University of California, Irvine

Independent Accident Investigation

Injury and Fire Resulting From
Benzene Vapor Explosion in a Chemistry Laboratory
Frederick Reines Hall,
University of California, Irvine
July 23, 2001

FINAL REPORT
January 24, 2002

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Executive Summary

Accident Description and Response

On July 23, 2001, at 3:43 p.m., an accident occurred at the University of California, Irvine (UCI), located in Irvine, Orange County, California. The accident in a chemistry laboratory in Frederick Reines Hall (Room 2022) resulted in an injury to a doctoral student and a fire that caused approximately $3.5 million in damage including repair/refurbishment costs. The student, who was also a University employee doing work for a principal investigator's (PI's) funded project, received serious burns from a benzene vapor explosion in a fume hood. The student had been purifying benzene using a reflux/distillation apparatus. The system became over-pressurized, and the student attempted to physically hold the distillation head on the distillation flask. The over-pressurization caused the system to disassemble at the sintered glass fitting between the two components, and a fine mist of benzene was released into the fume hood, where an unknown ignition source ignited the benzene vapor, resulting in an explosion and subsequent fire. While the direct cause of the over-pressurization was not determined, the lack of a clear path from the distillation flask through the pressure-relief portion of the apparatus resulted in the system disassembling and releasing a fine mist of benzene.

The injured student was able to evacuate the immediate accident scene and was taken by private automobile to the UCI Medical Center, where he was hospitalized for four days. The student is not expected to suffer any long-term health effects from this accident. His professor and fellow students evacuated the laboratories on the second floor. The resulting fire actuated a smoke detector tied into the building fire alarm system, which also transmitted a fire alarm signal to the campus Police Department (UCIPD), who in turn called the Orange County Fire Authority (OCFA) Dispatch Center.

Emergency response was immediate and the fire was extinguished within two hours of the four-alarm response. The PI of the affected laboratory, his students, and staff from several UCI departments assisted the OCFA with planning the attack on the fire. Occupancy of all portions of the building except the affected laboratories and instrument room was restored within five days.

Investigation Process

On July 25, 2001, the UCI Chancellor authorized the formation of an independent accident investigation team to review the explosion and fire at Frederick Reines Hall. The team leader was on campus three days after the accident, and the rest of the investigation team arrived on campus within a week of the accident. The team consisted of the team leader, who is an expert in accident investigation and emergency management and response; a chemistry professor and university chemical safety officer intimately familiar with the procedure involved in the accident; a fire protection engineer and California Fire Code expert; and an industrial hygienist/industrial safety expert. No member of the accident investigation team is a UCI employee. The investigation was intended to review the events leading to the incident, the incident itself, and the response to the incident.

Experimental Process
The distillation procedure involves refluxing the solvent and a small amount of benzophenone in an inert atmosphere over sodium or sodium/potassium. As the reflux proceeds, and the moisture and oxygen are removed, the benzophenone ketyl develops a deep blue color, which indicates that the solvent is ready for recovery by distillation and subsequent use. Usually the reflux process is continued for several hours to ensure solvent purity. See diagram of the reflux/distillation process at the end of the Executive Summary.

The procedure, which is usually carried out in a hood or other fire-safety area, involves apparatus for the reflux and final distillation, as well as provision for an inert atmosphere. In this case, the apparatus was set up in a walk-in hood, approximately eight feet wide and six feet high. A waist-high shelf had been installed to support the apparatus.

The apparatus included a Schlenk-type manifold with space for four separate reflux units. At the time of the accident, only the benzene purification apparatus was in use. The manifold included two parallel horizontal glass tubes with oblique three-way stopcocks that allow a worker to interchangeably purge the system with inert gas or evacuate the system via a vacuum pump. Two oil bubblers were attached to the manifold to serve as a vent for built-up pressure. One of the bubblers included an internal back-flow restriction device.

A reflux/distillation head was connected to the manifold by flexible tubing to allow reflux or evacuation, as required. The reflux/distillation head also included connections to the condenser section for access to cooling water, as well as several side stopcock joints for removal of solvent samples.

The reflux/distillation head was fitted into a 5-liter, single-neck, round-bottom flask containing the solvent and reagents. The flask was placed into an electric heating mantle, which was connected to a Variac power source, and the reflux/distillation begun. Approximately four and one half hours later, this apparatus disassembled, resulting in the explosion and fire.

Fire Code, Building Construction, and Mechanical and Fire Protection Systems
Reines Hall was designed and constructed in accordance with the 1981 California Building Code and the 1979 Uniform Building Code, the codes in effect when the design funding was approved for the project. The building was constructed of noncombustible, fire-resistive-rated material, and the occupancy of the building was determined during the design process to be B-2 occupancy. When the building was constructed, automatic sprinklers were not required throughout the five-story building (six levels including the service floor of the Chemistry Wing). However, sprinklers were provided in the service level of the building, which was defined by the building code as a basement.

Internal fire-rated partitions were provided to separate occupied spaces from the exit corridors. The building had standpipe systems for occupant and fire department use, as well as a fire alarm and detection system.

The laboratory areas were served by a mechanical ventilation and exhaust system that incorporated 100% fresh supply air and 100% exhaust to the outside of the building. The mechanical ventilation system continued to operate as designed until it was manually turned off during the fire.

The building's fire-resistive compartmentalization (e.g., fire-rated partitions and corridors) and its mechanical ventilation systems were beneficial for restricting fire damage to the affected laboratory (Room 2022) and the adjacent laboratory (Room 2004) and instrument room (Room 2004A).

Existing Environmental, Health, and Safety (EH&S) Systems
The University has a number of EH&S policies and procedures that define requirements for providing a safe working environment for employees and students. These documents include sets of detailed written procedures for hazardous operations, safety and other appropriate training, a process for oversight by the EH&S Office on campus, the University's chemical hygiene plan (CHP), and departmental safety reviews. These procedures incorporate requirements of regulatory agencies and professional standards of practice.

The University is subject to the requirements of the Hazardous Material Disclosure—Chemical Inventory and Business Emergency, Chapter 6.95 of Division 20 California Health and Safety Code and the related implementation requirements as specified by the State Office of Emergency Services (OES) at Title 19, California Code of Regulations (CCR) §2620 et seq. These regulations delegate administrative responsibility for chemical inventory receipt and distribution to the local Certified Unified Program Agency (CUPA), which in this case is the Orange County Fire Authority. The UCI EH&S Office submitted the required report to OCFA that contained information on maximum amounts of chemicals, which exceeded reporting thresholds contained in Building 401 (Frederick Reines Hall). Although the report complied with the requirements of state law and regulations, the investigation team considers the report to be inadequate for providing firefighters with sufficient information on amounts and types of chemicals in a specific laboratory.

During this incident, excellent resources, such as the PI and knowledgeable students, were available in a timely manner to provide the level of detail needed by OCFA. However, if an incident occurred at night or on the weekend, when such resources may not be readily available, fire-fighting efforts could be significantly delayed. OCFA's response to the fire relied heavily on reconnaissance to determine the extent of the fire in the laboratory. The OCFA Incident Commander obtained specific information from the PI and his students on the laboratory's configuration and contents. The school safety coordinator provided the laboratory's emergency notification form showing more specific hazard-related information about the laboratory in question.

Under Title 24 of the California Code of Regulations, the UCI Fire Marshal, who is also a Deputy State Fire Marshal, has been delegated authority to perform inspections and plan reviews of new construction and modifications of buildings on the UCI campus. Under Title 19 of the California Code of Regulations, the University has the responsibility to perform annual inspections of buildings for purposes of fire planning. According to the EH&S Office, the inspections were not being done because of a lack of resources and because plan reviews of construction activities had been deemed a higher priority for the UCI Fire Marshal.

The UCI Administrative Policy "Physical Environment and Properties" includes the general EH&S policy, roles and responsibilities, and a list of programs (Section 903-10). Section 903-25 "Occupational Exposure to Hazardous Chemicals in Laboratories" stated that PIs are responsible for ensuring that their laboratories have a written chemical hygiene plan (CHP) in place and that rules and procedures are enforced. PIs are also responsible for ensuring that Laboratory employees receive training on the rules and procedures.

The policies of the University were clear in their requirements and their description of roles and responsibilities regarding the CHP. The CHP also contained clear requirements on the use and handling of chemicals in laboratories. A number of other documents containing requirements and/or guidance were provided to the team for review. There are a number of estimates of the quantities of chemicals stored in and around the fume hood involved in the fire; all suggest that excessive materials were inappropriately stored there. The storage of flammable solvents in the same fume hood in which the distillation/purification process took place was not prudent. Flammable solvents should be stored in approved flammable liquid storage cabinets. Although it has been common practice to store flammables and other hazardous materials in or under fume hoods, it is now recognized that separating hazardous materials from the location of hazardous operations is a better safety practice. In addition, a review of the Laboratory Survey Reports showed that a number of deficiencies, including the storage of flammable materials, had been identified in the laboratory involved in the explosion and fire and that not all had been corrected in a timely manner

"General Fume Hood Procedures" in the Industrial Hygiene and Procedures Manual contains a good procedure for testing fume hoods. There are, however, fume hood construction issues and potential ignition source issues that should be reviewed as a part of the general fume hood procedures used at UCI.

Under the California Code of Regulations, Title 8 Section 5191 (f) (1), "Occupational Exposure to Hazardous Chemicals in Laboratories," the employer shall provide employees with information and training to ensure that they are informed about the hazards of chemicals present in their work area. An examination of training records for students and employees in the affected laboratory showed that the student involved in the incident attended a required three-hour Training Workshop on September 23, 1996 (as a new graduate student). Chemistry faculty conduct refresher training for students during weekly lab meeting and through periodic School Safety Bulletins. The investigation team found that there was inadequate documentation of these refresher training sessions.

Emergency Response and Initial Accident Recovery Efforts

The University's response to the accident was initiated by an automatic smoke alarm, which is monitored by the UCIPD. UCIPD in turn contacted the OCFA Dispatch Center, which dispatched a first alarm assignment to Reines Hall. UCIPD also notified the UCI EH&S Office. The EH&S Office responded and confirmed that the fire was in a chemistry laboratory in Reines Hall, which in turn activated the EH&S Office's HAZMAT Team. The HAZMAT Team has been trained and equipped to respond to chemical spills on campus and to assist in assessing complex situations. The HAZMAT Team and the Campus Fire Marshal (who is also a staff member in the EH&S Office) arrived at the scene of the fire within 15 minutes of the call to the EH&S Office. Upon arrival, the Fire Marshal took responsibility as the University's primary interface with the OCFA Incident Commander, filling the "site representative" function in the OCFA incident command structure. The original OCFA Incident Commander, the Battalion 5 Chief, became the Operations Director when relieved by a senior OCFA official who took over as the Incident Commander. The Battalion 5 Chief took into account information provided by UCI students and staff familiar with Reines Hall and the affected chemistry laboratory, and the Fire Attack Plan was designed with significant input from UCI employees and students. Issues concerning building occupants not leaving the building immediately upon hearing the fire alarm and reentering the building were resolved with assistance with the UCIPD.

The Incident Commander raised the response to four alarms after an initial assessment of the fire and its potential to release hazardous materials to the environment. A detailed Fire Attack Plan was developed, and the fire was attacked from both within the building and from outside using a snorkel apparatus. On the afternoon of the day after the fire, Incident Command was turned over jointly to the University and the Orange County Health Care Agency (OCHCA). The University had a contract with Emergency Response Strike Team, Inc. (ERST) to assist with providing infrastructure support to the joint UCI/OCHCA incident command organization. Under the supervision of the UCI Incident Commander, ERST, HazMat Services, Inc. (UCI's hazardous materials cleanup/disposal contractor), and mutual aid providers from UCLA, UC Riverside, and UC San Diego worked effectively with UCI departments to restore operations in Reines Hall.

Conclusion

The direct cause of the accident was the reflux/distillation apparatus becoming over-pressurized. The over-pressurization caused the system to disassemble at the sintered glass fitting between the two major components of the distillation apparatus. This disassembly resulted in a fine mist of benzene being released into the fume hood, where an unknown ignition source ignited the benzene vapor; resulting in an explosion and subsequent fire.

A number of factors that contributed to the immediate consequences of the explosion in the fume hood (i.e., the injury and subsequent fire) were identified as a part of the accident investigation:

- Failure of the student to use all appropriate personal protective equipment.
- Failure to follow the CHP and other documents that specify safe handling procedures, quantities and storage locations for hazardous and flammable chemicals.
- Failure to keep fire doors closed.
- Failure to use the 911 call system to request help for the injured student or to initially transport the student to an appropriate medical facility.

Furthermore, while not directly related to the explosion, fire, and initial medical treatment of the injured student, a number of additional issues related to the accident were identified during the investigation that should be considered to provide overall improvements to laboratory safety at UCI. These, along with issues directly related, are summarized in the Judgements of Need section and explained in detail in the Facts and Analysis Section. In addition, a number of Noteworthy Practices are also identified that, in the opinion of the investigation team, reduced the severity of the accident.

Future Considerations for Solvent Purification Techniques

Distillation and purification of flammable solvents, using systems like the one involved in this accident, will continue to be an integral part of chemical experimentation (if only on a limited basis as alternative methods become available). However, with such processes come the risk of fire and associated injury and property loss. Safety considerations must be a high priority when such procedures are planned and carried out. Contingency plans addressing “what if” situations must be examined before distillation procedures are begun, and appropriate safety devices must be available at all times.

Most laboratories still use the reactive metal/ketyl process to purify solvents. However, there are now methods available commercially that do not involve distillation. Instead, they rely on absorbent columns within specialized apparatus that purge and purify the solvents. This approach requires a considerable initial financial investment and will not suit every laboratory’s requirements or resources. Furthermore, although these new methods do not require heating of flammable solvents, they do involve larger quantities of solvents than are typically used in laboratory-scale distillation procedures. Accordingly, storage and delivery of solvents to the purification system must include appropriate fire safety measures. A number of these types of apparatus are currently in use at UCI; the University should assess whether increasing the number of these absorbent column systems may lead to an overall improvement in laboratory safety.

Judgments of Need
Judgments of need are the institutional controls and safety measures determined by the investigation team to be necessary to prevent and/or minimize the probability or severity of a recurrence of a similar accident and are summarized here in the Executive Summary.

Judgment of Need #1- UCI needs to strengthen supervision of hazardous activities conducted in laboratories to ensure compliance with EH&S policies and procedures.

Judgment of Need #2- UCI needs to improve the identification of hazards and the implementation of controls associated with hazardous laboratory operations.

Judgment of Need #3- UCI needs to assess its use and storage of flammable and combustible chemicals, as well as of other hazardous materials.

Judgment of Need #4- UCI needs to take appropriate actions to improve emergency response to incidents like the Reines Hall accident.

Judgment of Need #5- UCI needs to ensure that safety training and training documentation are strengthened.

Judgment of Need #6- UCI needs to clarify the responsibilities of departments and the authority of the EH&S Office to ensure implementation of corrective actions identified in safety reviews and to assess the adequacy of resources to carry out its mission.

Noteworthy Practices
Noteworthy practices are the existing institutional controls, safety measures, and other practices identified by the investigation team present to prevent and/or minimize the probability or severity of a recurrence and are summarized here in the Executive Summary.

Noteworthy Practice #1- There was proper use of safety glasses by the student involved in the incident.

Noteworthy Practice #2- The solvent distillation process was performed in a fume hood.

Noteworthy Practice #3- The design and construction of Reines Hall was instrumental in containing the fire.

Noteworthy Practice #4- UCI has widely distributed emergency procedures presented to the campus community in a variety of formats.

Noteworthy Practice #5- UCI provided laboratory safety training for laboratory workers and periodic refresher briefings.

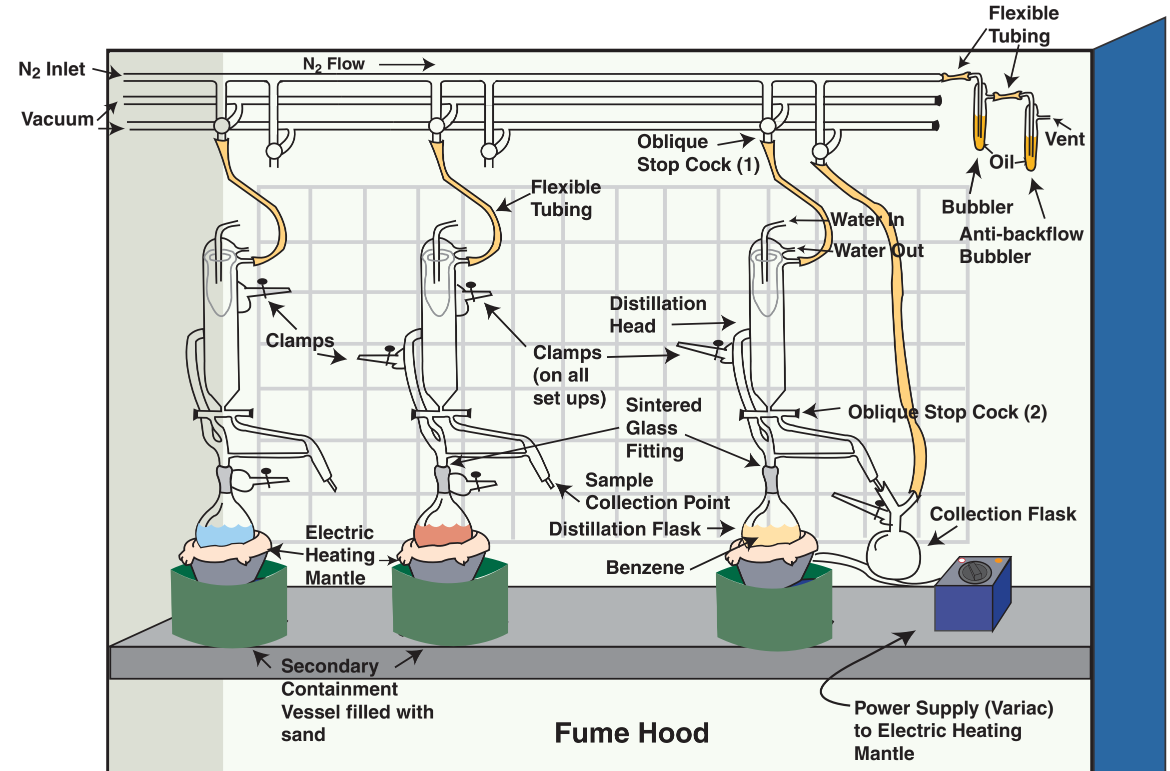
Noteworthy Practice #6- The resident school safety coordinator conducted periodic laboratory safety inspections and distributed periodic safety bulletins, which enhanced the general safety of Chemistry Department laboratories.

Noteworthy Practice #7- UCI employees and students greatly assisted the OCFA with preparing the Fire Attack Plan by providing current information about laboratory operations and a more detailed chemical inventory than legally required and by making critical adjustments to the mechanical and ventilation systems in Reines Hall.

Noteworthy Practice #8- Knowing its limitations on responding to an incident of this magnitude, the EH&S Office made immediate arrangements for support from expert contractors and other UC campuses to ensure timely recovery operations, which included an excellent reentry and sampling plan.

Noteworthy Practice #9- Other UC campuses (Los Angeles, Riverside, and San Diego) responded immediately to assist UCI with recovery efforts. Additional UC campuses were willing to assist if needed.

Diagram of Reflux/Distillation Process



Oblique Stop Cocks

(1) This stop cock controls the N_2 flow to keep the atmosphere in the Distillation head and reaction vessel inert. It also opens the apparatus to the vacuum line -- it is this stop cock that if clogged would not have allowed any pressure in the apparatus to reach the vent.

(2) This stop cock controls the flow of distilled product either back into the reaction vessel or to the sample collection point.

Investigation Team:
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Section 1 – Introduction

Accident Description and Response
On July 23, 2001, at 3:43 p.m., an accident occurred at the University of California, Irvine (UCI), located in Irvine, Orange County, California. The accident in a chemistry laboratory in Frederick Reines Hall (Room 2022) resulted in an injury to a doctoral student and a fire that caused approximately $3.5 million in damage (of which an estimated $1.2–1.5 million is required to repair the three fire-damaged rooms). The student, who was also a University employee doing work for a principal investigator's (PI's) funded project, received serious burns from a benzene vapor explosion in a fume hood. The student had been purifying benzene using a reflux/distillation apparatus when the system became over-pressurized and the student attempted to physically hold the distillation head on the distillation flask. The over-pressurization caused the system to disassemble at the sintered glass fitting between the two components, and a fine mist of benzene was released into the fume hood, where an unknown source ignited the benzene vapor, resulting in an explosion and subsequent fire. While the direct cause of the over-pressurization was not determined, the lack of a clear path from the distillation flask through the pressure-relief portion of the apparatus resulted in the system disassembling and releasing a fine mist of benzene.

The student, who was standing directly in front of the fume hood, was burned by the flash/explosion. The student's face, neck, right arm, and right leg received first- and second-degree burns. The student was wearing safety glasses at the time of the accident. The injured student was able to evacuate the immediate accident scene and was taken by private automobile ultimately to the UCI Medical Center, where he was hospitalized for four days. The student is not expected to suffer any long-term health effects from this accident, and he graduated on schedule with a Ph.D. in chemistry. His professor and fellow students evacuated the laboratories on the second floor. The resulting fire actuated a smoke detector tied into the building fire alarm system, which also transmitted a fire alarm signal to the Campus Police Department (UCIPD), who in turn called the Orange County Fire Authority (OCFA) Dispatch Center. Within minutes of the fire, two manual fire alarm stations in Reines Hall had also been pulled.

Emergency response to the scene was immediate and the resulting fire was extinguished within two hours of the initial OCFA response. The PI of the affected laboratory, his students, and the building facility staff assisted the OCFA with planning the attack on the fire. The affected laboratory, instrument room and one adjacent laboratory had significant fire and water damage. The laboratories across the hall and on the first and third floors of the building had some water and smoke damage, and the basement had some water damage. Except for the laboratory where the explosion and fire occurred and the adjacent laboratory and instrument room, the entire building was reoccupied within five days.

Investigation Process
On July 25, 2001, the UCI Chancellor authorized the formation of an independent accident investigation team to review the explosion and fire at Frederick Reines Hall. The team leader was on campus three days after the accident, and the rest of the investigation team arrived on campus within a week of the accident. The team consisted of the team leader, who is an expert in accident investigation and emergency management and response; a chemistry professor and university chemical safety officer intimately familiar with the procedure involved in the accident; a fire protection engineer and California Fire Code expert; and an industrial hygienist/industrial safety expert. No member of the accident investigation team is a UCI employee. The investigation was intended to review the events leading to the incident, the incident itself, and the response to the incident, with a focus on identifying and evaluating the following:

- Precursor events,
- Primary and contributing causes,
- Existing safety systems.
- Relevant training and/or procedures (and the degree to which they were implemented),
- The level of supervision and direction given to students and staff,
- Existing laboratory emergency response plans and procedures,

- Overall laboratory operations in the building, and
- Emergency response from UCIPD, the OCFA, and the UCI EH&S Office, including HAZMAT and medical assets.

The investigation team was directed to prepare a report that:

- Documents the background of the incident;
- Gives an overview of the team's findings, including observations, facts, and analyses;
- Lists judgments of need or deficiencies that may be addressed in a corrective action plan by the University; and
- Lists the noteworthy practices that were identified as part of the investigation.

Section 2 – Facts and Analyses

2.1 Experimental Process

The Chemical Process and Equipment

The process that resulted in the accident is a classic method for purifying solvents and removing water and oxygen from them (*The Manipulation of Air-Sensitive Compounds*, D.F. Shriver and M.A. Drezdzon, Wiley-Interscience, 1986). It is a common procedure in laboratories working with air- and moisture-sensitive compounds.

The procedure involves refluxing the solvent and a small amount of benzophenone in an inert atmosphere over sodium or sodium/potassium. As the reflux proceeds, and the moisture and oxygen are removed, the benzophenone ketyl develops a deep blue color, which indicates that the solvent is ready for recovery by distillation and subsequent use. Usually the reflux process is continued for several hours to ensure solvent purity.

The procedure, which is usually carried out in a hood or other fire-safety area, involves apparatus for the reflux and final distillation, as well as provision for an inert atmosphere. In this case, the apparatus was set up in a walk-in hood, approximately eight feet wide and six feet high. A waist-high shelf had been installed to support the apparatus.

The apparatus included a Schlenk-type manifold with space for four separate reflux units (for four concurrent purifications). At the time of the accident, only the benzene purification apparatus was in use. The manifold included two parallel horizontal glass tubes with oblique three-way stopcocks that allow the worker to interchangeably purge the system with inert gas or evacuate the system via a vacuum pump. Two oil bubblers were attached to the manifold to serve as a vent for built-up pressure. One of the bubblers included an internal back-flow restriction device.

A reflux/distillation head (see diagram in the Appendix) was connected to the manifold by flexible tubing to allow reflux or evacuation, as required. The reflux/distillation head also included connections to the condenser section for access to cooling water, as well as several side stopcock joints for removal of solvent samples.

The reflux/distillation head was fitted into a 5-liter, single-neck, round-bottom flask containing the solvent and reagents. The flask was placed into an electric heating mantle, which was connected to a Variac power source.

Review of the Process on the Day of the Incident

On Monday, July 23, at about 11 a.m., a fifth-year graduate student began the process of purifying benzene. The student was in the last months of his Ph.D. research program and had carried out similar solvent purifications many times. The student's research objective was to develop new catalysts for the polymerization of caprolactam into nylon 6. He was distilling benzene to use as a solvent for polymerization studies using caprolactam as the monomer and caprolactamate lanthanide salts he had synthesized as catalysts. He was using benzene so that the results could be directly compared with data on caprolactone polymerization in other solvents. After noting that the flask already contained benzene and reagents from a previous purification, he opened the system by removing the reflux/distillation unit from the flask opening and added sufficient commercially purified benzene to bring the volume to about 3 liters. He then regreased the sintered tapered glass joint and reassembled the apparatus. The nitrogen purge is always in operation to keep the apparatus, as well as the three other reflux units in the fume hood, under inert atmosphere. The student checked the nitrogen purge and the cooling water flows and then set the Variac to about 30%. After 20–30 minutes, reflux began. The process appeared to be proceeding normally as the blue color of the solvent intensified as expected. He checked the process every hour or hour and a half over the next 3–4 hours.

At about 3:40 p.m., when he was about ready to collect the purified solvent, the student noted that the reflux/distillation head was being forced up to relieve pressure in the apparatus. This resembled a repeated "puffing" as the glassware moved up and down within the standard taper joint from which benzene vapor evolved. He immediately moved to resecure the reflux/distillation head in the flask by reaching into the hood and pushing down on the reflux/distillation head. At that point, additional pressure appeared to build up in the apparatus and the reflux/distillation head was forced upward out of the flask as vapor and some liquid evolved. The vapor ignited, causing a flash that burned the student on the right arm, face, neck, and right leg. The student's clothes did not catch on fire, and because he was wearing eye protection, no injury occurred to his eyes. The hood area was in flames. The student immediately exited through the door at the far end of the laboratory and fellow students helped him to medical aid.

Only one other student, also a graduate student, was in the laboratory at the time of the flash/explosion. This student was at the far end of the laboratory and did not directly observe the explosion. Dr. Evans (the PI) and other students were also on the second floor of Reines Hall in offices and laboratories adjacent to the laboratory in which the explosion and fire occurred. They also did not observe the explosion.

Benzene Vapor Explosion Scenario

The student had been focused on the vapor leak and did not observe whether the bubbler was still functioning properly (which would indicate that inert gas was still flowing) or whether the cooling water was still flowing. He noted that an excessive amount of liquid seemed to be condensing in the upper part of the reflux/distillation head. Any of the following failures could have caused this excess condensate in the system:

- A cooling water disruption that would have allowed vapors to rise high in the head.
- A malfunction of the heating unit that resulted in excessive heating of the boiling flask.
- The pulsing buildup and release of pressure within the system, which would have caused rapid boiling of the solvent each time the pressure decreased.
- An increase in pressure of the inlet nitrogen.
- Blockage of the outlet for the nitrogen gas and/or solvent vapor.

Pressure buildup within the system forced hot benzene vapor/liquid out of the flask. The cause of this pressure buildup is still uncertain. An increase in the pressure of the inlet nitrogen seems unlikely since the openings in the inlet stopcocks are the same size as those of the outlet bubbler. The most likely cause of the pressure buildup is a blockage in the exit route of the nitrogen gas and/or solvent vapor. An exit stopcock could have turned slightly, particularly if solvent vapor were dissolving the stopcock grease, thereby reducing its viscosity. It is also possible that a particle could have flowed into a stopcock opening and plugged it.

The ignition source could have been any of the following: the vacuum pump motor located in the bottom right side of the hood, a piece of sodium/potassium metal that splashed out of the flask with the hot vapor/liquid, the heating mantle, or the Variac controlling the mantle. With a flash point of –11°C and lower and upper explosive limits of 1.4 and 8.0, respectively (measured in units of percent vapor in air that can sustain an explosion when ignited), benzene presents a fire and explosion hazard. The investigation team speculates that the vapor traveled a distance to cause an explosion far from the source, suggesting that benzene vapor had been escaping from the apparatus for some time. In this case, it appears that the explosion occurred not only in the fume hood but also in the connecting ventilation ducts; this also suggests that at least some of the escaping vapor had entered the building's ventilation system.

Direct Cause of Explosion (Ignition)
The direct cause of the event was a failure in the distillation/purification system that led to the over-pressurization, subsequent release, and ignition of benzene vapors. While the cause of the over-pressurization was not determined, failure of the pressure-relief system resulted in the apparatus disassembling when the student attempted to manually hold the reflux/distillation head onto the distillation vessel. The exact source of ignition is uncertain; however, several potential ignition sources (noted above) were present in the immediate area of the hood where the distillation was taking place.

Prevention of Future Accidents
The following actions might prevent a similar accident and should be considered:

- Incorporating a high-temperature alarm and/or a method for monitoring the temperature of the reaction vessel's or distillation flask's contents.
- Incorporating a method for monitoring the pressure within the distillation apparatus and/or the flow through the pressure-relief system to determine whether the flow adequately relieves pressure.
- Amending the standard operating procedure (SOP) to include more frequent surveillance by the person conducting the distillation and improved documentation of his/her observations. For example, a checklist or form could be developed that listed features (e.g., pressure/pressure relief, temperature, etc.) essential for determining proper function of the apparatus. The use of a checklist or form reduces the opportunity for human error or omissions in making observations.
- Reviewing types of laboratory fume hoods, performance criteria, and work practices that would better control distillation accidents and specifying such hood criteria within the applicable SOP.

Future Considerations for Purification of Solvents
Distillation and purification of flammable solvents, using systems like the one involved in this accident, will continue to be an integral part of chemical experimentation (if only on a limited basis as alternative methods become available). However, with such processes come the risk of fire and associated injury and property loss. Safety considerations must be a high priority when such procedures are planned and carried out. Contingency plans addressing "what if" situations must be examined before distillation procedures are begun and appropriate safety devices must be available at all times.

Most laboratories still use the reactive metal/ketyl process to purify solvents. However, there are now methods available commercially that do not involve distillation. Instead, they rely on absorbent columns within specialized apparatus that purge and purify the solvents. This approach requires a considerable initial financial investment and will not suit every laboratory's requirements or resources. Furthermore, although these new methods do not require heating of flammable solvents, they do involve larger quantities of solvents than are typically used in laboratory-scale distillation procedures. Accordingly, storage and delivery of solvents to the purification system must include appropriate fire safety measures. A number of these types of apparatus are currently in use at UCI; the University should assess whether increasing the number of these absorbent column systems may lead to an overall improvement in laboratory safety.

2.2 Fire Code, Building Construction, Mechanical and Fire Protection Systems

Description of the Building
Frederick Reines Hall was constructed between late 1987 and July 1990. The building was completed and certificates of occupancy issued during the summer of 1990. The building was designed and constructed in accordance with the 1979 Edition of the Uniform Building Code, as adopted by the 1981 Edition of the California Building Code.

The building was classified as B-2 business occupancy, in accordance with the building code. The B-2 occupancy classification includes "buildings or portions of buildings having rooms used for educational purposes beyond the 12th grade with less than 50 occupants in any room."

The building was constructed with a concrete structural-framing system, with concrete load-bearing walls, columns, floors, and slabs. The building construction type for application of building code construction requirements was designated as Type II-FR, which is defined as noncombustible, fire-resistive-rated construction. The Type II-FR designation required the building to be provided with a minimum of 4-hour fire-resistive-rated exterior walls and 2-hour-rated interior bearing walls and columns. The construction drawings actually detail 4-hour fire-resistive-rated columns and bearing walls, which appear to have exceeded the minimum code requirements.

The building is five stories high, and the height of the highest occupied floor level is approximately 72 feet above the level of Fire Department access. According to the definitions provided in the California Building Code, Reines Hall is not classified as a high-rise building.

Reines Hall has automatic sprinklers in the basement areas, as required by code, but lacks automatic sprinklers in other areas of the building. The building code did not require that sprinklers be provided for a Type II-FR building housing B-2 occupancy. Reines Hall does have Class I and Class II standpipe systems, as required by the building code. There is a 2.5-inch standpipe hose connection at each landing within the exit stair enclosures, and 1.5-inch hose valves in the corridors and main lobby areas on each floor. Portable fire extinguishers are located in the laboratories, as well as in the combination hose valve/fire extinguisher cabinets in the lobby and corridors on each floor.

As required by the code, the building has an automatic and manual fire alarm system, consisting of manual pull stations at building exits and smoke detectors in elevator lobbies, laboratories, storage rooms, and exit corridors. The fire alarm system is zoned by floor and by type of device. The fire alarm evacuation signal is sounded by electronic horns installed throughout the building.

Reines Hall is divided into two separate wings, the chemistry wing and the physics wing. A central lobby area containing passenger elevators, restrooms, and an exit stairwell joins the wings. There is an additional exit stairwell at the end of each wing. Fire-rated exit corridors connect the lobby areas with the remote exit stairs. The first-floor main lobby area is open to the second-floor lobby, as permitted by the building code. The third-, fourth-, and fifth-floor lobbies are separated from the adjacent floors, as required by the code.

Individual laboratories in the chemistry wing are separated from adjacent laboratories, storage or instrument rooms, and exit corridors by 1-hour fire-rated gypsum-board wall assemblies with 1-hour-rated fire doors. The 1-hour fire-rated corridor separation was required by the code; however, the 1-hour separation between laboratories and adjacent rooms appears to exceed minimum code requirements for B occupancy.

The mechanical ventilation systems serving the chemistry wing of the building consist of 100% fresh supply air and 100% exhaust from the laboratory spaces. Supply air enters and is conditioned by two air handlers, each of which serves one wing of the building. The supply air passes through two vertical shafts, each shaft serving one side of the main corridor, to reach the individual floors. Adjacent to the supply shaft is the exhaust shaft, through which exhaust from the laboratory space is ducted to dedicated exhaust fans located on the roof of the building. The vertical shaft containing the supply and exhaust air risers is separated from adjacent building areas with 2-hour fire-resistive construction, as required by the building code for a Type II-FR building.

From the vertical shaft, the supply air enters the second-floor space through a fire-rated damper installed within the vertical shaft wall. The fire damper is closed by a fusible-link actuating mechanism. Access to the fire damper is provided by ductwork access panels in the instrument rooms between adjacent laboratories. Inside each instrument room, the supply air duct splits so that a separate supply duct runs to each of the adjacent laboratory spaces. The duct penetration of the 1-hour fire-rated wall between the instrument room and the adjacent laboratory spaces was also protected by a fire-rated damper with a fusible-link actuating mechanism. The supply air ducts feed into variable-volume terminal units within the laboratory space. Five variable-volume terminal boxes serve the laboratory involved in the fire.

The exhaust system serving the laboratory involved in the fire takes exhaust air from a fume hood in the center of the room and the walk-in fume hood where the fire originated. Exhaust air ducting from the walk-in hood is connected into the main exhaust air duct immediately upstream of where the exhaust air duct enters the vertical shaft. The exhaust air ducts enter the vertical shaft, and the exhaust air is ducted up to four exhaust fans on the roof of the building. In contrast to the air supply system, the exhaust system lacks fire dampers where the ducts penetrate the vertical shaft wall. The absence of exhaust dampers was intended to allow continuous venting of exhaust air.

Governing Fire and Building Codes

The building was designed and constructed in accordance with the 1981 Edition of the California Building Code, which adopted the 1979 Edition of the Uniform Building Code. When the design funding was approved for this project in approximately 1984, the 1981 Edition of the California Building Code was current. According to personnel from the UCI Office of Design and Construction at the beginning of the Reines Hall project, the policy was that the building code in effect when the design funding was approved and the design contract granted was the code used for the project. The current policy, which is more in line with private sector requirements, is that the building code in effect when the project is submitted for regulatory-plan review is the code with which the design and construction must comply.

Construction of Reines Hall began in late 1987, and much of the facility was completed by 1990. In 1987, the 1985 Edition of the California Building Code was the current edition. The 1985 Edition of the California Building Code, however, referred to the 1979 Edition of the Uniform Building Code. It was not until the 1989 Edition of the California Building Code, which adopted the 1988 Edition of the Uniform Building Code, that the California Code referenced a post-1979 Edition of the Uniform Building Code.

It is also important to note that state construction projects are required to comply only with the California Building Code and not with local jurisdictions' amendments to the California Building Code or to the Uniform Building Code referenced therein. Although some local code requirements at the time were more restrictive than those in the state code, compliance with local requirements was not required for the design and construction of Reines Hall.

Occupancy Classification

As indicated above, Reines Hall was originally designed for B-2 occupancy. The B-2 occupancy classification was determined by the project architect and approved by the University and personnel from the State Fire Marshal's Office who were involved with the review of the project. Classifying University laboratories as B-2 occupancy, rather than a hazardous occupancy, was a typical practice.

The 1979 Edition of the Uniform Building Code required that buildings used for the storage and handling of flammable and combustible liquids, chemicals, and hazardous materials in quantities that exceed specified exempt amounts be classified as H-2 occupancy.

From our review of the chemical inventories of the chemistry laboratories in the building, it appears that the quantities of flammable and combustible liquids and hazardous materials present in the building at the time of the fire were in excess of the quantities allowed for B-2 occupancy by the 1979 Building Code. None of the project documentation reviewed by the investigation team indicated whether or not the project architect had had information regarding proposed chemical inventories for the facility when the occupancy classification was determined.

It must be re-emphasized, however, that college and university laboratory facilities were typically not classified as hazardous occupancies for application of building code construction requirements. To do so would have resulted in very restrictive construction code requirements for such facilities.

Both building and fire code requirements applicable to the storage, handling, and use of hazardous materials were revised significantly for the 1988 Edition of the Uniform Building Code and Uniform Fire Code, which were adopted by the California Building Standards Commission as part of the 1989 California Building Code and California Fire Code, respectively. The new hazardous materials requirements revised the regulations for hazardous occupancies, including new exempt amounts, new hazardous materials classifications, and new construction requirements. These changes, however, did not address the issues surrounding the classification of educational laboratory facilities.

To specifically address such facilities, the State of California developed a new hazardous occupancy classification. The H-8 classification, which first appeared in the 1992 Edition of the California Building Code, provided safeguards for such facilities beyond those required for B-2 occupancies but at the same time had less restrictive construction requirements than those for H-2 or H-3 occupancies. Current laboratory construction projects on the UCI campus are typically classified as H-8 occupancy for application of building code construction requirements. The current code for H-8 occupancy requires that buildings be protected throughout by automatic sprinklers and that fire-rated separations be provided between laboratories and other building areas.

Building Compartmentalization

The second floor of the chemistry wing of Reines Hall had 1-hour fire-rated separations between adjacent laboratories and other types of rooms and between the fire-rated corridors and all other areas on the floor. Similar fire-resistive compartmentalization was provided throughout the building.

The fire occurred in a fume hood that backed up to the 1-hour fire-resistive wall that separated the laboratory from the adjacent instrument room. The door between the laboratory and the instrument room was a 1-hour-rated fire door with self-closing and positive-latching hardware. At the time of the fire, this door was blocked open. The door on the other side of the instrument room, leading to the adjacent laboratory, was reported to have been closed and latched during the fire.

Because the fire door had been blocked open, fire spread rapidly into the adjacent instrument room. There appears to have been a substantial amount of fuel in the instrument room at the time of the fire. The fire in the instrument room caused the instrument room window to break, allowing the fire to vent out of the open window. This window broke after the one closest to the fume hood in the affected laboratory broke. The fire in the instrument room also allowed the fire to spread into the adjacent laboratory as the 1-hour-rated fire partition and fire door began to fail. Nevertheless, the fact that the door from the instrument room to the adjacent laboratory was closed appears to have significantly slowed down the spread of the fire into the adjacent laboratory.

The corridor wall and door assemblies held up well during the fire. Although smoke and water damage occurred in the corridor and adjacent areas, the fire was confined to the laboratories and the instrument room adjacent to the hood where the fire originated.

For the most part, the fire-rated separations in the chemistry wing of Reines Hall held up well under fire conditions, except for the door between the laboratory and instrument room, which was blocked open, nullifying its compartmentalization benefits.

Automatic Sprinkler Systems

In Reines Hall, automatic sprinklers protected the basement area, as that was the only area where sprinklers were required. As Reines Hall was designed and constructed as a Type II-FR building for B-2 occupancy, sprinklers were not required throughout the building.

Because the highest occupied floor level is 72 feet from the level of Fire Department access —slightly less than the 75 feet used to designate a high-rise building—Reines Hall was not required to meet requirements for high-rise buildings, which include complete automatic sprinkler system protection.

Although automatic sprinkler systems throughout Reines Hall were not required by the code, it is the opinion of the investigation team that automatic sprinklers would have been beneficial in controlling the fire. Sprinklers would have activated soon after the fire began, controlling the fire’s growth and subsequently limiting fire damage.

Although some safety professionals believe that sprinkler systems in such laboratories may not be appropriate due to the presence of water reactive chemicals, the investigation team argues that the presence of hazardous materials, including reactive and flammable materials, makes the installation of automatic sprinklers in these facilities that much more important. Although sprinklers may not suppress a fire involving reactive materials, sprinklers will control a fire involving combustible materials, thereby reducing the risk of nearby chemicals being exposed to fire. Every laboratory, instrument room, and storage room containing reactive materials should have appropriate portable fire extinguishers or extinguishing media readily available. Reducing fire exposure to chemicals in laboratories can prevent failure of primary containers and reduce the amount of chemicals released during a fire. It is for these reasons that the California Building Code now requires all buildings with hazardous occupancies to be protected throughout by automatic sprinklers.

It is also UCI’s current policy to protect laboratories and research facilities with automatic sprinklers; the H-8 occupancy classification, which is currently used by UCI for laboratory facilities, requires automatic sprinklers.

Standpipe Systems

As indicated previously in this report, Reines Hall was provided with Class I and Class II standpipe systems for Fire Department and occupant use, respectively. The occupant-use standpipe system, consisting of 1.5-inch hose valves and a 1.5 inch-diameter hose, was required by the building code.

The 2.5-inch hose connections for the Class I standpipes were located at each floor landing in the stairwells. OCFA used these hose connections during the fire on July 23.

The standpipe system was charged through the Fire Department connection at the rear of the building. The Fire Department extended its own standpipe hose lines from the hose connections in the stairwell. The standpipe systems functioned properly. We recommend that UCI inspect and test the standpipe system in accordance with fire protection system installation and testing standards. We also note the importance of keeping the fire department inlet connections capped and secured and of adequately draining the standpipe system after testing or use.

Fire Alarm System

Reines Hall has an automatic and a manual fire alarm system. Manual pull stations at building exits and smoke detectors in laboratories, other rooms, corridors, and elevator lobbies activate the system. In addition, the water-flow switches for the basement sprinkler system are also monitored by the fire alarm system.

The fire alarm system is zoned by floor and type of device. The fire alarm evacuation system uses electronic horn assemblies with flashing strobe lights.

The laboratory involved in the fire had six smoke detectors and the adjacent instrument room had one.

The fire alarm system appears to have functioned properly during the fire. Information from the fire alarm system status logs, taken from the fire alarm control panel and transcribed by UCI personnel, indicate the activation of a smoke detector on the second floor of the chemistry wing at 3:43 p.m. A manual pull station was activated on the fifth floor of the chemistry wing at 3:52 p.m., followed by the activation of a manual pull station on the second floor of the chemistry wing at 3:56 p.m. The system zoning does not identify which room or which smoke detector on the second floor was the first to be activated.

According to statements provided by some of the building occupants, the fire alarm system sounded in the building. There is concern, however, that some building occupants did not follow mandatory procedures that require immediate evacuation when the fire alarm system initially sounds and that these occupants relied on other cues, such as seeing or smelling smoke, before they evacuated the building.

Mechanical Ventilation Systems

At the time of the fire, the building's mechanical ventilation systems appeared to have been operating normally. Air-handling units located on the first floor provided supply air to the second floor of the building. The conditioned outside air was provided to the laboratory by variable-volume terminal boxes connected to supply air ducts running along the length of the room adjacent the building's outside wall.

Exhaust air was removed through the exhaust duct connections from the walk-in hood involved in the fire and the fume hood located in the center of the laboratory. The exhaust stream was ducted into the exhaust duct running along the length of the room adjacent to the corridor wall, into the exhaust duct shaft, and up to the exhaust fans on the roof of the building.

When the fire started in the walk-in hood, the exhaust system immediately began venting combustion products to the atmosphere through the exhaust fans on the roof. This continued for approximately two hours until the exhaust fans were shut down and restarted as directed by OCFA.

At an undetermined time during the fire, the fire dampers (located in the 1-hour fire-rated wall between the laboratory and instrument room and in the 2-hour fire-rated shaft wall for the supply air duct) activated and closed. Because of the dampers' proximity to the point of ignition and the localized area of fire damage, it appears that these dampers activated soon after the fire began. The closure of these dampers shut down supply air to the laboratory area, as designed.

It also appears that the failure of the window in the instrument room probably occurred around the same time as the closure of the fire dampers in the supply air system. The open window appears to have provided some make-up air for the exhaust system to continue to operate effectively. It appears that the exhaust system was effective at removing significant quantities of combustion products from the building during the fire, thereby reducing the amount of combustion products spreading to other areas of the building. Furthermore, the code-required practice of not having fire dampers on the exhaust duct of the ventilation system at the shaft wall appears to have been beneficial in this fire scenario.

There was some concern expressed by the OCFA that some smoke spread to other floors of the building through the ventilation system. As a result, the OCFA began directing the shutdown of various portions of the system later during the fire.

The ventilation system serving the second floor of Reines Hall appears to have performed well during the fire.

The arrangement of the system in Reines Hall is similar to that in new laboratory and research facilities on the UCI campus, except that the current practice omits fire dampers on both the supply and exhaust sides of the system. In the Reines Hall fire, the fire dampers' shutting down of the supply air did not significantly hinder the exhaust system since fresh air was provided though a broken window. However, if the window had not failed, the exhaust system probably would not have performed as well.

The benefit of having University personnel on-site during a fire incident to assist the OCFA in operating the mechanical exhaust and ventilation systems was also noted.

2.3 Existing Environmental, Health, and Safety Systems

Chemical Management and Reporting

The University is subject to the reporting requirements of the Hazardous Material Disclosure—Chemical Inventory and Business Emergency, Chapter 6.95 of Division 20 California Health and Safety Code, and its implementing regulations of the State Office of Emergency Services (OES) at Title 19, California Code of Regulations (CCR) §2620 et seq. The regulations delegate administrative responsibility for chemical inventory receipt and distribution to the local Certified Unified Program Agency (CUPA), which in this case is the Orange County Fire Authority. The UCI EH&S Office submitted the required report to OCFA that contained information on maximum amounts of chemicals, which exceeded reporting thresholds contained in Building 401 (Frederick Reines Hall). Although the report complied with the requirements of state law and regulations, the investigation team considers the report to be inadequate for providing firefighters with sufficient information on amounts and types of chemicals in a specific laboratory.

The issue the investigation team raises here is not whether UCI was or was not in compliance with applicable regulations, but rather what information would have been useful to OCFA when firefighters arrived at the fire. It was clear that more detail about the types and quantities of chemicals could have been helpful in planning the attack on the fire. During this incident, excellent resources, such as the PI and knowledgeable students, were available in a timely manner to provide the level of detail needed by OCFA. However, if an incident occurred at night or on the weekend, for example—fire-fighting efforts could be significantly delayed. The school safety coordinator gave the OCFA the laboratory's emergency notification form, which contained more specific hazard-related information about the laboratory in question. There is a mechanism whereby UCI provides information on a regular basis to OCFA that could be strengthened to provide a mutually acceptable level of detail that, while not required by statute, could benefit overall fire response efforts.

In the document titled "Miscellaneous Plans, Security and Site Safety," there is a document labeled "Evans' Lab Chemical Inventory;" whose status was unclear because of the absence of a date. Two years ago, the EH&S Office had requested a chemical inventory of Evans' laboratory (as a part of a complete inventory for all of Reines Hall), but the Evans' laboratory inventory had not been provided by the time of the fire. OCFA had apparently requested this information (through the EH&S Office) because OCFA personnel had wanted to tour the building. The point raised here is not related to the appropriate level of detail for OCFA, discussed in the previous paragraph, but rather timeliness and completeness of follow-through. Individual laboratory inventories should be current and updated on a timely schedule and available to OCFA and the EH&S Office whenever requested.

Under Title 24 of the California State Fire Code, the UCI Fire Marshal, who is also a Deputy State Fire Marshal, has been delegated authority to perform inspections and plan reviews of new construction and modifications of buildings on the UCI campus. Under Title 19 of the California State Fire Code, the University has the responsibility to perform annual inspections of buildings for purposes of fire planning. These inspections would have provided appropriate information (in a format usable by OCFA) on the types and amounts of chemicals present in various laboratories. According to the EH&S Office, the inspections were not being done because of a lack of resources and because plan reviews of construction activities had been deemed a higher priority for the UCI Fire Marshal. There appears to be more work than UCI's only fire marshal can handle in reviewing building plans and performing inspections of construction sites for major new projects. UCI should consider reviewing the fire marshal's duties and the appropriate amount of staffing to accomplish these duties.

UCI Policies and EH&S Related Procedures
The UCI Administrative Policy “Physical Environment and Properties” includes the general EH&S policy, roles and responsibilities, and a list of programs (Section 903-10). Section 903-25 “Occupational Exposure to Hazardous Chemicals in Laboratories” states that PIs are responsible for ensuring that their laboratories have a written chemical hygiene plan (CHP) in place and that rules and procedures are enforced. PIs are also responsible for ensuring that Laboratory employees receive training on the rules and procedures. A CHP dated 3-10-98 was signed by the PI and the EH&S representative for the second-floor chemistry laboratory involved in the fire.

The CHP specifies the following:

- Flammable substances (such as benzene) are to be handled only in areas free of ignition sources such as electrical equipment (especially motors, static electricity, etc.).
- Personal Protective Equipment (PPE)- Lab coats, appropriate chemical-resistant gloves, and goggles are provided and must be worn at all times in the laboratory.
- Inventory maintenance- Each group shall maintain a current chemical inventory with the full name of each chemical, its physical state, the maximum quantity on hand, maximum container size and type, approximate annual usage, storage location by room number, and hazard category: (i.e., carcinogen, flammable, etc.).
- A written standard operating procedure (SOP) must be prepared for the use of particularly hazardous substances and select carcinogens. Benzene is a select carcinogen.
- Lab personnel shall be trained in the use of fire extinguishers.
- The storage of chemicals and equipment in the hood must be kept to a minimum.

Appendix A, “Lab Survey Checklist—The School of Physical Sciences” (a short self-inspection checklist for laboratory workers) states the following:

1. Less than 10 gallons of flammables may be stored outside of a flammables cabinet.
2. Containers of flammables greater than one gallon shall be stored in a flammables storage cabinet.
3. Lab coat, eye protection, and gloves must be used.

Benzene is on the list of select carcinogens. It is also designated as a “particularly hazardous substance,” subject to special requirements, such as regulated or controlled work areas, personal hygiene, preparation for accidents, possible medical surveillance, an industrial hygiene evaluation, and an SOP for operations.

The policies of the University were clear in their requirements and their description of roles and responsibilities regarding the CHP. The CHP also contained clear requirements on the use and handling of chemicals in laboratories. There were a number of estimates of the quantities of chemicals stored in and around the fume hood involved in the fire; all the estimates suggested that quantities exceeded those specified in written requirements.

A number of other documents containing requirements and/or guidance were provided to the team and are described below.

One document titled “Evans’ Group Procedures” was apparently distributed by Dr. Evans to all of his graduate students. The document contains procedures such as glove box protocol; suggested laboratory safety procedures (which includes instructions to always wear safety glasses in the laboratory and to know where the fire extinguishers are and how to use them); suggested procedures for use of the dry box and solvent stills; as well as other laboratory procedures. This is the document that the student injured in the incident could describe and was most familiar with. However, the contents focused primarily on procedures and included limited information on safety hazards.

The investigation team also reviewed the *UCI Lab Safety Guide*, Section 4.15, “Storage Of Chemicals” (dated

01-75), and Section 8.10, “Use of Flammable Liquids” (dated both 01-75 and 09-82), as well as UCI *Laboratory Safety Guidelines 2000–2001* and the CHP that contained information on the storage of flammable liquids.

There were several documents in use that were similar to yet different from the CHP, which may have led to employees’ and students’ lack of familiarity with the CHP and its contents. It is noted that Cal/OSHA requires different yet similar documents to comply with overlapping regulatory standards.

Laboratory EH&S Surveys
The Lab Survey Summary (dated Oct. 6, 1999) identified the general hazards in several laboratories, including 2004A, 2022 (the laboratory affected by the fire), 2031, and 2031A. The survey identified chemicals/hazardous materials, flammable materials, gas cylinders, and UV sources. The Lab Safety Checklist is used when inspections are performed by members of the EH&S Department. Among other items, the checklist addresses the proper size and type of containers for combustible and flammable liquids and proper storage in “flammable safe” or explosion-proof refrigerators. A review of the Laboratory Survey Reports showed that a number of deficiencies had been identified and that not all had been corrected in a timely manner. Some had not been corrected by the time of the accident. The EH&S Office has only three full-time employees to perform all campus-wide multidisciplinary laboratory safety inspections (except radiation safety inspections). UCI has about 1500 laboratory rooms to be inspected, with at least one hundred being added each year. It appears that the UCI EH&S organization cannot conduct all of the necessary follow-up inspections to ensure that corrective actions have been completed with that level of staffing. As described in the CHP, UCI relies on laboratory workers to do their own self-inspections and to report completion of corrective actions. While self-assessment is a critical part of laboratory safety; inspections by EH&S professional staff is still a needed component of the overall safety program and is the element that ensures timely identification and implementation of corrective actions by principal investigators or other laboratory supervisors.

Fume Hood Testing/Construction
The “General Fume Hood Procedures” section of the *Industrial Hygiene and Procedures Manual* contains a good procedure for testing fume hoods. Information provided indicates that fume hood testing was up-to-date. When a hood is tested, the operational sash height is marked where the required face velocity is achieved.

There are fume hood construction issues that should be reviewed as a part of the general fume hood procedures used at UCI. Such issues include identifying the procedures/operations that will be done in which types of fume hoods. For example, the distillation/purification process involved in the accident might be restricted to certain classes or types of fume hoods and prohibited in walk-in fume hoods. Other issues include reviewing the strength of the glass in fume hood sashes so that the limitations and containment properties are better understood; determining the appropriate sash openings; and considering the use of additional safety shields within the fume hood when higher-hazard operations (such as distillations/purifications) are conducted.

ES&H Training
Under the California Code of Regulations, Title 8 Section 5191 (f) (1), “Occupational Exposure to Hazardous Chemicals in Laboratories,” the employer shall provide employees (including students receiving pay from a university) with information and training to ensure that they are informed about the hazards of chemicals present in their work area. An examination of training records for students and employees in Dr. Evans’ laboratory showed that the student involved in the incident attended a required three-hour training workshop on September 23, 1996. Chemistry faculty conduct refresher training for students during weekly lab meetings and through periodic School Safety Bulletins. The investigation team found that there was little documentation of these training sessions, such as agendas or lists of topics covered or even records of who attended. The issue of more formal refresher training and training documentation should be considered by UCI.

2.4 Emergency Response and Initial Accident Recovery Efforts

Initial Response by UCI
The EH&S Office responded when notified by the UCIPD and confirmed that the fire was in a chemistry laboratory in Reines Hall, which in turn activated the EH&S Office’s HAZMAT Team. The HAZMAT Team

has been trained and equipped to respond to chemical spills on campus and to assist in assessing complex situations, such as the fire in Reines Hall. The EH&S Office also notified the Campus Fire Marshal, a staff member of the EH&S Office. The HAZMAT Team and the Campus Fire Marshal arrived at the fire within 15 minutes of the call to the EH&S Office. Upon arrival, the Fire Marshal took responsibility as the primary interface between the OCFA Incident Commander and the University, filling the “site representative” function in the incident command structure.

In addition to EH&S representatives and campus police (the first UCI representatives on the scene), other campus organizations responded to the fire alarm, including members of the facilities management organization; the School of Physical Sciences facilities manager (whose office is in the basement of Reines Hall); and the PI from the affected laboratory and several of his students, who were familiar with the location and quantities of hazardous materials in the laboratory. Within a half-hour, representatives of the Vice Chancellor for Administration’s office, the Dean and the Assistant Dean of the School of Physical Sciences (both arrived within a few minutes), and other senior UCI officials arrived at the scene.

The OCFA’s response followed the established SOP for responding to a fire in a high-occupancy five-story building known to contain hazardous material. The Incident Commander raised the response to four alarms after an initial assessment of the fire and its potential to release hazardous materials to the environment. Reconnaissance teams were deployed to the floors above and below the affected second floor to assess the spread of the fire. UCIPD assisted OCFA with building security, and occupants who had not yet left were told to leave. A detailed Fire Attack Plan was developed and the fire was attacked from both within the building and from outside using a snorkel apparatus. On the afternoon of the day after the fire, Incident Command was turned over jointly to the University and the Orange County Health Care Agency (OCHCA). The University had a contract with Emergency Response Strike Team, Inc. (ERST) to assist with providing infrastructure support to the joint UCI/OCHCA incident command organization. Under the supervision of the UCI Incident Commander, ERST, HazMat Services, Inc. (UCI’s hazardous materials cleanup/disposal contractor), and mutual aid providers from UCLA, UC Riverside, and UC San Diego worked effectively with UCI departments to restore operations in Reines Hall.

Notifications were made within the required times by the EH&S Office to the following: Environmental Protection Agency National Response Center; California Governor’s Office of Emergency Services; California Department of Forestry and Fire Prevention; Office of the State Fire Marshal; California Department of Health Services, Radiologic Health Branch; Cal/OSHA; OCFA fire fighting, emergency medical, and hazmat emergency services; OCHCA, Environmental Health Division; Orange County Public Facilities Resources Department, Stormwater Section; South Coast Air Quality Management District; and the Irvine Ranch Water District.

Medical Assistance and Emergency Response

The University has developed a set of emergency procedures, which were posted at various locations and available on several UCI web sites. They include instructions on how to proceed in various situations including fires, medical emergencies, bomb threats, earthquakes, etc. The investigation team found this set of instructions to be an excellent resource. However, it was not clear that students and employees were familiar with the procedures. For example, instructions for a fire specify that one should activate the fire alarm and evacuate the building immediately. It also describes the general steps to be taken in a medical emergency, which include calling 911.

There are also instructions in the UCI CHP related to personal injuries. These instructions state that in an emergency one should dial 911 or seek care from the nearest emergency medical facility. A list of facilities and their addresses is also provided. This list did not include the facility where the injured student was initially taken. The investigation team noted that these instructions allow for discretion in emergency medical situations.

On July 23, 2001, the injured student was transported by private automobile to a medical clinic at UCI and then to the UCI Medical Center, which took a considerable amount of time. If his injuries had been more severe, this time loss could have had serious medical consequences.

UCI has a document titled "PS (School of Physical Sciences) Emergency Preparedness Information" that describes roles and responsibilities of floor wardens, building coordinators, and zone captains. The major roles are to evacuate the building promptly, identify personnel who might still be inside, and gather as much information about the physical state of the building and its contents as possible. This document designates assembly areas for evacuated personnel and names 10 trained members of the building evacuation team. It is not clear to what degree this emergency response policy was followed during the fire. The evacuation was inadequate, as the OCFA found several individuals still in the building upon its arrival and people were going back inside. It wasn't until the UCIPD arrived that the evacuation was effective and sustained.

Explosion

The investigation team speculates that there may have been an accumulation of benzene vapors in the exhaust portion of the ventilation system. This was based on information obtained from the students who reported that they heard a large explosion in the hallway, where tiles fell from the ceiling. An accumulation of vapors would indicate that the distillation process might have been malfunctioning for some time, releasing vapors that collected in the ventilation system and ignited simultaneously with the explosion in the fume hood.

Preservation of Evidence

An apparent lack of communication led to problems with the preservation of evidence at the fire scene. On Tuesday, July 24, 2001, at approximately 1:30 p.m., control of the site, which had been managed by OCFA, was transferred to UCI and OCHCA. According to the UCI Fire Marshal, the University was instructed to remove all chemical hazards but advised to preserve the "scene" in the laboratory, pending further investigation by the State Fire Marshal. At some time on Wednesday, July 25, the site was found to have been cleaned up. The State Fire Marshal was unable to determine the cause of the fire because evidence she believed to be crucial had been removed.

Recovery Operations

Re-entry of the facility was handled in an appropriate manner. Based on a written sampling strategy, air, surface swipes, debris, and water samples were collected and analyzed. The measurements obtained were compared with reference points that were one-tenth of the ACGIH (American Conference of Government Industrial Hygienists), and Cal/OSHA (California OSHA) permissible exposure limits for toxic substances. On Wednesday, July 25, the initial safety and health plan was developed, which described the various types of activities to be conducted and the specific level of protection that would be needed (e.g. Level B or C personal protective equipment [PPE] and respiratory protection). Because the debris was handled as hazardous waste, the provisions of the OSHA Hazardous Waste Operations and Emergency Response Standard, which requires specific training for personnel cleaning up and handling the hazardous waste, were applied.

Section 3 – Judgments of Needs

Judgments of needs are the institutional controls and safety measures determined by the investigation team to be necessary to prevent and/or minimize the probability or severity of a recurrence of a similar accident.

Judgment of Need #1- UCI needs to strengthen supervision of hazardous activities conducted in laboratories to ensure compliance with EH&S policies and procedures.

Specific findings include the following:

- A lapse in PIs' consistent and thorough monitoring of laboratory activities contributed to the accident. PIs must ensure that CHPs and SOPs for specific highly hazardous operations are fully understood and implemented by students and other laboratory workers.
- PPE was not used as described in safety documents. PPE may protect workers from chemical and thermal burns and from skin absorption of hazardous materials. If used as required, an appropriate lab coat and gloves may have reduced the extent and severity of the student's burns from this incident (as the safety glasses did for his eyes).

Judgment of Need #2- UCI needs to improve the identification of hazards and the implementation of controls associated with hazardous laboratory operations.

Specific findings include the following:

- The hazard identification and analysis of the distillation/purification process did not identify all potential failure points and preventative actions.
- The walk-in type of fume hood in which the accident occurred might not have provided sufficient airflow to prevent an accumulation of explosive fumes nor the physical containment required to mitigate the consequences of the accident. Therefore, the use of a walk-in hood should be reconsidered for solvent distillation procedures.
- The presence of ignition sources in close proximity (for example, inside the same fume hood), including non-intrinsically safe electrical outlets and appliances, should be re-evaluated during review/revision of SOPs for hazardous laboratory procedures.

Additional comments: We recommend that the University

- Ensure that all hazardous activities to be performed are reviewed by appropriate subject matter experts from both academic and support organizations (in this case, the Chemistry Department and the EH&S Office, respectively) to ensure that potential hazards are adequately analyzed and controls established.
- Consider the use of absorbent columns within specialized apparatus that purge and purify solvents. A number of these types of apparatus are currently in use at UCI; the University should assess whether increasing the number of these absorbent column systems may lead to an overall improvement in laboratory safety.

Judgment of Need #3- UCI needs to assess its use and storage of flammable and combustible chemicals, as well as of other hazardous materials. All should be monitored and additional engineering controls implemented when appropriate.

Specific findings include the following:

- Appropriate limits for quantities of flammable and combustible liquids and hazardous materials stored and used in laboratory facilities should be enforced.

Additional comments: We recommend that the University

- Assess laboratory facilities that store and utilize flammable and combustible liquids and hazardous materials, including reactive chemicals and radioactive materials regarding the need for automatic fire suppression systems. Where such systems are determined to be appropriate, existing laboratory facilities should be retrofitted with automatic sprinklers (or other fire suppression mechanisms) when substantial renovations or modifications are undertaken or as part of a campus-wide fire protection upgrade initiative.

Judgment of Need #4- UCI needs to take appropriate actions to improve emergency response to incidents like the Reines Hall accident.

Specific findings include the following:

- Emergency planning deficiencies include inadequate response from students and others who should have immediately evacuated and not re-entered Reines Hall, confusion about the proper procedure and source for emergency medical care, and the absence of immediately available detailed information on chemical inventories.
- Access controls were not adequate to prevent unauthorized personnel from re-entering the building.
- Standpipes in Reines Hall were not routinely inspected and tested.
- Fire doors need to be maintained in operable condition and not blocked open.

Additional comments: We recommend that the University

- Reevaluate the frequency of annual fire and evacuation drills to determine such drills' effectiveness.
- Ensure that campus policy on the use of fire extinguishers is clear and fully understood.
- Review the 911 call-system instructions as they relate to requesting assistance for serious injuries or illnesses on campus.
- The University (EH&S Office), in consultation with OCFA, should determine whether an alternative laboratory chemical inventory documentation system would improve emergency response, and if so devise a mutually acceptable system.

Judgment of Need #5- UCI management needs ensure that safety training and training documentation are strengthened.

Specific findings include the following:

- Students receive initial safety training upon entering the graduate program and periodically afterwards, when the other students or PIs conduct a review of a new or potentially hazardous procedure. These periodic safety briefings are not adequately documented.
- The student involved in the incident may have responded differently if he had anticipated the potential failure points of the distillation/purification apparatus or had received training in appropriate emergency responses.

Additional comment: We recommend that the University

- Ensure that all faculty, graduate students, researchers, and employees who work in laboratories receive initial and periodic refresher training and that such training is adequately documented.

Judgment of Need #6- UCI needs to clarify the responsibilities of departments and the authority of the EH&S Office to ensure implementation of corrective actions identified in safety reviews and to assess the adequacy of resources to carry out its mission.

Specific findings include the following:

- Deficiencies in laboratory procedures and operations, identified through periodic EH&S reviews, were not in all cases corrected effectively.
- Responsibilities of the Campus Fire Marshal and EH&S professionals to perform campus-wide laboratory safety inspections may exceed currently available on-site resources.

Section 4 – Noteworthy Practices

Noteworthy practices are the existing institutional controls, safety measures, and other practices identified by the investigation team present to prevent and/or minimize the probability or severity of a recurrence.

Noteworthy Practice #1- There was proper use of safety glasses by the student involved in the incident.

Noteworthy Practice #2- The solvent distillation process was performed in a fume hood.

Noteworthy Practice #3- The design and construction of Reines Hall was instrumental in containing the fire.

Specific findings include the following:

- Current University practice is that the design and construction of new laboratory facilities take into account the quantities and types of hazardous materials that will be stored and used at the facility. Furthermore, the materials and processes slated for a laboratory facility are thoroughly reviewed before occupancy classifications are determined.
- Current University policy is to provide automatic sprinklers for laboratory buildings, including both most new construction projects and existing facilities, even when substantial retrofitting is required.
- The design of the mechanical ventilation systems in the laboratory spaces allows for use of the mechanical exhaust system under fire conditions.
- Providing fire-resistive compartmentalization around the laboratories in Reines Hall helped to limit fire damage to adjacent areas.

Noteworthy Practice #4-UCI has widely distributed emergency procedures presented to the campus community in a variety of formats (e.g., wall charts, electronically via web sites and e-mail, and handouts in training seminars).

Noteworthy Practice #5- UCI provided laboratory safety training for all laboratory workers (including graduate students) and periodic refresher briefings (led by PIs and advanced graduate students and held weekly in the Chemistry Department).

Noteworthy Practice #6- The resident school safety coordinator (a professional-level EH&S staff member) conducted periodic laboratory safety inspections and distributed periodic safety bulletins, which enhanced the general safety of Chemistry Department laboratories.

Noteworthy Practice #7- UCI employees and students greatly assisted the OCFA with preparing the Fire Attack Plan by providing current information about laboratory operation and more detailed chemical inventory than legally required and by making critical adjustments to the mechanical and ventilation systems in Reines Hall.

Noteworthy Practice #8- Knowing its limitations on responding to an incident of this magnitude, the EH&S Office made immediate arrangements for support from expert contractors and other UC Campuses to ensure timely recovery operations, which included an excellent reentry and sampling plan.

Noteworthy Practice #9- Other UC Campuses (Los Angeles, Riverside, and San Diego) responded immediately to assist UCI with recovery efforts. Additional UC campuses were willing to assist if needed.

Appendices

- Independent Investigation Team Members and Qualifications
- List of Documents Reviewed (partial)
- List of Photographs/Drawing used in the investigation

Independent Investigation Team Members and Qualifications

Investigation team leader (expert in accident investigations, and emergency response and operations)—K.L. "Ken" Groves, President, Sevorg Services, Rutheron, NM

- Former Deputy Director, Environment, Safety and Health; University of California, Office of the President (Laboratory Administration Office), Oakland, CA (1995-2001)
- Former Senior ES&H Manager and Director, Emergency Management and Response Office, Los Alamos National Laboratory, Los Alamos, NM (1986-1995)
- Retired Navy Commander, last assignment: Director, Navy Radiological Controls Program Office, Washington, DC (1980-1986)
- BA, Chemistry (University of New Mexico), MS, Biophysics/Health Physics (Texas A&M University)

Expert in chemistry—Stanley H. Pine, Professor of Chemistry and University Chemical Safety Officer, California State University, Los Angeles

- Former member Committee on Prudent Practices for Laboratory Safety, National Academy of Sciences
- Former Chair, Committee on Chemical Safety, American Chemical Society
- Consultant, National Institute of Standards and Technology (National Bureau of Standards) - Executive safety training
- Ph.D., Chemistry University of California, Los Angeles, and Postdoctoral: Harvard University, Cambridge, MA.

Expert in industrial hygiene/industrial safety—Barbara C. Hargis, Program Manager, Occupational Safety and Health, Los Alamos National Laboratory (LANL)

- Group Leader, Industrial Hygiene & Industrial Safety, Los Alamos National Laboratory, Los Alamos, NM (1990-2001)
- Technical Staff Member, ES&H Division, LANL (1988-1990)
- Program Manager, Surveillance & Enforcement, Air Quality Division, New Mexico Environment Department, Santa Fe, NM (1986-1988)
- Program Manager, OSHA, New Mexico Environment Department, Santa Fe, NM (1978-1986)
- American Board of Industrial Hygiene, Board of Directors
- BS, Biology, New Mexico Institute of Mining and Technology, MS Industrial Safety, Central Missouri State University
- Certified Industrial Hygienist and Certified Safety Professional

Independent Investigation Team Members and Qualifications (con't)

Expert in fire protection engineering—Michael J. Madden, P.E., Principal/Los Angeles Office Manager, Gage-Babcock & Associates

- Project Manager, fire protection systems design and code consulting, numerous fire protection projects including educational and health care facilities, manufacturing and warehousing facilities, and private and governmental research facilities
- Fire Protection Engineer, fire protection systems design and code consulting, multiple projects including hazardous waste facility and multi-building laboratory facilities
- Fire Protection Engineer, Phoenix Fire Department, Division of Fire Protection (1982-1990)
- Member of several National Fire Protection Association Technical Committees, including position as Chair.
- BS, Fire Protection Engineering, University of Maryland
- Registered Fire Protection Engineer, California, Nevada, Arizona

List of Reviewed Documents (partial)

1. UCI Chemical Hygiene Plan
2. UCI Laboratory Safety Guidelines 2000-2001
3. School of Physical Sciences “Lab Survey Checklist”
4. PS (School of Physical Sciences) Emergency Preparedness Information
5. Evan’s Lab Procedures
6. UCI Business Emergency Plan
7. UCI Injury and Illness Prevention Program
8. Relevant Training Records
9. Relevant EH&S Inspection Reports
10. Chemical Inventory Documentation (multiple sources)
11. UCI and EH&S Office Organization Charts
12. Reines Hall Fire Recovery and Sampling Plan

List of Photographs/Drawing relevant to the investigation

1. Drawing of a fume hood showing the location/identification of Critical Components of the distillation/reflux apparatus and walk-in fume hood

2. Photo of a similar multiple distillation/purification fume hood set-up at UCI

3. Photos of mock-up of the equipment used in the procedure

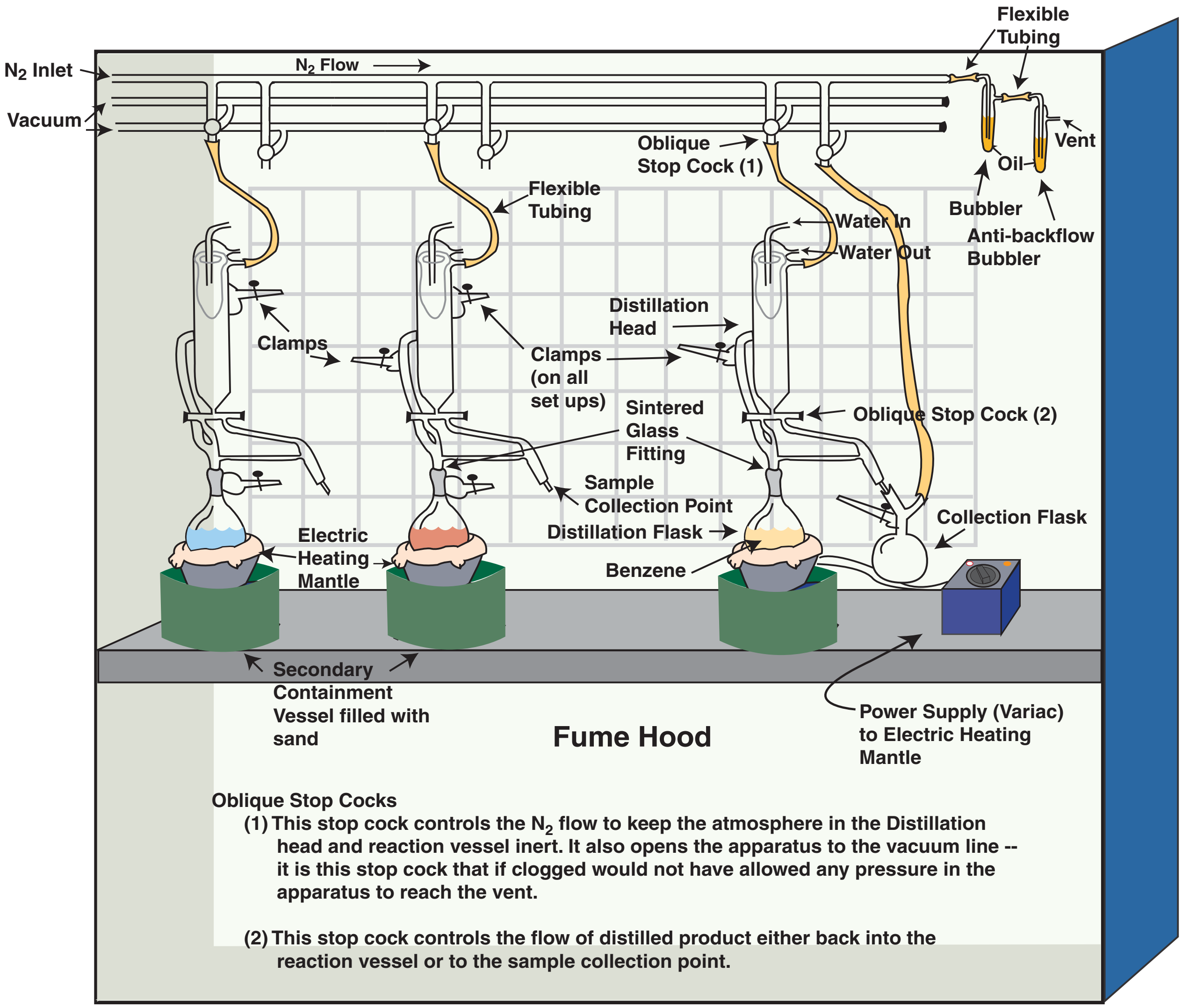
4. Photo of the building fire (from Orange County Register)

5. Photo of the fume hood in room 2022 after the accident

6. Photo of the desk adjacent to fume hood in Room 2022

7. Photo of a five-gallon can under fume hood in Room 2022

Diagram of Reflux/Distillation Process



Drawing of a fume hood showing the location/identification of critical components of the distillation/reflux apparatus and walk-in fume hood configuration.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Photograph of similar set-up showing four distillation/reflux units in a fume hood to show generalized location of components. This set-up is in Rowland Hall (School of Physical Sciences). This is a “standard” fume hood rather than a “walk-in” type fume hood involved in the accident in Reines Hall.

Photograph of the distillation/reflux apparatus that was involved in the incident in Reines Hall on July 23, 2001. This photograph shows the glassware used and was constructed by Dr. Evans to assist the Investigation Team visualize the set-up involved in the incident.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Photograph of the fire at Reines Hall (7/23/2001); the flames are coming from the storage room next to the laboratory where the fire started (to the right in the photograph). The fire door between the laboratory and the storage room was open and the storage room contained a large amount of combustible material. The photograph was provided by the Orange County Register (Mark Avery photographer).

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Photograph of fume hood involved in fire

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Photograph of laboratory (fume hood is to the right)

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Photograph of 5-gallon can in fume hood