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UNDERWATER LASER PEENING

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Abstract

Stress Corrosion Cracking (SCC) is one of the major concerns for aged nuclear reactors. SCC-susceptible materials have been employed in a wide variety of applications in the nuclear industry. Laser Peening (LP) is a method of SCC-mitigation that eliminates surface tensile stress using the impulsive effect of high-pressure plasma induced by irradiation with high-power laser pulses in water. To apply laser peening for nuclear reactor internals, Toshiba has developed a new process that needs no protective coating on the materials and optimizes the conditions for the laser irradiation. Its effects for stress improvement and SCC-mitigation of laser-peened materials were confirmed through SCC tests for austenitic stainless steels and nickel-based alloys, and the integrity of the laser-peened materials was also confirmed through various examinations. Toshiba has developed a laser peening system for the core shroud and the reactor bottom part of BWRs and has applied it to actual Japanese nuclear reactors since 1999. As for PWRs, Toshiba has developed a system for Bottom-Mounted Instrumentation (BMI) nozzles and other Reactor Vessel (RV) nozzles, and has started to apply it for Japanese PWRs since 2004. Toshiba has already completed laser peening operations for two PWR plants and eight BWR plants in Japan. In consideration of extending the application to BWRs and PWRs in the overseas market, a portable laser peening system equipped with a small size laser oscillator has been developed.

1. Introduction

Stress Corrosion Cracking (SCC) is one of the major factors to reduce the reliability on components of nuclear reactors. SCC-susceptible materials have been employed in a wide variety of applications in the nuclear industry. Welded repair and replacement of these susceptible materials is sometimes possible, but often entails considerable expense and schedule impact. Alternate methods of mitigation against SCC are available for field implementation. One typical mitigation alternative entails grinding and welding, which, while often effective, can result in substantial radiation exposure as well as challenges to both weld quality and final examination of weld deposits. It is widely recognized that SCC requires three key factors to occur: a) a susceptible material; b) a corrosive environment; and c) a tensile stress. Mitigation alternatives that eliminate any one of these three factors effectively mitigate SCC by eliminating SCC susceptibility.

The underwater laser peening process is a method of SCC mitigation that eliminates one of these three key factors, i.e., tensile stress. Shot peening, which utilizes the collision of high-speed small shots, has been used to introduce the compressive stress and extend the fatigue life of metal components for many years in the industrial field. A similar effect can be achieved with laser peening by irradiating an intense, short laser-pulse on the metal surface in water to create a high-pressure plasma, which in turn creates plastic strain. The laser peening process, which is an inertia forceless process, has some advantages compared to the shot peening, in that laser peening can be applied in narrow and highly radioactive spaces. Toshiba has developed a remote processing system for laser peening and has applied it to existing nuclear power plants to reduce the susceptibility to SCC since 1999 [1].

2. Fundamental Process

Figure 1 shows the fundamental process of Underwater Laser Peening. When a nanoseconds-order laser pulse is focused on a metal material in water, its surface absorbs the laser energy and the metal plasma is created through the ablative interaction. The inertia of water acts to confine the metal plasma and prevent it from expanding quickly, and, as a result, high-pressure plasma forms on the metal surface. The plasma pressure, which impinges the metal surface, reaches several GPa and exceeds the yield strength of metal material. The surrounding metal material constrains the strained region and forms compressive stress in the surface layer. The residual compressive stress can be introduced in the metal surface layer by scanning the laser pulses across the entire surface to be treated [1].

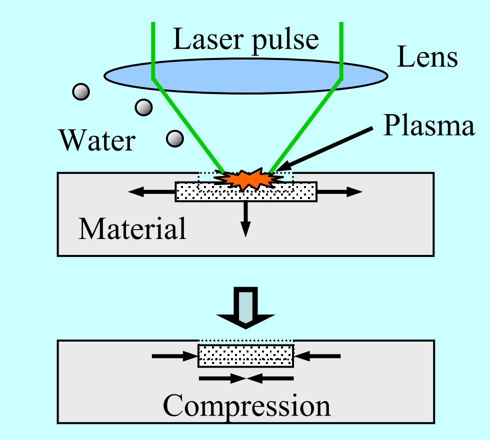


Figure 1. Fundamental Process of Underwater Laser Peening

The conventional method of laser peening has utilized a protective coating (sacrificial overlay) on the material surface to enhance laser absorption and to prevent the surface from melting or being damaged. It is usually formed from black paint prior to laser irradiation and the remaining portions are removed after the treatment. Toshiba has developed a new process without coating. This process employs a smaller power laser source under carefully controlled conditions to mechanically deform the surface of an SCC-susceptible material. This mechanical deformation effectively eliminates surface tensile stresses, and thereby mitigates SCC-susceptibility.

3. Effect on Materials

Figure 2 shows a depth profile of the residual stress in the surface of a laser-peened Alloy 600 sample, which was peened in a small water tank. The laser source was a Q-switched Nd:YAG laser with water-penetrable wavelength of 532nm. Laser pulses were scanned horizontally and vertically as shown in Figure 3. The residual stress was measured in the X and Y directions using the X-ray diffraction method. The result shows that compressive residual stresses can be created, and these stresses extend from the surface to a depth of more than 1mm.

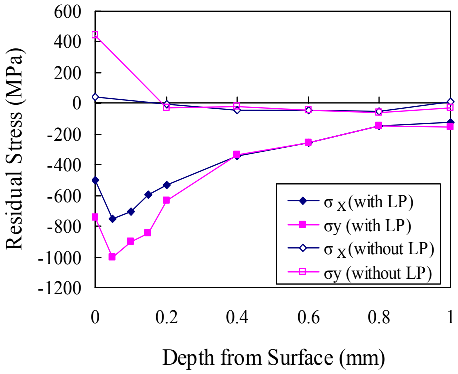


Figure 2. Depth Profile of Residual Stress (Alloy600)

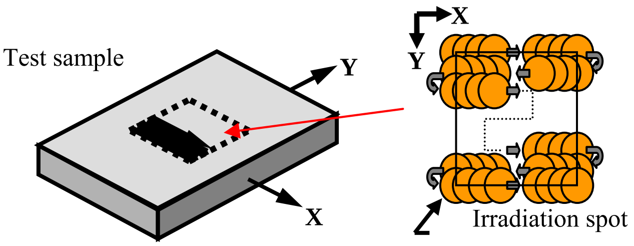


Figure 3. Test Sample and Scan Method

Figure 4 shows a depth profile of the residual surface stress and the cross-sectional microstructure of a laser-peened Type 304 Stainless Steel sample. This sample was 20 % cold-worked to simulate the strength of neutron-irradiated material. The compressive residual stress can extend from the surface to a depth of nearly 1mm, and there is no change in the metallurgical structure of the material between peened and unpeened samples. There is no metallurgical change because the average power of the laser beam is less than 30W (even though peak laser power exceeds 10MW during the narrow pulse width of 8nsec).

The SCC-susceptibility of the peened and unpeened Type 304 stainless steel test samples was evaluated by Creviced Bent Beam (CBB) type tests. Test samples (10 mm x 50 mm x 2 mm thick) were prepared from Type 304 stainless steel with a high carbon content (0.06wt%). Test samples were thermally sensitized (893°K x 24 hours) followed by 20% cold working. Test samples were bent in a holder to form a surface tensile strain of 1%, and then were peened on the holder. Laser-peened and unpeened samples (five each) were prepared by making a surface crevice (using graphite wool) to accelerate corrosive attack. After preparation, samples were immersed in high-temperature (561°K) water using an autoclave for 500 hours. The surface of each test sample was examined and each was cut into two pieces in the longitudinal direction. These cuts served to allow observation of the sample's cross section to confirm whether it was cracked or not. Results showed that typical SCC occurred in all unpeened samples (five test pieces), while no cracks were observed in any of the five laser-peened samples. This test clearly demonstrates that the SCC susceptibility of Type 304 stainless steel in the corrosive environment was completely suppressed by the laser peening [2].

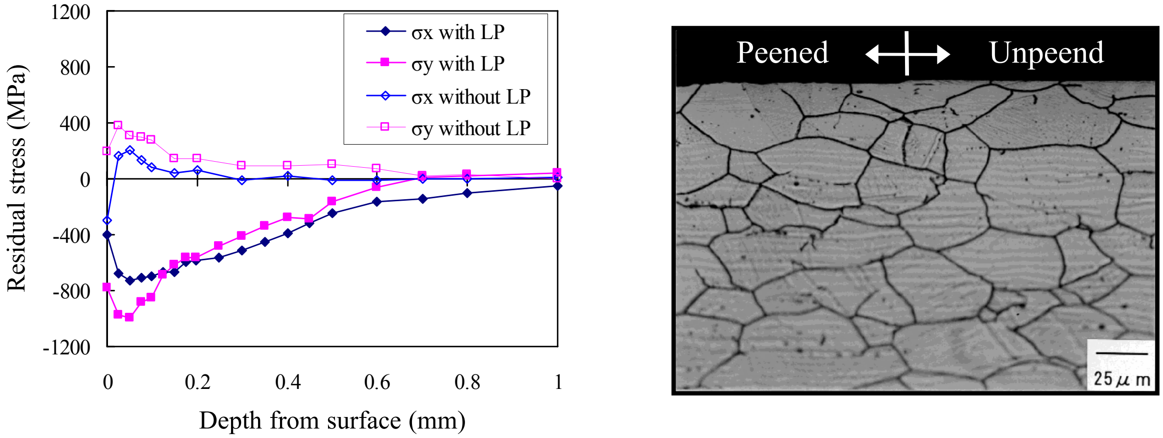
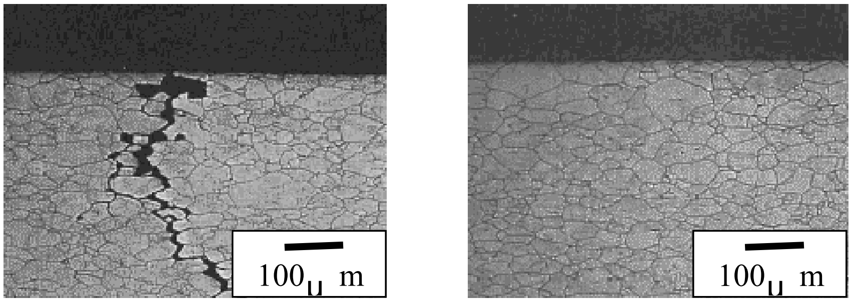


Figure 4. Depth Profile of Residual Stress and Microstructure of Laser-peened Sample (20% Cold Worked Type 304 Stainless Steel)



Unpeened

Laser-peened

Figure 5. Microstructures on Cross Section of SCC Test Samples

4. Laser Peening System and Its Applications

A key advantage of Underwater Laser Peening is the fact that the entire operation is performed underwater, which enables significant reductions in radiation dose associated with mitigation efforts. Underwater implementation can also reduce impact on nuclear plant outage schedules. The use of laser energy for this mitigation results in a process that has the ability to gain access to locations where other conventional mitigation alternatives cannot reach. These and other advantages make LP a viable candidate for SCC mitigation in nuclear power plants, both Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

4.1. BWR Applications

In the past decade, Toshiba has continued the development of laser peening systems to prevent SCC of welded components in nuclear power plants. Cutting edge improvements resulting from ongoing laser technology research have been incorporated into these systems. At first, laser peening systems employed mirror-delivery (for application to operating nuclear power plants in 1999 [1]). For these applications, laser irradiation position was controlled within an accuracy of 0.1 mm at 40 m by an elaborate system of alignment and tracking optics. In 2002, system improvements enabled delivery of 10 MW laser pulses through optical fibers [2]. Figure 6 illustrates the systems applied to BWRs and Figure 7 shows a sample of target locations in applications for Japanese BWRs.

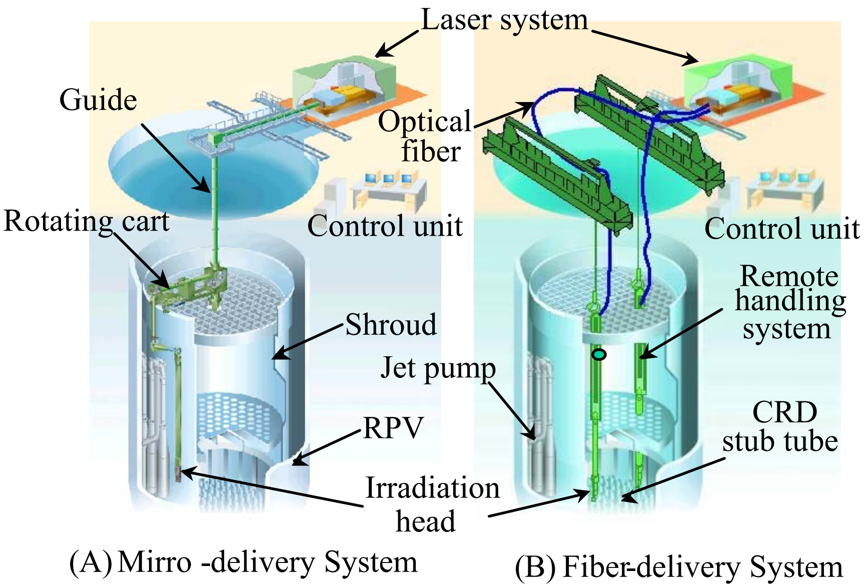


Figure 6. Underwater Laser Peening Systems for BWRs

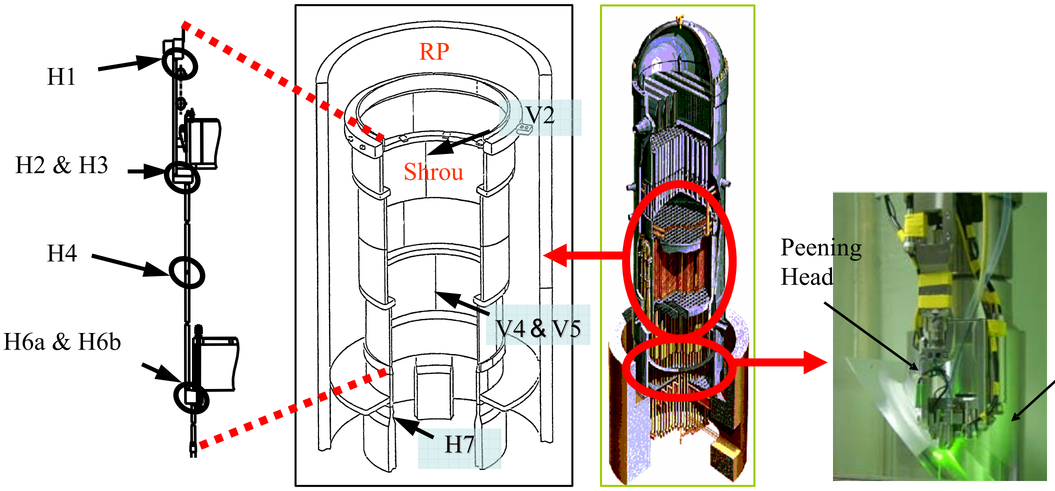


Figure 7. Applications for Japanese BWRs

4.2. PWR Applications

Toshiba has employed laser peening in Japanese PWRs since 2004 [3]. Figure 8 shows the underwater laser peening system for PWRs. In this system, laser oscillators and control devices are packed into two containers stacked on the refueling floor to minimize their footprints. Laser pulses are delivered through twin optical fibers to peen two separate locations in parallel to reduce operation time. Laser peening devices are suspended under work platforms set on top of the RV.

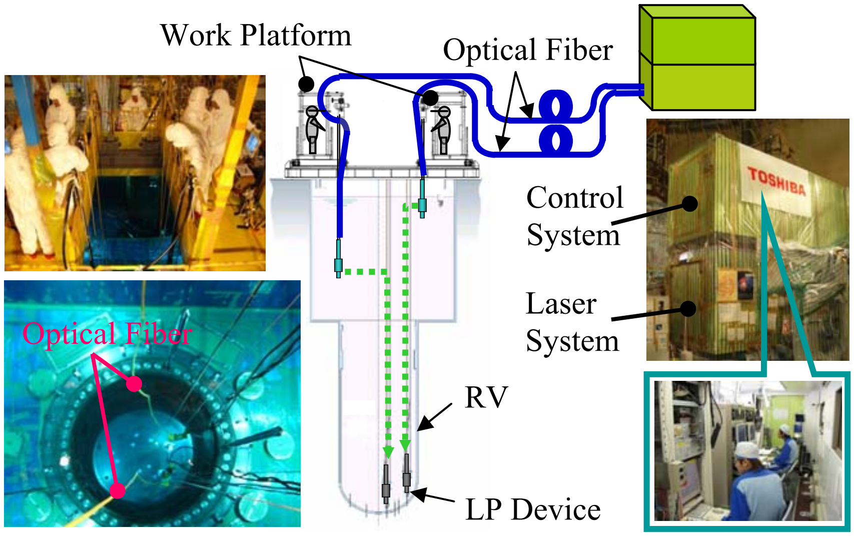


Figure 8. Underwater Laser Peening System for PWRs

Figure 9 shows target nozzles in applications for Japanese PWRs. Peening has been accomplished on the inner surface and outer surfaces of the J-groove welds on bottom-mounted instrumentation (BMI) nozzles. Peening has also been accomplished on the inner surface of dissimilar metal welds (i.e., nickel base welds joining a safe-end to a low alloy metal nozzle) of the primary water inlet nozzles and the safety injection nozzles.

BMI nozzles are made of Alloy 600 and are welded to the RV using Alloy 600 weld metal. Both the inner surface of the welded part and the J-groove weld are known to be susceptible to PWSCC. Figure 10 shows the laser peening device and laser peening head used to peen the inner surface of the tube. To effectively peen the small inner diameter of the BMI, Toshiba has developed a tiny irradiation head (sketched in Figure 10), which is composed of a concave mirror. This concave mirror serves to reflect and focus the laser pulses on the inner surface of the 10 mm inner diameter of the BMI nozzle. Laser peening devices suspended from the work platform are set at the top of BMI, and the irradiation head inserted in the BMI is rotated and traversed vertically. This circumferential and axial movement enables laser pulse irradiation using a helical progression of the inner tube surface.

Figure 11 shows the laser peening device for the J-groove weld location on BMI nozzles. This device can be controlled in 6-motions of direction and can accurately trace the outer surfaces of BMI and J-groove welds to achieve effective laser beam mitigation.

Figure 12(a) shows the laser peening device for the primary water inlet nozzles. The device has two irradiation heads and can treat two separate locations simultaneously to reduce the operation time for these large areas. The device is placed in one nozzle and two irradiation heads are traversed axially across the weld and rotated to cover the whole area to be peened. After the peening treatment, the laser peening device is rotated into the next nozzle to be mitigated.

Figure 12(b) shows the laser peening device for safety injection nozzles. The device was set at a couple of safety injection nozzles on opposite sides of the RV, and an irradiation head was inserted into one nozzle. In a manner similar to that used for the primary water inlet nozzles, the irradiation head was traversed axially across the weld and rotated to cover whole area to be peened. After completion of one nozzle, the device was rotated to mitigate the next nozzle.

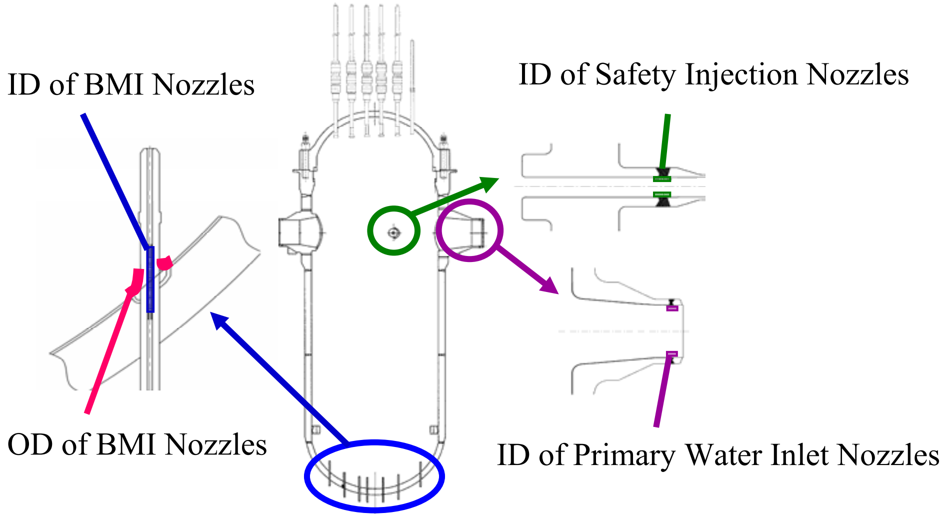
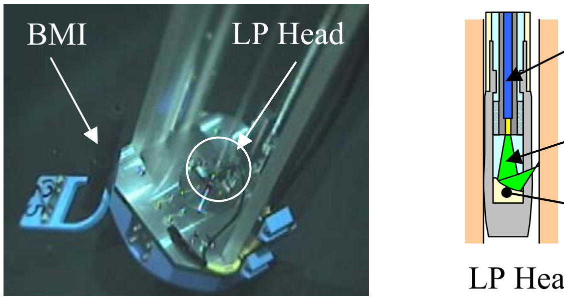


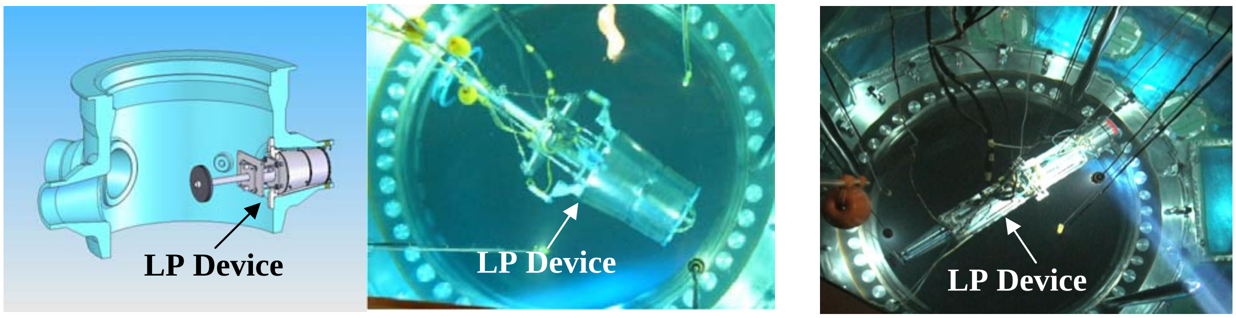
Figure 9. Applications for Japanese PWRs



LP Head for ID of BMI

Figure 10. LP Device for ID of BMI

Figure 11 LP Device for OD of BMI



(a) Primary Water Inlet Nozzles (b) Safety Injection Nozzles

Figure 12. LP Device for RV Nozzles

4.3. Portable LP System

An innovative concept was studied to enhance the usability and reliability of the laser peening system. Figure 13 illustrates the concept, wherein laser peening is applied to the weld of a stub tube for a BWR control rod drive (CRD) housing. A compact laser unit is integrated into the system named "Portable Laser Peening (PLP) system." This system is specifically designed to reduce the equipment footprint and enhance portability. The system can be easily delivered into reactor vessels because it is much smaller and less complex than previous systems. In addition, the time required for preparation, delivery and installation of the system can be drastically reduced. This modified system is highly reliable due to the smaller number of parts employed and the simplicity. This simplicity enables use of a reduced crew size for operation and maintenance [4][5]. Presently, we are using this concept to design new systems for both of the J-groove welds and the inner surface of BMI nozzles in PWRs.

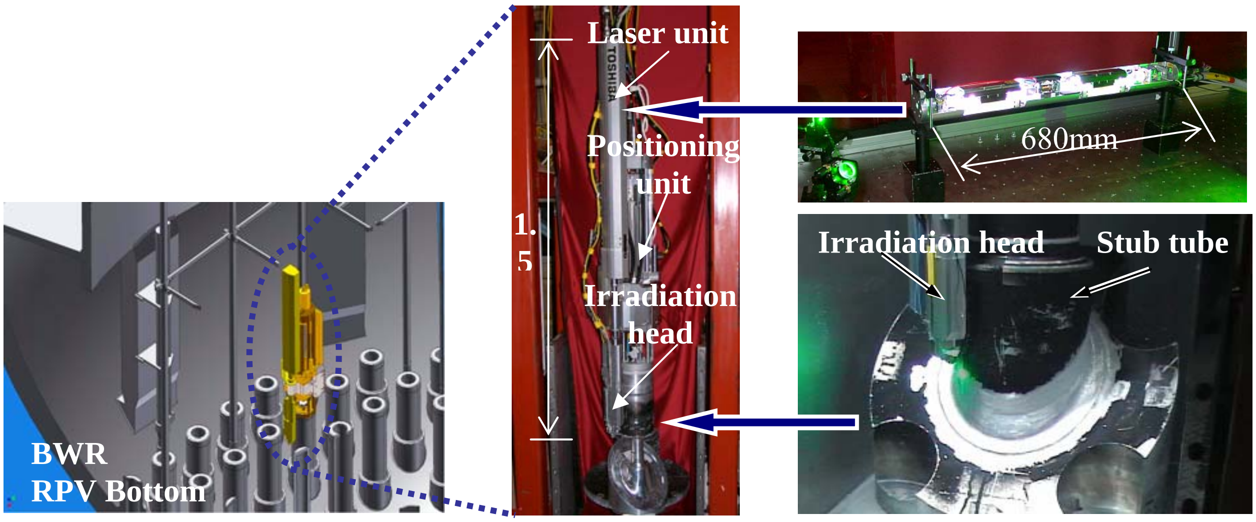


Figure 13. Portable LP System for BWRs

5. Conclusions

Toshiba has developed laser peening systems and utilized them for eight Japanese BWR plants and two Japanese PWR plants since 1999. The portable laser peening (PLP) system, which accomplishes laser peening with a significantly reduced footprint, is now ready to be used. This equipment advancement is a significant achievement, achieving the goals of both reduced size and improved simplicity. Since the volume and weight are drastically reduced, the system can be easily transported, even abroad. Its simple constitution, especially the elimination of the laser delivery system and conventional laser guide pipes and optical fibers, effectively reduces set-up time. We believe the PLP system can thus contribute to the life extension of operating nuclear power reactors in the world by providing effective mitigation against SCC.

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