INVESTIGATION REPORT

LANL Investigation of a Laser Eye Injury

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Acronyms, Abbreviations, and Definitions

ADO	Associate Director for Operations
ADSR	Associate Director for Strategic Research
ANSI Z136.1-2000	American National Standard for Safe Use of Lasers
C	Chemistry Division, Los Alamos National Laboratory
C-ADI	Advanced Chemical Diagnostics and Instrumentation group, C-Division
choroid	in the eye, a layer of blood vessels at the back of the retina
C-INC	Isotope and Nuclear Chemistry group, C-Division
C-PCS	Physical Chemistry and Applied Spectroscopy group, C-Division
DOE	U.S. Department of Energy
fovea	in the eye, the region of highest visual acuity defining the center of the retina
HCP	hazard control plan
HCP-C-ADI-001, R.3	Laser Ablation and LIBS HCP
HS	high school student
HSR-2	LANL Occupational Medicine group
IH	industrial hygienist
IR	infrared (outside the visible spectrum)
ISM	Integrated Safety Management
IWM	Integrated Work Management
IWD	Integrated Work Document
IWD-C-ADI-0004-04	LIBS Integrated Work Document
IWP	Integrated Work Process
J	joule, a unit of energy
L1	LIBS laser used to illuminate particles in the PIV experiment
L2	particle-generation laser used to suspend particles in the PIV experiment
LANL	Los Alamos National Laboratory
LEP	laser eye protection
LIBS	laser-induced breakdown spectroscopy
LIG	Laboratory Implementation Guidance
LIG 402-400-01.0	Safe Use of Lasers LIG
LIR	Laboratory Implementation Requirement
LIR 402-130-01.3	Abnormal Events LIR
LIR 402-400-01.3	Lasers LIR
LSO	laser safety officer
macula	in the eye, an area of pale yellow pigmentation in and around the fovea
μJ	microjoule, one-millionth of a joule

micron	one-millionth of a meter
mJ	millijoule, one-thousandth of a joule
ms	microsecond, one-millionth of a second
mm	millimeter, one-thousandth of a meter
MPE	maximum permissible exposure
MSDS	material safety data sheet
MWA	Management Walk-Around
nm	nanometer, one-billionth of a meter
ns	nanosecond, one-billionth of a second
NASA	National Aeronautics and Space Administration
Nd:YAG laser	a laser in which the laser rod is made of yttritium-aluminum-garnet (YAG) glass that has been doped with neodymium (Nd)
NHZ	nominal hazard zone
Notice 139	Notifications and ISM-Based Investigations of Safety Events at LANL
Notice 142	Integrated Work Management Interim Process
OD	optical density
OJT	on-the-job training
PA	physician’s assistant
PI	principal investigator
PIV	particle in vacuum
PPE	personal protective equipment
RBA	radiological buffer area
RCT	radiological control technician
retina	light-sensitive, seven-layered membrane that lines the eye’s inner surface
S1	the student injured in the July 14, 2004, laser incident
SME	subject matter expert
SRLM	safety-responsible line management
SRS	Stanford Research Systems
SWP	Safe Work Practices
TA	technical area
torr	unit of pressure equal to 1/760 atmosphere
UGS	undergraduate student
V	volt
Vdc	direct-current voltage

Executive Summary

On July 14, 2004, an undergraduate student was injured at Los Alamos National Laboratory (LANL) while working with an Nd: YAG laser in the Chemistry (C) Division's Advanced Chemical Diagnostics and Instrumentation group (C-ADI). The incident occurred at Technical Area 46, building 41, room 106.

The principal investigator (PI) mentoring the student (S1) was working with her on an experiment involving two lasers, one (L1) to analyze particles and the other (L2) to generate and suspend the particles inside a target chamber. However, on July 14 the PI used L1 in flash-lamp mode to illuminate rather than analyze the suspended particles. After firing and shutting down L2, the PI removed the beam stop from behind the target chamber's rear window and looked inside while L1's flash lamps continued to operate. When S1 bent down to look too, she immediately saw a flash and a reddish brown spot in her eye. The injury was subsequently diagnosed as a laser-caused hole in the retina of S1's left eye.

An Accident Investigation Team (the Team), appointed by LANL Director G. Peter Nanos and working from July 19 to August 27, 2004, interviewed personnel, reviewed documents, and characterized systems and conditions in room 106. The PI reported that he was operating L1with the Q-switch trigger cable disconnected from the Stanford Research Systems pulse generator. The Team's collected evidence confirmed that L1 could not lase under those conditions. However, because L1 *did* emit laser light on July 14, the Team believes, based on its collected evidence, that the laser was operated in one of three possible lasing modes.

The Team determined that *direct* and *primary* Integrated Safety Management (ISM) failures leading to this accident were, respectively, the PI's unsafe work practices and the institution's inadequate monitoring of worker performance. These failures are briefly summarized here.

Direct ISM Failures

- Neither the PI nor S1 was wearing laser eye protection (LEP), and there were no engineered safety measures.
- The PI did not recheck beam alignment or laser condition or check for beam reflections on July 13 or 14.
- The PI prepared an insufficiently detailed integrated work document (IWD) and did not resubmit a modified hazard control plan (HCP) to reflect experimental changes.
- The PI did not give S1 proper pre-job training, and he asked S1 to sign and predate the IWD after the accident.

Primary ISM Failures

- Safety-responsible line managers (SRLMs) did not monitor the PI's safety practices or his workspace and did not ensure his adherence to Laboratory Implementation Requirements, Laboratory Implementation Guidance, and C-Division work/worker authorization procedures.
- SRLMs and the laser safety officer signed the PI's IWD without noting the lack of detail.
- Management did not ensure that S1 completed all prerequisites for work.
- LANL's Student Mentoring Program did not require mentor training or monitor students and their mentors.

The Team recommends the following:

- LANL should implement a risk-based oversight program that systematically monitors the performance of every employee and workspace.

- LANL should establish nonpunitive processes that emphasize peer-to-peer and worker-to-manager communication of unsafe acts and near misses. Such processes would create an environment of open communication, encouraging legitimate concern for individual safety.

- LANL should assess the safety of laser operations throughout the Laboratory.

- C-ADI should correct the safety issues inside building 41, including the overall poor state of housekeeping.

- C-Division should implement a process that ensures the quality of IWDs and HCPs.

- LANL should conduct a continuing, periodic review of the quality of IWM implementation.

- LANL should develop and implement a formalized Student Mentoring Program that includes the following:

  – Qualification and training requirements for mentors

  – A monitoring and performance-asessment program for mentors and students

  – Requirements that mentors teach their students how to work safely

  – Requirements that students demonstrate their ability to work safely

- C-Division should take actions to modify worker and manager behaviors through the use of existing institutional processes.

- Using the institutional issues management system, LANL should address the concerns listed in Appendix H of this report.

1.0 INTRODUCTION

Los Alamos National Laboratory (LANL) Director G. Peter Nanos, in a memorandum dated July 16, 2004 (see Appendix A), established a team to investigate the laser incident that injured a student on July 14, 2004. The Accident Investigation Team (the Team) conducted its investigation July 19–August 27, 2004. The scope of the investigation was to (1) review and analyze the circumstances of the accident, (2) determine the causes of the accident, and (3) make recommendations. The Team used the following methodology:

- Inspecting and photographing the accident scene and individual items of evidence related to the accident
- Gathering facts through interviews and reviews of documents and evidence
- Conducting technical evaluations and measurements of the experiment being conducted when the accident occurred
- Reviewing emergency and medical response
- Using events and causal-factors analysis, barrier analysis, and fault-tree analysis to correlate and analyze facts and identify the accident's causes
- Based on analysis of the information gathered, developing recommendations to prevent recurrence

2.0 ACCIDENT DESCRIPTION, CONSEQUENCES, AND RESPONSE

2.1 Precursors to the Accident

2.1.1 Background

LANL's Chemistry (C) Division, part of the Strategic Research Directorate, consists of the division office, seven technical groups, an operations group, and several teams focused on administration, business, human resources, and communications (see Fig. 2.1). Many of C-Division's research and development projects span multiple groups and/or LANL divisions, and a number of them involve partnerships with academia, industry, or both. The division's annual budget comes from a diverse set of LANL program offices. Through those offices, the division works with program elements of the Department of Energy (DOE) and other federal agencies, such as the Department of Defense, the National Institutes of Health, the National Science Foundation, and the Department of Agriculture.

C-Division employs 497 people, including technical staff members, technicians, support personnel, students, and postdoctoral researchers. The postdoctoral and student employees make up roughly 20% of the total.

Advanced Chemical Diagnostics and Instrumentation (C-ADI) is a C-Division group specializing in advanced diagnostics and sensors used for national defense, stockpile stewardship, environmental monitoring, space exploration, process monitoring, and materials processing (see Fig. 2.2).

C-ADI employs the principal investigator (PI) who was working with the student, S1, when the accident occurred. S1 is an undergraduate student working on a research program through the National Aeronautics and Space Administration (NASA). S1 came to Los Alamos to join C-ADI as a guest affiliate, with the PI as her LANL mentor. She was working with the PI to analyze soil samples in a partial vacuum. A chemistry major entering her senior year, S1 had experience in electron microscopy but no experience in laser operations.

S1 arrived at LANL on June 1, 2004. Upon arrival, she completed the following LANL training courses:

- General Employee Training, #15503 (6/2/2004)
- Laser Safety, #17817 (6/3/2004)
- Initial Computer Security Briefing, #9369 (6/4/2004)

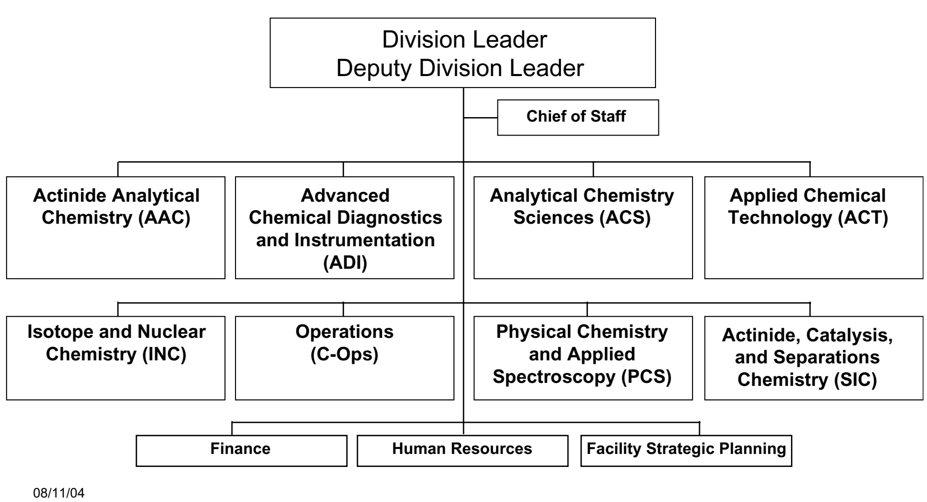

Figure 2.1. C-Division Organization Chart

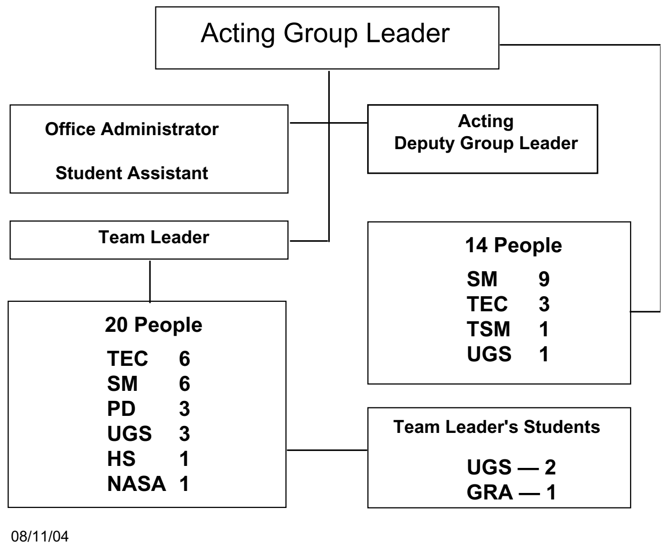

Figure 2.2. C-ADI Organization Chart

S1 began work with the PI at Technical Area 46 (TA-46), in building 41. Her work included handling gas cylinders and working in individual laser laboratories housed in the building. She subsequently completed the following additional LANL courses:

- Chemical Hazard Communication Introduction, #25418 (7/1/2004)
- Annual Security Refresher, #1425 (7/6/2004)
- Substance Abuse Awareness Program for Employees, #7863 (7/7/2004)
- Gas Cylinder Safety, #9518 (7/7/2004)
- LANL Electrical Safety Program, #16750 (7/8/2004)

S1 also attended a student orientation (6/7/2004) and a new-hire orientation (6/8/2004) presented by members of the C-Division staff. The orientations included expectations regarding Safe Work Practices (SWP), work/worker authorization, and “Stop Work.” LANL encourages but does not require mentor training. The PI had taken a mentoring course in the past and had extensive mentoring experience, having mentored more than 30 students during 23 years of work at LANL. During those years, his technical accomplishments have been exemplary, as indicated by his multiple R&D 100 Awards.

Over his years at LANL, the PI has developed knowledge, skills, and practices for conducting work in a laser laboratory. Some of his behaviors, however, violated established safety requirements and best-work practices. Examples include not consistently wearing laser eye protection (LEP) during Class IV laser operations, not consistently using laser interlocks and warning signs to control access to room 106, and not controlling laser beams and stray laser beam reflections. Therefore, stray laser beams were not consistently mitigated. Over the years, these practices became acceptable to the PI, who taught them to students. A co-worker did make repeated attempts to correct the PI’s behavior by reminding him to wear LEP. However, the PI did not change his behavior, and the co-worker did not take his concerns to line management.

Line management oversight of the PI’s work in room 106, the location of the accident, was minimal. Team leaders and group leaders did not visit room 106 during laser operations and inferred from the lack of prior mishaps and the PI’s technical reputation that his safety practices were adequate. Senior line management oversight in room 106 also was minimal but met LANL requirements. C-Division line management visited the building five times in the course of a year and had not observed or evaluated operations in 106.

2.1.2 Description of TA-46-41-106

Facilities throughout LANL's various technical areas (TAs) support research, development, and testing conducted by members of C-Division. TA-46, where the laser accident occurred, is situated about 2.5 miles southwest of LANL's main technical area, TA-3, on the north side of Pajarito Road, which connects TA-3 with White Rock, the community southwest of Los Alamos. The buildings at TA-46 are occupied by several LANL divisions, including C-Division, which is the managing division for building 41.

Building 41 is a standalone, steel-framed, 5,404-square-foot structure built in 1958 and oriented east to west. The building has exterior walls of concrete block and metal; interior walls of drywall and concrete block; and a roof of metal, asphalt, and gravel. It includes laboratories, plant and equipment rooms, storage rooms, and a restroom. C-Division occupies offices, laboratories (including room 106), and nonlaboratory space. Building 41 is shown in Fig. 2.3.

Figure 2.3. Building 41 at TA-46.

The PI has conducted research in building 41's rooms 106 and 112. Room 106 is a 415-square-foot laboratory devoted to experiments with laser-induced breakdown spectroscopy (LIBS), a plasma diagnostic technique that identifies a material's constituent elements. The PI has done LIBS research in that room for many years. The lab has two entrances, one with a double door providing access from the hallway and one with a single door providing access to and from lab room 110. Both entrances have laser warning lights mounted for a laser interlock system, as shown in Figure 2.4.

Figure 2.4. Laser warning lights on the hallway door leading into the laser lab in room 106.

The lab contains three separate laser systems. Two are on an optics table in the middle of the room. The third has been placed on a table that is built onto and elevated above the optics table. A fume hood built against the south (back) wall and facing west divides the room. There is a metal cabinet behind the fume hood. Lab work benches and shelves are built against most of the walls. The lab contains cylinders of compressed gas.

The Team observed a general state of poor housekeeping in room 106 (see Fig. 2.5). The area around the optics table was partially blocked by diagnostics on an additional table that had been positioned against the optics table and also by a gas cylinder and a vacuum pump. LEP was available for use throughout the lab, although the optical density (OD) rating labels on some were worn and therefore difficult to read.

Figure 2.5. Poor housekeeping in room 106.

2.1.3 Purpose of the Experiment

At the time of the accident, the PI and S1 were working on a particle-in-vacuum (PIV) experiment, part of ongoing LIBS research. The objective of the PIV experiment was to demonstrate that particles of simulated soil could be suspended by focusing a pulsed laser on a sample in a sealed target chamber that had been evacuated to about 7 torr.

2.1.4 History of the Experiment

The PIV experiment was a new experiment not described in the LIBS hazard control plan (HCP), HCP-C-ADI-001, R.3, or in its associated integrated work document (IWD), IWD-C-ADI-0004-04. In addition, the PIV experiment was not authorized.

Under HCP-C-ADI-001, R.3, the PI and other students had conducted previous LIBS experiments, for which the students collected and recorded data in a notebook. The experimental setup for the previous experiments comprised a detection laser (a Spectra Physics Quanta Ray INDI Q-switched laser), a target chamber, and a spectrometer in a configuration typical of that described in the HCP.

On July 13, 2004, the PI set up a new target chamber (an environmental chamber with a rear viewing window) and a second laser (an ablation laser to ablate and suspend particles). The experimental setup then involved two lasers: the original INDI detection laser, L1, and the newly introduced ablation laser, L2. Laser radiation from L1 and L2 is invisible, at an infrared wavelength of 1064 nm. The PI directed the laser paths of both lasers through the chamber with the use of turning mirrors and focusing lenses. See Figure 2.6.

Using two lasers, viewing particles in the chamber, and using L1's flash lamps for illumination were not described, evaluated, or authorized by the LIBS HCP. The Team found no record of a laser registration, Form #1552, for LI. Nor could the team find the associated hazard analysis.

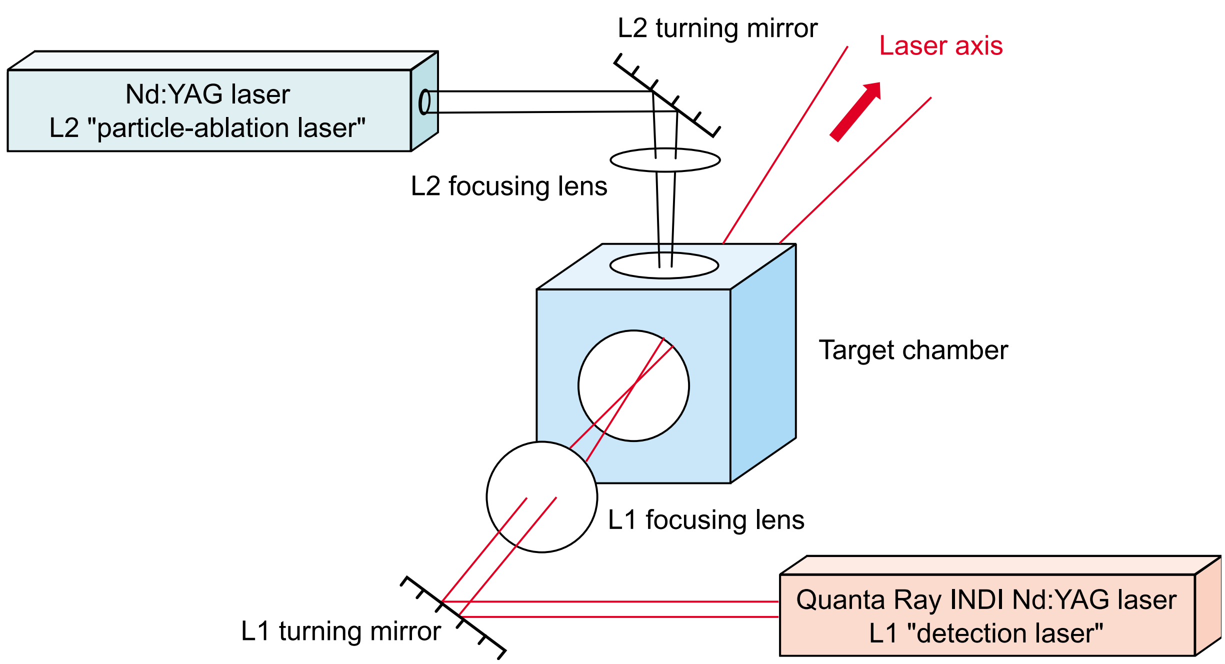

Figure 2.6. A diagram of the experimental system setup, showing the beam path along the L1 axis, through the target chamber, and out the chamber's rear window.

2.1.5 Description of the July 14, 2004, Experiment and the Target Chamber

The PI used a turning mirror to direct L1's beam 90 degrees toward the target chamber, which contained a sample of powdered soil simulant. A focusing lens in front of the chamber focused the laser beam through a front window to strike the particles that L2 had suspended within the chamber. Figure 2.7 shows L1's position in relation to the chamber. This configuration did not yet include a fiber-optic port to allow spectroscopic monitoring. L1 remained unchanged from a typical factory INDI laser configuration operating at 1064 nm and using an externally triggered Q-switch. This configuration does not employ and was not required to have a mechanical shutter to block light emission from leaving the laser.

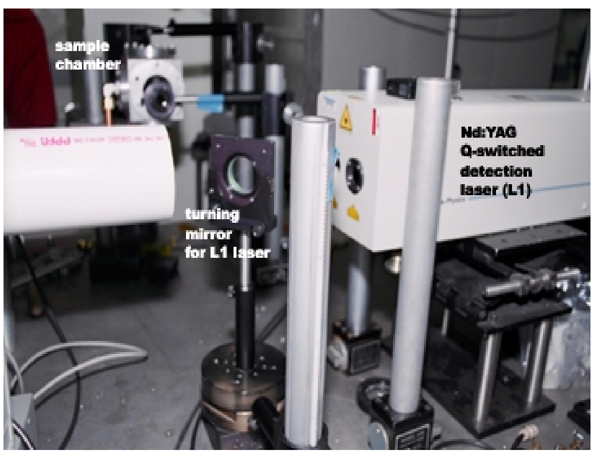

Figure 2.7. L1 output was turned 90 degrees toward the target chamber.

A top window on the chamber allowed L2's beam (also directed through the use of a turning mirror and focusing lens) to enter the chamber to strike and suspend particles of a powdered sample held in a cup. Figure 2.8 shows L2's position above the chamber. The chamber's rear window, used for viewing, was along the beam axis at the "back" of the chamber beyond the sample's location. A removable beam stop behind the rear window served to stop the beam from propagating beyond the optics table.

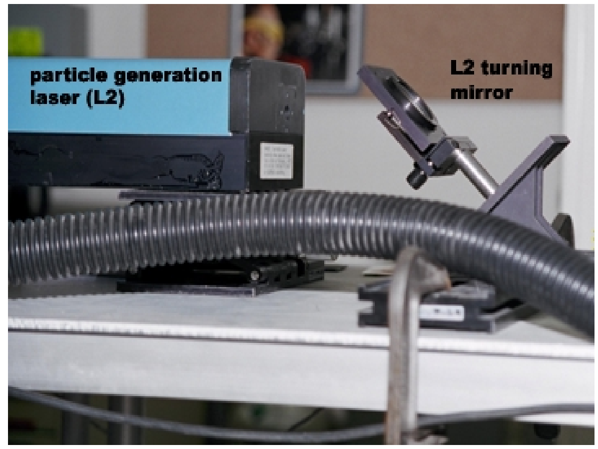

Figure 2.8. L2 was mounted on a table built onto and raised above the optics table. L2 was positioned above the target chamber. Neither the optics table nor the chamber are shown here.

Figure 2.9 gives a view through the rear window of the chamber, back out the front window, and through the focusing lens along the beam axis toward L1.

The IWD did not describe looking into the target chamber to view particles or using L1's flash lamps for illumination. Consequently, the hazards associated with these activities were not analyzed.

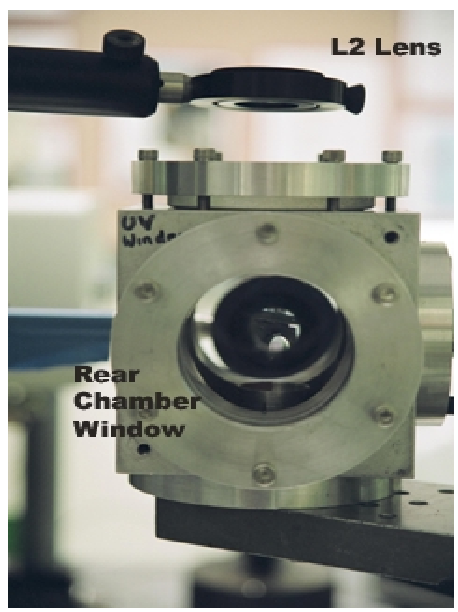

Figure 2.9. A view through the rear window of the target chamber, along the beam axis, toward the L1 beam source.

2.1.6 Experimental Process for the July 14, 2004, Experimental Setup

The experimental process involved placing the powder sample within the chamber and evacuating the chamber with a vacuum pump to about 7 torr. L2 was fired through the top window into the cup holding the powder sample, creating an impulse to physically ablate material and suspend it within the chamber atmosphere. L1 could then be fired to allow analysis of suspended particles. The PI and his student did not progress to the analysis portion of the experiment on July 14.

2.2 The Event

On July 13, 2004, the PI began setting up the PIV experiment in room 106. He installed the optical components and positioned the target chamber and beam stop. He configured L1 to operate in a Q-switch mode externally triggered by a Stanford Research Systems (SRS) pulse generator.

After putting on LEP and setting the warning light on the lab door to red, the PI set the pulse generator to 10 Hz, connected two trigger cables from the pulse generator to the laser power supply, and adjusted the laser energy control on the power supply to about 40 mJ. Using an infrared (IR) detection card to detect the laser beam position, the PI aligned the beam path to transport the laser beam to the turning mirror, through the focusing lens and target chamber, and onto the beam stop.

After completing the alignment, the PI did not check for spectral reflections or stray beams. The PI shut down the laser, but he has inconsistently reported whether or not he disconnected both trigger cables. Two cables were used, one to trigger the laser's flash lamps and the second to trigger the Q-switch and fire the laser.

On July 14, 2004, at about 12:00 noon, S1 went to the PI's office to discuss the PIV experiment and ask when they could start. Shortly thereafter, the PI and S1 entered room 106 to continue work on the experiment, which was configured as described in Section 2.1 of this report. They planned to demonstrate that L2 could suspend particles.

The PI believed the PIV experiment was authorized by the LIBS HPC and IWD. S1 had not completed all the training required by the LIBS HCP. S1 had also not completed all the training required or the baseline laser eye examination and was not authorized through C-Division's online worker authorization system to perform work under the LIBS HCP. In addition, the PIV experiment exceeded the scope of the HCP and the IWD.

S1 prepared a soil simulant sample. The PI placed the sample inside the target chamber, then sealed the chamber and established a partial vacuum inside it. The PI turned on the power supply for L2. He also turned on the power supply for L1 because he believed the particles could be more easily seen in the chamber if he used L1's flash lamps for illumination. The PI turned the laser lab warning lights to yellow. He did not believe that L1 was producing laser light because of the following indications:

- The IR card did not indicate lasing.
- No green light from doubling was visible on the focusing lens.
- No plasma was visible inside the target chamber.
- There was no "pinging" sound to indicate laser pulses hitting the beam stop.

Neither S1 nor the PI put on LEP.

The PI connected L1's flash-lamp cable to the SRS pulse generator, which caused L1's flash lamps to operate at 10 Hz and illuminate any suspended particles. The PI inconsistently reported whether or not the Q-switch trigger cable was connected. The PI set L1's energy knob to a setting previously determined to be 40 mJ. Without turning the laser lab warning light to red, the PI then proceeded to the target chamber side of the experiment, closed his eyes, and fired L2 for about 5 seconds. He then turned off L2 and opened his eyes.

After turning the room lights out, the PI removed the beam stop and saw particles suspended inside the target chamber. S1 was now standing next to him. When the PI told her to look, she stepped forward and bent down to view the target chamber. She immediately saw a flash and a reddish-brown substance floating in her left eye. The reddish-brown floater was obscuring her vision. A re-creation of S1's position when looking into the target chamber is shown in Fig. 2.10.

Figure 2.10. A team member demonstrates S1's position when she looked into the target chamber on July 14.

2.3 Initial Response and Notification

After the injury, S1 told the PI that she was experiencing vision problems. The PI suggested that they wait and see what developed. During this time the PI instructed S1 about how to avoid looking into the beam. After about 30 minutes, S1 again told the PI about her concerns. The PI stopped work and took S1 to LANL's Occupational Medicine group, HSR-2.

The physician's assistant (PA) at HSR-2 diagnosed the injury as a nonoccupational retinal detachment, but the diagnosis was heavily influenced by the PI's and S1's report that the laser was off. This information led the PA to discount a possible laser-induced eye injury. The PA referred S1 to an eye specialist in Los Alamos and arranged for her to be seen immediately. The PI drove S1 to the eye specialist's office.

After seeing S1, the eye specialist suspected a laser eye injury but could not make a positive diagnosis, so he arranged for S1 to see a retinal specialist in Santa Fe the following morning. S1 and the PI returned to work and subsequently went home. Before leaving work for the day, the PI tried to call the acting C-ADI group leader but could not reach him by telephone. The PI stopped by the group office on his way home, but no one was there.

The next morning, the PI picked up S1 and drove her to Santa Fe for her 8:00 a.m. appointment. The Santa Fe retinal specialist diagnosed the injury as a laser eye injury. At about 10:00 a.m., the PI telephoned his acting group leader and informed him of the accident. The PI and S1 drove back to Los Alamos and met with the acting C-ADI group leader at about 11:00 a.m.

The notification process did not proceed in a timely manner and senior safety-responsible line managers (SRLMs) were not notified of the event until about 5:30 p.m., July 15, the day after the accident. A detailed chronology of response and notification is provided in Appendix B.

2.4 Consequences

The accident caused a hole to be formed in the retina of S1's left eye. The hole is about 400 microns in diameter and about 250 microns deep. At that depth, seven layers of the retina were vaporized, but a tiny bit of the choroid may remain in place. The hole is in the macula and extends almost to the macula's center. Although it is not centered exactly on the fovea, the fovea may be damaged. Since the hole extends into the choroid, there was some hemorrhaging near the hole and some hemorrhaging into the vitreous fluid below the fovea.

The following occurred in S1's left eye immediately after the eye's exposure to bright light from L1 on July 14, 2004:

- A sudden change in visual acuity
- A floater resembling a "jellyfish"
- Acute, bright-red blood over the retinal lesion

Based on those factors, the preponderance of medical evidence indicates that S1 suffered the injury to her eye on July 14, 2004.

S1 was taken to Johns Hopkins Hospital, where her visual acuity was measured at 20/100 with the left eye and 20/20 with the right eye. The injury is currently causing blurring of the central vision of the left eye and some slight difficulty with depth perception. Peripheral vision in the left eye remains intact. The student is experiencing some difficulty with reading but has been able to finish writing a report on her project. She has no restrictions concerning driving, reading, taking classes, or using a computer.

The student's prognosis is guarded. The injury has resulted in permanent loss of the central vision in her left eye. It will take 1–2 months to determine if she is a candidate for surgical repair of the macular hole, and it may take up to a year to determine the final outcome of the injury and/or surgery. Although surgery would have the potential to repair the macular hole, it probably would not restore her central vision.

For a detailed discussion of the injury, see Appendix C.

3.0 ESTABLISHED FACTS

3.1 Event Facts and Observations

The bulleted facts and observations provided here support the causal analysis of the Class IV laser operations on July 14, 2004, in a laboratory used by C-ADI personnel.

3.1.1 Performance-Monitoring Facts

- S1 was not provided sufficient information about laser-operation safety controls, such as proper use of LEP, function and purpose of interlocks, and correct use of IR cards and IR viewers.
- The PI frequently elected not to use LEP, although wearing LEP was required and was included in work documentation that authorized his laser operations/activities.
- The PI instructed subordinate personnel that LEP was not necessary unless the laser was “on” (a lasing hazard was present), so subordinate personnel also regularly failed to wear LEP when the laser was in simmer mode, the flash lamps were on, and the Q-switch was disconnected.
- The PI modeled unsafe practices with respect to LEP and the use of laser safety interlocks to students.
- S1 understood from her online laser safety training that LEP was needed, but her use of LEP diminished as a result of the PI’s influence.
- The PI did not reinforce what students were told in the C-Division student orientation about safety processes such as work authorization, worker authorization, the “Stop Work” policy, Integrated Work Management (IWM), and Integrated Safety Management (ISM).
- The PI did not provide sufficient supervision to know that students were working alone in laser laboratories aligning lasers.
- The PI incorrectly assumed he was fully cognizant of the laser configuration and the laser beam path on July 14. He did not formally control the configuration of his equipment on either July 13, when he aligned the lasers, or July 14, when he operated the lasers.
- The PI did not analyze the potential hazard posed by using flash lamps to illuminate samples in a target chamber and did not incorporate that hazard into work-control documents.
- Students operating under the PI were not enrolled in the required pre–work-assignment Laser Medical Surveillance program. Students were not provided the services detailed in that required program, although they and the PI had been alerted to this requirement by laser safety training.
- Students operating under the PI could not demonstrate an understanding of the Nd:YAG laser’s various operating modes or the potential for lasing to occur while the flash lamps were being used for illumination of target chamber samples.
- Although laser registration forms and associated laser hazard analyses are required and are initiated by the P1, these could not be located for L1.
- The PI failed to fully implement multiple internal C-Division work-control policies, including the change-control policy; the event-notification policy; and the need for work-control documents to include formalized, written group leader authorization of workers assigned to LIBS laser work.
- The PI failed to fully implement the requirements of the laser LIR, Notice 139 and Notice 142.
- The PI failed to maintain a work environment that demonstrated good housekeeping and that allowed for sufficient egress, in spite of the fact that the C-Division leader shut down the division for all-day housekeeping April 2, 2004.
- The PI failed to confirm workers’ and students’ readiness to perform work and failed to provide students with substantive pre-job briefing information, as required by the IWM process.
- The previous C-ADI group leader set aside additional funding for team leaders to cover their supervision and oversight responsibilities; however, C-Division could not produce a job description for the C-ADI team leader. In addition, the C-ADI team leader had not been in room 106 for about nine months.
- The C-ADI team leader did not believe he was responsible for doing formal performance monitoring of the PI although he contributed to the PI’s performance appraisals.
- Early in calendar year 2004, laser safety officers (LSOs) had developed a laser-safety performance-assessment program on the recommendation of the C-Division Nested Safety Committee’s Laser Subcommittee, but that program had not yet been activated.

- The PI's SRLMs did not systematically cover all work areas or operations; consequently, the walk-arounds did not address and correct the issues in the PI's lab.
- The LSOs involved in the HCP review and approval could not remember the last time they had been in the PI's lab to evaluate the equipment configuration or operations.

3.1.2 Work Planning and Work Control

- LANL does not require a work plan to be developed between a worker and student.
- The two undergraduates working with the PI were not authorized in accordance with C-Division requirements to work under the LIBS laser HCP.
- C-ADI's acting group leader verbally approved S1 to work under the LIBS HCP in violation of C-Division work/worker authorization requirements.
- The LIBS laser HCP did not cover the use of flash lamps for target illumination and subsequently did not require or drive the analysis of the potential hazards posed by this activity/application.
- Although the activities at the time of the event were not covered in the HCP offered for the event, the HCP was not subjected to the C-Division change-control requirements of PRO-C-DO-006. The HCP was not modified, re-reviewed, or approved as required by the previous C-ADI group leader.
- The students working under the PI were not asked to sign the associated IWD until the day after the event; however, they were asked to date their signatures on the IWD with a date preceding the event. The students did not seem to understand what the document was or why they were asked to sign it.
- The students did not demonstrate knowledge of work/worker authorization.
- S1 was not provided with sufficient information to understand the hazards of using the laser without wearing LEP.
- The students conducted some work activities (such as using pressurized gas cylinders) before they received the required training.
- The PI did not meet work/worker authorization requirements, laser personnel registration, and laser registration.
- L2 was introduced into the lab without being interlocked to prevent personnel from being inadvertently exposed to laser-induced optical radiation hazards.
- Warning lights on the lab doors were improperly used.
- LEP requirements were not adhered to.
- Options for remotely viewing particles were not exercised.

3.1.3 Mentoring of Students

- LANL does not have an established policy for selecting mentors.
- LANL does not require mentor training.
- LANL does not require mentor performance assessment.
- LANL does not require mentors to review key management and safety policies with students.
- LANL does not require mentors to ensure that students demonstrate their knowledge about equipment configuration, work hazards, required controls, work-scope recognition, and what it means to sign work/worker authorization documents.

3.2 Post-Event Investigation Measurements for TA-46-41-106 Laboratory Conditions

Results of post-event measurements are summarized here. For a full report of experiments conducted and measurements taken in room 106 after the accident, see Appendix D.

3.2.1 Introduction

The Team, assisted by subject matter experts (SMEs) from the Physical Chemistry and Applied Spectroscopy group (C-PCS), completed experiments that characterized several conditions and systems in room 106. Characterizations included

- laser operating conditions for both L1 and L2,
- the optical beam path and scattered light,
- the laser interlock system, and
- IR card indications.

The post-event measurements were taken August 11, 12, 16, and 23, 2004.

3.2.2 Mode Selector Settings

Table 3-I indicates what configurations resulted in L1 lasing. In all combinations, the flash-lamp energy level was set at the 40-mJ pencil mark reference the PI used. BNC connections were between the SRS pulse generator and L1's power supply. Table 3-I shows that three conditions produced lasing.

3.2.3 Energy-Density Measurements for Light Entering S1's Eye

The Team also measured energy density in the location S1 occupied at the time of the accident (see Table 3-II). The measurements included not only lasing modes but also the simmer (nonlasing) mode.

From ANSI Standard Z136.1, American National Standard for Safe Use of Lasers, the intrabeam maximum permissible exposure (MPE) for the eye with a Q-switched Nd:YAG laser is 5 μJ/cm^2.
At 12 inches from the rear chamber window, running in simmer mode (flash lamps only, no lasing), the measured energy density is only 4.4% of the MPE. At the same position in long-pulse mode, the measured energy density is 1040 times the MPE; in Q-switch mode it is 840 times the MPE.

L2 was not interlocked in any way and emitted laser pulses only sporadically, regardless of repetition rate. Laser pulse energies were about 300 μJ.

3.2.4 Optical Beam Path and Scattered Light

The Team used an IR viewer to characterize the beam path and any stray reflections. The focusing lens mount was clipping the beam and created a rapidly diverging stray beam that was sent upward and backward toward the aisle around the optics table. The focusing lens itself was tilted in a way that caused Fresnel reflections to be directed up and backward, across the same aisle, onto the lab's front wall 59 inches above the floor. For a 25-mJ generated laser pulse, the Team measured about 3 mJ in the reflection.

Table 3-I: Possible LI Configurations

Pulse Generator				
Q-Switch BNC Cable Connection	**Flash Lamp BNC Cable Connection**	**Lamp Mode Selector (Fixed, Variable, External)**	**Q-Switch Mode Selector (Q-Switch, Long Pulse, External)**	**Laser Pulse Occurred**
OFF	ON	External	External	No
ON	OFF	External	External	No
ON	ON	External	External	Yes
OFF	ON	External	Long	Yes
OFF	ON	External	Q-Switch	Yes
OFF	OFF	External	Long	No
OFF	OFF	External	Q-Switch	No

Table 3-II: Energy Density for L1 in Lasing and Nonlasing Modes

Q-Switch Mode Selector (Q-switch, long pulse, external)	Maximum Energy (near the target)	Energy at 1 Foot (most likely position of S1)	Minimum Energy (near the cabinet)
Simmer	6.3 μJ/cm^2	0.22 μJ/cm^2	0.05 μJ/cm^2
Long Pulse	200,000 μJ/ cm^2	5,200 μJ/ cm^2	700 μJ/ cm^2
Q-Switch	160,000 μJ/ cm^2	4,200 μJ/ cm^2	567 μJ/ cm^2

Because L1's beam entered the focusing lens low, off-axis, it was turned upward through the chamber and, with the beam stop removed, hit the metal cabinet behind the fume hood 36 inches from the target chamber's rear window. S1's eye intersected this main beam path between the table and cabinet. Furthermore, the cabinet clipped the beam, and part of the beam impinged on a pressure gauge mounted on the back wall 59 inches from the floor and 83 inches from the target chamber's back window. After passing through its focal point in the target chamber, the beam expanded and was about 5 inches in diameter on the cabinet. (See Fig. 3.1)

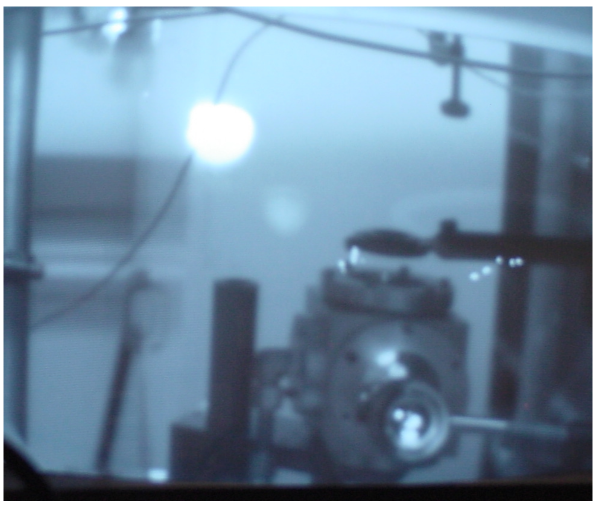

Figure 3.1. IR image of the transmitted laser pulse image on the back wall.

3.2.5 Laser Interlock System

L1 was connected to a manually operated laser interlock system designed to turn off L1's flash lamps and prevent lasing when either lab door was opened. A bypass box was installed and could be used to override the interlocks and allow the laser to continue running while either door was open. The laser interlock system also included an emergency "Off" switch. The interlocks could accommodate one laser, in this case L1. One interlock connection was held together with tape. The Team discovered and measured a potential difference of 12 Vdc between the bypass box and optics table. This condition was found by observing sparking between the box and optics table as the box was moved.

3.2.6 IR Card sensitivity

The PI said that a Newport F-IRC1 card was used during the time of the accident. The Team obtained the card and saw that it was badly damaged, with burns over most of its active area. It readily detected evidence of IR radiation; however, beam spatial profiles were not accurate because of the card's burned condition. Except for the burns, the PI's IR card performed essentially the same as a new, undamaged Newport card did.

The IR card detected evidence of IR radiation past the chamber while the laser was in simmer mode (no lasing action, 0.22 µJ/cm^2, as stated earlier). This light appeared as a broad spot on the card's active area. With L1 in Q-switch or long-pulse mode, a small, intense spot appeared on the active area. The spot was small enough and the burned area large enough in places that the lasing beam could not be seen.

4.0 CAUSAL ANALYSIS

The student's eye injury was caused by energetic laser pulses striking the retina of her left eye. Two conditions—the production of laser pulses and the lack of mitigation for the optical radiation hazard created by those pulses—allowed the injury to occur. The two conditions existed because the PI's work practices were unsafe, the performance of workers was poorly monitored, and work was inadequately planned and controlled. The Student Mentoring Program itself was also a significant contributing cause of the accident because the program does not address the unique safety issues associated with students working in a hazardous work environment.

The configuration of L1 at the time of the injury, as the PI described it, could not result in lasing, a fact the Team confirmed during experiments conducted after the accident.

However, based on the evidence collected, the Team is confident that L1 *did* produce pulsed laser energy while S1 was viewing the target chamber and that the laser energy produced caused S1's eye injury. The Team identified three potential scenarios that could have allowed this to happen (see Table 4-I).

1. The Q-switch cable was connected to the SRS pulse generator and was triggering L1. This condition is consistent with the conditions present during the alignment process performed the previous day. The PI could not consistently recall the cable configuration after he completed the alignment on July 13 and before work began on July 14.
2. With the flash-lamp trigger cable connected and the Q-switch trigger disconnected, the Q-switch mode-selector switch on the front of the power supply was configured to operate in long-pulse mode. See Fig. 4.1 for a view of the switches on the front of the power supply.
3. With the flash-lamp trigger cable connected and the Q-switch trigger disconnected, the Q-switch mode-selector switch on the front of the power supply was configured to operate in Q-switch mode.

Figure 4.1. The front of the laser power supply.

Table 4-I: Scenarios Consistent with Lasing

Pulse Generator				
Q-Switch BNC Cable Connection	**Flash Lamp BNC Cable Connection**	**Lamp Mode Selector (Fixed, Variable, External)**	**Q-Switch Mode Selector (Q-Switch, Long Pulse, External)**	**Laser Pulse Occurred**
ON	ON	External	External	Yes
OFF	ON	External	Long Pulse	Yes
OFF	ON	External	Q-Switch	Yes

Based on the observed stability of the laser during tests after the accident, the Team believes that L1 randomly generating laser pulses is an improbable scenario. The Team tried to create random pulses and observed the laser operating for an extended period during a lightening storm; in all cases the Team observed no random pulses. Even switching trigger cables did not result in spurious lasing. In addition, in the configuration described by the PI, the Team determined that the visible white light of the flash lamps could not have caused the eye injury.

4.1 Unsafe Work Practices

The Team determined the *direct* ISM failure in this accident was the PI's failure to perform work in accordance with established safety standards, processes, and procedures. The PI's failure to practice, model, and enforce safe behavior directly influenced the student and resulted in the eye injury.

The PI did not adhere to the requirements for Class IV laser operation as defined in the Laboratory Implementation Requirement and Guidance documents (LIR 402-400-01.3 and LIG 402-400-01.0, respectively), communicated in laser safety training, and based on industrial safety standards established in ANSI Z136.1. The PI also did not adhere to requirements contained in the HCP and the IWD. These implementing documents clearly emphasize the importance and necessity of controlling hazards associated with Class IV laser operations.

The PI did not routinely wear LEP (see Fig. 4.2). After aligning a laser, the PI was confident in his knowledge of the laser beam's position and characteristics. He trusted his ability to avoid the hazard. He transferred this knowledge and practice to his co-workers and students, including S1. As a result, S1 was injured when an unexpected and unidentified hazardous laser beam hit her left eye during Class IV laser operations.

Figure 4.2. LEP available for use in room 106.

Unbeknownst to him, the PI was exposing himself and S1 to significant laser beam hazards. The Team determined through measurements and observations that there were multiple reflections in the room when L1 was operating. The laser beam was not centered on the focusing lens and was steered upward. When the beam stop was removed, the laser beam hit the room's south wall at a height of about 59 inches. At least one of the reflections (4% Fresnel reflections from the focusing lens) was at a similar height on the north wall.

Considering the PI's practice of operating the Class IV laser without activating the room access interlocks or properly setting the warning lights, additional personnel could have entered room 106 without knowing the hazards that were present, and the laser would not have automatically shut down.

The PI also did not fully implement the IWM process that emphasizes defining work in sufficient detail to identify all hazards. IWM establishes a hierarchy of controls, beginning with substitution and engineered solutions. The use of personal protective equipment (PPE) to protect personnel from injury should not be the first choice. It is the last line of protection if other controls fail. The one barrier that could have been considered an engineered control had it been so defined was the beam stop. Because it was not clearly defined as an engineered barrier that provided specific protection, the PI informally removed it so that he and S1 could easily view the particles in the target chamber. Had the beam stop not been moved, it is likely that S1's eye would not have been directly exposed to the laser beam.

A detailed work description would have allowed both the misaligned beam hazard and the beam reflection hazard to be identified and mitigated using engineered controls such as the beam stop for the main beam and shielding devices for beam reflections. The work definition should also have contained a control-verification step that would have verified that the controls were in place and effective; in this case an IR viewer could have been used on the day of the incident. The PI incorrectly assumed that he had properly aligned the laser beam the previous day (or that the alignment was still correct and had not changed) and that there were no hazardous reflections.

The LIG lists about 43 recommendations for controlling Class IV laser hazards. They include the following:

- Interlocking critical beam stops that prevent beams from leaving the horizontal optical plane
- Terminating the beam at the end of its useful path
- Allowing no accessible unenclosed beam at eye level (nominally 4.5–6 feet above floor level)
- Confining the laser beam to the optics table
- Enclosing or shielding specularly reflective optics needed for beam control
- Locating, identifying, and controlling all hazardous direct and reflected beams, as well as any residual leakage, through the use of appropriate viewers, detectors, etc.
- Designing and specifying alignment procedures in the HCP or standard operating procedure to be used to keep exposure as low as practical
- Wearing LEP when other controls do not reduce the potential eye exposure to nonhazardous levels

The PI did not effectively implement any of these recommendations.

Finally, the PI did not properly fulfill his IWM role as the "person-in-charge" or as the direct supervisor. S1 was not authorized to work under the HCP, had not completed all of the required training, and had not received her required eye examination. The PI did not conduct a proper pre-job briefing, and he approached S1 to sign and predate the IWD after the accident occurred.

4.2 Inadequate Performance Monitoring

The Team determined that the *primary* ISM failure in this accident was the fact that existing institutional policies and practices regarding performance monitoring were not effective. The Team also determined that existing institutional policies and practices about work planning and execution are adequate to have prevented the accident from occurring, but they were not effectively implemented.

SRLMs did not adequately monitor the PI's performance and did not ensure the implementation of the LIR and LIG. LANL did not require systematic monitoring of work performed in all work areas to ensure adequate safety performance and compliance with existing requirements.

C-Division had developed (April 2004) but had not yet fully implemented a Strategic Safety Plan. That plan did require monitoring of all work areas. Adequate monitoring would have allowed managers to detect and then correct the unsafe behaviors and practices identified in this report.

The PI has been allowed to practice unsafe work behaviors in his laboratory for many years. The specific behavior of not wearing LEP has been common for him. He has modeled this behavior, and those who work with him in the laser laboratory have followed his example and instruction. Failure to wear LEP and improper use of system interlocks violate established laser safety standards (ANSI Z136.1), LANL's laser safety training, and LANL's implementation requirement regarding laser safety (LIR 402-400-01.3).

The PI's behavior, combined with a failure to implement many of the controls recommended in LIG 402-400-01.3 resulted in an unsafe work environment conducive to accidents. The PI's line managers did not detect and correct this unsafe work environment. They did not directly monitor the PI while he was performing laser operations, did not provide sufficient oversight of his work planning and execution to ensure compliance with and implementation of existing requirements, and did not ensure the safety of students assigned to the PI. SRLMs inferred the PI's safety performance from his world-class technical performance, his lack of prior mishaps, and his mentoring awards.

LANL does not have a formal process to ensure that line managers systematically monitor every worker's safety performance. The Management Walk-Around (MWA) process requires a line manager to perform a minimum of three walk-arounds per quarter. This does not ensure that worker performance is effectively monitored and that unsafe behaviors are quickly detected and corrected. Performance monitoring typically occurs at the group-leader level but can occur sometimes at the team-leader level. In this event, the team leader was not involved in supervising the PI. The PI did not have (and had not had for a significant time period) anyone monitoring his work.

Given that line managers did not formally monitor the PI's work, the conditions observed in building 41's rooms 106 and 112 should have caused concern. Entering either room should have triggered a response by any line manager or LSO. The results of unsafe behavior were obvious and easily detectable by the Team members. Housekeeping was poor. Egress routes were obstructed, gas cylinders were improperly stored, and some lasers were not interlocked. These indicators should have caused line managers to monitor operations in the room more frequently. By accepting these unsafe conditions, line managers set a low performance standard for the PI and his co-workers. Instead of correcting undesired and unsafe behaviors, line managers unknowingly reinforced them.

LANL does not have a process to ensure the effectiveness of performance monitoring. Recently, the institution began tracking properly documented MWAs and providing feedback to the manager. The tracking system allows the institution to see if line managers are meeting the minimum requirements, but it does not ensure the quality of the monitoring or systematic monitoring of the entire workforce. Comprehensive coverage of all workspaces, workers, and operations is also not ensured, increasing the probability that an unsafe work environment, such as the one present at the time of this accident, goes undetected until a mishap occurs.

Effective performance monitoring requires allotting sufficient resources for the task. Group leaders bear the largest responsibility for performance monitoring but are not always given the necessary time and resources for the task. A group leader's span of control can exceed his/her individual capacity. A single person cannot effectively monitor the day-to-day performance of a large number of employees. In addition, many line managers do not see performance monitoring as a daily priority.

C-Division has had a least two recent events involving similar failures. In one event, performance deficiencies were communicated to division personnel and to the Associate Director for Strategic Research (ADSR), but they never developed a formal corrective-action plan. The ADSR did not monitor or otherwise assist the C-Division leader in addressing the causal factors associated with the events.

4.3 Inadequate Work Planning and Control

The Team determined that C-ADI did not effectively implement LANL's interim IWM system. The PI wrote an insufficiently detailed IWD for LIBS experiments, and C-ADI line management and SMEs approved it. Consequently, the PI did not recognize that the PIV experiment exceeded the scope of the LIBS HCP and IWD. In addition, the PI implemented neither the IWM process nor safe work practices.

The PI, acting as the *preparer,* prepared part B of the IWD Form 2067. Notice 142 requires the preparer to define the tasks and steps in sufficient detail to ensure that the hazards associated with each task and step are identified. The IWD the PI prepared defined the work as shown in Table 4-II.

The PI did not prepare an IWD that defined the PIV experiment in sufficient detail to allow task-specific hazards to be identified and controls to be put in place. In particular, the nonstandard use of the Class IV laser flash lamps to verify that particles were suspended was not defined as a task/step, and the optical radiation hazard associated with this task was not identified. As a result, controls were not put in place to mitigate the hazard. In addition to wearing PPE (in this case, LEP) as a last line of protection, engineered controls could have included leaving the beam stop in place to keep the laser beam from leaving the optics table, using an IR filter on the target chamber's rear window, or using a camera to view the particles indirectly. The PI could also have considered using a less-hazardous illumination source than the Class IV laser to illuminate particles in the target chamber.

A second task insufficiently defined in the IWD and HCP was the alignment procedure. The PI used Q-switched laser energy to align the laser beam path. Had the HCP contained sufficient detail, an LSO could have identified the potential for specular reflections. The LSO could have required the PI to monitor for reflections and stray beams and recommended effective engineered controls to remove the hazards. Engineered controls would have allowed LEP to be a secondary control.

Table 4-II: Work as Defined by the PI in the IWD

Work Tasks/Steps	Hazards, Concerns, and Potential Accidents	Controls, Preventive Measures, and Boundaries	Supplemental Documents	Training
Identify sequence of work steps/tasks.	Identify hazards for each task/step. Identify site hazards that could affect workers.	Specify controls for each hazard (e.g., lockout/tagout points, specific PPE, etc.)	List permits, operating manuals, and other reference procedures.	List training requirements.
1. Design LIBS/laser-ablation experiment.	1. Design experiment in accordance with existing HCP-C-ADI-0001, R.3. 2. Determine if experiment involves new chemical hazards (e.g., toxic/corrosive/ explosive, etc., materials) not addressed by HCP-C-ADI-0001, R.3. 3. Determine if experiment involves new physical hazards (e.g., high pressures, high temperatures) not addressed by HCP-C-ADI-0001, R.3.	1. Incorporate controls, etc., specified in HCP-C-ADI-0001, R.3. 2. Consult appropriate SME regarding each new potential hazard to determine new controls, preventive measures, boundaries that may be required.	1. Have knowledge of documents specified in HCP-C-ADI-0001, R.3. 2. Consult appropriate SME regarding each new potential hazard to determine if additional supplemental documents are needed.	1. Obtain training specified in HCP-C-ADI-0001, R.3. 2. Consult appropriate SME regarding each new potential hazard to determine if additional training is needed.
2. Set up experiment as designed in STEP 1.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.
3. Notify others in experimental area/ building of any new hazards, if any.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.
4. Power-up Class IV laser system.	Refer to HCP-C-ADI-0001, R.3 for hazards associated with routine LIBS experiments. Light pulses emitted by laser (ocular hazard) are most routine hazard.	Refer to HCP-C-ADI-0001, R.3 for controls associated with LIBS experiments. Appropriate laser goggles as specified in HCP-C-ADI-0001, R.3., for laser ocular hazard.	Refer to HCP-C-ADI-0001, R.3 for documents associated with routine LIBS experimens. Operating manual for laser for ocular hazard.	Refer to HCP-C-ADI-0001, R.3 for training associated with routine LIBS experiments. Laser safety training course #17817 for Class IIIB & IV lasers.
5. Conduct LIBS experiments by focusing laser pulses onto sample material.	1. Light pulses emitted by laser are an ocular hazard for all LIBS experiments. 2. Hazards other than those listed in HCP-C-ADI-0001, R.3, if any, determined in STEP 1.	1. Appropriate laser goggles as specified in HCP-C-ADI-0001, R.3 for all LIBS experiments. 2. Control measures other than those listed in HCP-C-ADI-0001, R.3, if any, determined in STEP 1.	1. HCP-C-ADI-0001, R.3, and laser operating manual for safe laser operation. 2. MSDS for sample material. 3. Documents other than those listed in HCP-C-ADI-0001, R.3., if any, determined in STEP 1.	1. Laser safety training course #17817 for Class IIIB & IV lasers. 2. Training other than that listed in HCP-C-ADI-0001, R.3, if any, determined in STEP 1.
6. Change experimental parameters, if required, within operating envelope determined by HCP-C-ADI-0001, R.3, and results of STEP 1 evaluation by SME for new chemical/physical hazards.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.	Determined in STEP 1.
7. Power-down Class IV laser system.	Refer to HCP-C-ADI-0001, R.3.	Refer to HCP-C-ADI-0001, R.3.	Refer to HCP-C-ADI-0001, R.3.	Refer to HCP-C-ADI-0001, R.3.
8. Decommission of experimental setup.	1. As specified in HCP-C-ADI-0001, R.3, for routine LIBS experiments. 2. As determined in STEP 1 for new chemical/physical hazards (examples: disassembly of experiment components contaminated during experimentation, disposal of toxic materials).	1. As specified in HCP-C-ADI-0001, R.3, for routine LIBS experiments. 2. As determined in STEP 1 for new chemical/physical hazards (examples: labeling of contaminated enclosures).	1. As specified in HCP-C-ADI-0001, R.3, for routine LIBS experiments. 2. As determined in STEP 1 for new chemical/physical hazards.	1. As specified in HCP-C-ADI-0001, R.3, for routine LIBS experiments. 2. As determined in STEP 1 for new chemical/physical hazards.

The known hazards were not properly identified in the IWD. Instead of extracting information from the HCP, as required by Notice 142, the PI only referenced the HCP. A worker/student could not know the hazards specifically associated with the work by reading the IWD alone.

The Team concluded that, by approving this IWD, C-ADI failed to establish high standards for the quality of IWDs within the organization. C-ADI approved the IWD for LIBS work, even though the content was inadequate. The IWD did not adequately identify the tasks, the hazards associated with specific steps, or the controls necessary to mitigate those hazards. The controls associated with general Class IV laser operation that were specified in the HCP were not implemented and the lack of monitoring allowed workers to continue disregarding HCP requirements. Neither LANL nor C-Division has effectively implemented a process to monitor and ensure the quality of the IWM process, specifically including IWD rigor. The PI did not confirm readiness to continue with work.

4.4 Inadequate Mentoring

The Science and Technology Base Program Office describes a LANL mentor for students as "a trusted advisor, teacher, coach, facilitator, and/or role model." LANL relies on mentors to provide students with a challenging work assignment related to the student's academic goals. Within the context of the mentoring relationship, students should acquire an understanding of LANL expectations for working safely, analyzing hazards critically, and working within an authorized control set. Many students arrive at the Laboratory with less-than-robust training in safety practices from their university backgrounds, a fact revealed by the 2003 internal investigation involving a C-Division postdoc who was splashed with a hydrochloric-hydrofluoric acid solution.

Because LANL treats the mentoring relationship as a volunteer activity, it requires little in the way of training or qualification for mentors. Some divisions, not including C-Division, require mentors to teach their students LANL safety processes. Because LANL has no established set of required safety elements for the mentors, communication about and enforcement of safety requirements varies across divisions and individual mentors.

The July 14, 2004, laser accident revealed that students who worked with the PI were unsure of requirements for work/worker authorization and laser operation safety. Furthermore, their initial understanding about LEP, as obtained from LANL laser safety training, was replaced over time by the influence of the PI's ongoing practices and his reiteration that LEP was necessary only when the laser was lasing. The PI's statement did not account for the fact that LEP is required in the nominal hazard zone (NHZ) when the Class IV laser is on and the NHZ is defined as the closed room.

Mentors significantly influence the short- and long-term behaviors students adopt, and one mentor can influence multiple students over many years. Therefore, it is imperative that the Student Mentoring Program be structured to communicate, cultivate, and enforce robust safe-work practices in students, who represent the potential employee population of the future.

4.5 Inadequate Response

Notice 139 superceded the Abnormal Events LIR, 402-130-01.3, on April 7, 2004. The notice emphasized the need to improve abnormal event notifications and the event investigation process. Notice 139 underscores the intent to ensure that significant events are immediately communicated to senior LANL management. It further reminds all personnel that the associate directorate responsible for the area in which an event occurs is responsible for securing and preserving the scene of any mishap.

On September 4, 2003, the C-Division leader issued a division-wide e-mail announcement about C-Division's notification policy for abnormal events. That announcement stated, "Regardless of degree, always report the incident to your group management. If you cannot achieve verified notification (i.e., someone confirms that the message has been received) at your group level, you should contact the Division Office at 667-4457. If you cannot reach the Division Office, continue up the management chain and contact the ADSR office at 667-8597."

Immediately after injuring her eye on July 14, 2004, the student said she was concerned about her symptoms; however, she and the PI continued to work for more than 20 minutes. The PI took the student to

HSR-2 at about 1:50 p.m. and then to an ophthalmologist in the Los Alamos townsite. A laser eye injury was suspected but not confirmed. The PI called his group management and drove by the group leader's office that evening (July 14, the day of the accident). The phone call connected only with an answering service, and the group leader's office was closed. The PI took no further steps to make positive contact.

At 11:00 a.m., July 15, after a second ophthalmologist confirmed a laser eye injury, the PI and the student discussed the entire event with the acting C-ADI group leader. Telephone conversations between the acting C-ADI group leader and the C-Division chief of staff were ineffective and failed to communicate that a laser eye injury had occurred. The acting C-ADI group leader, in response to the chief of staff's request, then developed some text on the event, which was then reviewed by the PI and S1 before it was sent through e-mail to the division office at approximately 5:30 p.m., July 15. The acting group leader inconsistently reported his basis for the delay in getting the information to the division leader, stating in post-event interviews that he knew the division leader was busy.

As a result of the delay, it was impossible to establish event-scene integrity for an investigation. Significant time elapsed from the time of the accident until the accident scene was secured, which occurred on the following Monday, July 19. The delay resulted in an uninformed management chain and allowed personnel to reaccess the accident scene. After the event, the PI re-entered room 106 and attempted to determine what had happened. This included operating L1. Both the requirements and the intent of LANL and C-Division policies for reporting abnormal events were not met.

For a detailed response chronology, see Appendix B.

The tools used by the Team to analyze the July 14, 2004, laser incident are presented in Appendix E (Event and Causal Factor Chart), Appendix F, (Barrier Analysis), and Appendix G (Negative Fault Tree Analysis).

4.6 Analysis of Similar Events

The events described and evaluated here are represented graphically in the first five pages of the chart found in Appendix E.

4.6.1 Event 1: Chlorine Dioxide Explosion, January 8, 2002

In fiscal year 2001, LANL began planning the development of a biocide based on gas hydrates. Both chlorine dioxide and ozone were considered for the study. In April 2001 C-PCS developed a hazard control plan (HCP-C-PCS-003-R2) for the work. The HCP specified a mixture of dilute (2%–8%) chlorine gas (Cl_2) and water to form chlorine dioxide (ClO_2). Although the HCP set limits for the temperature, pressure, flow rate, and concentration, it did not define the temperature or pressure ranges under which condensation of ClO_2 could occur. In the condensed state, ClO_2 is a strong and extremely sensitive explosive.

In June 2001 the biocide project began, with ClO_2 used as the hydrate. When the C-PCS researchers decided a more-concentrated form of the hydrate was desirable, they were tasked with determining appropriate experimental conditions to produce the more-concentrated hydrate. On January 7, 2002, the researchers changed the experimental process, increasing the chlorine gas concentration to 100%.

The changes to the experimental process proved to be faulty: the researchers assumed the ClO_2 flow output to be equivalent to the flow input and did not accurately account for the ClO_2 vapor pressure, water temperature, and reaction time. Furthermore, the researchers did not subject the changes to the formal activity hazard analysis, risk determination, independent peer review, and formal authorization required for new activities in accordance with the Laboratory's Safe Work Practices LIR (LIR 300-00-01.4). As a result, when the modified experiments were begun on January 8, 2002, there was unexpected chlorine dioxide condensation within the containment vessel.

In the condensed state, ClO_2 is well known as a strong and extremely sensitive explosive. Researchers noted a more rapid than expected rise in the heat of the reaction and immediately vacated the laboratory. The reaction containment vessel, a Parr vessel, ruptured with 31.3 g of TNT equivalent. The explosion launched the vessel into the laboratory ceiling.

Causal Factors

An internal investigation team identified the root cause of the event as a failure of the researchers to conform to existing work-control requirements. When the researchers changed the original activity, they failed to analyze the changes made in the concentration of chlorine feed gas and the resultant hazards for the work and workers. The investigation team also identified contributing causes, including a control system that was not equipped to handle pure chlorine.

Corrective Actions

After the event, C-Division took several actions that focused on the failure to follow existing work-control requirements:

- C-PCS shut down its operations and reviewed safe work practices with the group supervisors.
- The group also reviewed the quality of its hazard-analysis documents and focused on how to improve hazard analyses. A group of representatives from throughout the division reviewed the C-PCS HCPs, modifying them and having them reauthorized as appropriate.
- The C-Division management team reviewed division HCPs, focusing on risk determination and identifying safety-significant parameters, limits, and change control.
- The C-Division management team received MWA training from an independent consultant, with a focus on staying within approved work parameters, ISM, and safety work permits.
- HCP walk-downs were included as standing agenda items for monthly Division Nested Safety Committee meetings.
- An MWA checklist was revised to prompt examination of HCP changes and worker familiarity with facility safety plans and tenant responsibilities.
- C-Division group leaders and sample group members completed the Process Safety Institute training for hazard analysis.
- C-Division formed subcommittees of the Division Nested Safety Committee. The subcommittees included the following topics: pressure and vacuum systems, cryogenic systems, radiological and waste, chemical, electrical, and lasers.
- Work-control issues were deferred to the IWM Committee. The committee's efforts were focused on improving work-control documentation and the work-management process.
- In March 2003 C-Division implemented PRO-C-DO-006, "Instructions for the Development, Review, and Change of HCPs," that required HCPs to be sent to the division document-control custodian for posting in the C-Division HCP database. Each HCP required a hazard analysis and a hazard ID checklist. The procedure further required that changes to the experimental limits or bounding conditions had to be submitted to the C-Division Change Control Process in accordance with the division Change Control Policy. The procedure further required that the group leader formally authorize minimal- or low-risk work in writing and authorize workers doing work of minimal, low, or medium residual risk, again in writing.
- After completion of the internal investigation, the C-Division leader revisited the Judgments of Need from the investigation and challenged his division to work to become a model of excellence in safety and Conduct of Operations, as well as in science.

4.6.2 Event 2: Postdoctoral Acid Splash, July 30, 2003

On July 30, 2003, a postdoctoral student in the Isotope and Nuclear Chemistry group (C-INC) prepared to perform a column separation, which required reconditioning the column resin. The student had previous chemistry experience in a university setting, was a foreign national, and had been at the Laboratory for about 6 months.

To perform the work, the postdoctoral student wore a lab coat, gloves, booties, and safety glasses and worked in a hood within a posted radiological buffer area (RBA). To recondition the column, the student used a pipette to introduce acid into the resin. This work was covered under the auspices of HCP-C-INC-021, R1. The student then decided to speed up the reconditioning process, at which time he inserted a syringe containing a solution of 4.0 molar hydrochloric acid/0.05 molar hydrofluoric acid into the top of the column, loosely connecting the syringe to the column with an improvised plastic ring seal. He then applied pressure to the syringe, and the corrosive solution sprayed into his face and eyes.

The changed methodology he was using to speed up the reconditioning was not covered in his work-control documents, so he was working outside the scope of those documents and failed to analyze the hazards he had introduced with his modifications.

Causal Factors

An internal investigation team identified multiple failures in performance monitoring and one failure in work planning that led to the unidentified, unanalyzed, and unauthorized work. The reconditioning work was presented to a work group for approval, but communication/language barriers, along with other communication failures, led to the corrosive spray hazard not being identified. In addition, the C-INC SRLM had not specified responsibilities for oversight to team leaders and had not specified the actions, activities, or processes by which to ensure the proper mentoring and oversight of the postdoctoral student. Furthermore, although radiological control technicians (RCTs) had talked to the student directly about some of his unsafe work practices, they did not take their concerns to SRLMs with the lines of accountability and authority to modify the student's practices. Finally, SRLMs had failed to conduct audits of the work practices in use in the lab and failed to effectively enforce expected work practices.

Corrective Actions

- IWM, through Notice 142 (previously Notice 131, effective 11/03/2003), was implemented across LANL and credited towards C-Division work-control corrective actions.
- C-Division's Operations group performed a self-assessment of IWDs in February 2004. C-INC implemented new employee orientation that emphasizes the communication of safety requirements.
- C-Division Office committed to meeting with each new employee and covering requirements for eye protection in the chemistry labs and the expectations for adhering to radiological control practices.
- C-INC committed to piloting a student mentoring program to improve the assignment of mentors and communicate the expectation that mentors model safe work performance and LANL safety culture/expectations.
- C-INC committed to integrating safety discussions into its group and team meetings.
- C-INC committed to forwarding concerns from its Nested Safety and Security subcommittees to C-Division Office.
- C-Division committed to opening its management meetings with safety and security issues.

NOTE: At the time of this report, the corrective action plan generated after the acid-splash event has not been completed, signed, and submitted to the LANL issues tracking system. Neither C-Division nor its ADSR developed and submitted a completed corrective-action plan, although the involved group and C-Division have committed to several corrective actions as listed here.

Based on the acid-splash event, C-Division took the following additional steps, indicating a willingness to improve operations within the division:

- In August 2003 the division held an all-hands meeting in which the division announced a requirement that all persons in a laboratory wear safety glasses equipped with side-shields. The division leader reminded all personnel to consider, "What is the worst possible thing that can happen to me in performing this task?" and told personnel to take measures to prevent the undesired outcome.
- C-Division required the use of all pressurized toxic reagents to stop until the management had reviewed and approved operations involving those reagents and the work-control documentation.
- In September 2003 C-Division distributed its internal Notifications Policy, which stated the following: "Regardless of [significance] always report [an] incident to your group management. If not a 911, then contact group management immediately, and if you can't achieve verified notification…contact Division Office… continue up the management chain to ADSR… ."
- On September 18, 2003, at the C-Division all-hands meeting, the division leader reviewed multiple safety incidents that had occurred at LANL in the recent past. He reiterated the causes, including failure to follow requirements, failure to identify hazards, failure to manage changes, and failure to incorporate lessons learned across organizations. The division leader's slides contained the following: "First and foremost,

a safe workplace is absolutely imperative to me, and I feel strongly that our current commitment to safety is unacceptable… . I want a workplace where each of us cares more about each other and our mutual safety than about anything else."

- The division committed to obtaining MWA training for all managers.
- In November 2003 C-Division formed and launched a Division Safety Council, which was chartered as an advisory board to guide the division in developing strategies and policies aimed at safety improvements.
- The Division Safety Council, in concert with the ADSR, developed the Division Strategic Safety Plan, which became effective in April 2004.

4.6.3 Analysis

Multiple latent conditions embedded in organizational processes continued to exist beyond these events, and those conditions allowed a repeat occurrence within C-Division. The issues fall into four broad categories: Work Control/Work Management, Performance Monitoring, Human Factors, and the LANL Student Mentoring Program.

Work Control/Work Management

Although the IWM directive, communicated as LANL policy through Notice 142, requires workers to identify, procedurally, steps to be taken in a task and then to identify the hazards associated with each step and the controls to mitigate the hazard for each step, these criteria continue to be poorly implemented. C-Division corrective actions included efforts to conduct a self-assessment of IWD implementation, but the laser eye injury event repeated a pattern in which personnel conducted work outside the scope of their authorized work.

The PI had an HCP and IWD for conducting LIBS research but was conducting an activity that was not described in either of the work documents. Therefore, the opportunity for hazard identification and analysis was missed. The laser was used to provide illumination in a target chamber that was viewed without any LEP. The work-control documents did not describe the activity and were self-referential. The included "What If" analysis reflected the lack of diligence applied to the hazard analysis activity. It posed the question, "What if a person fails to wear their required eye protection?" The control to protect against that situation was the following:
"Wear eye protection." These work-control documents were not critically analyzed for their generality and were endorsed by line management as well as by health and safety SMEs.

Although burdensome, the IWD methodology was designed to drive a hazard analysis process that was integrated with the work steps so that a worker could understand the hazards and controls posed by each step of the work. The specified steps were intended to further provide a worker with a definitive authorized work scope so that an unauthorized work scope, or changes made in the field, could easily be identified as requiring a new hazard analysis and authorization.

The laser eye injury event illustrated the fact that critically analyzed hazards and controls are not yet consistently occurring. It further reflects the fact that personnel continue to engage in work as though authorization of desired work activities is secondary to conducting the work.

The work/worker authorization process was further diminished in the laser eye injury event because the PI's students were not provided with a comprehensive pre-job briefing for their work, including the particle-viewing activity. Instead, the PI approached the students to sign and predate the pre-job acknowledgment portion of the work control documentation after the injury occurred.

Performance Monitoring

All three events reflected a failed implementation of performance monitoring. Performance-surety measures, including performance monitoring, constitute a portion of all Conduct of Operations programs. Through performance monitoring of operations and personnel, line management can assess and correct at-risk behaviors.

Because performance monitoring was not evaluated in the chlorine dioxide explosion event of 2002, no corrective actions were developed to address the issue. The acid-splash event investigation raised the performance-monitoring issue and the fact that although support personnel both witnessed and addressed unsafe behaviors, the accountable line management was not apprised of the concern.

Although an anonymous online safety-concern program exists at LANL, its utilization and implementation must be evaluated to assess the effectiveness of the program. The hesitation to report such observations to line management recurred in the laser eye injury event. Personnel who were in the same work area as the PI addressed the PI about unsafe practices, including the misuse of interlocks and the failure to wear required LEP while operating a Class IV laser. The PI acknowledged the concerns but failed to change his behaviors, and the SRLMs were not made aware of the issue.

An effective performance-monitoring program requires more elements than the tools to assess operations. At LANL, both group and division self-assessments are conducted on the implementation of the work-control requirements. In addition, the Audits and Assessments group conducts independent assessments of the work-control program implementation. In the case of the laser operations at TA-46-41, the C-Division SRLMs had visited the area on several occasions. However, for multiple reasons, they focused their efforts on an adjacent laboratory and failed to observe the PI conducting work in his laser labs. The line management had not specified safety oversight responsibilities for the PI's team leader, line management focused MWAs on another facility that was being evaluated for a facility hazard-level reduction, and the line management was confident in the PI's safety record. Therefore, the PI's lab, his activities, and his work documentation were not scrutinized, although housekeeping concerns were brought to his attention.

Finally, the MWA online system was originally designed with the intent to drive the frequency with which managers conducted field observations of work. The requirements for these observations do not require a systematic evaluation of all work facilities or all operations within a manager's purview. Furthermore, the tool does not account for the span of control variation between group managers across LANL and does not provide for necessary resources of time and personnel to conduct performance-monitoring activities. Consequently, MWAs can repeatedly evaluate one activity or one area but not systematically evaluate all operations and all personnel. In addition, the walk-arounds are not geared to follow up on abnormal, event-related data or leading performance indicators.

Human Factors

It is well identified and described in safety and human-performance literature that human-performance errors are directly responsible for the greatest portion of mishaps. The chlorine dioxide explosion investigation, the acid-splash event investigation, and the laser eye injury investigation all indicate a failure to recognize two significant human factors issues.

First, where high or medium initial risk is lowered to a minimal or low residual risk through administrative controls alone, the entire safety envelope for the activity depends on a 100% compliance level that includes a repeatedly concerted and alert effort focused on the task at hand. Because human performance and administrative controls are less reliable than engineered controls, the degree of performance monitoring must necessarily increase to maintain expected human performance under these conditions.

Second, as personnel become comfortable with their knowledge of a given hazard, they also become comfortable with the practices they have developed for working in the presence of that hazard. This complacency will drive compliance and human performance downward.

LANL Student Mentoring Program

The LANL Student Mentoring Program is based on the underlying philosophy that mentors are providing a volunteer service for students and that students acquire challenging academic and career experience during their stay at LANL. Students create a unique challenge to the cultivation of safe work practices because their academic experience does not usually prepare them for working within the institution's expectations and because students often rely heavily on input from their mentors to shape their own work practices. The acid-splash event and the laser eye injury both illustrated that mentoring was deficient because mentors either were not present or did not model the safety culture expected by LANL policies.

The Student Mentoring Program does not require mentors to attend the mentoring training that is made available by the Science and Technology Base Program Office. LANL does not require mentors to invest significant time and make a concerted effort to ensure that students understand the hazards and controls associated with the work to which they are assigned. LANL does not require mentors to ensure that students understand fundamental concepts associated with safety, such as work/worker authorization, “Stop Work,” the need to challenge those around them to verify an activity’s safety, and the principles of ISM.

Mentors may be but are not always evaluated based on their students’ understanding of these principles and policies, nor are they evaluated based on the students’ understanding of the work-control documentation, the identified hazards and controls for the activity, and the implementation of those requirements. Neither the postdoctoral student who ended up with hydrochloric-hydrofluoric acid in his eye nor the undergraduate student working with Class IV lasers fully understood the scope of the authorized work or the necessity to incorporate specific safety precautions into daily work practices.

It is also worth noting that the student whose eye was injured by a laser expressed a sense that students could not effectively challenge a mentor upon whom they were dependent for recommendations for future academic and possibly career opportunities. A second communications chain must be clearly established for the resolution of any concerns related to the work environment or work activities to which students are assigned.

A failure to correct these significant issues will result in a failure to structure a work environment in which expected safety behaviors consistently occur within the current worker population as well as within the population of students and new-hires at LANL.

5.0 RECOMMENDATIONS

Conclusion	Recommendation(s)
1. Performance monitoring failed to identify and correct at-risk behaviors, requirement violations, work-control deficiencies, and deficient mentoring of C-ADI students.	1.1 LANL should implement a risk-based oversight program that systematically monitors the performance of every employee and workspace. 1.2 LANL should establish nonpunitive processes that emphasize peer-to-peer and worker-to-manager communication of unsafe acts and near misses. Such processes would create an environment of open communication, encouraging legitimate concern for individual safety. 1.3 LANL should assess the safety of laser operations throughout the Laboratory. 1.4 C-ADI should correct the safety issues inside building 41, including the overall poor state of housekeeping.
2. Execution of the IWM process failed to produce a detailed work description and associated hazard analysis and controls that would have mitigated the potential optical radiation hazard.	2.1 C-Division should implement a process that ensures the quality of IWDs and HCPs. 2.2 LANL should conduct a continuing, periodic review of the quality of IWM implementation.
3. The LANL Student Mentoring Program failed to provide sufficient oversight of students.	3.1 LANL should develop and implement a formalized Student Mentoring Program that establishes the following: – Qualification and training requirements for mentors. – A monitoring and performance-assessment program for mentors and students. – Requirements that mentors teach their students safe work practices. – Requirements that students demonstrate their ability to work safely.
4. Workers and managers involved in this accident failed to execute their roles and responsibilities, resulting in the PI and S1 not performing work safely.	4.1 Using existing institutional processes, C-Division should take actions to modify worker and manager behaviors.
5. During the investigation, the Team identified deficiencies in processes, programs, and procedures (see Appendix H). Although these deficiencies did not prove to be causal, they do present improvement opportunities.	5.1 Using the institutional issues management system, LANL should address the concerns in Appendix H.

APPENDIX A

Letter of Appointment

1943 - 2003
Los Alamos
NATIONAL LABORATORY
Ideas That Change the World

memorandum

To/MS:	Distribution
From/MS:	G. Pete Nanos, DIR, A100
Phone/Fax:	7-5101/7-2997
Symbol:	DIR-04-243
Date:	July 16, 2004

SUBJECT: APPOINTMENT OF INVESTIGATION TEAM FOR THE JULY 14, 2004 LASER EYE INJURY AT TA-46, BUILDING 41

I hereby establish a team to investigate the event of July 14, 2004, in which a student working with the Advanced Chemical, Diagnostics and Instrumentation Group, C-ADI, received a retinal injury to her left eye while working with a Class IV, Nd:YAG, pulsed (Q-switched) laser. The student and supervisor were performing a series of experiments while using the laser. At the time of the incident, they believed the laser was not producing laser light. The student stated that while performing the experiment, she saw a flash of light followed by the appearance of reddish-brown spots in the visual field of her left eye. The student was taken to HSR-2, referred to retinal specialists, and subsequently diagnosed as having a 300 micron deep retinal lesion and associated hemorrhaging in her left eye. The source of light causing this injury, i.e., either the laser pumping lamps or an unexpected pulse of infrared laser light, will be determined by the appointed team.

I appoint Richard Mah, Associate Director for Weapons Engineering and Manufacturing, as the investigation team Chair. Full team composition will be as follows:

- Richard Mah, ADWEM, Chair
- Dennis Derkacs, HSR-DO/ISM Program Manager, Vice Chair
- Ron Geoffrion, HSR-DO/ADWEM-deployed, Certified DOE Accident Investigator
- Rita Henins, PS-7, Investigator/Certified DOE Accident Investigation Board Chair
- Matt Hardy, PS-7, Investigator/Certified DOE Accident Investigation Board Chair
- Tom Turner, ADSR, Physical Chemistry/Lasers
- John Milewski, MSM-5, Laser Processing
- Gary Lewis, MST-6, Chemistry/Lasers
- Connon Odom, DX-5, Laser Safety Officer
- Consultant, Dr. William Brady, HSR-2, LANL Medical Director
- Consultant, Steve Greene, P-DO, Work Control/IWM Process
- Consultant, Phil Kruger, LC-ELL, Legal Counsel/Employment Law
- Consultant, Tim Babicke, HR-SR, Staff Relations
- Observer, Deidra Yearwood, PS-PAAA, Nuclear Safety
- Observer, Louie Lincoln, PS-2 Advisor
- Observer, Dean Decker, NNSA LASO
- Independent Reviewer, Dave Herbert, National Safety Council

The Chair will identify additional advisors, consultants and other support personnel as necessary to complete the investigation. The team will conduct a causal analysis of the event and the subsequent response, and will provide a report on the causal factors and recommendations for my approval no later than close of business Friday, August 20, 2004. The scope of the team's investigation will include, but not be limited to the following:

DIR:04-243 -2- March 5, 2004

- events and conditions leading up to and immediately following the event
- equipment/system malfunctions associated with the event
- determine the ISM causal factors, including work scope identification, hazard analyses, hazard controls, work authorization, training/qualification/authorization of workers, readiness, and work performance
- actions and inactions of supervisors and managers relevant to the ISM process
- evaluate the adequacy of institutional and division-level policies, requirements, procedures, training/certification relevant to the work
- evaluate immediate response to the event, including notifications and emergency response
- evaluate the effectiveness of corrective actions from previous similar events
- evaluate the effectiveness of lessons learned from previous similar events
- develop recommendations for human performance, management system and safety program improvements

Upon my acceptance of the causal factors and recommendations, ADO will coordinate development of the necessary corrective action plans, and shall present these for my approval by September 17, 2004. The final corrective action plan shall be appended to the investigation team's final report and distributed to all stakeholders.

Discussions of the investigation and copies of the draft report will be controlled until I authorize release of the final report.

Distribution:
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D. Derkacs, HSR-DO, K491
R. Geoffrion, HSR-DO, A107
R. Henins, PS-7, K999
M. Hardy, PS-7, K999
T. Turner, ADSR, A127
J. Milewski, MSM-5, P917
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G. Lewis, MST-6, G770
W. Brady, HSR-2, D421
S. Greene, P-DO, D434
P. Kruger, LC-ELL, A187
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K. Jones, DX-DO, P918
F. Dickson, LC, A183
Director's File

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memorandum

To/MS:	Distribution
From/MS:	G. Pete Nanos, DIR, A100
Phone/Fax:	7-5101/7-2997
Symbol:	DIR-04-
Date:	August 16, 2004

SUBJECT: APPOINTMENT OF FREDERICK A. TARANTINO TO INVESTIGATION TEAM FOR JULY 14, 2004 LASER EYE INJURY

I hereby amend memo DIR-04-243 (copy attached) which established the investigation team for the July 14, 2004 Laser Eye Injury. Frederick A. Tarantino, Principal Associate Director for Nuclear Weapons Programs will replace Richard Mah as the Chair of the investigation team.

GPN:ccg

Distribution:
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D. Herbert, HSR-DO, K491
T. Babicke, HR-SR, P126
W. Brady, HSR-2, D421
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J. Milewski, MSM-5, P917
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Director's File

APPENDIX B

Initial Response Chronology

Wednesday, July 14, 2004

~1:00 p.m.

S1 bends down to view particles suspended in a target chamber and illuminated by the flash lamps of a detection laser. She immediately sees a burst of bright light and notices a reddish-brown substance floating in her eye. She mentions this to the PI, and he suggests that they wait and see what happens. He states that because the laser is set in a nonlasing mode, S1 might be experiencing an aftereffect similar to what happens to a person who looks at a camera flash bulb. Neither the PI nor S1 thinks to stop work immediately and get S1 to HSR-2 for an evaluation.

~1:20 p.m.

About 20 minutes after the incident, S1 asks the PI if there is an ophthalmologist at the Laboratory. She thinks a capillary may have broken in her eye. The PI decides S1 should be evaluated at HSR-2, Occupational Medicine, and calls HSR-2 to report that they are on their way. He does not notify line management. The PI drives S1 to HSR-2.

1:52 p.m.

S1 is logged in at HSR-2.

At HSR-2, the triage nurse talks to S1 about her symptoms, then takes her to the eye-examination room and calls for the physician's assistant. The PI intercepts the assistant on his way to the examination room and tells him the injury could not have been caused by the laser because the laser was turned off. Both the PI and S1 tell the nurse and the physician's assistant repeatedly that the laser was off.

In the examination room, the nurse briefs the physician's assistant on the symptoms and describes the incident, reiterating that she has been told the laser was off, which S1 again confirms. The physician's assistant examines the eye and finds the vitreous humor clouded.

The nurse and the physician's assistant concur on a diagnosis—a detached retina—and the physician's assistant reports the injury as nonoccupational. He does not report the incident to the HSR-2 group leader, which he would have done if he thought the injury was occupational.

The physician's assistant later admits that he relied too much on assurances that the laser was off and that he would have reported the incident differently except for those assurances. Although both the nurse and the physician's assistant have previous experience with eye injuries and ailments, neither has ever evaluated a laser injury before.

In any case, the physician's assistant says that his next action would have been the same for any type of eye injury: making an appointment for S1 at Eye Associates of New Mexico (Los Alamos).

~3:00 p.m.

An Eye Associates doctor examines S1's eye and tells the PI that there is both hemorrhaging and a lesion in the eye, suggesting a laser injury. The PI tells the doctor he does not think it could be a laser injury because the laser was not on. The Eye Associates doctor makes arrangements for S1 to see a Santa Fe retinal specialist the next morning. S1 does not return to HSR-2 with the Eye Associates diagnosis, nor does the PI call HSR-2 with the information.

~4:00 p.m.

S1 and the PI return to the Laboratory, and S1 goes to her office at TA-46, building 314, before returning home.

~4:30 p.m.

The PI returns to building 41, room 106, and secures the lab. He calls the group office to report the incident but gets only a voice message. He drives to the acting group leader's office but finds it dark.

Thursday, July 15, 2004

~6:45 a.m.

The PI picks up S1 and drives her to the retinal specialist in Santa Fe.

8:00 a.m.

The PI and S1 arrive at the retinal specialist's office in Santa Fe.

8:20 a.m.

The retinal specialist examines S1 and informs her that she has a lesion on the retina and extending into the capillary bed beneath the retina.

8:50 a.m.

The retinal special listens to the PI's description of the incident. The specialist declares that a laser caused the injury—a hole near the fovea of S1's left eye.

9:05 a.m.

A technician takes retinal pictures of S1's eye. Afterward, the PI and S1 leave the specialist's office for the return trip to Los Alamos.

~9:30—10:00 a.m.

The two stop at a store on the way out of Santa Fe so S1 can buy an eye patch. The PI uses S1's cell phone to call the acting C-ADI group leader and report that he and S1 will be in the acting group leader's office in about an hour.

~10:00 a.m.

The HSR-2 nurse who along with the HSR-2 physician's assistant saw S1 the previous day calls both S1 and the PI on behalf of the physician's assistant to inquire about S1's condition. She leaves phone messages.

~10:45 a.m.

The acting C-ADI group leader calls the C-Division chief of staff to report the accident. He does not call the division leader because he knows the division leader is busy. The chief of staff asks the acting group leader if the incident is reportable, and the acting group leader says he does not think it is. He also tells the chief of staff that the PI and S1 are returning from Santa Fe and will come directly to his office. The chief of staff tells the acting group leader it is very important to get definitive information to the division leader as soon as possible.

11:00 a.m.

The PI and S1 arrive at the acting C-ADI group leader's office and explain events to him. The PI tells the acting group leader he has not touched anything in room 106 since the accident. The acting group leader calls the C-Division chief of staff twice more.

11:15 a.m.

The PI and S1 return to room 106, although S1 has not been cleared by HSR-2 to return to work. The PI tells others in the building that S1 has a broken capillary in her eye. He tells them the laser was off, and something suspicious happened.

Afternoon

The acting C-ADI group leader writes up the event as requested by the C-Division chief of staff. He has both S1 and the PI review the write-up for accuracy before sending it to the division office.

The PI returns to room 106 that afternoon to check for leakage from the Nd:YAG laser. He says he did not check for leaks before starting the PIV pre-experiment work of suspending particles.

~2:00 p.m.

The PI approaches S1 about signing the IWD and predating her signature to the date when she signed HCP-C-AD-001, R.3, Laser Ablation, LIBS—June 29, 2004. He also asks a second student to sign the IWD and date it June 29, 2004.

~3:00 p.m.

The PI returns the HSR-2 nurse's call and reports the Santa Fe specialist's diagnosis of a laser injury. He also tells her the laser's Q-switch was off, but other lights were on and the laser was not pulsing. The nurse does not fully understand what the PI has told her, so she calls the Laboratory LSO to reiterate what the PI has said and ask questions. The Laboratory LSO tells her that either laser light was present or someone is lying.

~3:10—3:15 p.m.

The nurse calls the HSR-2 group leader and reports on her telephone conversations with the PI and the Laboratory LSO. The HSR-2 group leader calls the associate director for operations (ADO) and the Santa Fe retinal specialist.

~3:30—4:00 p.m.

The C-Division chief of staff reports to the C-Division leader that the acting C-ADI group leader called her to tell her that a student got something in her eye and was taken to the doctor. She tells the division leader that S1 is back at work and that the incident is not reportable.

4:00 p.m.

The C-Division chief of staff goes home.

5:00 p.m.

The ADO reports receiving a call from HSR-2 regarding the incident. The ADO notifies PS-7, Occurrence Reporting.

5:23 p.m.

The acting C-ADI group leader electronically mails the event write-up to the C-Division chief of staff.

5:30 p.m.

The PS-7 group leader calls the C-Division leader to ask if he knows he had a laser accident on July 14.

5:45 p.m.

The PS-7 group leader and the C-OPS group leader go to the C-Division leader's office.

6:00 p.m.

The ADO calls the deputy associate director for strategic research (ADSR), the C-Division leader, and the C-ADI group leader.

Friday, July 16, 2004

8:30 a.m.

An event critique is conducted in building 24, TA-46. The Laboratory Director stands down the Laboratory.

Wednesday, July 21, 2004

The HSR-2 group leader accompanies S1 to John Hopkins Hospital, Baltimore, Maryland, to see a retinal specialist.

Thursday, July 22, 2004

The HSR-2 group leader returns to the Laboratory and briefs the Accident Investigation Team that a July 14 laser accident caused a traumatic hole 400 microns wide and 250 microns deep in the retina of S1's left eye.

APPENDIX C

Medical Consequences

Overview of the Eye and Retina

As light enters the pupil, it is focused and inverted by the cornea and lens and projected onto the back of the eye, the retina (Fig. B-1). The retina has layers of alternating cells and processes that convert a light signal into a neural signal. The actual photoreceptors are the light-sensitive cells known as rods and cones.

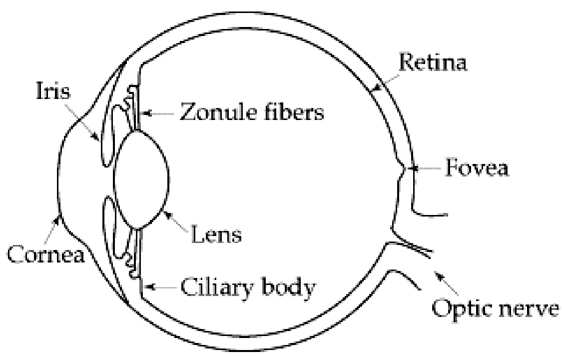

Figure B-1. Structure of the human eye.

The cells that transmit the neural signal to the brain are the ganglion cells, which make up the optic nerve, the single route by which information leaves the eye.

The retina is a seven-layered structure involved in signal transduction (Fig. B-2).

Essentially, light enters from the ganglion cell layer first and must penetrate all cell types before reaching the rods and cones, the photoreceptors. The photoreceptors are distributed unevenly throughout the retina. Most cones lie in the fovea and, overall, greatly outnumber rods. The rods, which dominate peripheral vision, are for black and white vision and are very sensitive to low light. The cones are for color vision and are less sensitive to low light.

The fovea defines the center of the retina. As the region of highest visual acuity, it is directed towards whatever object you wish to study most closely, for example, something you are reading. The fovea is almost exclusively cones, and the cones are at their highest density there. At the fovea, the ratio of

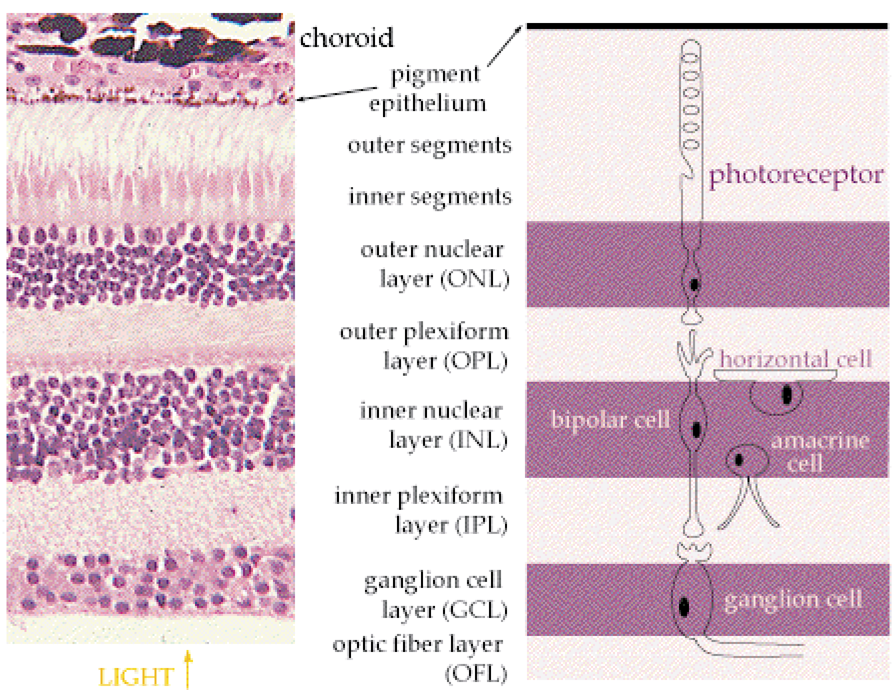

Figure B-2. The eye's seven retinal layers.

ganglion cells to photoreceptors is about 2 to 1, a higher ratio than anywhere else in the eye. In addition, at the fovea, all of the other cell types squeeze out of the way to allow the most light to hit the cones (Fig. B-3).

In and around the fovea is an area of pale yellow pigmentation called the macula, which is visible through an ophthalmoscope (Fig. B-4).

Retinal Injury Caused by Light Penetration

Heat-caused mechanical injuries to the retina—thermomechanical injuries—are quite rare. Such injuries typically occur in industrial settings if a powerful Q-switched laser is misfired during an alignment procedure while the beam is being viewed by an individual not wearing appropriate eye protection.[1, 2, 3, 4] These injuries usually are thermomechanical (a burn) rather than ablative (removal of tissue). The damage is caused by rapid expansion of the whole complex of ganglia and photoreceptors, the retinal pigment epithelium (a layer of pigmented tissue), and the layer of blood vessels known as the choroid at the back of the retina. The hole is caused by the localized vaporization of tissue, which in turn can create a mechanical shockwave to be propagated through the tissue (an acoustic effect). The acoustic effect has been reported in the literature to be accompanied by a "snapping sound" at the time of injury.

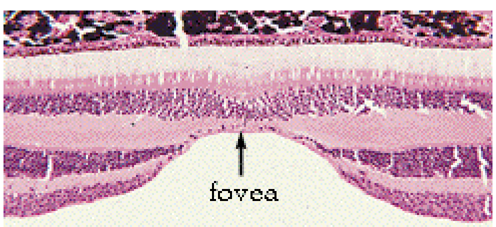

Figure B-3. The fovea, at the center of the retina.

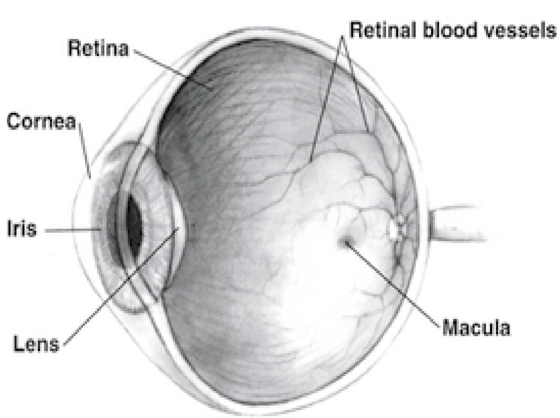

Figure B-4. Cross section of the eye, showing the macula, which surrounds the fovea.

Student Injury

The accident caused a hole to be formed in the retina of the student's left eye. The hole is about 400 microns in diameter and about 250 microns deep. At this depth, seven layers of the retina were vaporized, but a tiny bit of the choroid may remain in place. The hole is in the macula and extends almost to the macula's center. Although, it is not centered exactly on the fovea, the fovea may be damaged. Since the hole extends into the choroid, there was some hemorrhaging near the hole and some hemorrhaging into the vitreous fluid below the fovea.

The following occurred in the student's left eye immediately after the eye's exposure to bright light from L1 on July 14, 2004:

- A sudden change in visual acuity
- A floater resembling a "jellyfish"
- Acute, bright-red blood over the retinal lesion

Based on those factors, the preponderance of medical evidence indicates that the student suffered the injury to her eye on July 14, 2004.

The student was taken to Johns Hopkins Hospital, where her visual acuity was measured at 20/100 with the left eye and 20/20 with the right eye. The injury is currently causing blurring of the central vision of the left eye and some slight difficulty with depth perception. Peripheral vision in the left eye remains intact. The student is experiencing some difficulty with reading but has been able to finish writing a report on her project. She has no restrictions concerning driving, reading, taking classes, or using a computer.

Prognosis: Guarded

The injury has resulted in permanent loss of the central vision in the student's left eye. It will take 1–2 months to determine if the student is a candidate for surgical macular hole repair, and it may take up to a year to determine the final outcome of the injury and/or surgery. Although surgery would have the potential to repair the macular hole, it probably would not restore the student's central vision.

The contributing factors are the following:

1. Is enough of the choroid still present to allow the hole to heal with some vision improvement?
2. Can mechanical reattachment or closure of the hole by surgery result in any vision improvement?
3. Is there a possibility of fibrous tissue proliferation or other kinds of scarring? If so, how will such problems be treated? How will vision be affected?
4. If the blurring of the left eye's central vision continues, how long will it take for the brain to ignore the blurring and the right eye to become dominant?

Discussion

Allen Thach, et al.,[4] published a study in the *American Journal of Ophthalmology* in June 1995 on the clinical course of accidental, single-focus Nd:YAG laser injuries to the macula. In this study, the authors reviewed the clinical course of five eye injuries in four patients who sustained macular injuries from a Nd:YAG laser. All patients were examined within 24 hours of injury and were observed without surgical intervention for a mean of 20 months (range, 12–32 months).

A single full-thickness foveal or parafoveal retinal hole was apparent in all eyes, either on initial examination or within 2 weeks of injury. All macular holes were within 650 microns of the foveal center. The mean visual acuity was 20/60 (range, 20/25–20/400) and was related to the distance between the macular hole and the foveal center.

The authors' study concluded that Nd:YAG laser injuries to the unprotected eye may potentially cause retinal injury with macular hole formation; macular pucker; abnormal development of blood vessels in the choroid; and preretinal, intraretinal, and subretinal hemorrhage. The authors' results suggested that as long as the foveal center is not involved in the initial injury, the potential for spontaneous visual recovery is excellent, despite poor initial visual acuity.

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APPENDIX D

Measurements Made for the Incident Investigation

Report of Measurements Made for the Incident Investigation

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The report details the results of measurements made for the Accident Investigation Team, August 11, 12 and 16, 2004. The measurements were conducted on two lasers in Room 106, Bldg. 41, TA-46. The two lasers are defined as the LIBS laser, a Spectra Physics Indi Nd:YAG laser, and the ablation laser, a Laser Photonics Nd:YAG laser.

Summary: The room interlock and warning light system were tested. The LIBS laser was tested and characterized for pulse energy, intensity and beam divergence in the three different Q-switch settings (internal, long pulse, and external). A pulse energy measurement was made on the ablation laser. The optical paths were documented, including optics damage and stray light/reflections. Sensitivity tests were performed on the IR detection cards used in the room.

The report is organized as follows:

I. Room warning light and interlock system
II. Room conditions and optical paths
III. The LIBS laser
IV. The ablation Laser
V. Sensitivity of IR detection cards

I. Room warning light and interlock system

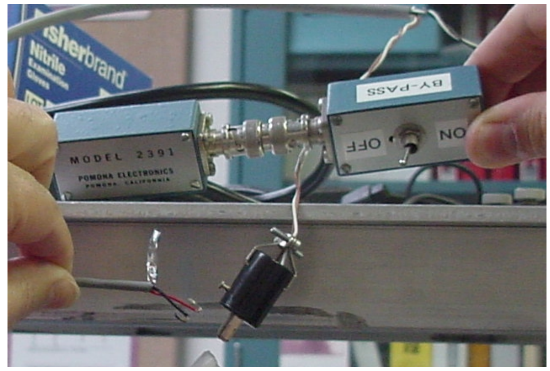


Figure 1: The interlock bypass switch showing box that was floating at 12V.

The room warning light system was functioning properly, indicating a green/yellow/red condition as set. The indicator lights functioned properly for all settings on the external warning lights to the hall and adjacent room. The room warning light system operates independently of the laser interlock system in this room. The room interlock system was functioning properly, interrupting LIBS laser operation when either of the two room doors was opened or a single panic button was pressed. The interlock system was only connected to the LIBS laser. The interlock system was wired with a bypass switch such that when "off," the interlock system operated normally, and when "on," the interlock system was defeated and LIBS laser operation could not be interrupted. A 12 V potential relative to building ground was observed on the case screws, switch, and case ground of the box containing the bypass switch. This caused a short to the table when in contact. This short typically caused an interruption of the interlock system. This box is shown in Figure 1.

II. Room conditions

A. Condition of the designed optical path

A schematic of the designed optical path and chamber is shown in Fig. 2. The definitions of the components are also shown. We first observed what looked like damage from the laser on the input and output windows of the target chamber, see Figs. 3 and 4. There was dust on the top chamber window but no damage, see Fig. 5. The turning mirror for the LIBS laser was clean and intact. The lens in front of the chamber had some dust but no damage.

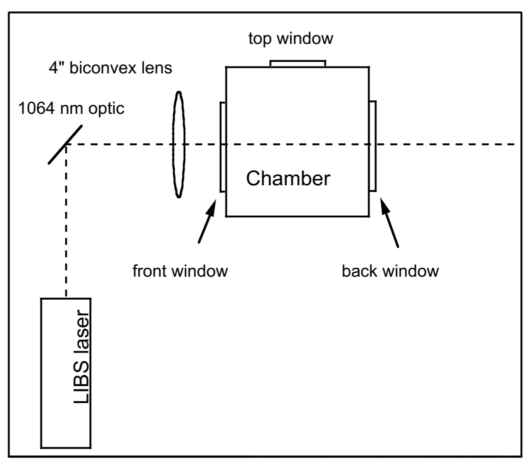


Figure 2: Schematic of the designed optical path and chamber.

The optical path of the laser conformed to the designed path, being turned first by what appeared to be a 1064 nm dichroic optic (from the efficiency with which it turned the laser). The laser then passed low through the lens and out the back side of the chamber.

B. Reflections and stray light

We surveyed the room for laser scatter (diffuse and specular) using several IR viewers. We found significant specular reflection off of the lens in front of the chamber. The LIBS laser was hitting this lens very low, and the lens was tilted off of the normal incidence angle, causing the scatter to angle upwards towards the front wall and the transmitted beam to angle upwards towards the back wall. Scatter on the reflected and transmitted side is documented in Fig. 6. The back scatter energy was ~ 3 mJ, with a 25 mJ pulse energy, which is approximately a 12% reflection.

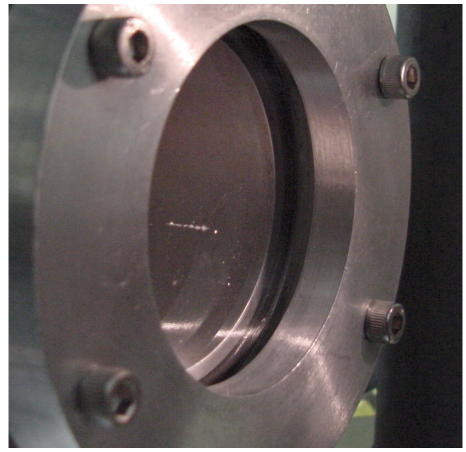


Figure 3: Back chamber window showing damage.

III. The LIBS laser

The three modes of emission by the LIBS laser are shown in Fig. 7. The data were taken on a Tektronics 740 oscilloscope, recording the voltage from a Si photodiode. The data are plotted as the voltage as a function of time. The signals from the three traces are not directly comparable in this graph. The bottom trace is the voltage recorded from a pulse obtained with the Q-switch trigger selection set to Q-switch (the mode in which the Q-switch is internally triggered). The second trace is the voltage from a free-running pulse obtained with the Q-switch trigger selection set to long pulse (the mode in which the Q-switch is held open for the duration of the flashlamp pulse). Both traces are plotted against time on the bottom axis. The pulse width of the traces in this graph is broadened due to saturation of the photodiode. The quoted width of the Q-switched pulse is 5 to 8 ns. A more-careful measurement of the individual pulse width in long-pulse mode yielded a width of 440 ns (a lower limit, as the photodiode could still be broadening the measured pulse). The top trace is voltage obtained with the Q-switch trigger selection set to EXT, without an external Q-switch trigger pulse. The laser flashlamp trigger selection was set to EXT for all measurements, with a TTL trigger applied from a Stanford Research Systems (SRS) delay generator. The top trace is plotted as a function of

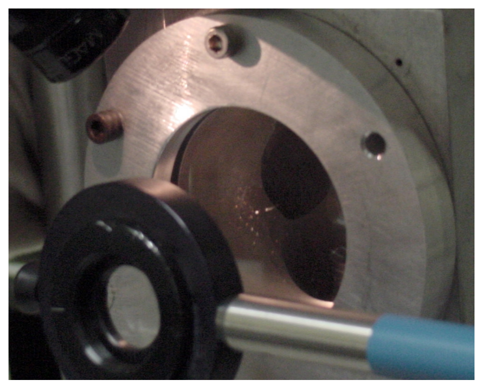


Figure 4: Front chamber window showing damage.

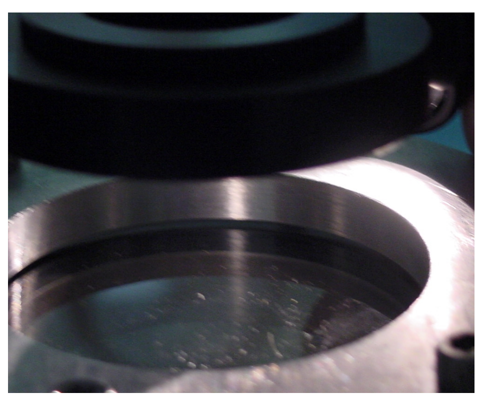


Figure 5: Top chamber window.

time on the top axis. Note the several-hundred-microsecond time scale typical of the flashlamp pulse in Nd:YAG lasers of this type.

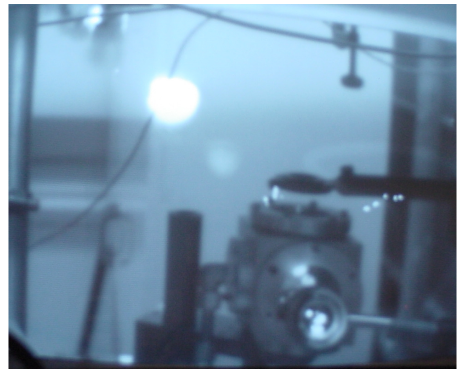


Figure 6: IR image of transmitted laser pulse image on back wall.

A. Pulse energy

1. Q-switch mode

With the laser flashlamp and Q-switch trigger selection set to EXT and a TTL trigger supplied to both from the SRS delay generator, the energy in the Q-switch pulse ranges from ~20 to 65 mJ at threshold lamp voltage to over 400 mJ at full flashlamp voltage. The beam diameter at the laser is 5 mm, as measured with the Tokin SHG-type IR card.

2. Long pulse mode

The total energy in this mode is comparable to the energy in Q-switch mode (~20% higher at the same flashlamp setting) but, as shown in Fig. 7, is distributed in a series of sub-microsecond pulses (laser free running). The beam diameter at the laser is 5 mm, as measured with the Tokin SHG-type IR card.

3. Simmer mode

With the laser flashlamp and Q-switch trigger selection set to EXT and a TTL trigger supplied only to the flashlamp trigger input from the SRS delay generator, the energy density in the simmer pulse ranges from 26 µJ/cm^2 at threshold lamp voltage to 56 µJ/cm^2 at full flashlamp voltage. Past the dichroic turning mirror, lens, and chamber, the energy in the simmered light pulse is down to 4 µJ at threshold and 8 µJ at full flashlamp voltage. The simmer pulse was strongly diverging from the laser housing and was only partially turned by the 1064 nm mirror. We looked for evidence of laser light leaking through the closed Q-switch in this mode and did not see evidence of it.

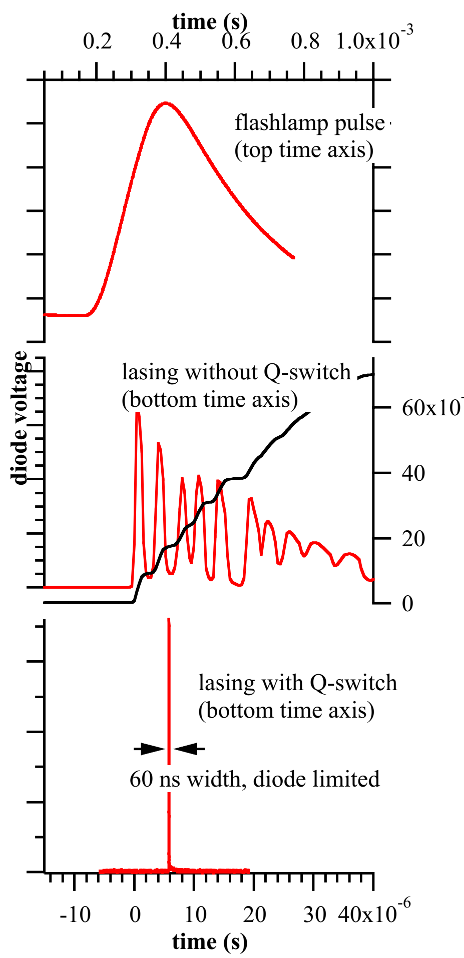


Figure 7: The temporal shapes of all conditions. The measured Q-switch pulse width is limited by the photodiode response time.

B. Far field beam divergence

1. Lasing pulses

With the laser in either Q-switch (EXT, trigger supplied) or long-pulse mode, the beam divergence in the far field, past the chamber, was the same within our measurement uncertainties. The beam radius was measured in the far field for both the Q-switched and long pulses by exposing photographic paper with the beam. The image radius measured in this way for both modes is shown in Fig. 8. The beam image radius in Fig. 8 is plotted as a function of the distance from the external surface of the back window on the chamber, with the image radius on the window surface plotted at 0. When plotted in this way, fitting the data to a line yields the divergence and focal point. If the slope, m, and intercept, b, are determined from $y = mx + b$, where y is the beam image radius and x the distance from the chamber window, then the divergence angle is given by $\theta = 2$ atan(x), and the focal point, x_o, by $x_o = -b/m$. The solid and dashed lines of Fig. 8 are the resulting fit to the data, and the parameters are shown in the figure as well. The beam divergence for a lasing pulse in the far field is determined to be $\theta = 4^o \pm 0.3^o$ and the focal point $x_o = -2.92$". The negative value for the focal point places the laser focus approximately 3 inches into the chamber, from the external surface of the back window, or near the front half of the chamber.

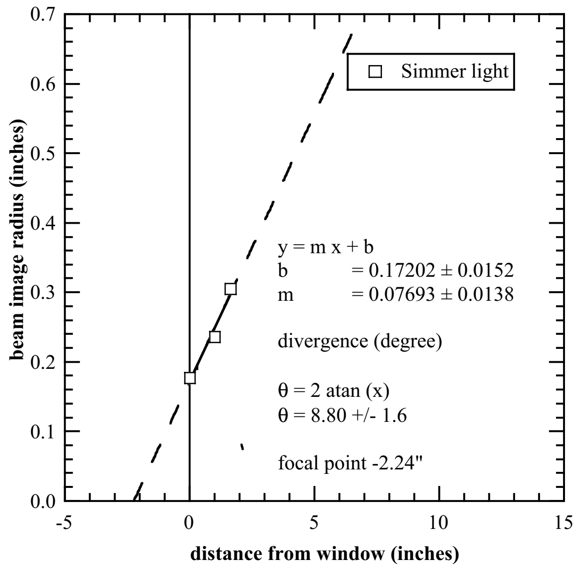


Figure 8: Far field divergence in the simmer pulse.

The energy was measured for both lasing modes immediately behind the chamber. The total energy measured at the back chamber window was essentially equal to the near-field energy for both modes, indicating little divergence until the far field, past the 4" lens.

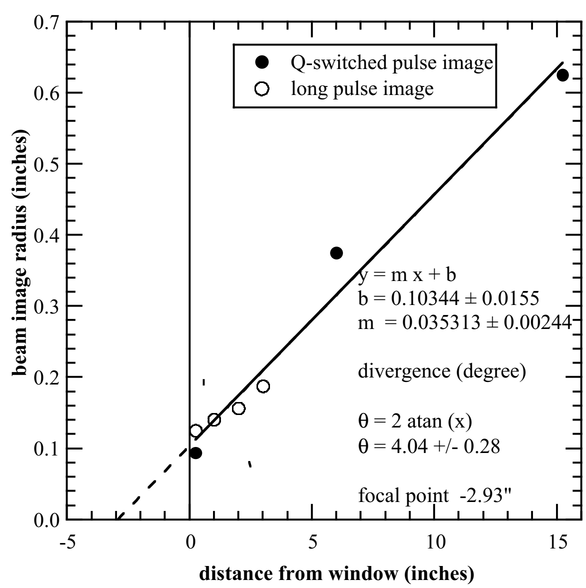


Figure 9: Far field divergence in the laser pulse.

2. Simmer pulse

With the laser in Q-switch (EXT, no trigger supplied), the far field divergence of the simmer pulse was measured. The beam radius was measured by projecting the image onto a white piece of paper.

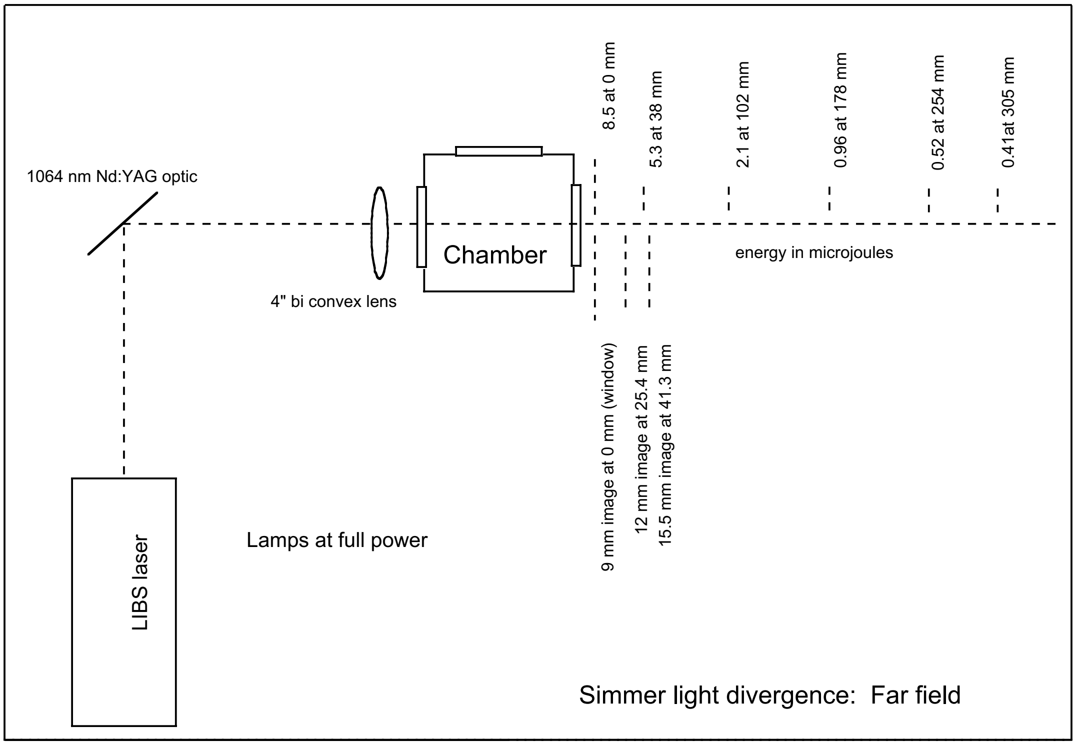


Figure 10: Position index of energy measurements made on the simmer pulse.

The image radius measured in this way is shown in Fig. 9. The beam image radius in Fig. 9 is plotted as a function of the distance from the external surface of the back window on the chamber, with the image radius on the window surface plotted at 0, as in Fig. 8. The solid and dashed lines of Fig. 9 are the resulting linear fit to the data, as done for Fig. 8, and the parameters are shown in the figure as well. The beam divergence for a lasing pulse in the far field is determined to be $\theta = 8.8^{o} \pm 1.6^{o}$ and the focal point $x_o = -2.2"$. The focal point places the simmer focus approximately 2 inches into the chamber, from the external surface of the back window, or near the center of the chamber.

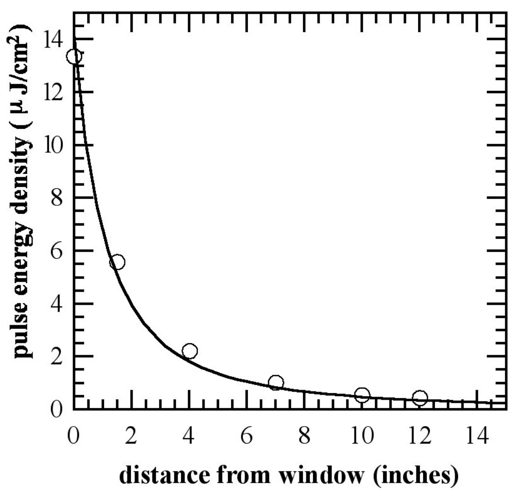


Figure 11: Energy density as a function of distance from the back chamber window for the simmer pulse.

The energy was also measured for the simmer pulse as a function of position behind the chamber. The simmer pulse energy was measured with the flashlamp trigger selection set to EXT and driven by the SRS delay generator and the Q-switch trigger selection set to EXT with no trigger pulse applied. The flashlamp voltage for the energy measurements was set to full. A position index of the energy measurements made for the simmer pulse is shown in Fig. 10. These data were then divided by the aperture area of the energy meter used, or 0.95 cm^2, to yield the energy density as a function of position past the back chamber window. The data are plotted in Fig. 11 as a function of distance behind the back chamber window, with the external window surface at $x = 0$, as before. The solid line is a calculation of the energy density, E, as a function of the same distance from the back chamber window, r, using $E = E_o\,(r_o/r)$, where E_o is the energy density at the external surface of the window, with image radius r_o.

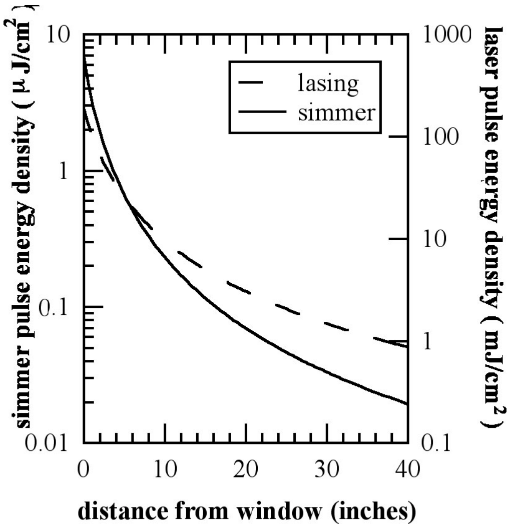


Figure 12: Calculated energy density as a function of distance from the back chamber window for both simmer and laser pulses.

The calculated energy density as a function of position is shown in Fig. 12 for both lasing and simmer modes. The distance scale is referenced to $x = 0$ at the external surface of the back chamber window, as before. The calculation is for threshold emission, with the flashlamp voltage set at the minimum threshold to produce a laser pulse (as indicated on the laser with a pencil mark).

The divergence of the simmer and laser beams is shown schematically in Fig. 13. The height of the center of the beams was measured to be 48" at the back chamber window and 59" at the back wall, which is 83" horizontally from the back chamber window.

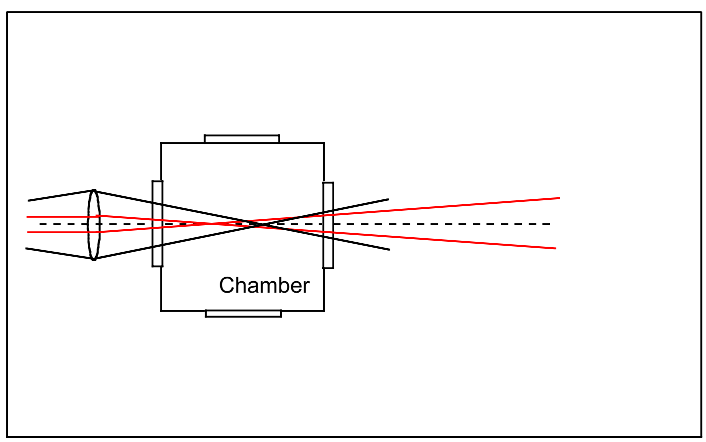


Figure 13: Schematic of the beam divergence in the far field. The red lines depict the laser beam path and the black lines the simmer light.

C. Simmer mode trigger test

1. Continuous lasing through “leaking” cavity

With the laser flashlamp and Q-switch trigger selection set to EXT and a TTL trigger supplied only to the flashlamp trigger input from the SRS delay generator, the laser was tested to determine whether some laser light could be “leaking” from the cavity, even in the absence of a Q-switch trigger pulse. These measurements were made at both the threshold flashlamp voltage setting and full voltage. A long-pulse-mode laser pulse was first obtained by setting the Q-switch trigger selection to “long pulse.” A peak voltage of approximately

7 V was measured while using a long pass filter, RG 850, as well as the 1064 nm dichroic turning mirror in order to discriminate against the simmer light and optimize the sensitivity to measuring a laser pulse. The Q-switch trigger selection was then set to EXT, and measurements of the baseline were made. No laser pulse was observed in this manner over the entire time period of the laser duty cycle and particularly not during the duration of a flashlamp pulse. Results of the two experiments are shown in Fig. 14. Using an integrated intensity for the long-pulse-mode laser pulse of 40 mJ and noting that the leading pulse in the long-pulse train is approximately 10% of the energy leads to a value of 4 mJ for the energy of a single pulse in long-pulse mode or a conversion factor of 6 x 10^{-4} J/V. The measured baseline in Fig. 14, obtained under the same conditions as the long-pulse data, gives a baseline sensitivity of 10 μV or an upper limit to any laser pulse present of 5 nJ.

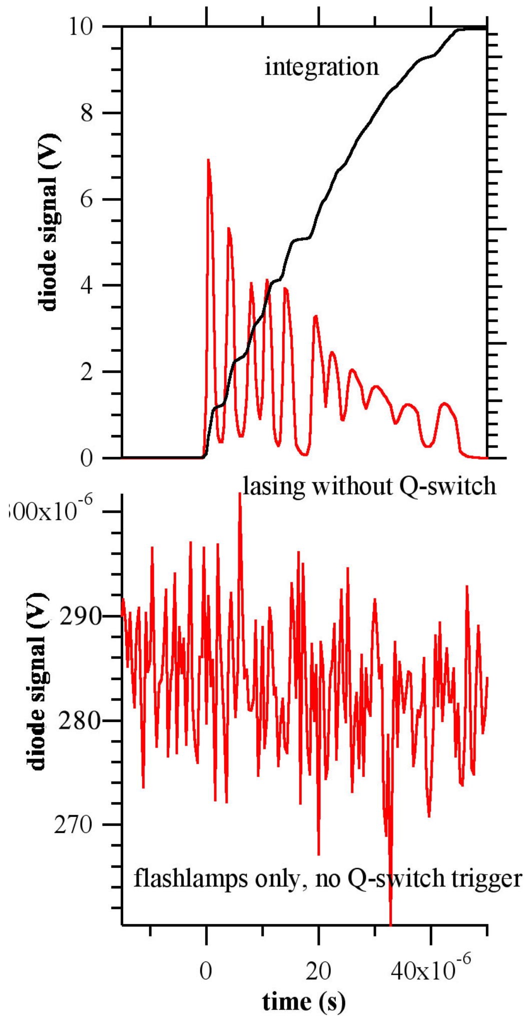


Figure 14: The long pulse signal on a Si photodiode is shown in red. The signal is plotted in volts. The black line is the integration of the signal. The zero amplitude measurement made in search of a lasing condition is shown in the bottom panel.

2. Spurious trigger of the Q-switch

Additionally, in this mode we tested for spurious laser pulses caused by a transient Q-switch pulse during a lightning storm and caused by voltages on the table. We were unable to observe such a pulse.

IV. Laser Photonics Laser

This laser emitted laser pulses only sporadically.
At the laser head, we were able to directly measure the pulse power of only a few pulses and found them to be approximately 300 μJ per pulse, which was just above the limit of sensitivity for our detector. We saw only 3 pulses in approximately 10 minutes. The laser is apparently just at the threshold for lasing, and due to the sporadic nature of its emission, we were unable to characterize its divergence characteristics. We expect the pulses to be approximately 10 ns long.

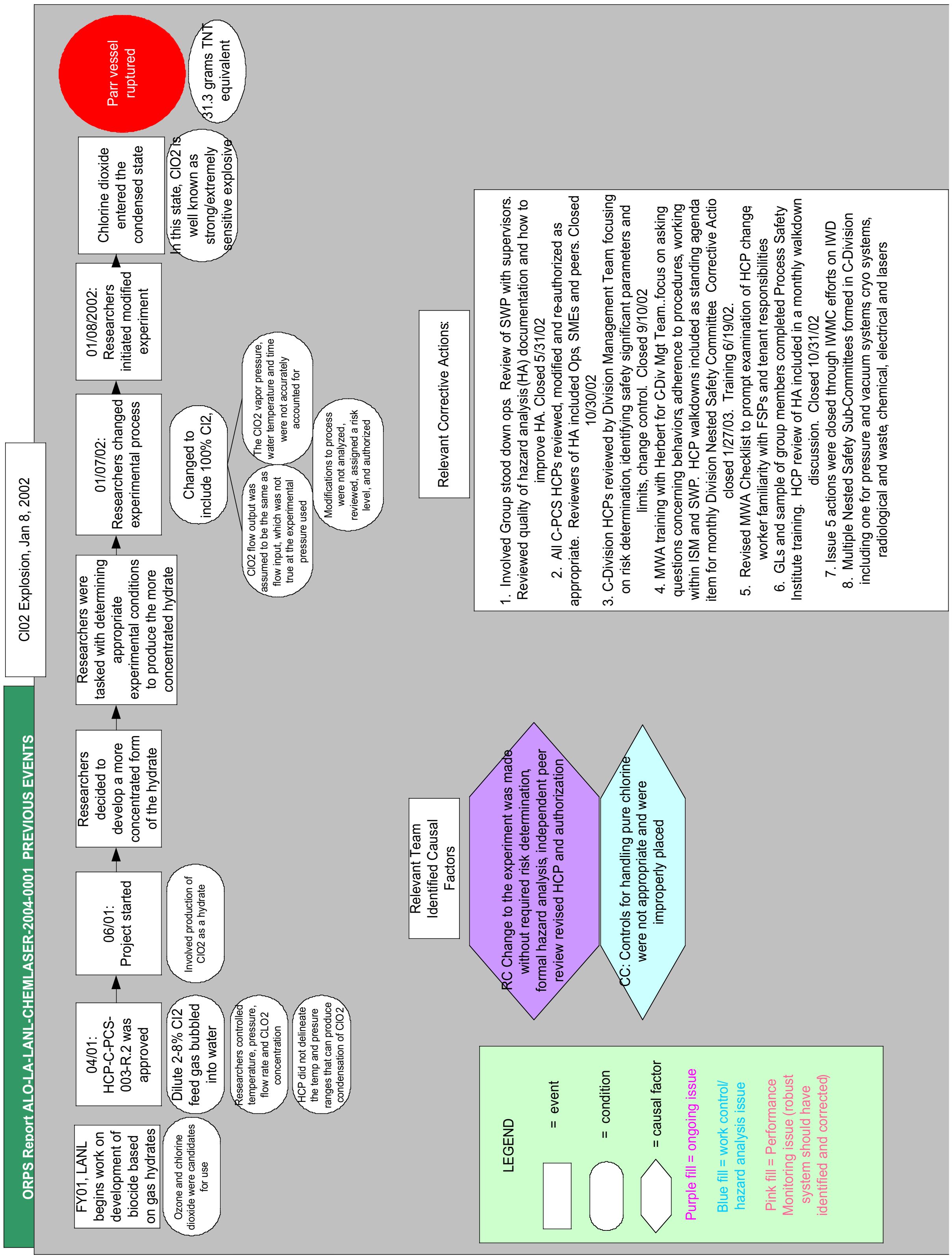
V. IR card sensitivity

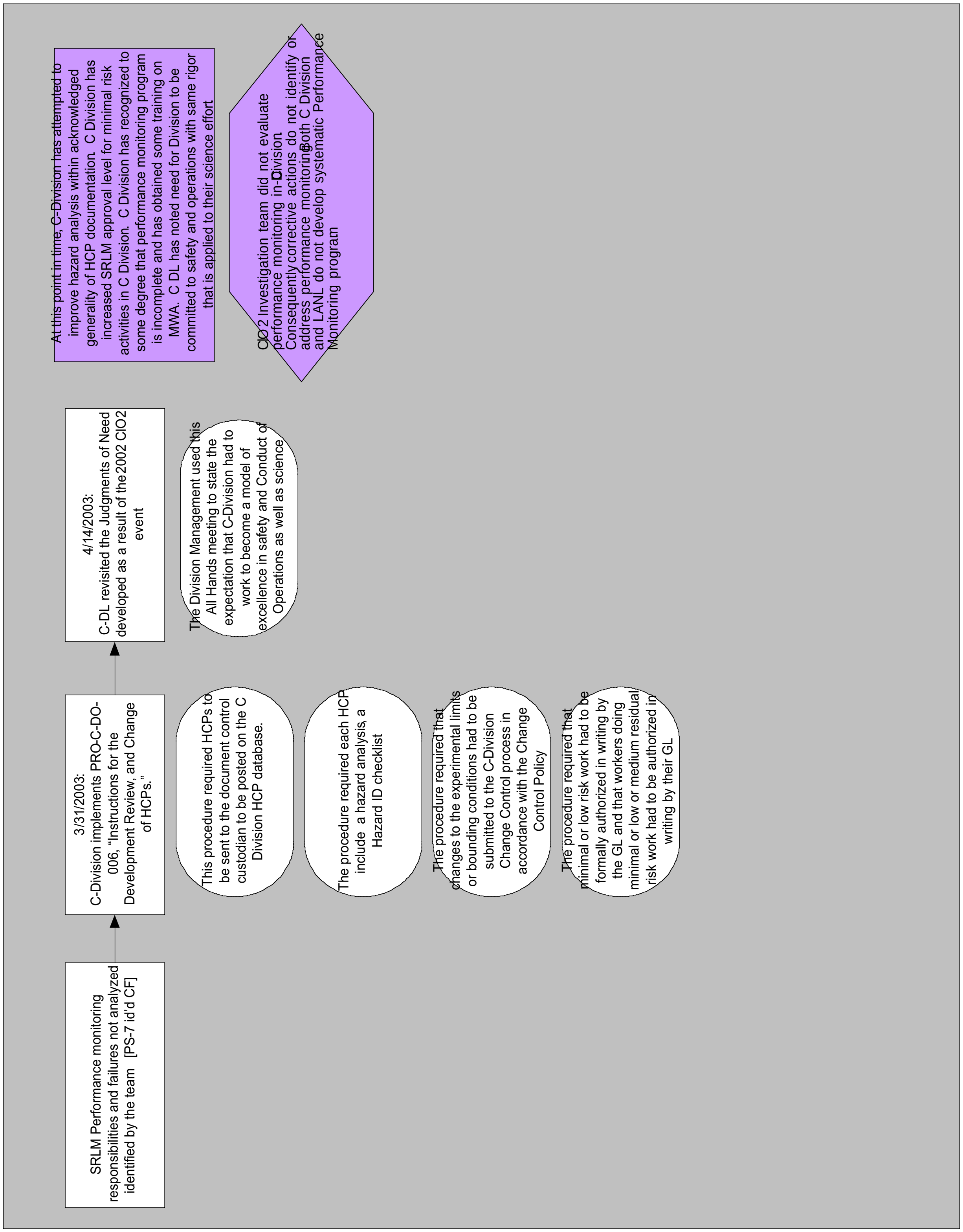
We looked with both Q-switched and long-pulsed mode with flashlamps set at the same place (giving 20 mJ Q-switched and 25 mJ long pulse). We tested the viewability of the cards at 36" from the chamber (at the cabinet wall) and at 86" from the chamber (the bit of the transmitted beam that is not incident on the chamber and goes to the far wall). We found the following:

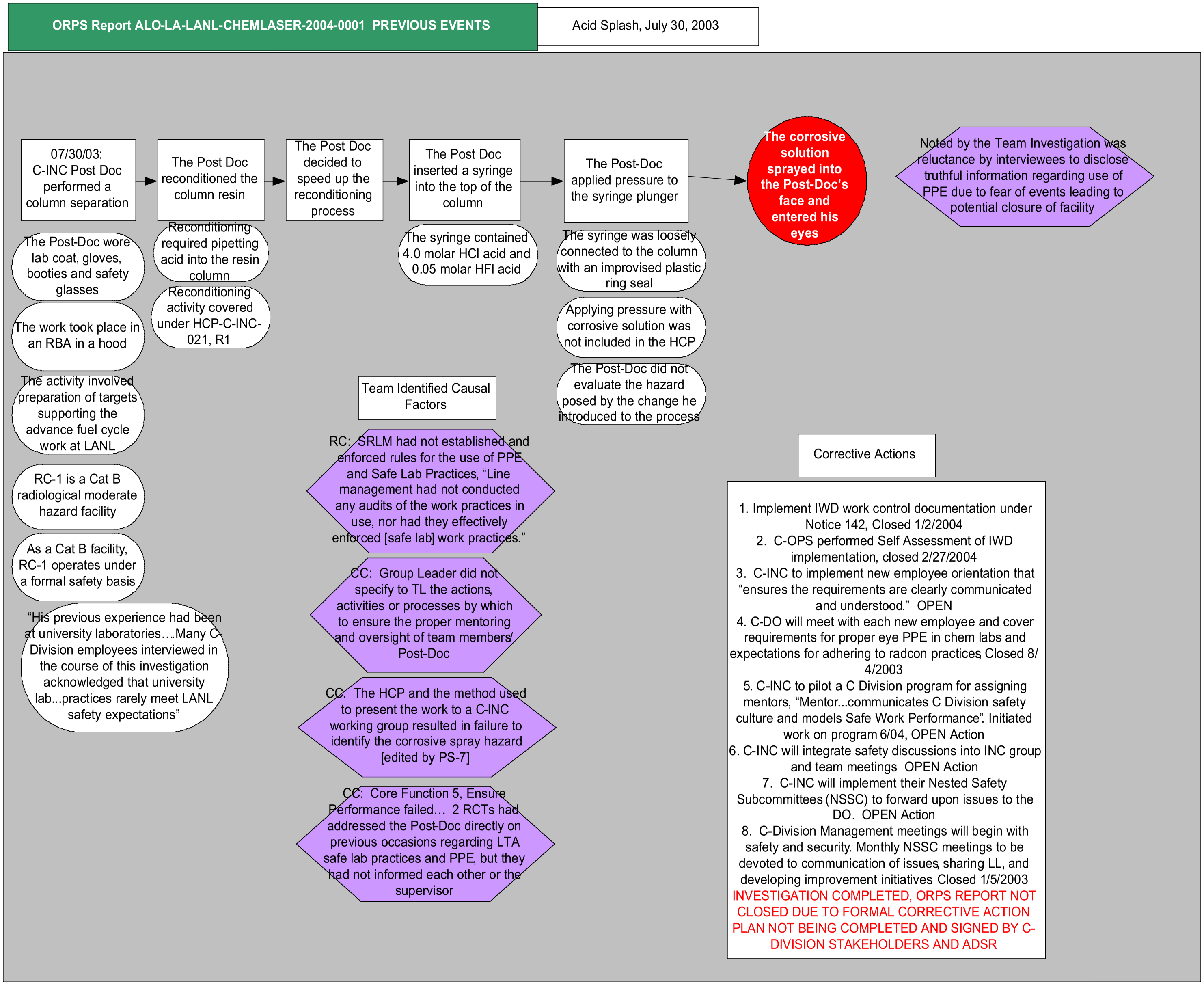
IR Card	Viewable at 36"	Viewable at 86"
Newport F-IRC1 pristine condition	Yes	Yes
Newport F-IRC1 from LIBS table (badly damaged)	Yes	Yes
ThorLabs VC-VIS/IR card	Yes	No
Tokin and Pocket-IR SHG type cards	No	No

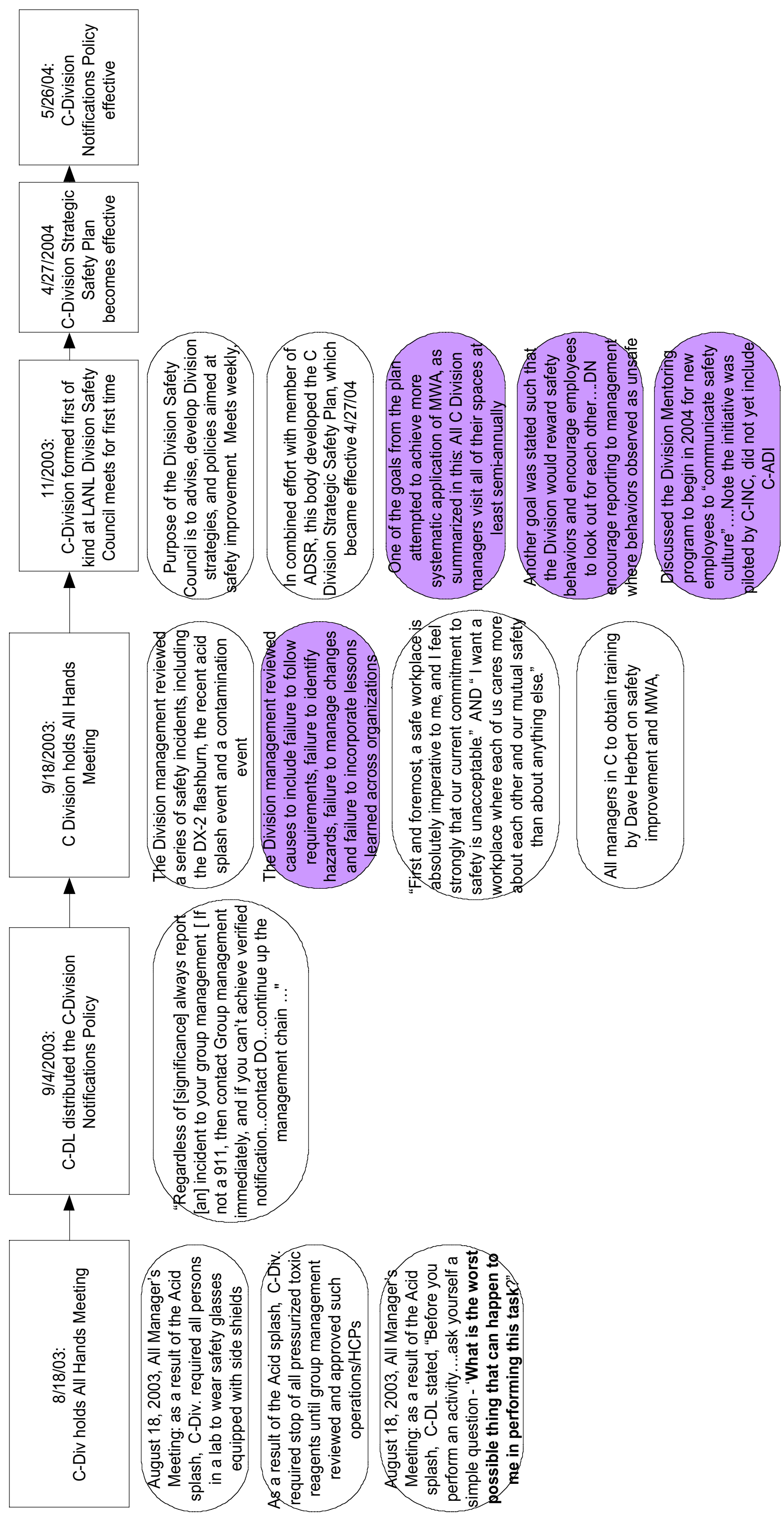
APPENDIX E

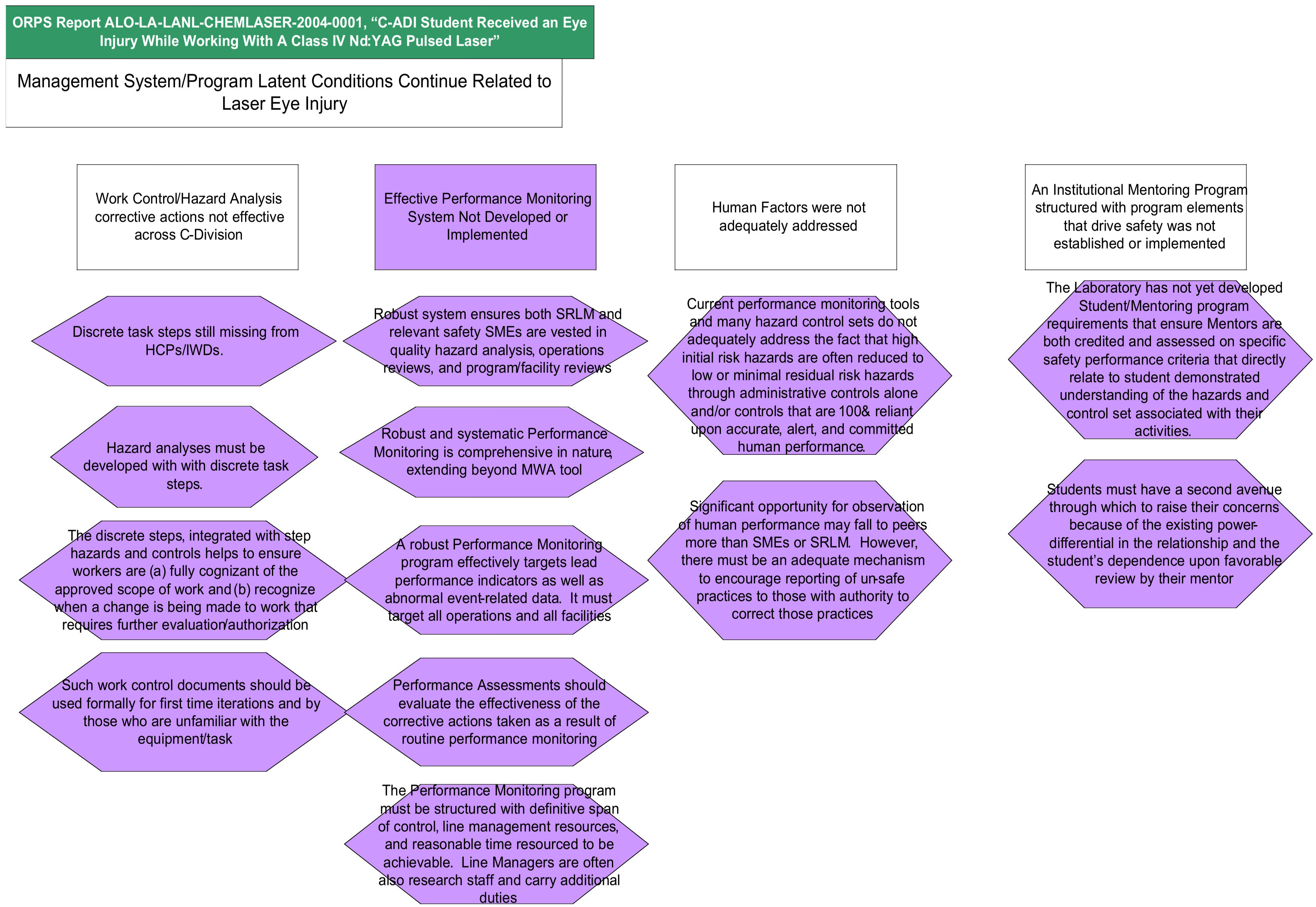
Event and Causal Factor Chart

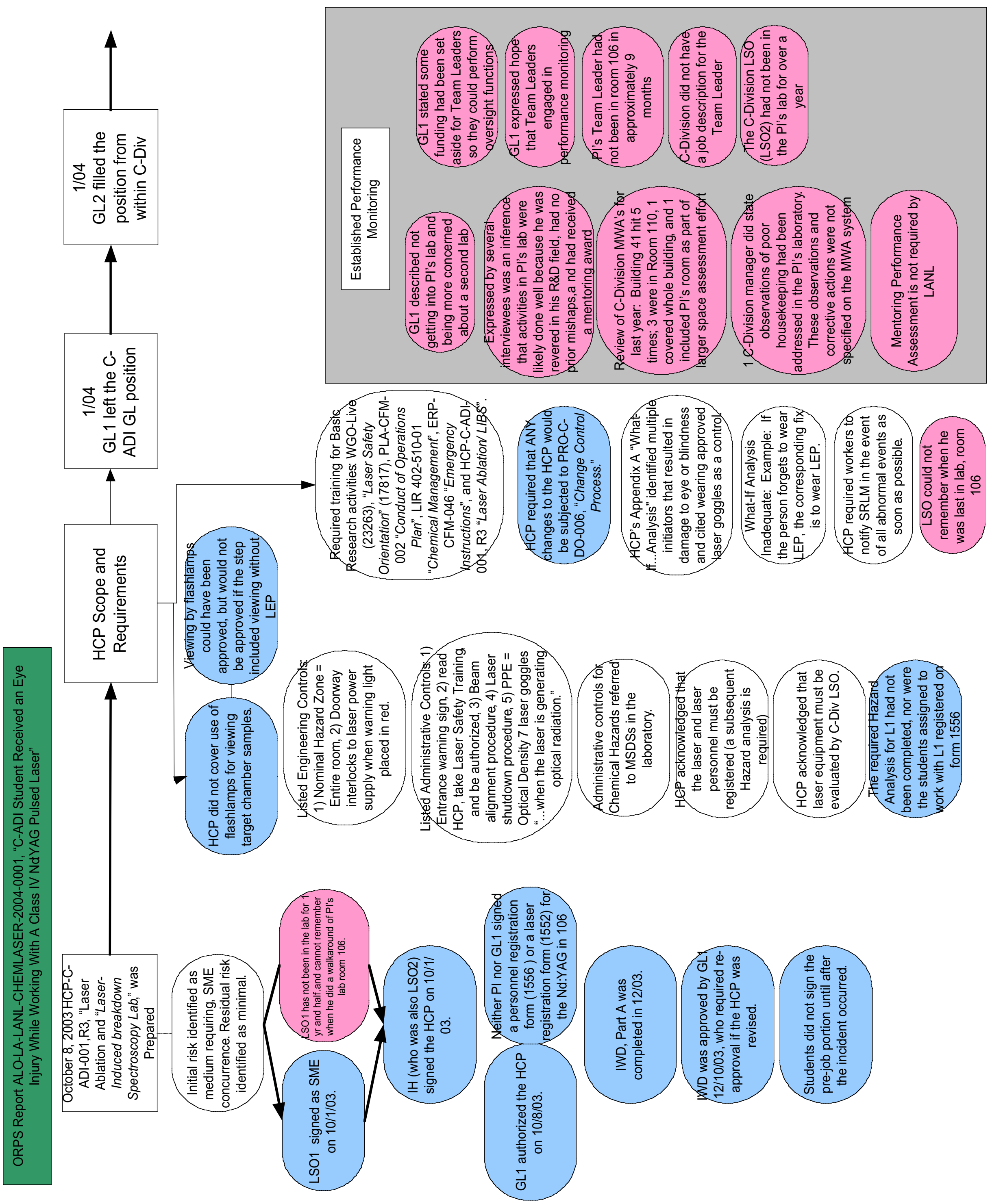

ORPS Report ALO-LA-LANL-CHEMLASER-2004-0001 PREVIOUS EVENTS
Cl02 Explosion, Jan 8, 2002
FY01, LANL begins work on development of biocide based on gas hydrates
Ozone and chlorine dioxide were candidates for use
04/01: HCP-C-PCS-003-R.2 was approved
Dilute 2-8% Cl2 feed gas bubbled into water
Researchers controlled temperature, pressure, flow rate and CLO2 concentration
HCP did not delineate the temp and presure ranges that can produce condensation of ClO2
06/01: Project started
Involved production of ClO2 as a hydrate
Researchers decided to develop a more concentrated form of the hydrate
Researchers were tasked with determining appropriate experimental conditions to produce the more concentrated hydrate
01/07/02: Researchers changed experimental process
Changed to include 100% Cl2,
ClO2 flow output was assumed to be the same as flow input, which was not true at the experimental pressure used
The ClO2 vapor pressure, water temperature and time were not accurately accounted for
Modifications to process were not analyzed, reviewed, assigned a risk level, and authorized
01/08/2002: Researchers initiated modified experiment
Chlorine dioxide entered the condensed state
In this state, ClO2 is well known as strong/extremely sensitive explosive
Parr vessel ruptured
31.3 grams TNT equivalent
LEGEND
= event
= condition
= causal factor
Purple fill = ongoing issue
Blue fill = work control/ hazard analysis issue
Pink fill = Performance Monitoring issue (robust system should have identified and corrected)
Relevant Team Identified Causal Factors
RC Change to the experiment was made without required risk determination, formal hazard analysis, independent peer review revised HCP and authorization
CC: Controls for handling pure chlorine were not appropriate and were improperly placed
Relevant Corrective Actions:
1. Involved Group stood down ops. Review of SWP with supervisors. Reviewed quality of hazard analysis (HA) documentation and how to improve HA. Closed 5/31/02
2. All C-PCS HCPs reviewed, modified and re-authorized as appropriate. Reviewers of HA included Ops, SMEs and peers. Closed 10/30/02
3. C-Division HCPs reviewed by Division Management Team focusing on risk determination, identifying safety significant parameters and limits, change control. Closed 9/10/02
4. MWA training with Herbert for C-Div Mgt Team..focus on asking questions concerning behaviors, adherence to procedures, working within ISM and SWP. HCP walkdowns included as standing agenda item for monthly Division Nested Safety Committee. Corrective Actio closed 1/27/03. Training 6/19/02.
5. Revised MWA Checklist to prompt examination of HCP change worker familiarity with FSPs and tenant responsibilities
6. GLs and sample of group members completed Process Safety Institute training. HCP review of HA included in a monthly walkdown discussion. Closed 10/31/02
7. Issue 5 actions were closed through IWMC efforts on IWD
8. Multiple Nested Safety Sub-Committees formed in C-Division including one for pressure and vacuum systems, cryo systems, radiological and waste, chemical, electrical and lasers

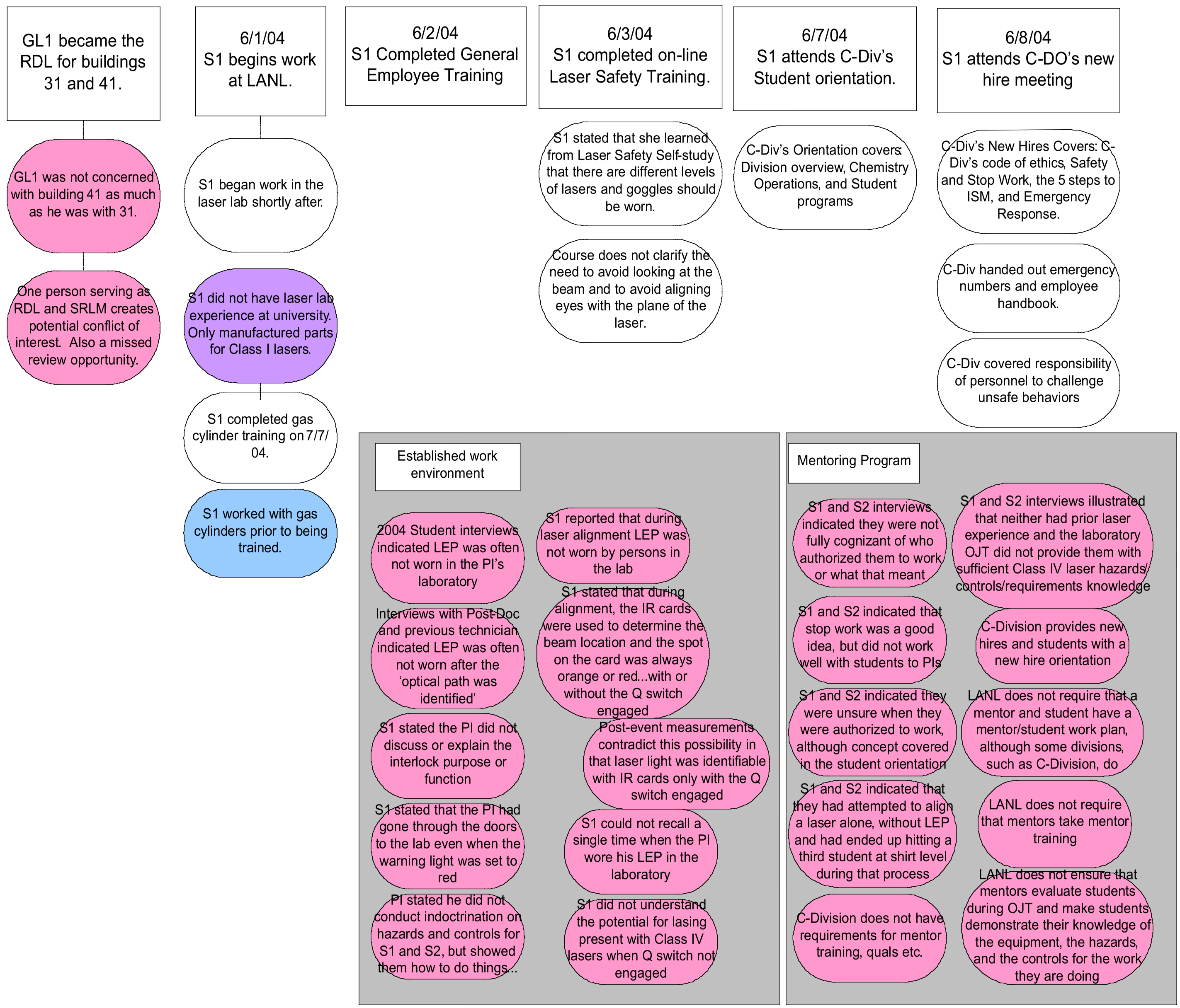

SRLM Performance monitoring responsibilities and failures not analyzed identified by the team [PS-7 id'd CF]
3/31/2003: C-Division implements PRO-C-DO-006, "Instructions for the Development Review, and Change of HCPs."
This procedure required HCPs to be sent to the document control custodian to be posted on the C Division HCP database.
The procedure required each HCP include a hazard analysis, a Hazard ID checklist
The procedure required that changes to the experimental limits or bounding conditions had to be submitted to the C-Division Change Control process in accordance with the Change Control Policy
The procedure required that minimal or low risk work had to be formally authorized in writing by the GL and that workers doing minimal or low or medium residual risk work had to be authorized in writing by their GL
4/14/2003: C-DL revisited the Judgments of Need developed as a result of the2002 CIO2 event
The Division Management used this All Hands meeting to state the expectation that C-Division had to work to become a model of excellence in safety and Conduct of Operations as well as science
At this point in time, C-Division has attempted to improve hazard analysis within acknowledged generality of HCP documentation. C Division has increased SRLM approval level for minimal risk activities in C Division. C Division has recognized to some degree that performance monitoring program is incomplete and has obtained some training on MWA. C DL has noted need for Division to be committed to safety and operations with same rigor that is applied to their science effort
CIO2 Investigation team did not evaluate performance monitoring in-Division Consequently corrective actions do not identify or address performance monitoring. Both C Division and LANL do not develop systematic Performance Monitoring program

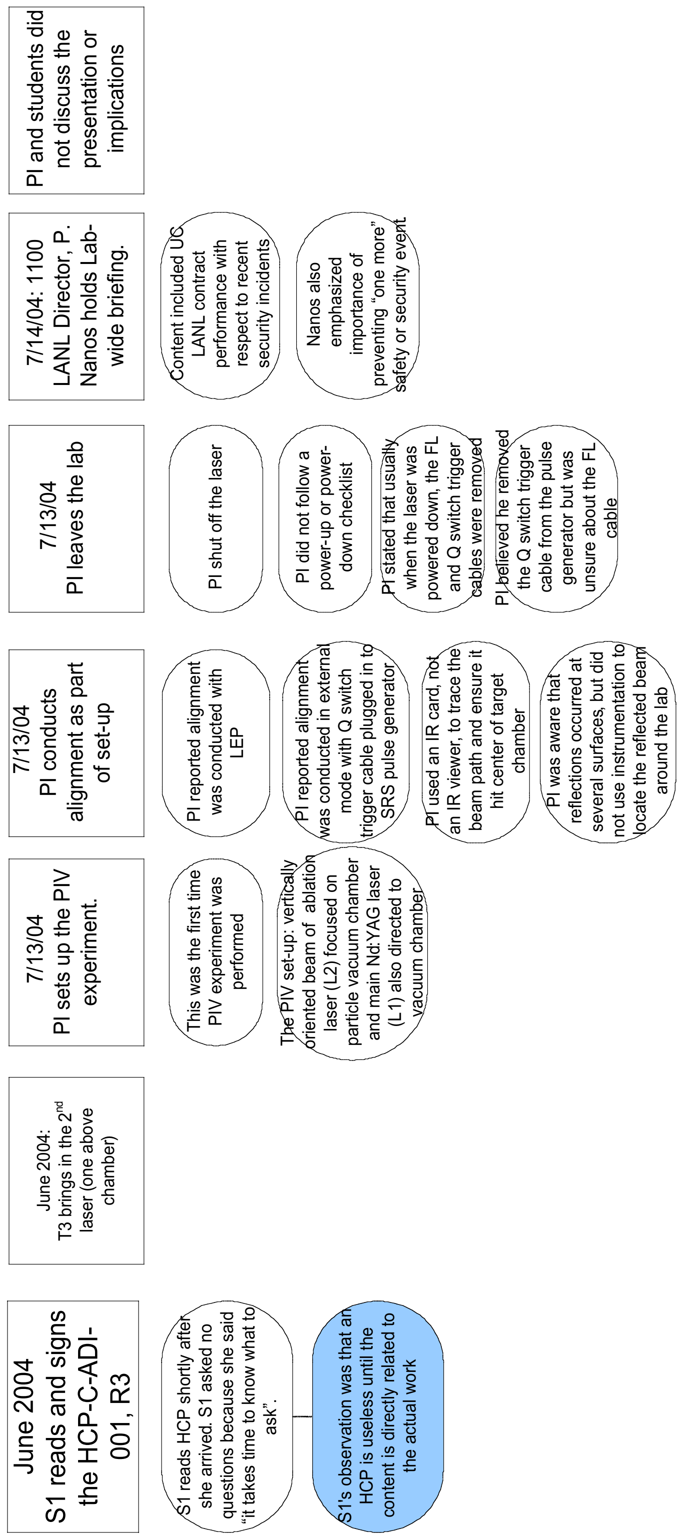

ORPS Report ALO-LA-LANL-CHEMLASER-2004-0001 PREVIOUS EVENTS
Acid Splash, July 30, 2003
07/30/03: C-INC Post Doc performed a column separation
The Post Doc reconditioned the column resin
The Post Doc decided to speed up the reconditioning process
The Post Doc inserted a syringe into the top of the column
The Post-Doc applied pressure to the syringe plunger
The corrosive solution sprayed into the Post-Doc's face and entered his eyes
Noted by the Team Investigation was reluctance by interviewees to disclose truthful information regarding use of PPE due to fear of events leading to potential closure of facility
The Post-Doc wore lab coat, gloves, booties and safety glasses
The work took place in an RBA in a hood
The activity involved preparation of targets supporting the advance fuel cycle work at LANL
RC-1 is a Cat B radiological moderate hazard facility
As a Cat B facility, RC-1 operates under a formal safety basis
"His previous experience had been at university laboratories….Many C-Division employees interviewed in the course of this investigation acknowledged that university lab...practices rarely meet LANL safety expectations"
Reconditioning required pipetting acid into the resin column
Reconditioning activity covered under HCP-C-INC-021, R1
The syringe contained 4.0 molar HCl acid and 0.05 molar HFl acid
The syringe was loosely connected to the column with an improvised plastic ring seal
Applying pressure with corrosive solution was not included in the HCP
The Post-Doc did not evaluate the hazard posed by the change he introduced to the process
Team Identified Causal Factors
RC: SRLM had not established and enforced rules for the use of PPE and Safe Lab Practices, "Line management had not conducted any audits of the work practices in use, nor had they effectively enforced [safe lab] work practices."
CC: Group Leader did not specify to TL the actions, activities or processes by which to ensure the proper mentoring and oversight of team members/ Post-Doc
CC: The HCP and the method used to present the work to a C-INC working group resulted in failure to identify the corrosive spray hazard [edited by PS-7]
CC: Core Function 5, Ensure Performance failed… 2 RCTs had addressed the Post-Doc directly on previous occasions regarding LTA safe lab practices and PPE, but they had not informed each other or the supervisor
Corrective Actions
1. Implement IWD work control documentation under Notice 142, Closed 1/2/2004
2. C-OPS performed Self Assessment of IWD implementation, closed 2/27/2004
3. C-INC to implement new employee orientation that "ensures the requirements are clearly communicated and understood." OPEN
4. C-DO will meet with each new employee and cover requirements for proper eye PPE in chem labs and expectations for adhering to radcon practices Closed 8/4/2003
5. C-INC to pilot a C Division program for assigning mentors, "Mentor...communicates C Division safety culture and models Safe Work Performance". Initiated work on program 6/04, OPEN Action
6. C-INC will integrate safety discussions into INC group and team meetings OPEN Action
7. C-INC will implement their Nested Safety Subcommittees (NSSC) to forward upon issues to the DO. OPEN Action
8. C-Division Management meetings will begin with safety and security. Monthly NSSC meetings to be devoted to communication of issues, sharing LL, and developing improvement initiatives Closed 1/5/2003
INVESTIGATION COMPLETED, ORPS REPORT NOT CLOSED DUE TO FORMAL CORRECTIVE ACTION PLAN NOT BEING COMPLETED AND SIGNED BY C-DIVISION STAKEHOLDERS AND ADSR

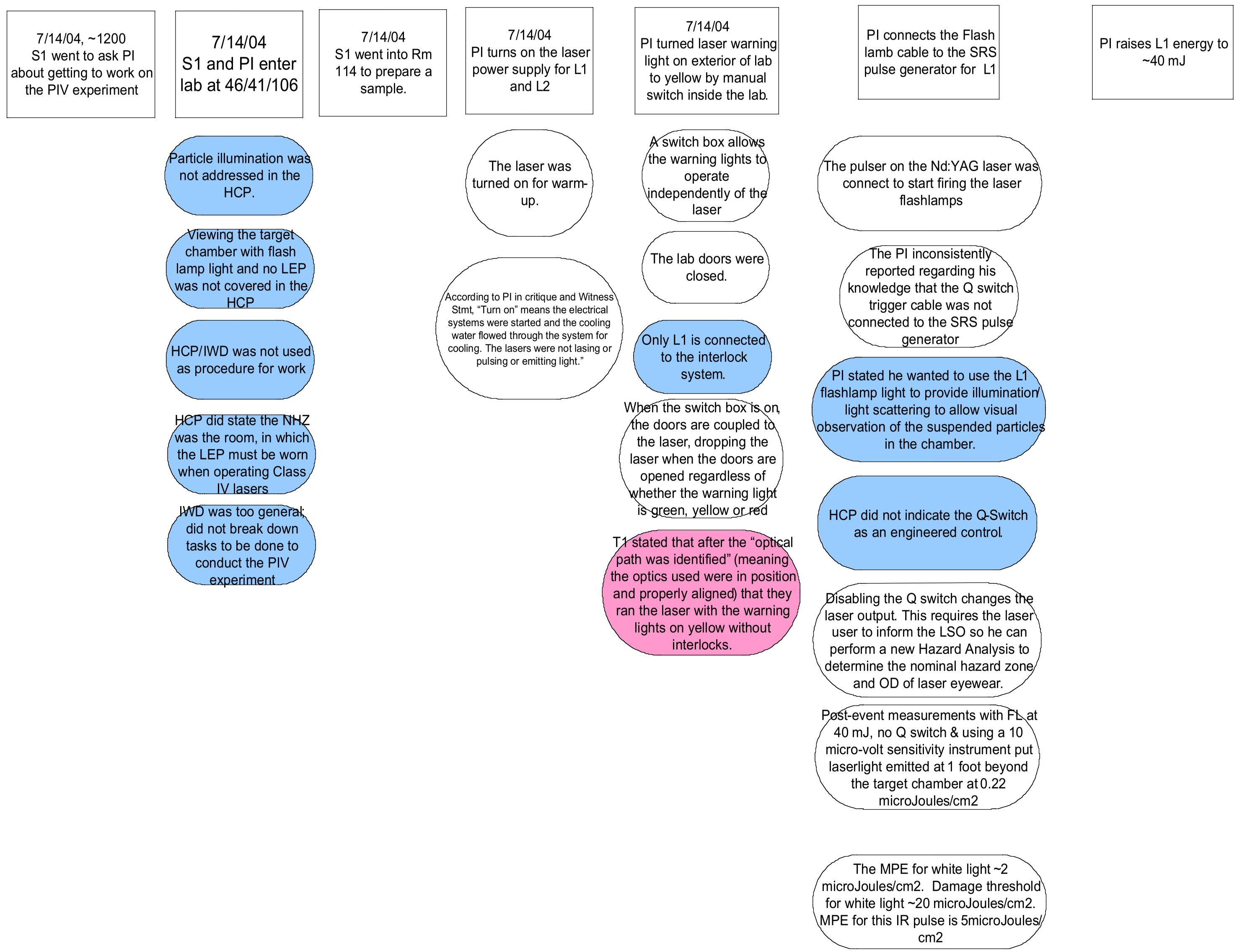

8/18/03:
C-Div holds All Hands Meeting
August 18, 2003, All Manager's Meeting: as a result of the Acid splash, C-Div. required all persons in a lab to wear safety glasses equipped with side shields
As a result of the Acid splash, C-Div. required stop of all pressurized toxic reagents until group management reviewed and approved such operations/HCPs
August 18, 2003, All Manager's Meeting: as a result of the Acid splash, C-DL stated, "Before you perform an activity….ask yourself a simple question - '**What is the worst possible thing that can happen to me in performing this task**?"
9/4/2003:
C-DL distributed the C-Division Notifications Policy
"Regardless of [significance] always report [an] incident to your group management [If not a 911, then contact Group management immediately, and if you can't achieve verified notification...contact DO...continue up the management chain …"
9/18/2003:
C Division holds All Hands Meeting
The Division management reviewed a series of safety incidents, including the DX-2 flashburn, the recent acid splash event and a contamination event
The Division management reviewed causes to include failure to follow requirements, failure to identify hazards, failure to manage changes and failure to incorporate lessons learned across organizations
"First and foremost, a safe workplace is absolutely imperative to me, and I feel strongly that our current commitment to safety is unacceptable." AND " I want a workplace where each of us cares more about each other and our mutual safety than about anything else."
All managers in C to obtain training by Dave Herbert on safety improvement and MWA,
11/2003:
C-Division formed first of kind at LANL Division Safety Council meets for first time
Purpose of the Division Safety Council is to advise, develop Division strategies, and policies aimed at safety improvement. Meets weekly,
In combined effort with member of ADSR, this body developed the C Division Strategic Safety Plan, which became effective 4/27/04
One of the goals from the plan attempted to achieve more systematic application of MWA, as summarized in this: All C Division managers visit all of their spaces at least semi-annually
Another goal was stated such that the Division would reward safety behaviors and encourage employees to look out for each other….DN encourage reporting to management where behaviors observed as unsafe
Discussed the Division Mentoring program to begin in 2004 for new employees to "communicate safety culture"….Note the initiative was piloted by C-INC, did not yet include C-ADI
4/27/2004
C-Division Strategic Safety Plan becomes effective
5/26/04:
C-Division Notifications Policy effective

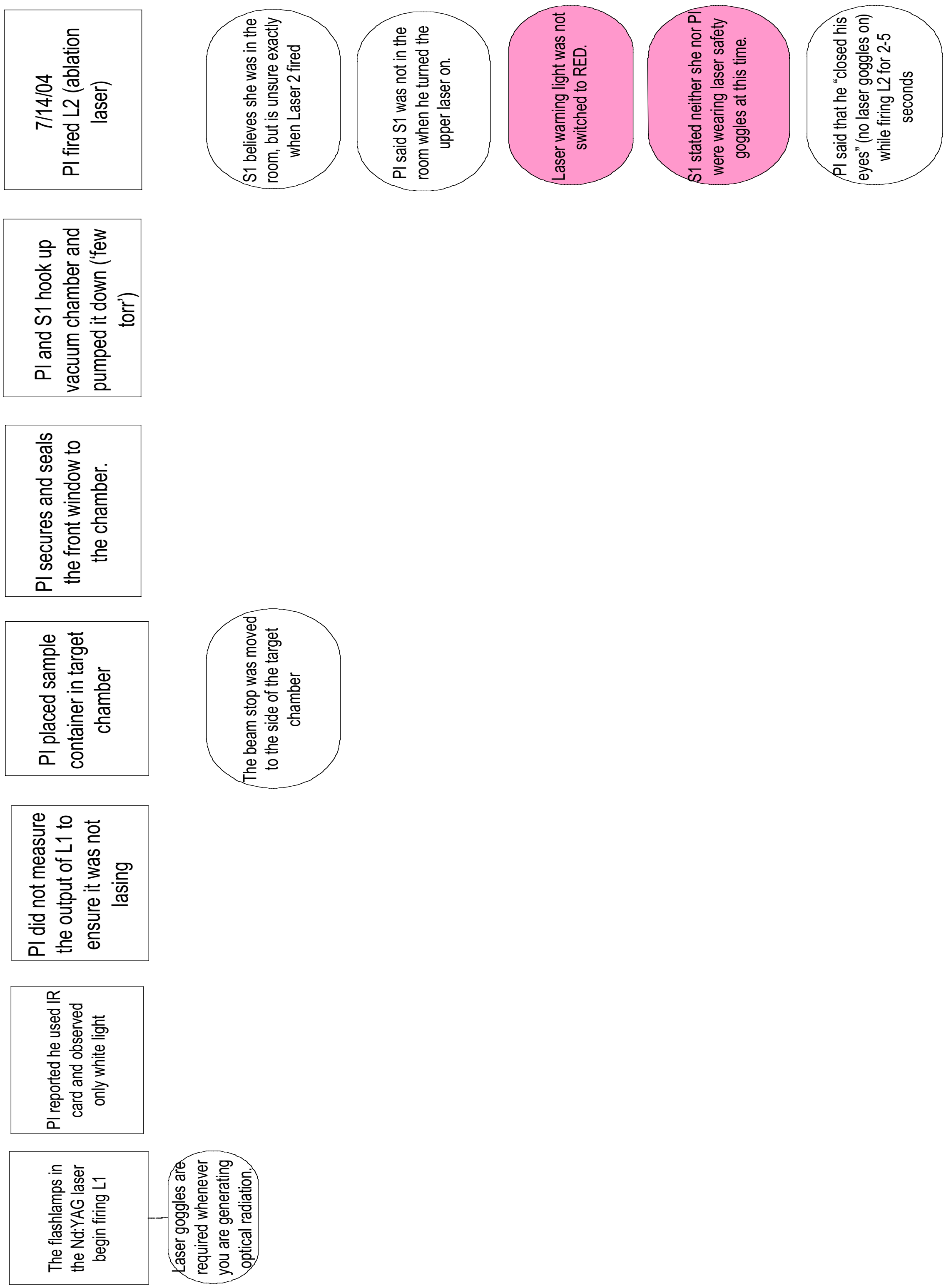

ORPS Report ALO-LA-LANL-CHEMLASER-2004-0001, "C-ADI Student Received an Eye Injury While Working With A Class IV Nd:YAG Pulsed Laser"
Management System/Program Latent Conditions Continue Related to Laser Eye Injury
Work Control/Hazard Analysis corrective actions not effective across C-Division
Discrete task steps still missing from HCPs/IWDs.
Hazard analyses must be developed with with discrete task steps.
The discrete steps, integrated with step hazards and controls helps to ensure workers are (a) fully cognizant of the approved scope of work and (b) recognize when a change is being made to work that requires further evaluation/authorization
Such work control documents should be used formally for first time iterations and by those who are unfamiliar with the equipment/task
Effective Performance Monitoring System Not Developed or Implemented
Robust system ensures both SRLM and relevant safety SMEs are vested in quality hazard analysis, operations reviews, and program/facility reviews
Robust and systematic Performance Monitoring is comprehensive in nature, extending beyond MWA tool
A robust Performance Monitoring program effectively targets lead performance indicators as well as abnormal event-related data. It must target all operations and all facilities
Performance Assessments should evaluate the effectiveness of the corrective actions taken as a result of routine performance monitoring
The Performance Monitoring program must be structured with definitive span of control, line management resources, and reasonable time resourced to be achievable. Line Managers are often also research staff and carry additional duties
Human Factors were not adequately addressed
Current performance monitoring tools and many hazard control sets do not adequately address the fact that high initial risk hazards are often reduced to low or minimal residual risk hazards through administrative controls alone and/or controls that are 100& reliant upon accurate, alert, and committed human performance.
Significant opportunity for observation of human performance may fall to peers more than SMEs or SRLM. However, there must be an adequate mechanism to encourage reporting of un-safe practices to those with authority to correct those practices
An Institutional Mentoring Program structured with program elements that drive safety was not established or implemented
The Laboratory has not yet developed Student/Mentoring program requirements that ensure Mentors are both credited and assessed on specific safety performance criteria that directly relate to student demonstrated understanding of the hazards and control set associated with their activities.
Students must have a second avenue through which to raise their concerns because of the existing power-differential in the relationship and the student's dependence upon favorable review by their mentor

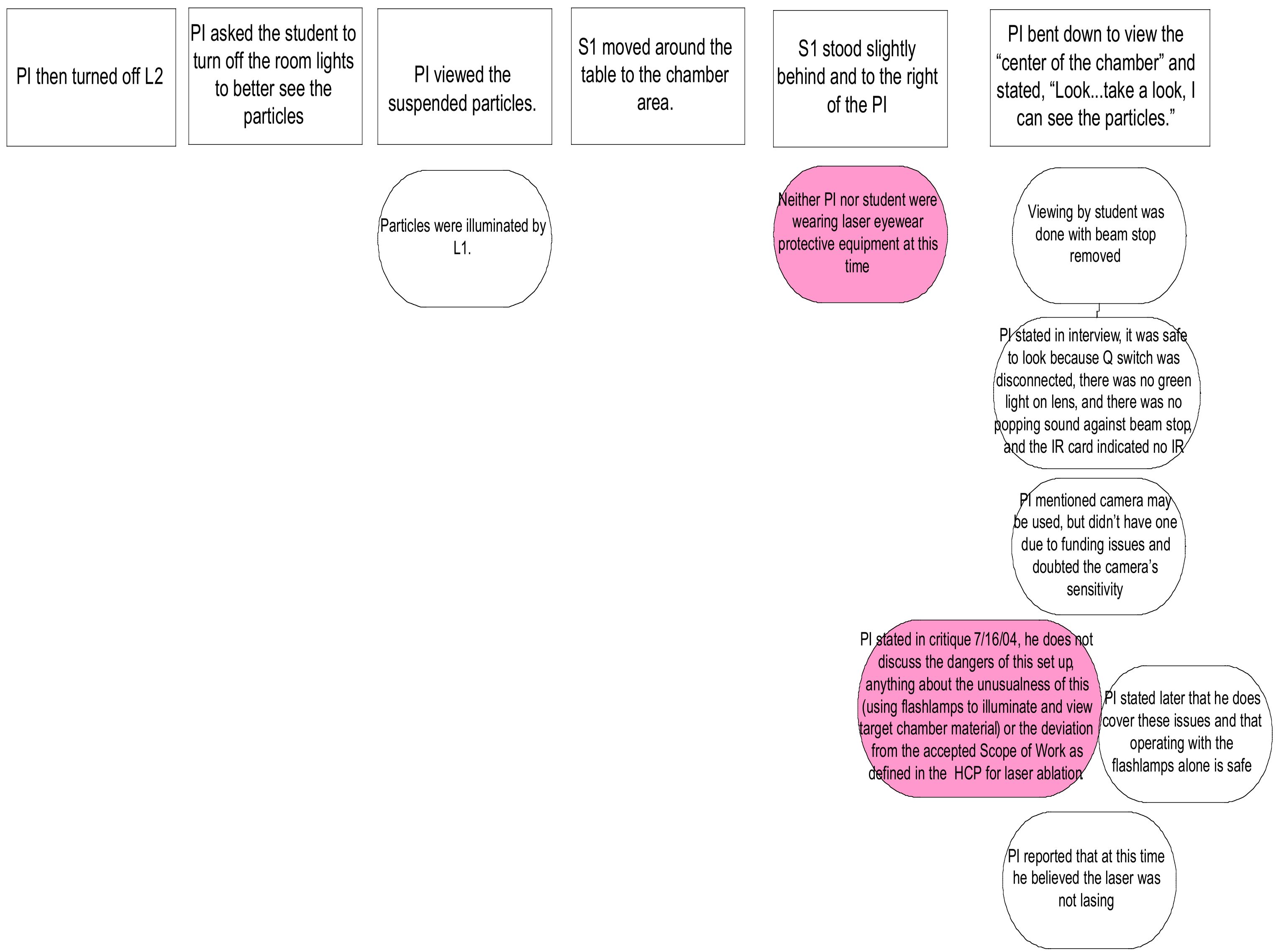

ORPS Report ALO-LA-LANL-CHEMLASER-2004-0001, "C-ADI Student Received an Eye Injury While Working With A Class IV NdYAG Pulsed Laser"
October 8, 2003 HCP-C-ADI-001,R3, "Laser Ablation and "Laser-Induced breakdown Spectroscopy Lab," was Prepared
HCP Scope and Requirements
1/04 GL1 left the C-ADI GL position
1/04 GL2 filled the position from within C-Div
Initial risk identified as medium requiring, SME concurrence. Residual risk identified as minimal.
LSO1 signed as SME on 10/1/03.
LSO1 has not been in the lab for 1 yr and half and cannot remember when he did a walkaround of PI's lab room 106.
IH (who was also LSO2) signed the HCP on 10/1/03.
GL1 authorized the HCP on 10/8/03.
Neither PI nor GL1 signed a personnel registration form (1556) or a laser registration form (1552) for the Nd:YAG in 106
IWD, Part A was completed in 12/03.
IWD was approved by GL1 12/10/03, who required re-approval if the HCP was revised.
Students did not sign the pre-job portion until after the incident occurred.
HCP did not cover use of flashlamps for viewing target chamber samples.
Viewing by flashlamps could have been approved, but would not be approved if the step included viewing without LEP
Listed Engineering Controls: 1) Nominal Hazard Zone = Entire room, 2) Doorway interlocks to laser power supply when warning light placed in red.
Listed Administrative Controls: 1) Entrance warning sign, 2) read HCP, take Laser Safety Training, and be authorized, 3) Beam alignment procedure, 4) Laser shutdown procedure, 5) PPE = Optical Density 7 laser goggles "…when the laser is generating optical radiation."
Administrative controls for Chemical Hazards referred to MSDSs in the laboratory.
HCP acknowledged that the laser and laser personnel must be registered (a subsequent Hazard analysis is required)
HCP acknowledged that laser equipment must be evaluated by C-Div LSO.
The required Hazard Analysis for L1 had not been completed, nor were the students assigned to work with L1 registered on form 1556
Required training for Basic Research activities: WGO-Live (23263), "Laser Safety Orientation" (17817), PLA-CFM-002 "Conduct of Operations Plan", LIR 402-510-01 "Chemical Management", ERP-CFM-046 "Emergency Instructions", and HCP-C-ADI-001, R3 "Laser Ablation/ LIBS".
HCP required that ANY changes to the HCP would be subjected to PRO-C-DO-006, "Change Control Process."
HCP's Appendix A "What-If…Analysis" identified multiple initiators that resulted in damage to eye or blindness and cited wearing approved laser goggles as a control.
What-If Analysis Inadequate: Example: If the person forgets to wear LEP, the corresponding fix is to wear LEP.
HCP required workers to notify SRLM in the event of all abnormal events as soon as possible.
LSO could not remember when he was last in lab, room 106
Established Performance Monitoring
GL1 described not getting into PI's lab and being more concerned about a second lab
Expressed by several interviewees was an inference that activities in PI's lab were likely done well because he was revered in his R&D field, had no prior mishaps,a nd had received a mentoring award
Review of C-Division MWA's for last year: Building 41 hit 5 times; 3 were in Room 110, 1 covered whole building, and 1 included PI's room as part of larger space assessment effort
1 C-Division manager did state observations of poor housekeeping had been addressed in the PI's laboratory. These observations and corrective actions were not specified on the MWA system
Mentoring Performance Assessment is not required by LANL
GL1 stated some funding had been set aside for Team Leaders so they could perform oversight functions
GL1 expressed hope that Team Leaders engaged in performance monitoring
PI's Team Leader had not been in room 106 in approximately 9 months
C-Division did not have a job description for the Team Leader
The C-Division LSO (LSO2) had not been in the PI's lab for over a year

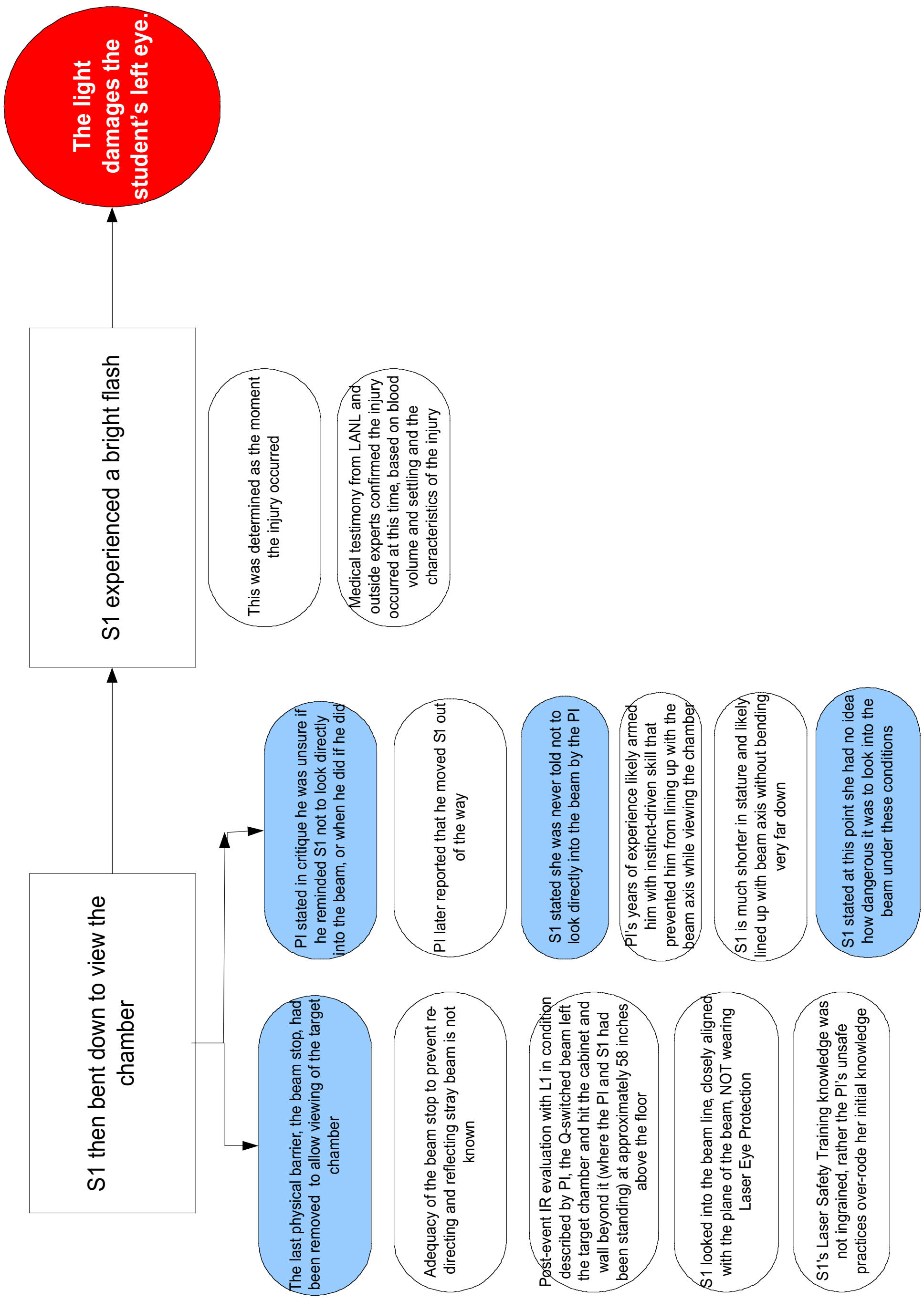

GL1 became the RDL for buildings 31 and 41.
GL1 was not concerned with building 41 as much as he was with 31.
One person serving as RDL and SRLM creates potential conflict of interest. Also a missed review opportunity.
6/1/04 S1 begins work at LANL.
S1 began work in the laser lab shortly after.
S1 did not have laser lab experience at university. Only manufactured parts for Class I lasers.
S1 completed gas cylinder training on 7/7/04.
S1 worked with gas cylinders prior to being trained.
6/2/04 S1 Completed General Employee Training
6/3/04 S1 completed on-line Laser Safety Training.
S1 stated that she learned from Laser Safety Self-study that there are different levels of lasers and goggles should be worn.
Course does not clarify the need to avoid looking at the beam and to avoid aligning eyes with the plane of the laser.
6/7/04 S1 attends C-Div's Student orientation.
C-Div's Orientation covers Division overview, Chemistry Operations, and Student programs
6/8/04 S1 attends C-DO's new hire meeting
C-Div's New Hires Covers: C-Div's code of ethics, Safety and Stop Work, the 5 steps to ISM, and Emergency Response.
C-Div handed out emergency numbers and employee handbook.
C-Div covered responsibility of personnel to challenge unsafe behaviors
Established work environment
2004 Student interviews indicated LEP was often not worn in the PI's laboratory
Interviews with Post-Doc and previous technician indicated LEP was often not worn after the 'optical path was identified'
S1 stated the PI did not discuss or explain the interlock purpose or function
S1 stated that the PI had gone through the doors to the lab even when the warning light was set to red
PI stated he did not conduct indoctrination on hazards and controls for S1 and S2, but showed them how to do things...
S1 reported that during laser alignment LEP was not worn by persons in the lab
S1 stated that during alignment, the IR cards were used to determine the beam location and the spot on the card was always orange or red...with or without the Q switch engaged
Post-event measurements contradict this possibility in that laser light was identifiable with IR cards only with the Q switch engaged
S1 could not recall a single time when the PI wore his LEP in the laboratory
S1 did not understand the potential for lasing present with Class IV lasers when Q switch not engaged
Mentoring Program
S1 and S2 interviews indicated they were not fully cognizant of who authorized them to work or what that meant
S1 and S2 indicated that stop work was a good idea, but did not work well with students to PIs
S1 and S2 indicated they were unsure when they were authorized to work, although concept covered in the student orientation
S1 and S2 indicated that they had attempted to align a laser alone, without LEP and had ended up hitting a third student at shirt level during that process
C-Division does not have requirements for mentor training, quals etc.
S1 and S2 interviews illustrated that neither had prior laser experience and the laboratory OJT did not provide them with sufficient Class IV laser hazards/controls/requirements knowledge
C-Division provides new hires and students with a new hire orientation
LANL does not require that a mentor and student have a mentor/student work plan, although some divisions, such as C-Division, do
LANL does not require that mentors take mentor training
LANL does not ensure that mentors evaluate students during OJT and make students demonstrate their knowledge of the equipment, the hazards, and the controls for the work they are doing

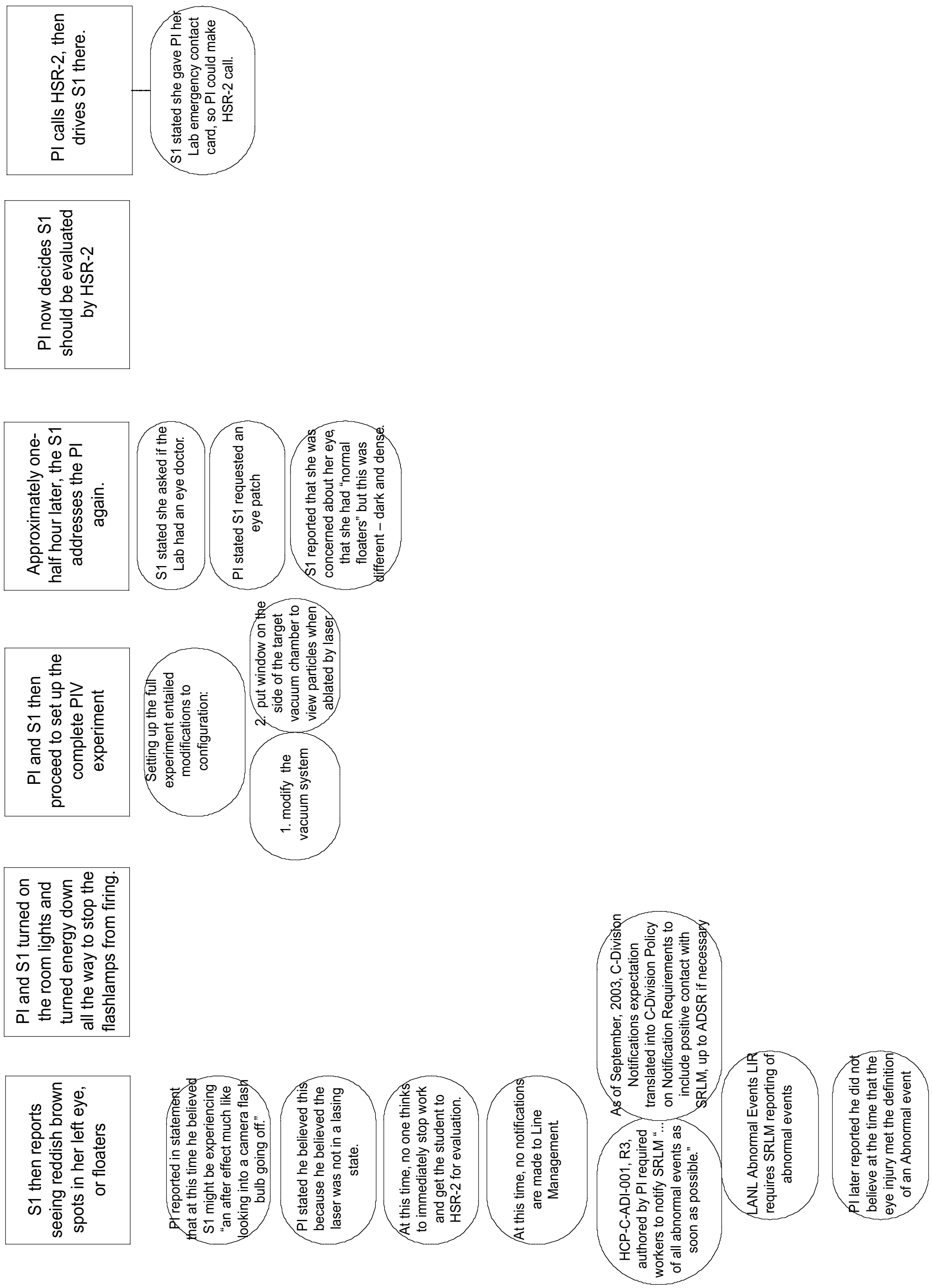

June 2004
S1 reads and signs the HCP-C-ADI-001, R3
S1 reads HCP shortly after she arrived. S1 asked no questions because she said "it takes time to know what to ask".
S1's observation was that an HCP is useless until the content is directly related to the actual work
June 2004:
T3 brings in the 2nd laser (one above chamber)
7/13/04
PI sets up the PIV experiment.
This was the first time PIV experiment was performed
The PIV set-up: vertically oriented beam of ablation laser (L2) focused on particle vacuum chamber and main Nd:YAG laser (L1) also directed to vacuum chamber
7/13/04
PI conducts alignment as part of set-up
PI reported alignment was conducted with LEP
PI reported alignment was conducted in external mode with Q switch trigger cable plugged in to SRS pulse generator
PI used an IR card, not an IR viewer, to trace the beam path and ensure it hit center of target chamber
PI was aware that reflections occurred at several surfaces, but did not use instrumentation to locate the reflected beam around the lab
7/13/04
PI leaves the lab
PI shut off the laser
PI did not follow a power-up or power-down checklist
PI stated that usually when the laser was powered down, the FL and Q switch trigger cables were removed
PI believed he removed the Q switch trigger cable from the pulse generator but was unsure about the FL cable
7/14/04: 1100
LANL Director, P. Nanos holds Lab-wide briefing.
Content included UC LANL contract performance with respect to recent security incidents
Nanos also emphasized importance of preventing "one more" safety or security event
PI and students did not discuss the presentation or implications

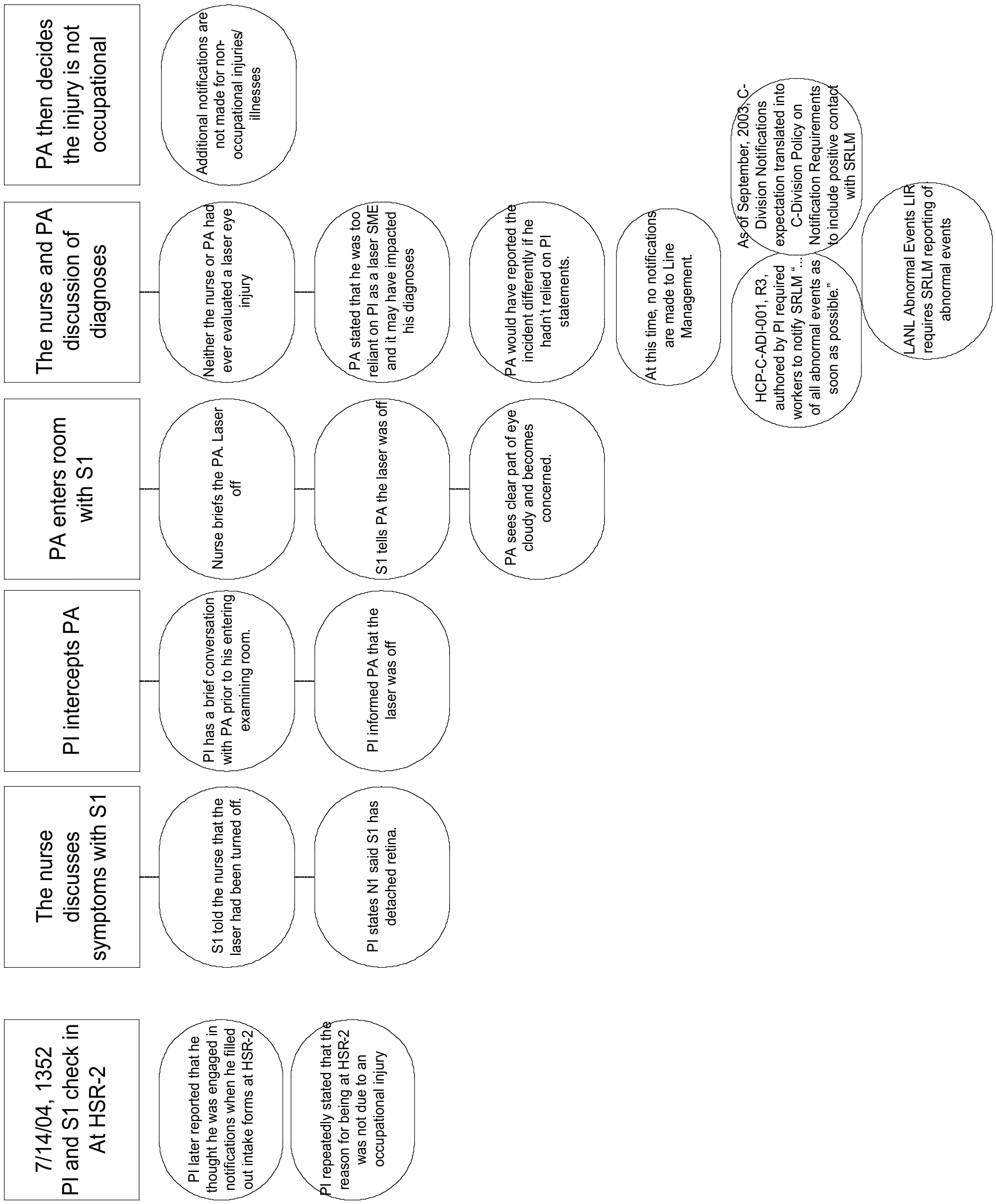

7/14/04, ~1200
S1 went to ask PI about getting to work on the PIV experiment
7/14/04
S1 and PI enter lab at 46/41/106
Particle illumination was not addressed in the HCP.
Viewing the target chamber with flash lamp light and no LEP was not covered in the HCP
HCP/IWD was not used as procedure for work
HCP did state the NHZ was the room, in which the LEP must be worn when operating Class IV lasers
IWD was too general; did not break down tasks to be done to conduct the PIV experiment
7/14/04
S1 went into Rm 114 to prepare a sample.
7/14/04
PI turns on the laser power supply for L1 and L2
The laser was turned on for warm-up.
According to PI in critique and Witness Stmt, "Turn on" means the electrical systems were started and the cooling water flowed through the system for cooling. The lasers were not lasing or pulsing or emitting light."
7/14/04
PI turned laser warning light on exterior of lab to yellow by manual switch inside the lab.
A switch box allows the warning lights to operate independently of the laser
The lab doors were closed.
Only L1 is connected to the interlock system.
When the switch box is on, the doors are coupled to the laser, dropping the laser when the doors are opened regardless of whether the warning light is green, yellow or red
T1 stated that after the "optical path was identified" (meaning the optics used were in position and properly aligned) that they ran the laser with the warning lights on yellow without interlocks.
PI connects the Flash lamb cable to the SRS pulse generator for L1
The pulser on the Nd:YAG laser was connect to start firing the laser flashlamps
The PI inconsistently reported regarding his knowledge that the Q switch trigger cable was not connected to the SRS pulse generator
PI stated he wanted to use the L1 flashlamp light to provide illumination/ light scattering to allow visual observation of the suspended particles in the chamber.
HCP did not indicate the Q-Switch as an engineered control.
Disabling the Q switch changes the laser output. This requires the laser user to inform the LSO so he can perform a new Hazard Analysis to determine the nominal hazard zone and OD of laser eyewear.
Post-event measurements with FL at 40 mJ, no Q switch & using a 10 micro-volt sensitivity instrument put laserlight emitted at 1 foot beyond the target chamber at 0.22 microJoules/cm2
The MPE for white light ~2 microJoules/cm2. Damage threshold for white light ~20 microJoules/cm2. MPE for this IR pulse is 5microJoules/cm2
PI raises L1 energy to ~40 mJ

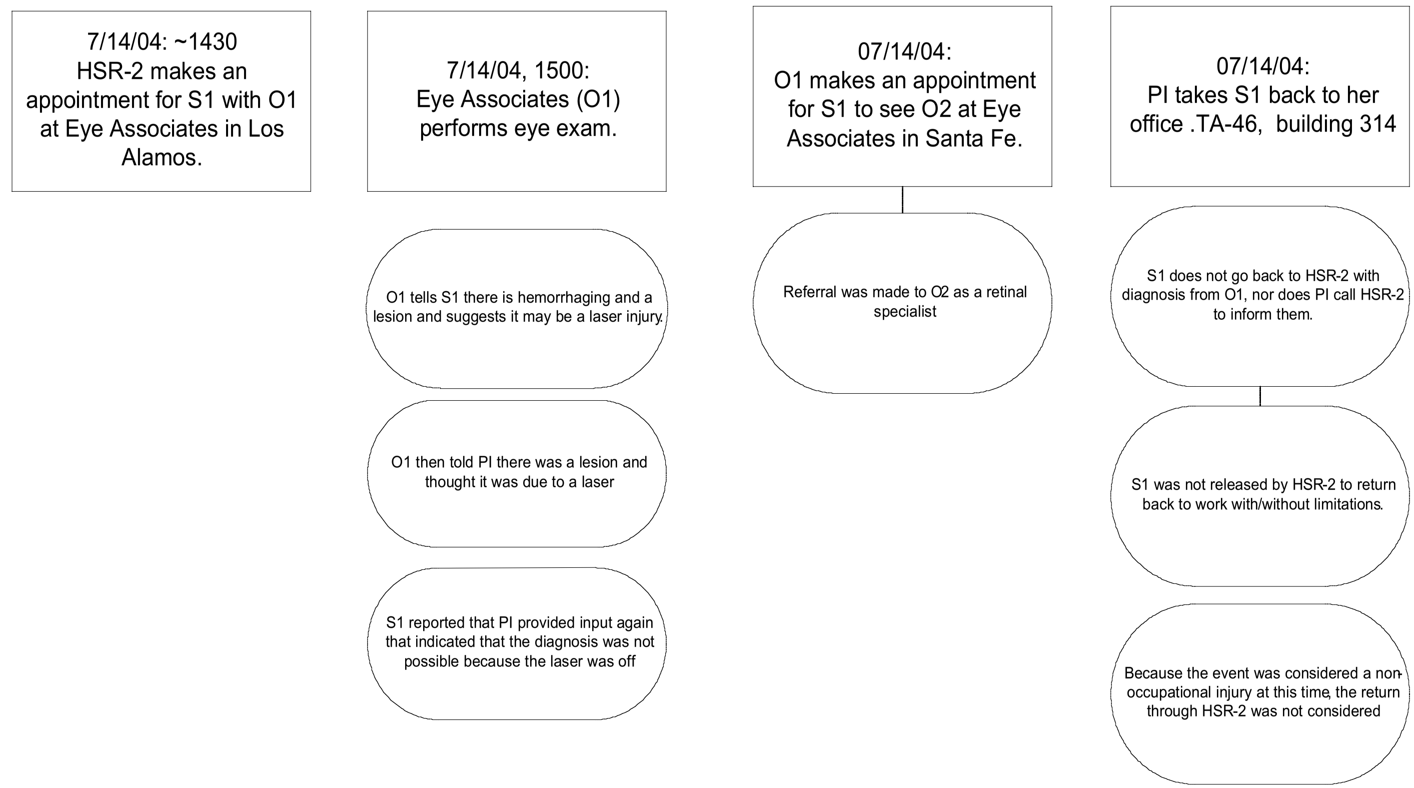

The flashlamps in the Nd:YAG laser begin firing L1
Laser goggles are required whenever you are generating optical radiation.
PI reported he used IR card and observed only white light
PI did not measure the output of L1 to ensure it was not lasing
PI placed sample container in target chamber
The beam stop was moved to the side of the target chamber
PI secures and seals the front window to the chamber.
PI and S1 hook up vacuum chamber and pumped it down ('few torr')
7/14/04 PI fired L2 (ablation laser)
S1 believes she was in the room, but is unsure exactly when Laser 2 fired
PI said S1 was not in the room when he turned the upper laser on.
Laser warning light was not switched to RED.
S1 stated neither she nor PI were wearing laser safety goggles at this time.
PI said that he "closed his eyes" (no laser goggles on) while firing L2 for 2-5 seconds

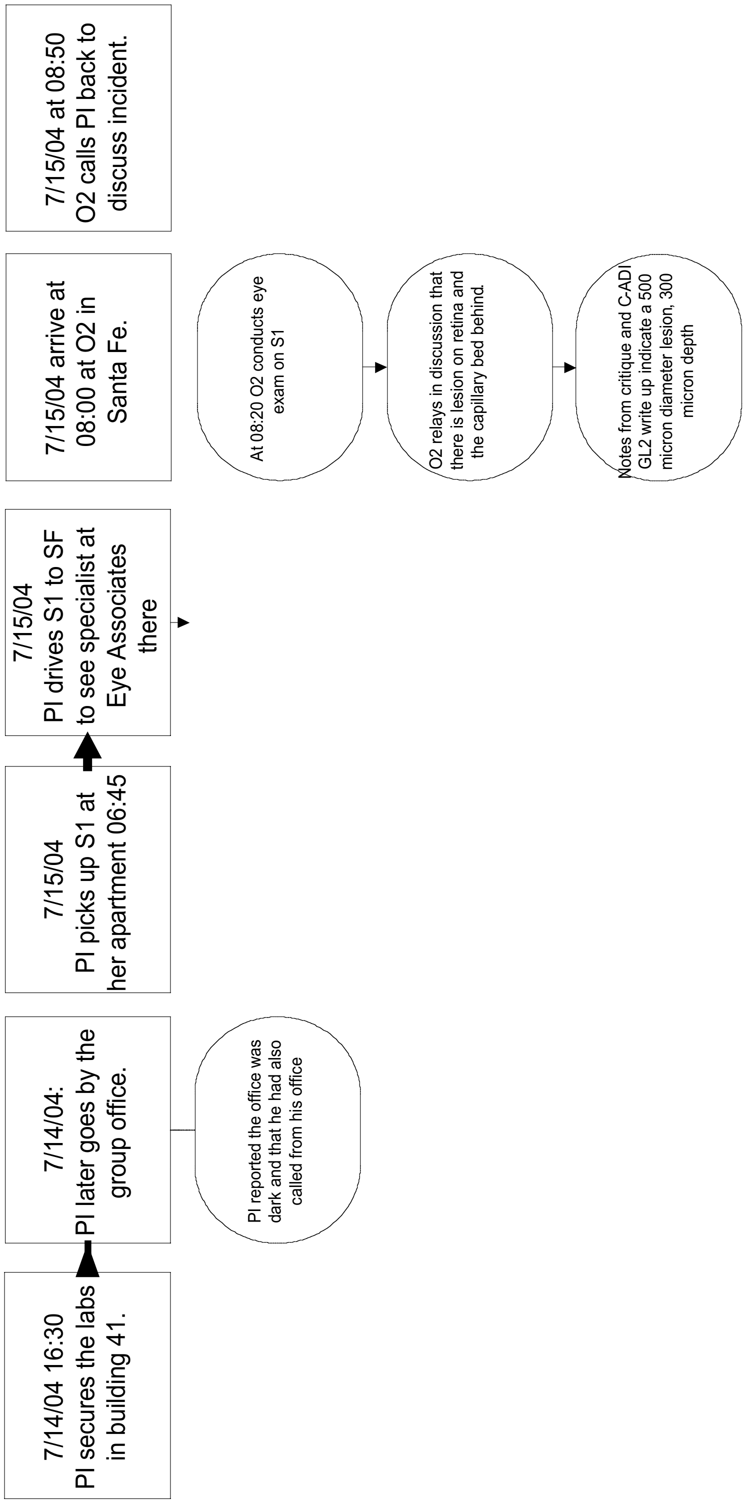

PI then turned off L2
PI asked the student to turn off the room lights to better see the particles
PI viewed the suspended particles.
Particles were illuminated by L1.
S1 moved around the table to the chamber area.
S1 stood slightly behind and to the right of the PI
Neither PI nor student were wearing laser eyewear protective equipment at this time
PI bent down to view the "center of the chamber" and stated, "Look...take a look, I can see the particles."
Viewing by student was done with beam stop removed
PI stated in interview, it was safe to look because Q switch was disconnected, there was no green light on lens, and there was no popping sound against beam stop, and the IR card indicated no IR
PI mentioned camera may be used, but didn't have one due to funding issues and doubted the camera's sensitivity
PI stated in critique 7/16/04, he does not discuss the dangers of this set up, anything about the unusualness of this (using flashlamps to illuminate and view target chamber material) or the deviation from the accepted Scope of Work as defined in the HCP for laser ablation
PI stated later that he does cover these issues and that operating with the flashlamps alone is safe
PI reported that at this time he believed the laser was not lasing

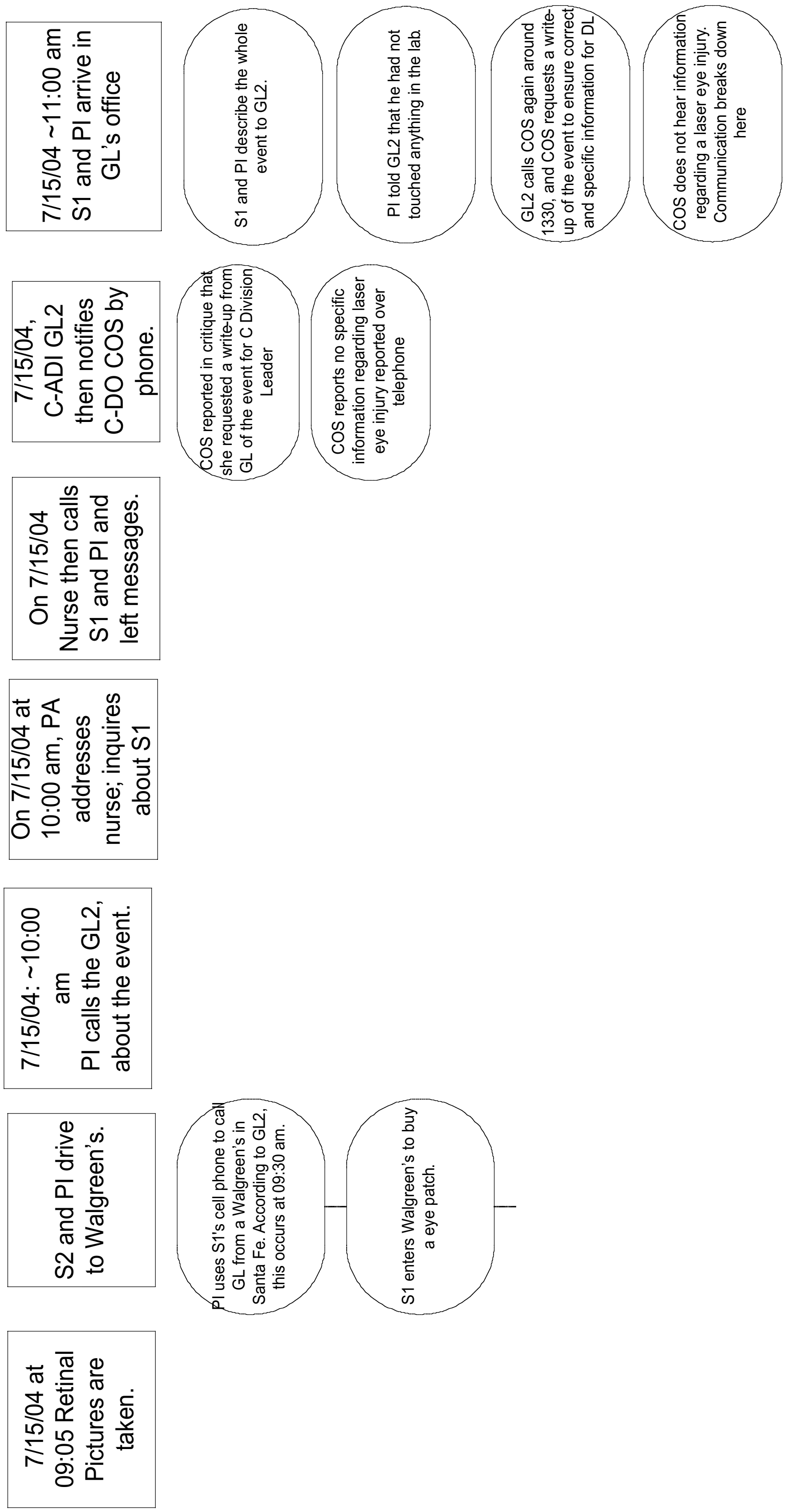

S1 then bent down to view the chamber
The last physical barrier, the beam stop, had been removed to allow viewing of the target chamber
Adequacy of the beam stop to prevent re-directing and reflecting stray beam is not known
Post-event IR evaluation with L1 in condition described by PI, the Q-switched beam left the target chamber and hit the cabinet and wall beyond it (where the PI and S1 had been standing) at approximately 58 inches above the floor
S1 looked into the beam line, closely aligned with the plane of the beam, NOT wearing Laser Eye Protection
S1's Laser Safety Training knowledge was not ingrained, rather the PI's unsafe practices over-rode her initial knowledge
PI stated in critique he was unsure if he reminded S1 not to look directly into the beam, or when he did if he did
PI later reported that he moved S1 out of the way
S1 stated she was never told not to look directly into the beam by the PI
PI's years of experience likely armed him with instinct-driven skill that prevented him from lining up with the beam axis while viewing the chamber
S1 is much shorter in stature and likely lined up with beam axis without bending very far down
S1 stated at this point she had no idea how dangerous it was to look into the beam under these conditions
S1 experienced a bright flash
This was determined as the moment the injury occurred
Medical testimony from LANL and outside experts confirmed the injury occurred at this time, based on blood volume and settling and the characteristics of the injury
The light damages the student's left eye.

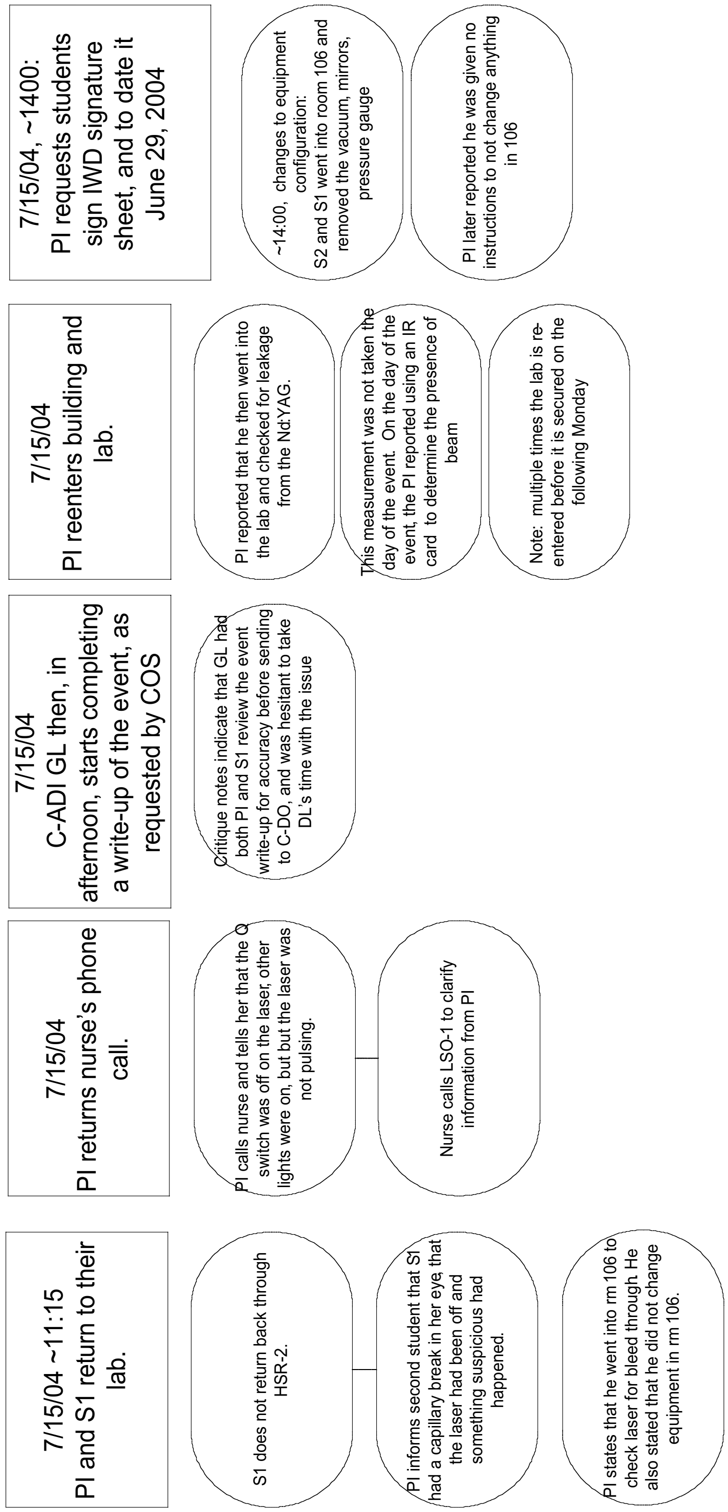

S1 then reports seeing reddish brown spots in her left eye, or floaters
PI reported in statement that at this time he believed S1 might be experiencing "an after effect much like looking into a camera flash bulb going off."
PI stated he believed this because he believed the laser was not in a lasing state.
At this time, no one thinks to immediately stop work and get the student to HSR-2 for evaluation.
At this time, no notifications are made to Line Management
HCP-C-ADI-001, R3, authored by PI required workers to notify SRLM "… of all abnormal events as soon as possible."
As of September, 2003, C-Division Notifications expectation translated into C-Division Policy on Notification Requirements to include positive contact with SRLM, up to ADSR if necessary
LANL Abnormal Events LIR requires SRLM reporting of abnormal events
PI later reported he did not believe at the time that the eye injury met the definition of an Abnormal event
PI and S1 turned on the room lights and turned energy down all the way to stop the flashlamps from firing.
PI and S1 then proceed to set up the complete PIV experiment
Setting up the full experiment entailed modifications to configuration:
1. modify the vacuum system
2. put window on the side of the target vacuum chamber to view particles when ablated by laser
Approximately one-half hour later, the S1 addresses the PI again.
S1 stated she asked if the Lab had an eye doctor.
PI stated S1 requested an eye patch
S1 reported that she was concerned about her eye, that she had "normal floaters" but this was different – dark and dense.
PI now decides S1 should be evaluated by HSR-2
PI calls HSR-2, then drives S1 there.
S1 stated she gave PI her Lab emergency contact card, so PI could make HSR-2 call.

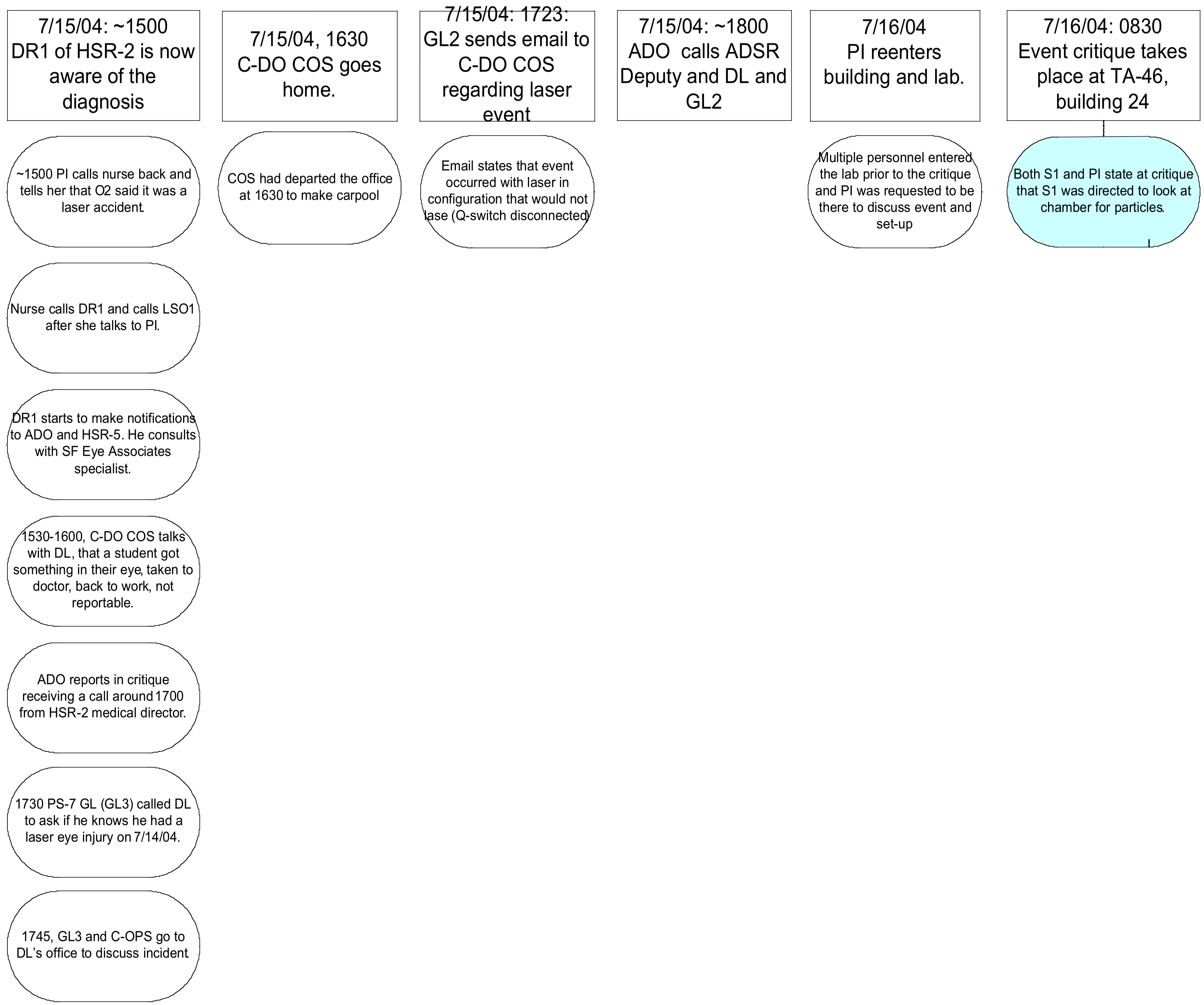

7/14/04, 1352 PI and S1 check in At HSR-2
PI later reported that he thought he was engaged in notifications when he filled out intake forms at HSR-2
PI repeatedly stated that the reason for being at HSR-2 was not due to an occupational injury
The nurse discusses symptoms with S1
S1 told the nurse that the laser had been turned off.
PI states N1 said S1 has detached retina.
PI intercepts PA
PI has a brief conversation with PA prior to his entering examining room.
PI informed PA that the laser was off
PA enters room with S1
Nurse briefs the PA. Laser off
S1 tells PA the laser was off
PA sees clear part of eye cloudy and becomes concerned.
The nurse and PA discussion of diagnoses
Neither the nurse or PA had ever evaluated a laser eye injury
PA stated that he was too reliant on PI as a laser SME and it may have impacted his diagnoses
PA would have reported the incident differently if he hadn't relied on PI statements.
At this time, no notifications are made to Line Management.
HCP-C-ADI-001, R3, authored by PI required workers to notify SRLM "… of all abnormal events as soon as possible."
As of September, 2003, C-Division Notifications expectation translated into C-Division Policy on Notification Requirements to include positive contact with SRLM
LANL Abnormal Events LIR requires SRLM reporting of abnormal events
PA then decides the injury is not occupational
Additional notifications are not made for non-occupational injuries/ illnesses

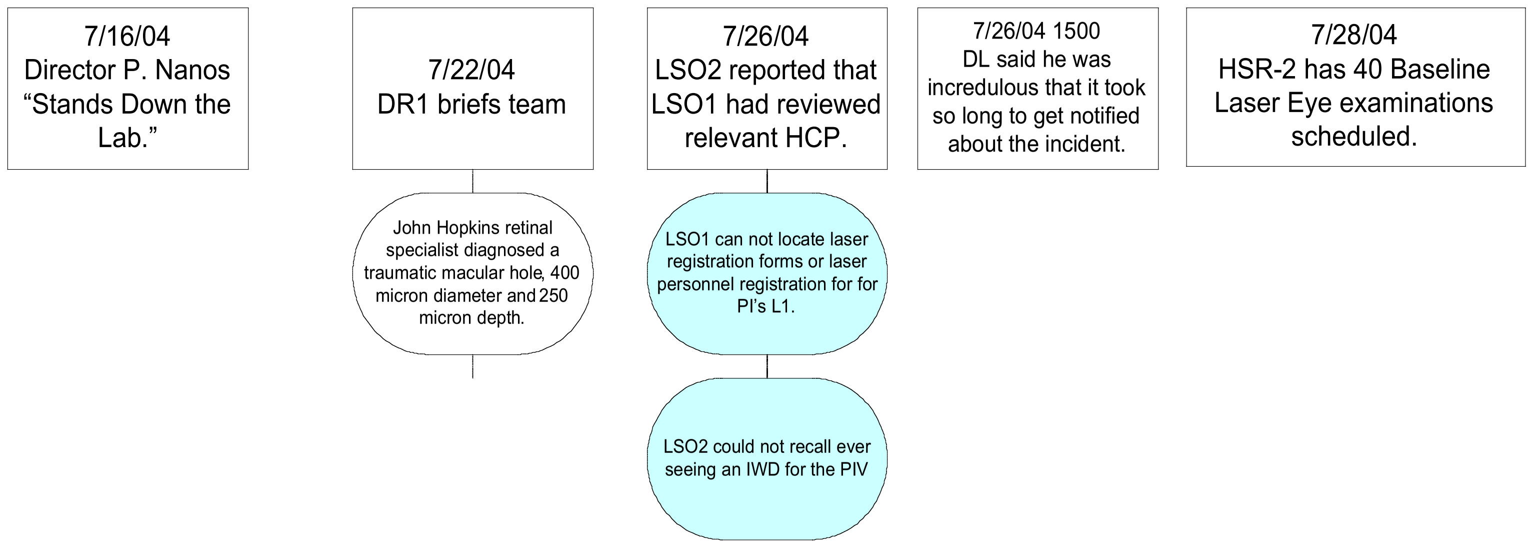

7/14/04: ~1430
HSR-2 makes an appointment for S1 with O1 at Eye Associates in Los Alamos.
7/14/04, 1500:
Eye Associates (O1) performs eye exam.
O1 tells S1 there is hemorrhaging and a lesion and suggests it may be a laser injury.
O1 then told PI there was a lesion and thought it was due to a laser
S1 reported that PI provided input again that indicated that the diagnosis was not possible because the laser was off
07/14/04:
O1 makes an appointment for S1 to see O2 at Eye Associates in Santa Fe.
Referral was made to O2 as a retinal specialist
07/14/04:
PI takes S1 back to her office .TA-46, building 314
S1 does not go back to HSR-2 with diagnosis from O1, nor does PI call HSR-2 to inform them.
S1 was not released by HSR-2 to return back to work with/without limitations.
Because the event was considered a non-occupational injury at this time, the return through HSR-2 was not considered

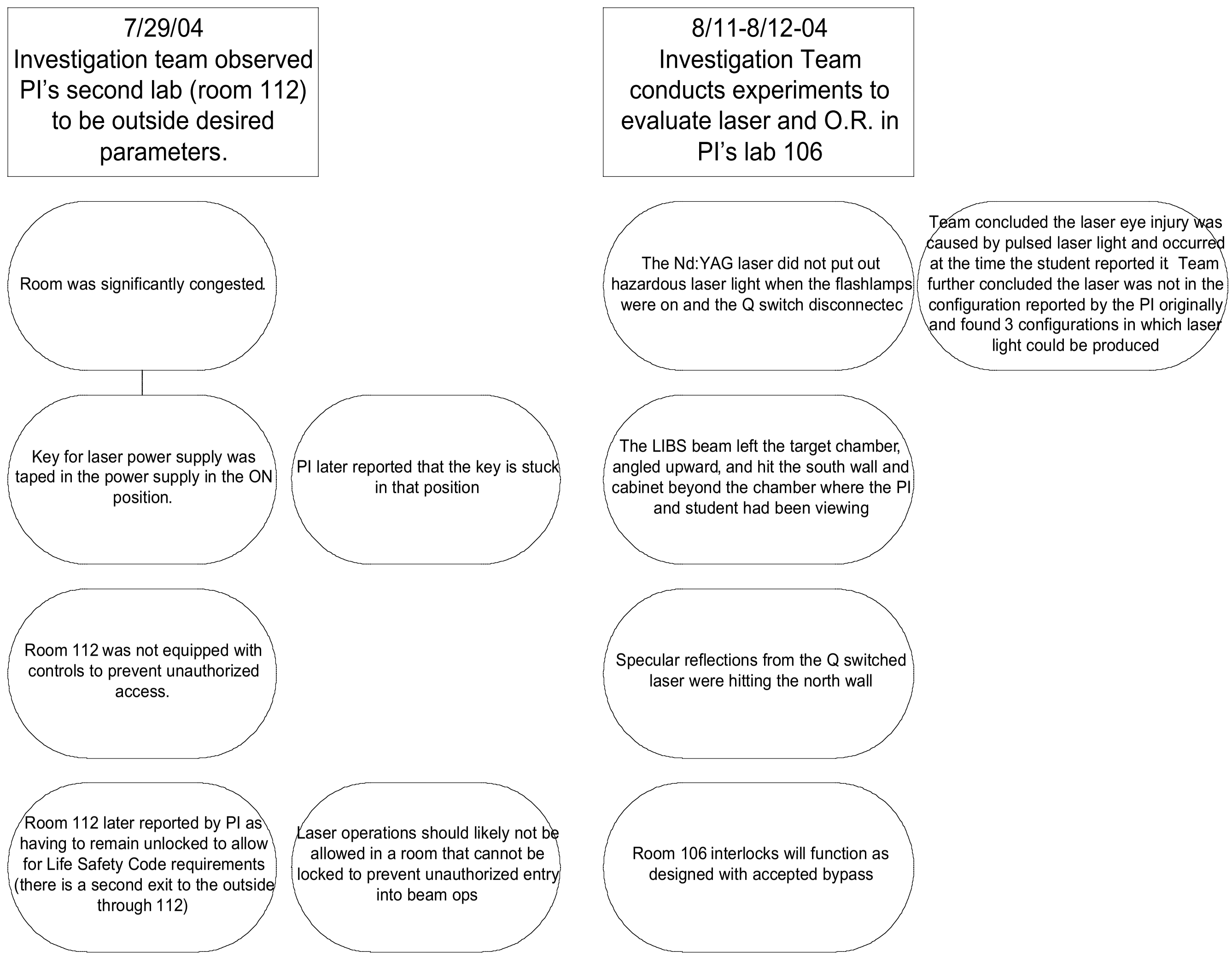

7/14/04 16:30 PI secures the labs in building 41.
7/14/04: PI later goes by the group office.
PI reported the office was dark and that he had also called from his office
7/15/04 PI picks up S1 at her apartment 06:45
7/15/04 PI drives S1 to SF to see specialist at Eye Associates there
7/15/04 arrive at 08:00 at O2 in Santa Fe.
At 08:20 O2 conducts eye exam on S1
O2 relays in discussion that there is lesion on retina and the capillary bed behind.
Notes from critique and C-ADI GL2 write up indicate a 500 micron diameter lesion, 300 micron depth
7/15/04 at 08:50 O2 calls PI back to discuss incident.


7/15/04 at 09:05 Retinal Pictures are taken.
S2 and PI drive to Walgreen's.
PI uses S1's cell phone to call GL from a Walgreen's in Santa Fe. According to GL2, this occurs at 09:30 am.
S1 enters Walgreen's to buy a eye patch.
7/15/04: ~10:00 am PI calls the GL2, about the event.
On 7/15/04 at 10:00 am, PA addresses nurse; inquires about S1
On 7/15/04 Nurse then calls S1 and PI and left messages.
7/15/04, C-ADI GL2 then notifies C-DO COS by phone.
COS reported in critique that she requested a write-up from GL of the event for C Division Leader
COS reports no specific information regarding laser eye injury reported over telephone
7/15/04 ~11:00 am S1 and PI arrive in GL's office
S1 and PI describe the whole event to GL2.
PI told GL2 that he had not touched anything in the lab.
GL2 calls COS again around 1330, and COS requests a write-up of the event to ensure correct and specific information for DL
COS does not hear information regarding a laser eye injury. Communication breaks down here


7/15/04 ~11:15
PI and S1 return to their lab.
S1 does not return back through HSR-2.
PI informs second student that S1 had a capillary break in her eye, that the laser had been off and something suspicious had happened.
PI states that he went into rm 106 to check laser for bleed through. He also stated that he did not change equipment in rm 106.
7/15/04
PI returns nurse's phone call.
PI calls nurse and tells her that the Q switch was off on the laser, other lights were on, but but the laser was not pulsing.
Nurse calls LSO-1 to clarify information from PI
7/15/04
C-ADI GL then, in afternoon, starts completing a write-up of the event, as requested by COS
Critique notes indicate that GL had both PI and S1 review the event write-up for accuracy before sending to C-DO, and was hesitant to take DL's time with the issue
7/15/04
PI reenters building and lab.
PI reported that he then went into the lab and checked for leakage from the Nd:YAG.
This measurement was not taken the day of the event. On the day of the event, the PI reported using an IR card to determine the presence of beam
Note: multiple times the lab is re-entered before it is secured on the following Monday
7/15/04, ~1400:
PI requests students sign IWD signature sheet, and to date it June 29, 2004
~14:00, changes to equipment configuration:
S2 and S1 went into room 106 and removed the vacuum, mirrors, pressure gauge
PI later reported he was given no instructions to not change anything in 106


7/15/04: ~1500 DR1 of HSR-2 is now aware of the diagnosis
~1500 PI calls nurse back and tells her that O2 said it was a laser accident.
Nurse calls DR1 and calls LSO1 after she talks to PI.
DR1 starts to make notifications to ADO and HSR-5. He consults with SF Eye Associates specialist.
1530-1600, C-DO COS talks with DL, that a student got something in their eye, taken to doctor, back to work, not reportable.
ADO reports in critique receiving a call around 1700 from HSR-2 medical director.
1730 PS-7 GL (GL3) called DL to ask if he knows he had a laser eye injury on 7/14/04.
1745, GL3 and C-OPS go to DL's office to discuss incident
7/15/04, 1630 C-DO COS goes home.
COS had departed the office at 1630 to make carpool
7/15/04: 1723: GL2 sends email to C-DO COS regarding laser event
Email states that event occurred with laser in configuration that would not lase (Q-switch disconnected)
7/15/04: ~1800 ADO calls ADSR Deputy and DL and GL2
7/16/04 PI reenters building and lab.
Multiple personnel entered the lab prior to the critique and PI was requested to be there to discuss event and set-up
7/16/04: 0830 Event critique takes place at TA-46, building 24
Both S1 and PI state at critique that S1 was directed to look at chamber for particles.


7/16/04
Director P. Nanos
“Stands Down the
Lab.”
7/22/04
DR1 briefs team
John Hopkins retinal
specialist diagnosed a
traumatic macular hole, 400
micron diameter and 250
micron depth.
7/26/04
LSO2 reported that
LSO1 had reviewed
relevant HCP.
LSO1 can not locate laser
registration forms or laser
personnel registration for for
PI’s L1.
LSO2 could not recall ever
seeing an IWD for the PIV
7/26/04 1500
DL said he was
incredulous that it took
so long to get notified
about the incident.
7/28/04
HSR-2 has 40 Baseline
Laser Eye examinations
scheduled.


7/29/04
Investigation team observed PI's second lab (room 112) to be outside desired parameters.
Room was significantly congested.
Key for laser power supply was taped in the power supply in the ON position.
PI later reported that the key is stuck in that position
Room 112 was not equipped with controls to prevent unauthorized access.
Room 112 later reported by PI as having to remain unlocked to allow for Life Safety Code requirements (there is a second exit to the outside through 112)
Laser operations should likely not be allowed in a room that cannot be locked to prevent unauthorized entry into beam ops
8/11-8/12-04
Investigation Team conducts experiments to evaluate laser and O.R. in PI's lab 106
The Nd:YAG laser did not put out hazardous laser light when the flashlamps were on and the Q switch disconnectec
Team concluded the laser eye injury was caused by pulsed laser light and occurred at the time the student reported it. Team further concluded the laser was not in the configuration reported by the PI originally and found 3 configurations in which laser light could be produced
The LIBS beam left the target chamber, angled upward, and hit the south wall and cabinet beyond the chamber where the PI and student had been viewing
Specular reflections from the Q switched laser were hitting the north wall
Room 106 interlocks will function as designed with accepted bypass

APPENDIX F

Barrier Analysis

Barriers	Purpose	How It Functioned	Reason for Failure	Contributed to Event?
Laser Eye Protection (LEP)	Reduce optical radiation to less than the maximum permissible exposure (MPE)	Failed	The PI and students did not typically wear LEP after the beam path was established. Optimal optical density was not available in the laboratory, and LEP in the laboratory was visibly worn and scratched, thereby further reducing visibility during use. The PI modeled unsafe behavior with regard to LEP. The PI and students did not adhere to laser LIR eye-protection requirements, ANSI Z136.1 (2000), laser safety training, or laser manual eye-protection requirements. In general, the PI believed he knew when LEP was necessary. He believed eye protection was not required when the Q-switch was disconnected from the SRS pulse generator, although lasing is possible in this configuration. Students did not have sufficient knowledge or laser experience to question not using LEP. They trusted the PI and therefore did not challenge the PI on this point. The PI did not formally enact the hierarchy of controls that would have made engineering controls the first line of defense against potential eye exposure.	YES
Worker Authorization	Ensure that worker skill and knowledge are commensurate with the work to be performed.	Failed	The PI did not adhere to C-Division requirements for authorizing workers through the online authorization system. The students were not authorized through formal group leader signature (as required) to do the work. The PI and the acting group leader authorized the students' work through a verbal agreement. Students were not sufficiently informed or aware of Nd:YAG laser operations or experimental hazards. The PI failed to perform a pre-job briefing or confirm readiness.	YES. All reflect Conduct of Operations failures that compromised formality in the interest of convenience and led to workers having an inadequate understanding of hazards and controls associated with the work they engaged in.
Interlocks	Keep unauthorized people out of the nominal hazard zone (NHZ).	Failed	Interlocks frequently were not activated during laser operations or were operated in a mode that allowed personnel to enter the lab without deactivating the laser. The ablation laser (L2) was not interlocked. The interlock was set to yellow. Red could have prompted personnel to wear LEP.	NO

Walls	Define the NHZ.	Functioned properly		NO
Beam Stop	Terminate the laser beam before it leaves the table.	Probably functioned properly until removed	The PI removed the beam stop.	YES
NHZ	Define eye-protection requirements.	Functioned properly	Proper eye protection was defined.	NO
Knowledge	Develop hazard analysis and controls on an accurate model of laser operation.	Not identified or developed	Students had incomplete knowledge of Q-switch operation and the potential hazards associated with relying on the Q-switch to prevent lasing. The PI did not measure IR output throughout the room when the laser was operating in the Q-switched mode and therefore did not know about the spectral reflections in the room that could result in eye damage. The PI became complacent over time as his mode of operation and experience led to no adverse consequences.	YES Laser light was not controlled adequately in the lab, and neither the student nor the PI was certain of the location of the laser light.
Performance Monitoring	Validate worker's knowledge and use of controls.	Did not validate workers' knowledge or use of controls	Line management assumed safe operations based on the technical reputation of the PI. The MWA system reflects that none of C-Division's SRLMs evaluated operations in room 106. SRLM did not critically analyze interlock usage, LEP practices, or the over-generality of the IWD. LSOs did not evaluate the PIV experiment, adequately evaluate the work control documents (the IWD), or evaluate actual operations in room 106. The laser subcommittee of C-Division's Nested Safety Committee had developed a self-assessment program, which would provide for evaluations of operations in the laser labs. This assessment program had not yet been launched when the event occurred. Peer assessments and recommendations were disregarded. Team leader responsibility for performance monitoring is not defined. LANL does not require performance monitoring of mentors.	YES Unsafe practices and informal operations had continued in the PI's labs over a long time. However, neither line management nor the safety support personnel were adequately informed, so the practices were never corrected.

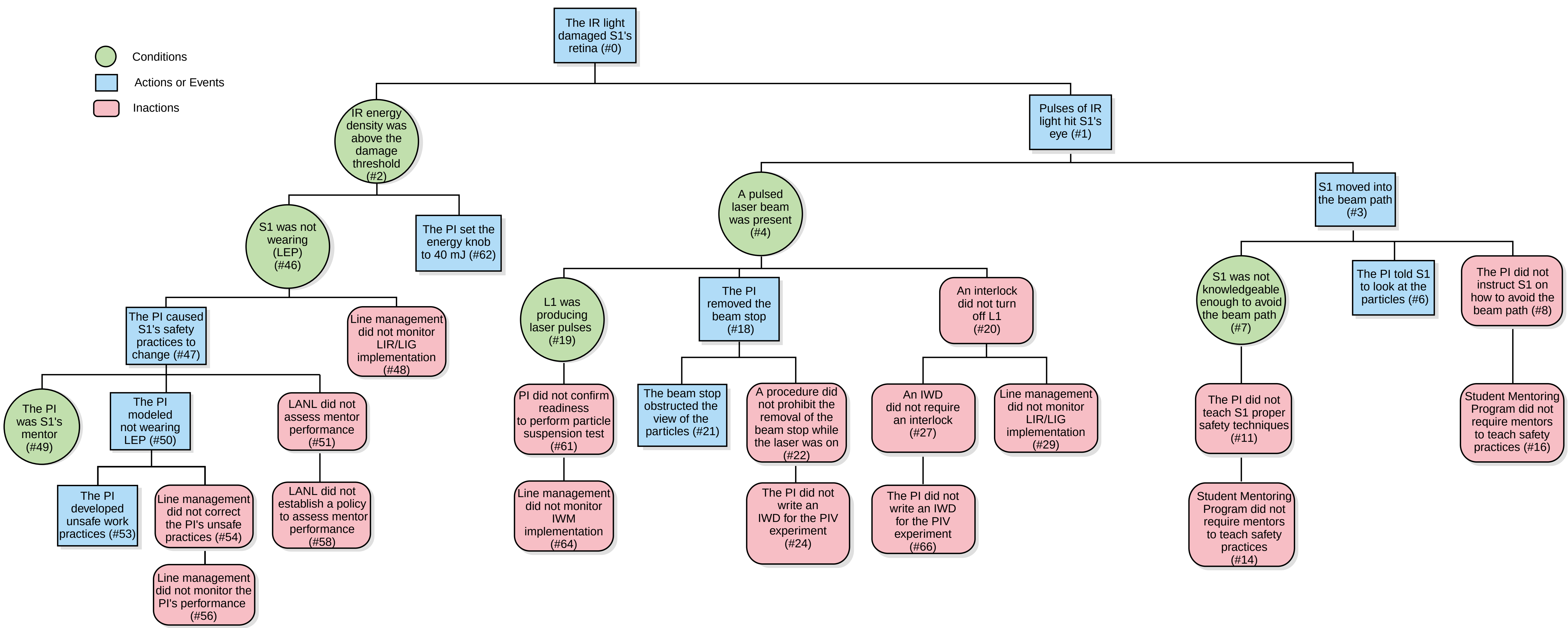
On-the-Job Training (OJT)	Apply knowledge of hazards, controls, and responsibilities to the specific work. Demonstrate and implement safe work practices.	Failed	PI-provided OJT did not give students an adequate understanding of the hazards posed by the work they engaged in. OJT did not reinforce requirements, precautions communicated in laser safety training, or safe work practices. The PI did not ensure that the students demonstrated adequate knowledge of the equipment or operational hazards and controls before engaging in work activities involving an operating Class IV Nd:YAG laser. The PI did not review or discuss the IWDs with the students. The PI's approaching the students about reading and signing the IWDs without using them in the laboratory during operations reinforced an underlying philosophy that the IWDs were not useful and were not integrated into laboratory operations. Students did not ask the PI questions about hazards or controls.	YES. If the mentor had applied and reinforced safe work practices, the students would likely have used LEP.
Mentor Training	Establish technical and safety expectations. Communicate LANL expectations.	Failed	LANL does not require mentor training, although such training is available and is encouraged by the LANL mentor/student program. The expectation is not as strong when persons come to LANL through an affiliate arrangement.	NO
LSO Training	Maintain qualified and trained laser SMEs.	Functioned properly	The C-Division LSO who signed the work-control documents had no prior laser work experience.	Potential concern: LSOs and other SMEs signed IWDs that were too general, that did not define all the steps intended to be implemented, and that did not integrate steps with step hazards and controls.
LSO Qualification	Match skills, knowledge, and abilities to the job. Ensure the correct engineering controls, administrative controls, and PPE are in place.	Functioned poorly	The C-Division LSO who signed the work-control documents had no prior laser work experience.	NO. Potential concern, in that signatures were provided on general IWDs. Some LSOs, C-Division included, have had no experience with lasers.

Requirements	Provide formal operations and maintain a safety envelope in operations.	Failed	The PI did not adhere to specific laser-safety requirements, work-authorization requirements, and notification requirements.	YES
Redundant Controls	Avoid reliance on or challenging of the last line of defense: LEP.	Failed	Not implemented. The PI did not use an IR-blocking window, an IR viewer to measure the laser output, remote monitoring of the target, or a fixed beam stop.	YES
Not Looking into the Beam	Avoid known beam path.	Failed	PI prompted the student to look into the target chamber. The student did not have sufficient experience to look at the beam path from an oblique angle.	YES
Student Mentoring Program	Provide a challenging academic and work experience in a safe work environment.	Failed	LANL does not have an established policy for selecting quality mentors. LANL does not require mentor training. LANL does not require mentor performance assessment. LANL does not require mentors to review key management and safety policies with students. LANL does not require mentors to ensure that students demonstrate their knowledge about equipment configuration, work hazards, required controls, work-scope recognition, and what it means to sign work/worker authorization documents.	YES Monitoring of students in the mentoring program would provide an opportunity for assessing students' understanding of the hazards and controls associated with their work.
Experimental Procedure	Verify suspended particles safely.	Failed	No written procedure was developed covering the PI's use of flash lamps for illumination or alignment. The viewing method was not defined or analyzed.	YES
Laser Table Height	Keep hazard below eye level.	Functioned for L1 Failed for L2	L2 was above the optics table.	NO
Lessons Learned	Modify practices based on operational experience.	Failed	Extent-of-Condition Reviews were not completed on the ClO_2 event and acid-splash event in C-Division. C-Division had implemented efforts to train personnel to conduct better hazard analyses, to know when a change had occurred requiring reevaluation, and to perform MWAs. The institution failed to recognize that performance monitoring as a program was flailing and needed program infrastructure, definition, and resources to thrive. Extensive reliance was placed on compliance with administrative controls. Recognition of human performance failings was not incorporated into institutional knowledge in order to improve control sets and performance assessment. The PI failed to integrate the use of LEP in spite of past events at LANL in which personnel were injured during alignment processes because they were not wearing LEP. The PI failed to verify laser light in the lab and failed to use remote viewing capabilities.	YES

APPENDIX G

Negative Fault Tree Analysis

Negative Fault Tree Analysis



APPENDIX H

Observations and Concerns

During the investigation, the Team identified deficiencies in processes, programs, and procedures. While these deficiencies did not prove to be causal, they do present improvement opportunities. The Team recommends that LANL resolve these observations and concerns using the institutional issues management system.

1. The Laser Safety Officer program does not ensure that LSOs have the necessary experience and knowledge to effectively carry out their duties and responsibilities.
2. The laser safety training program does not place enough emphasis on avoiding direct exposure, especially eye exposure, to the beam. Training states that personnel must "avoid looking directly at the beam." Emphasis should be on keeping eyes away from the beam's axis. Additionally, the Team questions the appropriateness of online self-study as training for a high-hazard activity such as operating a Class IV laser.
3. LANL has not consistently demonstrated the ability to develop and implement effective corrective-action plans after the completion of an occurrence investigation.
4. The laser accident addressed by this report was not promptly reported, and line managers were not notified quickly. Communications were poor and ineffective. A related concern is HSR-2's practice of not informing line management about a nonoccupational injury.
5. The accident scene was not promptly secured and controlled after the accident. This failure hindered the Team's ability to accurately determine the scene's status and configuration when the accident occurred.
6. The student was allowed to return to work the day of the accident without medical clearance from HSR-2. A medical diagnosis was not complete and the extent of the injury and its impact on the student's ability to work safely was not understood.
7. The student did not receive a baseline laser eye examination before working with lasers. LANL should ensure that this and all other worker authorization requirements are met before laser work begins.