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Inductive Double-Contingency Analysis of UO_2 Powder Bulk Blending Operations at a Commercial Fuel Plant (U)

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by

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ABSTRACT

An inductive double-contingency analysis (DCA) method developed by the criticality safety function at the Savannah River Site, was applied in Criticality Safety Evaluations (CSEs) of five major plant process systems at the Westinghouse Electric Corporation's Commercial Nuclear Fuel Manufacturing Plant in Columbia, South Carolina (WEC-Cola.). The method emphasizes a thorough evaluation of the controls intended to provide barriers against criticality for postulated initiating events, and has been demonstrated effective at identifying common mode failure potential and interdependence among multiple controls. A description of the method and an example of its application is provided.

INTRODUCTION

The Westinghouse Electric Corporation's Columbia Plant manufactures fuel assemblies and core components for use in commercial nuclear power reactors. In part to address increasing Nuclear Regulatory Commission (NRC) expectations with regards to reporting the loss of criticality safety controls[1], but also as the first phase in the development of Integrated Safety Assessments (ISAs) for the facility, WEC-Cola. initiated a project to upgrade existing Criticality Safety Assessment (CSA) reports with new Criticality Safety Evaluations (CSEs) for five of the plant's major process systems.

The standard ANS-8.1 (ANSI N16.1-1975) establishes in paragraph 4.2.2,[2] the double-contingency principle:

> Process designs should, in general, incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.

Existing CSA reports prepared by WEC-Cola. document compliance with the double-contingency principle for all process systems operated at the plant. However, a review of these reports by the NRC identified areas for improvement. While it was determined that the approach used to develop the CSA reports sufficiently characterized and evaluated the "unlikely" aspect of changes in process conditions, it did not, however, adequately address the concept of "independence." A new DCA method was needed to provide a structured and consistent approach to the analysis, and specifically recognize and address interdependence of controls due to common mode failure (CMF) potential.

A prominent section of the new CSEs is dedicated to the double-contingency analysis of the subject process system. The DCA method used in the CSEs was formalized by the criticality safety function at the Savannah River Site (SRS), and documented[3] in partial fulfillment of the technical support contract between WEC-Cola. and the Westinghouse Savannah River Company (WSRC). It represents the Site's accepted standard for DCAs currently performed at SRS. The method emphasizes identification of the criticality safety controls; and is a particularly effective tool for identifying common mode failure potential and interdependence among controls. Following is a description of the method and an abbreviated example of its application to evaluate double-contingency compliance and identify CMF potential in the WEC-Cola. Plant UO_2 powder bulk blending process.

DESCRIPTION OF METHOD

Traditional double-contingency analyses typically invoke deductive reasoning, and rely extensively on the use of fault tree logic diagrams. With an unplanned criticality accident as the starting assumption of the analysis, details of location, consequence, mechanism, phenomena, initiators, and precursors are developed in a logic diagram format. While fault trees are a particularly useful tool for probabilistic risk assessment studies, inherent limitations in their ability to adequately define controls and clearly identify CMF potential and interrelationship among controls renders their use for DCAs only marginally effective.

An alternative to this approach employs an inductive argument whereby initiators to process upsets are first identified, and then the effectiveness of the barriers or defenses designed to prevent each from culminating in a possible criticality accident are thoroughly evaluated. A structured and systematic approach is required for the successful application of this method. Of paramount importance is a complete and thorough engineering understanding of the system being evaluated. It is often useful and necessary to evaluate separately each process unit where a criticality potential exists, and then consider its interrelationship with the other units in the system. A partial list of fundamental initiators called Initiating Events (IEs) is presented in Table I.

Factors that directly affect the neutron multiplication factor (k_{eff}) of a system can, in general, be categorized as the nine physical process parameters listed below.

- fissile mass
- moderator-to-fissile ratio
  (concentration/moderation)
- geometry
- spacing
  (of multiple fissile units)
- density of fissile
  (homogeneous/heterogeneous)
- neutron absorbers
- fissile isotopic enrichment
- neutron reflection
- temperature

While common usage is to group these components into the three general categories of "mass," "moderation," and "configuration," for the purposes of a comprehensive DCA it is important that the nine parameters remain separate and distinct, thereby facilitating identification of CMF potential. Each parameter is then regulated within acceptable ranges by either bounding assumptions (BAs), or criticality safety limits (CSLs) implemented by criticality safety controls (CSCs). BA values are assigned to those parameters that are not directly and deliberately controlled, and represent the most reactive condition for the system under consideration. CSLs are the values within which a parameter is controlled by CSCs to ensure specified subcritical margins. A unique defense table must be established for each identified Initiating Event, and comprises the set of BAs, CSLs, and CSCs on each of the nine physical process parameters necessary to ensure the specified subcritical margin against the IE. An example of a defense table is presented in Table II.

An Initiating Event consists not only of a change or upset in process condition, but also of the resulting challenge to the provided defense. If an IE violates a BA or a CSL, or causes a physical process parameter to change in such a way as to directly and adversely affect neutron multiplication, it constitutes a primary contingency (PC). An IE that challenges or fails only a CSC, but does not violate the associated CSL or change the value of the controlled parameter, is a secondary contingency (SC) since k_{eff} is not directly affected as a result of the CSC failure. Defense element descriptions should

TABLE I

Partial Listing of Typical Initiating Events

<u>Events Due to Human Error</u> • Improper labeling/identification of fissile material, containers, moderators, or precipitating/concentrating agents • Improper labeling of valves and valving errors • Improper addition/interspersion of moderators and precipitating/concentrating agents • Analytical laboratory errors due to equipment calibration, misperformance of lab procedures, recording/reading of laboratory results • Errors in fissile material mass logs/inventory records or mass overbatching • Process equipment calibration/measurement errors • Failure to take corrective actions in response to correct instrument readings or procedural requirements • Errors and oversights in written procedures • Substitution of wrong equipment parts • Improper spacing, storage in unapproved locations, or lack of fissile material cleanup • Use of unapproved containers for fissile material storage • Improper termination of plant utilities • Inadvertent dissolution • Inappropriate fire-fighting methods
<u>Events Due to Chemical Attacks on Hardware</u> • Changes in dimensions due to corrosion/erosion or due to fire, explosions, excessive operating pressures • Leaking valves and/or process containers/vessels • Phase changes (e.g., extraction, precipitation, freezing) that concentrate fissile material • Buildup of fissile material on vessel walls or deposits leading to blocked overflow lines • Attacks/leaching of fixed neutron absorbers and Raschig rings • Plating-out of fissile material upon fixed neutron absorbers and Raschig rings • Unwanted dissolution of fissile material • Deposits of fissile material in HVAC or other ventilation lines
<u>Events Due to Mechanical Hardware Failure/Design</u> • Structural failures of Passive-Engineered CSCs • Unintended siphon transfers of fissile solutions, moderators, or precipitating agents • Evaporation/settling of fissile material out of solution • Movement of structures and equipment changing reflection and/or approved spacing • Blockage of overflows and drains • Piping/container or equipment failure resulting in leaks of fissile solutions, moderators, or precipitating agents into unapproved locations • Vacuums or pressure transients moving fissile materials into unapproved locations
<u>Events Due to Temperature</u> • Phase changes concentrating fissile solutions • Phase changes that rupture process vessels (e.g., heating an overfilled UF_6 cylinder) • Thermal expansion changing safe dimensions • Use of cryogenic equipment that reduces Doppler absorption
<u>Events due to Natural Phenomena</u> (excluding seismic events and airplane crashes) • Damage to structures and/or containment from high wind and lightning • Interruption of plant utilities from high wind and lightning • Malfunction of electronic controls due to lightning-induced surges or wind-driven rain • Introduction of moderation into unapproved areas by high wind • Loss of required spacing due to high wind

TABLE II

General Example of a Defense Table

Parameter Addressed	Defense Element		
	BA	CSL	CSC
Mass	Unrestricted		
Moderation Concentration	Optimal		
Geometry		20 cm ID x 230 cm	Passive-Engineered
Spacing		Infinite Array 90-cm Pitch	Passive-Engineered
Density	Homogeneous $UO_2 + H_2O$		
Absorbers		0.5 cm SS-304 Wall	Passive-Engineered
Enrichment		$\leq 5\%$ ^{235}U	Procedural
Reflection	Full Water		
Temperature	≥ 293 K		

be specific enough to identify a particular procedural requirement, job responsibility, hardware item, or specification. This level of detail is necessary so that a direct comparison of the defense associated with each IE to every other IE defense allows easy identification of common controls, thereby revealing the potential for CMF. Although the number of comparisons that could be made among even a small group of IEs often proves prohibitively large, engineering knowledge of the system being evaluated can be used to reduce comparisons to a more manageable level by only considering those defenses related by common defense elements and potential criticality scenarios.

Finally, a determination is made of exactly what elements comprise the first and second (independent) defenses for a particular IE. Independence of the defenses is ensured by the CMF potential evaluation previously described. Often more than two independent defenses will exist for each IE. The double contingency principle is then satisfied when it is established that a criticality is not possible without at least a concurrent Primary and Secondary Contingency.

APPLICATION AND RESULTS

The following is an example of the inductive DCA method as it was applied to the UO_2 powder bulk blending operations at the WEC-Cola. fuel manufacturing plant[4].

UO_2 powder produced by the ammonium diuranate (ADU) conversion process is packaged, prior to release for blending, inside small, geometrically favorable (20.3 cm diameter) containers called polypaks. Each polypak typically contains approximately 16 kg of UO_2 powder. Although the ADU conversion process is designed to produce relatively dry powder, criticality safety of the stored material is ensured by mass and geometry control (provided by the polypak) until an acceptably low powder moisture content is confirmed through diverse material sampling and redundant moisture analyses. Upon confirmation that the UO_2 powder contains less than 0.3% water by weight, the contents of approximately 100 polypaks are transferred into a large, 1700 kg moderation control (modcon) container, which is subsequently tumble blended to homogenize the powder.

The first of two diverse powder samples is designated the "pink dot" sample and is a one-gram grab sample removed from the top of each polypak when it is filled. Approximately forty sequentially filled polypaks comprise a batch; therefore, forty one gram samples make up the composite pink dot sample. A single laboratory moisture analysis is performed on the pink dot sample. If the results of this analysis conform to established acceptance criteria, a second sample of UO_2 powder, designated the "blue x" sample, is obtained for confirming analysis. The blue x sample comprises core samples removed from three randomly selected polypaks. Each of the three individual samples is analyzed separately, and the calculated arithmetic mean of the results represents the moisture content of the blue x sample as a whole. If the results of both the pink dot sample and the blue x sample moisture analyses meet established acceptance criteria, then the entire batch (approximately 40 polypaks) of UO_2 powder is authorized safe for transfer to a non-favorable geometry (NFG) 1700 kg modcon container in preparation for bulk blending.

All material moisture content analyses are performed in an analytical laboratory using any of three titration-type moisture meters. A 0.5- to 1.0-gram sample of UO_2 is weighed on an analytical balance and placed inside a quartz tube where it is heated, and dry nitrogen is used to transport moisture liberated from the sample into the cell where it reacts with the titration reagent. The charge required for regeneration of the titration reagent provides a quantitative measure of the moisture liberated from the sample. The end point of the titration is automatically evaluated and the result displayed on a digital readout.

Part of the criticality safety design for the 1700 kg modcon containers used in UO_2 powder bulk blending operations is predicated on restricting the moisture content of the powder contained within to less than 0.3% water by weight. Two of the many Initiating Events postulated to challenge this design are listed below, and summarized in greater detail by the defense tables presented in Table III.

- IE-1: False low result of pink dot sample moisture analysis due to laboratory failure
- IE-2: False low result of blue x sample moisture analysis due to laboratory failure

Each IE constitutes a challenge to the barrier designed to prevent the inadvertent transfer UO_2 powder with an unacceptably high moisture content from polypaks into an NFG vessel. A direct comparison of the defense elements associated with each IE (Table III) identifies significant commonalty between the CSCs, thereby revealing the potential for CMF. These defenses are not entirely independent, indicating that reliance upon the pink dot/blue x sampling and analysis technique alone is not sufficient to ensure double-contingency protection in this case.

CONCLUSIONS

Although the ADU conversion process under normal and routine operating conditions produces inherently dry (< 0.3 wt.% water) UO_2 powder, it is imperative that the actual moisture content be verified acceptable before the powder is transferred into an NFG vessel. Compliance with the double-contingency principle is, in this case, strongly reliant upon the accuracy and dependability of the pink dot/blue x sampling and analysis program. Common mode failure potential was identified by the application of an inductive DCA method to the evaluation of this program. Programmatic changes and procedural modifications implemented subsequent to the evaluation have been effective at significantly increasing the level of double-contingency protection for the system. These include:

- frequency of standard sample check has been increased
- the same moisture meter may no longer be used for both the pink dot and the blue x analyses

The inductive DCA method described herein has been successfully applied, and proved useful as a tool for demonstrating system compliance with the double-contingency principle.

TABLE III

Comparison of Two Initiating Event Defenses

Parameter Addressed	IE-1: pink dot analysis false low			IE-2: blue x analysis false low		
	Defense Element			Defense Element		
	BA	CSL	CSC	BA	CSL	CSC
Mass	≤ 6800 kg UO_2			≤ 6800 kg UO_2		
Mod./Con.		≤ 3 wt.% H_2O	sample moisture analysis procedures and equipment		≤ 3 wt.% H_2O	sample moisture analysis procedures and equipment
Geometry	Sphere R = 74 cm			Sphere R = 74 cm		
Spacing	N/A			N/A		
Density	Homogen. UO_2+H_2O @ ≤ 4 g/cc			Homogen. UO_2+H_2O @ ≤ 4 g/cc		
Absorbers	1.25 cm 304-SS 2.5 cm H_2O			1.25 cm 304-SS 2.5 cm H_2O		
Enrich.	≤ 5% ^{235}U			≤ 5% ^{235}U		
Reflection	1.25 cm 304-SS 2.5 cm H_2O			1.25 cm 304-SS 2.5 cm H_2O		
Temp.	≤ 293 K			≤ 293 K		

Potential Common Mode Failures:

1. Both the pink dot and the blue x analyses are controlled by the same administrative procedures.
2. Any one of the three moisture meters is permitted to be used for any of the required sample analyses.
3. Analysis of both the pink dot sample and the blue x samples by the same laboratory technician is not explicitly prohibited
4. Period between standard source checks often exceeds turn-around time for both analyses

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