3
RELEVANT PLANT PEENING EXPERIENCE

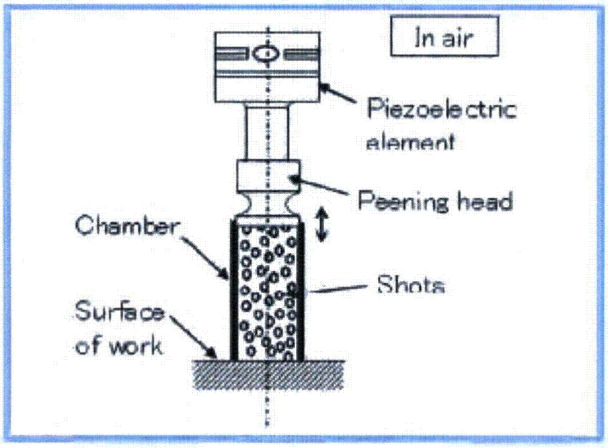
3.1 Japanese PWR and BWR Peening Experience

3.1.1 Overview and Peening Methods Used in Japan

It has been known for many years that application of peening to surfaces of metals in order to develop a surface layer with compressive stresses can significantly increase resistance to occurrence of SCC [27]. As discussed in Section 3.2, shot peening was applied to steam generator Alloy 600 tubes starting in 1985 in Europe, the U.S. and then Japan as a mitigation method against occurrence of PWSCC in the tube sheet and top of tube sheet areas. Based on this experience, and recognizing that both BWRs and PWRs had other reactor coolant system and reactor internals components that were susceptible to SCC, several Japanese firms began development in the 1990 – 1995 time period of methods to peen surfaces of susceptible core internal and pressure boundary components in BWRs and PWRs ([28], [29], [30], [31]). These methods began to be applied in BWRs in 1999 and in PWRs in 2001. As of late 2011, these methods had been applied in many locations in many PWRs and BWRs, as shown in Table 3-1 and Table 3-2.

The peening methods used in Japan in BWRs and PWRs have included the water jet peening (WJP) and underwater laser peening (ULP) methods described in Section 2 at the plants and locations listed in Table 3-1 and Table 3-2. In addition a third peening process called ultrasonic shot peening (USP) has been developed and used in PWRs in Japan. The USP process is illustrated in Figure 3-1. It involves peening using 3 to 4 mm diameter nickel-base alloy shot that are locally accelerated in a small chamber held to the surface of the part using a piezoelectric element. This method was reported in 2009 as having been used at SG inlet or outlet nozzles at more than 10 PWRs, at the inlet and outlet nozzle to safe-end welds of the reactor vessel at a PWR under construction, and at the CRDM to RVH J-groove welds of several PWRs. It results in a compressive stress layer about 1 mm deep.

MHI has performed USP on at least nine replacement heads with Alloy 690 nozzles for the J-groove welds in Japan since 2006. MHI has applied both USP and WJP to Alloy 690 material: USP has been applied to replacement SG nozzle welds and new plant RV head J-groove welds, and WJP has been applied to new plant RV Inlet/Outlet nozzles and BMI nozzles.



The method applies shot peening by giving the shots a to-and-fro motion between the object and the peening head in a chamber by the ultrasonic vibration of a piezoelectric element.

Figure 3-1
Ultrasonic Shot Peening [32]

3.1.2 Development and Qualification

The peening methods used in Japan have been subjected to an extensive development and qualification process ([28], [29], [30], [31], [33]), and have been accepted by industry and regulatory authorities. In more detail:

- Hitachi-GE notes that WJP was certified by JAPEIC (Japan Power Engineering and Inspection Corporation) as an acceptable SCC mitigation method to be applied to reactor internals and has been incorporated into the Japan Society of Mechanical Engineers (JSME) Code. JAPEIC is an independent third party agency that validates newly developed technologies for repair and SCC mitigation. During the peening validation process, technical justification of the technology was reviewed by a committee of academic experts. The data submitted for review included peening parameters and their ranges, process control methods, effects on material properties, effects on welds, etc.

  Hitachi-GE further notes that preventive maintenance is performed in Japan in accordance with the JSME Code for Nuclear Power Generation Facilities, which is JSME NA1 "Rules on Fitness-for-Service for Nuclear Power Plants." In JSME NA1-2004 SCC mitigation technologies such as peening are incorporated as technologies that can be used to relax inspection periods. In addition, WJP was also incorporated into Japan Nuclear Technology Institute's (JANTI's) Guideline for Preventive Maintenance Method "Peening Method" [34]. Hitachi-GE notes that the JANTI guideline indicates that WJP can be applied even if defects exist on the surface because WJP has no adverse effect on the existing defects and mitigates propagation of the cracks if they are shallow. However, relaxation of inspection periods is not allowed if peening is applied to a surface with cracks. Thus, in most cases in Japan, if cracks are detected, the cracks are removed if practical or a repair method is applied.

- MHI notes that WJP has been certified by JAPEIC as an acceptable SCC mitigation method and has been qualified by the Japanese Nuclear Safety Authority for use on BMI nozzle ID surfaces, BMI nozzle J-groove welds, RV inlet and outlet nozzles, and RV safety injection nozzles.
- Toshiba notes that laser irradiation for stress improvement and material integrity subsequent to underwater laser peening have been certified by the JAPEIC Committee. Toshiba further notes that underwater laser peening will be incorporated into JSME Code "Rule on Fitness for service for Nuclear Power Plants (JSME S NA1-2011)". This applies to the underwater laser peening (ULP) system that has been used so far in Japan and to a more recently developed portable laser system that utilizes a small laser unit that can be brought close to the area to be peened.

Details of the qualification tests that have been carried out for the peening processes used in Japan are discussed in the references cited in this section, Section 4 and the appendices in this report.

3.1.3 Process Controls

Careful application of process controls is important to the peening processes to ensure that the area to be peened is fully covered with no missed spots, and to ensure that the strength of the peening is within the qualified bounds over the full peened area. The process controls used for underwater laser peening and water jet peening in Japan and have been the following:

3.1.3.1 Underwater Laser Peening

The process controls used for underwater laser peening in Japanese PWRs are described in the JANTI guidelines [34]. The process controls have been established and qualified by means of a thorough set of mockup tests which have shown that the desired compressive stresses are developed and no material damage is caused if the parameters are kept within the qualified ranges. In summary, the process controls cover:

- Laser type (wavelength)
- Pulse energy (mJ/pulse)
- Pulse repetition rate (pulses/sec)
- Pulse duration (ns)
- Laser spot footprint dimensions (mm)
- Pulse number density (pulses/mm^2)
- Temperature of water

Additional requirements include ensuring that the process is performed underwater and that the water temperature is within the qualified range (<50°C). Following the underwater laser peening application the peening process records are examined to ensure that the control parameters were with the specified ranges. Full coverage is assured by post application visual inspections – surfaces that have been laser peened are visually different from non-peened areas.

3.1.3.2 Water Jet Peening

The process controls used for water jet peening in Japanese PWRs are described in the JANTI guidelines [34]. The process controls have been established and qualified by means of a thorough set of mockup tests which have shown that the desired compressive stresses are developed and no material damage is caused if the parameters are kept within the qualified ranges. In summary, the process controls cover:

- Nozzle diameter
- Jet stand-off distance and nozzle offset in ID applications
- Water flow rate
- Application time
- Injection angle
- Stationary nozzle time

Additional requirements include ensuring that the water level is sufficiently high and that the water temperature is within the qualified range (<50°C). The control system for the process employs interlocks to prevent the process from proceeding if any of the parameters get out of the qualified ranges. The JANTI guidelines (Note 3-4 on page 1-10 of [34]) require that test samples such as split rings be peened before and after the WJP treatment of the PWR plant components as a quality control measure.

3.1.4 Service Experience

Field experience with ULP and WJP has been accrued through the application of these surface stress improvement techniques on both BWRs and PWRs in Japan. Table 3-3 and Table 3-4 summarize the treated components in Japanese PWRs while a more detailed treatment is located in Table 3-1. This experience can be directly used in designing and applying ULP and WJP for U.S. and international plants. As mentioned above, details on the implementation of ULP and WJP on BWRs can be found in Table 3-2.

With regard to service experience, there have been no reports in the technical literature of cracks being detected in peened components in Japan in the years following application of peening. However, the only firm report available at the time of writing of this report of a post-peening inspection is for Tokai Unit 2 [35]. Hitachi-GE reported that the core shroud of Tokai Unit 2, which was the lead application of WJP in 1999, was inspected visually using modified visual testing MVT-1 (same as enhanced visual testing EVT-1) in 2008. The inspection indicated no cracks and no adverse conditions in the peened area after nearly 10 years of operations.

As noted above, there have been no reports of cracks detected during service after peening. However, there was one case of an indication being detected in a bottom mounted instrument (BMI) nozzle (i.e., BMN) before peening. This case was at Takahama 1 in 2002 [36]. The indication, which may have been a crack, had not changed significantly after one fuel cycle, was removed, and the BMI nozzle was water jet peened.

While there have been no reported problems of purposely peened parts, there have been two problems of damage of other parts in BWRs associated with the use of water jet peening:

- In 2006, at the Shimane-2 BWR, damage was detected of deflectors and nozzles of the high pressure core spray system [37]. It was concluded that these problems were caused by flow induced vibration of these parts that occurred as a result of WJP of adjacent areas of the reactor internals. The Japanese safety authority, NISA, ordered Japanese utilities who have ever applied WJP to visually inspect surrounding components. NISA also published instructions that require evaluation of the possibility of FIV problems prior to application of WJP and inspection of surrounding components after WJP.
- In 2010, at the Kasiwazaki Kariwa-2 BWR, it was found during post-inspection of WJP of the core shroud that a jet pump sensing line was broken [38].

These experiences indicate that WJP can cause FIV problems of components such as nozzles and instrument lines that are located close to the areas being treated by WJP. For this reason, the potential for such problems needs to be evaluated prior to application of WJP, and visual inspections of adjacent areas should be performed after application of WJP.

3.1.5 Inspection Methods and Results

The inspection methods used for examination of areas to be peened are discussed to a limited extent in the JANTI guidelines [34]. The JANTI guidelines indicate that areas to be peened should be checked to ensure that there are no cracks or other severe defects near the surface, and that visual (MVT-1) and nondestructive methods can be used. There are no details provided regarding the sizes of cracks that must be detectable by the inspection methods, nor regarding the required probability of detection. Hitachi-GE indicates that inspections of areas to be peened in BWRs are performed using visual examination methods to detect cracks, although ET is used for sizing of detected cracks. MHI indicates that ET is used for flaw detection and reliably detects cracks of 0.5 mm depth at DMWs in reactor vessel nozzles and on the ID of BMN nozzles, and 1.0 mm depth in J-welds. MHI further indicates that these capabilities were demonstrated using multiple test blocks and have been "authorized by Japanese regulations (NISA)." The JANTI guidelines indicate that visual inspection is mainly been used in connection with underwater laser peening [34], but Toshiba indicates in that in one case the utility had the area inspected by another organization using ET.

With regard to results of pre-peening inspections in PWRs in Japan, it is understood that the situation is as follows:

- ET inspections were performed prior to planned ultrasonic shot peening (USP) of steam generator nozzle welds at 15 PWRs with susceptible welds. Twenty-six hot leg nozzles were free of indications and were treated by USP [39]. Twenty-one hot leg nozzles in nine units were found to have crack indications, and were repaired by a variety of means, including cutting out and replacing parts and also including light grinding and polishing followed by USP.
- ET inspections have been performed prior to water jet peening of many reactor vessel outlet nozzles, with the only case of detected indications being for an Ohi 3 outlet nozzle [40]. The defect in that nozzle was ground out and later weld repaired.
- There have been no cases of detected defects in areas in PWRs that were peened using underwater laser peening.

Table 3-1
Experience of WJP and ULP for Japanese PWR plants

Utility	Plant – Unit	Number of Loops	Peening application to Alloy 600/82/182 locations of RV				
			BMN (BMI Nozzle)		Outlet/Inlet Nozzle		Safety Injection Nozzle
			Tube ID	Tube OD and J-Groove Weld	Outlet Nozzle	Inlet Nozzle	
Kansai Electric Power Co.	Mihama – 1	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Mihama – 2	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Mihama - 3	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Takahama - 1	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Takahama - 2	3	WJP (M)	WJP (M)	INLAY	INLAY	—
	Takahama - 3	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Takahama - 4	3	WJP (M)	WJP (M)	INLAY	INLAY	—
	Ohi - 1	4	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Ohi - 2	4	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Ohi - 3	4	WJP (M)	WJP (M)	WJP (M) / INLAY	WJP (M)	—
	Ohi - 4	4	WJP (M)	WJP (M)	INLAY	WJP (M)	
Kyusyu Electric Power Co.	Genkai - 1	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Genkai - 2	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Genkai - 3	4	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Genkai - 4	4	— (Alloy 690)	WJP (M)	INLAY	INLAY	—
	Sendai - 1	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
	Sendai - 2	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
Shikoku Electric Power Co.	Ikata - 1	2	ULP (T)	ULP (T)	INLAY	ULP (T)	ULP (T)
	Ikata - 2	2	ULP (T)	ULP (T)	INLAY	ULP (T)	ULP (T)
	Ikata - 3	3					
Hokkaido Electric Power Co.	Tomari - 1	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Tomari - 2	2	WJP (M)	WJP (M)	WJP (M)	WJP (M)	WJP (M)
	Tomari - 3	3	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—
Japan Atomic Power Co	Tsuruga - 2	4	WJP (M)	WJP (M)	WJP (M)	WJP (M)	—

"WJP (M)": WJP applied by Mitsubishi under license from Hitachi-GE; "ULP (T)": ULP applied by Toshiba; "—": N/A; "Blank": under planning

Table 3-2
Experience of WJP and ULP for Japanese BWR plants

Utility	Plant – Unit	Type of Plant	Type of Treatment	Components with SSI Treatments
Chubu Electric Power Co.	Hamaoka – 1	BWR	ULP (T)	Core shroud
	Hamaoka – 2	BWR	ULP (T)	Core shroud
	Hamaoka – 3	BWR	ULP (T)	Core shroud, Bottom head drain nozzle
Chugoku Electric Power Co.	Shimane – 1	BWR	WJP (H)	Core shroud, ICM housings / Guide tubes
	Shimane – 2	BWR	WJP (H)	Core shroud
	Shimane – 3	ABWR	WJP (H)	Core shroud, CRD housings / Stub tubes, RIP
Hokuriku Electric Power Co.	Shika – 1	BWR	WJP (H)	Core shroud
	Shika – 2	ABWR	WJP (H)	Core shroud, CRD housings / Stub tubes, RIP
Japan Atomic Power Co	Tsuruga – 1	BWR	WJP (H)	Core shroud, ICM housings / Guide tubes
	Tokai – 2	BWR	WJP (H)	Core shroud, CRD housings / Stub tubes , Jet pumps, Instrument nozzles
J-POWER	Ohma – 1	ABWR	WJP (H)	Core shroud
Tohoku Electric Power Co.	Onagawa – 1	BWR	ULP (T)	CRD housing / Stub tubes, ICM housing
Tokyo Electric Power Co.	Fukushima I-6	BWR	ULP (T)	CRD housing / Stub tubes
	Fukushima II-1	BWR	ULP (T)/ WJP (H)	CRD housing / Stub tubes, ICM housing, Core shroud
	Fukushima II-2	BWR	WJP (H)	Core shroud
	Fukushima II-3	BWR	WJP (H)	CRD housings / Stub tubes
	Fukushima II-4	BWR	WJP (H)	Core shroud
	Kashiwazaki-Kariwa-1	BWR	WJP (H)	Core shroud, CRD housings / Stub tubes
	Kashiwazaki-Kariwa-2	BWR	ULP (T)/ WJP (H)	Core shroud
	Kashiwazaki-Kariwa-3	BWR	ULP (T)/ WJP (H)	Core shroud, CRD housings / Stub tubes
	Kashiwazaki-Kariwa-4	BWR	WJP (H)	Core shroud
	Kashiwazaki-Kariwa-5	BWR	WJP (H)	Core shroud

"WJP (H)": water jet peening applied by Hitachi-GE; "ULP (T)": underwater laser peening applied by Toshiba.

Table 3-3
ULP on PWRs performed in Japan

Treated Component	Plant Name	Application Date
BMN ID	Ikata Units 1 and 2	2004, 2005, and 2007
BMN OD and J-groove weld		
RPV nozzles		
Deluge nozzles		

Table 3-4
Japanese experience using WJP on PWRs

	Number of Plants	Details of Plants Treated	First Application
BMN ID	20 plants (958 nozzles)	(2-loop) 1 plant: 30 nozzles (2-loop) 5 plants: 36 nozzles (3-loop) 8 plants: 50 nozzles (4-loop) 6 plants: 58 nozzles	February 2001
BMN OD and J-groove weld	21 plants (1016 nozzles)	(2-loop) 1 plant: 30 nozzles (2-loop) 5 plants: 36 nozzles (3-loop) 8 plants: 50 nozzles (4-loop) 7 plants: 58 nozzles	December 2005
RV Inlet/outlet nozzle	18 plants (104 nozzles)	(2-loop) 6 plants: 4 nozzles (3-loop) 6 plants: 6 nozzles (4-loop) 6 plants: 8 nozzles	December 2005

3.2 Experience with Peening of Steam Generators

3.2.1 Introduction

The objective of this section is to summarize the extensive amount of experience with peening of PWR steam generator tubes since about 1979. This peening has been of two main types:

- Peening of OD surfaces of Alloy 800 tubes in steam generators supplied by Kraftwerk Union/Siemens/AREVA (henceforth Siemens) starting in about 1979, and also in the steam generators for one Canadian CANDU plant that were supplied by Babcock and Wilcox Canada. The objective of this OD peening is to improve resistance to ODSCC.
- Peening by many suppliers of the ID surfaces of Alloy 600MA and Alloy 600TT tubes in the tube sheet and top of tube sheet region, starting in about 1985. The objective of this peening is to increase resistance to PWSCC in tubes in the tube sheet and top of tube sheet (TTS) regions which had been expanded by hard rolling, explosive or hydraulic techniques.

3.2.2 Experience with OD Peening of Alloy 800 Tubes

Siemens introduced peening of the OD surfaces of the Alloy 800 tubes in the steam generators that they supplied starting in 1979 [41]. They indicated that the objective of this OD peening is to improve resistance to ODSCC. OD peening has been applied to the original steam generators for 11 Siemens designed PWRs, and to replacement steam generators for five PWRs, i.e., to a total of 16 plants.

The peening was performed using glass beads. It developed OD axial and circumferential compressive stresses of about 400 to 500 MPa, which decreased linearly to a compressive stress of 150 MPa at a depth of 150 μm [42].

There have been no reports of occurrence of ODSCC of peened tubes in the Siemens supplied PWRs [43]. These plants started commercial operation in 1979 to 1989, and have operated for about 22 to 32 calendar years with no detected ODSCC. None of these units have reported the detection of denting at the top of the tube sheet, which differentiates them from the replacement steam generators discussed in the next paragraph.

Two PWRs with replacement steam generators supplied by Siemens have detected circumferential ODSCC at the top of the tube sheet in dented tubes[44]. The steam generators in these units started operation in 1997 and 1995 respectively and had operated 12 years and 14 calendar years respectively at the time that the ODSCC was detected. It should be noted that the denting occurred only about 3 years before the ODSCC was detected. The occurrence of the ODSCC is attributed to the high strains and stresses induced by the denting, as illustrated in Figure 3-2, and not due to a problem with the peening. However, the experience at these units indicates that the protective compressive stresses induced by peening can be overwhelmed by application of large plastic strains, and that the cold worked layer developed by the peening can result in high tensile stresses being developed if the plastic strains applied subsequent to the peening are sufficiently large.

Experience with the peened tubes in the Canadian CANDU unit is that there has been no detection of ODSCC at this plant. It started commercial operation in 1983 and thus has about 28 calendar years of operating experience.

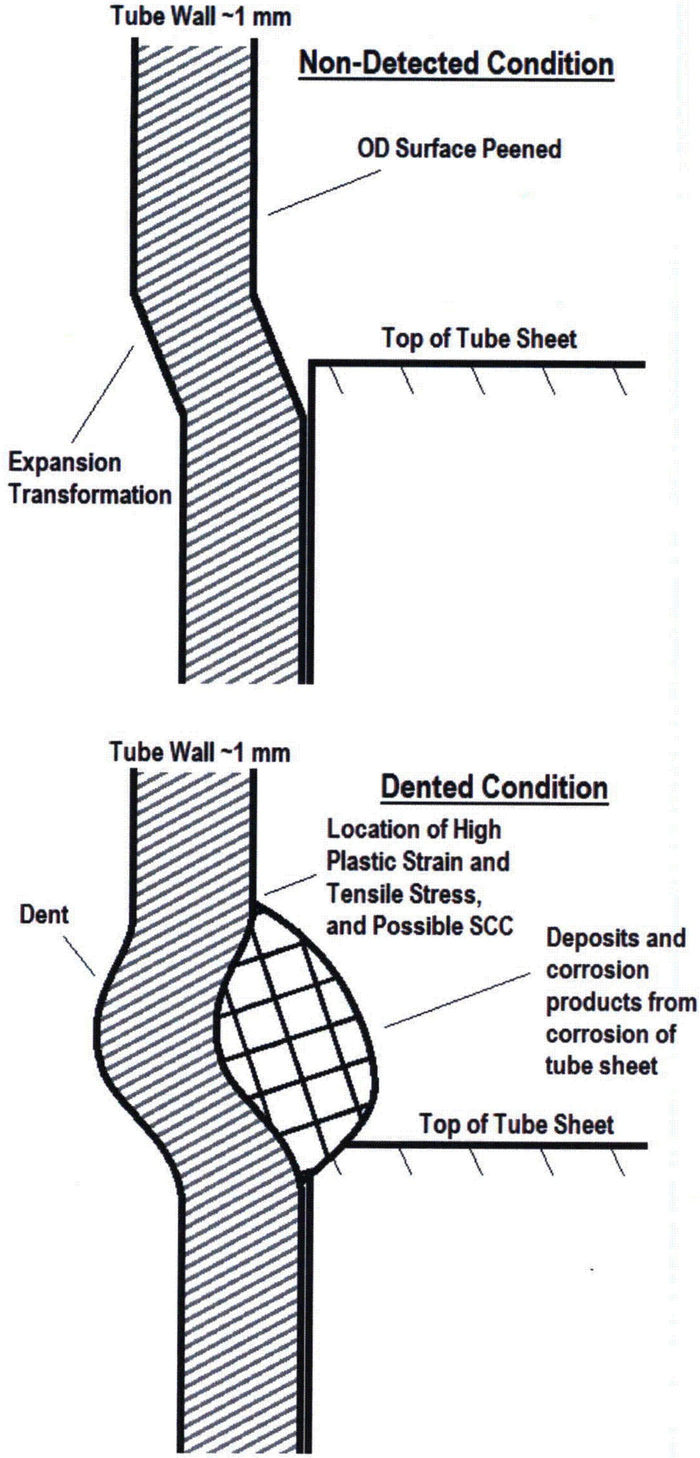


Figure 3-2
Effect of Denting on Residual Stress and Susceptibility to ODSCC

3.2.3 Experience with ID Peening of Mill Annealed Alloy 600 (600MA) Tubes

Because of a rapid increase in occurrence of PWSCC at the roll transitions at the top of the tube sheet and at roll overlaps in the tube sheet region, peening of tube ID surfaces was developed and applied starting in 1985 [45]. This effort initiated in France and Belgium as a result of the rapid occurrence of PWSCC in kiss rolled areas at the top of tube sheet in these countries; the kiss rolls applied a half step expansion just above the top of the tube sheet and served to reduce OD residual stresses, but inadvertently increased stresses and cold work on the ID. Both rotopeening using flappers and shot peening using stainless steel shot were developed and used, but most steam generators were treated using shot peening. The shot peening developed axial and circumferential stresses on the ID surface of about 500 MPa [46]. Shot peening was applied to steam generators with hard rolled (of both the kiss rolled and non-kiss rolled type), explosively expanded, and hydraulically expanded 600 MA tubes at large numbers of plants in Belgium, France, Japan, Spain, Sweden, the USA, and elsewhere.

Experience subsequent to peening was that it reduced but did not stop the occurrence of PWSCC in the tube sheet and expansion transition regions of steam generators that had operated before application of the peening ([45], [46]). This was attributed to the presence of cracks in the tubes that had depths that exceeded the depth of the compressive stress layer developed by the peening. Consistent with this observation is the fact that the effectiveness of the peening was greater the earlier in life that the peening was performed [47].

Experience with 600MA steam generators that peened before operation was that the peening reduced to low numbers the occurrence of PWSCC. It is suspected the few tubes that did develop PWSCC had manufacturing flaws such as laps that were deeper than the depth of the compressive stress field developed by the peening.

Evaluation of pulled tubes indicates that the compressive stresses developed by peening dropped from ~400 to ~700 MPa immediately after peening to ~250 MPa after 3 to 7 cycles of service, which was judged to be high enough to prevent initiation of new SCC ([46], [48]).

A search of the relevant experience revealed no reports of SCC or other problems developing at the transitions of the peened areas to the non-peened areas of the steam generator tubes.

3.2.4 Experience with ID Peening of Thermally Treated Alloy 600 (600TT) Tubes

PWSCC was detected at the kiss roll transitions at the top of the tube sheet of steam generators in some French plants with 600TT tubes in the late 1980s. As a result, all 28 of the EDF PWRs with 600TT tubes were peened by about 1993. A few of these were peened before operation. All of the EDF 600TT steam generators units are still in operation. In this regard, in France, tubes with short axial cracks at the TTS are allowed to remain in service since it is known that the cracks grow slowly.

The service experience with these Alloy 600TT steam generator tubes has been sufficiently good that all these steam generators are still in operation. However, it is known that some numbers of the tubes that were peened since the start of operation have developed cracks, and a relatively modest fraction of those have required plugging.

A search of the relevant experience revealed no reports of SCC or other problems developing at the transitions of the peened areas to the non-peened areas of the steam generator tubes.

3.2.5 Conclusions Regarding Peening of SG Tubes

The main conclusions developed by review of experience with peening of steam generator tubes are as follows:

- A very large number of steam generator tubes (several hundred thousand) have been peened, with the experience extending more than 30 years, with generally satisfactory results.
- With regard to ODSCC, peening of the OD correlates with a complete absence of ODSCC except at two plants where the peening was overwhelmed by occurrence of large dents.
- With regard to PWSCC, peening of plants that operated before peening was found to reduce the initiation and growth of cracks as compared to the behavior of those plants before peening. However, pre-existing cracks with depths greater than the depth of the compressive stress field generated by peening continued to grow subsequent to the peening.
- Small numbers of PWSCC cracks developed in units peened before service. The causes of these cracks are not known. Possibly they are due to the presence of manufacturing flaws (e.g., laps) in the tube material that were deeper than the depth of the compressive stress field.
- While peening provides a significant measure of protection against PWSCC and ODSCC, one needs to be aware that SCC can still occur as the result of the presence of pre-existing non-detected flaws, or if the peening is overwhelmed by application of large plastic strains.
- A search of the relevant experience revealed no reports of SCC or other problems developing at the transitions of the peened areas to the non-peened areas of steam generator tubes.

3.3 Use of the Abrasive Water Jet Process

The abrasive water jet (AWJ) conditioning or peening process is a process patented by Framatome (now AREVA) that has been available for use in PWSCC mitigation and repairs since the late 1990s [49]. The process utilizes a high pressure water jet containing abrasive particles to remove surface layers and also to develop compressive stresses in the remaining surface layer. The process can be used in a boring mode to remove a thin surface layer of the hole that is being conditioned, and can also be used as a local excavation tool.

The AWJ conditioning process has been qualified with the following main results [50]:

- Qualifications were performed on Alloy 600 CRDM nozzle mockups (2.75" ID) and ICI nozzle mockups (4.75" ID).
- Removal of thin surface layers serves to remove non-detectable shallow cracks below the typical detection limit for ET of 0.020 inches (0.5 mm).
- Conditioned surfaces have compressive axial and hoop stresses of about 100 ksi (690 MPa) at the surface, and the stresses remain compressive to depths of about 0.010 inches (0.25 mm) in Alloy 600 base material and about 0.003 inches (0.08 mm) in Alloy 182/82 weld metal.

- The surface finish produced by the abrasive water jet process ranges from 90-150 micro-inches (2.3-3.8 μm).
- The conditioned surfaces are compatible with performance of UT, ET, and PT.
- The process imparts cold work to the surface. The cold work was quantified using an X-ray diffraction peak broadening technique and ranged from 13-80% at the surface to less than 5% at a depth of 1 to 5 mils (25-125 μm).
- Some of the abrasive particles become embedded in the surface. Most of the particles are removed as part of a final high pressure pure water rinse that is part of the AWJ process, but some embedded particles remain. The abrasive is silicon dioxide, aluminum oxide and ferric oxide. The sizes of the embedded particles range up to 1 mil (25 μm). Conservative estimates of the amount of remaining material indicate that, even if it all should become loose and enter the reactor coolant system, the quantity is so small that it would not cause any problems.

The abrasive water jet conditioning process has been widely used for more than a decade. The most recent status report by AREVA indicates that as of July 2010 [51]:

- 123 RVH penetrations had been repaired using the ID temper bead repair technique since 2001; this process involves a final step of abrasive water jet conditioning.
- 26 repaired penetrations were still in service. Of these, 2 penetrations had been in service for ~ 6 years (3 cycles), with a 3rd volumetric examination period to occur in Fall 2010, and 24 penetrations had recently been placed into service.
- The remaining repaired penetrations had been taken out of service by installation of new heads.

AREVA notes that the AWJ process has been qualified for general nozzle remediation and flaw removal [51]. The process leaves an SCC mitigating compressive residual stress (above 100 ksi (690 MPa)) near the surface and a surface devoid of previous SCC damage. The AWJ process is characterized by AREVA as being a viable approach for removing/repairing flaws in LWR components and mitigating cracking mechanisms such as PWSCC, IGSCC, and IASCC.

3.4 Application of Peening on Alloy 600 Pressurizer Heater Sheaths

Calvert Cliffs Unit 2 replaced Pressurizer Heaters in 1990. The replacement heater sheath material was Alloy 600. The heaters are swaged in two stages during manufacturing. The replacement heaters were annealed after the first swage and shot peened after the second final swage operation to improve resistance to PWSCC. All heaters have remained operational after over 20 years of service in the pressurizer environment. One heater was removed in 2011 and liquid penetrant and destructive examination showed no signs of PWSCC initiation in the Alloy 600 heater sheath material.

3.5 Application of Peening to Alloy 718 Fuel Assembly Screws

Several failures of fuel assembly top nozzle spring screws made of Alloy 718 were reported to have occurred in the 1998 – 2003 time period [52]. These failures occurred with material that was age hardened after the threads were rolled. The failures were indicated as occurring at the

inside corner of the transition from the full bar diameter to the thread rolling diameter in the South Texas Project Electric Generating Station failures, and as occurring near the top thread in Westinghouse laboratory tests. The specific stress levels at the failure locations were not reported. The morphology of the cracking was intergranular cracking consistent with PWSCC. The remedial approach adopted was to use Alloy 718 screws with improved resistance to PWSCC provided first by peening, and then by an improved manufacturing sequence coupled with peening [53], [54]. The peening was performed using glass beads and developed a compressive stress of about 100 ksi (690 MPa). There have been no reports of failures of peened Alloy 718 screws in this application.

4 EFFECTIVENESS OF SURFACE STRESS IMPROVEMENT

4.1 Effectiveness Criteria

The SSI techniques mitigate PWSCC by reversing the tensile stress at the surface exposed to reactor coolant to compressive residual stress. Initiation of PWSCC flaws requires as a necessary condition tensile stress at the surface. Moreover, any existing flaws that are in the surface compressive stress zone when the SSI process is applied cannot grow via PWSCC because of the lack of tensile stress driving force.

The goal of an SSI application is to reliably mitigate the PWSCC concern for a plant component for long-term operation. The following mitigation effectiveness criteria may be used to assess this goal:

- The stress in the surface region following the SSI treatment is compressive to a specified depth, including the effect of normal operating stress.
- Laboratory tests confirm the resistance to PWSCC initiation on the treated surface, as well as growth of pre-existing flaws located in the specified compressive stress zone.
- A compressive stress condition is maintained to the specified depth for the intended mitigation period (e.g., remaining plant operating period) given the effects of operating temperature and load cycling. The operating temperature range of greatest interest is from 285-320°C (545-608°F), which approximately covers the range of reactor cold leg and hot leg temperatures in operating U.S. PWRs. The PWR piping DMWs that operate close to pressurizer temperature (345°C (653°F)) have largely already been mitigated by weld overlay.

The MRP is currently evaluating appropriate inspection requirements for RPVHPNs and piping DMWs that are mitigated by SSI. Pre-existing flaws significantly deeper than the compressive stress zone may continue to grow in depth during future operation. The appropriate inspections to be performed during and after the application outage are currently being assessed by MRP in combination with consideration of appropriate relaxation following the SSI treatment of the inspection requirements for unmitigated locations. These assessments are considering the minimum flaw depth for reliable flaw detection for different nondestructive examination (NDE) techniques as applied to different Alloy 600/82/182 components.

In addition to an SSI treatment being effective, the process must be confirmed not to produce any unacceptable side effects. The process must not generate any cracks in the material, and the process must not cause any significant growth of any pre-existing flaws in case they were present. Appendix A includes experimental data confirming that SSI does not compromise material integrity.

4.2 Experimental Verification of Effectiveness of Surface Stress Improvement To Mitigate PWSCC

In order to verify the effectiveness of the SSI techniques to mitigate PWSCC, the SSI vendors have performed several series of laboratory tests. These tests include measurements of the stress in the region of the treated surface, as well as corrosion cracking tests. In addition, EPRI commissioned AREVA NP to perform independent corrosion cracking tests of Alloy 182 weld samples treated by multiple vendors using different methods. Some tests were performed using simplified test sample configurations such as flat plates and U-bend samples, and others used mockup test samples to confirm the effectiveness of the process for actual plant geometries of interest.

The various tests performed are documented in Appendix A and summarized below. In addition, Section 2 also includes the results of additional stress measurements for peened samples in the context of the theory and background of the SSI methods.

4.2.1 Residual Stress Measurements

Residual stress measurements were performed on a wide variety of geometries to determine if compressive residual stress could be achieved by the various peening methods. The simplest geometry is the flat plate, and all stress measurements on flat plates are shown in Section A.1.1. Flat plates made from Alloy 600 or Alloy 132 were treated with underwater laser peening by Toshiba, and the residual stress was measured showing that compressive residual stress is achieved to a depth of at least 1 mm. Toshiba also peened a plate of 20% cold worked Type 304 stainless steel and compared the residual stress profile as a function of depth and the surface residual stress profile in the peened plate to an unpeened plate. Compressive residual stress was also achieved to a depth of 1 mm and tensile stresses outside the peened area did not exceed those of the unpeened sample. Hitachi-GE applied water jet peening to plates made from Alloy 600, Alloy 182, Type 304 stainless steel, or Type 316L stainless steel and measured residual stress on the surface and into the material. Compressive residual stress was achieved to a depth of at least 0.04 inch (1 mm) and to at least 1.5 inches (38 mm) from the center spot of the impinging water jet in all alloys as shown in Figure A-5 to Figure A-8. Hitachi-GE also compared peening-induced residual stresses in Type 304 stainless steel with Alloy 600 and Alloy 182 peened with similar process parameters. It was observed that Type 304 stainless steel was conservative compared to the nickel based alloys, justifying the use of stainless steel in peening parameter optimization experiments. This finding aligns with theoretical expectations as stainless steel has lower mechanical properties than the nickel based alloys, and thus develops lower compressive stresses. MIC provided experimental measurements of surface residual stress for a partially peened plate of Alloy 600, and tensile stresses were not created in the area adjacent to the peened section.

Stress measurements in the longitudinal and transverse directions were also performed on a variety of welded plates made of different combinations of stainless steels and/or nickel based alloys. Specimens treated with ULP or WJP are detailed in Section A.1.2, and data from Alloy 22 welds treated with ALP are shown in Section 2.4.2. One application of these specimens is to assess the applicability of the methods to large diameter butt welds. Welded plate specimens made from Alloy 600 plates joined by Alloy 182 and treated with underwater laser peening by Toshiba had more compressive stresses compared to similar unpeened specimens. Mitsubishi

Heavy Industries, Ltd. (MHI) water jet peened welded flat plates of Alloy 600 and Type 316 stainless steel joined with Alloy 132 weld metal to determine applicability to large radius or flat surface components such as reactor vessel nozzle safe end weld. Residual stress was compressive to a depth of 1.3 mm and was improved compared to the as-welded state. These results from MHI were used to support the applicability of WJP to surfaces with pre-existing cold work, surfaces with rough ID such as piping butt welds, and areas with pre-existing tensile stress. Alloy 22 welds were treated with ALP, and depth dependent residual stress profiles were measured at three locations: at the center of the weld bead, at the weld toe, and 30 mm from the weld center. In all three locations, residual stress was made compressive to a depth of at least 4 mm, and to a depth of at least 6 mm, the residual stress in the peened sample was decreased compared to the unpeened sample. The residual stress profiles also justify that ALP will not create tensile residual surface stress within treated areas, but balancing tensile stresses deeper than the compressive stress layer are expected.

The response of the alloys in actual plant geometries is also important, so BMN size pipes and BMN mock ups were also peened. Toshiba treated BMN size pipes with ULP on the outer diameter and the inner diameter and found that peening the outer diameter makes the residual stress compressive in the axial and hoop directions. Peening the inner diameter induced compressive residual stress on the inner surface and slightly reduced the magnitude of the compressive stress on the outer surface, but it was still improved compared to the as received condition. Toshiba, Hitachi-GE, and MHI all constructed BMN mockups by welding pipes to flat plates. Several different locations were peened including the pipe inner diameter, the pipe outer diameter, the J-groove weld, and the corner made by two flat plates, and residual stress was measured before and after to show that it became compressive following peening. Details are provided in Sections A.1.3 to A.1.6 of Appendix A. The stress measurements show that the ULP and WJP processes are capable of producing a reliable layer of compressive residual stresses to a depth of roughly 1 millimeter (0.04 inch) in most of the configurations tested, although the depth of compressive residual stress attained for the WJP process for the BMN tube ID configuration was approximately 0.5 millimeter (0.02 inch). In this regard, the depth of the compressive field achieved by WJP is most strongly affected by the impingement angle, which is necessarily low inside small diameter nozzles. This is reason why the nozzle ID residual stresses developed by WJP may be lower than those developed on OD surfaces where large impingement angles are practical.

Other properties were also measured on peened surfaces to ensure that they were not adversely affected by peening. Surface roughness measurements were performed on flat plates of Alloy 600 peened by Toshiba, MIC and MHI to ensure that peening treatment does not induce high surface roughness as shown in Section A.1.7. Hitachi-GE measured surface roughness by 3D height mapping of Type 316L stainless steel plates to compare three plates with different treatments applied: heavily ground only, water jet peened by Hitachi-GE, and shot peened. The water jet peened plate had a roughness profile much closer to the ground only plate than the shot peened plate. Hardness was also measured as it indicates the amount of cold work done on the surface. Microhardness measurements were performed on Alloy 600 flat plates peened by Toshiba and MIC using a variety of peening processing parameters. Hitachi-GE compared hardness measurement on flat plates of Alloy 600 and Alloy 182 treated with its own peening technique to unpeened flat plates and to shot peened flat plates and found that hardness profiles for water jet peened plates were much closer to unpeened plates than to shot peened plates.

Vickers hardness was measured by MHI on the inner diameter, the outer diameter, and the J-groove weld of BMN mockups, and all near surface hardness values were below 300 Hv. All hardness measurements are found in Section A.1.8.

To ensure that peening a surface at extreme conditions, such as for a longer period of time than intended, would not adversely affect the treated surface, MHI performed a series of stuck nozzle tests where a particular location was peened for much longer than the prescribed, optimized treatment time. Locations included pipe inner diameter (ID), pipe outer diameter (OD), flat plates welded together, and a tube welded to a flat plate. After treatment, surfaces were examined by visual inspection and penetrant inspection, and no adverse surface effects were detected. Results of the inspections are shown in Section A.1.9. MIC has also examined the possibility of "over-peening" a surface. The supporting data and discussion is located in Section 2.4.2. Alloy 22 specimens have been peened with multiple layers, and there was not a significant difference between the residual stress profile after 5 layers and 10 layers. There are also mechanisms in place to protect against an excessively energetic laser shot such as breakdown of the water tamping layer, the saturation mechanism within the laser and the power supply control.

4.2.2 Corrosion Cracking Tests

The vendors performed experiments to determine if peening is effective at reducing initiation of SCC in samples with no pre-existing flaws, which are elaborated in Section A.2.1. Toshiba examined the formation of stress corrosion cracks in Type 304 stainless steel in a creviced bent beam (CBB) jig and in Alloy 132 U-bends. Hitachi-GE welded together two flat plates of Type 304 stainless steel by SMAW, applied water jet peening to half of the plate, and immersed the plate in boiling 42% $MgCl_2$ solution. MHI subjected both peened and unpeened BMN J-groove weld mock ups to boiling 42% $MgCl_2$ solution. In all of these experiments, no SCC was generated on the peened surfaces while SCC was detected on the unpeened surface. According to MHI, SCC initiation is not expected at transition zones between WJP treated and unpeened areas because only a thin region near the surface is affected by peening and the thickness of the entire component is expected to prevent a peak of tensile stress. MIC performed SCC testing on two butt welds, one of which was air laser peened, using boiling $MgCl_2$ solution. Stress corrosion cracking developed on the unpeened surface, but no SCC was detected in or around the peened butt weld. This figure and supporting discussion is located in Section 2.4.1.

To verify that pre-existing SCC cracks do not grow during the application of ULP, Toshiba compared the crack depth distribution of pre-cracked specimens that were subsequently peened to that of pre-cracked, unpeened specimens for Alloy 600 and Type 304 stainless steel. Comparison by a t-test for both alloys showed no significant difference between the distributions. Similar experiments were performed for WJP in which MHI ruptured the cracks of specimens that had been pre-cracked, peened and heat tinted in order to open up the crack faces. There was no ductile fracture present in the temper colored region, as seen in Section A.2.2.1, which shows that the application of WJP did not cause crack growth.

Section A.2.2.2 describes several experiments which were performed to determine how the growth of pre-existing stress corrosion cracks during operation is affected by peening. Toshiba initiated cracks in 20% cold worked Type 304 stainless steel coupons, divided the coupons into three groups, and performed a different treatment on each group of coupons. Coupons that were peened and subjected to BWR water had a similar crack depth distribution to control coupons

that had only been pre-cracked, indicating that no growth occurred in the peening specimens; however, the average crack depth increased in coupons that were subjected to BWR water without peening. Hitachi-GE produced fatigue cracks to three different depths in Alloy 182 coupons that were fitted into CBB jigs and peened, and then the coupons were exposed to high purity water at 288°C. Cracks that were relatively shallow (1.5 mm and 3.5 mm) did not grow, but cracks that were relatively deep (5.5 mm) continued to grow. MHI initiated stress corrosion cracks of various depths from 0.4 mm to 1.1 mm by exposure to polythionate solution on the outer diameter of the Alloy 600 tube, applied water jet peening to the outer surface, and exposed the tube to polythionate solution again. No growth was observed for cracks initially shallower than 0.5 mm, cracks originally between 0.5 mm and 1.0 mm had significantly reduced growth, and the growth of cracks originally deeper than 1.0 mm was not mitigated but was also not accelerated. MHI also performed experiments on weld plates of Type 316 stainless steel and Alloy 600 comparing the flaw depth distributions of three different treatments. All specimens were pre-cracked, two of the specimens were peened, and both a peened specimen and the unpeened specimen were subjected to further SCC testing. No difference was found between peened plates before and after SCC testing, suggesting that there was no crack growth in peened specimens despite being subjected to a corrosive environment. There was a noticeable difference in SCC progression between the peened and unpeened sample, indicating that the SCC testing was performed under appropriate conditions. MIC compared crack growth in three Alloy 600 U-bends immersed in thiosulfate solution and found that peened samples did not have any crack growth, whether or not the sample was pre-cracked, but pre-cracked samples that had not been peened had extensive crack growth.

Independent testing of SCC initiation in samples without pre-existing flaws was performed by AREVA and can be found in Section A.3. Alloy 182 weld deposits on Alloy 600 specimens were used to make U-bends, either spring-loaded or bolt-loaded, of two different thicknesses. The U-bends were treated with WJP, ULP, or ALP. The U-bends were then exposed to simulated PWR water at 360°C for a total of 3000 h over two phases of experimentation. Compared with the reference "heavily ground" surfaces where cracks were observed in most samples, U-bends treated with ULP by Toshiba, ALP by MIC, or WJP by Hitachi-GE or MHI did not have any cracks detected following PWR water exposure. These results show that ULP, WJP, and ALP are effective at mitigating PWSCC of even heavily cold worked weld metal.

4.3 Long-Term Effectiveness of Surface Stress Improvement

The effectiveness of surface stress improvement in terms of creating compressive stress at exposed surfaces to mitigate PWSCC has been demonstrated in Section 2 and Appendix A. However, given the elevated temperatures and mechanical load cycling applicable to plant operation, the compressive residual stress induced at a surface treated by SSI is subject to some degree of relaxation with time. The thermal effect is due to creep effects that may occur at primary system operating temperatures, while the load cycling shakedown effect is the result of the nonlinear material behavior that occurs given the combination of cyclic applied stresses and high-magnitude peening residual stresses.

In order to verify the long-term effectiveness of SSI treatment, the SSI vendors have performed thermal exposure tests and load cycling tests to investigate the sustainability of the peening compressive residual stress. In addition, EPRI commissioned Nuclear Research Institute (NRI) in the Czech Republic to perform independent tests under conditions of high temperature and cyclic

loads that were carefully designed to enable comparison of test samples before and after different surface peening processes. These efforts, which are documented in Appendix B and summarized below, are intended to establish confidence in evaluating and validating SSI as a mitigation technique for PWR plants. Note that, as summarized below, the thermal exposure tests were performed at temperatures up to 450°C in order to accelerate the effect of creep relaxation of the residual stress profile.

4.3.1 Thermal Exposure Tests

Toshiba, Hitachi-GE, and MHI all performed experiments to evaluate the effect of exposing a peened surface to high temperatures. The full details for the Toshiba experiments are shown in Section B.1.1, while the remaining experiments can be found in Section B.1.2.2. Toshiba exposed reversed U-bends of Alloy 600 to 360°C simulated primary water for 1000 h and the residual stress remained compressive and significantly different from the un-peened condition. Toshiba also provided results of thermal relaxation testing done on Alloy 600 at 350°C for 1646 h and Type 316 stainless steel at 420°C for 883 h. In both cases, the residual stress was still compressive at the end of the experimentation and no significant relaxation was observed. Hitachi-GE applied water jet peening to coupons of Alloy 600, Alloy 182, and Type 316L stainless steel and exposed them to 450°C for 1000 h. The residual stress relaxed slightly in the first hour but remained compressive, and no further relaxation was observed. MHI produced plates of Alloy 690 each with a trough of Alloy 132, applied water jet peening to the surface, and subjected different plates to three different temperatures for a maximum of 1400 h. Again, slight stress relaxation was observed after the first hour, but the residual stress remained compressive and no significant stress relaxation was observed thereafter.

4.3.2 Load Cycling Tests

Hitachi-GE and MHI both examined the effect of load cycling on the relaxation of compressive residual stress in a water jet peened surface, as shown in Section B.1.2.1. Hitachi-GE took coupons of Type 316L stainless steel, Alloy 182, and Alloy 600 and subjected them to load cycling from zero strain to a strain amplitude of 0.15% for 100 cycles. A slight reduction in the compressive stress magnitude was observed in the first ten cycles, but no reduction was observed over the remaining cycles.

MHI performed two sets of tests. For the first set MHI applied tensile stress to peened test coupons using a three point bending method for a maximum of 2000 cycles from zero stress to a maximum stress of 245 MPa tensile. The effect on the compressive residual stress was insignificant for maximum stresses up to 150 MPa, and a modest reduction in compressive residual stress was observed for a maximum stress of 245 MPa. MHI also conducted load cycling testing at elevated temperature conditions. The test coupons simulated a dissimilar metal weld of Alloy 600 and Type 316 stainless steel material butt welded with Alloy 132. After WJP treatment, one specimen was subjected to 300 cycles of cyclic loading from 0 to +130 MPa at 420°C over 100 hours, while a control was subjected only to the elevated temperature conditions for the same period of time. Residual stress measurements performed over the course of the experiment revealed that the residual stresses remained significantly compressive and that the relaxation due to cycling at high temperature conditions was modest, from ~420 MPa after peening to ~320 MPa at the end of the test.

NRI performed experiments to evaluate stress relaxation of the compressive residual stresses induced by peening. Alloy 600 plate material was used to make test samples that were peened by Toshiba, Hitachi-GE, MHI, and MIC, with one set left in the as-manufactured condition, and exposed to load cycling in the tensile range in PWR water at 300°C in an autoclave loop. The cycles involved consisted of ramping from zero load up to 75% of the yield strength, holding for 10 days, and ramping down to a load of zero. The metallography, the microhardness depth profile and the surface stress were all examined, and the full results can be found in Section B.2. Surface and subsurface microhardness values were increased to 20-25% higher than the bulk material by WJP and ULP, compared to 10% higher at the surface for unpeened samples, and these values were not significantly changed by exposure to high temperature or load cycling. Samples treated by ALP had an increase of 60% compared to bulk material in surface and subsurface microhardness values, but this difference decreased with exposure to cycling. After 8 cycles, the difference was down to 20-25% above bulk material values. No change was observed in the microstructure following exposure to cycling, whether or not the specimen was peened. Modest reductions in the surface compressive stresses due to peening in both the longitudinal and transverse directions were observed for the peened specimens at the end of the testing. Also, it is noted that the variation in surface stress across different specimens was typically found to be reduced after peening in comparison to the unpeened state.

4.4 Thermal Relaxation Calculation

This section describes calculations performed using the thermal relaxation experimental data to determine if the compressive residual stress induced by the various peening methods will last for the full operating lifetime of the plant. Thermal relaxation experiments described in Section 4.3.1 and shown in detail in Appendix B were often performed at elevated temperatures to accelerate the effects of thermal relaxation and creep and to characterize the behavior of peened surfaces which would occur over the plant lifetime in a more experimentally appropriate period of time. In order to estimate the equivalent operating lifetime over which the same relaxation would occur, an activation energy approach was used. Was et al. determined a range for activation energy for creep of Alloy 600 in primary water [55], and this interval was verified by comparing it to calculated activation energy values from fitting the experimental relaxation data to the Zener-Wert-Avrami mode for stress relaxation described below. Once the activation energy range was deemed reasonable for this application, it was used to determine an equivalent lifetime for RPVHPNs and hot leg DMWs at actual operating temperatures on the basis represented by each of the thermal relaxation experiments that had been performed.

4.4.1 Verification of the Activation Energy Range using the Zener-Wert-Avrami Function

The activation energies were taken from a range determined by Was et al. [55] for creep of Alloy 600 in primary water. Was cited an activation energy range of 188 to 281 kJ/mol. To verify the suitability of this range to the current application, the Zener-Wert-Avrami model for stress relaxation, as described by Zhou et al. [56], was used to calculate activation energy values from vendor produced experimental data. The Zener-Wert-Avrami function has the following form:

$$\frac{\sigma^{RS}}{\sigma^{RS}_0} = \exp\left[-(At)^m\right] \qquad [4\text{-}1]$$

where σ^{RS}_0 is the initial value of residual stress (in this case, after peening but before relaxation), σ^{RS} is the residual stress at a given time *t* and temperature *T*, *m* is a numerical parameter dependent on the dominant relaxation mechanism, and *A* is a function of the material and the temperature. This functional dependence is expressed by:

$$A = B\exp\left[-\frac{\Delta H}{kT}\right] \qquad [4\text{-}2]$$

in which *B* is a constant, *k* is the Boltzmann constant, and ΔH is the activation energy in the time and temperature range of interest.

To obtain a value for activation energy from thermal relaxation data, the first step is to plot $\log_{10}(\ln(\sigma^{RS}_0/\sigma^{RS}))$ as a function of $\log_{10}(t)$, which is a linearization of the Zener-Wert-Avrami function, as shown in the following equation:

$$\log_{10}\left(\ln\left(\frac{\sigma^{RS}_0}{\sigma^{RS}}\right)\right) = m\log_{10}(t) + \log_{10}(A^m) \qquad [4\text{-}3]$$

The slope of the line corresponds to the relaxation mechanism parameter *m*, so this method invokes the assumption that the dominant relaxation mechanism does not change over the temperature interval of interest. Once *m* is specified, it can be used with the intercept to calculate *A*. Once *A* has been calculated for all temperatures, it can be graphed on an Arrhenius plot (i.e., ln *A* as a function of 1/T) where the intercept corresponds to *B* and the slope is $-\Delta H/k$.

There are two requirements that should be fulfilled in order to have confidence in the activation energy calculated using the Zener-Wert-Avrami function. Relaxation data at multiple temperatures must be available to produce an Arrhenius plot, which is used to calculate the activation energy. Also, in order to be consistent with the relaxation (i.e., a decrease in magnitude) of the residual stress, the slope of the linearized Zener-Wert-Avrami function must be positive. The basis of comparison for the activation energies calculated using this method was the range of activation energy values determined by Was et al. cited above (188 to 281 kJ/mol) [55].

The only alloy with data that could be used to assess relaxation using the Zener-Wert-Avrami function was Alloy 600. Three vendors performed experiments with Alloy 600. Hitachi-GE treated three Alloy 600 plates with water jet peening and then subjected the plates to a high temperature (450°C) to accelerate the relaxation process for 1000 h. MHI performed similar experiments at three different temperatures closer to operating temperatures (320°C, 350°C, and 380°C) with replicates for different periods of time depending on the temperature (100 h for plates at 320°C, and 1400 h for the other plates). This data is shown in Table B-1 and depicted in

Figure B-9. Experiments performed by Toshiba with Alloy 600 could not be used in this analysis because residual stress was only measured at one time point after relaxation.

The thermal relaxation of Alloy 182 and Type 316 L SS were also investigated by Hitachi-GE at 450°C after peening as shown in Figure 4-1 (which is a subset of the data featured in Figure B-9). In this testing, three replicates were peened for each material included, and the surface stresses in both surface directions, referred to as σ_x and σ_y, were measured over time. Peening was applied in the y-direction. On each plot, each color corresponds to one of the three specimens of each material that were tested. Because only one temperature was used in these experiments, the data cannot be used to calculate an activation energy for these alloys. Analysis of the relaxation data for Alloy 182 and Type 316 L SS suggest that most of the relaxation occurs between the initial development of residual stress after peening and the first stress relaxation measurement, independent of direction, with little significant relaxation in subsequent measurements.

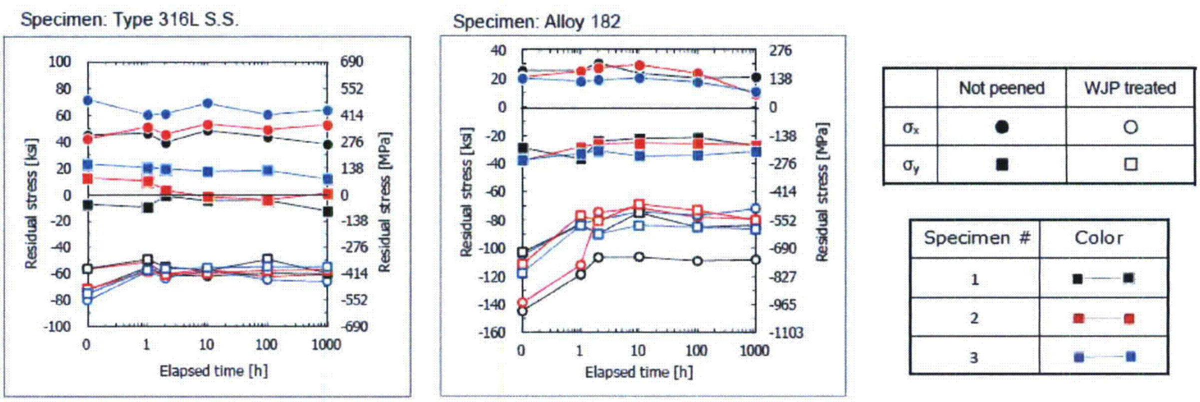


Figure 4-1
Thermal relaxation of Alloy 182 and Type 316 L SS at 450°C for 1000 h provided by Hitachi-GE

Two different approaches were used to calculate an activation energy from the vendor provided data. One approach used that satisfies the requirements above was to take the MHI residual stress measurements at all time points, and find a trend line for each plate where the slope value was pre-specified to be the Hitachi-GE slope value. This essentially corresponds to calculating an "intercept of best fit". The slope from Hitachi-GE was positive and fit the data well as shown in Figure 4-2, but the Hitachi-GE experiments could not be used to find an activation energy because they were only performed at one temperature. The "best-fit intercept" and the "pre-fit slope" were used to calculate values of A, which were in turn used to determine a value for the activation energy with an Arrhenius plot as a function of temperature shown in Figure 4-3. The best fit slope of the linearized data was used to calculate the activation energy of the thermal relaxation process. The value of the activation energy found using this method was 276 kJ/mol, which is within the range determined by Was et al. [55].

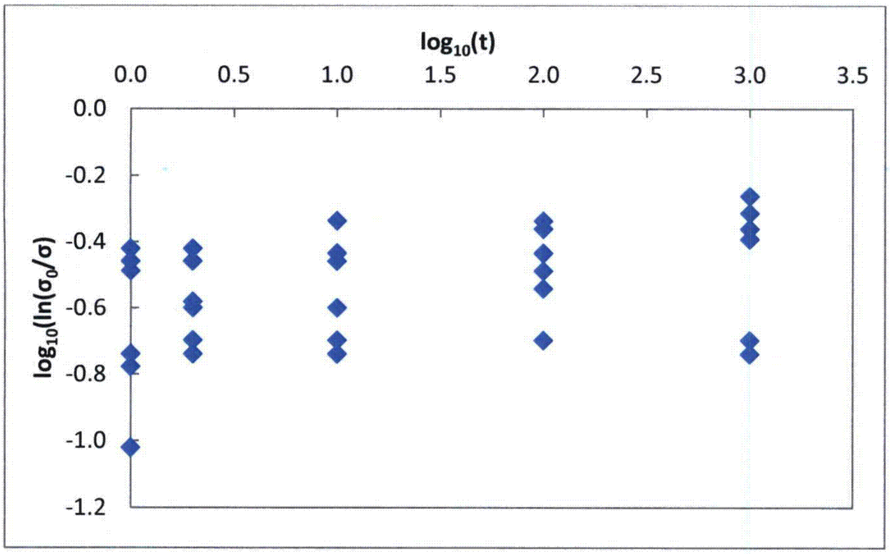


Figure 4-2
Thermal Relaxation Data from Hitachi-GE for Alloy 600 plates treated with water jet peening and held at 450°C for 1000 h

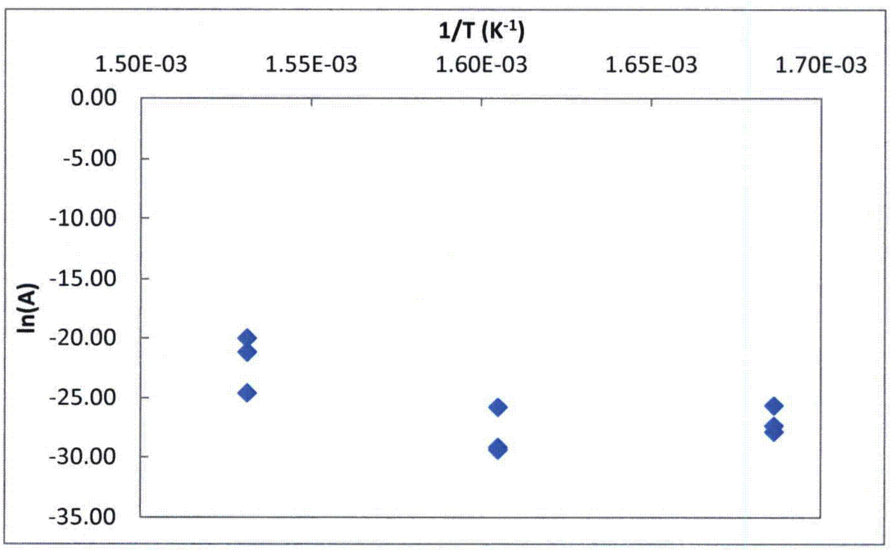


Figure 4-3
Arrhenius plot for the first approach to thermal relaxation data treatment (based on data provided by Mitsubishi and Hitachi-GE)

In the second approach used to satisfy both requirements described above, the A values were calculated from the slope from the Hitachi-GE data and the MHI residual stress measurement taken at $t = 1$ hr, which happens to lie on the Y-axis, making it the "experimental intercept." The residual stress measurements taken at $t = 1$ hr were chosen from the MHI data because the most significant relaxation happened between the initial residual stress measurement and the first

stress relaxation measurement, which occurred at time t=1 hr. The remaining time dependent residual stress profile was relatively flat with some noise, making activation energy estimation with all the data difficult. Using only the experimental intercept, with three replicates at three different temperatures, allowed for some of this noise from the entire data set to be filtered out. Then, the values for A were graphed on an Arrhenius plot, as shown in Figure 4-4, to determine an activation energy. Using this approach, the value of the activation energy calculated was 316 kJ/mol, which is almost within the activation energy range determined by Was et al [55].

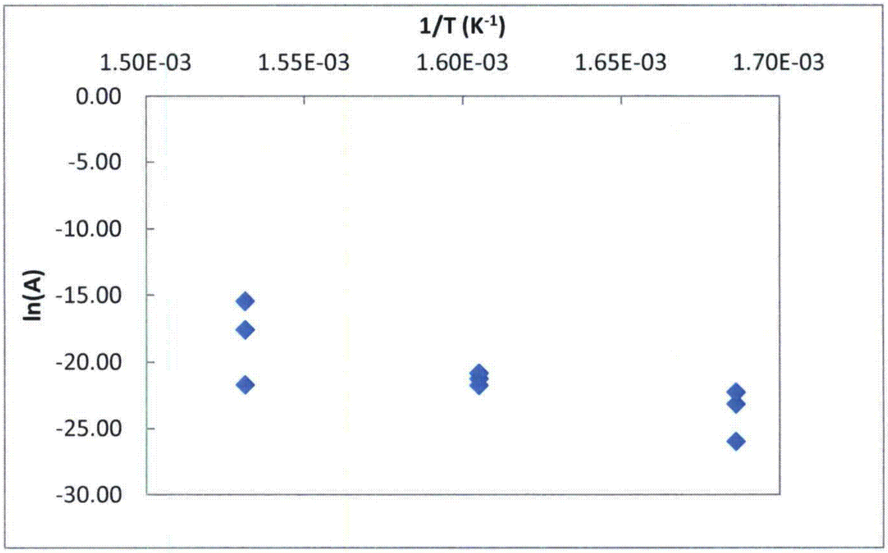


Figure 4-4
Arrhenius plot for the second approach to thermal relaxation data treatment (based on data provided by Mitsubishi and Hitachi-GE)

The two approaches to activation energy estimation described above result in values close to the cited creep activation energy interval, supporting its relevance to the current application. A summary of the calculated and cited activation energy values is summarized in Table 4-1 below.

Table 4-1
Summary of Activation Energy Values for Alloy 600 Stress Relaxation

Method of Activation Energy Determination	Activation Energy (kJ/mol)
Approach 1	276
Approach 2	316
Was et al. interval	188-281

4.4.2 Calculation of Equivalent Lifetime from Thermal Relaxation Experiments

Once the Alloy 600 creep activation energy interval determined by Was [55] was deemed relevant to the current application, an activation energy approach was used to calculate the lifetime corresponding to the different combinations of experimental temperature and test duration performed by the vendors. Table 4-2 and Table 4-3 below show the operating lifetimes hot leg butt welds and CRDMs, respectively, for which credit can be taken from the various thermal relaxation experiments assuming three different activation energy values from the range (the minimum, the midpoint, and the maximum). The experiments performed by Hitachi-GE, which were at the highest temperature, scaled using the lower bound of the activation energy interval, which is the more conservative value, covers 61.1 years of operation for butt welds operating at 329°C and even longer for CRDM nozzles, suggesting that the process is effective for more than the full 60-year extended operating period at normal operating temperatures.

Table 4-2
Lifetime Equivalency of Hot Leg Butt Welds Operating at 329°C

Vendor	Alloy	Temperature (°C)	Duration (h)	Activation Energy [kJ/mol]		
				lower bound of Was range [55]	midpoint of Was range [55]	upper bound of Was range [55]
				188	234.5	281
				equivalent time at operating temp (yr)		
Hitachi-GE	Alloy 182	450	1000	61.1	289	1369
Hitachi-GE	Type 316L SS	450	1000	61.1	289	1369
Hitachi-GE	Alloy 600	450	1000	61.1	289	1369
Toshiba	Alloy 600	360	1000	0.72	1.13	1.78
MHI	Alloy 600	380	1400	3.00	6.20	12.79
MHI	Alloy 600	350	1400	0.57	0.77	1.06
MHI	Alloy 600	320	100	0.01	0.01	0.00
maximum operating time accounted for				61.1	289	1369

Table 4-3
Lifetime Equivalency of CRDMs Operating at 315°C

Vendor	Alloy	Temperature (°C)	Duration (h)	Activation Energy [kJ/mol]		
				lower bound of Was range [55]	midpoint of Was range [55]	upper bound of Was range [55]
				188	234.5	281
				equivalent time at operating temp (yr)		
Hitachi-GE	Alloy 182	450	1000	149.5	882.2	5207
Hitachi-GE	Type 316L SS	450	1000	149.5	882.2	5207
Hitachi-GE	Alloy 600	450	1000	149.5	882.2	5207
Toshiba	Alloy 600	360	1000	1.75	3.45	6.78
MHI	Alloy 600	380	1400	7.33	18.89	48.67
MHI	Alloy 600	350	1400	1.38	2.36	4.03
MHI	Alloy 600	320	100	0.02	0.02	0.02
maximum operating time accounted for				149.5	882.2	5207

4.4.3 Effects of Operating Stresses on Relaxation of Peening Induced Compressive Stresses

Steady-state pressure-applied operating stresses at the wetted surfaces are expected to be tensile, and thus will reduce the absolute magnitude of the compressive stresses at the wetted surface during normal power operation. Since creep rates decrease as the absolute magnitude of stresses decrease, the presence of pressure-applied operating stresses is expected to decrease the rate of stress relaxation of peening induced compressive stresses.

While the effects of steady state pressure-applied operating stresses are not expected to increase rates of stress relaxation, the effects of relatively high transient tensile and compressive stresses need to be considered. After peening, the surface has a high compressive stress field and also has a high yield strength. For example, after peening, surface hardnesses are typically about 250 Hv or higher, as discussed in Appendix A. Using standard ASTM hardness conversion tables for nickel-base alloys [57] and a hardness to yield strength curve from an INCO handbook [58], a hardness of 250 Hv is about 22.5 on the Rockwell C scale, which corresponds to a yield strength of about 90 ksi for nickel-base alloys. This value will decrease by about 10% or less when the temperature is raised from room temperature to an operating temperature of about 620°F (327°C), based on data in the Special Metals brochure for Alloy 600 [59]. Thus, the peened surface layer will have a yield strength of about 81 ksi or more at operating temperature.

The ASME Code limits the range of applied service stresses in Class 1 components to 3 Sm. Sm is 16.6 ksi for austenitic stainless steels at 600°F (316°C). Thus, the maximum range of applied service stresses at, for example, a dissimilar metal butt weld with stainless steel safe end at a vessel nozzle is 3 x 16.6 = 50 ksi. Since steady state applied stresses are expected to be tensile, e.g., 10 ksi due to pressure, the likely maximum compressive stress is expected to be the sum of the initial applied stress of +10 ksi reduced by the maximum magnitude compressive stress of -50 ksi, for a resulting maximum compressive stress of 40 ksi. Using the same logic, the likely maximum tensile stress is +10 +50 = +60 ksi.

Since the largest compressive and tensile stresses in the peened layer that could occur by allowed service load induced stresses (i.e., -40 ksi and +60 ksi) are well below the yield strength of the peened surface layer of 81 ksi, no yielding of the peened surface layer is expected to occur as the result of the maximum allowed service stresses. This indicates that the compressive stresses in the peened layer will not be reduced by application of the maximum allowed service stresses.

4.4.4 Summary

Three arguments have been presented to justify that residual stresses resulting from peening will remain compressive for the full operating life of a nuclear power plant including one license extension periods. Fitting the experimental results to the Zener-Wert-Avrami function to estimate activation energy resulted in values very close to the activation energy range identified by Was et al. Calculation of equivalent plant lifetime from experimental data using an activation energy approach resulted in long operating lifetimes of the residual stress. Finally, theoretical arguments can be made that the effect of operating stresses is to reduce the magnitude of the stress present at the surface and that this tends to reduce the relaxation of the peening induced stresses. It is also worth noting, as discussed in Section 3.2 that the steam generator pulled tube data confirmed that residual stresses were still strongly compressive after 7 cycles of operation.

4.5 Verification of No Unacceptable Side Effects caused by Peening

Another important concern when considering application of peening is assuring that no unacceptable side effects are caused by peening. Examples of unacceptable side effects include growth of existing flaws during the peening process, accelerated subsequent growth of pre-existing flaws, decreased ability to inspect the peened surface, or vibrational damage. An important source of confidence that application of WJP and ULP generally do not result in adverse side effects is the application of these technologies in Japan since 2001 and 2004, respectively, with no reported damage to peened parts, but with some flow induced vibration problems of adjacent parts (see Section 3.1.4). Section A.2.2.1 contains experimental results from Toshiba and MHI indicating that ULP and WJP do not cause crack growth during application. In Section A.2.2.2, experimental results from all four peening vendors support that accelerated crack growth does not result within the compressive stress depth when the peened component is brought back into operation. Section A.4.1 contains a detailed experimental procedure and the results for experiments performed by Hitachi-GE verifying that WJP does not affect the flaw sizing capabilities of UT. Similarly, MHI has performed tests in parts with EDM slits and confirmed that peening did not affect the detectability of the slits by either ET or UT. Hitachi-GE also examined the vibrational effects that both target and adjacent components are subjected to during the peening process, specifics of which can be found in Section A.4.2. Peak frequencies for normal peening parameter values are in the range of 400-500 Hz, and Hitachi-GE

has stated that it has techniques to reduce vibrational effects if need be. Mitsubishi also has conducted experiments examining the vibrational frequency of WJP, the characteristic frequency of BMI nozzles, and the stress produced by WJP in BMI nozzles. The experimental results and subsequent calculations revealed that the characteristic frequency of BMI nozzles is not in the range of WJP vibrational frequencies. However, as noted in Section 3.1.4, if the WJP flow impinges on adjacent parts such as instrument lines or small nozzles, flow induced vibration can occur and result in damage. This possibility needs to be evaluated before application of WJP.

Pre-existing residual stress profiles are not expected to diminish the ability of ULP, WJP, or ALP to modify the residual stress of a component and to establish a relatively uniform high compressive stress. Areas initially in tensile stress will experience a greater response to treatment since these areas are statically biased higher up on the stress-strain curve, so they will achieve more plastic deformation upon relaxation. In a related way if an area is initially compressively pre-stressed, the peening induced pressure has to overcome more elastic resistance before achieving plastic deformation that leads to compressive residual stress. Therefore the process is somewhat self-normalizing in that regions with higher tensile pre-stress will attain a more effective peening than regions of neutral stress, and areas with a pre-existing compressive stress will show less response to the peening. The net result is that the variability in the post peening stresses in relatively small, and much less than the variability that can be present in pre-peening residual stresses.

Concerns have been expressed that high tensile stresses might develop at transition areas at the edges of peened to unpeened areas. The service experience discussed in Section 3 indicates that this is not a concern with regard to peening for mitigation of PWSCC since there have been no reported problems at the transition areas of the many thousands of steam generator tubes that have been shot peened or rotopeened. Further, there have been no problems reported for transition areas in the many Japanese PWRs and BWRs that have been peened. In addition, the test data discussed in Section 4.2.2 and illustrated in Figures A-3, A-5 through 8, A-10, and A-11 show that high stresses have not been developed in the transition areas of test specimens. It is concluded that the types of peening being considered for surface stress mitigation do not cause significant tensile stresses at the transition areas between peened and non-peened regions. It is also noted that driving stresses for any undetected cracks that might be present in normal transition areas are low, and that this provides further assurance that the transition areas are not a concern. A related concern is that, if undetected interruptions in water jet peening occurred, they would introduce transitions to unpeened areas. Both HGNE and MNES indicate that they have procedures in place that prevent this from occurring.

The potential for adverse effects resulting from peening has also been considered in the context of a safety evaluation per Section 50.59 of 10 CFR 50. Over the course of this consideration, it was determined that peening the ID surfaces of the candidate components has no adverse effects on the ability of the parts to maintain leak tight integrity. In fact, peening should increase resistance to PWSCC on these surfaces. Also, the possibility of an accident or a malfunction important to safety is not expected to be affected by peening. While peening is considered to not raise risks of damage to the peened parts themselves, experience has shown that WJP can cause flow induced vibration of adjacent parts. This needs to be evaluated as part of 50.59 evaluations, and appropriate actions need to be taken to ensure that no flow induced vibration problems occur (see Section 3.1.4).

4.6 Issues Related to Cold Work

The process of peening involves plastic deformation of surface layers of the metal, and thus introduces cold work. Another aspect related to cold work is that the surface to be peened is likely to have experienced some level of cold work, possibly in an irregular pattern. There are several questions of interest related to cold work and the use of peening as a mitigation measure against PWSCC:

- What levels of cold work are developed by the proposed peening processes?
- Does the cold work caused by peening increase risks or rates of SCC or other degradation modes?
- Can high levels of prior cold work in surface material to be peened result in the peening not being effective at generating the desired compressive stress field?
- How does the level of cold work in the peened surface layer affect the long term relaxation or loss of the compressive stress field developed by the peening? In this regard, can high levels of cold work result in so much loss of the stress field that it eventually becomes ineffective?
- Can high levels of cold work in the metal lead to phase instability that can affect the long term performance of the peened material, as has been postulated for waste disposal containers planned for use in geological disposal sites?

Responses to the above questions are discussed in later parts of this subsection.

4.6.1 Background Information – Cold Work vs. Hardness and Strength

Cold work is measured in various ways. The most straight forward way is by the percent cold work, meaning the percent cold reduction in cross sectional area of a plastically deformed material. It is also measured by changes in hardness and tensile strengths. Cold work can also be measured in terms of dislocation density, e.g., as indicated by line broadening in X-ray diffraction measurements. For the purposes of this report, hardness measured by percent cold reduction, hardness and tensile strength are used since they are the most commonly used measures. Data relating these parameters are shown in Table 4-4 and Figure 4-5, which are based on data in two brochures from a material supplier [60], [61]. For reference purposes, it should be understood that Alloy 600 nozzle material typically has a tensile strength in the range of 85 to 90 ksi (590 to 620 MPa), i.e., it has a cold work of about 0% as shown by the data in Table 4-4.

Table 4-4
Relationship between Cold Reduction, Hardness and Tensile Strength for Alloy 600

% Cold Reduction	Vickers Hardness	Rockwell B or C	Tensile Strength
0	150	80 B	89
10	207	14.5 C	114
20	245	22.5 C	128
30	272	26.4 C	136
40	292	29.5 C	145
50	307	32.0 C	153
60	312	32.4 C	154
70	312	32.4 C	154

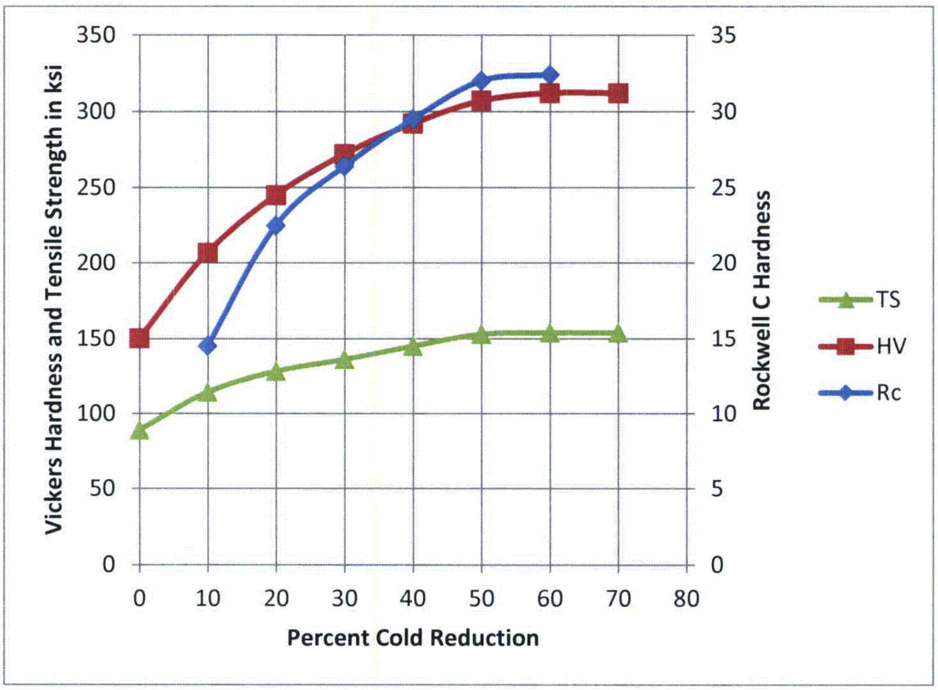


Figure 4-5
Relationship between Cold Reduction, Hardness and Tensile Strength [60], [61]

4.6.2 Levels of Cold Work Developed by Peening

4.6.2.1 Hitachi-GE Water Jet Peening

Data showing the effects of water jet peening and, for reference, conventional shot peening on cold work at the surfaces of Alloy 600, Alloy 182, and Type 316 stainless steel are shown in

Figure A-85 of Section A.1.8, provided by Hitachi-GE [60]. As can be seen from the data shown in the figure, water jet peening increased hardness from about 200 Hv to 250 Hv, while shot peening increased it to about 400 Hv. Using the cold work – hardness – tensile strength correlations shown on Table 4-4 and Figure 4-5, the effects of the peening on cold work are as follows:

Table 4-5
Effects of Hitachi-GE Water Jet Peening and Standard Shot Peening on Hardness and Percent Cold Work of Alloy 600 and Alloy 182

Condition	Vickers Hardness	Percent cold Work(*)
Non-Peened	200	8
Water Jet Peened	250	20
Shot Peened	400	>50

(*) Calculated value based on Figure 4-5

Hitachi-GE performed EBSD examinations of electropolished and then water jet peened specimens and compared them to those of shot peened specimens. These examinations showed no visible distortion of the water jet peened specimens but significant distortions to a depth of 200 microns for the shot peened specimens. This confirms that the level of cold work associated with water jet peening is much less than that associated with shot peening.

4.6.2.2 MHI/MNES Water Jet Peening

Hardness results for a BMN nozzle and J-groove weld are shown in Figure A-83 and Figure A-84 provided by MHI/MNES. The hardness increase at the nozzle ID caused by water jet peening is from about 200 Hv to 250 Hv, the change at the OD for the Alloy 600 base material is from about 200 to 300 Hv, and the change in the Alloy 132 weld metal is also from about 200 Hv to 300 Hv. Using the cold work – hardness – tensile strength correlations shown on Table 4-4 and Figure 4-5, the effects of the peening on cold work are as follows:

Table 4-6
Effects of MHI Water Jet Peening on Hardness and Percent Cold Work of Alloy 600 and Alloy 132

Material and Condition	Vickers Hardness	Percent cold Work (*)
Non-Peened Alloy 600	200	8
Non-Peened Alloy 132	200	8
Water Jet Peened Alloy 600 at BMN ID	250	20
Water Jet Peened Alloy 600 at BMN OD	300	43
Water Jet Peened Alloy 132 at BMN Weld OD	300	43

(*) Calculated value based on Figure 4-5

4.6.2.3 Westinghouse – Toshiba Underwater Laser Peening

Data showing the effects of underwater laser peening on the surface of Alloy 600 are shown in Figure 4-6, provided by Westinghouse - Toshiba. As can be seen from the data shown in the figure, underwater laser peening increased hardness from about 250 Hv to 280 Hv near the surface. Using the cold work – hardness – tensile strength correlations shown on Table 4-4 and Figure 4-5, the effects of the underwater laser peening on cold work are as follows:

Table 4-7
Effects of Westinghouse – Toshiba Underwater Laser Peening on Hardness and Percent Cold Work of Alloy 600

Condition	Vickers Hardness	Percent cold Work
Non-Peened	250	20
Underwater Laser Peened	280	35

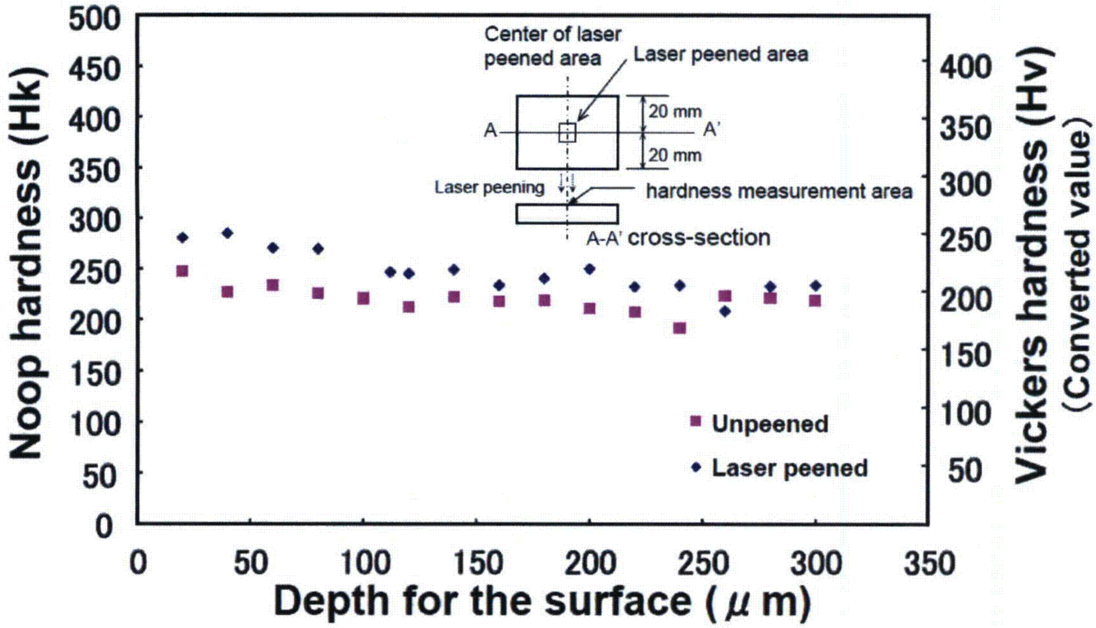


Figure 4-6
Effects of Underwater Laser Peening on Hardness of Alloy 600, data provided by Toshiba

4.6.2.4 MIC Air Laser Peening

Data showing the effects of air laser peening on the surface were available for Alloy 718 material, another austenitic nickel-base alloy, as shown in Figure 4-7 [62]. The figure also shows results for shot peening and gravity peening, which is peening using larger shot. As can be seen from the data shown in the figure, air laser peening increased the cold work by only a small amount, about 6%, while shot peening increased it to about 30% and gravity peening to about 16%.

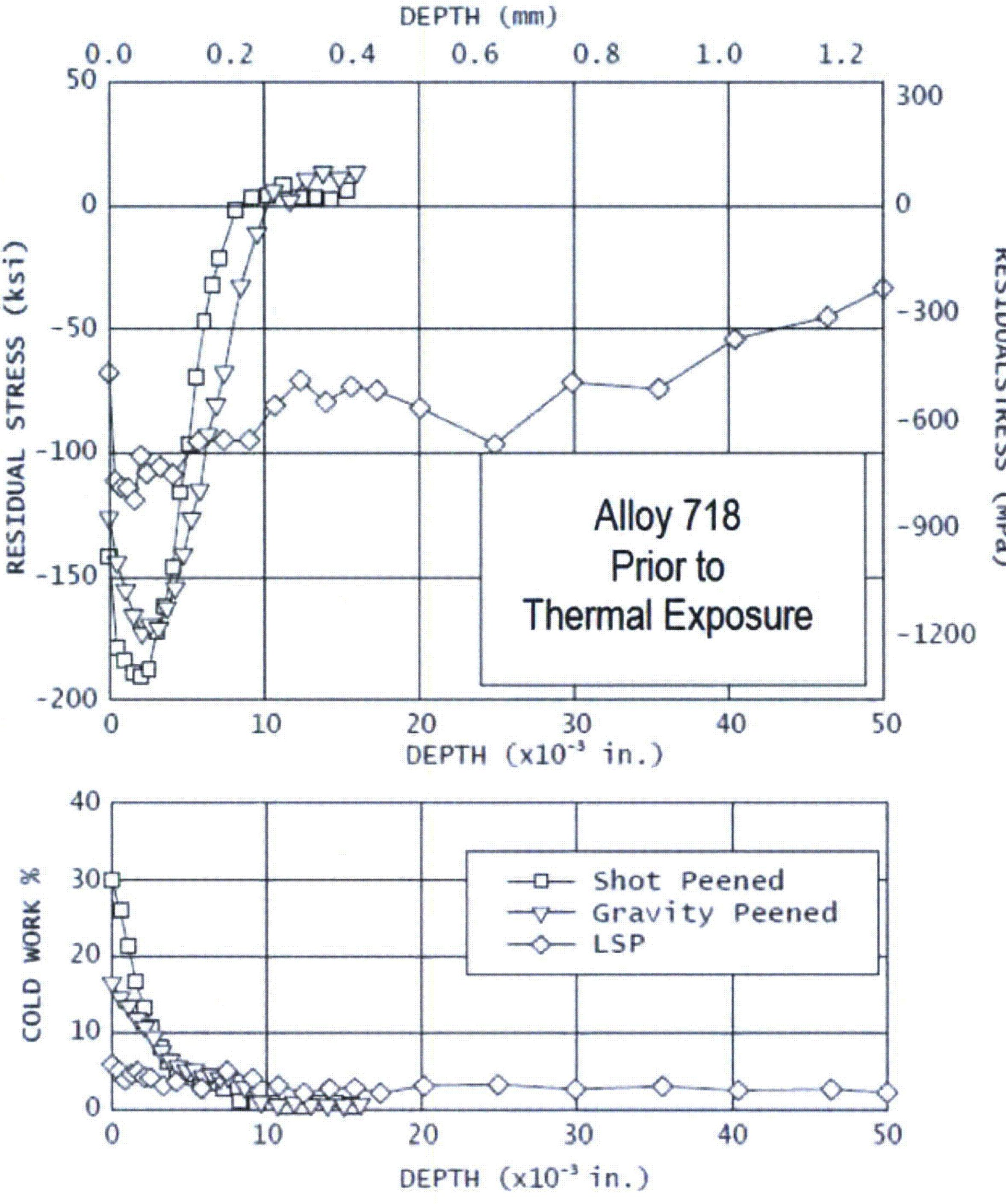


Figure 4-7
Residual Stress and Cold Work Distributions Developed in Alloy 718 Coupons Using Shot Peening, Gravity Peening and Air Laser Peening

4.6.3 Effect of Cold Work from Peening on SCC and other Modes of Degradation

Many tests have shown that cold work on surfaces, if present together with tensile stresses, increase susceptibility to initiation of SCC. Tests also show that the growth rate of initiated cracks is higher in cold worked material, and increases as the level of cold work increases. However, tests and service experience also show that these concerns do not apply to properly peened surfaces as the result of the compressive stresses developed by peening that inhibit the initiation and growth of cracks. In this regard, peening has been widely applied as a mitigation measure against fatigue cracking and SCC for many years and in many industries [63], without it having caused problems such as increased risk of fatigue or SCC, with one notable exception in the nuclear power industry, as discussed below.

If a peened part is subsequently subjected to high plastic strains that overwhelm the compressive stress field developed by the peening, then high tensile stresses and susceptibility to SCC can result since the cold worked layer has a high yield stress that allows development of high residual stresses. This is apparently the cause of the ODSCC that has occurred in steam generator tubes at two Spanish plants that experienced denting at the top of the sheet (this experience is discussed in Section 3.2.2). This type of event is not considered applicable to butt welds or nozzle J-groove welds since there has been no experience of these parts being subjected to large plastic strains.

It is known that peening can sometimes cause microstructural damage, such as fracturing of precipitates, that can increase susceptibility to problems such as SCC if for some reason the compressive stress field is lost. However, as discussed in other parts of this report, the peening processes considered in this report, i.e., water jet peening, underwater laser peening, and air laser peening, have been found to not cause significant microstructural changes in Alloy 600 and its weld metals. In addition, as also discussed earlier in this section, tests and analyses indicate that the compressive stresses developed by peening will remain protective for extended plant life times and will prevent cracking in the cold worked layers associated with peening. In addition, this conclusion is supported by tests and service experience with steam generator tubes (Sections 3.2.3 and 3.2.4) that show that peening stresses in Alloy 600 remain sufficiently high after extended service to be protective as long as large plastic strains are not applied.

4.6.4 Effect of Prior Cold Work on Ability to Effectively Peen

The process of peening involves application of plastic strains that develop high compressive stresses. If the material being peened is so hard that it does not plastically strain as result of the peening, the desired compressive stresses are not developed. With regard to industry experience on this topic, shot peening of alloy 600 SG tubes is known to be effective at mitigating PWSCC at roll transitions, which have significant levels of cold work. However, while this is encouraging, it does not provide conclusive evidence that other peening methods will be similarly effective. Data related to this topic specifically for water jet peening and for laser peening of Alloy 600 and similar alloys is discussed below.

- MHI has measured residual stress profile as a function of depth for weld plates all of which included a cold worked area due to surface grinding. MHI confirmed that the tensile stress existing prior to WJP became compressive following WJP. These data are presented in Figure A-34.

- Toshiba has produced data showing that peening prevented cracking of 20% cold worked specimens of austenitic stainless steel that cracked badly in the same environment when not peened. These data are presented in Figure A-90. Since austenitic stainless steel and Alloys 600, 182 and 82 have similar mechanical properties and behavior, this indicates that prior cold work at least to about 20% will not prevent effective peening.
- PWSCC initiation tests of U-bend specimens of heavily ground Alloy 182 material are described in Section A.3 of Appendix A. The WJP, ULP, and ALP processes all developed high compressive stresses at or near the surfaces[6] of these heavily ground surfaces, and also prevented initiation of SCC at these surfaces, while most unpeened specimens rapidly cracked. These test results indicate that these types of peening would be effective at preventing PWSCC initiation at most ground areas of plant components. However, the authors of the report of the U-bend tests concluded that "the laboratory heavy grinding procedure had not reproduced the extent of cold work that has been observed on some field components" [64]. This indicates that there is a possibility that some local areas with especially heavy grinding may not respond to peening.
- With regard to ALP, MIC reports that it has been shown to effectively peen a variety of very hard materials, such as AerMet and HyTuf steels and carburized materials such as 8620 and 9310 gear and bearing steels. MIC notes that ALP treated AerMet 100 in a HRC 53 hardened condition (UTS of 287 ksi) has demonstrated excellent fatigue performance. The ALP treatment developed surface compressive stresses of -150 to -190 ksi (-1034 to -1310 MPa). Based on this experience, it seems probable that the ALP process will be able to successfully peen any cold worked conditions present in Alloy 600/182/82 materials in PWRs.

4.6.5 Effect of Cold Work on Stress Relaxation

Evaluations of the effects of stress relaxation on loss of the compressive stress developed by peening are a concern for peened parts that are used at elevated temperatures, such as Alloy 718 gas turbine parts (e.g., [56]). The amount of relaxation is found to be a function of the level of cold work as well as of the temperature and various material factors. Most of the relaxation occurs in the early part of the exposure to high temperatures.

An analytical evaluation of stress relaxation based on an activation energy approach is discussed above in Section 4.4. It shows that the high temperature tests performed by a vendor, when adjusted for the lower temperatures of plant components using an activation energy analysis, indicate that peening will remain effective for at least 61 years.

As discussed in other sections of this report, peening has been widely used as a PWSCC mitigation measure for steam generator tubes in areas that were significantly cold worked, e.g., roll overlaps and roll transitions. Service experience indicates that the peening has remained effective since its application in the late 1980s, i.e., for over 30 years. In addition, evaluation of the stress levels in tubes after up to seven fuel cycles of operation showed that the residual

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[6] As discussed in Section A.1.1.3 of Appendix A, the stresses developed by LSP without an ablative layer are tensile at the surface but rapidly decrease to highly compressive values within about 35 μm. The stresses then remain compressive until at least a depth of 1.5 mm. The underlying high compressive stresses act to inhibit formation of significant cracks at the surface.

compressive stresses were still sufficiently high to provide effective protection against initiation of PWSCC [46].

4.6.6 Effect of Cold Work on Phase Instability

Evaluation of peened alloys for use in high temperature (>500°C) gas turbine applications has indicated that the cold work associated with shot peening can lead to phase instabilities at the high temperature involved, and that the phase instabilities can lead to degraded performance. However, this concern is not considered applicable to PWR reactor coolant hot leg environments because of the lower temperatures involved, less than about 327°C. The main evidence in this regard is the fact that thousands of peened steam generator tubes continue to provide satisfactory service for times of 20 years or more.

4.7 Conclusions

Key conclusions from the extensive experimental work summarized in Appendices A and B are as follows:

- The ULP and WJP methods typically result in a compressive residual stress layer that is roughly 1 millimeter (0.04 in.) deep. Because of its relatively high power laser source, the ALP process is capable of inducing deeper compressive residual stress layers, up to several millimeters deep.
- The effectiveness of the SSI treatments to reliably preclude future SCC initiation and to arrest growth of shallow flaws located in the compressive stress zone is demonstrated by stress profile measurements and corrosion cracking tests. In the case of the ULP and WJP processes, these tests included mockups representative of BMN and large-diameter piping DMWs such as RV outlet/inlet DMW geometries. The ULP and WJP processes are considered to be demonstrated for the BMN and large-diameter piping DMW geometries. Additional work including testing on mockups representative of actual PWR component geometries is necessary to demonstrate the ALP process for mitigation of PWSCC in PWRs.
- An additional series of tests performed by vendors and EPRI demonstrate the long-term sustainability of a substantial compressive residual stress at the surface treated by SSI. These tests address both stress relaxation due to exposure to primary system operating temperatures, as well as stress shakedown due to load cycling. Service experience with peened steam generator tubes also demonstrates that peening compressive stresses remain high enough to inhibit PWSCC after many cycles of plant operation.
- Calculations of the operating time over which the compressive residual stress layer can be maintained from the thermal relaxation experimental data justify that the peening process is effective for more that the full 60-year extended operating period at normal operating temperatures.
- To date, no experiments have revealed that peening causes unacceptable side effects to target or adjacent components. This conclusion is also supported by the absence of any reports of unacceptable side effects at any of the many Japanese BWRs and PWRs at which peening has been performed over the past 13 years (other than some problems with flow induced vibration for WJP in BWRs as described in Section 3.1.4).

In summary, peening vendors and EPRI performed separate verification experiments—among them corrosion cracking and stress relaxation tests—to confirm the effectiveness and sustainability of SSI treatments in various environments, including a simulated PWR environment. The extensive experimental results demonstrate that SSI treatments are effective measures in preventing or mitigating PWSCC.

5

IMPLEMENTATION CONSIDERATIONS OF LASER AND WATER JET PEENING TECHNIQUES

5.1 Introduction

The previous section has established a scientific basis that demonstrates that the surface stress improvement techniques are effective measures to mitigate PWSCC. This section discusses some important implementation aspects of the candidate surface stress improvement processes, i.e., ULP, ALP, and WJP. Typical plant application issues including control strategy, facility preparation, and personnel training are discussed here because of their importance to the safety and reliability of peening processes. These considerations might impact decisions in the selection of mitigation methods. As ALP is not yet fully commercialized for use in LWR applications, the discussion of ALP in this section focuses on the steps required for its use in nuclear power plant applications.

All three of these SSI techniques are applicable to treatment of RPVHPNs, BMNs, and piping DMWs. Specialized tooling would be necessary to apply WJP to the outer diameter surface and J-groove weld of RPVHPNs including CRDM/CEDM nozzles given that mitigation would be performed while the head is located on its storage stand. In the case of ULP, demonstration work including mockup testing and field experience has been performed in an underwater environment, but the process can be adapted to be performed in air. Use of ALP for BMN or piping DMW locations would require that these areas be drained during the maintenance outage, or that the laser beam be piped to the underwater target location.

With regard to the ULP process discussed in this report, it has the advantage that the entire operation may be performed underwater, which results in significant reductions in radiation dose associated with the process. Underwater implementation can also reduce the impact on nuclear plant outage schedules. The use of laser energy for mitigation results in a process that can potentially be applied to locations where other conventional mitigation alternatives cannot be applied due to limited access.

WJP has the advantage of underwater treatment with no foreign materials involved and no heat involved; in addition, no wastage is generated during treatment. The WJP procedure uses a simple water transfer line, and can be easily controlled with high precision. The simplicity in tooling minimizes the required outage time for WJP application in actual plants. In addition, WJP has no adverse influence on materials, such as stress-induced martensitic transformation or magnetization.[7] As with ULP, WJP can be applied to components with access limitations, such

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[7] Formation of martensite is an issue in BWRs where it has been associated with increased susceptibility of stainless steels to IGSCC in normal BWR water chemistry. Formation of martensite has not been a significant issue in PWRs, i.e., has not been a significant factor in the occurrence of SCC of stainless steels in PWRs. Formation of martensite

as the ID surface of BMNs in PWRs. While WJP has no adverse effects on the peened surfaces, it can cause flow induced vibration problems of adjacent parts such as instrument lines or small nozzles, and this possibility needs to be considered when using WJP.

The ULP and WJP methods typically result in a compressive residual stress layer that is roughly 1 millimeter (0.04 in.) deep. Because of its relatively high power laser source, the ALP process has the advantage of being capable of inducing deeper compressive residual stress layers, up to several millimeters deep.

Due to physical differences between a tube ID configuration and a large-radius flat surface configuration, the WJP process usually produces a deeper layer of compressive stress on a large-radius flat surface than on a tube ID surface. This is due to the fact that the impingement angle is necessarily lower when peening the tube ID, as well as the use of a lower flow rate for the tube ID (although the different water jet nozzle configurations designed for these two types of surfaces result in a similar water jet flow speed for both processes). As previously discussed, the mitigating effect is created when residual compressive stresses are created at the surface that prevent initiation of PWSCC. The data presented in Appendix A show that the WJP process is capable of producing a reliable layer of compressive residual stresses to roughly a depth of 1 millimeter (0.04 inch) for the large radius flat surface configuration, and to an approximate depth of 0.5 millimeter (0.02 inch) for the BMN tube ID configuration.

Section 5.2 below addresses implementation of underwater laser peening (ULP), Section 5.3 addresses implementation of water jet peening (WJP), and Section 5.4 addresses implementation of air laser peening (ALP). Section 5.5 presents key conclusions.

5.2 ULP System Development and Engineering Design

5.2.1 Control Strategy and Interlocks

To ensure the quality of ULP, the parameters listed in Table 5-1 are continuously monitored, and interlocks are set up for each parameter. The irradiation density of the laser pulses is calculated and confirmed to be within the limit immediately after the treatment of each batch.

Table 5-1
ULP control parameters

Parameter	Limit	Remark
Laser power (pulse energy)	Low/High	
Laser scanning speed	Low/High	
Driving motor torque	High limit	For each axis
Irradiation head distance	Low/High	Outside treatment only

does not occur in Alloys 600, 182, and 82. For these reasons, the formation of martensite is not further addressed for WJP and is not addressed at all in this report for ULP and ALP.

As listed in Table 5-1, laser power (pulse energy), head distance, and irradiation density are controlled within certain limits. The distance of the irradiation head to the surface of the treated component is controlled within an adequate response time in order to keep the laser spot an appropriate size on the surface.

5.2.2 Safety Strategy

Laser light is a potential safety hazard, especially to the eyes. Therefore, operational personnel are appropriately trained before any application of the ULP process. However, the ULP system confines laser light completely inside the system, namely inside the casing of the laser oscillator and the optical fiber or laser guide pipe. With regard to ULP of BMNs, the reflected light at the bottom of the reactor vessel is no longer hazardous to the eyes. Any damage to the optical fiber is readily apparent given the distinctive green light.

A high voltage is transmitted from the laser power supply to the laser oscillator. The power supply will automatically be shut down if a leakage of electricity is detected.

5.2.3 ULP System Architecture

Schematic drawings of portable laser peening (PLP) devices are shown in Figure 5-1 for the inside diameter surface of BMNs and in Figure 5-2 for the outer BMN surfaces including the J-groove weld. Figure 5-3 shows the outline of the key equipment comprising the ULP system.

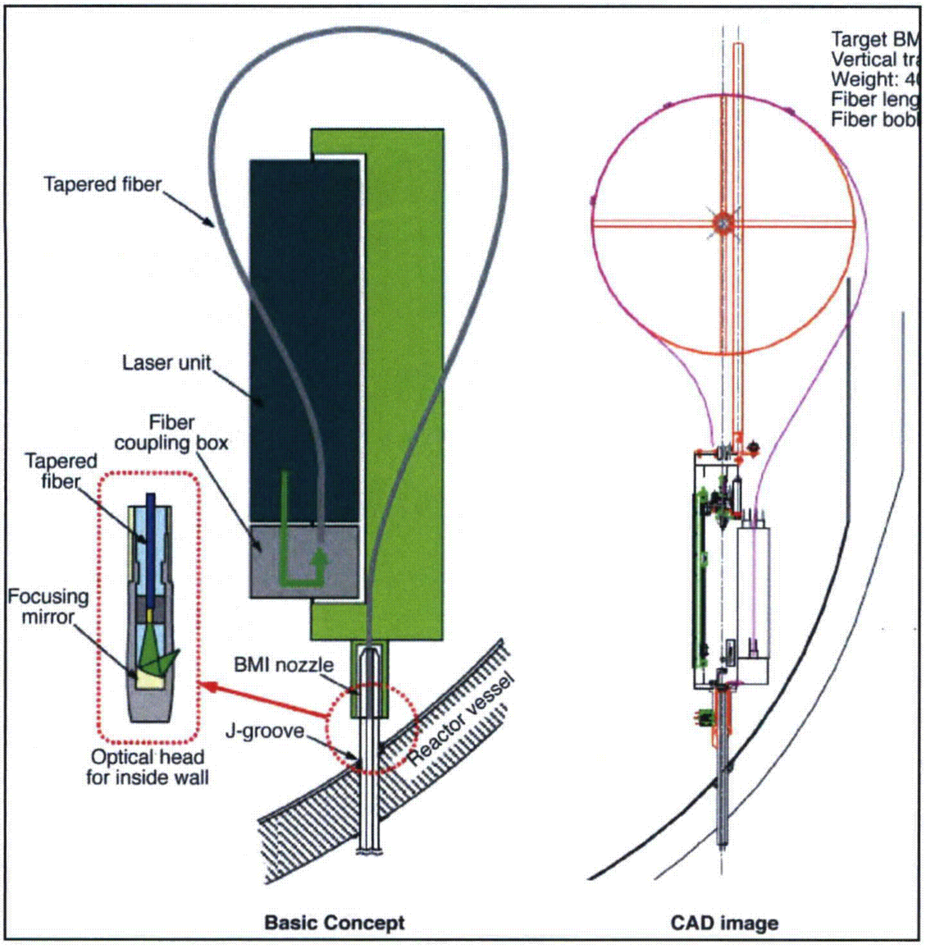
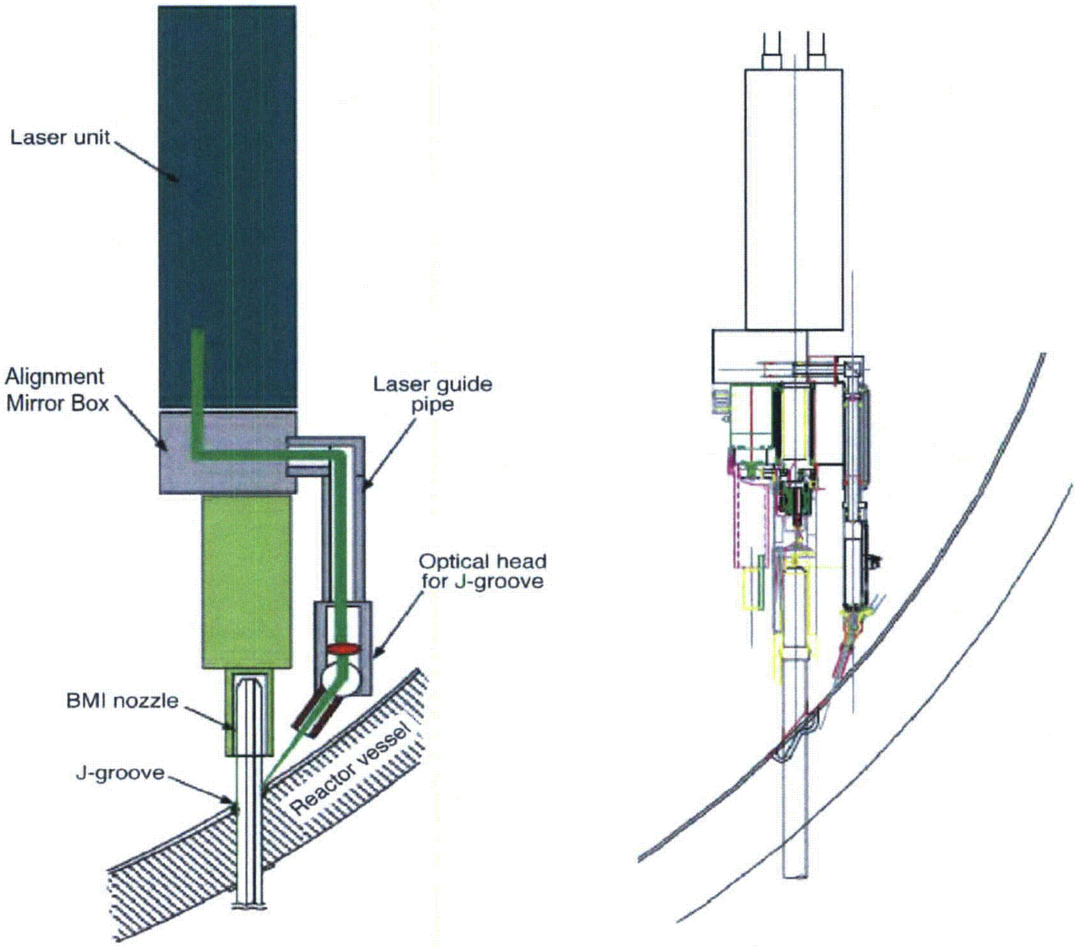


Figure 5-1
Portable laser peening (PLP) system for inner surfaces of BMNs, by Toshiba



Basic Concept **CAD image**

Figure 5-2
Portable laser peening (PLP) system for outer surfaces of BMNs, by Toshiba

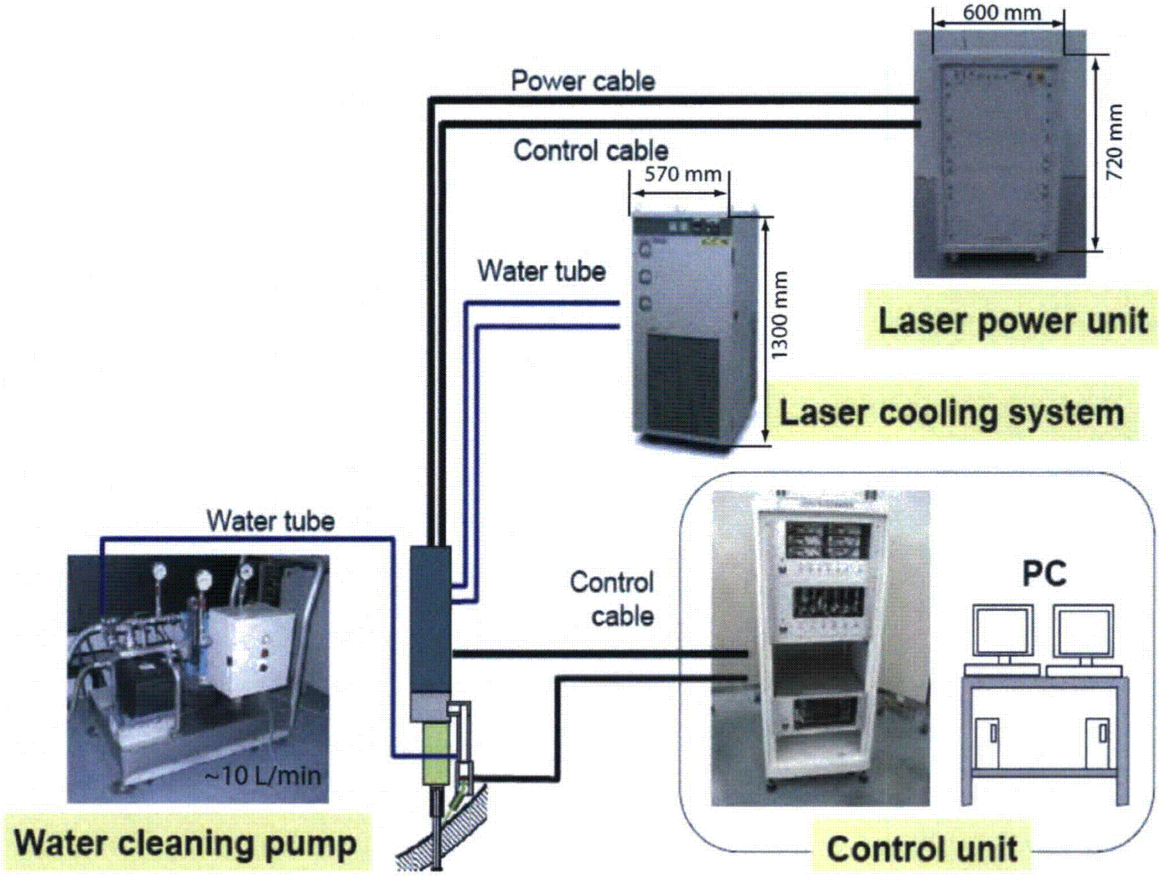


Figure 5-3
Key support equipment for the ULP system, by Toshiba

5.2.4 Other ULP Implementation Considerations

- In preparation for ULP treatment of BMNs, reactor internal components are removed to allow accessibility to the BMNs. Water temperature in the reactor vessel must be less than 50°C.
- ULP generates a slight amount of radioactive waste, namely ablative product due to the interaction between the laser pulses and the surface material being peened. The amount of the waste can be estimated by calculation. No cleaning process was required in Japan because the waste consisted of microparticles and its amount was negligibly small.
- The implementation of ULP mitigation is scheduled in consideration of other outage activities. Figure 5-4 [65] shows the operation process schedule for two Japanese PWR units, Ikata Unit 1 and 2. For Ikata Unit 1, the critical path was 18.4 days from December 2004 to January 2005. For Ikata Unit 2, the critical path was 19 days from December 2005 to January 2006. Note that LUT refers to Laser Ultrasonic Testing, which is used to detect surface cracks and evaluate the size of shallow cracks.

Other implementation requirements include electric power supplies, cooling water, compressed air, process water, communications, and manipulation space.

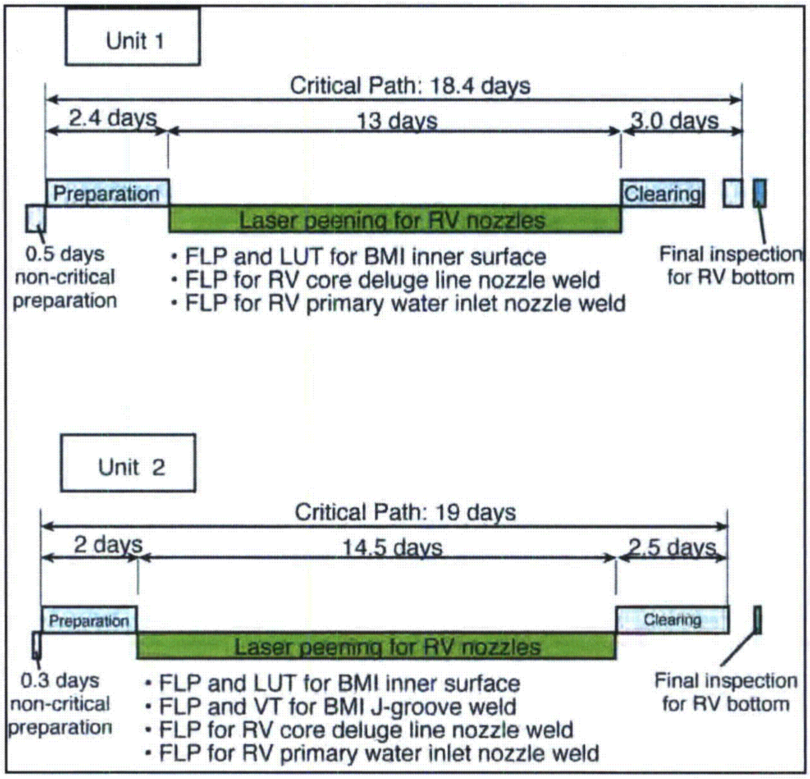


Figure 5-4
Critical paths for ULP Application at Ikata Unit 1 and 2, by Toshiba

5.3 WJP System Development and Engineering Design

As has been previously mentioned, the WJP process is delivered underwater as this is essential to creating the cavitation effect. The process is operated robotically from the refueling floor, which greatly reduces the dose received by operators and technicians. Typically, a WJP delivery system consists of a pump—which is capable of delivering the pressures and flow rates required to produce the WJP effect—along with the piping, nozzle, and robotic equipment required to deliver the nozzle to the required position. In addition, a control system is used to monitor and control the process parameters during the operation, as well as control the location of the WJP equipment.

The WJP equipment is comprised of three main components: the system controllers, the high pressure pump with attached flow meter, and the WJP nozzle and associated delivery system. Signal cables run between both the system controller and the WJP delivery system, as well as between the system controller and the high-pressure pump. These connections allow the operator at the system controller to control all process parameters for the WJP process from a central location. The system controller controls the positioning of the nozzle and the speed at which it is moved. Also the nozzle stand-off and application time for the WJP process are controlled from this location.

5.3.1 Control Parameters

The WJP process parameters to be controlled as essential variables include the WJP nozzle specification, the flow rate, the stand-off distance from the target surface, the treatment time (pinpoint treatment time and traverse speed), and the angle of impingement as shown in Figure 5-5. If the range of essential variables needs to be changed for any reason, an additional optimization test on the changed parameter condition is performed. The WJP control system required for these parameters consists of a plunger pump that generates high pressure water, a control panel, a delivery tool that manipulates the WJP nozzle, a high-pressure hose, and the WJP nozzle. A typical WJP system configuration for BWRs is demonstrated in Figure 5-6. The system configuration is similar for PWRs is shown in Figure 5-7. The application equipment for BMI nozzles is depicted in Figure 5-8, and the application equipment for RPV Outlet/Inlet nozzles is shown in Figure 5-9.

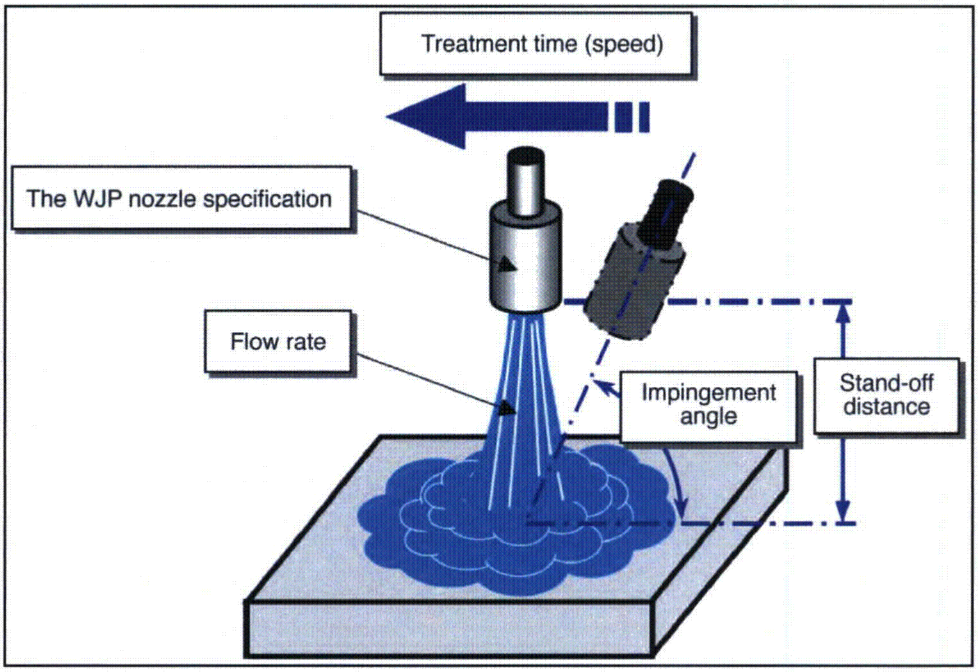


Figure 5-5
Essential variables of the WJP process to be controlled, by Hitachi-GE

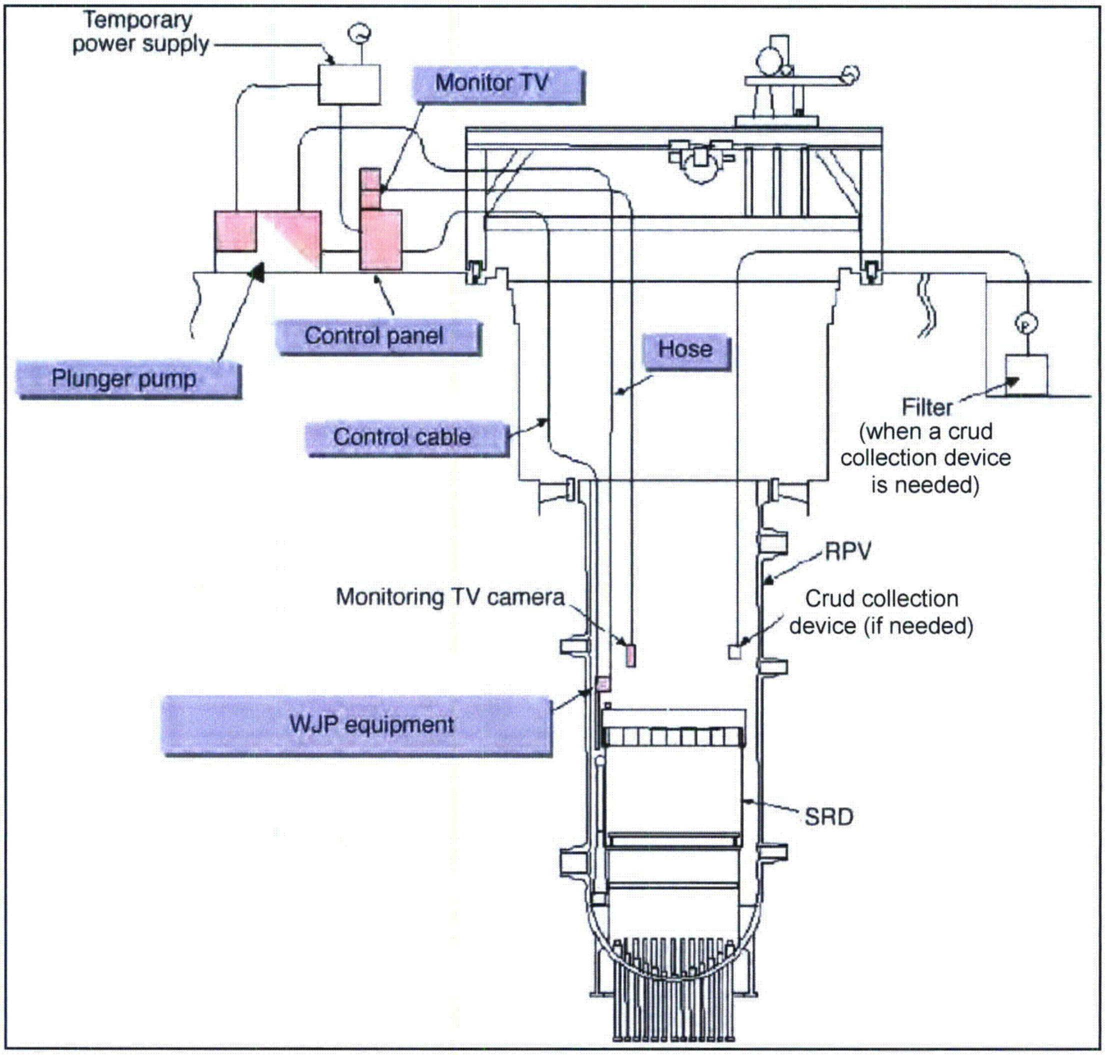


Figure 5-6
Typical WJP system configuration in BWRs, by Hitachi-GE

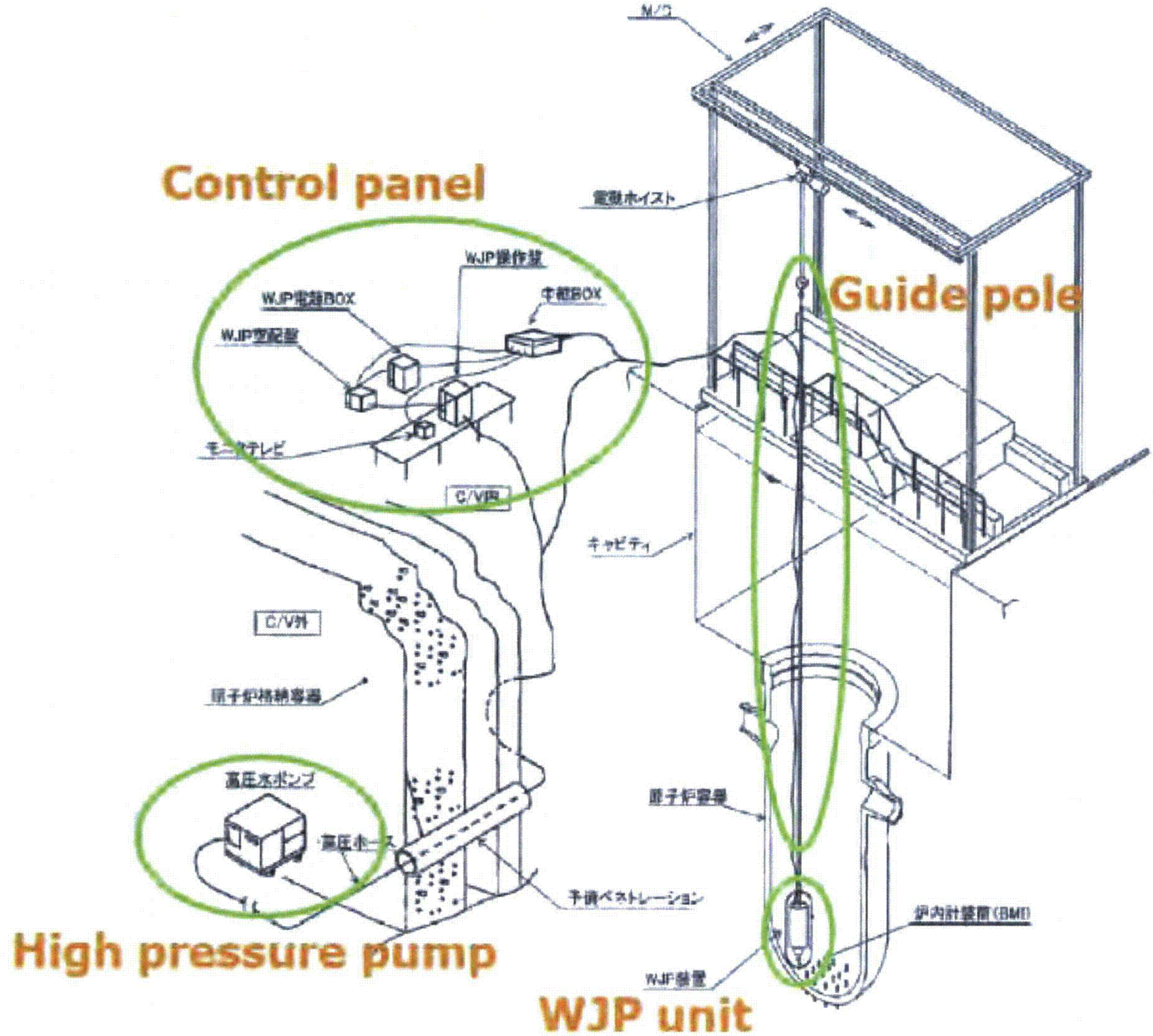


Figure 5-7
WJP system for BMI nozzles, by MHI

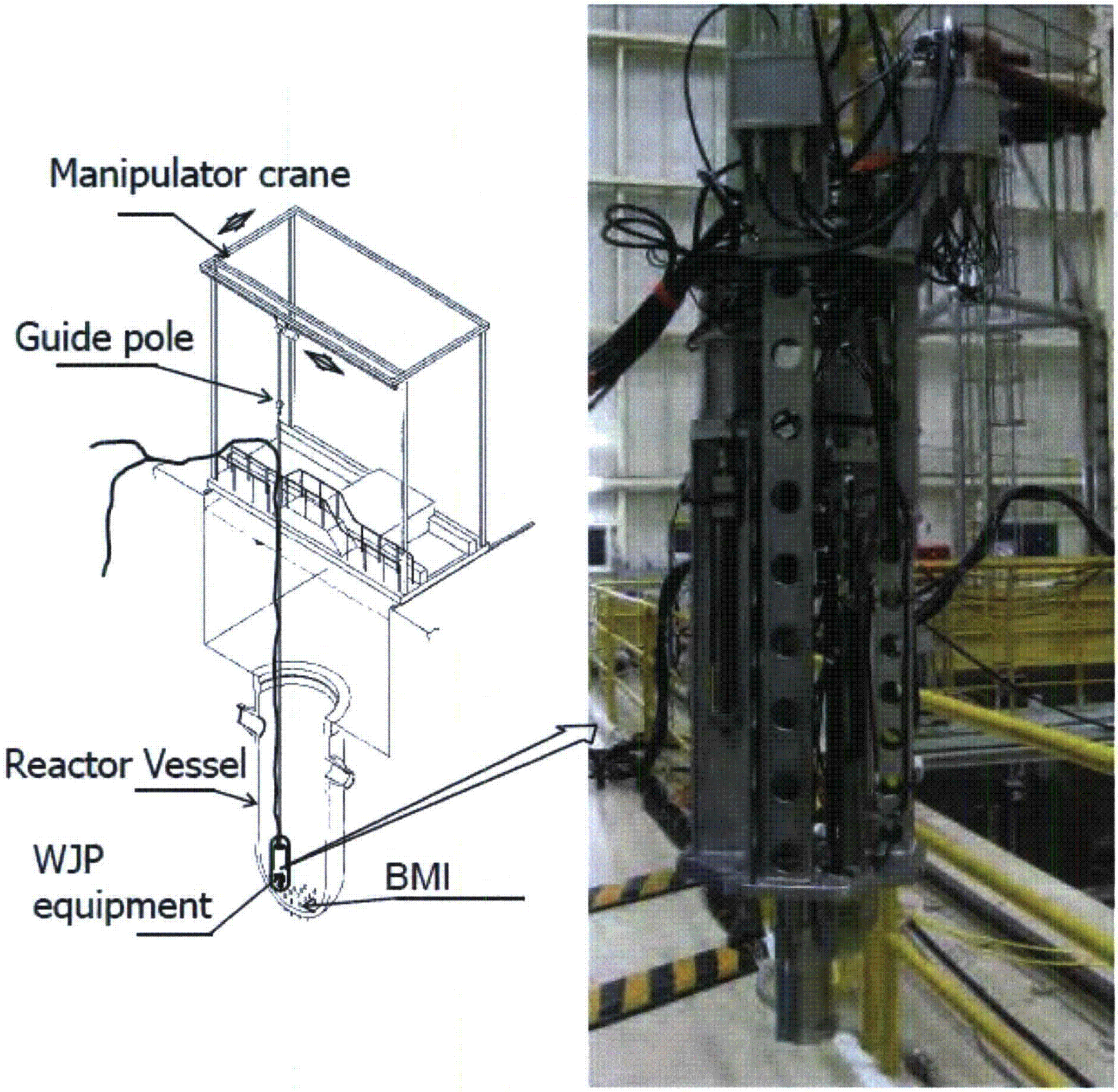
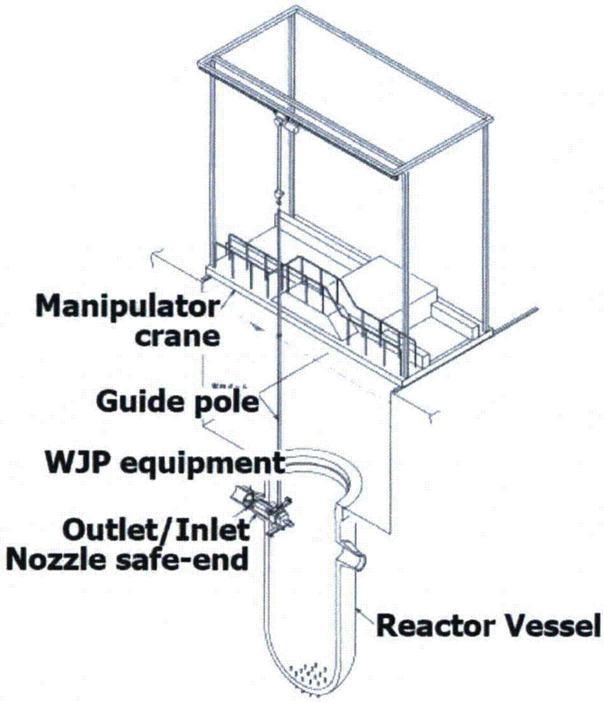


Figure 5-8
WJP application equipment for BMI nozzles, by MHI



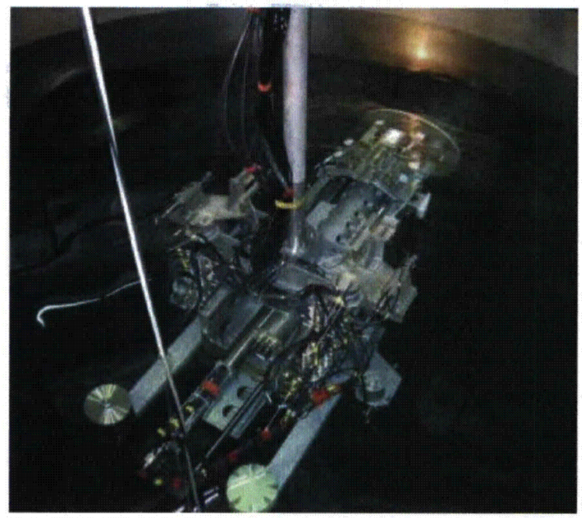


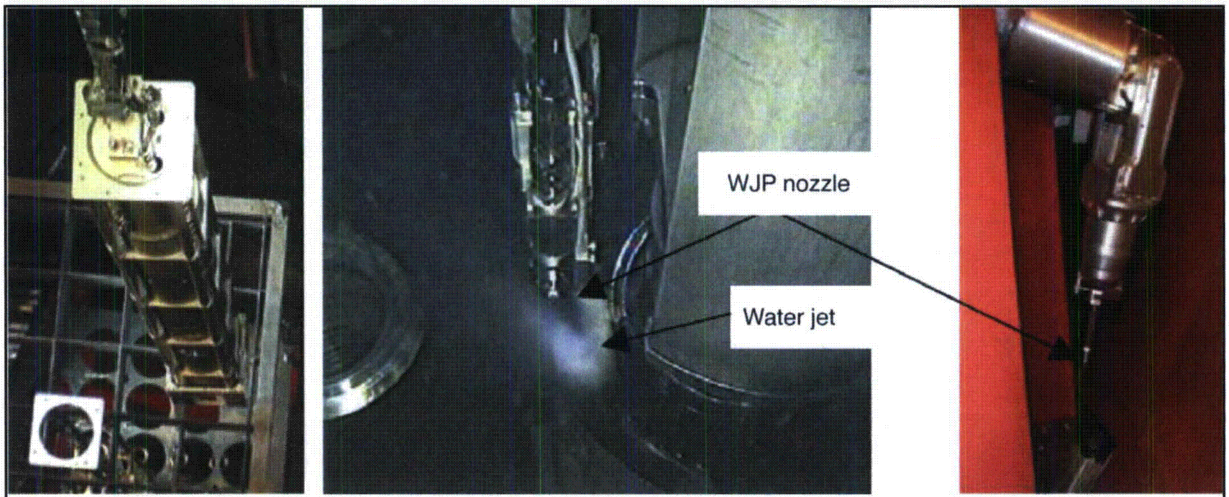
Figure 5-9
WJP application equipment for RPV Outlet/Inlet nozzles, by MHI

The plunger pump generates high-pressure water with a relatively large flow rate. The pressurized water is transferred through a high-pressure hose to the WJP nozzle attached to the WJP delivery tool. The WJP delivery tool manipulates the WJP nozzle (sometimes several nozzles) to control the water jet, using optimized parameters automatically and remotely. Process optimization has been achieved in laboratory tests at room temperature. In outage work, underwater technicians deliver the WJP delivery tool to the designated position and remove it after the treatment. Required parameters such as flow rate and treatment time are recorded in the memory device of the control panel or on record sheets by an operator.

Required parameters such as the WJP nozzle specification, the stand-off distance, and the angle of impingement are controlled by the designs of the WJP nozzle and the WJP delivery tool, with controlled tolerances. Since the WJP nozzle specification and the flow rate are controlled, water pressure is not an essential variable and is treated as a reference value. Additionally, it is not necessary that the water temperature and water pressure at the target area be controlled parameters.

5.3.2 Control Strategy and Interlocks

The typical WJP system configuration has already been shown in Figure 5-6. Examples of a custom-built WJP delivery tool are shown in Figure 5-10.



a) CRD housing/stub tube b) Shroud support leg

Figure 5-10
Examples of a custom-built WJP delivery tool, by Hitachi-GE

A typical WJP system has both mechanical and software interlocks to suit its intended purpose. In most cases, the transverse path is limited by the mechanical design. The flow rate and treatment time are controlled with software interlocks. For WJP system control, a control panel with an LCD monitor is used to show the location and path, to enable monitoring of parameters in operation, and to allow inputting of implementation parameters for each target area to be mitigated.

To ensure 100% treatment coverage, the WJP process uses several paths that overlap each other in most cases. Typically, a WJP treatment coverage extends to an additional area of approximately 25 mm (1 in.) outside of the target area to ensure 100% coverage of the target area. This additional area is determined taking into consideration worst-case assumptions combining the heat-affected zone (HAZ), margin for tolerances in setting the tool, and accuracy of targeting by the tool. This coverage is verified in mockup tests before site implementation. This strategy is illustrated in Figure 5-11.

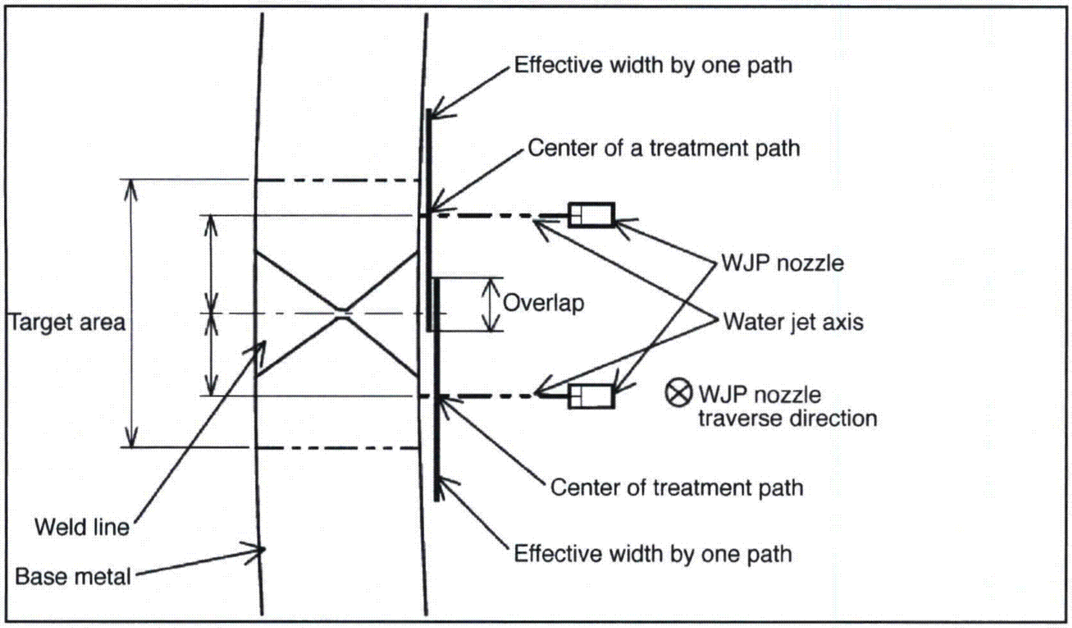


Figure 5-11
Control strategy of ensuring 100% treatment coverage, by Hitachi-GE

5.3.3 Safety Strategy

During the development of system tools, performance of a pressure proof test is required on all of the high-pressure lines in the WJP system to avoid any breaks in mockup tests and site operation. Safety-related electrical tests are also performed. The maximum speed of the tool in all directions is limited by software and motor driver electronics with an electrical current limit value. Safety significant issues are addressed by automatic controls including by interlocks.

5.3.4 Other WJP Implementation Considerations

Other WJP implementation considerations include the following:

- To apply WJP on BMNs, reactor internal components are removed to allow accessibility of the WJP delivery tool to BMNs including the J-groove weld locations.
- For WJP, the utility and vendor need to agree on the water source for the peening (e.g., demineralized water, processed RCS water, or refueling pool RCS water).
- Detailed drawings of the area where the WJP delivery tool will be installed and the treatment should be applied (dimensions with tolerances, materials, shapes, and surface finish) and any differences between as-built and present status are needed as the primary information from the plant.
- The layout of the operation floor and the access route during the outage are needed for the WJP system and site-work planning.
- Information regarding the dose rate of the area where the WJP delivery tool will be installed and the treatment should be applied is required.

- Other parameters to be considered:
  - The number of available work platforms
  - Crane capacity
  - Power capacity
  - Pure water delivery and disposal capability
  - Service air/water capability
  - Cavity water temperature
  - Cavity water chemistry
  - Temperature and pressure at the target component location
  - Electromagnetic compatibility (EMC) requirement if applied
  - Any other restrictions

Other implementation requirements include electric power supplies, cooling water, compressed air, process water, communications, and manipulation space.

HGNE and MHI have procedures in place to ensure that WJP is applied to a surface as intended. During the WJP operation process, operators will always be watching the operating parameters to prevent unusual operation. Also, the WJP equipment is programmed to stop automatically when the operating parameters, such as the running speed and the stroke of the equipment, are not within the optimum range. The high pressure pump will be automatically or manually stopped when the fluid volume flow rate or pressure exceeds its pre-set limit. If the WJP equipment needs repair, the process will be stopped and can be applied again to the area requiring peening. Japanese authentication tests have confirmed that peening operation for a designated time period is available to mitigate tensile residual stress and does not adversely affect the materials. These procedures are expected to prevent the introduction of unexpected transition areas between peened and unpeened surfaces.

5.3.5 Typical Schedules

Although WJP procedures are usually vendor specific, the following three phases are critical steps to be followed.

1. Planning Phase

   When custom-built tooling is needed for a new application, initial tooling design typically starts 12-18 months prior to site work to reflect plant-specific information. The planning phase includes the WJP system design (if a custom-built design is needed), manufacturing, and testing; site work planning; the WJP treatment parameter verification testing (to be used in "site procedures and work control documents"); performance testing (including mockup training); maintenance before site work; and shipping.

2. Treatment Phase

   The schedule for the treatment phase is planned to include inspection requirements, tool installation and removal time, and treatment time. A detailed schedule for each plant should be planned in coordination with the customer's requirements for the area to be mitigated.

3. Post-Treatment Phase

   The WJP system will be immediately removed from the operation floor after decontamination of tooling.

Site procedures and work control documents are delivered before implementation. A project final report including the treatment record should be expected after the site work.

5.4 Application of ALP To Nuclear Power Plants

Air laser peening has made a major transition from being a laboratory R&D activity to becoming a reliable fully production qualified technology that is filling an important role in commercial aviation. Air laser peening offers the designer the ability to place compressive residual stress into key areas of components so as to retard crack initiation and growth, and thus enable increased fatigue strength and SCC resistance.

5.4.1 Development and Current Use of ALP Technology

The science of laser peening has been well understood since the 1960's. In the Curtiss-Wright Metal Improvement Company (MIC) process an approximately 20 Joule beam of laser light from a neodymium glass laser strikes the surface of the part to be peened. A thin stream of water flows over this area providing a momentum "tamping layer" for the process. The laser light passes through the water and impacts on the surface to form and heat a plasma, whose pressure builds rapidly to the yield stress of the material being processed. This creates a shock wave that penetrates into the metal and plastically compresses the surface layer creating a compressive stress to a depth of 1-8 mm depending on the material, component geometry, and laser peening parameters. This deep level of compressive stress creates a barrier for crack formation and growth. The deep level of compression closes intergranular boundaries retarding the penetration of corrosives. The process thus enhances the fatigue lifetime and resistance to stress corrosion cracking and hydrogen embrittlement of the part.

Although the science of laser peening is well understood, the lack of a high-pulse-repetition-rate and high-power laser limited production applications until MIC in cooperation with the Lawrence Livermore National Laboratory adapted an existing high power laser and developed an advanced, high throughput air laser peening process. The process is currently used on critical rotating turbine engine parts by both military and commercial aviation. A mobile air laser peening unit has been fielded and deployed in several applications, most specifically to peen in a field overhaul application key structural components for the F-22 fighter jet. This basic technology is also directly suitable for use in treatment of large heavy components such as nuclear reactor vessel heads and other LWR components susceptible to stress corrosion cracking.

5.4.2 Application to Nuclear Power Plants

Air laser peening technology is ready to be adapted for nuclear power plant applications. The specific steps to deploy the technology are as follows:

- Full-scale demonstration of process to verify effectiveness for target component
- Design and build of site-specific beam delivery hardware
- Deploy at specific reactors and perform processing

It is envisioned that for LWR applications, the MIC air laser peening process would be performed without an ablative layer to avoid concerns and complexities that would be introduced by the need to clean up waste products associated with use of an ablative layer. Processes with and without the use of an ablative layer have been successfully applied in the aerospace industry. Also, the MIC proposed approach to processing would not include a step for removal of the tarnish layer after processing. Additional planned work is anticipated by MIC to show that leaving the tarnish in place is acceptable with no significant detrimental effect.

Process controls are used to ensure that the desired area is peened for the desired number of pulses per unit area. Verification of complete coverage is performed automatically. The ALP process is high robotically controlled and every pulse is recorded to maintain the desired process parameters and spot placement. For processing at a PWR, a 3D model of the as-built reactor surfaces to be peened would be stored in the processing computer, and as each spot is fired by the laser, its energy and pulse duration are recorded. Over the course of ALP application, acceptable conditions for each pulse can be verified in real time as can the desired physical placement of each pulse. Spots are typically placed with an accuracy of 100 micrometer. Energy on average is controlled to 1% and shot-shot energy stable to 10%. Pulse duration is monitored and stable to 10%. If due to a laser fault a region, even a single spot, were left unpeened or peened to a lesser extent than anticipated, that specific spot could be rectified. This is standard practice for MIC's ALP for over a decade since industrial processing began. Finally, a visual inspection may be performed to ensure that all of the desired surface shows visible signs of peening (ALP changes the surface enough to make obvious the difference between peened and unpeened areas).

5.4.3 Application to RPVHPNs

A possible first application for the ALP process in LWR systems is for the outer surface of CRDM/CEDM and other RPVHPNs in a PWR. The RV head would be treated while on its storage stand during the refueling outage. Unlike the other SSI treatments described in this report, the ALP process has historically not been performed underwater.

The basic MIC beam transport concept is described in Section 2.4.4.3. Given the energy level of the beam, the beam is delivered by either air or vacuum propagation through stainless steel pipes between the laser trailer and the laser peening processing area. Mirror boxes are installed between sections of the pipe to allow changes in the beam direction. The existing beam transport system can be readily adapted to treat RPVHPNs. It is envisioned that the laser trailer would be located outside the reactor building, and that the beam pipe would enter the reactor building through the equipment hatch. As shown in concept in Figure 5-12, the beam emerges from the trailer and is brought down to near ground level with a two-mirror periscope. The beam pipes may be stabilized without floor fasteners using braces attached to ~80 lb steel plates. In the reactor building, the pipes and mirror boxes would be temporarily secured to floors (using weighted bags, clamps, and other available methods), walkways, and/or scaffolding to deliver the beam to the processing area under the RV head.

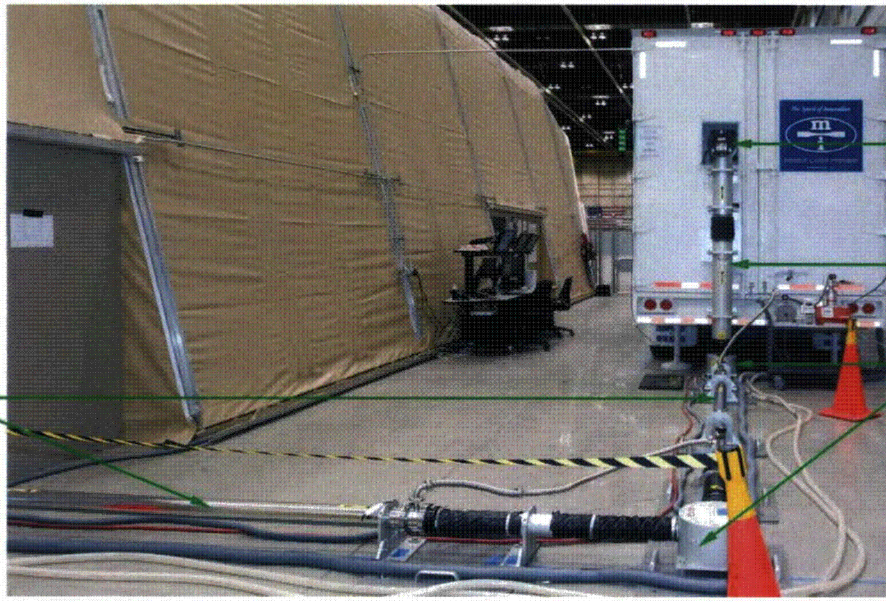


Figure 5-12
Transportable air laser peening system showing the output beam periscope and the first portion of the beam delivery pipes

In the processing area under the RV head, the outer surface of the RPVHPNs would be treated using the MIC beam scanning approach described in Section 2.4.4.4. The specialized optical tooling of the MIC beam delivery system can readily be adapted to the laser peening of the wetted surfaces of the J-groove weld and outer diameter of the nozzle tube of RPVHPNs. The robotic system (see Figure 2-32) has the ability to direct the beam across a complex geometry on the work piece, placing a uniform pattern of spots across the laser peening treatment area. The beam is automatically adjusted for each spot, changing its divergence angle, beam rotation, polarization rotation, and aspect ratio to apply a uniform square spot, regardless of incidence angle onto the target surface. This allows a pattern of spots to be applied while keeping the delivery tool stationary. The wide field of view of the delivery tool would allow multiple RPVHPNs to be peened without relocating the tool. By laser peening from a collection of fixed delivery tool locations, line-of-sight obstructions can be avoided, allowing all of the target areas on the RPVHPNs to be reached.

For the laser peening of RPVHPNs, it is envisioned that the transmitter gimbal of the beam delivery system (Figure 2-32) would be located just outside the head storage area, where it would automatically direct the high energy peening beam to the receiver gimbal. Note that the robot arm of the system would be replaced by a custom polar-coordinate positioning stage installed under the RV head.

5.5 Conclusions

The surface stress improvement methods of ULP and WJP have been applied at Japanese PWRs in order to mitigate important reactor components including RV outlet/inlet nozzle DMWs and BMNs (including the J-groove attachment welds) in PWRs against PWSCC. These implementations have generated valuable experience on engineering issues and effective

benchmarks for U.S. and international plants. Although ALP has not yet been performed in nuclear power plants, it is actively applied as a commercialized technology in critical aerospace applications. ALP technology is readily adaptable to LWR applications. An extensive base of experience is available supporting the effectiveness of ALP, including the depth of compressive residual stress that may be attained.

As discussed in this section, some important issues of process safety, critical parameter control, and system design must be considered before the implementation of these techniques. Key implementation considerations are as follows:

- The component surface is treated in accordance with vendor-defined procedures. The process must be controlled to maintain the key process control parameters within predetermined limits. The treatment period varies with the mitigation technique and the specific geometric and material characterization of the component being treated.
- The system design will be drawn up by the vendor, based on design parameters from the utility, including engineering drawings related to the component to be treated and historical structural inspection results. Vendors should provide detailed process specifications and specific requirements such as personnel training, power and water supplies, and on-site facilities.
- Decisions regarding selection of mitigation techniques are based on factors such as component locations, age of the plant, component operating temperatures, material condition, and piping loads. In selection of a suitable surface treatment method, the decision maker should consider not only the cost to implement the mitigation, but also the effect on scheduled maintenance and the schedule critical path during the refueling outage (RFO).
- A peening system design is often plant-specific, so a collaborative process between plants and vendors is appropriate.

6
CONCLUSIONS AND RECOMMENDATIONS

In order to facilitate the implementation of SSI techniques as PWSCC mitigation methods, this report provides process information and experimental data supporting the effectiveness of currently available laser peening (ULP and ALP) and water jet peening (WJP) processes. The intent is to provide alternative mitigation options for utilities addressing PWSCC concerns for PWR locations including RPVHPNs, BMNs, and DMW locations such as RV inlet/outlet nozzle welds.

6.1 Key Conclusions

Key conclusions based on the information presented in this report are as follows:

- The ULP and WJP techniques have been implemented for SCC mitigation in dozens of BWR and PWR plants in Japan, and are fully commercialized for use in U.S. and international PWRs to mitigate PWSCC. Although ALP has not yet been performed in nuclear power plants, it is actively applied as a commercialized technology in critical aerospace applications. ALP technology is readily adaptable to LWR applications, and an extensive base of experience is available supporting its effectiveness.
- The ULP and WJP methods typically result in a compressive residual stress layer that is roughly 1 millimeter (0.04 in.) deep. Because of its relatively high power laser source, the ALP process is capable of inducing deeper compressive residual stress layers, up to several millimeters deep.
- Peening vendors and EPRI performed separate verification experiments—among them corrosion cracking and stress relaxation tests—to confirm the effectiveness and sustainability of SSI treatments in various environments, including a simulated PWR environment. The extensive experimental results demonstrate that SSI treatments are effective measures in preventing or mitigating PWSCC when performed in combination with appropriate non-destructive examinations. When properly applied, SSI treatments—converting stress status from tension to compressive to a certain depth—can successfully eliminate the potential for future SCC initiation at surfaces exposed to reactor coolant.
- The peening vendors have also performed tests confirming that the SSI processes do not produce unacceptable side effects. Experience at Japanese BWRs and PWRs supports the conclusion that unacceptable side effects are not a concern.
- The ULP and WJP processes are considered to be demonstrated for the BMN and large-diameter piping DMW geometries. Additional work including testing on mockups representative of actual PWR component geometries is necessary to demonstrate the ALP process for mitigation of PWSCC in PWRs.

- Unlike the ALP technique, the ULP and WJP techniques have historically been performed underwater. All three techniques are applicable to treatment of RPVHPNs, BMNs, and piping DMWs. Specialized tooling would be necessary to apply WJP to the outer diameter surface and J-groove weld of RPVHPNs including CRDM/CEDM nozzles given that mitigation would be performed while the head is located on its storage stand. In the case of ULP, demonstration work including mockup testing and field experience has been performed in an underwater environment, but the process can be adapted to be performed in air. Use of ALP for BMN or piping DMW locations would require that these areas be drained during the maintenance outage, or that the laser beam be piped to the underwater target location.

In summary, the SSI techniques covered in this report are viable options for effective long-term mitigation of PWSCC of Alloy 600/82/182 components exposed to the reactor coolant environment, when performed in combination with an appropriate program of non-destructive examinations.

6.2 Recommendations

Based on discussions in this report, several recommendations are offered with regard to implementation of ULP, ALP, and WJP as SSI techniques for PWSCC mitigation, as follows:

- SSI techniques are a key option for locations, such as CRDM/CEDM nozzles and BMNs, where other mitigation methods have not been demonstrated, or for piping DMWs with limited access at the pipe exterior.
- SSI might be applied after weld in-lay or weld on-lay to further improve the resistance to PWSCC of the new material in contact with the reactor coolant.
- SSI mitigation is generally not a suitable repair technique for locations with flaw indications that are detected to be deeper than the compressive residual stress zone produced by SSI treatment. For such cases, the possibility of needing to repair the component using a different technique should be considered.

This technical basis report supports additional work by the MRP to define process and inspection requirements associated with SSI applications to mitigate PWSCC, including specific relaxed intervals for periodic inspections of key Alloy 600/82/182 locations in PWRs.

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