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Lessons Learned from a Laser Injury Event

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LESSONS LEARNED FROM A LASER INJURY EVENT

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Abstract

A technician at the Idaho National Laboratory received 2nd degree burns to his left middle and ring fingers while performing maintenance on a Class 4 industrial laser. The task required “target” placement in the beam path to verify mirror alignment. The technician, believing the laser was in a safe mode, reached into the beam pathway to place the target, saw a flash and immediately withdrew his hand. Investigation included a review of lab-wide safety procedures, equipment-specific operating procedures, maintenance documents, and training records, interviews of maintenance technicians, safety support, and management personnel, and a physical verification of equipment condition. Subsequent weaknesses were identified in training, work direction details, the performance of work following vendor-recommended safe work practices, safety professionals’ understanding of a complex system and reliance on the maintenance technician’s training and experience to conduct an effective hazard analysis.

Introduction

The Idaho National Laboratory (INL) is a federal site under the jurisdiction of the Department of Energy Idaho Office (DOE-ID), supporting activities and research, such as nuclear energy research and development, Department of Homeland Security technologies development and demonstration, and environmental restoration. The INL covers portions of five counties, an area of approximately 890 square miles, in south eastern Idaho. Several active, geographically separated facilities exist throughout the INLs acreage, one of which is the Specific Manufacturing Capabilities (SMC) facility located within Test Area North (TAN). In contrast to the INLs research and development activities, SMC is one of the few manufacturing facilities, producing armor products for the U.S. Army. It is at SMC, on August 30, 2011, where a maintenance technician received 2nd degree burns to his left hand while performing maintenance on a Class 4 industrial laser.

Background

The SMC project utilizes several Class 4 industrial lasers to fabricate components for various customers. These laser systems require periodic maintenance, including optics cleaning, replacement and alignment to maintain optimal performance.

The particular laser system involved in this incident, a Cincinnati CL-707 delivery system with a Rofin DC-035 resonator, was installed in 2005. Three basic components comprise this system:

1. The beam generator (resonator), Rofin model DC-035, which contains “slab” electrodes, a rear mirror, an output mirror, a diamond window, a bending mirror, a spherical mirror, a spatial filter, a cylindrical mirror, a power mirror, and shutter (beam dump). In whole, these are referred to as the “internal optics.” This portion of the beam is unfocused, with an approximate diameter of ¾”, and is available whenever high voltage (HV) is supplied to the “slab” with sufficient energy to produce photons.
2. The beam delivery system, Cincinnati model CL-707, which contains the beam delivery optics external to the resonator cabinet, laser head, gantry, table, Human-Machine Interface (HMI) console and pendant for remote operation. These components are referred to as the “external optics.”
3. Material handling system, custom-built by Progressive, which includes vacuum transporters, an overhead gantry, a scrap fork, and a transfer table. This portion of the system has no laser components.

Ten individuals, including electrical control technicians, system engineers, and work planners, have received training from Rofin, Cincinnati or a combination of the two. Training is specific to the component system. Meaning, Rofin training only covers those components within the resonator cabinet and Cincinnati training only covers the “external optics” portion of the system. The most recent training on the “internal optics” portion of the system occurred in May, 2010. Less formal training has taken place when electrical control technicians observed factory representatives performing maintenance on the laser systems while visiting SMC.

Each vendor recommends various preventive maintenance (PM) activities, including a 2000 hour runtime PM. In addition to identifying tasks and providing instructions for maintenance activities, the PM also contains a section that identifies hazards and mitigating actions to control arc flash and shock, mechanical motion of the gantry, table and laser head, the high power invisible laser beam, chemical products, pinch points and sharp edges, pressurized gases, noise, and elevated work. Mitigating actions may include lockout and tagout (LOTO), exclusive control of the pendant, barriers and signs, personal protective equipment (PPE) and training. Included in the PM are references to vendor procedures that detail maintenance tasks recommended by the vendor. The PM for this particular system was performed using a planned work order (WO), Electrical 2000 Hr. Run Time PMs, and included the following items:

1. Laser cooling system checks.
2. Laser head inspection and cleaning.
3. Ball screw lubrication.
4. Electrical connection checks.
5. Laser gas leak testing.
6. Vacuum testing.
7. Internal optics alignment.
8. RF tube current testing.
9. Mode burns.
10. Safety mat inspections.
11. Gantry material handling system maintenance.
12. Four corner card shots.
13. Beam delivery alignment.

A key component of particular interest in this event is the "pendant." It is a device that allows the electrical control technician to maintain exclusive control of the HMI console when physically separated from the control console. When the pendant is "enabled," control of the laser system is removed from the HMI control console, and is only capable through the pendant control unit, allowing the technicians to perform system functions remotely from areas around the physical footprint of the system and while on either of the work tables.

Detailed Chronology of Activities

It has previously been established that off-site vendor training was completed approximately 15 months prior to performing this type of PM. Approximately 2 months prior to performing this PM, the WO was updated, including hazard mitigations, reviewed and approved by the System Engineer, the Maintenance Supervisor, a Safety Engineer and the Laser Safety Officer (LSO).

In August, 2011, about 2 weeks prior to the event on this particular system, nearly identical PM work was performed on a similar laser system without incident.

Beginning on August 29, 2011, PM work on this laser system commenced with a pre-job briefing by the acting Foreman. Three electrical control technicians were assigned to perform the work, and one of them was identified as the person in charge (PIC). The electrical control technicians completed steps 1-24.

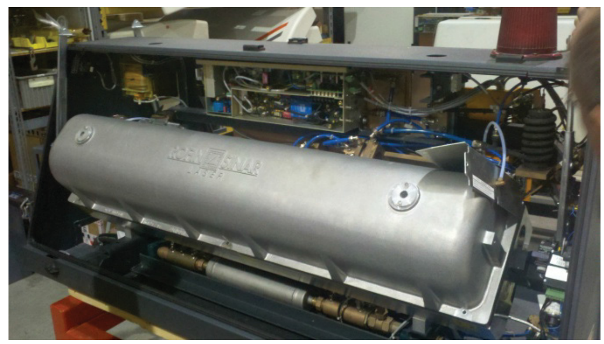

Figure 1. Optical cavity houses the slab and is equipped with sight glasses.

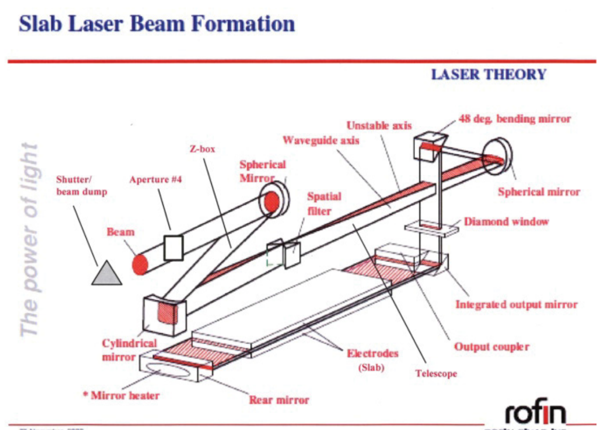

Figure 2. A schematic of the slab and internal optics.

The following shift, August 30, 2011, the electrical control technicians continued the PM, at step 25, with a paper shot. This shot is taken downstream of the shutter to determine if alignment within the resonator of the internal optics is needed. The PIC selected the "Mirror Alignment" screen on the HMI and entered/verified the parameters. Control was switched to the pendant, the pendant was enabled, and the "Cycle Start" button was pushed. Once the "Cycle Start" button was pushed, a beam was present, or active, through the beam-forming telescope and z-box (Fig. 2) to the shutter/beam dump. Thermal paper was positioned at an aperture just beyond the shutter. The PIC used the pendant to flash the shutter and take the shot and an image was burned onto the thermal paper. The image shown on the thermal paper indicated that the internal optics required some attention and possibly alignment.

The system was placed under LOTO to continue with step 26, inspection of the spatial filter assembly and beam absorber for coating damages. The z-box (Fig. 3) cover was removed to inspect the cylindrical, spherical, and power mirrors. Burn spots were found on the cylindrical and power mirrors, and they were replaced with new mirrors. The spherical mirror was cleaned and reinstalled.

Figure 3. Z-box.

The LOTO was released. Power was restored to the laser system, and the laser head was homed. The PIC, then, selected the “Mirror Alignment” program from the HMI screen, enabled the pendant and pressed the “Cycle Start” button.

Each of the electrical control technicians believed the laser system to be in “simmer” mode. In this mode, HV is on, power is sufficient to create a limited amount of optical radiation in the optical cavity; however, energy is insufficient for optical radiation to exit the diamond window and create a beam throughout the beam-forming telescope and z-box (Fig. 2).

At this point, indicators were present which, if not overlooked, would have alerted the PIC to the possibility of an exposed beam throughout the beam-forming telescope and z-box (Fig. 3). The screen on the HMI console showed a power level of 2500 Watts and the phrase “beam on.” Visual indication through sight glasses on the optical cavity (Fig. 1) showed a bright optical glow. “Beam on” was assumed to be equivalent to “simmer.”

After accessing the resonator platform and discussing where to take crosshair shots to verify or adjust the beam alignment, the technicians decided to start with the #4 aperture target (Fig. 2).

As one of the three technicians reached into the beam path to insert a crosshair target at aperture #4, they all saw a flash, and the technician immediately removed his hand with the crosshair target. The technician’s fingers were burned.

Work associated with the PM was promptly discontinued. The PIC turned off the HV at the pendant, all electrical control technicians left the work, the Forman and Supervisor were notified, and the injured technician was escorted to the on-site medical dispensary for evaluation.

Prior to the end of the shift, a fact-finding meeting was held after which the laser system was secured and placed in a safe configuration for future evaluation.

Investigation and Analysis

A cause analyst was charged with conducting an investigation to determine the cause or causes of the event as they relate to the 5 core functions of the Integrated Safety Management System (ISMS). In addition to reviewing training records and work control documentation, conducting interviews with the electrical control technicians, the Foreman, the Supervisor, the System Engineer and the LSO, the cause analyst utilized two analysis techniques, an Event and Causal Factors Analysis and Barrier analysis.

Core Function 1 – Define the Scope of Work. *Missions are translated into work, expectations are set, tasks are identified and prioritized, and resources are allocated.*

The work scope as identified in the WO was to perform the Electrical 2000 Hr. Run Time PMs as suggested by the vendor. This scope was well defined and understood by the electrical control technicians. They had previously performed the same PM tasks on a similar laser system and had a clear understanding of what was required to complete the work.

This core function was met.

Core Function 2 – Analyze the Hazards. *Hazards associated with the work are identified, analyzed, and categorized.*

A significant effort was made during 2010 to evaluate the hazards associated with laser maintenance activities. This effort reviewed the existing WO, observed laser maintenance tasks ongoing at the time, and reviewed LOTO practices. The LSO, System Engineer and Safety Engineer were extensively involved with this evaluation. The hazard evaluation focused on how and for what tasks the LOTO process was incorporated, as some tasks, particularly alignment tasks, must be performed with power available to maintain temperature equilibrium within the optics. While the obvious hazards were identified, the subtleties of how and at what point in the process these hazards would introduce themselves were not well-identified. This related back to the programming screens on the HMI console and how the program controls the beam, particularly in "simmer" mode.

This core function was not fully met.

Core Function 3 – Develop and Implement Hazard Controls. *Applicable standards and requirements are identified and agreed upon, controls to prevent/mitigate hazards are identified, the safety envelope is established, and controls are implemented.*

The details of the task were not fully defined during the work planning phase of this activity. As a result, specific information regarding the development of controls was not well defined. The controls implemented in the WO were based on LOTO to eliminate electrical, mechanical and beam hazards. Some tasks were never observed or discussed, and, as a result, specific controls for live beam work were not recognized or implemented. Some of these controls, such as turning off the HV versus effecting a full LOTO and checking the beam path with thermal paper prior to placing hands in the beam path were identified in the vendor's training and/or procedures; however, they were not formally incorporated into the WO. Specific controls for live beam tasks that needed a HV switch turned off, as opposed to being placed under LOTO, were not provided in sufficient detail in the WO. There was excessive reliance on the skill, training and experience of the electrical control technicians to perform the tasks safely.

This core function was not fully met.

Core Function 4 – Perform Work Within Controls. *Readiness is confirmed and work is performed safely.*

The WO contains a good, but incomplete set of hazards and controls. Hazard controls for mirror replacement (LOTO), open beam paths (establishment of a temporary laser control area (TLCA)), and mechanical motion (LOTO or exclusive control of the pendant) were followed. Other hazard controls requiring lower beam power settings, keeping body parts clear of the beam path, and wearing laser eye protection were not followed. Administrative controls such as following safety training tenets and using reference materials from the vendor were not followed. Most of the vendor PM procedures were referenced in the WO, yet the electrical control technicians sought to perform a number of the tasks from memory rather than having the documented procedures physically available for reference and review.

This core function was not fully met.

Core Function 5 – Provide Feedback and Continuous Improvement. *Feedback information on the adequacy of controls is gathered, opportunities for improving the definition and planning of work are identified and implemented, line and independent oversight is conducted, and, if necessary, regulatory enforcement actions occur.*

Prior to this event, the controls appeared to be adequate. The electrical control technicians had performed the same task a few weeks prior on a different, but similar, laser system without incident. Maintenance management was unaware of any concerns or difficulty following the WO. Safety and the LSO were not aware of any difficulty maintaining compliance with the controls or that the controls were inadequate.

This core function was met.

Conclusions

The direct cause of this event was the misunderstanding regarding beam functions while in the "Mirror Alignment" program screen. Factors contributing to the event include training, work planning, hazard analysis and work performance issues. The electrical control technicians received relevant training and had sufficient experience to perform the work safely but did not follow some key safe work practices, such as turning off the HV switch and checking for a beam prior to placing a target in the beam path.

The Safety Engineer, a Certified Safety Professional (CSP), has 23 years of experience with extensive knowledge in hazard analysis, LOTO practices and machine guarding. The LSO, a Certified Industrial Hygienist, CSP and Certified LSO, also has 27 years of experience with extensive knowledge in physical and health hazard analysis, laser safety, exposure assessment and LOTO. The System Engineer, with a bachelor's degree in electrical engineering and more than 10 years of experience with laser systems, was new to the facility (fewer than 10 months) and still learning about the laser systems to which he was assigned. Education and experience in safety, industrial hygiene and engineering disciplines is no substitute for hands-on knowledge and experience, and it is sometimes difficult to admit one's limitations. It is imperative that craft personnel, with hands-on knowledge and experience, and safety and engineering professionals work together, educate each other, to provide a clear understanding of the tasks to be performed, to expand awareness of the hazards, and provide a thorough hazard analysis.

The WO, while more detailed than most work instructions found in private industry, lacked critical instructions regarding the alignment task and did not reference the specific Rofin procedure for the alignment task. Profound differences in how LOTO requirements are implemented in private industry versus a Department of Energy facility contributed to the limited formal use of vendor procedures and resulted in the performance of tasks from memory. There is a strong possibility that the step-by-step use of the vendor procedure would have prevented the injury-inducing interaction with an active laser beam. The concerns regarding the inconsistency in implementation of LOTO requirements were not discussed or communicated to the LSO or management in the maintenance organization and common ground was not established with the safety engineer, thus, the hazard analysis gap was not identified and there was little opportunity to formally incorporate the vendor procedures such that they complied with in-house LOTO and safety policies.

Training Issues

1. Vendor training on the resonator system was conducted using a Rofin HMI that was not the same as the Cincinnati HMI available to the electrical control technicians at SMC. The technicians were unfamiliar with the differences in system status of the program screen they used. The "Mirror Alignment" screen flashes the shutter (Fig. 2) and is primarily designed for alignment of the external optics in the Cincinnati portion of the laser system. The "Resonator Service" screen flashes the resonator and is designed for alignment of the internal optics in the Rofin portion of the laser system. The electrical control technicians were more comfortable accessing the "mirror alignment" screen. Although alignment of the internal optics may be achieved using this program, from a safe work practice perspective it is not the preferred method.
2. The electrical control technicians performing the PM misunderstood the concept of "simmer" mode. As was previously explained, insufficient energy is present to produce a beam beyond the diamond window. Theoretically, no exposed beam would be present, and, thus, no beam hazard. This belief appears to have been created through a combination of circumstances. First, when the technicians had performed crosshair shots in the resonator chamber on the internal optics (Rofin portion of the laser system upstream of the shutter), the "Resonator Service" program was used creating the "simmer" mode. The beam was not present prior to and after taking a shot, as evidence by the paper inserted in the crosshair target. The beam fired (resonator flashed) and returned to "simmer" mode. The Rofin training and procedures require the HV to be switched off prior to placing anything in the beam path. Second, when working on the external optics (Cincinnati portion of the laser system downstream of the shutter), the shutter mechanism prevents the beam from entering the beam delivery system, a level of protection preventing an active beam presence in the external optics beam path. Cincinnati technicians would have used the "Mirror Alignment" program, and pressed the "cycle start" button to generate a beam beyond the diamond window, through the telescope and z-box, to the shutter/beam dump. When the beam fired, the shutter would flash, allowing the beam to travel into the beam delivery system and through the external optics. The "simmer" mode was misconceived as applying to both situations and not corrected by either vendor.
3. Although electrical and laser operator training and qualifications were identified and required to perform these tasks in the WO, the specialized vendor training courses, retraining requirements every 18-24 months, and methods to track the off-site training were not defined. The difference between the Rofin and Cincinnati training was not recognized.

Work Planning Issues

1. The hazard identification process relied on the skill, training and experience of the electrical control technicians and did not identify some important safety rules established by the vendors. As such, the work order lacked specific controls required to safely perform the work tasks.
2. The WO did not provide a thorough set of work instructions, specific hazard controls, or references to specific vendor procedures to perform the tasks safely. The WO relied on specialized training rather than establishing consistent instructions for the electrical control technicians to follow.

3. Laser eye protection was specified in the WO, and polycarbonate safety glasses were worn. The eyewear worn met ANSI Z87 requirements for safety eyewear; however, the eyewear had not been formally evaluated for laser use and was not labeled with the optical density (OD) and wavelengths for which protection is afforded. It was later determined that safety glasses with polycarbonate lenses were sufficient protection for the tasks to be performed.
4. Applicable vendor procedures were not appropriately incorporated or referenced in the WO.
5. Section I, step 26, of the WO instructions did not provide adequately detailed instruction, reference the correct vendor procedure or discuss applicable safety requirements to perform the task safely. This step instructed the electrical control technician to inspect the spatial filter assembly and beam absorber for coating damages using Rofin procedure VA-19-01-24. The first step in this procedure for ensuring proper spatial filter adjustment is to ensure there is a good alignment from the diamond window through the whole beam forming telescope, which is performed using Rofin procedure VA-19-01-033. This instruction was not included or detailed in the WO, nor was the proper Rofin procedure for that alignment activity referenced or included.

Work Performance Issues

1. The electrical control technicians performed portions of the task from memory rather than refer to the Rofin vendor manual procedure VA-19-01-33. During the post-incident investigation interviews, electrical control technicians identified concerns regarding inconsistencies in the implementation of LOTO policies at SMC versus private industry and how the vendor procedures could be executed when those procedures directed the technicians to turn off the HV rather than place the system under LOTO. These concerns were not communicated to the LSO or anyone in the maintenance management chain of command. A lengthy discussion took place with the safety engineer but common ground was not reached regarding when or if LOTO was appropriate for all tasks. Because Rofin procedure VA-19-01-33 did not meet the policy expectations for LOTO at SMC, the document was not incorporated or referenced in the WO. The technicians attempted to perform the steps of this procedure from memory and failed to perform an initial key safety step: turn off the HV prior to entering the beam path.
2. Vendor training encouraged the practice of inserting a piece of thermal paper into the beam path to verify the beam was not present prior to placing anything in the beam path; however, this practice was not consistently practiced by every vendor technician. This variance in practice by the vendor technicians, along with the expectation that an exposed beam was not present in “simmer” mode, reinforced a bad habit of not checking for an active beam prior to interacting with the beam path.
3. The electrical control technicians developed a level of confidence based on their experience with other laser systems at SMC. In some cases, this confidence led to a departure from safe work practices encouraged at the vendor training.

Hazard Analysis Issues

1. During the hazard assessment, the support team (Safety Engineer, LSO, and System Engineer) relied on the electrical control technicians’ skills, training, and experience to educate them on the work tasks and activities in order to develop the hazards and controls. After the WO was issued, these support personnel provided insufficient follow-up of the work activities to verify the effectiveness of controls and that the actions taken by the electrical control technicians were appropriate for the level of risk.
2. The assessment of risk relied on expert-based controls rather than standards-based controls as was the expectation from line management. When non-standard controls are used, the effectiveness of those controls must be confirmed. In this case, follow-up monitoring to verify the work was being performed in a safe and compliant manner was not adequately performed.

Lessons Learned

The training audience, content and frequency of retraining are critical to understanding complex systems, how components from multiple vendors interface, where hidden or subtle hazards may manifest themselves, and for maintaining a level of competency with respect to these complex systems.

These laser systems merge major components from multiple vendors. Each vendor provided training independent of the other and did not recognize the limitations of the training once the components were merge into a single system.

Confidence in one’s skill and knowledge sometimes limits critical communication between work groups, allowing assumptions to be followed and insufficient identification of hazards. Work environments which foster open communication between all work groups without hesitation allow more thorough evaluations of work activities.

Providing written work steps of sufficient detail and inclusive of all hazards and controls is always more consistent than performing work steps from memory. When bypassing interlocks and controlling the laser system from the pendant, the following additional controls were implemented.

1. The PIC is solely responsible for operating the pendant and ensuring personal are clear of hazards.
2. Establish and document conditions under which it is appropriate to switch off the HV versus placing the system under LOTO.
3. Prior to live electrical or beam work, validate the HV status using signal lights and indicators on the HMI console.
4. In addition to noting the shutter position on the HMI console, physically check the status of the shutter position.
5. Prior to entering the beam path, physically verify the absence of a beam with thermal paper.

Although the electrical control technicians, Safety Engineer, LSO and System Engineer were all well-educated, trained and skilled in their respective fields, trust and communication are imperative to understanding complex systems, work objectives and tasks. Objective evaluation and follow-up monitoring are necessary to ensure appropriate safety practices are implemented and to identify when they can be improved.

Tekla A. Staley, CIH, CSP, CLSO, *is a senior S&H engineer at the INL. She has a BS in chemistry with a minor in business management from the College of Idaho and 27 years of experience in the field of IH and safety. Tekla has been employed at the INL since 1990 with assignments at the Reactor Technologies Complex, TAN, Idaho Nuclear Technologies and Engineering Center, and SMC, and is experienced in semiconductor manufacturing and asbestos abatement. She is responsible for Asbestos and Laser Safety programs; was assigned to the Three Mile Island Fuel Drying/Storage and the Cask Dismantlement projects; has consulted with the US Army on proposed methods for destruction of VX nerve agent; and assists DOE-ID in providing independent IH assistance at US Army contract facilities in the US. Tekla is a member of the ANSI Z136 committee for Safe Use of Lasers in Manufacturing Environments.*

Keven S. Butler, MS, CSP, *is a member of the Idaho National Laboratory Safety and Health Organization. He holds a BiT Degree in Industrial Technology and MS Degree in Industrial Safety from the University of Idaho. Keven has 23 years experience as a safety professional specializing in machine guarding, event investigation, cause analysis, risk assessment and human performance. Keven has performed event investigations and safety assessments throughout the Department of Energy complex, including the Nevada Test Site, Brookhaven National Laboratory, Oak Ridge National Laboratory and Idaho National Laboratory. Keven currently supports the Specific Manufacturing Capabilities (SMC) project at the INL.*