KAERI/TR-4098/2010

기술보고서

사용후 핵연료 동적 환경영향 해석 모델 개발

Development of Dynamic Spent Nuclear Fuel Environmental Effect Analysis Model

2010년 7월

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KAERI/TR-4098/2010

제 출 문

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본 보고서를 2010년도 자체연구개발 과제 (세부과제: 동적 사용후핵연료 환경영향 해석 모델 개발)의 기술 보고서로 제출합니다.

2010. 7

과제명: 동적 사용후핵연료 환경영향 해석 모델 개발
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ABTRACT

The dynamic environmental effect evaluation model for spent nuclear fuel has been developed and incorporated into the system dynamic DANESS code. First, the spent nuclear fuel isotope decay model was modeled. Then, the environmental effects were modeled through short-term decay heat model, short-term radioactivity model, and long-term heat load model. By using the developed model, the Korean once-through nuclear fuel cycles was analyzed. The once-through fuel cycle analysis was modeled based on the Korean “National Energy Basic Plan” up to 2030 and a postulated nuclear demand growth rate until 2150. From the once-through results, it is shown that the nuclear power demand would be ~70 GWe and the total amount of the spent fuel accumulated by 2150 would be ~168000 t. If the disposal starts from 2060, the short-term decay heat of Cs-137 and Sr-90 isotopes are 2.3×10^6 W and 1.8×10^6 W in 2100. Also, the total long-term heat load in 2100 will be 4415 MW-y. From the calculation results, it was found that the developed model is very convenient and simple for evaluation of the environmental effect of the spent nuclear fuel.

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I. INTRODUCTION

The spent fuel (SF) accumulation has become a main issue for sustainable operation of nuclear power plant. If an once-through (OT) fuel cycle is selected, the SF will be disposed into the repository. Otherwise, in case of fast reactor (FR) or reuse cycle, the SF will be reprocessed and the high level waste (HLW) will be disposed. Usually, the amount of the SF or HLW is calculated by the nuclear fuel cycle analysis results. These SF or HLW are cooled in the storage pool or interim storage. After cooling, the SF is reprocessed or disposed into the repository. The short-term decay heat at the shutdown of a repository active cooling and the integrated long-term decay heat determine the amount of waste that can be emplaced into the repository [1]. Also, these short-term, long-term decay heat, and radioactivity are considered as main environmental parameter of the SF and HLW.

Conventionally, the radioactivity or decay heat has been calculated by independent tool from the fuel cycle analysis code. This calculation system is time consuming and requires very complicated procedure.

In this study, the dynamic calculation models for radioactivity, short-term decay heat, and long-term heat load of the SF are developed and incorporated into the DANESS [2] code, which is very simple and convenient for decay heat or heat load calculation. Recently, the dynamic method is used widely in the nuclear fuel cycle [3-5].

II. MODEL DEVELOPMENT

II.1 Isotope Decay Model

In this study, 69 isotopes have need selected as main isotope, also short-lived fission products (SLFP) and long-lived fission products (LLFP) were considered. Table 1 shows the main isotopes and their half-lives etc. In this study, the chain decay was also considered for the effect of daughter isotopes.

The isotope concentration is the difference between decay in and loss by decay out and reprocessing as s following:

IC(Fuels, Iso) = (Decay to daughter) – (Decay) – (Removal by Reprocessing) (1)

Each terms can be calculated by following:

Decay(Fuels, Iso) = IC(Fuels, Iso)*LOGN(2)/T_{half_Iso} (Iso) (2)
Decay to daughter(Fuel,Iso) = Decay(Fuels,Iso)*Br(Iso,Iso)/N(Iso) (3)
Removal by Reprocess = Reprocess Fraction (Fuels,Iso)*
Reprocess Amount (Fuels) (4)

where, IC (Fuels, Iso): isotope concentration of fuel type and isotope type [g]
T_{half_Iso} (Iso]: half life of isotope [yr]
Br(Iso,Iso): fraction of chain decay.

Figure 1 shows the dynamic model for isotopic decay process.

II.2 Radioactivity and Heat Load Calculation Model

When the isotopic concentration is calculated, then the radioactivity, instant decay heat, and long-term heat load can be calculated.

The short-term or instant decay heat can be calculated by:

$$SDH(Iso) = DHF(Iso) * IC(Fuels, Iso) \quad (5)$$

where, SDH(Iso): short-term decay heat [w]
DHF(Iso): decay heat factor of isotope [w/g]

Also, the radioactivity is calculated by:

$$ACT(Iso) = SACT(Iso) * IC(Fuels, Iso) \quad (6)$$

where, ACT(Iso): activity of isotope [Ci]
SACT(Iso): specific activity of isotope [Ci/g]

The shot-term heat is the instant decay heat from disposal to 100 years. Figs. 2 and 3 show the instant decay heat and radioactivity calculation model, respectively.

After 100 years, the decay heat is integrated until 1500 years, which is a long-term heat load. The cumulative amount of heat generated by the spent fuel and/or high-level waste between the time when cooling is stopped and 1500 years after discharge is quantified by integrating the individual isotope decay heat over that period. [1]

The heat load factors are calculated by the following equation:

$$LTH[Iso] = HLF[Iso]*ID[Iso] \quad (7)$$

where LTH[Iso]: Heat load [W-yr],
HLF[Iso]: Integrated heat load factor [W-yr/g].
ID[Iso]: Isotope disposing [g]

The *HLF* can be calculated by

$$HLF(Iso) = DH_m(Iso)*DHF_m(Iso) + DH_d(Iso)*DHF_d(Iso) \quad (8)$$

where $DH_m(Iso)$: decay heat of mother isotope [W/g],
$DHF_m(Iso)$: decay heat factor of mother isotope [yr],

DH_d(Iso): decay heat of daughter isotope [W/g],
DHF_d(Iso): decay heat factor of daughter isotope [yr]

The DHF_m(Iso) and DHF_d(Iso) can be calculated by

$$DHF_m = \frac{1}{\lambda_m}\left[e^{-\frac{t_1}{\lambda_m}} - e^{-\frac{t_2}{\lambda_m}}\right] \tag{9}$$

$$DHF_d = \frac{\lambda_m}{\lambda_d - \lambda_m}[DHF_m - DHF_d] \tag{10}$$

where λ_m = decay constant of mother isotope [1/yr],
λ_d = decay constant of daughter of isotope [1/yr],
t_1 = starting time of integration [yr],
t_2 = termination time of integration [yr].

Fig.4 shows the long-term heat load calculation model. Once the heat load factor for each tracked isotope is calculated, the factor is then used as a multiplier for the isotope inventory tracked by the system dynamics code, to calculate the contribution of the isotope to the long-term repository heat load. The total long-term repository heat-load indicator is calculated as the sum of contributions from different isotopes.

III. HEAT LOAD ANALYSIS

The once-through (OT) fuel cycle was at first modeled and analyzed based on the current nuclear power plant construction plan and existing nuclear power plants such as the pressurized water reactor (PWR) and Canada deuterium uranium (CANDU) reactor. Then, the fast reactor (FR) scenario was then modeled based on the same nuclear energy demand used for the once-through fuel cycle. The FR fuel cycle was analyzed for two kinds of conversion ratio (CR) of FR.

In the OT cycle, the SF is cooled at reactor storage pool for 10 years, and then it is stored for 50 years in the interim storage. After that the SF starts to be disposed into the repository. In the FR cycle, the PWR SF and FR SF are reprocessed. The cooling time for both SF was assumed to be 5 years. The cooling time and interim storage time of the CANDU SF are same as those of the OT. Also, the FR is deployed from 2030, and the PWR SF reprocessing begins from 2025.

The OT cycle was modeled by the “National Energy Basic Plan” [6]. The detailed modeling procedure and results are described in Ref. [7]. Fig. 4 sows the variation of nuclear power demand and deployed capacity with time. In 2150, both the demand and deployed capacity are expected to be ~70 GWe, and they are maintained until 2150. As shown in Fig. 5 the total SF inventory continuously increases with time and becomes ~186500 t 2150. The SF in storage pool remains almost constant value of 14000 t, while the amount of SF in the interim storage increases and will be ~101000 t. From 2060, the SF will be disposed into the repository and it will become ~72000 t in 2150.

First, the annual inventory of main isotope is analyzed. Fig. 6 shows the inventory of the uranium (U) isotopes. The main isotopes are U-238, U-235, and U-236 isotopes, and their concentrations are ~67000 t, ~470 t, and 330 t, respectively, in 2150. The plutonium (Pu) and neptunium (Np) isotope concentrations are shown in Fig. 7. The concentration of Pu-239, Pu-240, Pu-242, and Np-237 are ~390 t, ~180 t, ~52 t, and ~49 t, respectively, in 2150. As shown in Fig. 8, the concentrations of americium (Am) isotopes in 2150 are ~88 t, and ~14 t for Am-241 and Am-243, respectively. The main curium (Cm) isotope, which is shown in Fig. 9, is Cm-244, and its concentration in 2150 is ~1.3 t. From the Fig. 10, the concentration of main fission products (FP) of Cs-135, Cs-137, I-129, Tc-99, and Sr-90 are ~33.6 t, ~39.7 t, ~15.8 t, ~67.0 t, and ~17.4 t, respectively, in 2150. All the isotope increases with time, which is because the SF accumulated continuously with time.

For evaluation of the short-term environmental effect which is dominated mainly by FP isotopes, the variation of the isotope concentration is investigated in the specific time. Figs. 11 – 13 show the variations of the FP isotope concentrations in 2100. Fig. 11 shows the short-lived FP (SLFP) concentration change for 100 yrs from 2100. The Cs-137 and Sr-90 concentrations reduce to 10% of initial value after 100 yrs. The Cs-134 and Co-60 decay out during 100 yrs. The Kr-85 reduces to 1/1000 of initial value after 100 yrs. As shown in Fig. 12, the long-lived FPs (LLFPs) such as Sc-135, I-129, and Tc-99 do not change during 100 yrs. The almost of actinides concentrations, shown in Fig. 13, do not change during 100 yrs, while Pu-241 isotope decays to 1/100 of initial concentration.

By using the above isotope concentration, the short-term decay heat (STDH) and radioactivity are calculated with the reference year of 2100. The radioactivity and short-term decay heat are calculated for 100 yrs. Fig. 14 shows short-term decay heat of Cs-137 and Sr-90 isotopes. The initial STDH are 2.27×10^{6} W and 1.84×10^{6} W, respectively, and they decrease to 1/10 of initial values. The SRDH of actinides is shown in Fig. 15. The STDH of Am-241 maintains constant value of $\sim3.0\times10^{6}$ W. The STDH of Pu-238 is slightly decreases from 10 yrs after disposal. The STDH of Cm-244 isotope decreases rapidly from 2.3×10^{6} W to 5.0×10^{4} W. As shown in Fig. 16, the radioactivity of LLFP maintains constant value of 1.46×10^{4} Ci and 4.51×10^{5} Ci, respectively, during 100 yrs. The radioactivity of Cs137, Sr-90, and Kr-85 decrease to ~1/600, ~1/10, and ~1/10 of initial vale, respectively. The radioactivity of the actinides is shown in Fig. 17. The radioactivity of Pu-241 decreases rapidly from 10 yrs after disposal. The radioactivity of Am-241, Pu240, and Pu239 maintain by $\sim1.0\times10^{8}$ Ci, 1.7×10^{7} Ci, and 1.0×10^{7} Ci, respectively. The radioactivity of Pu-238 decreases slightly after 10 yrs.

The actinide isotopes contribute mainly to the LTH. Fig 18 shows the LTH Pu isotope with time. The LTH is integrated from each time to 1500 yrs. The LTH of Pu isotopes increase with and they will be 1700, 1050, 1030, and 460 MW-y for Pu-240, Pu-241, Pu-239, and Pu-238, respectively, in 2150. The LTH of Am isotope is shown in Fig. 19, The LTH of Am-241 in 2150 will be 5130 MW-y which is the highest value among the LTH of the actinides. The LTH of Am-243 is 120 MW-y in 2150. As shown in Fig. Cm-244, the LTH of Cm-244 will become 14 MW-y in 2150. The total LTH is shown in Fig. 21, from which it can be seen that the total LTH will be 10460 MW-y in 2150.

In order to investigate the effect of the cooling time to the LTH, the LTH was calculated with the cooling time of 100, 200, and 300 yrs in the reference year of 2100. The integration periods are 100 – 1500, 200 – 1500, and 300 – 1500. Fig. 22 shows the variation of the LTH of Pu isotopes. The LTH of Pu 241 decreases from 780 to 550 MW-y, which is decreased by ~30%. The decreasing rate for Pu-238, Pu-239, and Pu-240 are ~80, ~15, and ~15%, respectively. As shown in Fig. 23, the LTH of Am-241 decreases from 1740 to 1230 MW-y which is decreased by ~30%. The decreasing rate of Am-243 is ~15% which relatively small compared to that of the Am-241. The total LTH, which is shown in Fig. 24, decreases from 4420 to 3250 MW-y, which is decreased by ~26% in 2100.

IV. SUMMARY

The dynamic environmental effect evaluation model for spent nuclear fuel has been developed and incorporated into the system dynamic DANESS code. First, the spent nuclear fuel isotope decay model was modeled. Then, the environmental effects were modeled through short-term decay heat model, short-term radioactivity model, and long-term heat load model. By using the developed model, the Korean once-through nuclear fuel cycles was analyzed. The calculation results can be summarized as follows:

- The nuclear power demand grows to ~70 GWe in the year 2150, from which the total spent fuel inventory is expected to be 186500 t in 2150.
- The concentration of U-238, U-235, and U-236 isotopes are ~67000 t, ~470 t, and 330 t, respectively, in 2150. The concentration of Pu-239, Pu-240, Pu-242, and Np-237 are ~390 t, ~180 t, ~52 t, and ~49 t, respectively, in 2150.
- The concentrations of Am isotopes in 2150 are ~88 t and ~14 t for Am-241 and Am-243, respectively, for Am-242 and Am-243. For Cm-244 concentration in 2150 is ~1.3 t.
- In the reference year of 2100, the short-term decay heat of Cs-137 and Sr-90 isotopes are 2.3×10^6 W and 1.8×10^6 W. They will decrease to 1/10 of initial value after 100 yrs. Also, the radioactivity of Cs137, Sr-90, and Kr-85 are 2.0×10^9 Ci, 1.6×10^9 Ci, and 6.4×10^7 Ci, and they will decrease to ~1/600, ~1/10, and ~1/10 of initial vale, respectively.
- In the reference year of 2100, the long-term heat load of Pu-239, Pu-240, Pu-241, and Am-241 are 420, 670, 780, and 1740 MW-y. They will decrease with longer cooling time. The total long-term heat load in 2100 is 441- MW-y.

From the above results, it is known that the newly developed method can be easily applied to evaluate the environmental effect of the spent fuel. In future, the toxicity calculation model will be added.

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Table 1 Isotope Data

	Half Life (yr)	Decay to Daughter	Fraction	Specific Decay Heat (W/g)	Specific Activity (Ci/g)
U 232	7.20E+01	Th228	1	2.21E+01	2.21E+01
U 233	1.59E+05	Th229	1	9.64E-03	9.64E-03
U 234	2.45E+05	Th230	1	6.22E-03	6.22E-03
U 235	7.04E+08	Pa231	1	2.16E-06	2.16E-06
U 236	2.34E+07	Th232	1	6.47E-05	6.47E-05
U 237	1.85E-02	Np237	1	8.17E+04	8.17E+04
U 238	4.47E+09	Th234	1	3.36E-07	3.36E-07
Pu 236	2.85E+00	U232	1	5.23E+02	5.23E+02
Pu 237	1.25E-01	Np237	1	1.22E+04	1.22E+04
Pu 238	8.78E+01	U234	1	1.71E+01	1.71E+01
Pu 239	2.41E+04	U235	1	6.21E-02	6.21E-02
Pu 240	6.54E+03	U236	1	2.27E-01	2.27E-01
Pu 241	1.44E+01	Am241	1	1.03E+02	1.03E+02
Pu 242	3.87E+05	U238	1	3.96E-03	3.96E-03
Pu 244	8.27E+07	Pu240	1	1.83E-05	1.83E-05
Pu 246	2.97E-02	Cm246	1	4.90E+04	4.90E+04
Np 235	1.09E+00	Pa231	2.60E-05	1.40E+03	1.40E+03
Np 236	1.15E+05	U236	0.911	1.32E-02	1.32E-02
	1.15E+05	Pu236	0.089	7.05E-04	1.32E-02
Np 237	2.14E+06	Pa233	1	3.43E+00	7.05E-04
Am 241	4.64E+02	Np237	1	1.05E+01	3.43E+00
Am 242m	1.52E+02	Pu242	0.176722	2.00E-01	1.05E+01
	1.52E+02	Cm242	0.823279	3.31E+03	1.05E+01
Am 243	7.39E+03	Pu239	1	5.17E+01	2.00E-01
Cm 242	4.15E-01	Pu238	1	8.10E+01	3.31E+03
Cm 243	2.85E+01	Pu239	0.9976	1.72E-01	5.17E+01
	2.85E+01	Am243	0.0024	3.07E-01	5.17E+01
Cm 244	1.81E+01	Pu240	1	9.05E-05	8.10E+01
Cm 245	8.50E+03	Pu241	1	4.24E-03	1.72E-01
Cm 246	4.73E+03	Pu242	1	8.22E-02	3.07E-01

Cm 247	1.56E+07	Am243	1	3.07E+04	9.05E-05
Cm 248	3.39E+05	Pu244	1	8.20E+02	4.24E-03
Cm 250	8.50E+03	Pu246	0.25	1.98E-01	8.22E-02
	8.50E+03	Cm246	0.14	2.06E-02	8.22E-02
Th 227	5.13E-02			1.10E-07	3.07E+04
Th 228	1.91E+00			2.32E+04	8.20E+02
Th 229	7.34E+03			4.73E-02	1.98E-01
Th 230	7.71E+04			2.08E+04	2.06E-02
Th 232	1.41E+10			7.23E+01	1.10E-07
Th 234	6.60E-02	U234	1	1.54E+05	2.32E+04
Pa 231	3.28E+04			1.29E+03	4.73E-02
Pa 233	7.40E-02	U233	1	1.15E-03	2.08E+04
Ac 227	2.18E+01	Ac227	0.00138	8.70E+01	7.23E+01
Rn 222	1.05E-02			1.05E+03	1.54E+05
Cs 134	2.06E+00			2.84E-02	1.29E+03
Cs 135	2.30E+06			9.27E+02	1.15E-03
Cs 137	3.00E+01			3.18E+03	8.70E+01
Sb 125	2.77E+00			2.70E+02	1.05E+03
Sn 126	1.00E+05			4.93E+02	2.84E-02
Pm 147	2.63E+00			2.63E+01	9.27E+02
Ce 144	7.79E-01			1.77E-04	3.18E+03
Eu 154	8.61E+00			3.93E+02	2.70E+02
Eu 155	4.96E+00			1.37E-01	4.93E+02
Sm 151	9.01E+01			2.51E-03	2.63E+01
I 129	1.57E+07			1.87E-01	1.77E-04
Kr 85	1.07E+01			1.71E-02	3.93E+02
Se 79	6.50E+04			5.14E-04	1.37E-01
Zr 93	1.53E+06			3.32E+03	2.51E-03
Nb 94	2.03E+04			7.35E+08	1.87E-01
Tc 99	2.13E+05			4.17E+09	1.71E-02
Pd 107	6.50E+06			4.46E+00	5.14E-04
Ru 106	1.01E+00			0.00E+00	3.32E+03
Ag 108	1.27E+02			2.74E+06	7.35E+08
Ag 110	6.85E-01			3.00E+07	4.17E+09
C 14	5.73E+03			1.31E-03	4.46E+00

Cl 36	3.01E+05			9.67E-02	3.24E-02
Ni 59	8.00E+04			2.08E+00	5.01E-02
Ni 63	9.20E+01			1.41E+02	5.32E+01
Ca 41	8.10E+04			2.45E+00	8.47E-02
Mn 54	8.56E-01			3.83E-01	9.02E-10
Co 60	5.27E+00			8.26E-08	7.41E+02
Sr 90	2.91E+01			1.64E-01	1.41E+02

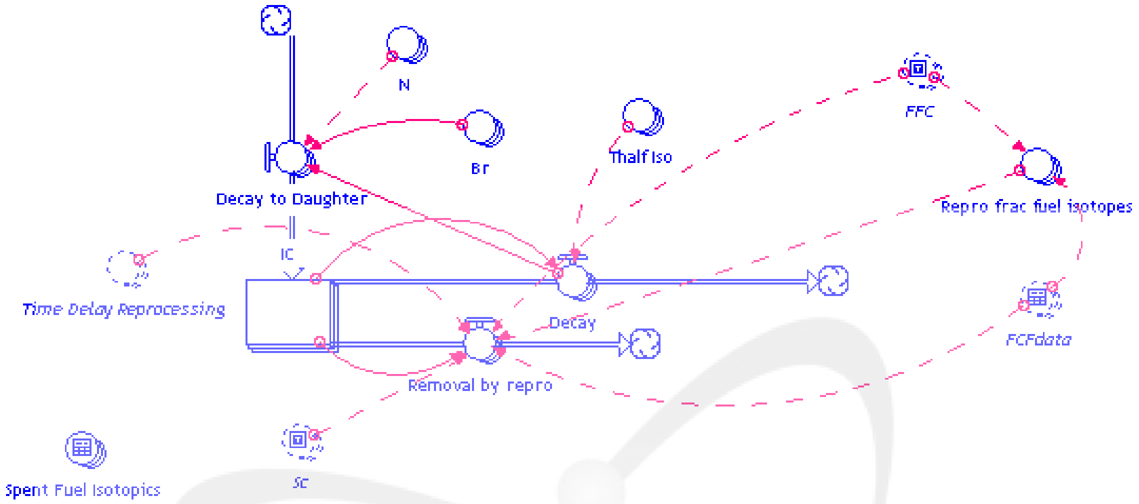


Fig.1 Isotope Decay Model

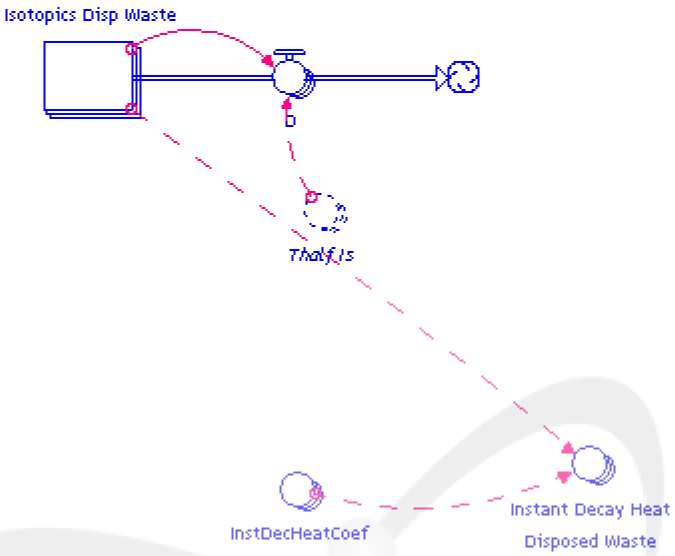


Fig.2 Short-Term Decay Heat or Radioactivity Calculation Model

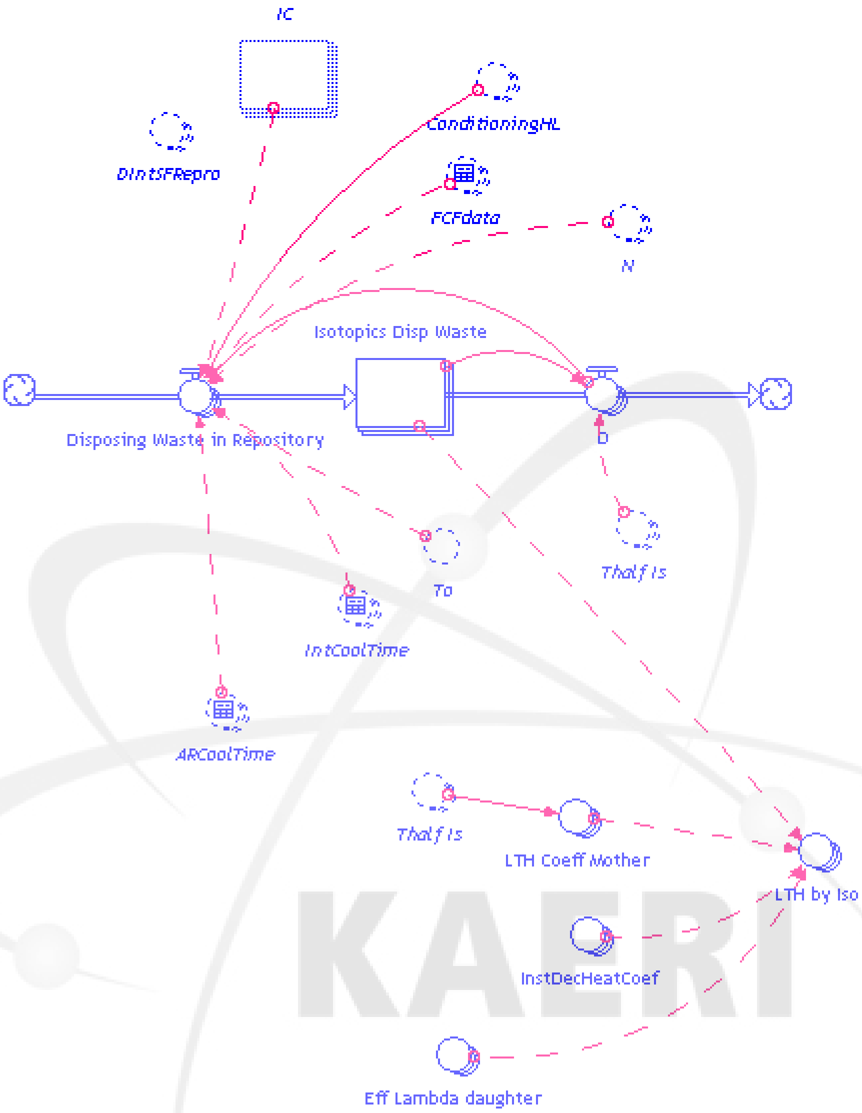


Fig.3 Long-Term Heat Load Calculation Model

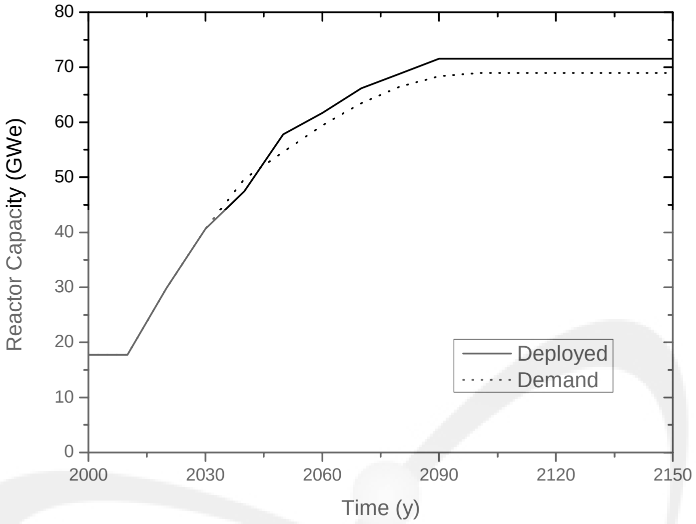


Fig.4 Nuclear Power Demand and Deployed Capacity

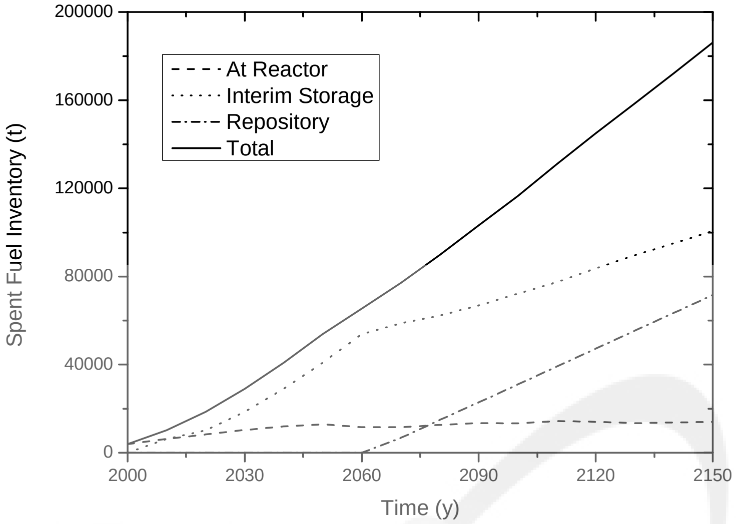


Fig.5 SF at Each Facility

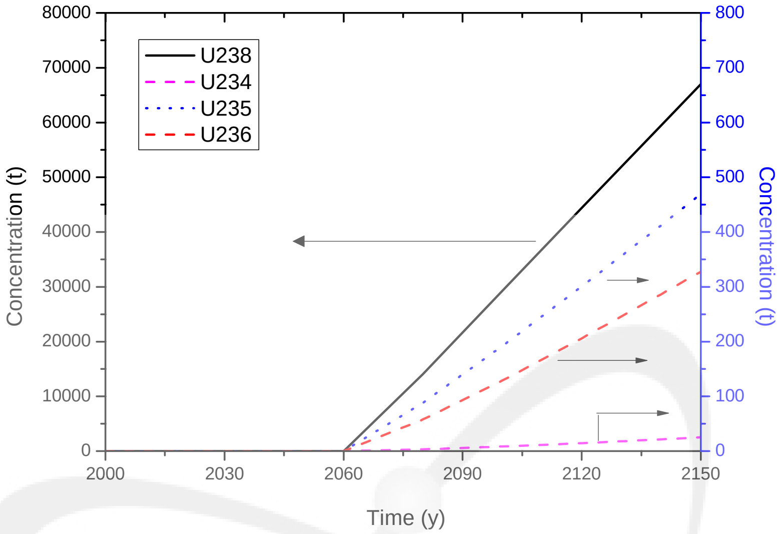


Fig. 6 Uranium Isotope Concentration with Time

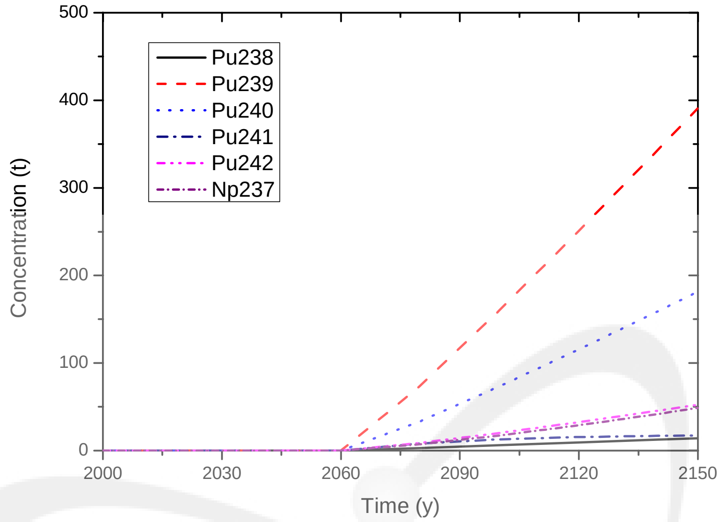


Fig. 7 Plutonium and Neptunium Isotope Concentration with Time

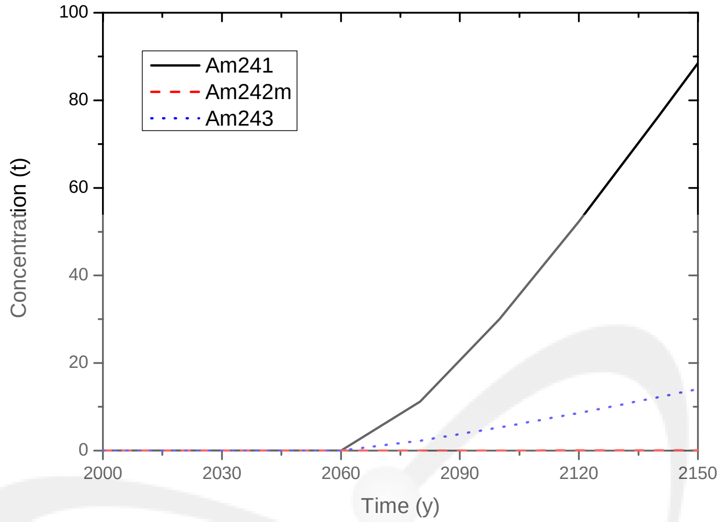


Fig. 8 Americium Isotope Concentration with Time

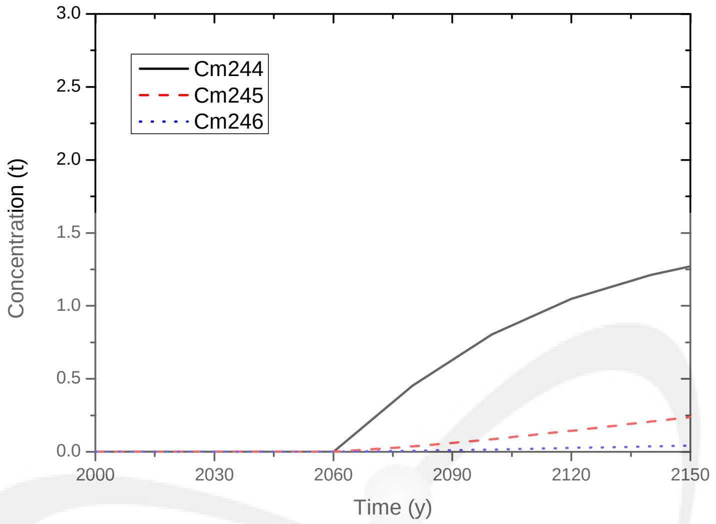


Fig. 9 Curium Isotope Concentration with Time

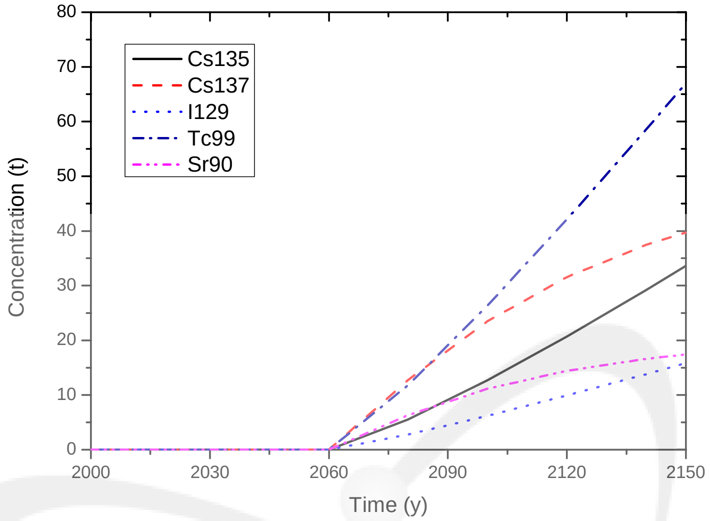
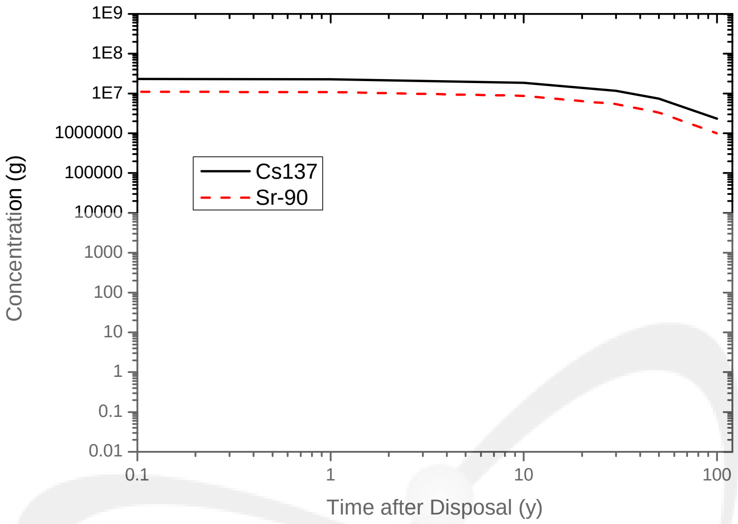
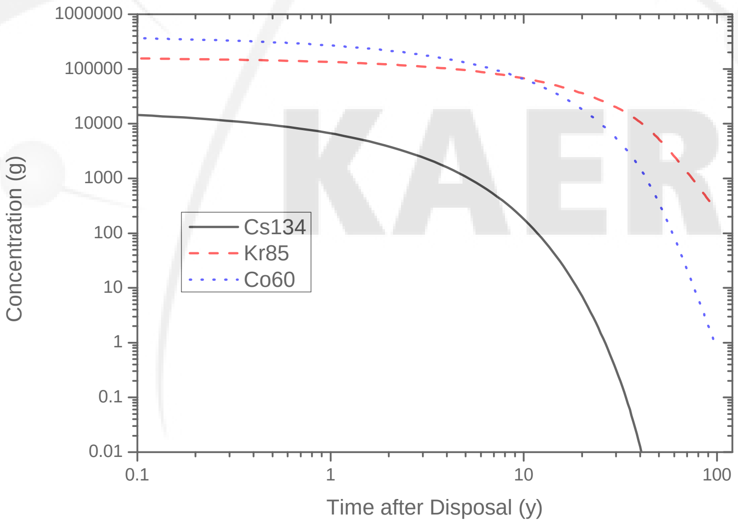


Fig. 10 Fission Products Isotope Concentration with Time



(a) Cs-137 and Sr-90



(b) Cs-134, Kr-85, and Co-60

Fig.11 Concentration of Short-Lived Fission Products after Disposal in 2100

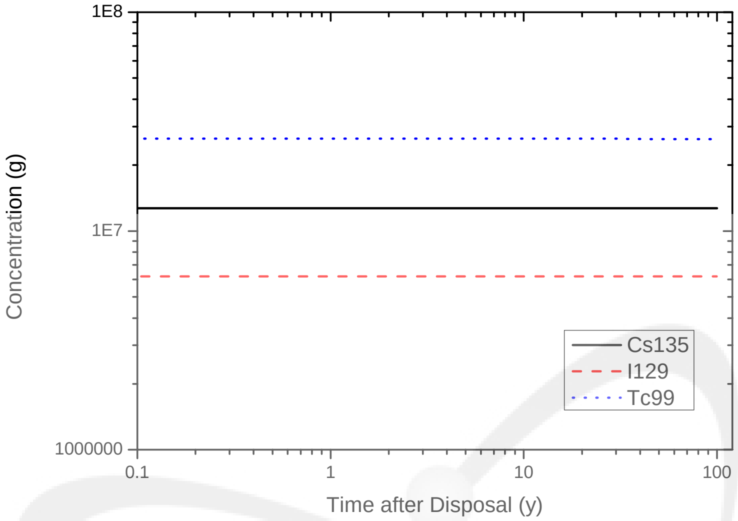


Fig. 12 Concentration of Long-Lived Fission Products after Disposal in 2100

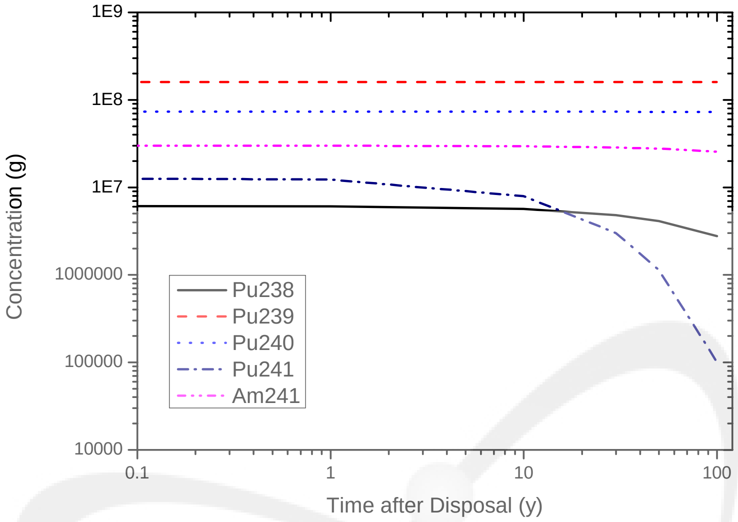


Fig. 13 Concentration of Actinides after Disposal in 2100

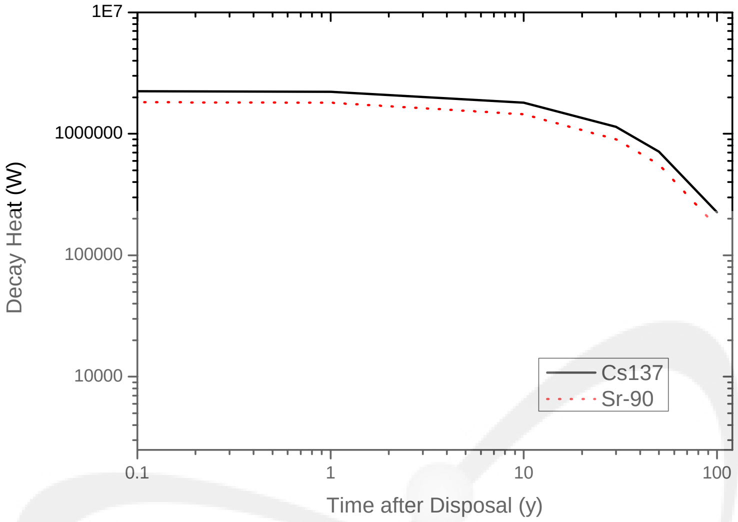


Fig. 14 Short-Term Decay Heat of Main Fission Products after Disposal in 2100

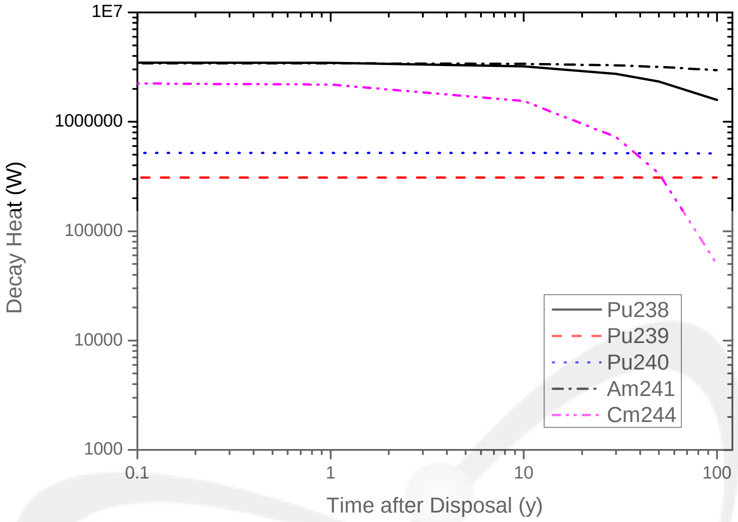


Fig. 15 Short-Term Decay Heat of Main Actinides after Disposal in 2100

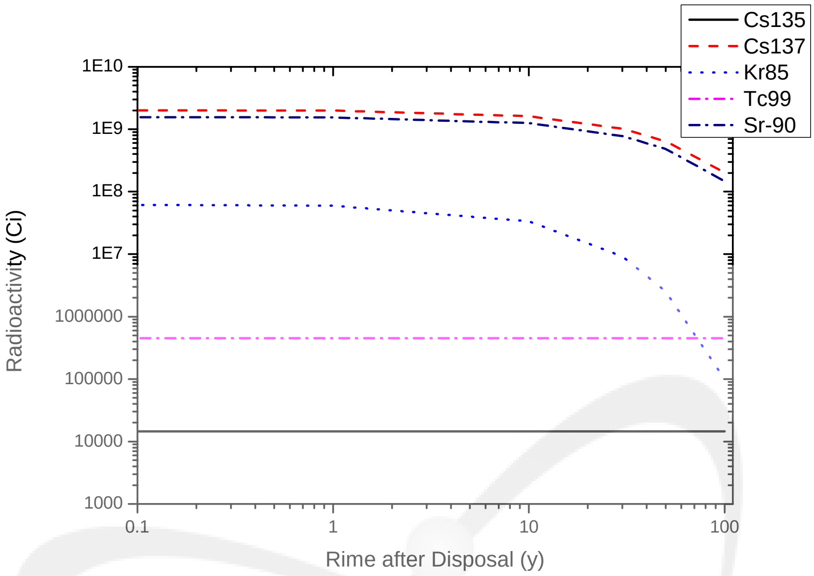


Fig. 16 Short-Term Radioactivity of Main Fission Products after Disposal in 2100

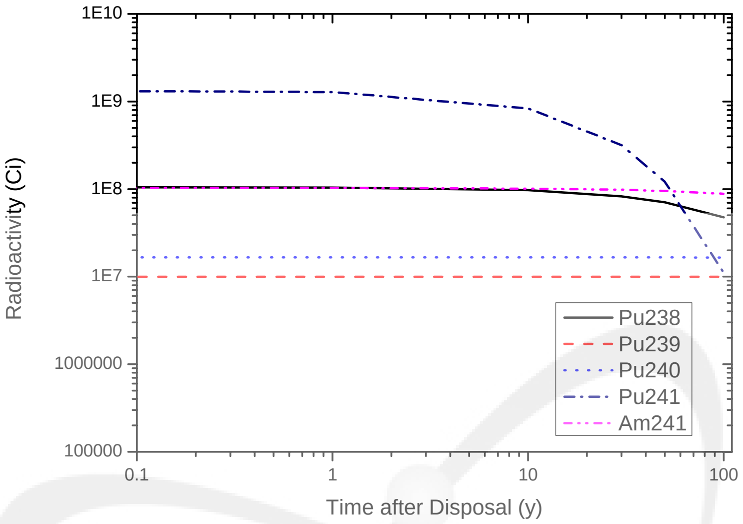


Fig. 17 Short-Term Radioactivity of Main Actinides after Disposal in 2100

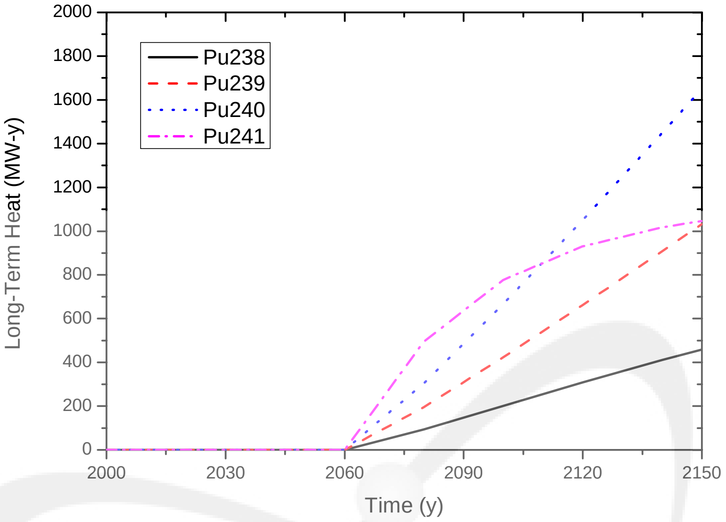


Fig. 18 Long-Term Heat Load of Pu Isotopes with Time

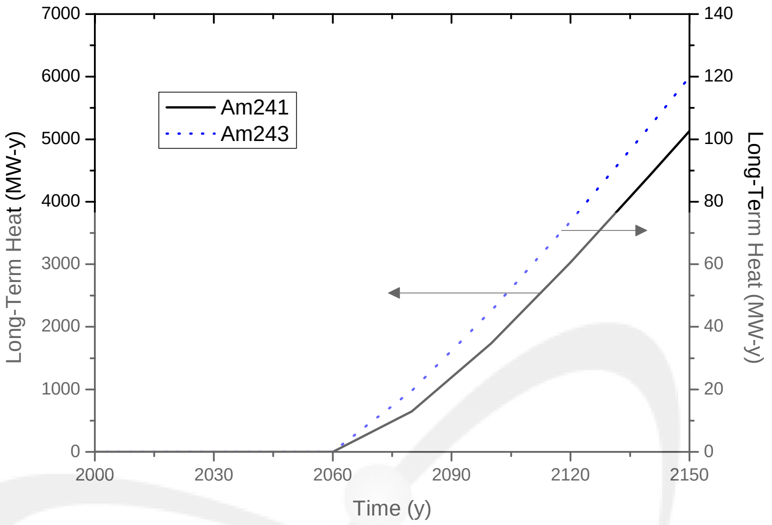


Fig. 19 Long-Term Heat Load of Am Isotopes with Time

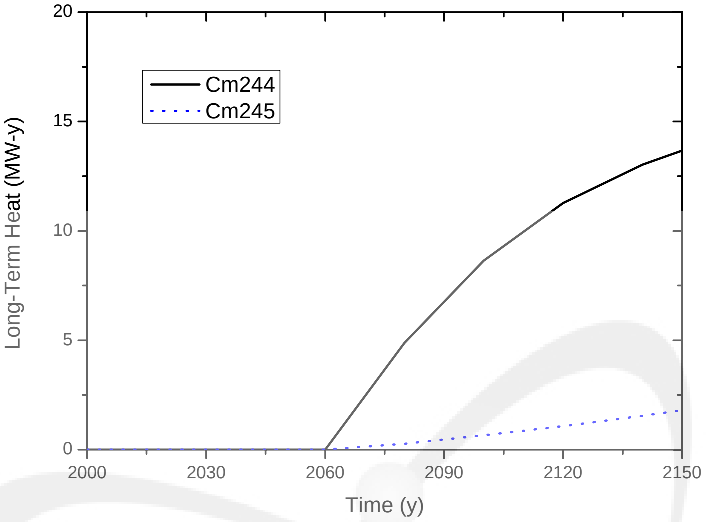


Fig. 20 Long-Term Heat Load of Cm Isotopes with Time

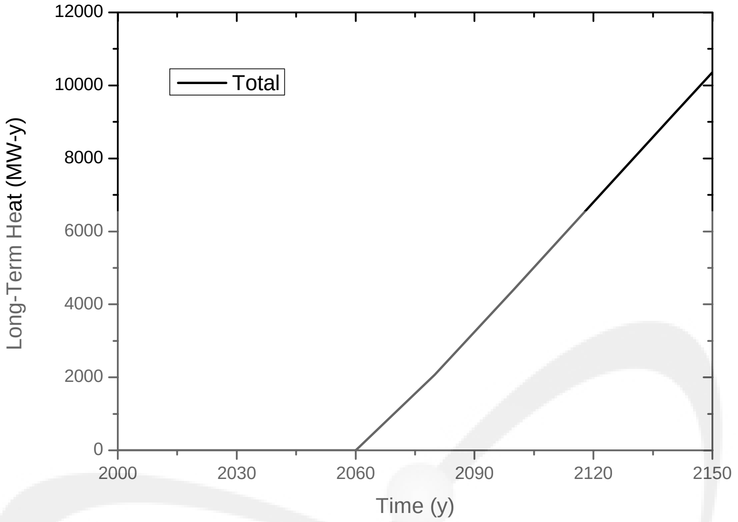


Fig. 21 Total Long-Term Heat Load with Time

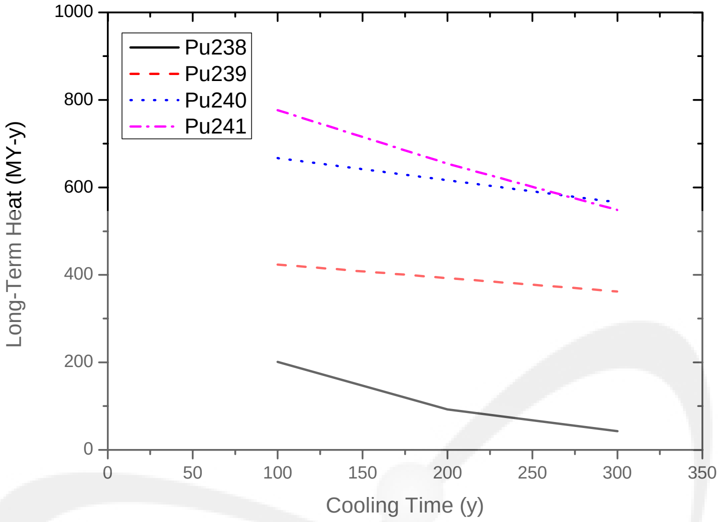


Fig. 22 Long-Term Heat Load of Pu Isotopes with Cooling Time

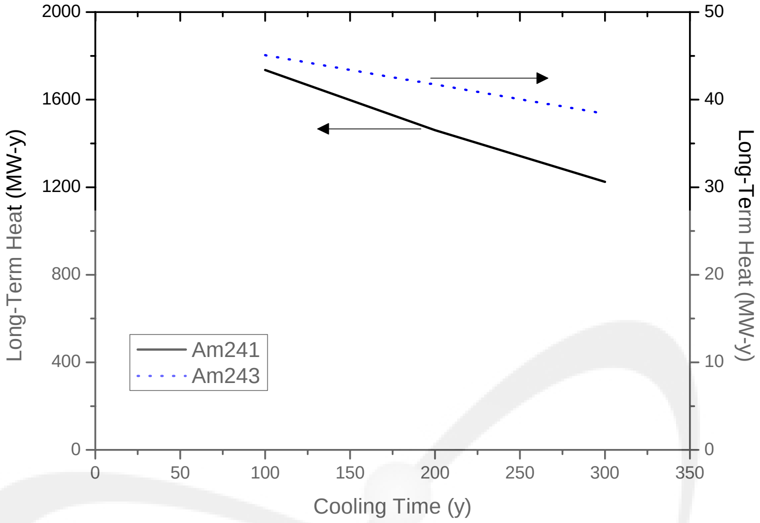


Fig. 23 Long-Term Heat Load of Am Isotopes with Cooling Time

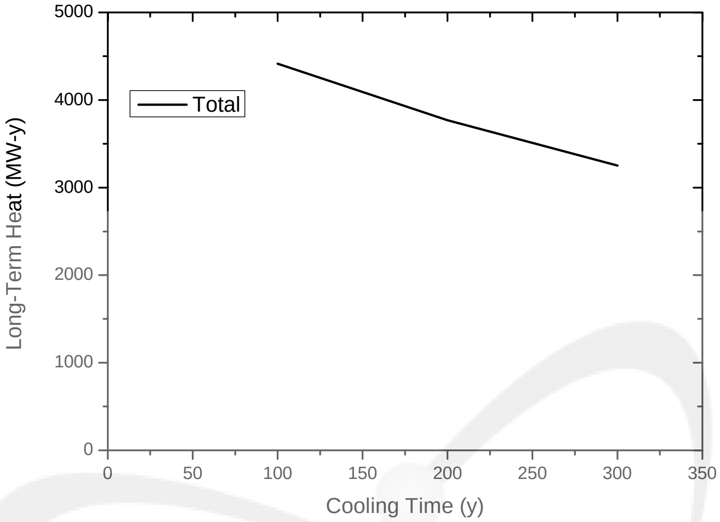


Fig. 24 Total Long-Term Heat Load with Cooling Time

서지정보양식

수행기관보고서번호	위탁기관보고서번호	표준보고서번호	INIS 주제코드
KAERI/TR-4098/2010			

제목/부제	사용후 핵연료 동적 환경영향 해석 모델 개발
연구책임자 및 부서명	정창준 (국제전략 연구부)
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출 판 지	대전	발행기관	한국원자력연구원	발행년	2010.7.
페 이 지	41 p.	도 표	있음(O), 없음( )	크 기	26 Cm.
참고사항					

비밀여부	공개(O), 비공개( ), 대외비( ), __ 급비밀	보고서종류	기술보고서
연구위탁기관		계약 번호	

초록 (15-20줄내외)

사용후 핵연료 동적 환경 영향 평가 모데을 개발하였으며, system dynamic 코드인 DANESS 코드에 적용하였다. 이를 위해 먼저 사용후 핵연료 동위 원소의 붕괴 모델을 작성하였다. 그 후 단기 붕괴열 계산 모델, 단기 방사능 계산 모델 및 장기 열부하 계산 모델 등을 통하여 환경 영향 평가 모델을 개발하였다. 개발된 모델을 이용하여 국내 직접 처분 주기 해석을 수행하였다. 직접 처분 주기는 국가 에너지 기본 계획에 따라 2030년까지 원자력 발전량을 고려하였고, 그 이후 2150년까지는 원자력 발전 증가율을 가정하여 사용하였다. 계산 결과에 의하면, 2150년도에 원자력 시설 용량은 70 GWe이 되고 사용후 핵연료 누적량은 168000 t 이 될 것으로 예측된다. 사용후 핵연료가 2060년부터 처분된다고 가정하면 2100년도에 C3-137 및 Sr-90 원소의 단기 붕괴열은 2.3×10^6 및 1.8×10^6 W 가 되며, 장기 열부하는 4415 MW-y 가 될 것으로 예측되었다. 이러한 계산 결과를 통해 이번에 개발된 모델을 사용후 핵연료 환경영향을 편리하고 간단히 평가할 수 있는 것으로 나타났다.

주제명키워드 (10단어내외)	환경영향, 사용후 핵연료, DANESS 코드, 직접 처분 주기, 붕괴열, 방사능, 장기-열 부하

BIBLIOGRAPHIC INFORMATION SHEET

Performing Org. Report No.	Sponsoring Org. Report No.	Standard Report No.	INIS Subject Code
KAERI/TR-4098/2010			

Title/Subtitle	Development of Dynamic Spent Nuclear Fuel Environmental Effect Analysis Model
Main Author	Jeong, Chang Joon (Division of Strategic and International Studies)
Researcher and Department	Ko, Won Il, Lee Ho Hee Cho Dong Keun, Park Chang Je

Publication Place	Daejeon	Publisher	KAERI	Publication Date	2010. 7.
Page	41 p.	Ill. & Tab.	Yes (O), No ( )	Size	26 Cm.
Note					

Classified	Open (O), Closed( ), __Restricted( ), -- Class Document	Report Type	Technical Report
Sponsoring Org.		Contract No.	

Abstract (15-20 Lines)

The dynamic environmental effect evaluation model for spent nuclear fuel has been developed and incorporated into the system dynamic DANESS code. First, the spent nuclear fuel isotope decay model was modeled. Then, the environmental effects were modeled through short-term decay heat model, short-term radioactivity model, and long-term heat load model. By using the developed model, the Korean once-through nuclear fuel cycles was analyzed. The once-through fuel cycle analysis was modeled based on the Korean “National Energy Basic Plan” up to 2030 and a postulated nuclear demand growth rate until 2150. From the once-through results, it is shown that the nuclear power demand would be ~70 GWe and the total amount of the spent fuel accumulated by 2150 would be ~168000 t. If the disposal starts from 2060, the short-term decay heat of Cs-137 and Sr-90 isotopes are 2.3×10^{6} W and 1.8×10^{6} W in 2100. Also, the total long-term heat load in 2100 will be 4415 MW-y. From the calculation results, it was found that the developed model is very convenient and simple for evaluation of the environmental effect of the spent nuclear fuel.

Subject Keywords (About 10 words)	environmental effect, spent nuclear fuel, DANESS code, once-through cycle, decay heat, radioactivity, long-term heat load