Nuclear Fabrication Consortium Technical Summary Report

Project 52293NFG

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Prepared for:
Nuclear Fabrication Consortium

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EWI
We Manufacture Innovation

Report

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Nuclear Fabrication Consortium Technical Summary Report

to

Nuclear Fabrication Members

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Abbreviated Terms

ASME	American Society of Mechancial Engineers
AWS	America Welding Society
BWR	boiling water reactors
CGR	crack growth rate
CII	construction industy institute
CT	compact testing
CTOD	crack-tip-open displacement
DOE	Department of Energy
GB	grain boundaries
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HAZ	heat-affected zone
HED	high-energy density
HLAW	hybrid laser arc welding
IASCC	irradiation-assisted stress corrosion cracking
IDF	invention disclosure forms
IGSCC	intergranular stress corrosion cracking
IO	internal oxiation
LOP	lack of penentration
LSM	laser surface melting
NDE	nondestructive evaluation
NE	Nuclear Energy
NFC	Nulcear Fabrication Consortium
NRC	Nuclear Regulatory Commission
OEM	original equipment manufactures
PEC	penetration-enhancing compound
PPMOF	prefabrication, preassembly, modular, offshore application
PWR	pressurized water reactors
PWSCC	primary water stress corrosion cracking
RG	regulatory guidelines
RT	radiographic testing
SAW	submerged arc welding
SC	short circuit trasfer
SCC	stress corrosion cracking
SFR	sodium-colled fast reactor
SiC	silicon carbide
SSRT	slow strain rate testing
UT	ultrasonic testing
VHTR	very high-temperature reactor

1.0 Introduction

This report summarizes the activities undertaken by EWI while under contract from the Department of Energy (DOE) – Office of Nuclear Energy (NE) for the management and operation of the Nuclear Fabrication Consortium (NFC). The NFC was established by EWI to independently develop, evaluate, and deploy fabrication approaches and data that support the re-establishment of the U.S. nuclear industry: ensuring that the supply chain will be competitive on a global stage, enabling more cost-effective and reliable nuclear power in a carbon constrained environment. The NFC provided a forum for member original equipment manufactures (OEM), fabricators, manufacturers, and materials suppliers to effectively engage with each other and rebuild the capacity of this supply chain by :

- Identifying and removing impediments to the implementation of new construction and fabrication techniques and approaches for nuclear equipment, including system components and nuclear plants.
- Providing and facilitating detailed scientific-based studies on new approaches and technologies that will have positive impacts on the cost of building of nuclear plants.
- Analyzing and disseminating information about future nuclear fabrication technologies and how they could impact the North American and the International Nuclear Marketplace.
- Facilitating dialog and initiate alignment among fabricators, owners, trade associations, and government agencies.
- Supporting industry in helping to create a larger qualified nuclear supplier network.
- Acting as an unbiased technology resource to evaluate, develop, and demonstrate new manufacturing technologies.
- Creating welder and inspector training programs to help enable the necessary workforce for the upcoming construction work.
- Serving as a focal point for technology, policy, and politically interested parties to share ideas and concepts associated with fabrication across the nuclear industry.

2.0 Approach

The mission of the NFC was accomplished through both public and private funding. The list below outlines the projects identified for initiation under congressional and DOE funding along with each projects objectives.

2.1 Congressionally Funded Projects

1. Automation of Advanced Nondestructive Evaluation (NDE) Technologies

   The objective of this project was to improve the reliability of NDE methods by increasing the automation content.

2. Advanced Laser Technology

   The objective was to identify laser applications that offer significant productivity gains over the current processes being used, and create laser demonstration pieces that illustrate the suitability of laser's for nuclear construction applications.

3. State-of-the-Art Fabrication Technology Survey

   The object was to provide the nuclear industry with the understanding required to select new joining processes to validate and codify for nuclear construction applications.

4. NFC Operations and Management

   The objective of this project was to oversee and manage all NFC activities, including but not limited to center start-up, rapid response technical issues, industry outreach, develop new initiatives for NFC members, support DOE-NE meetings, etc.

5. Nuclear Supplier Development

   The objective was to develop and deploy a workshop series that will enable the nuclear industry to better understand what is required to be a nuclear supplier.

6. Gen IV Fabrication Centric Roadmap

   The objective of this project was to develop a succinct document that will allow current manufacturers to position themselves for Gen III(+) fabrication using current and near-term fabrication technologies and simultaneously keeping their eyes focused on what will be required for Gen VI facilities.

7. Regulatory Review

   The objective was to work with industry to create a global review and data dissemination program that will result in a series of white papers for submission to NRC for Regulatory Guideline improvements and abandonment.

8. Real-Time Weld Quality Monitoring

   The objective was to work with existing technologies to advance weld quality monitoring and closed loop feedback for welding systems and techniques typically used in the nuclear industry.

9. Stress Corrosion Cracking (SCC) Mitigation and Monitoring

   The objective was to develop a new approach for understanding and monitoring the fundamental mechanisms that cause SCC.

10. Fabricated Forgings

    The objective of this project was to map out the current landscape and what options/implications would enable or prohibit fabricated heads.

11. Techniques for Modularization from other Industries

    The objective of this project was to work with EWI members and review existing public domain literature to baseline the availability of existing modularization technologies for potential deployment in the nuclear industry with the focus on not repeating the mistakes already experienced in other industries.

12. ASME Radiographic Testing (RT) vs Ultrasonic Testing (UT) in codes and Standards

    The objective of this project was to develop a process by which ASME and industry both agree on that will help lessen the discrepancies currently existing between ASME Sections III, IIX, and XI.

2.2 DOE-NE Funded Projects

1. HLAW in Nuclear Industry

   The objective of this program was to determine the functional limits of the hybrid laser arc welding (HLAW) and HLAW-penetration-enhancing compound (PEC) processes for joining thick section nuclear specific materials.

2. Ultrasonic Brazing SiC

   The objective of this project was to develop a tool and process for ultrasonically brazing SiC assemblies and subsequently test the joint strength.

3. Sol Gel Coating Development

   The objective of this project was to apply "sol-gel" or solution borne ceramic coatings technology that could be applied using methods similar to paint or fusion bonded epoxy to mild steel, stainless steel, or nickel-based alloy substrates to provide a protective layer on the substrates.

4. High-Productivity Fabrication Process Demonstrations

   The objective of this project was to perform welding and machining evaluations and demonstrate the enhancements in productivity offered by laser, HLAW and ultrasonic machining processes to the NFC members as well as other interested fabricators.

3.0 Results

3.1 Congressionally Funded Projects

3.1.1 Task 1: Automation of Advanced NDE Technologies

This task was completed and documented in a final report on April 26, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-2. The following paragraphs summarize the work completed under this project.

A brief review of the NDE needs for nuclear fabrication components was performed. Two major directions for research and development were identified – computer modeling of NDE techniques and NDE automation for improved inspection reliability. An analysis of a typical NDE automated system was conducted for the purpose of automated weld inspection. After review of current and emerging NDE modalities, electromagnetic technologies were identified for further research and development.

Industry (EPRI) provided heat exchanger tube specimens made of new ferromagnetic materials - SAF2205, type 439 and Sea-Cure where modeling of eddy current NDE techniques was of particular interest. The tube electromagnetic properties where determined with destructive conventional techniques (magnetic and electrical) and nondestructive eddy current model-based technique. The conventional magnetic and electrical techniques were conducted at direct and alternate (50 Hz to 2.5 kHz) current excitation. The electrical conductivity, magnetic permeability, coercivity, retentivity, and other magnetic parameters were measured in tube axial and circumferential direction, in open and closed magnetic circuits in large range of magnetic field intensities from 3.4 A/m to 82 kA/m. The unique set of results revealed that a certain anisotropy of properties existed between the two geometric directions. The NDE modeling approach was used for both optimization of eddy current measurement sensors and implementation of the measurement process with the optimized sensors. The agreement between the measurements from the different techniques was good where comparison was possible.

Six butt-weld specimens made of stainless steel 316L plate (thickness 12.5 mm) were fabricated using laser autogenous welding process to demonstrate automated eddy current inspection technique. The specimens represented acceptable welds and welds with lack of penetration (LOP) and missed seam. An array eddy current technique capable of detecting and sizing flaws in any direction was developed and demonstrated. Validation of technique performance was conducted through destructive testing at limited number of flaw indication locations. The technique was fast, productive and successfully imaged, detected and sized typical flaw conditions such as general and localized LOP and missed seam.

3.1.2 Task 2: Advanced Laser Technology

This task was completed and documented in a final report on September 1, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-5. The following paragraphs summarize the work completed under this project.

During construction of the last generation of nuclear power plants, laser technology was in its infancy. Over the past few decades, major technological advancements in both high- and low-power lasers have brought laser processing to the forefront of many manufacturing industries (automotive, aerospace, medical, and heavy manufacturing to name a few). The goal of this research was to identify three laser welding applications that offer significant productivity gains over the current processes being used, and to perform laser welding trials that demonstrate the suitability of lasers for nuclear construction applications. The three chosen applications were:

- Tube-to-tubesheet welding (autogenous laser welding)
- Thick-section laser welding (autogenous and hybrid welding) of 316L stainless steel
- Narrow-gap laser welding (with filler) of thick-section, structural steel butt joints.

The results from the welding trials completed during this project suggest that modern, solid-state lasers are capable of producing the high-quality welds that are required for tubesheet applications. Relatively low power levels (<2 kW) would be required if the penetration requirements remain similar to the current gas tungsten arc welding (GTAW) requirements. The challenge moving forward will be to determine the optimal method for automating the laser welding process on large tubesheets. EWI is currently working with several NFC members to demonstrate how the laser welding technology might be deployed in production facilities.

Thick-section welding of 316L stainless steel (and other nuclear alloys) is another application that is well suited for laser welding. The current laser power levels that are commercially available are capable of producing high-quality, thick-section welds in a single pass. The main challenge with employing lasers for this application is obtaining appropriate joint fit-up for the welds. Maintaining precision alignment to the joint during welding of large-diameter pipes or large plates and vessels is another challenge. Vision systems and adaptive process control are tools that can help to mitigate these challenges.

Narrow-gap laser welding was shown to produce comparable deposition rates but higher productivity than narrow-gap GTAW. The heating profile of the laser system was customized to fit in a groove of 8 mm or less. By using focused light to produce melting in the depths of a narrow groove, the groove width is no longer constrained by the dimensions of a GTAW torch. With such a laser system, the width of the wire feed apparatus now determines the minimum groove width. While the productivity and narrow groove-width of the laser process are promising, more testing is required to improve sidewall fusion and produce consistent weld quality that is competitive with the narrow-groove GTAW.

3.1.3 Task 3: State-of-the-Art Fabrication Technology Survey

This task was completed and documented in a final report on March 22, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-1. The following paragraphs summarize the work completed under this project.

Since there has not been any nuclear construction in the U.S. since the 1980s there are now many new construction techniques that the industry could use to control the cost and schedule of construction. Recent construction of facilities in Asia has shown that these new approaches can decrease construction costs and reduce construction schedules. Some of these techniques are not covered by the American Society of Mechanical Engineers (ASME) codes that are used to regulate nuclear construction in the U.S.

Welding is an important part of the construction process for new nuclear power plant construction and fabrication. Several new arc welding techniques have been developed since the codes were written and approved. Early generations of these techniques had performance problems that have been resolved. The second-generation techniques have demonstrated improved productivity and quality in other industries but they have not been approved for use in nuclear facilities.

To help the industry select which processes to develop for code case consideration, EWI reviewed the processes recognized by the American Welding Society (AWS). The technology readiness level of each process was evaluated along with their applicability for the materials and geometries involved in nuclear construction. Based on this analysis, we conclude that the following processes are on a path to help the nuclear fabricators improve productivity and quality in nuclear related construction.

Technique	Availability	Change
Short circuit/pulsed GMAW	Immediate	Evolutionary
Tandem GMAW	Near term	Evolutionary
Hybrid laser GMAW	Intermediate term	Evolutionary
Friction stir	Long term	Evolutionary

Each of these techniques is described and the process for developing a roadmap to bring these techniques into use is outlined. This report is only the first step of the roadmap. A further review of the recommended processes by a wide range of nuclear fabricators will be necessary to develop a detailed development roadmap for the industry.

These new arc welding developments could be better used by the nuclear industry. Some of them are already covered by the ASME Section IX code. The Section IX Code Committee is actively working on procedure and welder qualification requirements for the others. The following techniques/approaches should be of greatest interest to the members of the NFC.

- Short circuit transfer (SC): SC is currently included in ASME Section IX but due to the low heat input characteristics, the process it is prone to producing lack-of-fusion defects. As a result, the Section IX Code Committee added more restrictive stipulations to its use. New advancements in welding power supply software and hardware have reduced the chances of lack of fusion will improving wed quality. The code does not consider these recent developments.
- Narrow groove: This technique is covered in ASME Code but this design may not be commonly employed.

- Tandem gas metal arc welding (GMAW): Tandem GMAW is currently included in ASME Section IX by the inclusion of technique variable. The use of tandem GMAW could be better applied to welding thick-section components to improve productivity and quality.
- Hybrid laser GMAW: Hybrid welding is currently not included in ASME Section IX. The Section IX Code Committee is currently developing welding procedure and welder qualification requirements for this process. The anticipated publication date is 2012.
- Friction stir welding: Friction stir welding is currently not included in ASME Section IX. The Section IX Code Committee is currently developing welding procedure and welder qualification requirements for this process with the proposed publication date of 2012.

Those interested in participating in the ASME Section IX qualification effort can contact EWI for details.

3.1.4 Task 4: NFC Operations and Management

All tasks under the original congressionally directed funding have been completed with final reports uploaded and described herein.

3.1.5 Task 5: Nuclear Supplier Development

Task completed and documented through course feedback forms.

3.1.6 Task 6: Gen IV Fabrication Centric Roadmap

This task was completed and documented in a final report on April 1, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-12. The following paragraphs summarize the work completed under this project.

The nuclear industry needs to remain focused on both the current marketplace as well as future opportunities. In the world of nuclear fabricators, this means positioning themselves for Gen III(+) fabrication using current and near-term technologies while keeping an eye on requirements for Gen IV facilities. There are currently six Gen IV reactor concepts being explored for use in the world. The U.S. is seriously pursuing two of the six designs that were chosen to meet national goals: Very-High-Temperature Reactor (VHTR) System and the Sodium-Cooled Fast Reactor (SFR) System. The designs are in varying stages of development and most have significant technological hurdles in the area of materials, material joining, and general manufacturability. The current supplier base cannot be expected to attack research and development projects for all designs and need guidance to focus efforts over the next ten years. The issue remains that manufacturing processes for Gen IV reactors must be qualified by governing bodies [ASME, Nuclear Regulatory Commission (NRC), etc.], but the processes cannot be qualified until they are developed. Furthermore, the processes will not be developed spontaneously, so development must start soon to be ready by the estimated implementation date of 2030. Some manufacturability issues cross several designs. Suppliers, as part of the NFC, may partner funds to research the most promising technologies. Understanding the issues facing the designs and working with proponents of the reactor designs will help improve supplier base readiness concurrently, rather than waiting until the "winning" design(s) shake out.

Each of the Gen IV concepts of six general reactor categories rely on advanced fabrication technology. The NGNP has been significantly simplified from a fabrication perspective by aiming for lower power and lower helium output temperature. Some areas of fabrication technology require additional development, which can extend to multiple Gen IV applications, such as:

- Thick-section welds in pressure boundary materials
- Dissimilar welds, most notably for steam generator tubing
- Fabrication in areas with coated surfaces
- Options for compact heat exchangers require additional joining development as well.

3.1.7 Task 7: Regulatory Review

This task was completed and documented in a final report on May 13, 2010. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-13. The following paragraphs summarize the work completed under this project.

This report provides a broad summarization of the ten divisions of regulatory guides (RG) authored by the NRC. The first section in this report gives an aggregate view the regulatory guides and fabrication related issues within the regulatory guides. The second section in this report provides a high level summarization of the contents of each division. The appendices within this report contain brief summarizations of the individual regulatory guides.

3.1.8 Task 8: Real-Time Weld Quality Monitoring

This task was completed and documented in two reports submitted on October 7, 2011 and January 12, 2012. The reports were submitted via DOE Form F 241.3, and the report numbers are DOE/NE0000279-3 and DOE/NE0000279-4, respectively. The following paragraphs summarize the work completed under this project.

DOE/NE0000279-3 – Real-Time Weld Quality Monitoring - Welder Trainer

In the welding realm the pursuit of real-time quality monitoring techniques is one that has been followed globally and at an increasing pace over the past few decades. Until recently, all attempts to monitor welding in real-time have been focused on attributes of the arc, whether that is electrical input values (current and voltage) or arc by-products (sound and light). These attributes, while informative, only tell a half of the quality story for manual welding operations. The remaining information lies within the manipulation of the welding torch.

Over the past four years EWI has developed the first technology capable of monitoring the essential torch manipulation variables while welding. The technology is optically based using a single camera to track a target, mounted to the welding torch. The position and orientation of the target can then be used to calculate torch manipulation variables including work angle, travel angle, torch offset, travel speed, and the proximity to joint.

This research work played a role in the development of EWI's welder monitoring technology. Specifically, development of the final key torch manipulation variable, proximity to joint, was performed under this work. Additionally, retooling of the tracking algorithms allowed for accuracy improvements placing system readings in the ballpark of one degree for the torch angles, 0.1 in. for the distances, and 0.5 ipm for travel speed. Changes to the calibration procedure and tools for troubleshooting were also added.

An investigation into how welder monitoring fits in the nuclear industry was performed. It was observed that once the capabilities to train under the GTAW process and on pipe are developed, the following benefits could be realized:

- Train welders more efficiently and effectively
- Provide welders with a better understanding of the torch manipulation variables and their effect on weld quality
- Generate a data-driven track record of a welder's development
- Screen out those trainees that are not developing
- Relay the emphasis on the precision needed for nuclear welding
- Gain the ability to learn the muscle memory of a welding technique without starting an arc and wasting material.

DOE/NE0000279-4 – Real-Time Weld Quality Monitoring - Sensor Fusion

In the welding realm the pursuit of real-time quality monitoring techniques is one that has been followed globally and at an increasing pace over the past few decades. Until recently, most attempts to monitor welding in real-time have been focused on one specific technique, whether that is electrical input values (current and voltage) or arc by-products (sound and light). Each of these techniques has their specific advantages and disadvantages. This means that an implementation of one technique makes the concession that certain defects are to be unresolvable.

The following research looked to make an initial attempt at moving beyond the single technique monitoring system and into a sensor fused system with synchronized information coming from multiple monitoring sources. A laboratory monitoring system was constructed combining arc current, arc voltage, and arc light, and applied to a narrow-groove GTAW application. One joint consisting of 54 welds was monitored to completion. Within the joint a number of defects, including arc instability, porosity, tungsten inclusion, and lack of fusion, were attempted. After welding, the completed weldment was scanned using phased-array ultrasonic testing to provide a volumetric quality map, and verifying the realization of the defect attempts. A cursory analysis of the real-time data was then performed to check for correlations to the formation of defects. Analysis techniques for the current and voltage signals were kept simple, looking at raw and moving average data traces. The light analysis was more novel as the raw spectrums, key wavelength variation, and integral spectrum variation were calculated and studied.

Overall, the current signals and the light signals performed the best and worked together as a natural pair, complementing each other’s advantages. Additionally, it was observed that the multiple novel techniques for arc light analysis all produced essentially the same result. Each key wavelength followed the same trends in addition to the integral spectrum traces.

3.1.9 Task 9: Novel Approaches for Stress Corrosion Cracking Mitigation and Monitoring

This task was completed and documented in three final reports on April 6, 2011, March 21, 2011, and March 15, 2011. The reports were submitted via DOE Form F 241.3, and the report numbers are DOE/NE0000279-6, DOE/NE0000279-7, and DOE/NE0000279-8, respectively. The following paragraphs summarize the work completed under this project.

DOE/NE0000279-6 – Novel Approaches for Stress Corrosion Cracking Mitigation and Monitoring - IGSCC

Intergranular stress corrosion cracking (IGSCC) in nickel-based materials has been a problem from the earliest days of commercial nuclear power reactors. This report summarizes the literature regarding the causes and remedies of secondary-side IGSCC in pressurized water reactors (PWR), where it has been manifest most dramatically in steam generator tubes. A three-part analysis published in 2003-2004 provided a quantitative evaluation of this phenomenon; this work formed the basis for much of the current report. In this analysis, nine distinct variants of IGSCC were identified and characterized, with extensive citation of operating plant experiences and laboratory investigations for each variant. In addition to steam generator tube cracking, this report identifies other components which have experienced IGSCC in both PWR and boiling water reactors (BWR). In the latter, removal of crevices all but eliminated the problem of IGSCC except for ongoing issues with safe ends. Means of testing for and controlling IGSCC are highlighted. The report closes with a summary of some aspects of secondary side IGSCC which still are not well understood, the further study of which would benefit the industry.

DOE/NE0000279-7 – Novel Approaches for Stress Corrosion Cracking Mitigation and Monitoring - PWSCC

Corrosion-related issues continue to be one of the largest un-resolved problems for nuclear power plants worldwide. The most severe corrosion problem in PWR is primary water stress corrosion cracking (PWSCC) of nickel-based alloys. This report presents a general review of PWSCC of nickle-based alloys including damage location, PWSCC mechanisms and influential variables, alternative mechanistic models, PWSCC of welded joints, and testing and control of PWSCC.

Location of PWSCC Damage: Manifestation of PWSCC of nickle-based alloys in PWR was first observed in the 1970s in tight U-bends and cold worked transitions and became a major cause of steam generator tube cracking in the 1980s. PWSCC of instrument thick nozzles in the pressurizer, and penetration for control-rod drive mechanism (CRDM) in the reactor vessel closure heads followed in the 1980s and after. PWSCC of weld metals (IN182 and IN82 alloys) was later observed in primary joints and weld butters of several plants after 17 to 27 years of service.

PWSCC Variables: Environmental cracking of nickel-based alloys in high-temperature water is influenced by numerous variables related to the environment, stress conditions, materials, and their synergistic interactions. Nuclear power plants operate in carefully controlled and chemically-treated high purity water environments. For nickle alloys (where the Ni/NiO transition can be transverse) both H_2 fugacity and temperature are important. SCC initiation and crack growth rate of nickel-alloys seems to be thermally activated (Arrhenius-type law). There is scatter in the apparent activation energy that may results from potential effect of other factors including cold work, stress intensity factor, or hydrogen. The addition of zinc to the primary water seems to delay the crack initiation in nickle-based alloys including alloy 600 due to enrichment of the external layer of oxide with zinc (1 to 10%).

While water chemistry provides the best option for SCC mitigation in existing plants, it is important to be able to predict the growth and future trajectory of a crack. Therefore, among many factors, the effect of varying stress intensity factor, K, profiles as the crack advances is an important issue. Dynamic strain is an essential element in the PWSCC mechanism for crack advance. Thus, SCC depends fundamentally on sustained strain at the crack tip and not on K.

In pure primary water, chromium has a pronounced effect on SCC of nickel-chromium-iron alloys which may explain the resistance to SCC of Alloy 690. The presence of minor elements like titanium and niobium may affect the SCC fracture behavior. Metallurgical and microstructural variables having a significant influence on PWSCC response include carbide precipitation, sensitization, grain boundaries (GB) characteristics, chemical composition profiles across GBs, and plastic deformation or cold work. Elevation of yield strength can originate from different sources, but all forms appear to produce a similar enhancement in SCC crack growth rate.

Mechanisms of PWSCC: The three most commonly proposed mechanisms for PWSCC include slip dissolution, film-induced cleavage, and hydrogen embrittlement. The slip dissolution or slip-film rupture-oxidation model of crack advance is the most widely accepted model. In recent reports, an internal oxidation (IO) mechanism has been proposed to explain PWSCC of nickel-based alloys in high-temperature water. For the slip dissolution model, the amount of metal dissolution at the crack tip controls the cracking kinetics, whereas the diffusion rate of oxygen along GB is a primary factor in the IO model.

The common approach of most studies on PWSCC in nuclear plants is based on "local cell action" combined with fracture mechanics. However, it has been observed that the SCC crack tip is as narrow as 1-5 nm. These dimensions are much smaller than the dimensions of crack-tip-open displacement (CTOD) and plastic zone that are used in a normal fracture mechanic approach. The dimension of the crack tip does not provide the volume for a liquid continuum but it is a molecular domain. This introduces a different paradigm for modeling and understanding of PWSCC. Additionally, a macroscopic approach or "long-cell action" different from the "local cell action" has also been proposed. Corrosion activities are aggravated in anodic areas of the long cell, whereas those in the cathodic areas are alleviated, which is similar to the principle of cathodic protection. International joint initiatives are needed to prove or disprove the existence of the long cell action mechanisms in the nuclear industry. Different and new approaches for corrosion control may be needed based on the long cell action as compared to the local cell action approach.

PWSCC of Welded Joints: There are some unique characteristics in nickle-based Alloy 182 weld metals and its susceptibility to PWSCC. Crack growth rate (CGR) in Alloy 82/182/132 is strongly affected by the microstructure of the weld and by the orientation of the crack growth with respect to the dendrites orientation. PWSCC initiation has been associated with plastic deformation and high energy GB, which represent a large fraction of the GB in weld metals. However, some clustering of grains having similar orientation has been observed in weld metals and may affect the SCC propagation. Weld metals with 30% chromium are resistant to cracking, with a threshold for PWSCC resistance being between 22 and 30% chromium. Due to the microstructure and compositional segregation in the weld metal, uneven crack fronts and incomplete engagement of SCC cracks are sources of potential uncertainty in measurement of CGR of welds. Welding thermal cycles can dissolve carbides, produce high localized residual stresses and strains, and promote SCC in the heat-affected zone (HAZ). Additionally, the behavior of different regions across a welded joint may be related to the intragranular microstructure and creep resistance of the various regions, differences in the exposed area of each region (random event), or differences in the film stability due to the higher chromium content in the weld metal.

PWSCC Testing: Most studies regarding PWSCC of Alloy 600 either look into the crack propagation stage using compact tension (CT) specimens among other methods, or evaluate the entire crack growth process (initiation and propagation) by constant load or slow strain rate tests (SSRT). However, data on growth of PWSCC in the initiation stage, on which the life of the PWR plant component is presumed to be dependent, is lacking. PWSCC testing requires strong familiarity with different disciplines and close control of many variables. The observed large scatter make it almost impossible to identify the effect of numerous relevant variables and their synergistic interactions. Evaluation of available data by international experts indicated that the scatter in the data is substantially the result of data quality issues such as specimen machining, fatigue precracking, transition from the transgranular precrack to an intergranular SCC, crack measuring anomalies associated with highly uneven crack fronts, inaccurate control and measurement of corrosion potential, and water purity.

Various ASTM standards for fracture toughness (E399) and fatigue (E647) are applied to SCC testing. The requirements of ASTM standards E647 and E1820 generally used by researchers to select specimen sizes seems to be very conservative. Most of the tests reported in open literature used thick-section standard fracture mechanics specimens. However, a SCC test methodology using specimens in the shape of tubes has been developed and reported in the literature.

Control of PWSCC: There is consistent engineering pressure to define threshold conditions below which immunity to SCC exists. However, "engineering threshold" should not be confused with a genuine regime of immunity to SCC. In 2003, a CGR disposition curve for PWSCC of thick-section Alloy 600 material was reported. This curve has been incorporated into ASME section XI code for flaw and integrity evaluation. The need for a similar equation for alloy 82/182/132 weldments was identified for estimating the remaining life of components, and to determine inspection intervals. An international panel of PWSCC experts supported this development and a deterministic CGR curves for Alloy 182/132 and Alloy 82 was developed and proposed.

Mitigation of PWSCC of nickel-based alloy has been tried with different operational and fabrication techniques including operation at reduced temperature, chemical or electrochemical potential control techniques, stress relief heat treatment for U-bends, mechanical surface enhancement, and environmental barrier or coatings. Stress corrosion cracks of IN182 in nuclear plants may be repaired with laser surface melting (LSM). Optimization of repair procedures is required to achieve the right penetration without defects. Compared with GTAW for repair techniques, laser welding offers high precision, reliability, efficiency, and productivity.

DOE/NE0000279-8 – Novel Approaches for Stress Corrosion Cracking Mitigation and Monitoring - SCC

This report is a literature review on SCC of austenitic stainless steel alloys in high-temperature water environments. More specifically, this report focuses on the problem of IGSCC/irradiation-assisted stress corrosion cracking (IASCC) in the nuclear industry in BWR and PWR environments. The major topics discussed within this report are the location of IGSCC/IASCC in the nuclear industry, industry approaches to solve the problem, testing methods used to assess the problem, and a detailed discussion of the factors that affect IGSCC/IASCC. The industry approaches to control the problem and the discussion of the factors that affect SCC are organized according to the classic Venn diagram for SCC: (i) microstructure, (ii) environment, (iii) and stress.

3.1.10 Task 10: Fabricated Forgings

This task was completed and documented in a final report on Novemer 23, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-9. The following paragraphs summarize the work completed under this project.

While large pressure vessels in early U.S. commercial nuclear reactors were made of multiple welded steel pieces, by the late 1970s virtually all these vessels were fabricated from large forgings. This change was based largely on the premise that vertical seam welds in these vessels could potentially experience radiation-induced embrittlement during plant operation, making them susceptible to brittle fracture. The lower stress experienced by circumferential welds made joining of large ring forgings less of a concern.

With the advent of better steel-making practices with lower residual elements, as well as new welding and inspection approaches, the use of fabricated assemblies in large nuclear pressure vessels needs to be re-examined. Moreover, there is a limited number of forging facilities which can manufacture the large vessels; none of these are in the U.S. Lead times for vessels could potentially be reduced from years to months with the use of welded assemblies which many domestic suppliers are capable of producing.

This report examines the material requirements for large nuclear pressure vessels and the regulatory and industry stances which have resulted. While the nuclear industry has adopted a policy of minimizing welds for in-service inspection and personnel radiation exposure reasons, there are potential cost and schedule benefits to using welded sections for vessel construction.

A newly-developed welding process, narrow-groove tandem GMAW was used to fabricate a test assembly that exceeds 5-in. thickness. There are a number of advantages which this process offers, including high deposition rates, lower heat input compared with submerged arc welding (SAW), and the use of a narrow-groove joint with enhanced sidewall-wetting capability. Mechanical properties and microstructures of this test joint were found to compare favorably with those typically obtained with SAW. As-welded properties met criteria established by the ASME Boiler and Pressure Vessel Code.

3.1.11 Task 11: Techniques for Modularization from other Industries

This task was completed and documented in a final report on January 25, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-10. The following paragraphs summarize the work completed under this project.

The nuclear industry is undergoing a renaissance with more than 20 new facilities under review by the NRC. To stay on schedule and on budget, the nuclear industry must also find ways to cut construction schedules and decrease costs. Modular construction is one technique that other industries have used to address these issues.

The modular approach was developed by the shipbuilding industry after World War II. It has since been adopted by the chemical process and oil refining industries as a way to reduce costs and to build facilities in remote locations. They found that moving work from the construction site to a manufacturing facility increases efficiency and reduces the construction schedule by allowing units to be constructed in parallel. The objective of the report is to capture the thought process behind the use of modular construction from the literature and from the experience of the nuclear and non-nuclear industries.

General Dynamics Electric Boat Division in Quonset Point Rhode Island is considered the benchmark for modular fabrication efficiency. They have developed designs and work processes that have reduced the cost of new submarines by 20% while also reducing the construction schedule substantially. They are convinced that the nuclear industry could achieve similar cost savings by adopting modular principles. They emphasize that the process works best when it is used as an integral part of the project from day one.

The Construction Industry Institute (CII) has developed a detailed description of a program for construction prework under the acronym PPMOF that stands for Prefabrication, Preassembly, Modular, and Offsite Fabrication. The evaluation protocol the CII has developed helps companies determine the most economically attractive prework approach for any large construction project.

The PPMOF process requires that companies evaluate fabrication and construction alternatives during the conceptual design phase of the project. If a high level of prework is beneficial to the construction schedule or the project budget, designs should be completed well before construction begins to allow module fabricators and equipment suppliers to be brought into the construction planning process.

The nuclear industry has used modules for construction of facilities in Asia. Many of the nuclear steam systems designers have sent staff to Asia to learn how the modular construction process is implemented there.

These alliances are now being developed for construction of the next wave of nuclear power plants in North America. Some of the fabrication alliances are also being developed. Many of the opportunities will require fabricators hold ASME N-stamps.

Fabricators have taken different approaches to these early project alliances. Some fabricators have developed a deep engineering staff that can do complex facility design using an array of 3D computer design programs that are now available. They are valued design partners for their clients. Other fabricators have chosen not to develop design capability in house. Instead, they have a small staff that can provide constructability reviews and develop bills of materials and work process sheets from the 3D designs. Their fabrication efficiency keeps them competitive. Both approaches have been successful.

Computer design capability will be increasingly important as the nuclear industry moves from Gen III to Gen III+ and finally Gen IV facilities. In this transition, the industry expects to move to electronic designs by the time Gen IV facilities are constructed beginning in 2018-2020. Fabricators will need to keep pace with this development.

Once the design is completed, changes must be limited to avoid expensive repair and rework. This requires that all of the parties involved in the construction of the nuclear facility communicate on a regular basis. This will involve regular onsite meetings and Internet communications. The team approach requires that the system designer and construction company share control with their supply chain partners while retaining ultimate responsibility for the project.

Using a modular construction approach allows fabrication to begin while foundation work is being completed onsite. Moving fabrication to a factory setting also improves quality, efficiency, and safety during construction. General Dynamics believes that modular assembly in a factory is eight times as efficient as stick building onsite. Careful design can limit the cost of extra structure required for shipping of modules from the factory to the construction site.

Prework including modular fabrication will be an important part of the construction of the next generation of nuclear power plants. It will require that designers complete their designs early in partnership with construction companies, fabricators, and equipment suppliers. This will require that all parties invest time and resources early in the program to insure an on time and on budget result.

General Conclusions and Findings
Other industries have proven that modular construction can decrease construction costs and cut construction schedules for large complex facilities. This has been validated by the recent construction of new nuclear power plant facilities in Asia.

Implementation of a modular construction approach requires a different thought process than onsite construction. It requires devoting more engineering resources to the project in the design phase to make sure that the design is complete before construction begins. This should involve a team from the nuclear steam system designers, the construction company, fabricators and equipment suppliers to insure that the design is efficient and meets constructability requirements. This increases the upfront costs. These costs may not be recovered on the first project.

Modular construction requires some additional structure to make sure that modules can be transported and installed without damage. The amount of additional structure is usually not large and the additional cost can be minimized with careful planning of the transportation route and lifting sequence.

Experience in Asia has shown that modular construction can reduce construction costs by 37% while at the same time reducing the construction schedule for a nuclear power plant from 64 to 53 months. Based on this experience, all of the nuclear steam system suppliers are planning to use some level of modularization for the next generation of facilities in North America.

3.1.12 Task 12: ASME RT vs UT in Codes and Standards

This task was completed and documented in a final report on March 18, 2011. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-11. The following paragraphs summarize the work completed under this project.

The ASME Boiler and Pressure Vessel Code is not just a code, it is a system of codes. As with any system the better the pieces work together, the more useful the product. The code exists to manage some of the most potentially dangerous systems mankind has yet invented, failure is unthinkable. The Boiler Code Committee was formed in 1911 which led to the Boiler Code being published in 1914-15 and later incorporated in to the laws of most U.S. states and territories and Canadian provinces. For the most part, the structure and how the code is used has remained the same but the amount of technical information the code governs has increased exponentially. The NFC Members noted that it appears there is an issue with RT vs UT in the code and asked the NFC to assess the hypothetical validity of the issue. After a survey of industry experts and professionals it was decided to dive into the code to map out the code. This report summarizes that activity.

3.2 DOE-NE Funded Projects

3.2.1 Task 1: HLAW in Nuclear Industry

This task was completed and documented in a final report on March 26, 2012. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-15. The following paragraphs summarize the work completed under this project.

High-energy density (HED) welding processes such as laser beam welding and electron beam welding have the ability to greatly improve productivity through their inherent depth of penetration. One novel idea recently proposed, developed, tested, and verified by EWI is the concept of a HLAW system for pipe and vessel fabrication. The HLAW process combines the use of a laser-heat source for deep penetration and a conventional arc welding method (GMAW) for filling. Such a technique is an ideal candidate for improving the productivity of thick-section welding in the nuclear industry.

The work-scope presented within this paper demonstrates the feasibility of using the HLAW process for nuclear applications. A weld procedure qualification has been conducted on thick-section nickel-based plate (Inconel 690), where the HLAW process was used to deposit the root pass. The qualification coupon passed all the NDE and mechanical testing requirements outlined by ASME Section III, Div.1, Subsection NB.

In addition to the weld procedure qualification, the residual stresses produced by conventional versus HED weld processes was examined. Microhardness mapping demonstrated that the HED welding processes produced welds with lower levels of residual stress than a conventional GTAW weld. Finally, the scope of work contained within this paper also tested the effect of PEC on the HLAW process; it was seen that PEC does not influence depth of penetration of HLAW welds.

3.2.2 Task 2: Ultrasonic Brazing SiC

This task was completed and documented in a final report on February 22, 2012. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-16. The following paragraphs summarize the work completed under this project.

Silicon Carbide (SiC) fuel cladding is an emerging technology that has the potential to provide revolutionary improvements in safety and cost reduction for existing and future fleets of light water reactors. In order to realize this vision, there are technological challenges that must be overcome to enable implementation. One such challenge is the joining of the end plug to the cladding tube after it has been loaded with fuel.

In this work, a new approach for brazing SiC to itself was developed. This approach uses a multiphase braze alloy consisting predominately of silicon and aluminum with a two-phase joined microstructure. This particular material system was selected based on stability under neutron irradiation and viability as a brazing material. Microstructural evaluation after joining showed a fully dense microstructure that is likely to be hermetic.

Preliminary tests have shown promising results from irradiation testing in The Ohio State University research reactor, post joining high temperature cycling up to 1200°C, and traditional mechanical testing. Meeting the 1200°C temperature threshold is particularly important as that is the temperature stability target for a design basis accident. Additionally, this approach does not require extensive heating times or pressure that would ultimately prove difficult and economically impractical for manufacturing of production fuel rod cladding assemblies. This is a key point as it allows for integration of mechanical features, such as a threaded joint or pins that would extend the temperature stability of the full joined solution to beyond design basis accidents.

3.2.3 Task 3: Sol-Gel Coating Development

This task was completed and documented in a final report on February 2, 2012. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-14. The following paragraphs summarize the work completed under this project.

High-temperature/high-pressure water presents special challenges in corrosion protection for metal alloys. High-performance alloys can be used, but they are expensive and sometimes difficult to fabricate. While carbon steels are inexpensive and relatively easy to weld, they lack the corrosion protection to withstand superheated water operating at, e.g., 300°C which produces pressure in excess of 1200 psi. The goal of this program was to examine potential for surface modification of carbon steel to provide corrosion protection in highly aggressive water environments.

This work has been focused on developing a combination sol-gel and surface conversion approach to produce an effective surface coating on steel for the high-temperature water environment. Sol-gels are inorganic polymers that produce ceramic-like coatings that can be used to protect metals against corrosion. Traditional organic coatings (paints) cannot withstand the temperatures of this application, much less the highly aggressive water environment. Thus an inorganic ceramic coating system was the starting point for investigation.

Sol-gels are produced from mixtures of inorganic salts or reactive precursors and water. The addition of water causes a polymerization reaction to begin and a gel network forms. This can be further reacted and condensed to produce glassy or ceramic coatings, but at fairly low temperatures. They are able to be applied in a paint-like fashion but form an inorganic ceramic as a thin film coating. Results from literature suggested that an aluminum-oxide or zirconium oxide precursor gel could provide the desired performance. After initial experiments the zirconium oxide system was down-selected because it proved easier to convert the precursor into the ceramic thin film.

In addition to the sol-gel coating, a surface conversion reaction on the steel substrate was implemented for corrosion protection. The mixed oxide $FeO{\cdot}Fe_2O_3$ is stable in water and has the potential to protect ferrous alloys from corrosion. It is possible to form this mixed oxide using a chemical conversion treatment which reduces Fe^{3+} to Fe^{2+}. Further, it is known that phosphoric acid treatment of ferrous metals produced iron phosphate ($FePO_4$) which is virtually insoluble in water. Due to the low solubility and excellent stability of the $FePO_4$ and $FeO{\cdot}Fe_2O_3$ a pre-treatment process was developed to be completed on the steel surface prior to sol-gel deposition. This pre-treatment seals the surface and acts as an inorganic anchor coating for the zirconia sol-gel coating.

After investigation of process parameters, the treatment protocol with the highest potential for protecting the steel substrate consisted of: (1) etch gritblasted 1018 steel in phosphoric acid solution to convert to $FePO_4$, (2) apply a conversion coating to produce the mixed oxide $FeO{\cdot}Fe_2O_3$, (3) apply the zirconia sol-gel seal coat, and (4) fire the finished coating to 550°C to convert the gel to ceramic.

Sample plates were tested in water at 200, 250, and 300°C in a degassed autoclave for 72 hours. At the end of those tests, the plates were intact and there was no sign of rust. This is an exciting result as it demonstrates the potential of this combination approach.

The potential of this approach has been shown based on the successful protection of plain carbon steel in aggressive high-temperature water conditions. Future work to optimize the processing and extended testing on actual pipe segments would enable deployment of this approach for protecting pipeline steel.

3.2.4 Task 4: High-Productivity Fabrication Process Demonstrations

This task was completed and documented in a final report on October 18, 2012. The report was submitted via DOE Form F 241.3, and the report number is DOE/NE0000279-17. The following paragraphs summarize the work completed under this project.

The demonstration of high productivity welding and machining processes was one of the topics defined by a team of NFC members, and other organizations within the nuclear industry, during the Nuclear Energy Enabling Technologies workshop held by DOE-NE on July 29th 2010. Demonstration of these technologies was determined to be core to the public good and to DOE-NE's mission of promoting nuclear power as a resource capable of meeting the Nation's energy, environmental, and national security needs by resolving technical and regulatory barriers through research, development, and demonstration. Major technological advancements in modern, solid-state lasers have brought laser processing to the forefront of many manufacturing industries. Equipment portability, size, electrical efficiency, output power, and reliability have been drastically improved; along with the quality of the laser beam itself. To improve the performance of "traditional" machining processes (e.g., drilling, turning, milling), EWI has developed methods to apply ultrasonic vibrations to the machining tools. This project set out to understand the cost benefit relationship for using high productivity welding and machining processes in nuclear fabrication and demonstrate the processes with the largest cost benefit relationship. The demonstrations held under this program included:

- Ultrasonic Drilling of Pressurizer Heater Nozzles
    - AREVA − Lynchburg, VA – June 9, 2011
- Autogenous Laser Welding of Tubes-to-Tubesheets for Steam Generator Applications
    - B&W − Barberton, OH – December 8, 2011
- Narrow Groove GMAW and Hybrid Laser GMAW for Thick Section Steel Applications
    - PCC/EWI − Columbus, OH – April 19, 2012

4.0 Discussion and Technology Transfer

A large amount of the outreach activities were completed under this program. The EWI management team has worked to make the NFC sustainable and the NFC members have expressed that the technical and educational programs offered through the NFC are of tremendous value to them and to the nuclear industry. The NFC technical projects offer a means for them to participate in industry critical technology development programs that benefit their companies as well as the whole of industry. With the current economic and political uncertainty for the U.S. nuclear industry, the transition through new plant builds into a nuclear renaissance may not advance as quickly as thought when the NFC was conceptualized.

Organizations need a champion (like the NFC) to help bring them up the technology curve when the renaissance becomes a reality. The NFC has become a venue.that provides interaction between the fabricators. There are few forums that vendors and clients congregate to discuss technical manufacturing needs. One of the greatest hurdles facing the nuclear industry is the lack of a technical home for component manufacturers. EWI will continue to support nuclear fabrication technologies and will continue to work with the DOE to advance manufacturing technology in the nuclear industry.

Under this program three internal invention disclosure forms (IDF) were completed. EWI only pursued EWI IDF #11-0013 under EWI Project 52684NFG for "Joining Ceramic Bodies". Subsequently, EWI filed for a provisional patent application (No. 61/538,409) on 09/23/2011, which was later converted to a U.S. utility patent application (No. 13/624,423) and a PCT (Patent Cooperation Treaty) patent application (No. PCT/US2012/056654), both of which were filed on 09/21/2012.