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Review

Nuclear criticality accident safety, near misses and classification

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A R T I C L E I N F O

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A B S T R A C T

The majority of known nuclear criticality accidents occurred during the 1950s and 1960s, this during a time when nuclear science was young and safety measures to deal with this new science were not fully understood. As the progression in the development of technology occurred, a new understanding for a focus on establishing a safety culture within the nuclear industry developed, this in turn has led over the decades post ceding the early years of nuclear, a decrease in the number of nuclear criticality incidents.

The purpose of this paper is to provide a brief summary of historical (pre 2000) criticality accident statistics and conclusions, while focusing on nuclear criticality incidents occurring after 2000. In preparing the historical overview statistics, it was found that there were several Russian submarine nuclear criticality accidents occurring before 2000 that were not previously widely presented in the public domain. Furthermore, noted were instances of Japanese power companies covering up rod withdrawal accidents, leading to unintended nuclear criticalities. To add in this other information to previously understood practices, a new method of characterizing criticality accident near misses is to be presented, followed by data analysis showing that the safety culture that has evolved since the emergence of nuclear energy on the world stage has provided the platform for the development of a strong and relevant nuclear criticality safety stance.

1. Introduction

The basic premise of any Nuclear Criticality Safety program is to prevent inadvertent nuclear criticality (Criticality Safety at Department of Energy Defense Nuclear Facilities). For a Nuclear Criticiality Safety program to be of value to the nuclear group under which the group operates such a program must, as its most basic elements, contain the following fundamental areas, which are: "(1) the analysis of criticality hazards and the development of adequate controls for those hazards, (2) implementation of the criticality controls in facility processes, and (3) feedback and improvement including the maintenance of controls to ensure their integrity and reliability over time" (Criticality Safety at Department of Energy Defense Nuclear Facilities). The arena known as nuclear criticality safety has come about to ensure that the risks associated with obtaining unwanted nuclear criticalities is minimized.

"Nuclear criticality safety is a field of nuclear engineering dedicated to the prevention of nuclear and radiation accidents resulting from an inadvertent, self-sustaining nuclear chain reaction" (Knief, 1985). As world energy needs continue to grow, and if nuclear energy is to play an important role in our economies in the future, fissile materials must be handled safely over the whole fuel cycle. Nuclear criticality safety has taken on a renewed importance following the Fukushima Daiichi accident in March 2011.

First, it is important to acknowledge that "absolute safety does not exist in relation to the production of nuclear power and that we are living with the possibility of nuclear risks" (Hasegawa, 2012). In realizing this, the nuclear criticality safety engineer understands that he/she is the last line of defense in determining whether nuclear energy will be a viable force for good in the future. Each day on the job, the nuclear criticality safety engineer is to following the letter and spirit of direction in entirety. It may be said that for the nuclear criticality safety engineer, "Theirs not to make reply, Theirs not to reason why, Theirs but to do" (Tennyson and Lord, December 1854) and thus ensure the safety of their neighbors in the communities in which he/she resides.

To achieve this aim, an understanding of the past helps us to foresee the future and provides stability in the work environment in the incorporation of these vital lessons learned. As the workforce ages, retires and then a new generation enters into the field of nuclear criticality safety, retention of this specific knowledge of the practice changes, resulting from past accidents, and an overview of

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the successes in this field will keep the new generation on the right path. In examining in-depth the chain of events leading to a criticality accident, an understanding of the causes leading to these accidents may be more fully obtained and, more importantly, a determination can be made regarding the common denominators to these accidents culminating in an outline provided on the methods to be used with which such possibilities of producing a criticality accident might be more mitigated.

This paper provides a review of past criticality accidents and near misses that have occurred worldwide. Criticality accidents that occurred before the year 2000 are well documented in *A Review of Criticality Accidents* (McLaughlin et al., 2000). Therefore, only a summary of historical data and conclusions from analysis of these well documented criticality accidents are presented. Further to this, this paper provides an updated look into the accidents and near misses where information was not previously made available to the public. In addition, an in-depth analysis of more recently near misses and reportable non-critical events is provided.

2. Overview of criticality accidents prior to Year 2000

The premier authority on the history of nuclear criticality accidents that have occurred prior to year 2000 is *A Review of Criticality Accidents* (McLaughlin et al., 2000). Accidents were categorized as occurring either within a process facility or an experimental reactor and critical experiment facility. Process facility operations use physical and administrative controls in attempts to prevent unintended criticalities (those occurring outside of a reactor). Criticality is not desired in a process facility and personnel are not necessarily technical experts. Conversely, reactor and critical experiment research facilities perform research where criticality is desired. Furthermore, personnel are experts in criticality physics. There were a total of 60 criticality accidents occurring before 2000. Out of these accidents, 22 occurred during process facility operations and 38 occurred during experimental reactor operations.

2.1. Process accidents

For a discussion about the 22 individual process facility criticality accidents, refer to (McLaughlin et al., 2000). The observations and lessons learned from (McLaughlin et al., 2000), however are discussed here. Table 1 lists the process facility criticality accidents occurring before the year 2000.

Table 1
Process facility Accidents occurring before the Year 2000

Date	Process facility accident location	Fatalities	Personnel exposed
3/15/1953	Mayak Production Association, R.F.	–	2
4/21/1957	Mayak Production Association, R.F.	1	5
1/2/1958	Mayak Production Association, R.F.	3	1
6/16/1958	Y-12 Plant, Oak Ridge, TN	–	7
12/30/1958	Los Alamos, NM	1	2
10/16/1959	Idaho Chemical Processing Plant, ID	–	2
12/5/1960	Mayak Production Association, R.F.	–	–
1/25/1961	Idaho Chemical Processing Plant, ID	–	–
7/14/1961	Siberian Chemical Combine, R.F.	–	1
4/7/1962	Hanford Works, WA	–	3
9/7/1962	Mayak Production Association, R.F.	–	–
1/30/1963	Siberian Chemical Combine, R.F.	–	–
12/2/1963	Siberian Chemical Combine, R.F.	–	–
7/24/1964	United Nuclear Fuels Recovery Plant, RI	1	2
11/3/1965	Electrostal Machine Building Plant, R.F.	–	–
12/16/1965	Mayak Production Association, R.F.	–	–
12/10/1968	Mayak Production Association, R.F.	1	1
8/24/1970	Windscale Works, U.K.	–	–
10/17/1978	Idaho Chemical Processing Plant, ID	–	–
12/13/1978	Siberian Chemical Combine, R.F.	–	8
5/15/1997	Novosibirsk Chemical Concentration Plant, R.F.	–	–
9/30/1999	Tokai-mura, JP	2	1

2.1.1. Observations

It was determined that none of the process facility accidents were caused by a single failure (all had multiple causes) with equipment failure found to be a minor or non-contributing factor in the accidents. Furthermore, no accident occurred during either the storage or transport of fissile material transport. No accidents were the result of incorrect calculations by criticality engineers and none of the accidents were caused by new physical phenomena (all were explained by the current knowledge of nuclear criticality). In all accidents, there was no significant radiation consequences outside of the accident facility (i.e., no damage to the environment or general public).

2.1.2. Lessons learned

As criticality is not intended in a process facility, a review of the 22 process facility criticality accidents led to the development of a lessons learned training tool. Discussed in detail in (McLaughlin et al., 2000), an overview of the 'operational lessons learned' from the 22 process facility criticality accidents is now presented. For a discussion on supervisory, managerial and regulatory lessons learned, please refer to (McLaughlin et al., 2000).

2.1.2.1. Unfavorable geometry. In areas where high-concentration solutions of fissile material are present, unfavorable geometry vessels should be avoided. If unavoidable, strict controls should be enabled to prevent unintended criticalities. Of the 22 process facility accidents, 21 involved fissile material solution/slurries. Due to the high percentage of accidents involving fissile material solution, it is easily seen that controls preventing unfavorable geometry vessels are vital.

2.1.2.2. Instructions, information and procedural changes must be written. As communication errors are a major contributor to any kind of accident, it is equally important in nuclear criticality safety. Instructions, information and procedural changes must exist in written form.

2.1.2.3. Identification of abnormal conditions. Abnormal conditions are only recognized when ideal conditions are well understood. Processes must be familiar and understood if abnormal conditions are to be recognized and dealt with.

2.1.2.4. Fissile material accountability. To prevent fissile material accumulation, the piping and equipment associated with fissile material operations must be monitored (inspection, cleanings, radiation measurements). Several accidents resulted from the loss of accountability of fissile materials.

2.1.2.5. Equipment malfunction response. Operating personnel must understand criticality concepts and the importance of criticality controls of the specific process they are involved with. This concepts lends itself to personnel identifying abnormal conditions and having appropriate responses to such conditions.

2.1.2.6. Personnel training. It is important that personnel be trained in the importance of not taking unapproved actions after evacuation. One accident occurred due to unapproved reentry into the accident site without an understanding of the criticality accident, resulting in loss of life.