuclides plotted. This phenomena can be explained with following plots using excel from output data.

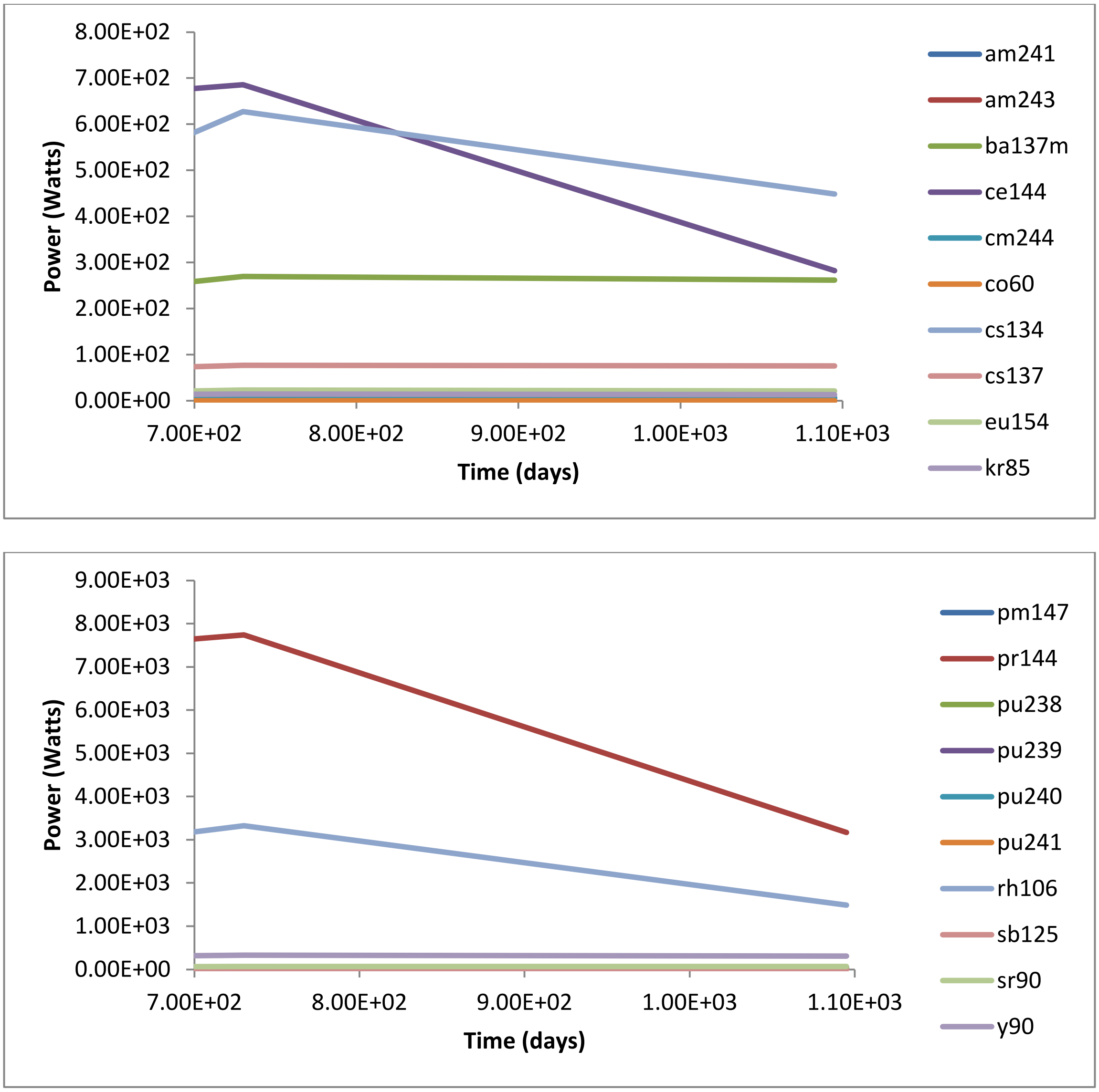

Fig. 4. US-APWR Excel decay heat power for 730 days operation and 365 days cooling.

Fig. 4 shows that the decay heat from many nuclides were significantly small. The two dominant nuclides that produced the most decay heat were ^{144}Pr and ^{106}Rh. The maximum total decay heat power of the core was 1.99 MW, and the power after one year cooling was 6.879 kW.

ABWR core design

The ABWR was modeled using Table 1, and its fuel assembly is shown in Fig. 5.

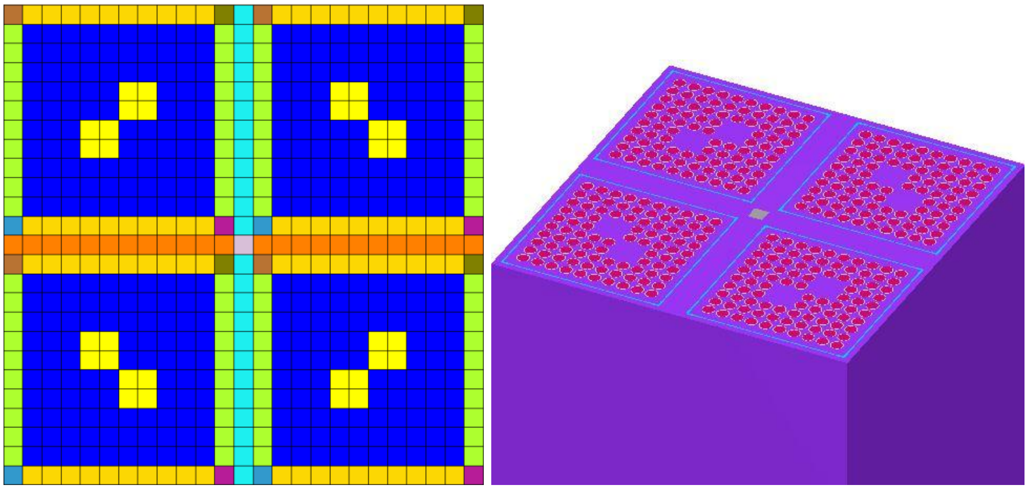

Fig. 5. ABWR fuel assembly.

The square boxes across vertical and horizontal centerlines are the control blades. The blue colored squared boxes are the fuel rods, and the yellow boxes are the water holes. Also, SS304 surrounded fuel rod assembly. Using this assembly, the ABWR's core was constructed as shown in Fig. 6.

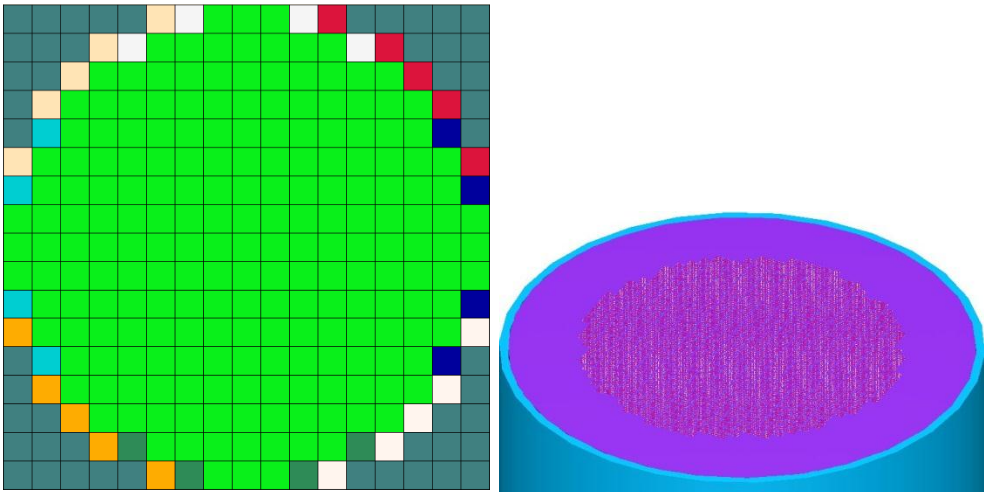

Fig. 6. ABWR core layout.

The green square boxes are the fuel assemblies and the dark greens are the water. The remaining squares contain either half an assembly or a quarter of an assembly.

ABWR decay heat

The ABWR model was simulated also assuming 730 days of operation and 365 days of cooling. Fig. 7 shows how the decay heat power changes during operation and cooling.

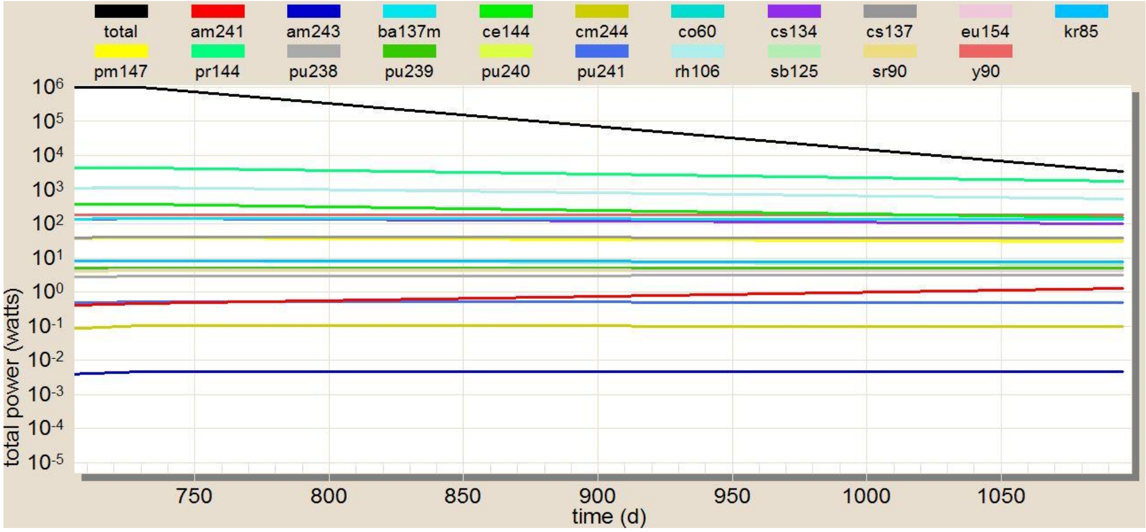

Fig. 7. ABWR Opus decay heat power for 730 days operation and 365 days cooling.

The result of ABWR simulation was similar to the US-APWR's result. The total power of decay heat was increased quickly at beginning of operation. Then, it stabilized and stayed at the same power level. After shut down, the decay heat decreased. The individual nuclides were plotted using output data as shown in Fig. 8.

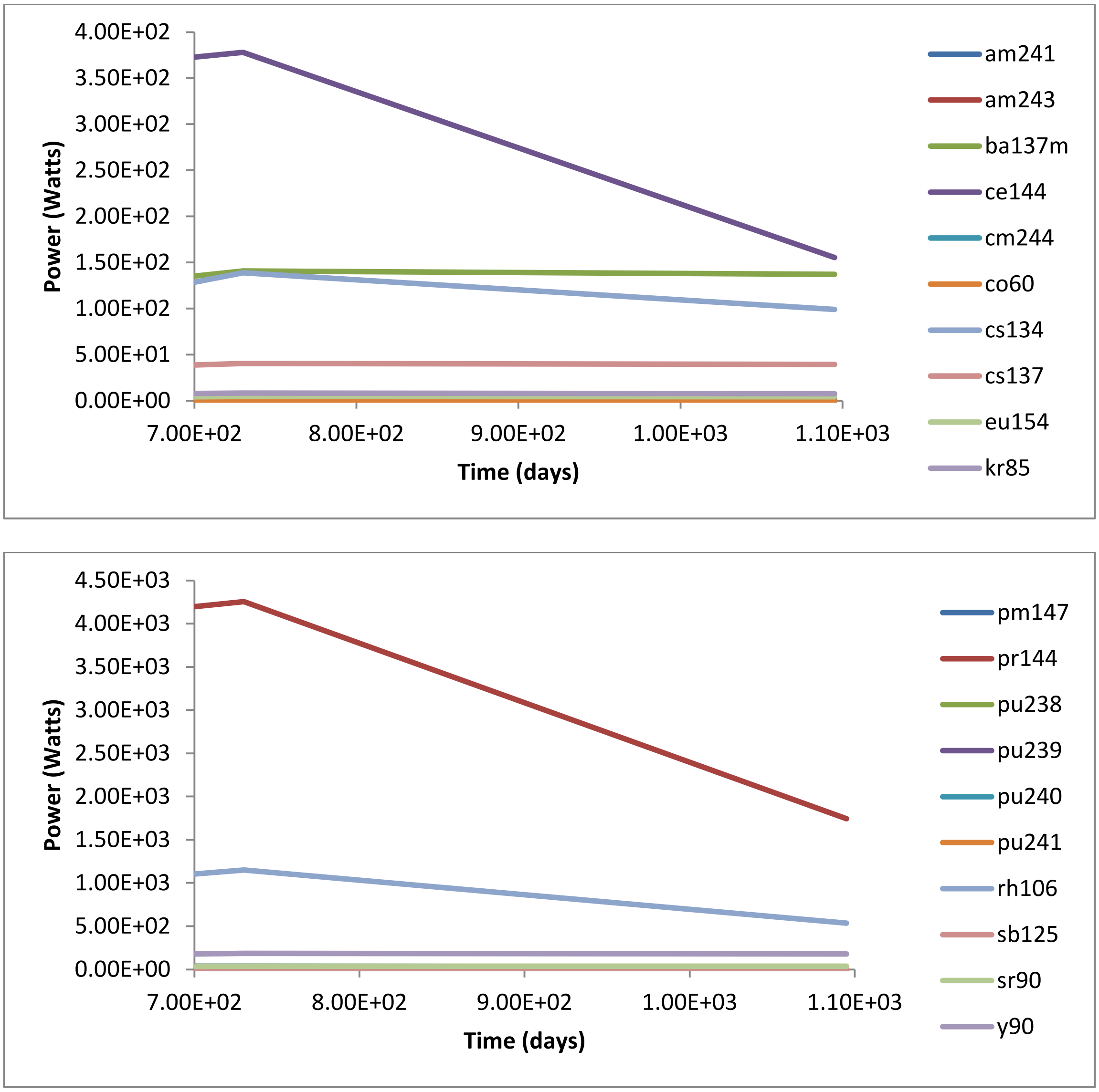

Fig. 8. ABWR Excel decay heat power for 730 days operation and 365 days cooling.

The major differences between the US-APWR and the ABWR were the magnitude of decay heat power and the contribution of ^{134}Cs and ^{106}Rh were decreased significantly. As with the US-APWR, the decay heat of almost all the nuclides was very small, and ^{144}Pr was the dominant nuclide. The maximum decay heat power of the core was 1.031 MW, and the power after one year cooling was 3.294 kW.

VHTR core design

The VHTR was developed by using data from Table 1 as shown in Fig. 9.

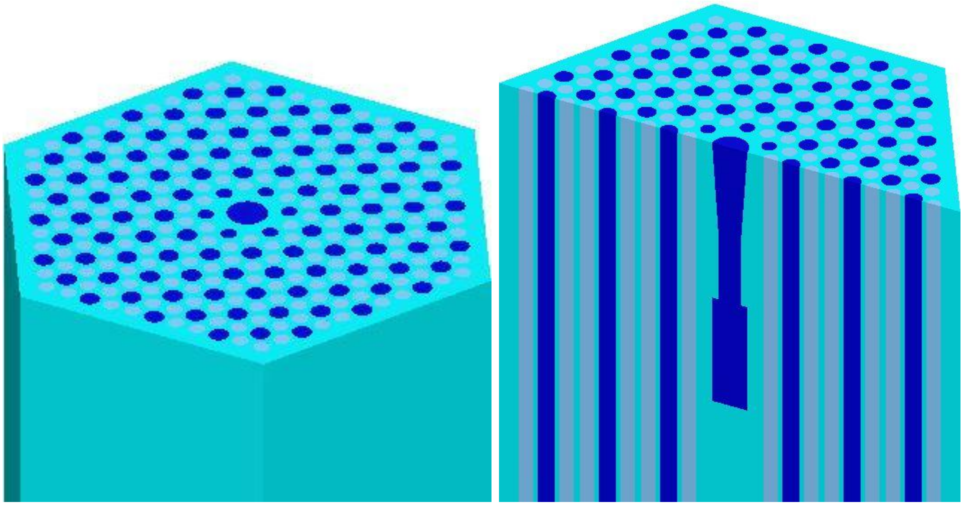

Fig. 9. VHTR fuel assembly.

The VHTR fuel has a triangular pitch, and it is assembled in a hexagonal graphite block. The gray colored circles are the fuel rods, and the blue colors are the coolant. The blue hole at the center is not the coolant channel but the assembly holder.

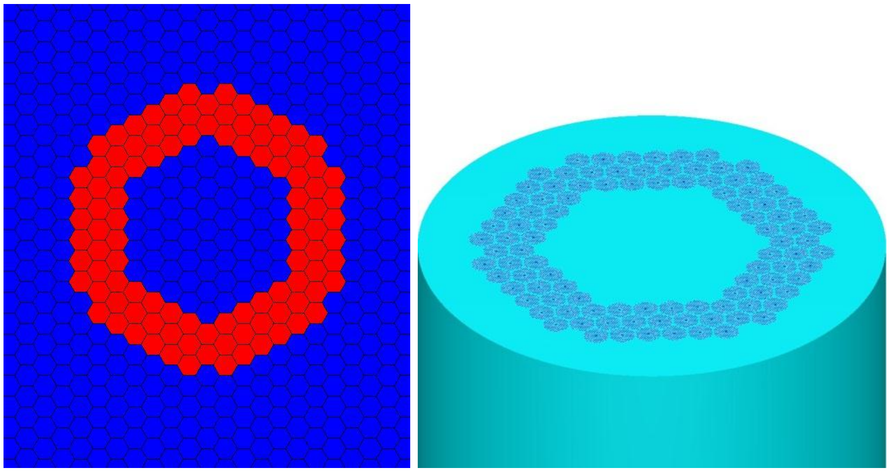

Fig. 10. VHTR core layout.

In Fig. 10 the red colored hexagonals are the fuel assemblies and the blue hexagonals are the graphite blocks.

VHTR decay heat

The VHTR model was simulated assuming 730 days of operation and 365 days of cooling. Fig. 11 shows how the decay heat power changes during operation and cooling.

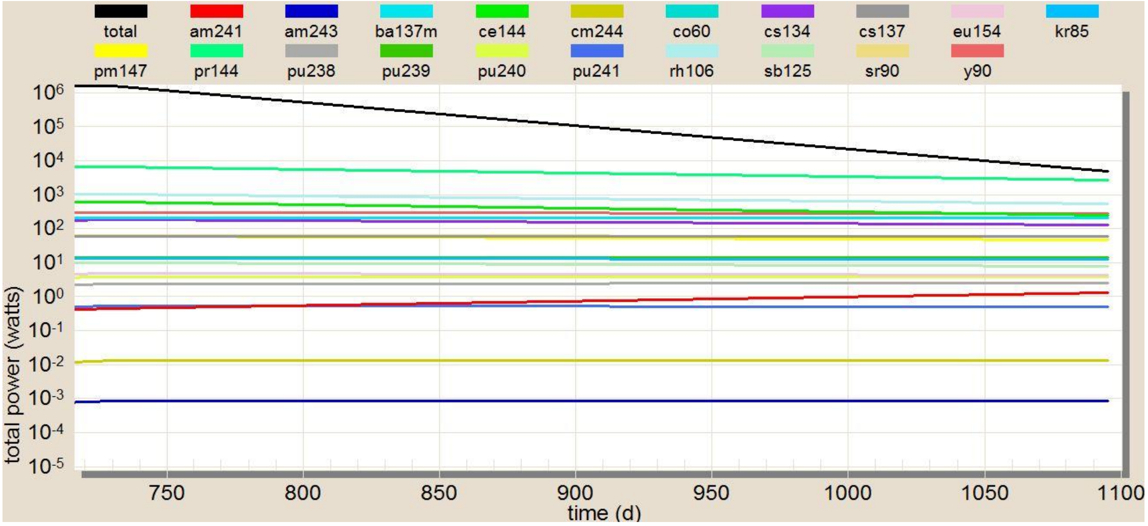

Fig. 11. VHTR Opus decay heat power for 730 days operation and 365 days cooling.

The total power of decay heat was increased very quickly, but again reached steady-state during operation. After shut down at 730 days, the power level decreased. The important nuclides were plotted using output data as shown in Fig. 12.

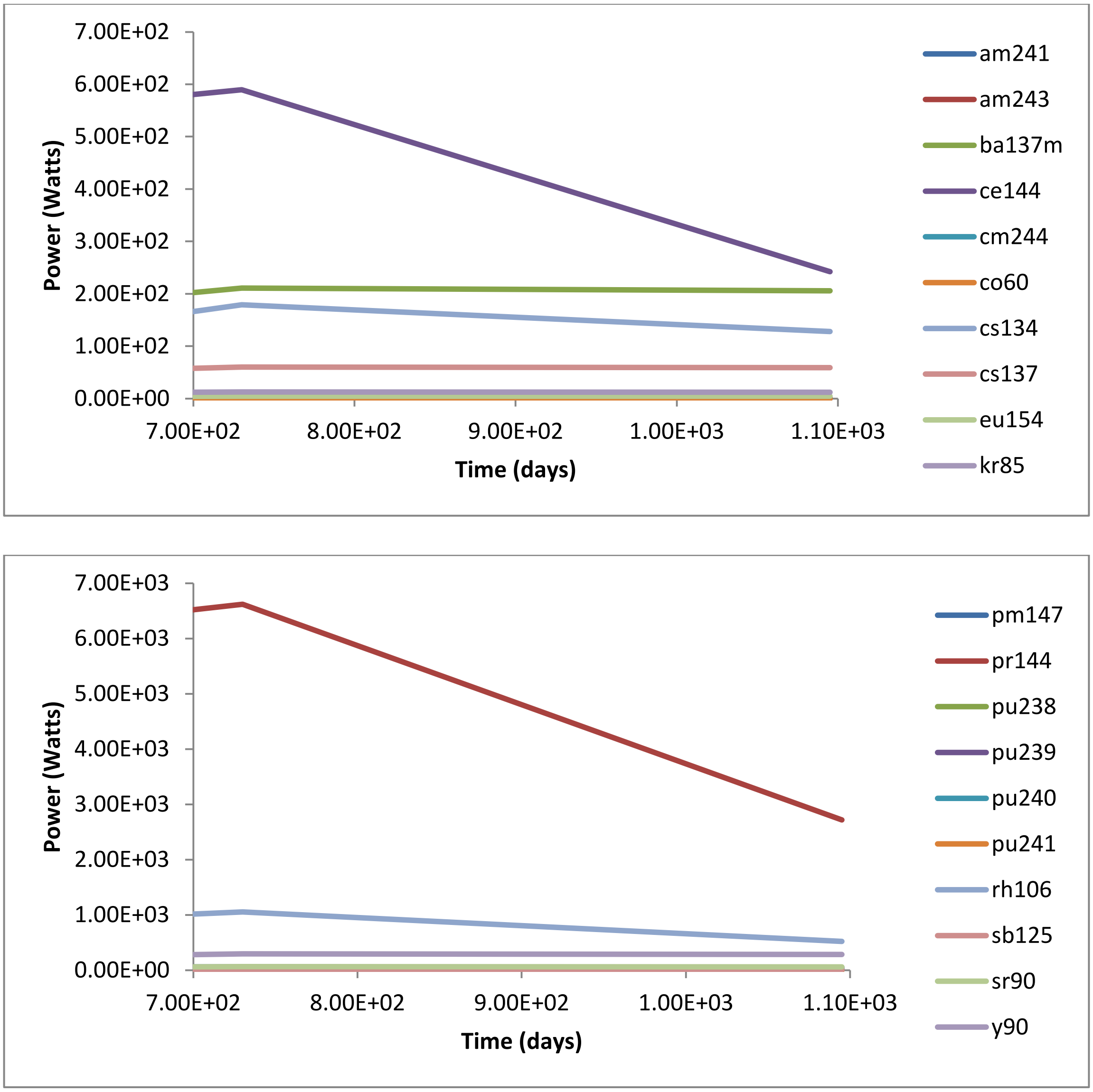

Fig. 12. VHTR Excel decay heat power for 730 days operation and 365 days cooling.

This figure is similar to the plot created for the ABWR but with a greater magnitude of decay power for ^{144}Pr. The contribution of ^{106}Rh was less compared to that of the ABWR. Also, as with the other reactors, ^{144}Pr was the dominant nuclide whereas other nuclides produced small amounts of power. The maximum decay heat power of the core was 1.56 MW, and the power after one year cooling was 4.785 kW.

ABR core design

The ABR was developed using data from Table 1 as shown in Fig. 13.

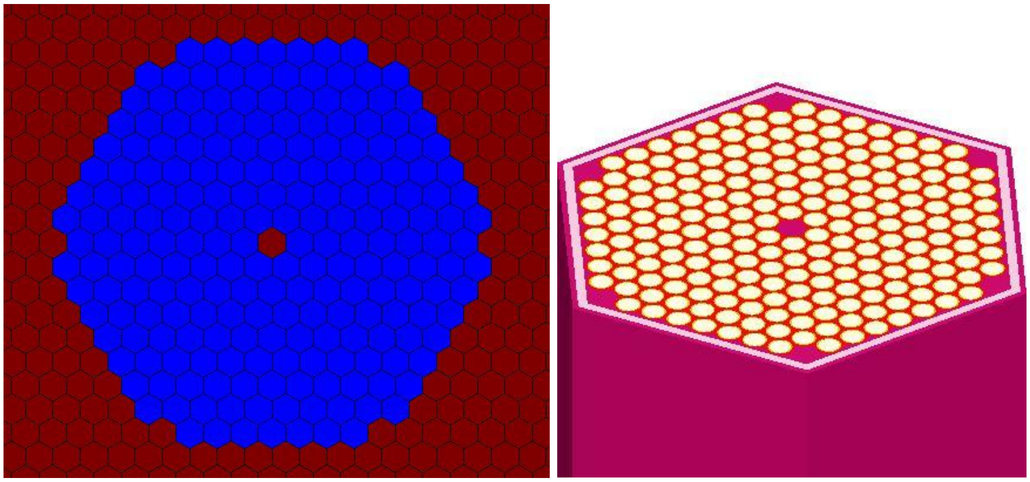

Fig. 13. ABR fuel assembly.

The ABR also a has triangular pitch, and it is arrayed in a hexagonal block. The small blue colored hexagonals are the fuel rods, and the maroon hexagonals are the sodium.

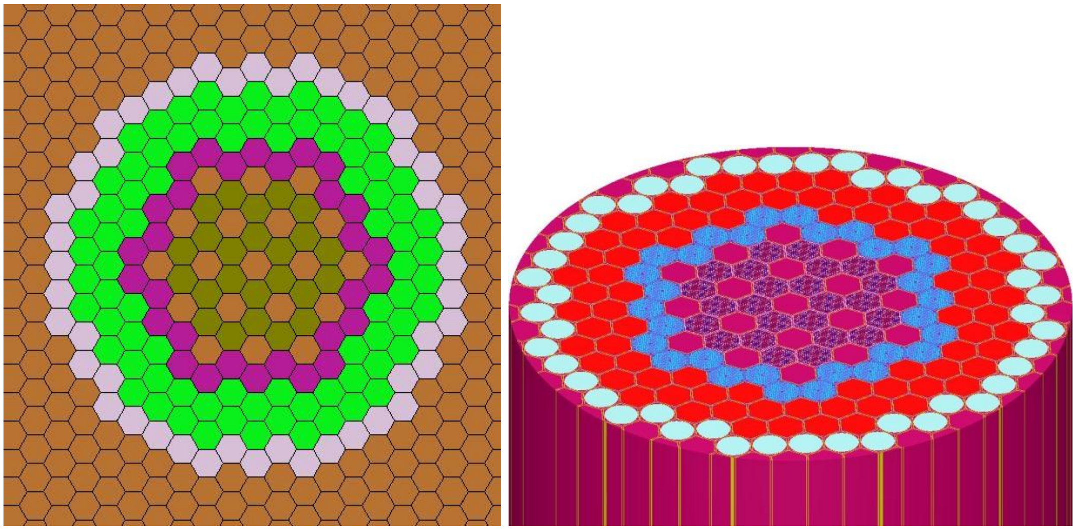

Fig. 14. ABR core layout.

In Fig. 14 the dark green colors are inner fuel assemblies, and the brown colors in and out of core are coolant. Inner fuel assemblies are surrounded by outer fuel assemblies which are indicated by the purple color. The light green is a reflector that is surrounded by a shield.

ABR decay heat

The ABR model was simulated assuming 730 days of operation 365 days of cooling. Fig. 15 shows how the decay heat power changes during operation and cooling.

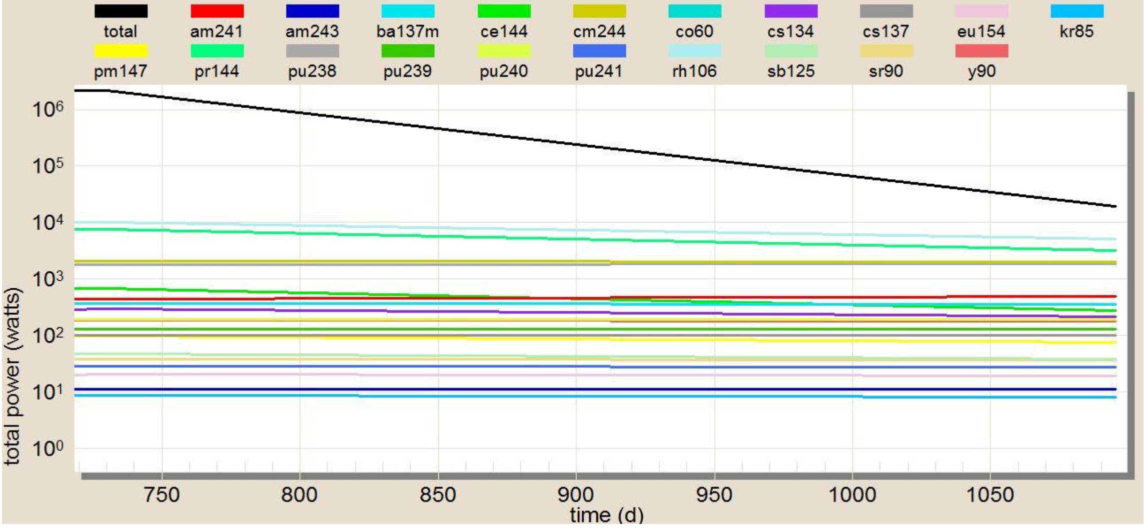

Fig. 15. ABR Opus decay heat power for 730 days operation and 365 days cooling.

The ABR was also like other reactors. The total decay heat power was increased very fast and it soon stayed at constant power level. After shut down the decay heat reduced. The decay heat productions from each nuclide were plotted as shown in Fig. 16.

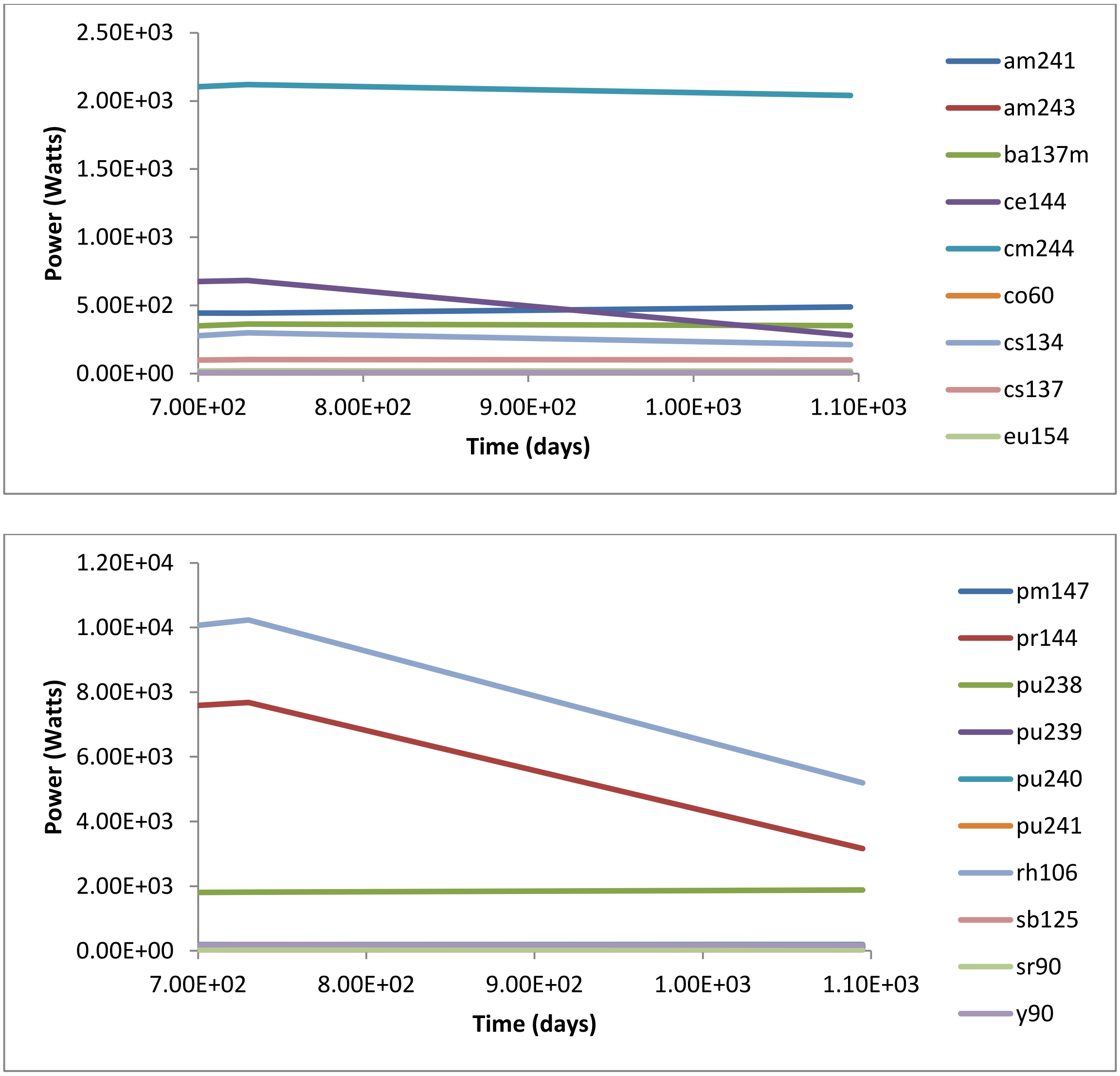

Fig. 16. ABR Excel decay heat power for 730 days operation and 365 days cooling.

The decay heat production of ABR was distinct from other reactors. The contribution of ^{244}Cm and ^{238}Pu were increased significantly. ^{144}Pr still had a significant contribution, but ^{106}Rh was the most dominant nuclide in the ABR. The maximum decay heat power of the core was 2.429 MW, and the power after one year of cooling was 19.7 kW.

Comparison

The maximum decay heat power productions and decay heat after one year were compared as shown in Fig. 17. The ABR produced the highest decay heat power during operation and after cooling. The US-APWR was the second highest decay heat producer, and the VHTR was ranked third. The ABWR produced the lowest decay heat among the reactors.

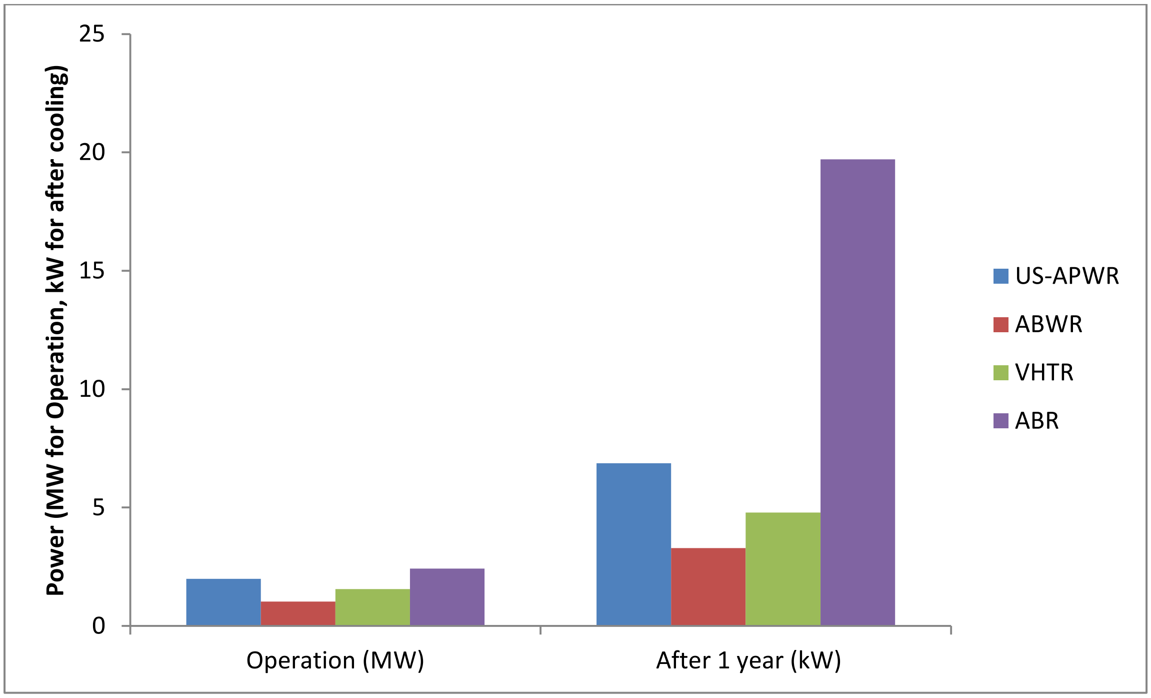

Fig. 17. Decay heat power changes for all reactors.

Table 2

Decay heat power reduction.

	US-APWR	ABWR	VHTR	ABR
Max total (MW)	1.99	1.031	1.56	2.429
End total (kW)	6.879	3.294	4.785	19.7
Remained (%)	0.345678	0.319496	0.306731	0.811033

At the end of all the simulations, almost all the decay heats were reduced to about 0.3 % of the maximum total power with exception of the ABR. The ABR's decay heat was reduced to 0.811% of its maximum decay heat power. Decay heat power for each reactor and its power reduction during cooling as shown in Table 2.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Four reactors, the US-APWR, ABWR, VHTR, and ABR, were simulated by using the program SCALE to study their decay heat conditions. During the 730 days of operation, the decay heat power of all the reactors increased very quickly and stayed nearly constant. It was found that ^{144}Pr and ^{106}Rh were the most dominant decay heat sources for all reactors. For the US-APWR, ABWR, and VHTR, ^{144}Pr was the most dominant nuclide whereas ^{106}Rh was the most dominant nuclide for the ABR. The contribution of ^{106}Rh was high for the US-APWR and then decreased for the ABWR and even more for the VHTR. However, the contribution of ^{106}Rh was even higher than the contribution of ^{144}Pr for the ABR. Also, ^{134}Cs contributed relatively more decay heat for the US-APWR compared to other reactors. For the ABR, decay heat power of ^{244}Cm and ^{90}Sr were significantly increased. The ABR produced the highest decay heat power, and the US-APWR, VHTR, and ABWR followed in order. The decay heat power reduced to around 0.3% of its maximum operation decay heat power after one year shut down for most reactors except the ABR which was reduced to 0.811%. Therefore, the ABR requires more coolant and cooling time than any other reactors where the ABWR requires least.

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