CORE MODELING AND SOURCE TERM CALCULATIONS USING MCNPX CODE FOR FUKUSHIMA DAIICHI UNIT-1 NUCLEAR POWER PLANT ACCIDENT

M. SHAAT.
Egyptian Atomic Energy Authority, (EAEA)
Cairo, Egypt
Email: m_shaat3073@yahoo.com

R. F. MAHMOUD
Egyptian Atomic Energy Authority, (EAEA)
Cairo, Egypt

M. M. ABDU
Zewail City of Science and Technology
Cairo, Egypt

Abstract

Management of severely damaged spent fuel and corium plays an important role in the nuclear safety issues for the nuclear power plants. The calculation of burned fuel inventory is required for determining the composition, activity of core melt and in the estimation of the radiological source term in the environment. Isotopic inventory of the burned fuel at the time of the accident of Fukushima Daiichi Unit 1 (FD-U1) was calculated using Monte Carlo analysis MCNPX 2.7 code linked to depletion calculation code CINDER'90 and ENDF/B-VII.0 cross section data library. The reactor core model results were validated with experimental measurements which was carried out by Japan Nuclear Energy Safety Organization (JNES) and verified with published results using ORIGEN-Code by Japan Atomic Energy Agency (JAEA). The verification comparison was in good agreement for all the radionuclides, and more radionuclides were obtained using MCNPX-Code. The total activity of the burned fuel at the time of the accident was 9.86E+19 Bq and after 50 Yrs. was 1.89E+17 Bq and the higher inventory concentration in the fuel was dominated by the trans-uranic elements. Also, the specific activity was calculated for the inventory at the time of the accident and after 50 Yrs. And found to be 1.84E+15 Bq/gm and 5.86E+12 respectively.

1. INTRODUCTION

On 11th March 2011, Fukushima Daiichi Unit 1 (FD-U1), was generating electricity when the earthquake occurred, it was shutdown automatically, however the resulted tsunami halted the emergency core cooling. Water levels in the reactor vessel dropped below the top of the hot fuel, and steam began reacting with the zirconium fuel cladding to produce large amounts of hydrogen and core began melting. Several published studies were dealt with the calculation of core inventory and source term for Fukushima Daiichi NPP accident using different methodologies and assumptions, the importance of the burned fuel inventory calculations is to assess the consequences of radionuclides releases following a nuclear accident [1, 2, 3, 4, 5, and 18].

Isotopic inventory of the burned fuel at the time of the accident of FD-U1 was calculated using Monte Carlo analysis MCNPX2.7 code linked to depletion calculation code CINDER'90 and using ENDF/B-VII.0 cross section data library. The results were validated with experimental measurements carried out by JNES and verified with JAEA.

2. REACTOR CORE MODELING

2.1. Core Configuration

FD-U1 is a BWR/3 type from General Electric and operated by Tokyo Electric Power Company. The reactor core contained of 400 fuel assemblies consist of 332(400) 9x9-9 type B and 68(400) 8x8-8 type STEP2, the fuel is Uranium Dioxide and its total charge of uranium content is 69 ton. Each fuel assembly contains fuel pins in square arrays and water channel that all are cladded in zircalloy fuel channel box.

The control rods located outside the fuel assemblies and are in cross-shaped arrangements of blades containing boron carbide (B4C). The fuel pins consist of low enrichment uranium oxide with an average value equal to 3.7% enclosed and sealed in zirconium cladding tubes. The fuel design and reactor core arrangements evolved over the years. The technical data of the FD-U1 is presented in Table 1.

TABLE 1. TECHNICAL DATA OF FD-U1 [6-15]

Core Configuration		
Total amount of uranium	69	ton
Reactor Thermal Power	1380	MW_t
Fuel Assembly		
Total number	400	
Channel Box material	Zircaloy-4	
Inner channel width	13.05	cm
Outer channel width	13.9	cm
Fuel Rod		
Diameter of pellet	0.94	cm
Diameter of cladding	1.1	cm
Thickness of cladding (Thickness of zirconium liner)	0.70 (0.1)	mm
Number of fuel rods in one fuel assembly	9x9-9 (water channel)	
Gap radius	0.48	cm
Cladding material	Zircaloy-4	
Fuel Rod Pitch	1.45	cm
Fuel Rod Active Length	366	cm
Fuel Density (97 % of theoretical density)	10.7	g/cm^3
Enrichment (approximated)	3.7%	
Cladding Density	6.56	g/cm^3
The average void fraction	40%	
Water Channel Box		
Water Channel Width	3.75	cm

2.2. Model Description

The last core loading before the accident was about one quarter of the core, and its configuration consist of fresh fuel assemblies and burned assemblies with five different burn ups with an average value equal to 19.25 GWd/MTU. The average core burn up at the time of the accident reached to 25.82 GWd/MTU, this core was operated for 165 days with thermal power 1380 MWth ended at 11 March 2011[9, 16,17].

The core modelling of FD-U1 using MCNPX Code was based on 400 assemblies of 9x9-9 type B and average enrichment to be 3.7% with preservation of the same amount of UO2. The last core burn up was estimated from previous operational histories to be 25.82 GWd/MTU, according to JAEA.

2.2.1. Geometrical Model

MCNPX modelling of the fuel assembly and fuel rod geometry are shown in Fig. 1.

FIG. 1. Modelling of Fuel Rod and Fuel Assembly 9x9-9 Type B.

2.2.2. Material Composition of the Core

The initial Atomic densities for cladding and channel box, Moderator and fuel meat composition are tabulated in Tables 2, 3 and 4.

TABLE 2. ZR-4 CLADDING AND CHANNEL BOX

Element	Atom Density (atoms/b.cm)
Cr	7.5891E-5
Fe	1.4838E-4
Zr	4.2982E-2

TABLE 3. MODERATOR

Void%	Nuclide	Atom Density (atoms/b.cm)
40	H-1	3.0588E-2
	O-16	1.5294E-2

TABLE 4. FUEL MEAT (wt. %=3.7)

Element	Atom Density (atoms/b.cm)
U-235	8.82E-4
U-238	2.27E-2
O-16	4.71E-2

2.3. Model Validation

The MCNPX model was validated and simulated for one fuel assembly and the results were compared with experimental measurements which were carried out by Japan Nuclear Energy Safety Organization (JNES) [10].

This experiment was carried out for samples of BWR 9x9-9 fuel assembly, which is the same as FD-U1 assembly. The Isotopic Dilution Mass Spectrometry was used for sample measurements. The measured sample results for U and Nd were compared with our model calculations as given in Tables 5 and 6. From these tables we can find that our results using MCNPX Code are in close acceptance with the measured values by JNES [10].

TABLE 5. COMPARISON FOR ISOTOPIC INVENTORIES OF URANIUM CONTENT

Isotope ID	MCNPX (atoms/b.cm)	Atom Density (atoms/total U atoms)	JNES [10] Measured atoms/total U atoms
U-233	8.70E-11	3.88E-09	-
U-234	5.94E-06	2.65E-04	3.00E-04
U-235	2.39E-04	1.07E-02	1.03E-02
U-236	1.54E-04	6.85E-03	7.00E-03
U-237	1.30E-07	5.81E-06	-
U-238	2.20E-02	9.82E-01	9.82E-01
U-239	5.98E-09	2.67E-07	-
Total density	2.24E-02		

TABLE 6. COMPARISON FOR ISOTOPIC INVENTORIES OF NEODYMIUM CONTENT

Isotope ID	MCNPX (atoms/b.cm)	Atom Density (atoms/total U atoms)	JNES [10] Measured atoms/total U atoms
Nd-142	1.01E-06	5.83E-03	5.60E-03
Nd-143	3.25E-05	1.88E-01	1.82E-01
Nd-144	5.62E-05	3.25E-01	3.46E-01
Nd-145	2.98E-05	1.72E-01	1.67E-01
Nd-146	3.16E-05	1.83E-01	1.71E-01
Nd-147	7.98E-08	4.61E-04	-
Nd-148	1.56E-05	9.02E-02	8.81E-02
Nd-150	6.13E-06	3.54E-02	3.99E-02
Total density	1.73E-04		

3. RESULTS AND DISCUSSIONS

The activity of the radionuclides for the source term of FD-U1 accident using MCNPX-Code were calculated and grouped according to the NUREG-1465 classification which presented at Table 7.

TABLE 7. RADIONUCLIDES CLASSIFICATION OF SOURCE TERM

Radionuclides grouping	Activity (Bq)
Nobel Gases (Xe, Kr)	3.96E+18
Halogens (I, Br)	4.00E+18
Alkali Metals (Cs, Rb)	4.78E+17
Tellurium group (Te, Sb, Se)	2.03E+18
Barium, strontium (Ba, Sr)	3.85E+18
Noble Metals (Ru, Rh, Pd, Mo, Tc, Co)	7.27E+18
Lanthanides (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y)	1.34E+19
Cerium group (Ce, Pu, Np)	3.45E+19

Concerning the amount of uranium in the core, for its last reloading it was 69 ton and at the time of the accident it reduced to 68.8 ton, the rest of the mass was depleted for about 165 days according to JAEA and the fission products mass found to be about 1.84 ton. In addition to that, the total estimated mass of the core composition was about 125.85 ton, which includes the depleted fuel, control rods and structural materials as shown at Table 8.

TABLE 8. ESTIMATED CORE MATERIALS INVENTORY AT THE TIME OF ACCIDENT

At the time of accident	Mass (Ton)
U [a]	69
UO_2 [a]	78.3
Fission Product [a]	1.84
Zircaloy (Clad) [b]	17.8
Zircaloy (channel box) [b]	13.82
Fe [c]	12.5
B_4C [c]	0.59
Inconel [c]	1
Total	125.85
a MCNPX calculations	
b Model Estimations	
c Fumiya TANABE [22]	

The activity of the calculated radionuclides at the time of the accident and after 50 years from the accident using MCNPX code were verified with ORIGEN2 code calculations which were carried out by JAEA [17]. The results were found in good agreement as shown at Figures [2-3], we can notice that, the activity and the specific activity of the major actinides after 50 Yrs. from the accident and its specific activity reduced to 3.42E+16 Bq and to 2.04E+11 Bq/gm respectively.

Moreover, the total activity of the core melt is 1.89E+17 Bq, is 1.5E+9 Bq/gm, assuming homogenized mixture of core melt, and that assist in the partitioning and safe handling of the corium for next stages of treatment or decommissioning.

In addition to that, the knowledge of the mass inventory for actinides can benefit in the recycling and manufacture of MOX fuel and radioactive waste management. Tab 9 and 10 present the inventories and corresponding activities of actinides and fission products for the core at the time of the accident and after 50 Yrs.

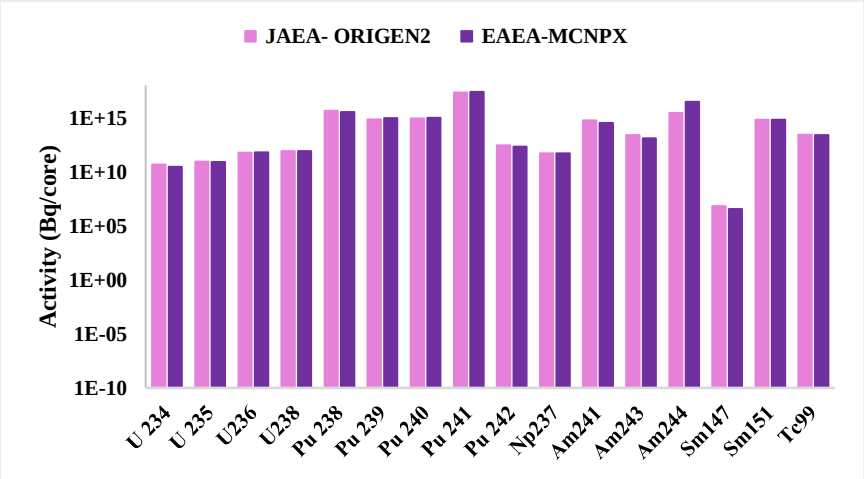

FIG. 2. Activity of the radionuclides at 0 Day (time of the accident).

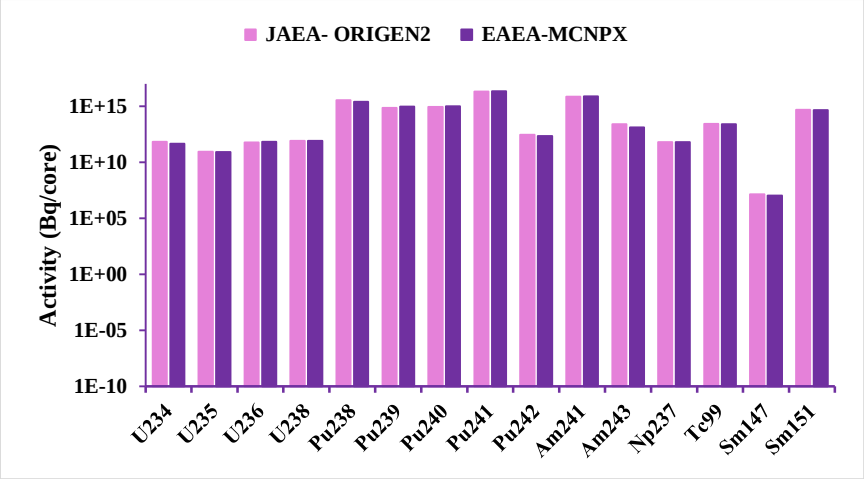

FIG. 3. Activity of selected radionuclides after 50 Years.

TABLE 9. THE VALUES OF THE INVENTORIES AND CORRESPONDING ACTIVITIES OF ACTINIDES AND FISSION PRODUCTS FOR THE CORE AT THE TIME OF THE ACCIDENT

Radionuclide	Activity (Bq/core)	Half-life$_{(T1/2)}$	Decay Mode	Inventory (gm/core)
U239	2.79E+19	23.45 min.	β(Np239)	2.25E+01
Np239	2.78E+19	2.356 D	β-(Pu239)	3.24E+03
Xe133	2.81E+18	5.243 D	β-(Cs133)	0.00E+00
I135	2.62E+18	6.57 h	β-(Xe135)	0.00E+00
Te132	1.94E+18	3.204 D	β-(I132)	0.00E+00
I131	1.37E+18	8.0252D	β-(Xe131)	0.00E+00
Xe135	1.12E+18	9.14 H.	β-(Cs135)	0.00E+00
U237	9.38E+17	6.752 H.	β-(Np237)	3.11E+02
Sm153	4.59E+17	46.284 H.	β-(Eu153)	0.00E+00
Np238	3.20E+17	2.099 D	β-(Pu238)	3.34E+01
Pm147	2.73E+17	2.6234 Yrs.	β-(Sm147)	0.00E+00
Pu241	2.48E+17	14.329 Yrs.	β-(Am241)	6.48E+04
Pu243	2.14E+17	4.956 H	β-(Am243)	2.23E+00
Cs134	2.11E+17	2.0652 Yrs.	β-(Ba134)	0.00E+00
Cs137	1.98E+17	30 Yrs.	β-(Ba137)	0.00E+00
Sr90	1.56E+17	28.79 Yrs.	β-(Y90)	0.00E+00
Am642	1.10E+17	16.02 H.	β-(Cm242)	3.69E+00
Cm242	5.54E+16	162.8 D	β-(Pu238)	4.52E+02
Am244	3.07E+16	10.1 H.	β-(Cm244)	6.52E-01
Kr85	1.83E+16	10.739 Yrs.	β-(Rb85)	0.00E+00
Am644	1.34E+16	10.1 H	β-(Cm244)	1.22E-02
Sb125	1.26E+16	2.75856 Yrs.	β-(Te125)	0.00E+00
Eu154	9.89E+15	8.601 Yrs.	β-(Gd154)	0.00E+00
Eu155	5.49E+15	4.753 Yrs.	β-(Gd155)	0.00E+00
Pu238	3.36E+15	87.7 Yrs.	α-(U234)	5.31E+03
Pu240	1.00E+15	6561 Yrs.	α-(U236)	1.19E+05
Cm244	9.25E+14	18.11 Yrs.	α-(Pu240)	3.09E+02
Pu239	9.11E+14	24110 Yrs.	α-(U235)	3.97E+05
Sm151	6.70E+14	90 Yrs.	β-(Eu151)	0.00E+00
Am241	3.35E+14	432.6 Yrs.	α-(Np237)	2.64E+03
Tc99	2.45E+13	2.111E+5 Yrs.	β-(Ru99)	0.00E+00
Am243	1.31E+13	7364 Yrs.	α-(Np239)	1.78E+03
Cm243	1.30E+13	29.1 Yrs.	α-(Pu239)	6.83E+00
Am242	6.52E+12	16.02 H	β-(Cm242)	1.68E+01
Eu152	5.13E+12	13.517 Yrs.	EC, β+(Sm152)	0.00E+00
Zr93	3.52E+12	1.61E+6 Yrs.	β-(Nb93)	0.00E+00
Pu242	2.14E+12	3.75E+5 Yrs.	α-(U238)	1.46E+04
Pu237	1.26E+12	45.64 D	EC(Np237)	2.79E-03
Cs135	1.22E+12	2.3E+6 Yrs.	β-(Ba135)	0.00E+00
Th234	1.16E+12	24.10 D	β-(Pa234)	1.36E-03
Se79	1.16E+12	3.27E+5 Yrs.	β-(Br79)	0.00E+00

Sn126	9.06E+11	2.3E+5 Yrs.	β-(Sb126)	0.00E+00
U238	8.11E+11	4.468E+9 Yrs.	α-(Th234)	6.52E+07
U236	6.43E+11	2.342E+7 Yrs.	α-(Th232)	2.69E+05
Pa233	5.47E+11	26.975 D	β-(U233)	7.12E-04
Np237	5.17E+11	2.144E+6 Yrs.	α-(Pa233)	1.98E+04
Am240	4.52E+11	50.8 H	EC-(Pu240)	4.77E-05
Pu245	2.02E+11	10.5 H	β-(Am245)	4.48E-06
Pd107	1.25E+11	6.5E+6 Yrs.	β-(Ag107)	0.00E+00
Pu236	1.18E+11	2.858 Yrs.	α-(U232)	6.10E-03
Th231	9.82E+10	25.52 H	β-(Pa231)	5.00E-06
Pa232	8.97E+10	1.32 D	β-(U232)	5.64E-06
Cm245	8.63E+10	8423 Yrs.	α-(Pu241)	1.36E+01
U235	8.31E+10	7.04E+8 Yrs.	α-(Th231)	1.04E+06
Ba133	5.62E+10	10.551 Yrs.	EC-(Cs133)	0.00E+00
Th233	5.39E+10	21.83 min	β-(Pa233)	4.03E-08
I129	4.81E+10	1.57E+7 Yrs.	β-(Xe129)	0.00E+00
U234	3.01E+10	2.455E+5 Yrs.	α-(Th230)	1.31E+02
Cm241	1.01E+10	32.8 D	EC-(Am241)	1.65E-05

TABLE 10. THE VALUES OF THE INVENTORIES AND CORRESPONDING ACTIVITIES OF ACTINIDES AND FISSION PRODUCTS FOR THE CORE AFTER 50 Yrs

Radionuclide	Activity (Bq/core)	Half-life$_{(T1/2)}$	Decay Mode	Inventory (gm/core)
Cs137	6.23E+16	30.08 Yrs.	β-(Ba137)	1.94E+04
Sr90	4.56E+16	28.79 Yrs.	β-(Y90)	8.73E+03
Pu241	2.22E+16	14.329 Yrs.	β-(Am241)	5.80E+03
Am241	7.40E+15	432.6 Yrs.	α(Np237)	5.84E+04
Pu238	2.47E+15	87.7 Yrs.	α(U234)	3.90E+03
Pu240	1.00E+15	6561 Yrs.	α(U236)	1.19E+05
Pu239	9.17E+14	2.411E+4 Yrs.	α(U235)	4.00E+05
Kr85	7.23E+14	10.739 Yrs.	β-(Rb85)	4.97E+01
Sm151	4.62E+14	90 Yrs.	β-(Eu151)	4.75E+02
Eu154	1.76E+14	8.601 Yrs.	β-(Gd154)	1.76E+01
Cm244	1.37E+14	18.11 Yrs.	α(Pu240)	4.57E+01
Tc99	2.46E+13	2.111E+5 Yrs.	β-(Ru99)	3.88E+04
Np239	1.31E+13	2.356 D	β-(Pu239)	1.52E-03
Am243	1.31E+13	7364 Yrs.	α(Pu240)	1.77E+03
Am242	5.10E+12	16.02 H.	β-(Cm242)	1.32E+01
Am642	5.08E+12	16.02 H	β-(Cm242)	1.70E-04
Cm242	4.21E+12	162.8D	α-(Pu238)	3.44E-02
Cm243	3.87E+12	29.1 Yrs.	α-(Pu239)	2.03E+00
Eu155	3.36E+12	4.753 Yrs.	β-(Gd155)	1.84E-01
Pu242	2.14E+12	3.75E+5 Yrs.	α-(U238)	1.46E+04
Cs135	1.22E+12	2.3E+6 Yrs.	β-(Ba135)	2.86E+04
Th234	8.11E+11	24.1 D	β-(Pa234)	9.47E-04
U238	8.11E+11	4.468E+9 Yrs.	α-(Th234)	6.52E+07
U236	6.45E+11	2.342E+7 Yrs.	α-(Th232)	2.69E+05
Np237	6.11E+11	2.144E+6 Yrs.	α-(Pa233)	2.34E+04
Pa233	6.11E+11	26.975 D	β-(U233)	7.95E-04
U237	5.31E+11	6.752 D	β-(Np237)	1.76E-04
Pm147	5.23E+11	2.6234 Yrs.	β-(Sm147)	1.52E-02
U234	4.57E+11	2.455E+5 Yrs.	α-(Th230)	1.99E+03
Eu152	3.81E+11	13.517 Yrs.	EC, β+(Sm152)	5.84E-02
Pd107	1.25E+11	6.5E+6 Yrs.	β-(Ag107)	6.58E+03
Cm245	8.60E+10	8423 Yrs.	α(Pu241)	1.35E+01
Th231	8.32E+10	25.52 H.	β-(Pa231)	4.23E-06
U235	8.32E+10	7.04E+8 Yrs.	α(Th231)	1.04E+06
I129	4.85E+10	1.57E+7 Yrs.	β-(Xe129)	7.42E+03
Sb125	3.94E+10	2.75856 Yrs.	β-(Te125)	1.02E-03
Np238	2.30E+10	2.099 D	β-(Pu238)	2.39E-06
Cs134	1.07E+10	2.0652 Yrs.	β-(Ba134)	2.24E-04
Cm246	7.01E+09	4706 Yrs.	α(Pu242)	6.17E-01
Np236	2.84E+07	1.53E+5 Yrs.	EC(U236)	5.82E-02
Xe135	1.93E+07	9.14 hrs.	β-(Cs135)	2.05E-10
I135	1.69E+07	6.58 hrs.	β-(Xe135)	1.29E-10
Xe133	1.55E+07	5.2475 day	β-(Cs133)	2.24E-09
Pu236	3.29E+06	2.858 Yrs.	α(U232)	1.70E-07
Cf249	1.34E+05	351 Yrs.	α(Cm245)	8.85E-07
Pu244	1.09E+05	8.13E+7 Yrs.	α(U240)	1.61E-01
Cm248	2.35E+04	3.48E+5 Yrs.	α(Pu244)	1.50E-04
Pu243	1.48E+04	4.956 H.	β-(Am243)	1.54E-13
Cm247	1.48E+04	1.56E+7 Yrs.	α(Pu243)	4.43E-03

4. CONCLUSIONS

In this paper, the spent fuel inventory and source term composition were calculated using MCNPX-Code for FD-U1 accident. The MCNP results were validated with the experimental measurements which were carried out by JNES. Also, the activity of the radionuclides using MCNPX Code was compared with JAEA calculations using ORIGEN 2 Code. The activity of the source term composition is categorized according to the NUREG-1465 which is important in the estimation of the radiological releases to the people and the environment.

At the time of accident, the total activity and the specific activity of the actinide and the non-actinide in the core was 9.86E+19Bq and 1.84E+15 Bq/gm respectively; and after 50 Yrs. the total activity and the specific activity of the actinide and the non-actinide in the core was 1.89E+17Bq and 5.86E+12Bq/gm respectively.

In addition to that, the knowledge of the mass inventory for actinides can benefit in the recycling and manufacture of MOX fuel and radioactive waste management.

ACKNOWLEDGEMENTS

The authors acknowledge and thank, IAEA for the sponsorship of this research work under a Coordinated Research Project Code: CRP-T13015, entitled, Management of Severely Damaged Spent Fuel and Corium Research Project; and Egyptian Atomic Energy Authority (EAEA) for supporting this work.

REFERENCES

[1] Mark Holt, Richard J. Campbell and Mary Beth Nikitin, Fukushima Nuclear Disaster, Congressional Research Service, January 18, 2012.

[2] Tokyo Electric Power Company (TEPCO), The Evaluation Status of Reactor Core Damage at Fukushima Daiichi Nuclear Power Station Units 1 to 3, Tokyo Electric Power Company, November 30, 2011.

[3] Earthquake Report No.91, Japan Atomic Industrial Forum (JAIF), https://www.jaif.or.jp/en/, May 25, 2011.

[4] Fukushima, one year later, initial analyses of the accident and its consequences, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Report IRSN/DG/2012-003, March 12, 2012.

[5] Shiaki Tsukuda, Hiroshi Hayashi, Katsuichiro Kamimura, Toshiitsu Hattori, Hirohisa Kaneko, Shinichi Morooka, Toru Mitsutake, Miyuki Akiba, Nobuaki Abe, Masahiko Warashina, Yasuhiro Masuhara, Jiro Kimura, Akira Tanabe, Yuji Nishino, Koujun Isaka and Riichiro Suzuk, Proving Test on Thermal-Hydraulic Performance of BWR Fuel Assemblies, Journal of Nuclear Science and Technology, Atomic Energy Society of Japan, Vol. 31, Issue 2, Published: February 28, 1989, Released: April 21, 2009.

[6] Katsuhiro Tsuda, Akira Itami, Yuichiro Kubo, Taketomi Shakudo, Dieter Kreuter, Takafumi Anegawa, Hideya KITAMURA & Masumi ISHIKAWA, Analysis of Core Stability Measurement Data of Advanced 9×9 Fuel Assembly in a BWR Core, Journal of Nuclear Science and Technology, March 15, 2012.

[7] Yoshitaka Naito and Hiroshi Okuno, OECD/NEA- Burrup Credit Criticality Benchmark- Phase IIIB," Nuclide Composition and Neutron Multiplication Factor of BWR Spent Fuel Assembly", Japan Atomic Energy Research Institute, November 1996.

[8] Toru Yamamoto &Yuichiro Kanayama, Lattice Physics Analysis of Burnups and Isotope Inventories of U, Pu, and Nd of Irradiated BWR9×9-9 UO2 Fuel Assemblies, Journal of Nuclear Science and Technology, January 2012.

[9] MCNPX User's Manual Version 2.7.0, April 2011.

[10] Toru Yamamoto, Compilation of Measurement and Analysis Results of Isotopic Inventories of Spent BWR Fuels, Japan Nuclear Energy Safety Organization, February 2009.

[11] Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF Project), Phase I Summary Report, March 2015.

[12] Compendium of Material Composition Data for Radiation Transport Modeling, PNNL-15870 Rev. 1, March 4, 2011.

[13] OECD, Reference Values for Nuclear Criticality Safety, https://www.oecd-nea.org/science/wpncs/Publications/ref-val-criticality-safety/, 2007.

[14] T. Yamamoto, Y. Kanayama, Lattice Physics Analysis of Burnups and Isotope Inventories of U, Pu, and Nd of Irradiated BWR 9×9-9 UO2 Fuel Assemblies, Journal of Nuclear Science and Technology, 45:6, 547-566, January 5, 2012.

[15] Toru Yamamoto & Munenari Yamamoto Nuclear Analysis of PIE Data of Irradiated BWR 8×8-2 and 8×8-4 UO2 Fuel Assemblies, Journal of Nuclear Science and Technology, 45:11, 1193-1214, January 5, 2012.

[16] INTERNATIONAL ATOMIC ENERGY AGENCY., The Fukushima Daiichi Accident Technical, Vol. 2, Safety Assessment, IAEA, Vienna (2015).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY., The Fukushima Daiichi Accident Technical, Vol. 4, Radiological Consequences, IAEA, Vienna (2015).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY., The Fukushima Daiichi Accident Technical, Vol. 1 Description and Context of the Accident, IAEA, Vienna (2015).

[19] Kenji Nishihara, Hiroki Iwamoto and Kenya Suyama, Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant, Division of Nuclear Data and Reactor Engineering, Japan Atomic Energy Agency, September 2012.

[20] Shuhei Miwa, Shinichiro Yamashita, Akihiro Ishimi, Masahiko Osaka, Masaki Amaya, Kosuke Tanaka, Fumihisa Nagase, Research Program for the Evaluation of Fission Product and Actinide Release Behaviour, Focusing on Their Chemical Forms, The Fourth International Symposium on Innovative Nuclear Energy Systems, INES-4, Energy Procedia 71 (168-181), 2015.

[21] Bratton, Isaac John, Modeling and validation of the Fuel Depletion and Burnup of the OSU research reactor using MCNPX/CINDER'90, Ohio State University, Nuclear Engineering, 2012.

[22] Fumiya Tanabe, Analysis of Core Melt Accident in Fukushima Daiichi-Unit 1 Nuclear Reactor, Journal of Nuclear Sciences and Technology, 48:8, 1135-1139, 1135–1139, January 5, 2012.