Nuclear Engineering and Design 338 (2018) 92–101

Contents lists available at ScienceDirect

Nuclear Engineering and Design

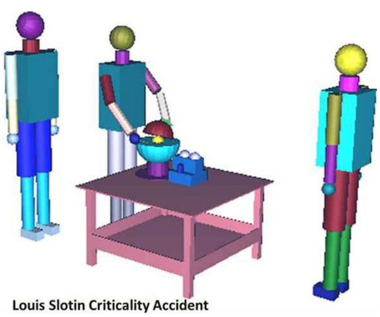
journal homepage: www.elsevier.com/locate/nucengdes

Criticality analysis of the Louis Slotin accident

Mikolaj Oettingen

AGH University of Science and Technology, Faculty of Energy and Fuels, Department of Nuclear Energy, al. Mickiewicza 30, 30-059 Krakow, Poland

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Criticality
Accident
Louis Slotin
MCB
Monte Carlo

ABSTRACT

In this paper, I present a criticality study on the Louis Slotin accident, which happened in Los Alamos Scientific Laboratory (LANL) on 21 May 1946. For the numerical reconstruction of the nuclear system, I used the Monte Carlo Continuous Energy Burnup Code (MCB) developed at the AGH University, Krakow, Poland (Akademia Górniczo-Hutnicza w Krakowie). I present the influence of the environment on the system criticality in the laboratory at the time of the accident. I consider locations, geometry and material composition of the elements forming the nuclear system: the plutonium core, the beryllium reflector, the human body. The numerical approach consists of three steps. Firstly, the isotopic composition of the core is estimated using the criterion of 10 cents excess reactivity achieved during the accident. Secondly, the effective neutron multiplication factor in the function of the Be hemisphere angle above the Pu core is shown. Lastly, the influence of each system component on K_{eff} is calculated. Additionally, the influence of the position of Slotin's hand on the criticality and the neutron spectrum in the core is presented. The study fills the gap in the numerical reconstruction of early criticality accidents and thus helps to preserve critical nuclear knowledge for future generations.

1. Introduction

On 21 May 1946, Louis Slotin, a physicist working on the Manhattan Project, was exposed to a lethal dose of radiation of about 2100 rem (21 Sv) while conducting an experiment with a metallic Pu239 critical assembly (McLaughlin et al., 2000; Harding et al., 1946; Hempelman, 1979). He died of acute radiation syndrome nine days later – on 30 May 1946. The accident was one of the most important events that initiated the development of a strong safety culture in the nuclear industry. However, nowadays – about 72 years after the accident – the knowledge about it seems to be limited to a few scientific reports and some popular-science papers available to the public. To the best of my knowledge, no numerical study on the accident has ever been presented in a scientific paper. Therefore, in order to partly fill this gap and to preserve critical nuclear knowledge, I numerically reconstructed the accident using novel numerical techniques and nuclear data libraries. The analysis may serve as a case study for training of future employees in the nuclear sector.

E-mail address: moettin@agh.edu.pl.

https://doi.org/10.1016/j.nucengdes.2018.08.006
Received 25 April 2018; Received in revised form 30 July 2018; Accepted 7 August 2018
0029-5493/

The paper shows a numerical reconstruction of the environment in the laboratory at the time of the accident. In the numerical model, I considered the main elements influencing the effective neutron multiplication factor K_{eff} i.e. the plutonium core, the beryllium reflector, the human body, the wooden table, lead bricks, aluminium and steel elements and others. I performed numerical simulations using the Monte Carlo Continuous Energy Burnup Code (MCB) (Oettingen et al., 2015; Cetnar, 2006) equipped with JEFF3.1 (Joint Evaluated Fission and Fusion) and ENDF/B-VII.1 (Evaluated Nuclear Data File) nuclear data libraries for numerical comparison (Santamarina et al., 2009; Chadwick et al., 2011). The MCB code is available at the supercomputer Prometheus of the Academic Computer Centre Cyfronet of the AGH University (Akademia Górniczo-Hutnicza w Krakowie) and has been used for modelling of many advanced nuclear systems (Stanisz et al., 2016; Kępisty et al., 2016). The numerical approach consists of three steps. Firstly, the isotopic composition of the core is estimated using the criterion of 10 cents excess reactivity above prompt criticality achieved during the accident (McLaughlin et al., 2000). The reactivity of the system is modified by changing atomic fraction of Pu240, because its amount in the core is unknown. This step allows for the estimation of the core plutonium isotopic composition. Secondly, the behaviour of the effective neutron multiplication factor K_{eff} in the function of the Be hemisphere angle above the Pu core is shown. The angle is changed within the range of 0–45°. Lastly, the influence of each system component on K_{eff} is calculated. Additionally, the influence of the position of Slotin's hand on the criticality and the neutron spectrum in the plutonium core is shown. In practice, due to the lack of sufficient data about the environment in the laboratory, I had to apply reliable assumptions in the numerical model, e.g. the body of Louis Slotin was reconstructed using a model of a "standard" human (Herman, 2007), the volume and thus the radius of the Pu sphere was calculated using known density and mass of the Pu core, material compositions used at LANL for other criticality experiments were applied. The author is aware that it is simply impossible to exactly reconstruct such a complicated and poorly documented problem. However, by using reliable assumptions, the main effects could be shown with satisfying accuracy.

Section 2 – *The accident* – describes the details of the criticality accident which happened in Los Alamos Scientific Laboratory on 21 May 1946. Section 3 – *The numerical model* – shows the numerical model developed and the numerical tools applied. Section 4 – *The results* – presents the numerical results obtained using the MCB code. In Section 5 – *Discussion and summary* – the results are discussed and some suggestions for a supplementary analysis are presented.

2. The accident

The accident designated as LA-2 happened on 21 May 1946 at 3:20p.m. in Los Alamos Scientific Laboratory (McLaughlin et al., 2000). Louis Slotin was demonstrating a technique of creation of a metal critical assembly with a plutonium sphere reflected by beryllium hemispheres to his successor, Alvin Graves. The technique used in the experiment was to bring the hollow Be hemisphere around the fissile Pu239 sphere placed in a similar hemisphere. The experiment was not scheduled and its conduct was the physicists' own decision, motivated by the fact that it was the best available way to teach its practical aspects. The experiment was performed using a 6.2 kg sub-critical plutonium sphere exposed to neutron radiation from 10^6n/s Ra-Be neutron source, placed in the vicinity. The experiment was carried out manually, because reliable remote-control mechanisms were not available at that time. Previously, a lot of critical assembly experiments were performed manually with just a minor exposure of operators. The uncontrolled chain reaction in the metallic plutonium sphere caused by the enhanced neutron reflection by the beryllium hemisphere, accidentally placed on the Pu sphere, caused a burst of neutron and gamma radiation.

Louis Slotin placed the upper Be hemisphere on the aluminium shim above the Pu sphere. Then, he caught it with his left thumb in the opening at the top and removed the shim. One edge of the top Be shell was lowered and touched the bottom of the Be shell. Subsequently, Slotin started to lower the second edge 180° away to the bottom shell, slowly covering the Pu sphere. Finally, the edge was placed at the blade of a screwdriver just slightly above the lower shell. Louis Slotin was taking out the screwdriver from under the shell with his right hand. Suddenly, the screwdriver slipped, and the top shell fell down and fully covered the Pu sphere, which caused the supercritical state and a burst of neutron and gamma radiation. A blue glow was observed, and a heat wave was felt by the experimenters. Louis Slotin immediately removed the top shell with his hands and threw it on the floor. The personnel left the room as quickly as possible, but one experimenter returned to the room and dropped film badges for further radiation measurement and estimation of the obtained doses. According to the available data, prompt criticality with excess reactivity of about 10 cents was achieved (McLaughlin et al., 2000). Eight people were present in the room at the time of the accident. Two of them were directly engaged in the demonstration (Louis Slotin and Alvin Graves). Louis Slotin received a dose of about 2100 rem (21 Sv) and died nine days later. Alvin Graves received a dose of about 360 rem (3.6 Sv) and recovered after several weeks of medical treatment (Harding et al., 1946). The remaining observers received lower radiation doses without a major impact on their health (Hempelman, 1979).

3. The numerical model

In this section, I focus on the developed numerical model for the numerical simulations using the MCB code (Oettingen et al., 2015). The numerical model is based on the available data about geometry and material composition of the elements forming the fissile system. In particular, I focus on the fissile Pu core, the Be reflector, the human body and the neighbouring environment. One of the most valuable sources of information used in the numerical reconstruction is a photograph of the accident mock-up (AHF, xxxx). It gives a general outlook on the working conditions in the laboratory at the time of the accident. The position of Alvin Graves and Dwight Young as well as the dimensions of the room were estimated using a drawing prepared by Louis Slotin just after the accident (Harding et al., 1946). However, the location of Louis Slotin in the photograph is different from the one in the drawing. Therefore, in my study, I assume that Louis Slotin was standing exactly in front of the assembly. In order to construct the numerical model in a reliable way, I used many different reports and publications from various scientific areas. The main publication used for the reconstruction of the accident is *A Review of Criticality Accidents* McLaughlin et al., (2000), which provides a general description of the accident and crucial data about the core, i.e. its mass and density. The material composition was taken from the benchmarks described in the *ICSBEP Handbook* (OECD, 2016) and complemented by the data from the *Compendium of Material Composition Data for Radiation Transport Modelling* (McConn et al., 2011). The model of a standard human and body isotopic composition was taken from the book *Physics of the Human Body* (Herman, 2007) and the paper *Calculating the ambient dose equivalent of fast neutrons using elemental composition of human body* Saeed et al., (2016) respectively. The information about the mass and height of the experimenters is available in the report *Radiation doses in the Pajarito accident of May 21, 1946* (Harding et al., 1946). Additional sources of information are shown in the following sections of this paper. A visualisation of the numerical model is presented in Fig. 1

3.1. The core

The total mass of the spherical core is 6.2 kg of (McLaughlin et al., 2000). The core is composed of δ-phase plutonium–gallium alloy with a density of 15.7 g/cm^3 and Ni cladding with a density of 8.9 g/cm^3 and thickness of about 0.013 cm (5 mils). The radius of the core of

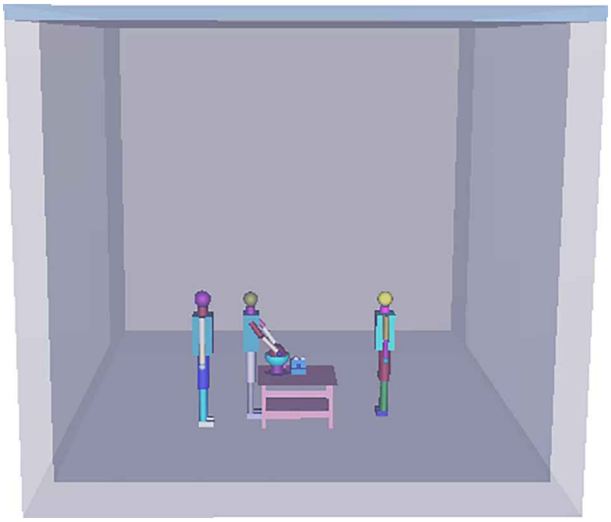


Fig. 1. Visualisation of the numerical model.

Table 1
Material composition.

ID	Material/Component	Density [g/cm^3]	Composition	
			Isotope/Element	wt.%
1	δ-phase plutonium–gallium alloy core	15.7	Pu239	9.38E-01
			Pu240	4.87E-02
			Pu241	3.10E-03
			Ga69	5.90E-03
			Ga71	4.10E-03
2	Nickel coating	8.9	Ni	1.00E + 00
3	Beryllium reflector	1.83	Be	9.80E-01
			O	2.00E-01
4	Stainless steel 316, ASTM A240 support	7.86	C	1.85E-03
			Cr	1.82E-01
			Fe	6.67E-01
			Ni	1.14E-01
			Mo	1.45E-02
			Mn	1.01E-02
			Si	9.91E-03
			P	4.04E-04
			S	2.60E-04

4.5539 cm was obtained using the core volume calculated by means of the available mass and density. Therefore, it consists of 6170 g of δ-phase plutonium–gallium alloy and 30 g of Ni plating, which gives 6200 g in total. The isotopic composition of the core is unknown. In the early criticality experiments performed at LANL before the 1960 s, the range of Ga was typically 1–1.1 wt%., of Pu240 4.5–6 wt% and of Pu241 0.27 to 0.35 wt%. The initial isotopic composition of the core (see Table 1) applied in the analysis was found in the description of *Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected by Beryllium (ID PU-MET-FAST-018)* performed in 1958 at LANL and presented in the *ICSBEP Handbook* (OECD, 2016). The estimation of the core isotopic composition is part of the study and is presented in Section 4.1. The concentration of Pu240 was changed in favour of the concentration of Pu239 at the fixed concentration of Pu241 and Ga until the excess reactivity above prompt criticality of about 10 cents was achieved. The core is resting in the beryllium hemisphere with a radius of 16.5 cm. The radius of the top hemisphere equals 11.4 cm (Hempelman, 1979). The upper beryllium hemisphere has an opening at the polar point, which is composed of two concentric cylinders, one on another, with assumed radii of 2.25 and 1.5 cm respectively. The reflector consists of 98 wt% Be and 2 wt% oxygen at a density of 1.83 g/cm^3 (OECD, 2016). The lower Be hemisphere is resting on the steel support. The air gap between the core and the reflector of 0.01 cm was modelled taking into account the possible curvature of the elements. The support is composed of a vertical cylindrical part and a horizontal plate. The thickness of the two parts equals 0.5 cm. It was assumed that the support was manufactured from 316 stainless steel (SSTL) at a density of 7.86 g/cm^3 (Favorite, 2016). Fig. 2 shows the experimental set-up for the most reactive configuration with the top hemisphere wholly covering the core. The material composition of the set-up is shown in Table 1. The values are presented as weight fractions; however, in further sections, I also use atomic fractions in order to be consistent with the original source of information.

3.2. The body

The most challenging task in the creation of the numerical model was the introduction of the human body. The model includes the bodies of Louis Slotin, Alvin Graves and Dwight Young, who were in the vicinity of the accident and thus their presence may have influenced the criticality. The detailed data about their anatomy, except for their heights and body masses, are unknown. Instead, for the numerical simulations, I decided to approximate them using a model of a “standard” human (Herman, 2007), which provides data about densities and masses of particular body parts. The model of a “standard” human also provides the length of the considered body segments but does not show the representative geometrical shapes. In my study, for the representation of body segments, I applied geometrical objects presented in Fig. 3. The dimensions and masses of particular body segments (Table 2) were normalised to the known heights and masses (Table 3) of experimenters, according to the equations provided for a standard human (Herman, 2007). In the numerical simulations, the location of Slotin’s upper arms, forearms and hands was changed in order to reconstruct the detailed environment in the room – see Section 4. The bodies of Alvin Graves and Dwight Young were reconstructed in a vertical position with shoulders down along the trunk. The isotopic composition of a human body presented in Table 4 was applied to the numerical simulations (Saeed et al., 2016). Every segment of a human body presented in Fig. 3 has the same isotopic composition but a different density and thus, a different mass.

3.3. The environment

Fig. 4 shows the designed configuration of the elements around the core and the body. The configuration of these components was fixed, and its location is not the case of the parametric study. The components of the system are enclosed in a cube which represents the room – see Fig. 5. The dimensions in the brackets show the centre-to-centre distances between the core and the particular system component. The walls and the ceiling of the room have the assumed thickness of about 30.5 cm (~1 ft) and 15.25 cm (~0.5 ft) respectively. The height of the room equals 5 m. The material of the walls and the ceiling used for numerical modelling is LANL Concrete Reinforced with 15% cold rolled steel by volume at a density of 3.093 g/cm^3 (Favorite, 2016). The room, as well as the remaining free space, is filled with an air with a density of 0.0009495 g/cm^3 (Favorite, 2016). The components which may have the largest influence on the criticality were placed on the wooden table (LWH (Length, Width, Height): 100 × 100 × 60 cm). The wood chosen for table material is fir with a density of 0.51 g/cm^3 (McConn et al., 2011). A set of bricks was placed in front of the core. The bricks were assumed to be made of lead with a density of 11.35 g/cm^3, because it is the most common shielding material. The bottom layer of the bricks was modelled as a cube with dimensions of 20 × 20 × 8 cm (LWH). The top layer of the bricks located on the bottom layer has the assumed dimensions of 20 × 10 × 8 cm (LWH). Two metal hemispheres with a radius of 4 cm assumed to be manufactured from 316 SSTL steel were put on the lead bricks (Favorite, 2016). The Pb container for the

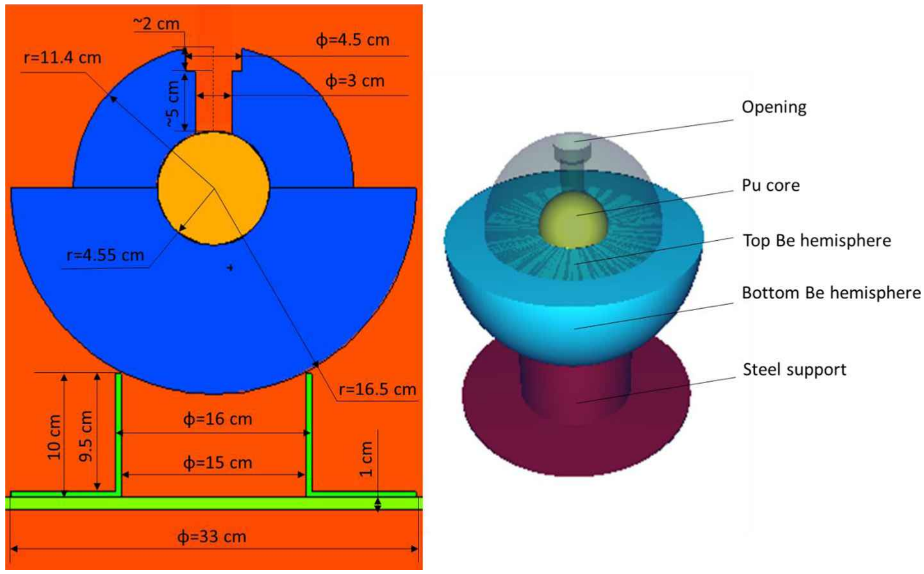


Fig. 2. Experimental set-up for the most reactive configuration.

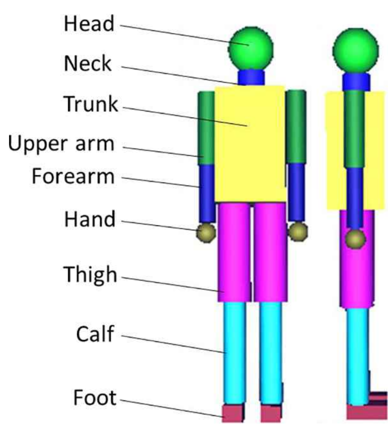


Fig. 3. Basic model of a "standard" human used for the normalisation of the bodies of Louis Slotin, Alvin Graves and Dwight Young.

neutron source lays on the bricks. The container was modelled as a cylinder with a height of 6 cm and a radius of 2.5 cm. The cylindrical Al plug with a length of 5 cm and a radius of 2.5 cm lays in the vicinity of the support and the bricks. The Al 6061 was used as the plug material (Favorite, 2016). The screwdriver in the right hand of Louis Slotin is also assumed to be fabricated from 316 SSTL steel. The screwdriver was modelled as a cylinder with a length of 13.5 cm and a radius of 0.2 cm. Additional elements visible in the photo of the accident mock-up, such as the empty bottle, the brush and the sheet metal, were neglected due to their low influence on the criticality. The composition of steel, aluminium, air and reinforced concrete was taken from the *ICSBEP Handbook*, benchmark *PU-MET-FAST-001* on Jezebel assembly operated

Table 3
Heights and masses of the experimenters (Harding et al., 1946).

Name	Mass [kg]	Height [cm]
Standard human	70	172
Louis Slotin	59.4	167.64
Alvin Graves	79.4	175.26
Dwight Young	68	165.1

Table 4
Body composition (Saeed et al., 2016).

ID	Element	wt.%
1	O	0.650
2	C	0.185
3	H	0.095
4	N	0.032
5	Ca	0.015
6	P	0.010
7	K	0.004
8	S	0.003
9	Na	0.002
10	Cl	0.002
11	Mg	0.001
12	Fe	0.001

Table 2
Masses and densities of body segments.

ID	Component	Density [g/cm^3]	Mass				
			Standard human [%]	Standard human [g]	Slotin [g]	Graves [g]	Young [g]
1	Hands	1.16	0.012	840	713	953	816
2	Forearms	1.13	0.032	2240	1901	2541	2176
3	Upper arms	1.07	0.056	3920	3326	4446	3808
4	Feet	1.10	0.029	2030	1723	2303	1972
5	Calves	1.09	0.093	6510	5524	7384	6324
6	Thighs	1.05	0.200	14,00	11,88	15,88	13,60
7	Head and neck	1.11	0.081	5670	4811	6431	5508
8	Trunk	1.03	0.497	34,790	29,522	39,462	33,796
	Total	n/a	1	70,000	59,400	79,400	68,000

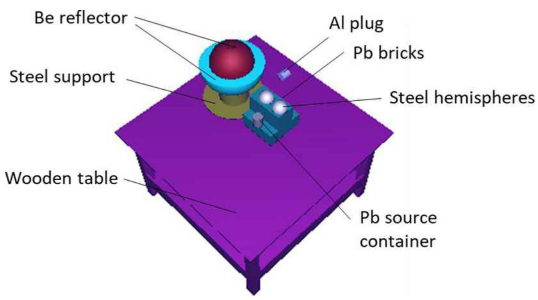


Fig. 4. Elements of the nuclear system.

in mid-1950 s at LANL (Favorite, 2016). Table 5 presents the material composition of the investigated components.

4. Results

4.1. The isotopic composition

The core isotopic composition was not reported in any available publication about the accident. Therefore, the criterion of 10 cents excess reactivity was applied to estimate the fraction of Pu240 in the core for the subsequent calculations (McLaughlin et al., 2000). The fractions of Ga and Pu241 were fixed (see Table 1), while the fraction of Pu240 was changed in favour of the Pu239 fraction for the calculations with JEFF3.1 and ENDF/B-VII.1 nuclear data libraries. The prompt method, which required two independent calculations to estimate the delay neutron fraction β_{eff} was applied (Bagchi et al., 2017). Eq. (1) shows the formula for the calculation of β_{eff}, where the effective neutron multiplication factor K_p considers only prompt neutrons, while the effective neutron multiplication factor K considers both prompt and delay neutrons.

$$\beta_{eff} = 1 - \frac{K_p}{K} \quad (1)$$

The TOTNU card available in the MCNP (Monte Carlo N-Particle Transport Code) family codes and implemented in the MCB code was used to calculate both values of K_{eff} (X-5 Monte Carlo Team, 2003). Two independent runs were performed for the same core isotopic composition. In the first run, the TOTNU card was used to calculate K and in the second run, the TOTNU card with entry NO was used to calculate K_p. For ENDF/B-VII.1 nuclear data libraries, the calculations were repeated

Table 5
Elements forming the environment around the core and the body (Favorite, 2016; McConn et al., 2011).

ID	Material/Component	Density [g/cm^3]	Composition	
			Element	at.%
1	Air/Free space in the room	0.0009495	H	4.39E-03
			He	2.61E-06
			C	1.58E-04
			N	7.79E-01
			O	2.12E-01
			Ne	9.07E-06
			Ar	4.66E-03
			Kr	5.69E-07
			Xe	4.34E-08
2	Aluminium 6061/Plug	2.70	Al	9.78E-01
			Cu	1.17E-03
			Si	5.80E-03
			Mn	3.70E-04
			Mg	1.12E-02
			Fe	1.70E-03
			Zn	5.19E-04
			Ti	4.25E-04
			Cr	1.02E-03
3	Lead/Bricks, Source container	11.35	Pb	1.00E + 00
4	LANL Concrete Reinforced with 15% CRS by Volume/Ceiling, Walls	3.093	H	7.00E-02
			O	4.99E-01
			Al	2.05E-02
			Si	2.01E-01
			Na	1.03E-02
			Ca	2.25E-02
			Fe	1.74E-01
			P	5.43E-05
			S	6.75E-05
			C	1.20E-03
			Mn	1.31E-03
5	Wood/Table	0.51	H	4.62E-01
			C	3.23E-01
			N	2.77E-03
			O	2.09E-01
			Mg	6.39E-04
			S	1.21E-03
			K	3.97E-04
			Ca	3.88E-04

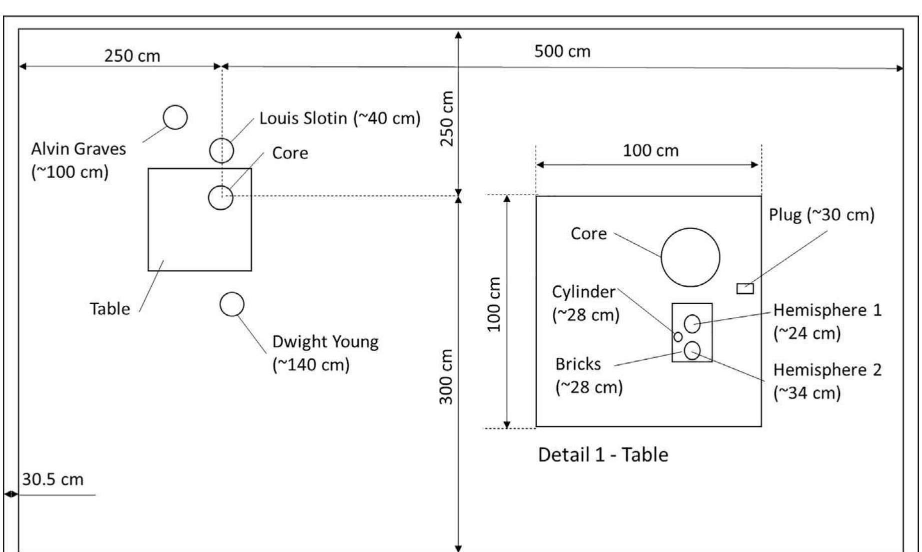


Fig. 5. Room and table configuration used in the numerical modelling (not in scale).

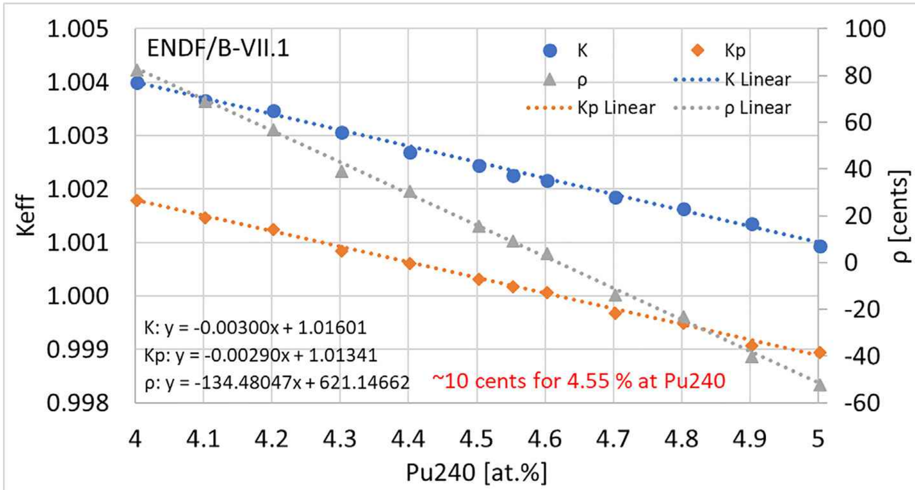


Fig. 6. Excess reactivity ρ, K_p and K in the function of Pu240 fraction for ENDF/B-VII.1 nuclear data libraries.

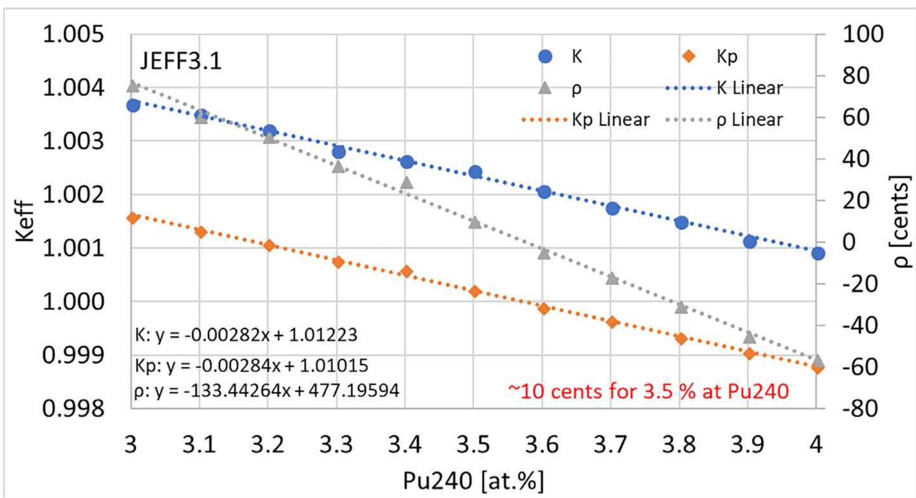


Fig. 7. Excess reactivity ρ, K_p and K in the function of Pu240 fraction for JEFF3.1 nuclear data libraries.

Table 6
Plutonium isotopic compositions.

Isotope	Fraction [at. %]		
	Initial	ENDF/B-VII.1	JEFF3.1
Pu239	0.9479	0.9514	0.9619
Pu240	0.0490	0.0455	0.0350
Pu241	0.0031	0.0031	0.0031

for changing atomic fraction of Pu240 in the range of 4–5% by 0.1%. The 10 cents excess reactivity above prompt criticality was achieved for 4.55 at. % Pu240 for β_{eff} of 208 pcm, K_p 1.0002 and K 1.00228. For JEFF3.1 nuclear data libraries, the calculations were performed for the Pu240 atomic fraction between 3 and 4%. The criterion of 10 cents excess reactivity was obtained for 3.5 at. % for β_{eff} 223 pcm, K_p 1.00022 and K 1.00246. All calculations were performed for $1.5 \cdot 10^6$ neutron histories for 30 inactive and 100 active cycles in the *kcode* mode of MCNP available in MCB. The obtained standard deviation of K_{eff} was below 6 pcm for all results. The spherical neutron source characterised by the Watt fission spectrum surrounding the core was applied (X-5 Monte Carlo Team, 2003). Fig. 6 and Fig. 7 show K_p and K as well as the excess reactivity above prompt criticality ρ in the function of Pu240 atomic fraction for both nuclear data libraries. The linear fitting was used to show the trends of the investigated parameters. Table 6 presents the obtained Pu isotopic compositions of the core for further analysis. The difference between Pu240 at. % for ENDF/B-VII.1 and JEFF3.1 nuclear data libraries is quite significant and equals 1.05 at. %.

4.2. The critical angle

The angle between the top Be reflector and the bottom Be reflector at which the criticality is obtained is defined as the critical angle. It was calculated for the fuel composition defined in Section 4.1 and the reference geometry defined in Section 3. To calculate the angle, initial ten runs for the range of 0–45° with a step of 5° were performed in order to find general behaviour of K_{eff} – see Fig. 8. Then, the interval in which the criticality is achieved was defined and subsequent calculations for subintervals of 1° were performed. The criticality for the subinterval of 0–5° presents linear behaviour. Thus, the linear regression method was used to determine the exact angle of the criticality presented in Fig. 9. The criticality is achieved for both fuel compositions almost at the same angle of 0.28–0.29°. In general, the neutron multiplication factor K_{eff} in the function of angle for the reference geometry and core composition presents exponential behaviour for both cross-section libraries. Fig. 9 also shows difference in K_{eff} between ENDF/B-VII.1 and JEFF3.1 libraries defined as $\Delta = K_{eff}^{JEFF} - K_{eff}^{ENDF}$. The differences depend on the position of the top Be reflector. The closer to the bottom reflector it is, the larger difference occurs. The maximum difference equals about

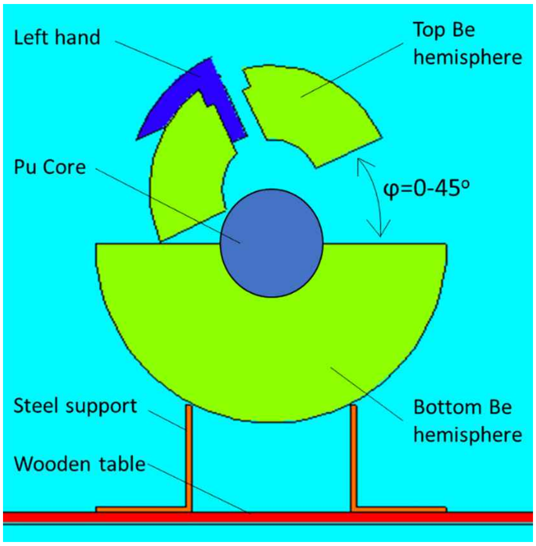


Fig. 8. Numerical model used for the calculation of the critical angle.

150 pcm.

4.3. System components

In order to estimate the influence of certain components of the numerical model on the criticality, an additional set of calculations was performed. In the calculations, the investigated component was removed from the numerical model. In this way, the difference $\Delta_C = K_{ref} - K_C^i$ could be defined, where K_{ref} is the neutron multiplication factor for the reference configuration considering the top hemisphere fully covering the core and K_C^i is the effective neutron multiplication factor obtained for the numerical model without the component *i*. The parametric study was performed for both nuclear data libraries. In addition, the difference Δ between nuclear data libraries, defined in Section 4.2, was calculated. Table 7 presents the influence of particular system components on the criticality. In the case of human bodies and Be hemispheres, the total influence of all three bodies and two hemispheres is additionally shown. The applied approach allows to find the components with the largest influence on the criticality. The largest influence of 25,670 pcm for ENDF/B-VII.1 and 25,480 pcm for JEFF3.1 libraries is caused by the Be reflector, which is consistent with theoretical predictions. The impact of the lower Be hemisphere is higher than that of the upper hemisphere of about 2200 pcm for both libraries because of its larger mass. However, calculations discarding both the top and the bottom reflector in the numerical model, compared with separate calculations with the top and the bottom reflector discarded respectively, show that the effect is not additive – see Table 7. The second important component is the body of Louis Slotin, whose influence equals 213 pcm for ENDF/B-VII.1 and 209 pcm for JEFF3.1 libraries. The bodies of Alvin Graves and Dwight Young have a low impact on the criticality – below 10 pcm. Therefore, it could be assumed that the bodies of the remaining five experimenters present in the room at the time of the accident could not significantly influence the criticality because of the larger distance from the core. The influence of the ceiling and the walls equals from 16 for ENDF/B-VII.1 to 35 pcm for JEFF3.1 nuclear data libraries. In general, the influence of the system components is rather larger for JEFF3.1 libraries, except for the Be reflector. It is worth mentioning that the prompt criticality state is not achieved for the top Be reflector covering the core in the absence of the body of Louis Slotin. Hence, the prompt criticality was the mutual effect of the top reflector and the placement of the body of Louis Slotin at the core. The influence of the supplementary components is rather small, taking into account the rule of three-sigma, especially for ENDF/B-VII.1 nuclear data libraries.

4.4. The hand effect

During the accident, the left hand of Louis Slotin was placed directly on the top Be hemisphere, which suggests its large influence on the criticality due to its moderation capabilities. The effect was investigated in a series of calculations considering an increase of the distance between the hand and the top reflector in 10 intervals of 0.5 cm for the reference calculation case (Fig. 10). The palm of Louis Slotin was modelled as a ¼ of spherical shell covering the top reflector, while the thumb was modelled as a ¼ of opening in the top Be reflector. The dimensions of the hand, due to its complicated geometrical shape, were normalised to its volume of 362 cm^3, calculated using the mass and the density shown in Table 2. Fig. 11 presents the effective neutron multiplication factor K_{eff} in the function of the distance from the top Be reflector. The influence of the hand is quite significant and equals 127 +/− 6 pcm for ENDF/B-VII.1 and 138 +/− 6 pcm for JEFF3.1 nuclear data libraries. The influence of the whole body of Louis Slotin on the criticality is about 210 pcm (Table 7). Therefore, the hand effect corresponds to about 60–65% of excess reactivity due to the body of Louis Slotin in the considered interval of 5 cm. The results suggest that the placement of the hand was the key factor leading to the prompt critical state of the assembly. The prompt criticality would not have been achieved if the hand had been placed a bit further from the top Be

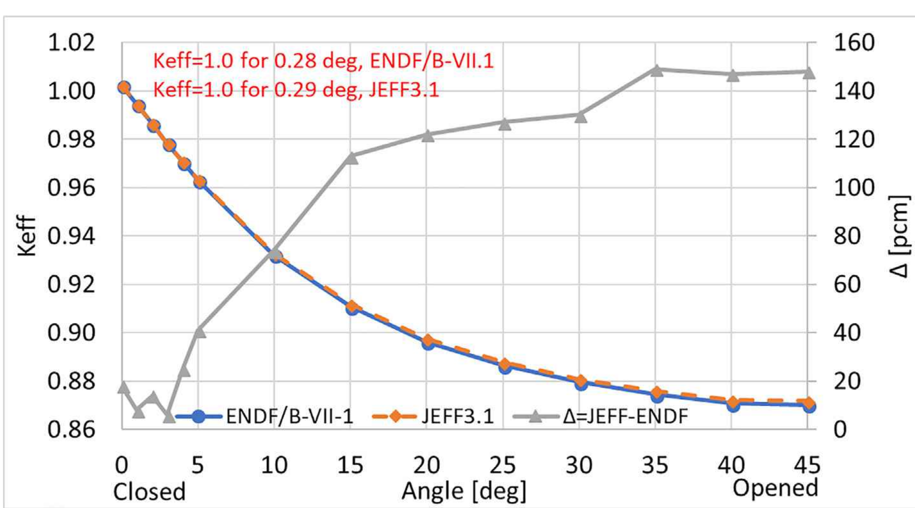


Fig. 9. K_{eff} in the function of angle for the reference case.

Table 7
The influence of the system components on the reactivity.

No	Element	ENDF/B-VII.1			JEFF3.1			Δ [pcm]
		K_C^i	σ [pcm]	Δ_C [pcm]	K_C^i	σ [pcm]	Δ_C [pcm]	
1	Reference case	1.00228	5	NA	1.00246	6	NA	18
2	Top Be hemisphere	0.85099	5	15,129	0.85256	4	14,990	157
3	Bottom Be hemisphere	0.82903	4	17,325	0.83064	5	17,182	161
4	Top and bottom Be hemisphere	0.74558	4	25,670	0.74766	4	25,480	208
5	Body of Louis Slotin	1.00015	6	213	1.00037	5	209	22
6	Body of Alvin Graves	1.00238	5	−10	1.00245	6	1	7
7	Body of Dwight Young	1.00227	6	1	1.00245	6	1	18
8	Bodies of Louis Slotin, Alvin Graves and Dwight Young	1.00021	6	207	1.00017	5	229	−4
9	Steel support	1.00211	6	17	1.00226	5	20	15
10	Wooden table	1.00224	6	4	1.0023	6	16	6
11	Pb bricks	1.00225	7	3	1.00224	6	22	−1
12	Steel hemispheres	1.00233	6	−5	1.00246	6	0	13
13	Pb source container	1.00238	6	−10	1.00237	6	9	−1
14	Al plug	1.00237	6	−9	1.00234	6	12	−3
15	Steel screwdriver	1.00231	6	−3	1.00229	5	17	−2
16	Concrete walls and ceiling	1.00212	6	16	1.00211	5	35	−1

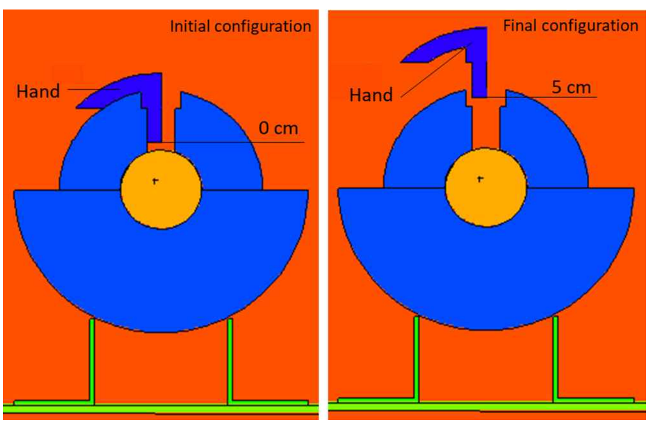


Fig. 10. The numerical model used for the calculation of the hand effect.

hemisphere.

4.5. Neutron spectra

The normalised to unity relative neutron fluxes in 100 energy group structure were calculated for three cases for both nuclear data libraries. The first case is the reference case with all system elements and the top Be reflector covering the core. In the second case, I considered the neutron flux in the core without the top Be reflector. In the third case, the body of Louis Slotin was discarded from the calculations. Table 8 presents thermal, resonance and fast fluxes obtained in the calculations. The largest influence on the thermal and resonance flux is induced by the top Be reflector. The hemisphere serves not only as a neutron reflector but also as a neutron moderator and increases thermal and resonance neutron flux more than two times from 0.0026 to 0.0063%. The influence of the body of Louis Slotin on the thermal flux is rather small (0.0004%), but its influence on the resonance flux is more significant: 0.0243% for ENDF/B-VII.1 and 0.0227% for JEFF3.1 nuclear data libraries. In Fig. 12, I present the neutron spectra for the first and second case. The shift to thermal energies by adding the top Be reflector is clearly observable. The flux depression due to the large Pu239 resonance at neutron energy of about 3×10^{-7} MeV is shown.

5. Discussion and summary

In this paper, I have presented the numerical analysis of the Louis Slotin accident by means of the MCB code. The accident was reconstructed using the available data about the room environment at the time of the accident. The study accurately shows the real conduct of the experiment and the following accident. The supercriticality was achieved for both nuclear data libraries for almost the same angle of

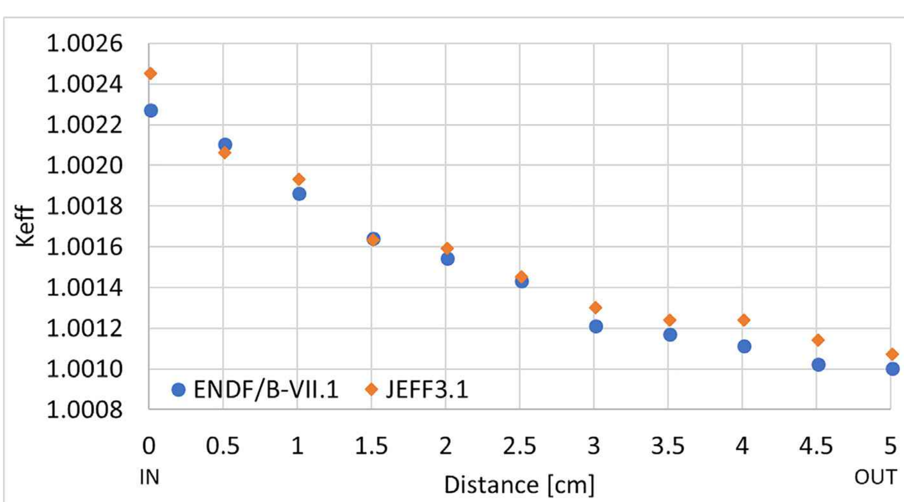


Fig. 11. The influence of the hand position above the top Be hemisphere.

Table 8
Relative normalised to unity neutron fluxes in the core.

Relative flux	All elements		No top Be		No Slotin's body	
	ENDF/B-VII.1 [%]	JEFF3.1 [%]	ENDF/B-VII.1 [%]	JEFF3.1 [%]	ENDF/B-VII.1 [%]	JEFF3.1 [%]
Thermal (< 1eV)	0.0063	0.0063	0.0026	0.0026	0.0059	0.0059
Resonance (< 1eV < 1KeV)	0.9218	0.9045	0.3344	0.3292	0.8975	0.8818
Thermal + Resonance (< 1 KeV)	0.9282	0.9108	0.3370	0.3319	0.9034	0.8877
Fast (> 1KeV)	99.0706	99.0878	99.6625	99.6676	99.0955	99.1110

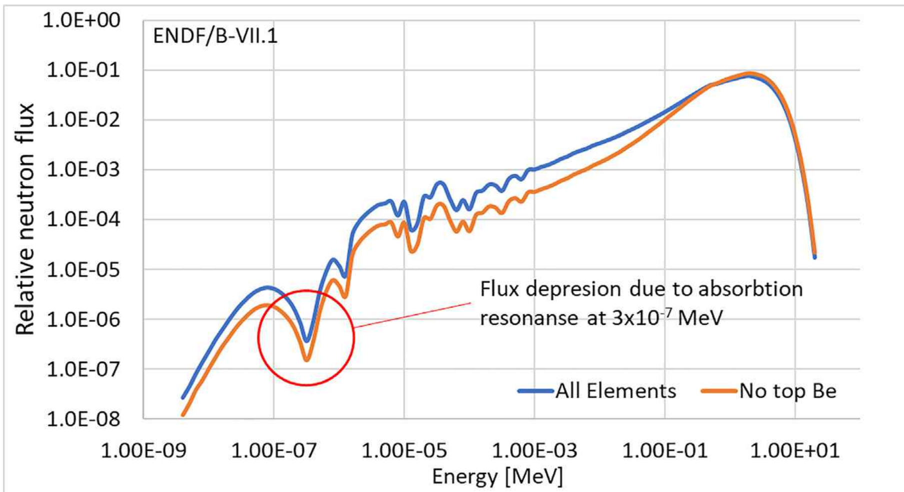


Fig. 12. Relative neutron flux in the core for ENDF/B-VII.1 nuclear data libraries.

0.28–0.29° but with Pu240 atomic fraction varying by 1.05%. The fraction of Pu240 in the core was estimated using the criterion of 10 cents excess reactivity above the prompt criticality. The numerical comparison study between ENDF/B-VII.1 and JEFF3.1 nuclear data libraries shows the differences between the K_{eff} values. The difference varied for the material composition as well as for the system geometry. The maximum difference of about 200 pcm was observed for the numerical model without the Be reflector. The study directly indicates the influence of the body of Louis Slotin on the system criticality of about 210 pcm. The crucial segment of the body is the hand covering the top Be reflector. The hand effect was estimated at about 130 pcm of excess reactivity. If the body of Louis Slotin had been placed a bit further from the core fully covered with the raised hand, the system would not have achieved the prompt criticality. The neutron spectra calculated in the core for the numerical model with the Be reflector and without it show a shift from fast to thermal neutron spectrum.

Future analysis of the accident may consider additional parametric study on the core material composition and geometry of the body of Louis Slotin, as these elements significantly influenced the system reactivity. The exact placement of the body at the time of the accident could not be reconstructed because of the lack of photographic documentation – only mock-up photos are available. In addition, the modelling of assembly kinetics and dynamics is necessary to estimate time-dependent reactivity and power changes, e.g. using the DYN3D code or its modification (Rohde, 2016). Calculations of general radiation field emitted by the core during the criticality excursion could be helpful for the estimation of radiation effects on the human tissue. This requires development of an advanced model of human body, including the organ system, as well as transport simulations of all particle types and their interaction with matter e.g. using GEANT numerical tool (Amako et al., 2006). This will allow for further dosimetry and radiobiological analysis.

To sum up, the study shows a novel approach to the numerical modelling of criticality accidents. The purpose of the study is to understand the physical background of the accident and to show crucial physical effects occurring at the time of the accident. The results show that the numerical model was developed with appropriate diligence and the main assumptions of the study were reached. The study may serve as the first advanced approach to further analysis of the Louis Slotin accident. Additionally, it may be used as a scientific case study for training of future employees of nuclear industry in order to increase their competences and to promote the safety culture.

Acknowledgements

The research was partially supported by PL Grid Infrastructure available at the Academic Computer Centre CYFRONET AGH. In addition, partial financial support of this study under the grant agreement 11.11.210.377 by the Polish Ministry of Science and Higher Education is kindly acknowledged.

References

The Atomic Heritage Foundation (AHF), https://www.atomicheritage.org/history/atomic-accidents.
Amako, K., et al., 2006. Geant4 and its validation. Nucl. Phys. B – Proceed. Suppl. 150, 44–49.
Bagchi Subhrojit, Sen Sujoy, Stephen Neethu H., John Aru A., Delayed Neutron Fraction Calculation in PFBR using MCNP, M&C 2017 – International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16–20, 2017, on USB (2017).
Brewer Roger W., 2016. Benchmark Critical Experiment of a Delta-Phase Plutonium Sphere Reflected by Beryllium, PU-MET-FAST-018, International Handbook of Evaluated Criticality Safety Benchmark Experiments, OECD 2016, NEA No. 7328.
Cetnar, J., 2006. General solution of Bateman equations for nuclear transmutations. Ann. Nucl. Energy 33 (7), 640–645.
Chadwick, M.B., Herman, M., Oblozinsky, P., et al., 2011. ENDF/B-VII.1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data. Nucl. Data Sheets 112 (12), 2887–2996.
Favorite Jeffrey A., Bare Sphere of Plutonium-239 Metal (4.5 at.% 240Pu, 1.02 wt.% Ga), PU-MET-FAST-001, International Handbook of Evaluated Criticality Safety Benchmark Experiments, OECD 2016, NEA No. 7328.
Harding Magnus, et al., 1948. Radiation doses in the Pajarito accident of May 21, 1946,

LA-687, Los Alamos scientific laboratory, Los Alamos, New Mexico May 26.
Hempelman Louis Henry, Lushbaugh Clarence C., Voelz George L, 1979. What has happened to the survivors of the early Los Alamos nuclear accidents?, LA-UR-79-2802, Los Alamos scientific laboratory, Los Alamos, New Mexico, October 2.
Herman, Irving P., 2007. Physics of the Human Body, Biological and medical physics, biomedical engineering, ISBN 978-3-540-29603-4. Springer, Berlin Heidelberg New York.
Kępisty, G., Stanisz, P., Cetnar, J., June 2016. Monte Carlo burnup in HTR system with various TRISO packing. Ann. Nucl. Energy 92, 419–430.
McConn, R.J., Jr, Gesh, C.J., Pagh, R.T., Rucker, R.A., Williams, R.G., III, 2011. Compendium of Material Composition Data for Radiation Transport Modeling, PIET-43741-TM-963, PNNL-15870 Rev. 1, Pacific Northwest National Laboratory Richland, Washington. March 4.
McLaughlin Thomas P., Monahan Shean P., Pruvost, Norman L., Frolov, Vladimir V., Ryazanov, Boris G., Sviridov, Victor I., 2000. A Review of Criticality Accidents, 2000 Revision, LA-13638, Los Alamos National Laboratory, Los Alamos, New Mexico. May.
International Handbook of Evaluated Criticality Safety Benchmark Experiments, OECD 2016 NEA No. 7328.
Oettingen, M. Cetnar, J., Mirowski, T. 2015. The MCB code for numerical modelling of fourth generation nuclear reactors, Computer Science ; ISSN 1508-2806. vol. 16 (4) pp. 329–350.
Rohde, U., et al., May 2016. The reactor dynamics code DYN3D – models, validation and applications. Progr. Nucl. Energy 89, 170–190.
Saeed, A., Nafee, Sherif S., Shaheen, Salem A., Raouf, Gehan A., Al-Hadeethi, Y., Kamal, Salahuddin M., Razvi, M.A.N., 2016. Calculating the ambient dose equivalent of fast neutrons using elemental composition of human body. Appl. Mathemat. Comput. 274, 604–610.
A. Santamarina et al. 2009.The JEFF-3.1.1 Nuclear Data Library, JEFF Report 22, Validation Results from JEF-2.2 to JEFF-3.1.1, ISBN 978-92-64-99074-6 Nucl. Energy Agency.
Stanisz, P., Oettingen, M., Cetnar, J., May 2016. Monte Carlo modeling of Lead-Cooled Fast Reactor in adiabatic equilibrium state. Nucl. Eng. Design 301, 341–352.
X-5 Monte Carlo Team, MCNP — A General Monte Carlo N-Particle Transport Code, Version 5 Volume II: User's Guide, LA-CP-03-0245, 2003.