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Criticality analysis of the Louis Slotin accident

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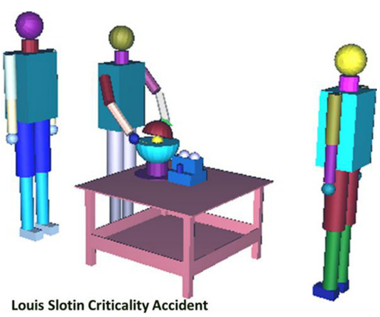
GRAPHICAL ABSTRACT



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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.

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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