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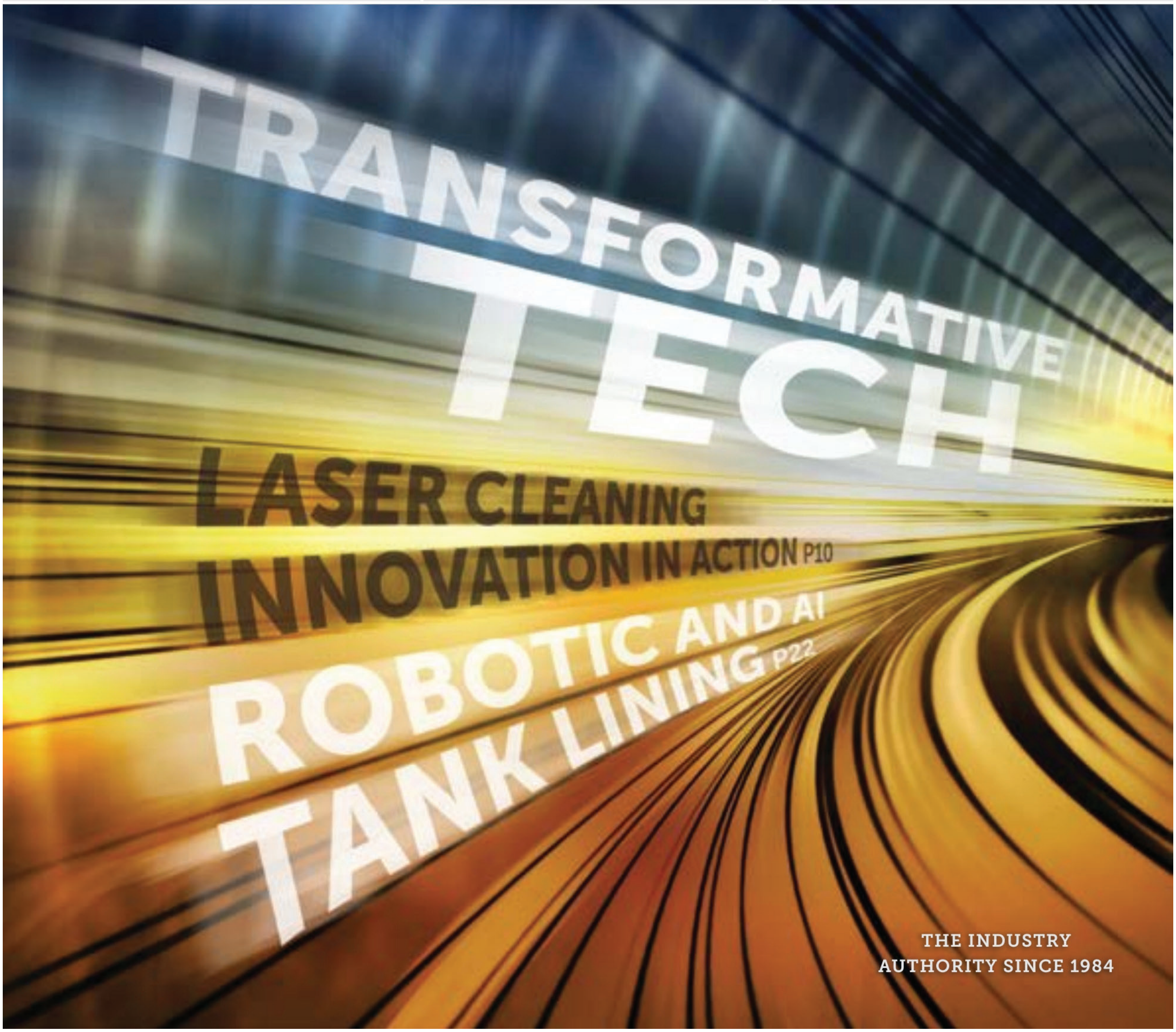

ZAP! LASER CLEANING ON BART'S TRANSBAY TUBE RETROFIT

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FIG. 1: Steel fabrication facility

It is the summer of 2018, and I am at a vast steel fabrication plant ***(Figs. 1 and 2)***. The first sets of steel plates for the BART (Bay Area Rapid Transit) Transbay Tube lining project are being shop coated. The 100%-solids epoxy system specified requires heated plural-component application equipment and the coating is notoriously intolerant of surface contamination. The onsite painting crew is relatively unfamiliar with the sophisticated equipment but has hired experts from the coating supplier to provide the plural pump with a skilled operator.

The Problem

The 5-foot-by-10-foot plates were successfully coated with a single monolithic coat of 30 mils and cured well. But there is a mysterious problem: on at least one of the plates, along just one edge, the coating is starting to lift. Visually, it looks fine. The cure and color are uniform and look good. The blast profile is angular and has a good 3-4 mil profile. All the QC checks were passed. But the coating at the edge is loose. A putty knife can lift off the coating for a few inches from the edge.

The other edges of the plate were masked for welding, and on those, the exposed edge of the coating is tight and no lifting with a putty knife is possible. Looking at the exposed blast under the lifted coating, it is clean and has the proper profile. No oil, grease or other waxy contaminants that could act as a bond breaker are visible. On the underside of the lifted coating, there is some evidence of slight (dust?)

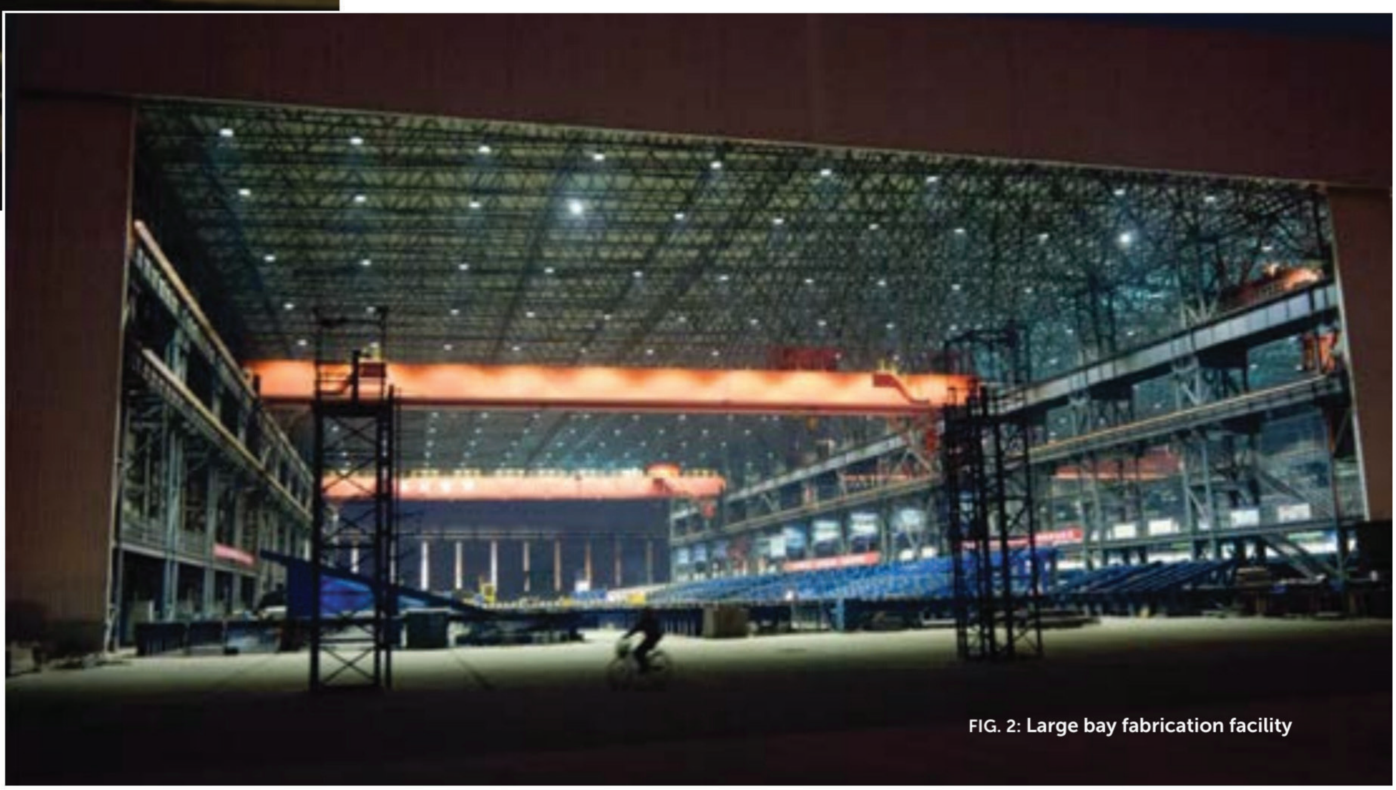

FIG. 2: Large bay fabrication facility

PHOTOS: COURTESY OF ROBERT IKENBERRY

contamination. Several inches of the coating on the edge of the plate is loose, but is tightly adhered on the rest of the plate ***(Figs. 3 and 4)***.

After much investigation and head-scratching, the layout foreman finally confessed that he had originally asked the masking crew to mask off the unbeveled edge of the plate, which they had done. Then he realized that only the three beveled edges needed masking, so they had removed the tape. This was done in the blast room. The final step was to blow down the plates before they were moved to the paint

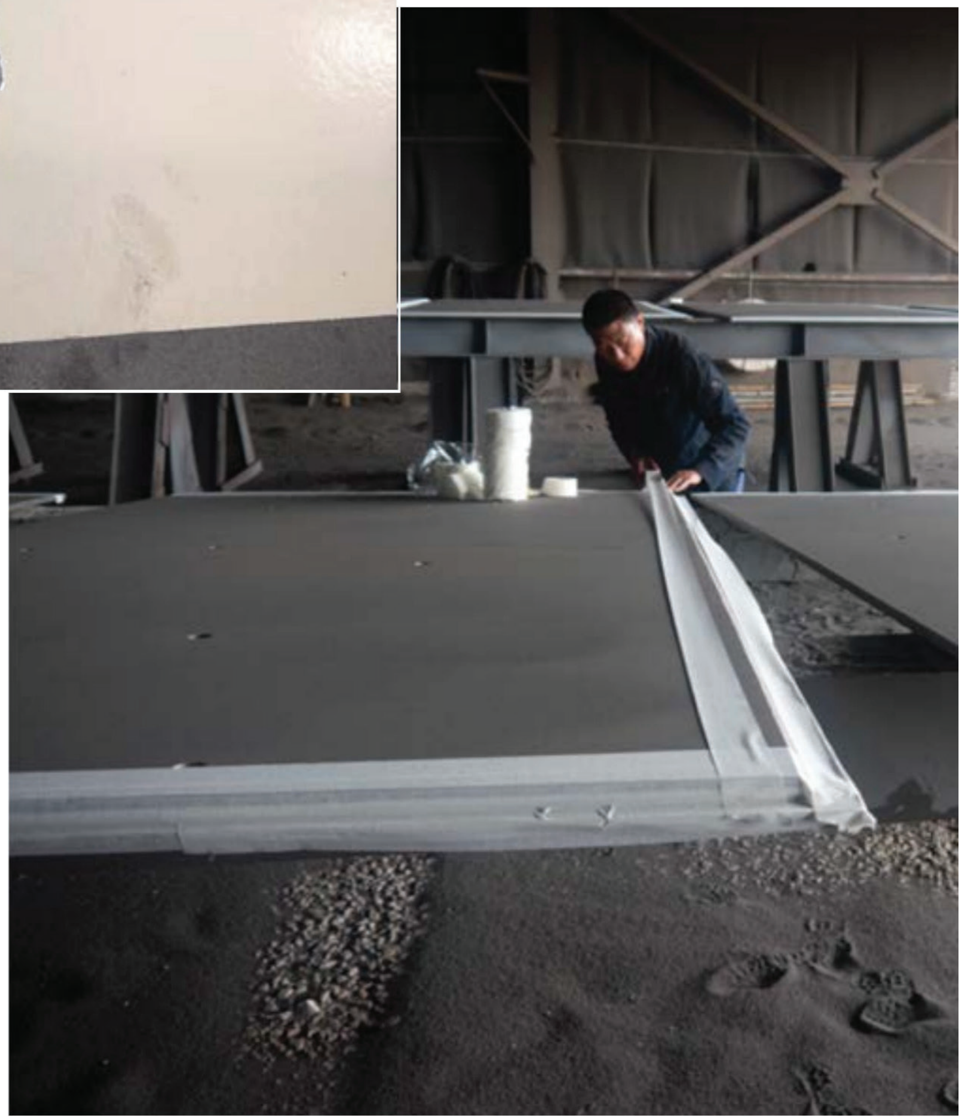

FIG. 3 *(above)*: Plates with masking *(note edge with no masking)*

FIG. 4 *(right)*: Lifted coating and large chip flipped over room. Apparently, dust stuck to the small amount of adhesive which was left over and caused a total coating adhesion failure.

The fix was simple – the plate was re-blasted and re-coated – but it got me thinking that we had a potential big problem in the tube, when months or years later, after ocean shipment, handling, installation, welding, NDT and exposure to the operating trains, we were going to have to clean and paint all these weld lanes. No blasting would be allowed in the tube, and no solvents would be permitted.

The Search

Finding an efficient, practical and cost-effective cleaning solution was going to be a problem. Plus, the blast profile applied to the plates, including the exposed edges, was solid and we wanted to preserve it if possible. Recent studies, including a personal opinion of one of the authors, questioned the benefit of re-blasting or spot-blasting previously blasted surfaces and the immediately adjacent painted surfaces. The issue was effectively moot, as blasting in the tube was prohibited, but we did know we wanted the cleanest, most angular substrate we could get, while removing all traces of rust, salt, oils, grease and dust (which may be magnetic and statically attracted to the steel). That was going to be a challenge.

In addition to the technical challenge of cleaning the weld lanes, there were immense logistical challenges on the job. The Transbay Tube runs over three miles under the San Francisco Bay and there were only two access points – Oakland and San Francisco. We were lining about 2,200 feet of the bores, one Eastbound and one Westbound, and there were typically five longitudinal weld joints in each tube and circumferential seams every 20 feet. That meant we had about 16,000 linear feet of welds to prepare and coat (about 16,000 square feet) and needed to do the work at the very end of the job when there was tremendous pressure to finish. All materials had to come in on a work train that arrived either after revenue service stopped (around 1:00 a.m.) or, if we were lucky, when the trains could be single-tracked with the other tube bore handling traffic in both directions (starting around 10:00 p.m. at the earliest). In either event, we had to be complete and out of the bore, cured and with trains ready to run by 5:00 a.m.

We considered numerous options for cleaning, including wet methods (water-based caustic cleaners,

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FIG. 5: **Custom painting rail car**

Just two questions remained. First, was the steel clean enough? And second, could we safely deal with the risks of a high-powered, invisible infrared laser? As it turned out, there was also a third question: Could we afford it?

detergents and non-flammable solvents) and abrasive methods (abrasive discs, wire wheels, flapper discs, roto-peen scaler, bristle blasters and new technologies). For application of the epoxy coating, we needed to use plural-component systems that could heat the material to about 110 F at time of application. We experimented with air-atomized dual-cartridge kits, but ultimately settled on typical industrial plural-component pumps. To accommodate the owner's requirement not to have exposed solvents in the tube, we developed a closed-loop, air-scrubbed flush kit that prevented exposed solvents and trapped vapor and odors (fuels were allowed in the tube on the diesel trains, so we modeled our system after a typical fuel system and limited the quantity to about three gallons total).

We developed a dedicated painting rail car to transport and handle the paint pumps and to provide elevated access to the interior surfaces of the tube ***(Fig. 5)***. Now, all we had to do was figure out how to clean the welds and the weld lanes.

A Possible Solution

I had been interested in high-energy lasers for field cleaning of steel since we had done a small job for the Lawrence Livermore National Laboratory for one of their NOVA laser guide pipes in the mid-1980s. It always seemed the technology was 10 (or 20) years away and 10 (or 100) times too expensive – much like fusion power.

PHOTO: COURTESY OF ROBERT IKENBERRY

We thought we would take another look at the state of the art in mid-2019. It turned out that the Air Force had been testing lasers for cleaning aircraft prior to painting at Travis Air Force Base, a local base in Fairfield, California. It looked like the Air Force had generally considered their tests to be a success, but I had trouble getting anyone associated with the program to talk to me. Eventually, we located the equipment manufacturer and late in 2019 took a trip to Kansas City, Missouri, to check it out. It was the dead of winter and just before the beginning of COVID-19 lockdowns. We brought a couple of sample pieces of steel, cut from a painted plate, with both blasted (and rusted) steel and coated portions, and put the equipment to the test.

I was impressed with the results. The laser appeared to quickly clean the blasted steel, re-exposing the surface profile applied in the shop, and could put an etch onto the adjacent coated areas ***(Fig. 6)***.

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PHOTO: COURTESY OF ROBERT IKENBERRY

FIG. 6: **Laser cleaned steel sample with etched coating in lower area**

Clean Steel

If it worked, the laser would solve a lot of problems – it could provide us with a scrupulously clean surface and expose the original profile that we knew was done well in the shop. There would be no spent abrasives to deal with and no significant waste generated from the process. The tiny amount of vaporized debris from the steel would be sucked up by a vacuum during the lasing process, and noise levels would be relatively quiet compared to abrasive blasting or grinding. We knew we could not deal with the noise and dust of abrasive blasting, and other methods were proportionally much, much slower compared to the laser method and would not ensure as good a profile. The laser really sounded perfect for our needs.

We sent back a couple more test coupons, intentionally contaminated with the types of contaminants we would have to deal with (like tool lubricants, salt from the ocean voyage, ultrasonic coupling gel, and metallic dust from the rails) and asked the laser manufacturer to clean them and then carefully seal them and send them back. We then contacted the coatings manufacturer and asked them how best to test the cleanliness and if they would approve the method. They said to paint the cleaned panels and then do some pull tests. If they passed, they would allow the cleaning method. We did this and they passed with flying colors. Our first question was answered.

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Safety Concerns

Our second question took a bit more work. We would offer that this is the most important part of this article. Please take careful note that the technology involved here is very powerful,

FIG. 7: **Protective eyewear with OD of 7 for IR radiation at 1064nm**

The human eye's protective reaction to light does not work with infrared lasers. There are no protective "flinches" from your eyes, like looking at the sun or a too-bright welding arc flash ... You do not know you are at risk until your retinas are instantly destroyed.

but invisible, and that constitutes one of the biggest risks. The human eye's protective reaction to light does not work with infrared lasers. There are no protective "flinches" from your eyes, like looking at the sun or a too-bright welding arc flash. Laser energy is at a whole other level. You do not know you are at risk until your retinas are instantly destroyed. Loss of sight is a crippling injury and not one to be taken lightly.

Because the laser light is coherent and collimated, the direct beam from the tool head does not spread, so distance, or reflection from a mirror, is not a safe measure of protection. The diffuse reflections from a non-specular surface (in other words, not a mirror) do spread with an inverse square reduction in intensity. Therefore, reflections from blasted steel or other surfaces are much less risky than direct exposure to the beam, but those reflections are still present.

Raw numbers probably do not mean much, so let us try an analogy. First, it is not a good idea to look directly at the sun on a bright, clear summer day. In fact, if you have normal reflexes, you will turn away in a fraction of a second, because your body knows it is not a healthy thing to do. Now, remember back to playing around with a magnifying glass on a similar sunny summer day. If you had a piece of wood handy, and a steady hand with a bit of patience, you could bring the light of the sun to a point on that wood and char the surface of the wood, maybe even raise a whiff of smoke. If you had a 4-inch-diameter glass and made a bright spot about 1/16th-inch across, that was a concentration of about 4,000 times. So, the sun was 4,000 times brighter to that scrap of wood and it singed it in seconds.

That is nowhere near as bright as our laser. Imagine what concentration power it would take to not just char the wood, but to actually cause the air at its surface to explode in a flash of ionization. We are talking more like millions of times brighter, not thousands.

Another reference is that to safely be around the laser, you need to wear safety glasses that have an infrared (IR) radiation protection factor (Optical Density or OD) in the wavelength of the laser (1,064 nm) of 7+ or less than 1/10,000,000 transmission. These safety glasses block out 99.99999% of the laser light.

To put it another way, if you have ever cupped your hand over a powerful flashlight in a dark room, you can still see a dim red glow through your hand. If IR worked the same way as visible light (it probably doesn't), covering your eye with the palm of your hand likely only provides a visible light OD of about 4 to 6. So, the intensity of the laser light would still be at least ten times too bright to safely look at — through your hand! ***(Fig. 7)***

Ideally, the active laser head would be interlocked to the surface to be cleaned. If an interlock like this was in place, the laser would only work if the head were in contact with the steel. Lift the tool and the laser stops. Unfortunately, we could not locate a head/interlock combination

PHOTO: COURTESY OF ROBERT IKENBERRY

that would work reliably — and, as it turned out, the actual use of the tool was most effective when held about 12 inches from the steel surface, not in contact.

Laser Safety Requirements

Referencing ANSI standard Z136.1 on Safe Use of Lasers, there was not a specific part of the standard for what we wanted to do: use a laser on an underground field construction project with adjacent workers, but no public exposure risk. So, we jumped into researching our options and obligations.

Lasers are categorized by risk, from Class 1 (your typical lecture hall laser pointer) through 1M, 2, 2M, 3R, 3B all the way to Class 4. Our Laser was a Class 4. That meant we were required to implement all of the standard's Laser Safety protocols:

1. Control measures
2. Training
3. Utilize a Laser Safety Officer (LSO)
4. Engineering Controls

Fortunately, our project safety team included a member with laser safety experience. He was qualified to act as our LSO and could guide the review of risks and help implement the necessary training and develop the Laser Safety Program and Laser Hazard Assessment.

We were confident we could operate the laser safely (more about that later). But could the laser do the job in the time limit we needed? And could we get the equipment in time? Testing showed that the laser was fast and that we could probably clean about 200 square feet per hour.

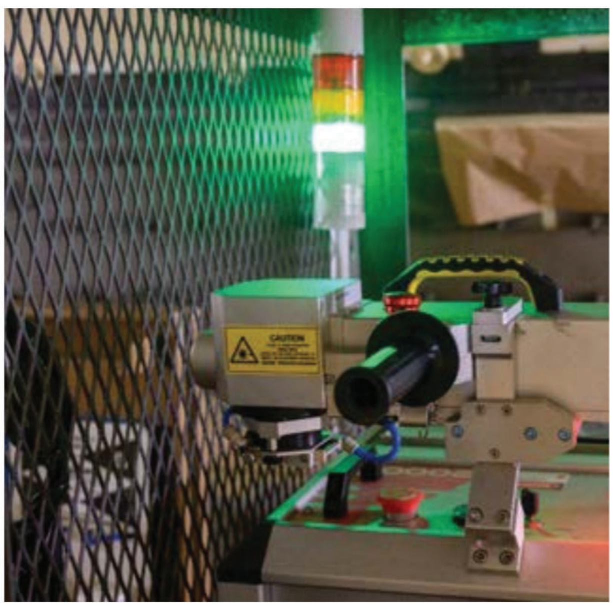
As mentioned before, time in the tube is critically important, as the trains can only be shut down for a few hours per night. The entire operation must be completed in about six hours, so considering getting the work train into position, setting up, laser cleaning, masking, preparing the plural-component equipment, spraying out the weld lanes and packing up and getting out in time for the trains to run in the morning — maybe two hours per night would be available for cleaning. If we could do 400 to 500 feet of welds in a night, this might be doable.

We ordered the laser.

Laser Containment

Because the laser system was so powerful (we ordered a 2,000-watt laser system), there was no reasonable safe distance that we could establish. In other words, if you were in the work zone, you could not be far enough away that if the direct beam from the laser shone in your eyes that you would be safe from possible injury. Therefore, anywhere the laser was operating was a Laser Controlled Area. The only way to protect non-involved workers was to isolate them. So first, we had to enclose the laser work area from all other non-laser workers.

The work areas are in the bores of the BART Transbay Tube, a typical subway track with a diameter of about 18 feet. We were working off a special-built rail car that housed the laser equipment, the plural-component paint spray equipment, and movable work platforms that allowed access to the interior surfaces of the Tube. A work zone of about 200 feet was established, and then shield drapes that were impervious to the IR laser radiation were hung at each end of the work zone, sealed to the floor and walls, and an interlock was established that would cut off the



Top to bottom:
FIG. 8: Laser Drape isolating the Laser Controlled Area

FIG. 9: Laser unit, green light = power on, no high voltage

FIG. 10: Lasing—all three lamps illuminated

PHOTOS: COURTESY OF ROBERT IKENBERRY

laser if anyone entered the drapes when the laser work was in process. If there were doors to the lower gallery within the work zone (doors are at intervals of about every 350 feet) or if there were ventilation louvers to the upper gallery (ventilation duct), they were also sealed and interlocked.

Adjacent to the interlock at the drape was a Visible Laser Radiation Emission Warning Device with three lamps. If all the lamps were dark, the laser was disconnected from power. If the green lamp was on, the laser had power but was not ready to fire. If the yellow lamp was on, the laser was powered up and ready to fire (high voltage on) but was not working at that time. If the red lamp was illuminated, the laser was operating. Before the yellow lamp was armed, all non-laser workers exited the laser work area and the entry to the enclosed area was secured. No one was permitted to open the drapes or otherwise defeat the interlock if the yellow or red lamps were on. Laser warning signs were posted at each entrance. The entire tube between the drapes became an Interlocked Removable Protective Housing, and a Laser Controlled Area as required for Class 4 lasers ***(Figs. 8-10)***.

Training Required

Next, we had to prepare a training program and protocol for all workers who would be operating the lasers or in the laser area while the laser was operating. The primary responsibility for ensuring the safety of laser operations are the operators (under the training and advice of the LSO). Operators needed to know how to safely handle the equipment, including the waveguides (cables sending the laser energy to the head) and the

FIG. 11: Laser in operation *(Note, the laser beam is invisible, but here one can see its path due to ionized dust particles that are being excited by the laser and show the beam.)*

PHOTO: COURTESY OF ROBERT IKENBERRY

laser head, including ensuring the optical windows are clean and sound. Once the operators were trained and knew how to safely handle the laser equipment and protect others, we instituted control measures.

Engineering controls were the first line of defense, such as the interlocks at the enclosure of the laser workspace. The operators used administrative controls, to know not to activate the laser if non-approved personnel were present, and how to operate the laser to minimize risks to other workers. Lastly, personal protective equipment, such as the laser eyewear with an OD of 7+ for the 1,064-nm laser wavelength, were always used by everyone in the Laser Controlled Area. Other measures, such as prohibiting magnifying lenses, mirrors or reflective vests in the LCA, were instituted as appropriate.

We were also fortunate to have the support and cooperation from the owner. BART recognized that this cutting-edge tool could improve both production speed and quality, creating a cleaner surface than any of the originally anticipated methods.

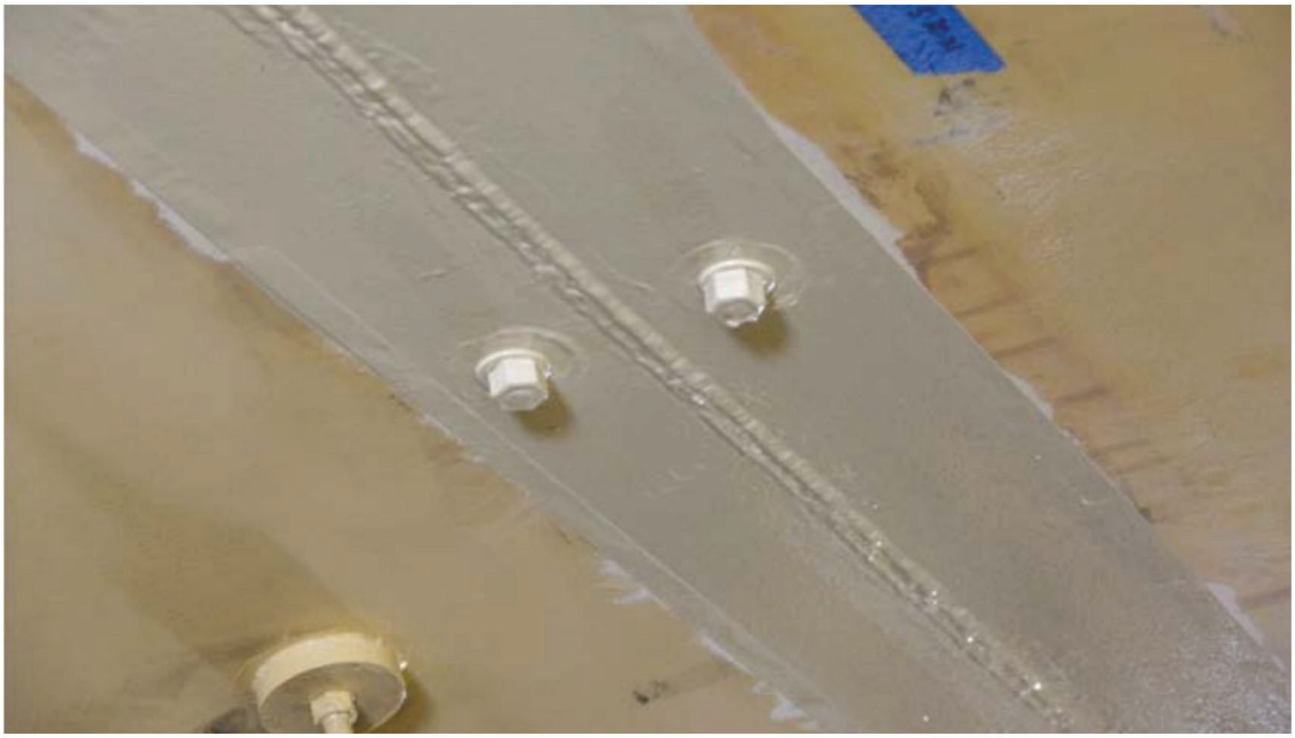
Laser Operation and Coating Application

Now the pieces were finally coming together. The equipment was in place, the work zone enclosures were designed and tested, the electrical power supply for the laser was secured (about 25KW for the laser and another 4KW for the chiller), the workers and operators were trained, the procedures and safety measures were in place, and we were ready.

But this is construction, so Murphy's Law applies. Nothing goes exactly to plan. Several shifts were required before all the parts would come together. The end of shift deadline to open the Tube and tracks to the morning commute was inviolate. In almost four years of work, we had never missed a track opening, and we were not going to miss one now. There were several times when difficult calls had to be made – when a missed milestone in the operation could have meant we would not have cured coating in time, or were not be able to pull the paint car out – and the shift had to be abandoned and clean-up started without putting on any paint.

In operation, the laser cleaning system used two operators – one to handle the actual laser head and one to keep a vacuum extraction head close to the work, but not in the beam of the laser ***(Fig. 11)***. Typically, no other workers were in the Laser Controlled Area for the cleaning operation.

After a few hiccups, we did get the procedures down so that the multiple Single Points of Failure (SPFs) were all routinely passed, and the weld seams were successfully coated. With the



Clockwise from top:
FIG. 12: **Spray application**
FIG. 13: **Checking WFT**
FIG. 14: **Finished weld lane**

PHOTOS: COURTESY OF ROBERT IKENBERRY

laser cleaning system and a full-scale plural-component pump system, we were able to apply the coating at rates multiple times faster than the manual cleaning (such as bristle blasting to SSPC-SP 11) and cartridge spray production rates we had originally anticipated ***(Figs. 12-14)***.

Conclusion

This was a very special application. Working in the Tube, under the Bay, we could isolate the work zone in secure ways that would not have been possible in an outdoor construction environment. The laser offered special advantages in speed and waste reduction for our particular and sensitive project that offset the spectacularly high cost of the equipment which would not have been justified on a project where abrasive blasting was allowed, or the daily time constraints were not so severe. A very specialized tool, but just the right one for a very special project. JPCL

ABOUT THE AUTHORS

Robert Ikenberry is Coatings Manager for California Engineering Contractors (CEC). He began his career in protective coatings at Fluor Engineers and Constructors as an associate engineer. Moving to the contractor side, Ikenberry worked as an estimator and project manager for Certified Coatings. In 1991, he transitioned to Safety Director, where he was an early specialist in lead compliance programs. He joined CEC in 2000 as Safety Director and in 2005 added Project Management duties. He has been a contributing editor for JPCL for almost 30 years and has authored numerous articles for the journal, as well as many blog posts for PaintSquare focusing primarily on safety and technology-related topics. In 2020, he was named to JPCL's newly formed Editorial Advisory Board.

Jim Healy is a Safety Manager with California Engineering Contractors with over 20 years of environmental, health and safety experience. He began his career as a ship engineer and moved into building ships in Japan and California, continuing as a mechanical and electronic technician in the air separation and petrochemical industries prior to starting his current career in environmental, health, and safety. Healy also has several years of laser safety experience at high-energy levels that he employed for the BART Transbay Tube project.

Ethan Standen is a Project Sponsor for Shimmick Construction with nearly 10 years of experience in industrial protective coatings for water treatment plants and marine environments. With his deep understanding of the intricacies of coating projects, he has successfully led multiple projects from conception to completion, ensuring high-quality workmanship, and timely delivery.

Mark Stewart is a principal at Stewart Consulting Solutions, where he consults on difficult and challenging coating applications, develops solutions and ensures successful implementation through hands-on follow up. He has been involved in protective coatings his entire career, starting with the use of the tools of the trade directly, moving on to working as a third-party inspector with real practical knowledge of all aspects of protective coatings. Stewart is a NACE-certified Level 3 Coatings Inspector (now AMPP Senior Certified Coatings Inspector).

For more information about the laser cleaning technology that was considered for the BART Transbay Tube project, visit laserphotonics.com or adapt-laser.com.

PHOTOS: COURTESY OF ROBERT IKENBERRY