ORNL/CF-01/41

Worker Burned by Caustic Solution When Capped Flask Failed

Accident Investigation Report

October 12, 2001

Compiled by

Gerald A. Harvey

Table of Contents

Exhibits, Figures, Tables iii

Acronyms iv

Executive Summary v

1. Introduction 1
   1.1. Background 1
   1.2. Facility/Site Description 1
   1.3. Scope, Purpose and Approach 1

2. Facts 2
   2.1. Overview of Accident 2
   2.2. Accident Description and Event Chronology 3
      2.2.1. Event Chronology 3
      2.2.2. Accident Description 3
      2.2.3. Emergency Response 4
      2.2.4. Medical Summary 5
      2.2.5. Management Response 5
   2.3. Hazards, Controls, and Management Systems 6
      2.3.1. Hazard Identification 6
      2.3.2. Physical Controls 7
      2.3.3. Work Control Documents 9
      2.3.4. Self-Assessment 10
      2.3.5. Training 10
      2.3.6. New Laboratory-Wide Electronic Work Control Process 11
   2.4. Human Factors 11

3. Analysis and Conclusions 12
   3.1. Overview of the Analysis Methodology 12
   3.2. What-Why Logic Hierarchy 13
      3.2.1. Flask Failure 13
      3.2.2. Eye/Body Damage 14
   3.3. Causal Factors, Direct Cause, Root Causes, and Contributing Causes 22
   3.4. Integrated Safety Management 24

4. Judgment of Needs 26

5. Board Signatures 27

Appendices

I List of Interviewees (Titles) A-1
II List of Reference Documents A-2
III Letter of Appointment A-3
IV Occurrence Report (reference) A-4
V Corridor Layout A-5
VI Lab A-21 Schematic A-6

Exhibits, Figures, and Tables

Exhibits

2-1 Flask on Floor of Lab 2
2-2 Close up of Flask 2
2-3 Close up of PI Glasses 7

Figures

3-2 What-Why Logic Diagram 16

Tables

2-1 Event Chronology 3
3-1 Direct and Root Causes 22
3-2 Contributing Causes 23
3-3 Weaknesses in the ISM Implementation 24
4-1 Judgment of Needs 26

Acronyms

ALD	Associate Laboratory Director
CERS	Chemical Energy Research Section
CFR	Code of Federal Regulations
CHP	Chemical Hygiene Plan
CTD	Chemical Technology Division
DOE	U.S. Department of Energy
DOE-ORO	U.S. Department of Energy, Oak Ridge Operations
DSO	Division Safety Officer
EESD	Energy and Engineering Sciences Directorate
ICD	Instrumentation and Controls Division
ISM	Integrated Safety Management
JHE	Job Hazard Evaluation
MSDS	Material Safety Data Sheets
NTRC	National Transportation Research Center
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PI	Principal Investigator
PPE	Personnel Protective Equipment
PSS	Problem Safety Summary
R&D	Research and Development
SBMS	Standards Based Management System
SSO	Section Safety Officer
TFA	Tank Focus Area
TPP	Technical Task Plan
WSRC	Westinghouse Savannah River Company
WSS	Work Smart Standards
WWLH	What-Why Logic Hierarchy
WPPC	Work/Project Planning System and Control

Executive Summary

On September 14, 2001, an accident occurred at Oak Ridge National Laboratory. A principal investigator (PI) working in laboratory A-21 of building 4500N received burns when a capped polymer flask containing a caustic solution burst. The PI was preparing reagents for an experiment by dissolving sodium hydroxide and aluminum nitrate in water in a 250-milliliter volumetric flask. A cap was mistakenly placed on the flask prior to completion of the exothermic dissolution process. The heat of dissolution caused an increased temperature and pressure in the capped flask to the point of flask rupture and subsequent spraying of the PI with concentrated caustic solution. The PI was not wearing splash goggles, labcoat, or gloves. The PI received first and second degree burns to the face, torso and right arm, a third degree burn on two fingers and chemical burns to both eyes.

The PI immediately began flushing his eyes at the laboratory sink where he was standing. After approximately one minute of eye washing, and because the caustic was also burning his torso, he removed his shirt and went to an emergency shower/eyewash station outside his laboratory approximately 30 feet down the hall. He did not use the eyewash/safety shower located inside his laboratory. A co-worker called 911 while the PI continued to flush his eyes and body, assisted by several co-workers, until an emergency response team arrived approximately seven minutes later.

Because of the severity of his burns and possible eye damage, the PI was air-lifted to the University of Tennessee Medical Center for treatment. He was released from the hospital two days later, but continues to receive daily treatment from an ophthalmologist due to clouded vision in one eye.

Emergency response, including clean up of the scene, was completed within six hours of the event. A critique was conducted within approximately two hours of the event. Work in the affected research section was suspended pending detailed safety reviews. The remaining research divisions in the Directorate were directed to conduct focused safety reviews of similar work. A “safety flash” describing the event and immediate lessons learned was distributed to all Directorate employees and forwarded to senior management for lab-wide use.

The Associate Laboratory Director for Energy and Engineering Science initiated a formal Accident Investigation Board on September 21, 2001. The Board completed its investigation and presented the report to the Associate Laboratory Director for acceptance on October 12, 2001.

The Board concluded that this accident and the resulting injuries were preventable. The investigation revealed examples of human error on the part of the injured PI, as well as several weaknesses in management technique and approach, and in the implementation of management systems at several levels.

The direct cause of the accident was that the PI prematurely capped the flask in which a solution was undergoing exothermic reaction. The Board identified three root causes of the accident and injury. They are: *

- *Failure of PI to Stay Focused* on the routine, but hazardous, task of dissolution
- *Local Controls (are) Considered Adequate* by division personnel who therefore tend to not always follow, or be aware of, Lab-level requirements
- The *Problem Safety Summary (PSS) (is) Not Recognized as the Primary Tool for Hazard Identification, Mitigation and Review,* thereby weakening the work planning and control process used and resulting in PPE not adequate for the hazards encountered.

Judgments of Need are the managerial controls and safety systems determined by the Board to be necessary to prevent and/or minimize the probability or severity of a recurrence. They flow from the causal factors, which are derived from the facts and analysis. Judgments of Need are directed at providing guidance for managers during development of corrective action plans. Table ES-1 contains the list of Judgments of Need.

JON #	Judgment of Needs Description	Related Causal Factors
1	**Line Ownership of Safety:** Line managers need to become more proactive in setting and communicating safety expectations in the workplace.	RC 2,3 CC 1,2,3,4,5,6,7,8
2	**Balanced Priorities:** Line managers must establish and convey a balanced set of priorities among programmatic and operational/ES&H needs. Working safely must become a condition of employment as is the case for maintaining programmatic funding and conducting high quality research on time and within budget.	RC 1 CC 3,4,7
3	**Commitment to Safety:** Line managers must establish more effective safety systems and convey a more disciplined approach to planning, conducting, and evaluating research operations.	RC 1,2,3 CC 1,2,4,5,6,7,8

*The actual root cause statements are shown in italics.

1.0 Introduction

1.1 Background

On September 14, 2001, an Oak Ridge National Laboratory (ORNL) Principal Investigator (PI) working alone in building 4500N at ORNL sustained injuries while performing a routine dissolution. The PI was working on a project for Westinghouse Savannah River Company (WSRC) entitled Aluminosilicate Formation Kinetic Study. The Chemical Technology Division (CTD) began an initial investigation on the day of the accident which was upgraded to a Directorate-level investigation on September 21, 2001.

1.2 Facility/Site Description

Operational facilities at ORNL are managed for the U. S. Department of Energy by UT-Battelle, LLC. The Chemical Technology Division conducts operations in approximately 40 buildings/facilities at ORNL. CTD performs research and development for both DOE and non-DOE sponsors. Much of their work is related to energy or to the environment and includes the fields of inorganic and organic chemistry and radiochemistry. CTD occupies several chemical laboratories within building 4500N, including room A-21, where the accident occurred. Room A-21 is a typical chemistry research laboratory comprised of hoods, sinks, bench tops, and emergency equipment. The accident took place on the south side of the laboratory in front of the sink. See lab layout in Appendix VI.

1.3 Scope, Purpose, and Approach

A Directorate-level Investigation Board (Board) was appointed on September 21, 2001 (see Appendix IV) and began its investigation on that day. The investigation was completed by the Board on October 5, 2001. The scope of the Board as defined by the ORNL Associate Laboratory Director (ALD) for the Energy and Engineering Sciences Directorate (EESD) was to identify all relevant facts; analyze the facts to determine the direct, contributing, and root causes of the incident; develop conclusions; and determine Judgments of Need that, when implemented, should prevent recurrence of the accident. The Board used the following approach:

- Facts relevant to the accident were gathered through interviews and review of documents.
- The accident scene was inspected.
- Photographs taken of the scene were reviewed.
- Physical evidence was inspected, and chemical analysis was performed.
- Thermodynamic calculations were performed to verify the accident scenario.
- Facts were analyzed to identify the causal factors using events and causal factor analysis, barrier analysis, and root cause analysis.
- Judgments of Need for corrective actions to prevent recurrence were developed to address the causal factors of the accident.

2.0 Facts

2.1 Overview of the Accident

On Friday afternoon, September 14, 2001, at approximately 1509 hours EDT, a highly caustic solution ejected from a ruptured polypropylene volumetric flask (see Exhibits 2-1 and 2-2) and sprayed a research PI at ORNL while he was dissolving sodium hydroxide (NaOH) and aluminum nitrate in water. The flask, which was inadvertently capped by the PI, ruptured because of heat-induced softening produced by the exothermic reaction and associated pressure build-up in the closed flask. The PI suffered first, second, and third degree burns from the hot caustic solution, which also entered both eyes causing significant damage to one of them.

Exhibit 2-1

Exhibit 2-2

The PI was dressed in a short-sleeved personal shirt, pants, and shoes, and was wearing non-safety reading glasses. He was not wearing a labcoat or gloves. The caustic spray hit the PI on the right arm and upper right area of the chest, resulting in the solution entering the eyes, primarily the right eye. The PI was standing about three feet from a sink, the closest source of water. He immediately splashed water on his face to remove the caustic from his eyes. The PI then removed his shirt and made his way to the hallway, where a coworker assisted him to the eyewash/safety shower about thirty feet from the laboratory door. Coworkers continued flushing the affected areas with water.

A call for emergency assistance was made at 1512 hours and according to witnesses, emergency response personnel arrived at 1516. The PI was transported to ORNL medical facilities where he received initial treatment. He was then transported to the University Of Tennessee Medical Center via Lifestar helicopter.

2.2 Accident Description and Event Chronology

2.2.1 Event Chronology Table

Time	Event
~1500	PI adds 138 g NaOH solids to flask
~1505	Adds 50-100 mL water to flask
~1507	Adds 140.7g aluminum nitrate to flask
~1508	Caps flask
1509	Flask ruptures
1509	Splashes face and torso with water from sink
1510	Removes shirt while leaving laboratory
1511	Coworker directs PI to shower/eyewash in hall
1512	911 call made, received
1512	PI says that water is needed on his back
1514	Coworker pours buckets of water on PI
1515	Alert on emergency radio channels
1516	Emergency personnel arrive
1517	ORNL ambulance arrives at medical
1517	Laboratory A-21 secured
1522	PI taken to ORNL medical
1535	IH personnel take initial photographs
1550	HAZMAT Team arrives
1550	Lifestar helicopter arrives
1600	PI taken to UT Medical Center
1600	Ambulance returns to ORNL Fire Dept.
1700	Event categorized as Off Normal
1720	Critique initiated
2100	Lab cleanup, posting complete

Table 2-1

2.2.2 Accident Description

The PI initiated the sequence of events resulting in the accident when he began to prepare a 250 mL solution of sodium hydroxide, aluminum nitrate and water. He had prepared many similar solutions since January of 2001 for the WSRC waste form chemistry research. However, the solution being prepared contained the highest concentration of hydroxide in the test series. The preparation of these solutions is a standard chemical operation that was not considered part of the actual experiment when the hazard evaluation was conducted. The PI was preparing the solution in a narrow-necked, screw-cap polypropylene volumetric flask, and began by adding approximately 138 grams of solid sodium hydroxide to the flask, then adding an estimated 50 mL to 100 mL of distilled water from a squirt bottle. He then added about 140.7 grams of aluminum nitrate, swirling the flask to promote dissolution of the solids. When sodium hydroxide dissolves in water, the reaction releases

heat (exothermic), and the aluminum nitrate absorbs heat (endothermic). The exothermic heat can be enough to cause boiling of the water.

The PI screwed the cap onto the flask before the reactions were complete, which he stated he had never done in any previous solution preparations and further stated that he did not know why he used a cap this time. At about 1509 hours, while transferring the flask from the hood to the sink for cooling, the flask ruptured, causing a superheated caustic solution, probably with undissolved particles of sodium hydroxide and aluminum nitrate in it, to be ejected from a rupture in the flask approximately 1/2 inch in diameter (see Exhibit 2-2). The superheated water likely partially flashed to steam, ejecting most of the flask contents with enough energy to spray up to about 12 feet, and possibly contributing to the severity of the chemical burns. A small residue of wet solids remained in the flask, representing 10% of the 279 grams initially added. Subsequent analysis of these solids was consistent with the PI's test plan.

2.2.3 Emergency Response

When hit in the chest and face by the ejected material, the PI immediately went to the adjacent sink, turned on the faucet fully (as opposed to going to the eyewash/safety shower station in the laboratory less than 15 feet away), and splashed his face with water. The PI, realizing that his shirt had caustic solution on it, removed it as he left the laboratory to use an eyewash/safety shower in the hallway. In the hallway, a colleague assisted the PI to the eyewash/safety shower. Other colleagues were alerted by the audible noise of water running from the eyewash and began arriving to assist. The initial colleague stayed with the PI and asked two other persons to call 911.

A call for ORNL emergency response personnel was made at about 1512 hours. ORNL emergency responsers arrived at about 1516 hours. The emergency responders activated the safety shower portion of the eyewash/safety shower station to flush his back as the PI continued to use the eyewash. The PI was then transported by gurney to the ORNL medical facility. The PI received medical treatment, and at about 1600 hours, he was flown to the University of Tennessee Medical Center in Knoxville by helicopter. The event was categorized as an Off Normal Occurrence at 1700 hours on the same day (ORO—ORNL-X10CHEMTEC-2001-0012).

ORNL HAZMAT personnel arrived at about 1550 hours and began to clean up the remnants of the caustic solution. The event was categorized by the ORNL Laboratory Shift Supervisor's office as a reportable off normal occurrence at 1700 hours.

A critique was conducted at approximately 1720 hours. On-scene investigation and evidence gathering started concurrently with Hazmat cleanup. At 0900 hours on Monday, September 17, 2001, the Chemical Energy Research Section (CERS) Section Head issued instructions to stand down laboratory work in his section.

2.2.4 Medical Summary

The primary damage of concern is the damage to the eyes, mostly the right eye. Initial reports indicated that the right eye could possibly be lost. The PI has been visiting an ophthalmologist on a daily basis since the accident. Currently, the left eye is completely healed and medications of the left eye ceased about 09/26/01. The prognosis for the right eye is still guarded, but loss of the eye is no longer a concern. The degree of recovery of the right eye is still indeterminate. The right eye shows good progress, but, as of this writing, there is still an area about 2 X 3 mm where stem cells have not regenerated. The PI is wearing a plastic lens to help promote stem cell growth in case tears or blinking were washing the new stem cells away. The PI spoke with his supervisor on the morning of October 2, 2001, and his supervisor stated that some damage is still visible, but the PI told him he had a noticeable increase in visual clarity in one day. Additional initial damage caused by the caustic solution included first degree burns to the right cheek and forehead, first and second degree burns to the right torso and chest area, and part of the right hand and arm. Third degree burns are located on the pad area of two middle fingers on the right hand. The first-degree burns on the cheek and forehead are completely healed, and there is no concern that the rest of the skin burns will not heal completely in time.

2.2.5 Management Response

<u>CER Section Response:</u> Initial investigation and evidence collection commenced at the scene of the accident on September 14, 2001. An accident investigation team was appointed by the CER Section Head on September 17, 2001. At 9:00 a.m., Monday, September 17, 2001, the next work day following the accident, the CER Section Manager conducted an “all-hands” Safety Review meeting for all staff within the CER Section, and at 10:30 a.m. he issued an e-mail to all section staff saying that “effective this morning at 9:00 a.m. we will stand-down all experimental work pending a complete review of our safety documentation to include PSS’s and operating procedures.” The e-mail contained as an attachment the view graphs used in the formal Safety Review. The Safety Review addressed four broad topics: a description of the accident; immediate actions to be taken; how time should be charged; and travel and emergency information. The actions to be taken included: suspension of laboratory work within the section; review of all active PSS’s used by the section; requirements for group leaders to report back to the section manager; and requirements to be met prior to resumption of work.

<u>Energy and Engineering Sciences Directorate Response:</u> In a meeting with his Division Directors on Monday, September 17, 2001, the Associate Laboratory Director (ALD) for the Energy and Engineering Sciences Directorate (EESD) verbally directed all his divisions to conduct a safety review of all work. This was followed that afternoon by e-mails from the ALD to his Division Managers delineating the specific nature of the required safety reviews and the necessary conditions, including ALD permission for restarting any work that had been suspended. On Thursday, September 20, 2001 the EESD Operations Director provided a debrief of the accident and subsequent management actions to the Laboratory Leadership Team. On Thursday, September 20, 2001 the ALD appointed the ORNL-level Accident Investigation Board and empowered it to assume all investigative responsibilities

previously initiated by CTD management. On Monday, September 24, 2001 the ALD issued a Safety Alert by e-mail to his Division Directors, other Laboratory ALDs, and Laboratory Directors of support organizations. Each division in the EESD initiated the directed safety reviews on September 17, 2001.

2.3 Hazards, Controls, and Management Systems

2.3.1 Hazard Identification

The process being conducted at the time of the accident was preparation of a tank simulant solution from sodium hydroxide, aluminum nitrate, and sodium nitrite. The intent was to use 138 grams NaOH, 140.7 grams $Al(NO_3)_3 \bullet 9H_2O$, 34.5 grams $NaNO_2$, and sufficient water to make 250 mL of solution. The PI's typical method of preparation was to place the weighed quantities of NaOH and $Al(NO_3)_3 \bullet 9H_2O$ in a narrow-necked polypropylene 250 mL volumetric flask, add a portion of the necessary water (not measured, but estimated at between 50 to 100 mL), and swirl the flask gently by hand until the solids were dissolved. Later the sodium nitrate ($NaNO_2$) would be added, dissolved, and the flask would be capped and cooled by immersion in a beaker of cold water.

The primary hazards of this process are the corrosive nature of the highly caustic solution, the production of heat from the exothermic reaction, and the possible evolution of nitric oxide gases during the sodium nitrite addition.

The third of these hazards, nitric oxide gas evolution, is mitigated by process order. The sodium nitrite, if added after the other species are completely dissolved, does not evolve these toxic gases. The process had not reached this step at the time of the accident, and this hazard will not be further discussed.

Sodium hydroxide solutions are highly caustic, especially in the highly concentrated form being prepared by the PI. Such material rapidly attacks tissue, the eyes being particularly vulnerable. Upon skin or eye contact, immediate dilution and rinsing are imperative to minimize damage.

The process being conducted evolved heat, primarily from the heat of solution of the sodium hydroxide, but secondarily from the reaction of hydroxide with aluminum nitrate. This is partially compensated by the fact that the dissolution of aluminum nitrate is endothermic (i.e., absorbs heat). Dissolution of the compounds used in similar preparations typically took 10 minutes. Heat is continuously generated during this time, and continuously being dissipated to the surroundings through the walls of the flask and by evaporation of water from the warm solution.

The immediate hazard of the heat evolution is to add a thermal component to the chemical burn hazard of the caustic solution. In the normal solution preparation process used by this PI, the hazard associated with heating is the possibility that the solution would reach the boiling point and spatter or overflow the flask. In many previous preparations, however,

this did not happen. The implication was that heat dissipation would keep the solution below the boiling point (approximately 108°C at the final solution composition, higher for the more concentrated intermediate solutions formed during the material preparation). The more serious hazard associated with the heat generation in this process is, however, indirect and applies only if the flask is capped prior to completion of dissolution of the solids.

The solid heel, approximately 10% of the initial solids, remaining in the flask after the accident was sent for chemical analysis to verify that the PI did not add any incorrect ingredients to the flask. The results of that analysis revealed the expected constituents: Al, Na, nitrate, free hydroxide, and carbonate (which would result from capture of CO_2 from the air). The possibility that incorrect ingredients were used in preparation of the solution is therefore dismissed as a factor in this accident.

The scenario developed to explain the bursting of the capped flask is: (a) the dissolution was not complete at the time of capping, and thus the solution was still generating heat; (b) heat generation increased the solution temperature (at least locally) above the (107°C) softening point of the polypropylene flask material; (c) higher solution temperature also led to higher water vapor pressure in the flask; (d) the pressure burst the softened flask; (e) the solution was propelled out of the breach by the pressure and most likely was amplified by the effect of superheated solution boiling when the pressure suddenly decreased upon flask rupture.

To determine if there was sufficient energy in the heat of solution and reaction to raise the solution temperature to the levels needed to sustain this scenario, a series of thermodynamic calculations were undertaken. These calculations can give only an upper limit of the temperatures and pressures that can be generated if the system were perfectly insulated and contained. Maximum temperatures and pressures varied with water content, but for a 100 mL water addition, the computed adiabatic temperature and pressure generated were 254°C and 24 atm. The actual temperature of the solution would depend heavily on heat transport to the surroundings during the dissolution and the actual pressure in the flask would be dependent on the temperature of the solution and of the wall of the flask above the liquid level. These thermodynamic calculation results should *not* be interpreted as suggesting that the computed temperature and pressure were likely to have been reached, but rather that there clearly was enough chemical energy present in the system to satisfy the flask rupture scenario.

2.3.2 Physical Controls

Physical controls available to the PI to serve as barriers against injury included, laboratory equipment, personal protective equipment (PPE), and emergency equipment. The primary potential barrier was the sash of the standard fume hood in use. Although the PI had initiated his solution preparation in the fume hood, he had removed the flask from the hood and was swirling it while standing near the sink when the accident happened.

Exhibit 2-3

A portable blast shield, which could have served in part as a splash shield, was available in the laboratory but was not used any time in the operation.

Available PPE included a labcoat, chemical-resistant gloves, safety glasses, splash goggles, and face shield. None of these were in use at the time of the accident. For eye protection, the PI was wearing reading glasses (see Exhibit 2-3). The glasses were not ANSI-approved safety glasses. However, this fact is likely not material to the injury received, as the ANSI standard for safety glasses provides mainly for impact resistance. The PI's attire afforded little protection. The PI's short-sleeve shirt exposed his arms and was quickly soaked through to the skin of his torso.

Laboratory A-21 is equipped with a permanent eyewash/safety shower combination (see Appendix VI). These were located against the mid-section of the wall separating the laboratory from the A-corridor hallway. Another permanent eyewash/safety shower combination is located in the hallway approximately 30 feet to the right upon exit from the south door of A-21 (see Appendix VI). Although not intended as emergency equipment, the nearby sink in A-21 was used by the PI as the first de facto eyewash facility. This required the PI to use his hands to splash water from the tap into his eyes and onto his body. There is an eyewash/safety shower station within 15 feet of the location of the PI at the time the flask ruptured; however, the PI thought it was a portable eyewash and was not aware that it was a permanently installed eyewash/shower combination.

Other physical controls at the PI's disposal included the type of containers for preparing the solution, the method of mixing the chemicals, including the order of addition of solution components, timing of the additions, and cooling method. According to the PI's testimony and his laboratory notebook, the experimental methodology had been worked out over the period of at least eight months prior to the accident. Germane to the accident, the dissolution of solids was not yet complete, and the PI had not yet performed the usual cooling step at the time of the flask rupture.

Prudent laboratory practice related to the preparation of the caustic solution is spelled out in commonly available manuals such as "Prudent Practices in the Laboratory", prepared by the National Research Council (National Academy Press, 1995). In addition to warning the reader concerning the danger of eye injury and the need for adequate eye protection when handling caustic solutions, this manual specifies (p.397) that one "Never add water in limited quantities to solid hydroxide." Rather, prudent practice dictates that one "always add caustics to water and stir continuously." By so doing, one provides for gradual evolution of heat. Alternatively, use of commercially available 50% sodium hydroxide solution is common practice for caustic solution preparation and avoids much of the heat generation associated with dissolution of solid sodium hydroxide. The combination of the choice of flask (volumetric) and means of mixing (hand swirling) forced the initial mixture to be much (~ three times) more concentrated than the final 250 mL stock solution. This deposited the heat of solution and reaction in a small mass, leading to higher temperatures than would be encountered in alternate solution preparation methods. Laboratory workers interviewed by the Board indicated a strong preference for wide-mouth containers.

2.3.3 Work Control Documents

The PI's laboratory project was authorized via the Technical Task Plan (TTP) OR16WT41. This TTP was the official funding vehicle under the Tanks Focus Area (TFA) of the DOE Office of Environmental Management. ES&H requirements were set by reference to CTD procedures (see below). More specific work scope was defined under a test plan entitled "Formation Kinetics Task Plan - Phase II Scoping Tests." The test plan was requested and approved by authorized managers of the Westinghouse Savannah River Company (WSRC), the primary beneficiary of the results of the PI's project. Such programmatic involvement by WSRC was normal for projects funded by the TFA expressly for the benefit of WSRC. Laboratory work was authorized for the period August 6, 2001 to September 10, 2001. A draft report was to be issued September 30, 2001, followed by a final report due October 31, 2001. Safety reviews and documentation were to be handled in compliance with CERS, CTD, and ORNL requirements.

The major component of the safety review was the Problem Safety Summary (PSS), which had already been approved for similar work scope and hazards on December 28, 2000. Although the test plan did not specifically identify the PSS as part of the safety review and documentation, the PSS is required for each significant research activity by the CTD Chemical Hygiene Plan CY2001 (CTD/CHP), ORNL Report No. ORNL/CF-01/12. The CTD/CHP identifies the PSS as the CTD vehicle for meeting job hazard evaluation requirements for research of the type performed by the PI and recognizes the PSS as an essential part of the safety program, the objectives being "(1) to provide information on hazards and work practices to all persons working on a problem, (2) to alert personnel not directly connected with the problem information on hazards present for the work in progress, (3) to ensure that the person responsible for the problem has made a satisfactory safety analysis, and (4) to ensure that the core functions of the Integrated Safety Management System (ISMS) are implemented via the PSS." In essence, the PSS is the CTD-recognized mechanism to: identify all of the hazards associated with work to be performed, to identify the controls to be used to mitigate these hazards, and to facilitate the review of these hazards and mitigation controls by peers, ES&H experts and line managers. The ORNL requirement for job hazard evaluations is found in the ORNL SBMS Subject Area "Job Hazard Evaluation", ORNL-SH-P29.

The PSS, in turn, refers to the CTD/CHP as "the reference for guidelines on safe handling of chemicals." The PSS provided a brief description of the operation to be performed upon preparation of the solutions, but the hazards involved in preparation of the caustic stock solutions was not discussed. No splash hazard was identified, and accordingly the PSS specified safety glasses as the only eye protection in its check list of required operational controls. The CTD/CHP stresses "that goggles, rather than standard safety glasses, should be worn in potential splash situations". The ORNL procedure ORNL-SH-P19, referred to in the CTD/CHP, more explicitly requires "Goggles shall be used when there is a hazard from chemical splash." A labcoat and neoprene or equivalent gloves were also marked as a requirement in the PSS check list. Section 6 of the PSS provided that "protective gloves will always be worn when samplings [sic] and working around the equipment."

With regard to emergency equipment, the PSS noted the availability of safety showers and eyewash stations both in the laboratory and in the hallway. Aluminum nitrate was not listed in the Chemical List of the PSS, and sodium hydroxide was given as only 3 molar, interpreted here as the maximum concentration in the final kinetic study. The target concentration of sodium hydroxide in the stock solution being prepared, however, was 13.8 M, and the concentration during the accident was likely significantly higher than that.

2.3.4 Self-Assessment

The CTD Self-Assessment program, which is based on a three year planning cycle, identifies line management as having overall responsibility for implementation,. A Self-Assessment Program Manager is designated to assist line management in coordinating their assessments. This has been an evolving program within CTD with new parts being added to align with changing management systems, the most recent being "Minding Our Business" to respond to the management performance objectives of the Laboratory's Agenda. Assessment activities performed in the last three years have focused on specific performance areas relating to the Necessary and Sufficient Work Smart Standards approved by the DOE and/or other functional areas to facilitate compliance with external regulations (e.g., DOE orders, CFR elements, P-AAA requirements).

The principle self-assessment functions referred to in CTD Self Assessment procedures include Policy and Procedures, Management Systems, Functional Areas, and Surveillances and Inspections. The work control and hazard identification system (PSS) has not been assessed by CTD during the last three years. Inspection of laboratory space for safety compliance is conducted on a quarterly basis by a team of section staff and ES&H personnel. However, those conducted within the CERS have not been documented, formally communicated to line management, or trended since 1998.

2.3.5 Training

ORNL policy is to implement a Lab-wide program to communicate training requirements for all divisions and have all divisions develop division-specific programs to satisfy the Lab-level requirements. CTD has determined training requirements for all CTD employees who work with chemicals and has developed a database to track the training status for all such personnel. The PI in this accident should have been trained on the following:

- CTD Chemical Hygiene Plan (CHP)
- Problem Safety Summaries (PSS), for Lab A-21, Bldg 4500N
- Personal Protective Equipment (PPE), relative to the PSS
- Emergency Equipment

The PI has been trained on the CTD-CHP and all PSSs for Lab A-21. He also received Site-Specific Training, including the necessary PPE for his specific PSS and the available emergency equipment.

However, the PSS completed by the PI failed to identify appropriate PPE for the mixing process, and the PI was not aware that there was an eyewash/shower combination station in Lab A-21. Neither did his co-workers understand the proper operation of the emergency equipment.

2.3.6 New Laboratory-Wide Electronic Work Control Process

A new work/project planning and control (WPPC) management system developed under the SBMS format has been issued by the Laboratory for Research and Development (R&D) activities. Starting October 1, 2001, all new and modified experimental work must be approved using this new WPPC. The WPPC system references an SBMS procedure entitled "Implementation of Integrated Management System (ISM) in Research and Development (R&D)," which describes a new process incorporating an electronic hazards assessment tool to be completed by the PI and coordinated through a review process involving subject matter experts similar to the approval process for the PSS. By September 30, 2002, all ongoing experiments must have their PSS documentation revised to the new format. After six months of laboratory use, the Office of Independent Oversight, will conduct a formal assessment of the implementation of the new WPPC system.

Since this new WPPC system replaces the PSS, it was reviewed by the Board as it relates to causal factors of this accident. Based on discussions with laboratory personnel familiar with the new tool and interviews with CTD personnel who have used it in "mapping" existing CTD PSS's into the new format, the Board's conclusion is that the new tool will improve hazard identification. This improvement is attributed to the specific questions contained in the assessment tool.

2.4 Human Factors

Human factor stressors include those conditions and events affecting how people make decisions about the work they perform and how they actually perform the work. The following stressors were identified as having a potential to distract the PI or influence the way work was conducted.

- Additional work performed without rescheduling the report due date (effectively September 28)
- PI needed analytical results from others outside his direct control for this report;
- PI is strongly motivated to solve a significant problem for the customer;
- PI is strongly motivated to maintain good customer relations and bring in additional projects/funding;
- Intense schedule pressure in WSRC work.
- Impending reorganization.
- National events of the week.

Analysis of these factors is in section 3.2.1

3.0 Analysis and Conclusions

3.1 Overview of the Analysis Methodology

After reviewing various causal analysis methodologies typically used in accident investigations, the Board elected to develop and use a simple "what-why" logic hierarchy (WWLH) that encompasses the same fundamental concepts.

The WWLH begins with the Board, in a group setting, facilitated by one of its members, asking the question "what happened in this accident" and articulating a set of possible answers, each expressed in the form of a simple statement. The starting ground rule in the initial part of this "what phase" was to be sure everything of significance that happened in the accident was captured.

Following this the Board asked the question "why did this happen" for every what statement identified in the initial "what phase" and articulating a set of possible answers, also expressed in the form of simple statements. The starting ground rule here was also to be sure that every possible reason why was captured. This "why phase" was then cascaded downward, i.e., for every "why statement" developed in the first step of this "why phase", the question why was again asked and answered. This was continued downward one, two or three levels until no further information could be gleaned. At times in this "why phase" additional "what statements" were identified.

The final step was to iterate the entire process a few times with the intent of removing redundancy without losing completeness. In other words, the Board sought a minimal number of independent, non-redundant "what statements" supported by a hierarchy of a minimal number of independent, non-redundant "why statements."

This culminated in two "what statements", i.e., The Flask Failed and Eye/Body Damage Occurred, four first-level "why statements" and a relatively simple set of lower level "why statements" as shown in Section 3.2.

The Board then examined the WWLH for possible causal factors, contributing causes and root causes and discovered that these were quite evident from the nature of the process. The results are presented and discussed in Section 3.3.

3.2 What – Why Logic Diagram

The WWLH methodology discussed above culminated in two basic events that occurred in this accident, one, the release of energy beyond its intended primary barrier (the flask), the other, the damage incurred to the PI from this energy release. These are identified at the top of the WWLH in "Cause Analysis-Top Level," Figure 3-2a, as Flask Failure and Eye/Body Damage, respectively.

3.2.1 Flask Failure

For the Flask Failure event, two primary causes were identified, one related to Inadequate Chemical Reaction Control by the PI and another related to the PI's action of Prematurely Capping the Flask prior to completion of the exothermic reaction. These primary causes are identified under the Flask Failure event in Figure 3-2a.

The Inadequate Chemical Reaction Control action is believed to involve two inappropriate choices made by the PI. First, for reasons discussed in the last two paragraphs of Section 2.3.2, relating to solution preparation methods, quantity of materials used and the flask size, the PI's use of a narrow-necked, volumetric flask is deemed to be an imprudent choice. Second, the addition of water to NaOH, as opposed to adding NaOH to water, is inconsistent with standard safe practices for mixing these two materials. Both of these actions are believed to have been conscious choices by the PI. The Premature Capping of Flask action is believed to be an Unintentional PI Action, as opposed to an intentional one, because he claims to have no idea as to why he did so, and his manager and peers likewise have no plausible explanation other than human error.

Figure 3-2b entitled "Inadequate Chemical Reaction Control" develops this high level "reason" for the Flask Failure in more detail. In particular, it delineates what the Board believes is the hierarchy of reasons behind the PI's selection of a narrow-necked volumetric flask and his decision about the order and rate of chemical mixing. In this, and all subsequent logic hierarchy figures, Contributing Causes are indicated by dark blue colored boxes, Root Causes are identified by dark blue colored boxes with bold-outlining and Causal Factors are the sum of these two causes. Based on material presented in the last two paragraphs of Section 2.3.2, relating to solution preparation methods, quantity of materials used and the flask size, the Board concluded the PI's selection of the narrow-necked volumetric flask is a Contributing Cause of Flask Failure in this accident scenario, and his decision to do so was based primarily on his considerable prior experience with identical flasks in similar mixing activities without unfavorable results. Based on interviews the Board concluded the PI was not discouraged from such practice by his peers, many of whom indicated they would use safer alternatives, primarily because they are reluctant to criticize a peer individually and have no in-lab peer review process for doing so. The Board also concluded there were limited management expectations for PIs to follow prudent practices. Based on material presented in the next to last paragraph of Section 2.3.2, the Board concluded the PI's decision to add water to NaOH, and not the reverse, was the second Contributing Cause of Flask Failure in this accident scenario, and

his decision to do so was based primarily on his perception of risk at this rate and scale of mixing.

The Board also concluded the PI was not discouraged from this practice for the same reasons noted previously for flask selection.

Figure 3-2c entitled "Premature Capping of Flask" develops this high level "reason" for the Flask Failure in more detail. It delineates what the Board believes is the fundamental reason behind the PI's unintended and accidental action of capping the flask prior to completion of the exothermic reaction. Several stresses could have potentially caused a lapse of attention during the routine, but hazardous, task of dissolution. The specific experiment for which the solution was being prepared was an addition to his defined work scope and was being undertaken at the PI's initiative. The PI hoped to include the results of this experiment in an upcoming presentation and a report (due September 28, 2001), as he believed he was working on a promising solution to an extremely important problem for SRWC. Adding scope without altering near-term due dates, in effect, compressed the PI's schedule, even though the PI stated that time pressure, in the sense of having to rush experimental steps, was not a factor in the accident because the work was not particularly time-consuming. A more likely cause of distraction is preoccupation with the many activities needed for completion of the report and presentation, complicated by the PI's dependence on several others outside his direct control to provide analytical results. Based on all available information, the Board concludes that, collectively, the self-imposed schedule pressure, a strong motivation to support the sponsor with additional results, and preoccupation with completion of the report and presentation are likely factors for failure of the PI to stay focused during the solution preparation. The Board also observed that the impending reorganization and national events of the week did have an impact on many in the organization.

3.2.2 Eye/Body Damage

For the Eye/Body Damage event, two primary causes were identified, one, related to Inappropriate PPE and Other Barriers used by the PI and, another, related to a Non-Optimum Immediate Accident Response on the part of the PI. These are identified under the Eye/Body Damage event in "Cause Analysis-Top Level," Figure 3-2a. The Inappropriate PPE and Other Barriers selection is believed to result from three factors: the Lab Requirements (for PPE and PSS information) were Not Met; there was Inadequate Information in and Review of the PSS; and there were Inappropriate PI Decisions made in regard to the selection of PPE and the Work Area. Based on interviews with CTD management and staff, the Board concluded that CTD personnel believe it is not necessary to meet all Lab-level requirements because local (CTD) controls are adequate for all research activities. The Board also concluded from these interviews that PSSs often contain inadequate information and/or are inadequately reviewed because: many CTD personnel do not recognize the PSS as the primary tool for identifying all hazards of planned work (including pre- and post-experimental steps), identifying mitigation controls for these hazards and facilitating the review of these by peers, ES&H experts and managers; there is often insufficient attention paid to the review

process; and, in general, CTD personnel are not familiar with Lab-level personnel protective equipment guidance. Finally, the Board concluded from its interviews that the PI made inappropriate decisions about his choice of PPE and Work Area because his performance expectations are not balanced between programmatic goals and safety goals; and there is a lack of peer pressure or management intervention to do things differently.

Figure 3-2d (continued on a second page) entitled "Inappropriate PPE and Other Barriers" develops this high level "reason" for the Eye/Body Damage in more detail. In particular, it delineates what the Board believes are the hierarchy of reasons behind local (CTD) controls being considered adequate by CTD personnel; the PSS not being recognized as the primary mechanism for identifying hazards, mitigation controls and review thereof; insufficient attention being devoted to PSS reviews; PSS reviewers not being aware of lab-level PSS requirements; performance expectations of the PI not being balanced; peer pressure being lax; and management intervention being lax. The Board has concluded that all seven of these factors are Contributing Causes, and the first two are Root Causes, to the Eye/Body Damage part of this accident scenario. Underlying reasons, also uncovered during the interview process, are listed for these causes.

An import factor in the PI's failure to wear proper PPE is related to hazard recognition. To protect against a splash hazard, the hazard must be recognized to exist. While it may have been difficult, in advance, to recognize the sequence of events in this accident, more conventional splash hazards were present in this experiment and these should have triggered recognition of better PPE, work location or both. Examples of such splash hazards include spatter from unintended solution boiling and simple dropping of the flask.

Figure 3-2e entitled "Non-Optimum Immediate Response to Accident" develops this high level "reason" for the Eye/Body Damage in more detail. It delineates what the Board believes is the hierarchy of reasons behind this action on the part of the PI. The Board believes the PI had inadequate training and knowledge about the merits of using the in-lab eyewash/safety shower station, as opposed to the nearby sink, for immediately neutralizing the caustic solution in his eyes, and the proper use of eyewash/safety showers. This lack of training/knowledge is identified as a Contributing Cause to the Eye/Body Damage part of this accident scenario. The Board recognizes that choice of immediate actions depends on circumstance and that the use of the sink for a defacto eyewash would have been the correct action had there not been an eyewash/safety shower inside the laboratory less than two seconds away.