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Light Water Reactor Sustainability Program

Develop Parameters and Characterize the Quality of Friction Stir and Laser Weld-Repaired, Irradiated Structural Materials Representative of Extended Reactor Service Life

M2LW-19OR0406014

April 2019

U.S. Department of Energy

Office of Nuclear Energy

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Develop Parameters and Characterize the Quality of Friction Stir and Laser Weld-Repaired, Irradiated Structural Materials Representative of Extended Reactor Service Life

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ABSTRACT

This report summarizes the most recent welding campaign on irradiated 304L stainless steel (304L SS) and 316L stainless steel (316L SS) at the Radiochemical Engineering Development Center (REDC), and post-weld quality and microstructure characterization, as well as, microhardness testing of ongoing weld campaigns using irradiated stainless-steel alloys at the Low Activation Materials Development and Analysis (LAMDA) facilities of Oak Ridge National Laboratory. Equipment and capabilities were developed jointly by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, the Electric Power Research Institute, Long Term Operations Program (and the Welding and Repair Technology Center), and Oak Ridge National Laboratory. Irradiated 304L SS and 316L SS, with target helium contents of 10 atom parts-per million (appm) and 20 appm, were laser welded and friction stir welded in the hot cell successfully. The in-depth friction stir weld microstructure characterization and Vickers microhardness testing were carried out with a scanning electron microscopy and a microhardness tester, respectively. The significant, on-going effort to weld irradiated alloys with high helium concentrations and comprehensively analyze the results will eventually yield validated repair techniques and guidelines for use by the nuclear industry in extending the operational lifetimes of nuclear power plants.

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DEVELOP PARAMETERS AND CHARACTERIZE THE QUALITY OF FRICTION STIR AND LASER WELD-REPAIRED, IRRADIATED STRUCTURAL MATERIALS REPRESENTATIVE OF EXTENDED REACTOR SERVICE LIFE

1. INTRODUCTION

After the first advanced welding campaign with three irradiated 304L stainless steel (304L SS) coupons in November and December 2017, the second welding campaign was carried out in the Radiochemical Engineering Development Center (REDC) welding cubicle at Oak Ridge National Laboratory (ORNL) by using advanced laser and friction stir welding in October 2018. During the second welding campaign, not only irradiated 304L SS coupons with various helium contents were welded, but also an irradiated 316L stainless steel (316L SS) coupon was laser welded. This one-of-a-kind, enclosed, hot cell welding cubicle was developed through a joint effort by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program and the Electric Power Research Institute (EPRI), Long Term Operations Program (and the Welding and Repair Technology Center), and ORNL. In FY18, laser and friction stir welds made at the first welding campaign were sliced into specimens in a hot cell of Irradiated Materials Examination and Testing (IMET). Initial microstructure characterizations were carried out by a scanning electron microscope (SEM) at the Low Activation Materials Development and Analysis (LAMDA) facilities. Detailed information of the irradiated material welds specimen cutting and initial characterization has been reported in the milestone report M2LW-18OR0406014 “Complete Report on Development of Weld Repair Technology.” Since then, additional microstructure characterizations have been carried out with SEM/ Energy Dispersive X-ray Spectroscopy (EDS) on the first friction stir weld to reveal details of features observed during the initial study carried out last year, and Vickers microhardness testing has also been carried out on this irradiated 304L SS friction stir weld to support post-weld evaluation and the development of validated weld repair techniques and guidelines for use by the nuclear industry.

This report summarizes the 2nd irradiated material advanced welding campaign and further post welding activities on the friction stir weld made in the 1st welding campaign. Included within are details on:

- The 2nd advanced welding campaign of irradiated materials (304L SS and 316L SS) with different targeted helium contents
- In-depth microstructure characterization of the irradiated 304L SS friction stir weld 304C-6 containing high helium concentration using SEM/EDS
- Vickers microhardness measurement, distribution and analysis of the irradiated 304L SS friction stir weld 304C-6 containing high helium concentration

Concurrently, we have completed the 2nd round of welding campaign with irradiated materials and we are preparing for the next round welding campaign covering even wider irradiated material conditions. Meanwhile, we are further characterizing irradiated material welds by SEM and microhardness testing, preparing the mechanical properties testing, and introducing the advanced welding technologies to nuclear industries.

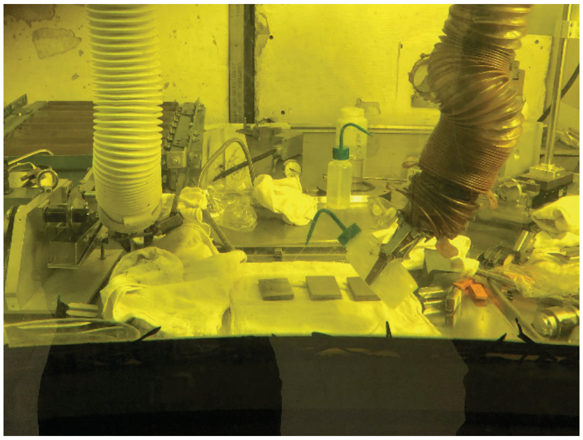
2. THE 2ND ADVANCED WELDING CAMPAIGN ON IRRADIATED MATERIALS

During the 1st welding campaign, three irradiated 304L SS coupons were chosen for advanced laser welding (LW) and friction stir welding (FSW). The LW was applied on the coupon 304D-1 which was later measured containing 20 appm helium, and the friction stir welding was applied on coupon 304C-6 and 304B-1, which were later measured containing 26 appm and 8.5 appm of helium, respectively. All helium measurements were carried out by Laser Ablation Mass Spectroscopy (LAMS). For specimens 304D-1 and 304B-1, measured helium values are close or higher than calculated values. The measured helium level in 304C-6 was significantly higher than expected and may require additional measurements on samples from other coupons of material heat 304C in the future when available. In this report, three irradiated stainless steel coupons, including irradiated 304L SS and 316L SS, were chosen for the 2nd welding campaign materials and detailed information is shown in Table 1.

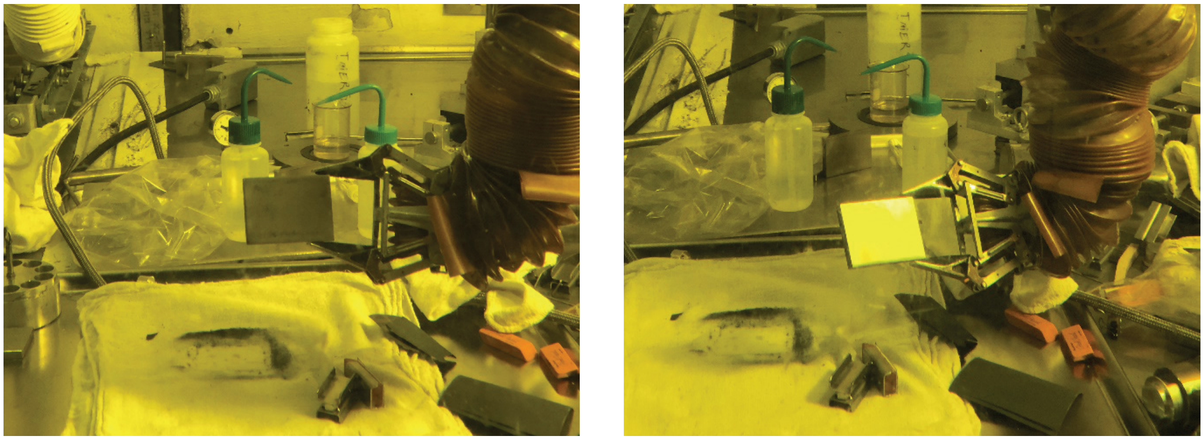
Table 1 Irradiated material coupons for the 2nd advanced welding campaign

Coupon No	Natural boron prior to irradiation, wppm/ targeted helium after irradiation, appm	Advanced welding technology
304D-5	20/20	FSW
304C-5	10/10	LW
316C-7	10/10	LW

The three selected irradiated coupons, 304D-5, 304C-5 and 316C-7, were picked out from the storage place at IMET and coupons' surface preparation was executed in a hot cell at the IMET. Before the surface preparation, coupon IDs were identified from the control room through a telescope. Coupon surface preparation procedures include surface oxides removal by grinding, operated through a pair of manipulators, with 400 grits silicon carbide papers, followed by alcohol cleaning and drying. The surface preparation, an irradiated coupon before and after the surface preparation are shown in Figure 1. From Figure 1, it is clear that oxides were generated during the irradiation process, and they were removed effectively by the surface preparation.



(a) Irradiated stainless steel coupons surface preparation before welding



(b) An irradiated coupon prior to surface preparation (c) The irradiated coupon after surface preparation

Figure 1 Irradiated coupons surface preparation before welding

After the surface preparation, the three irradiated coupons were sent to REDC for advanced LW and FSW.

The advanced FSW was carried out on the irradiated 304D-5 coupon with the same welding tool (Polycrystalline Cubic Boron Nitride (PCBN) tool), tool rotation rate (400 rpm) and tool traveling speed (2 ipm) of those applied in the 1st advanced welding campaign. Both friction stir welds produced in the 1st advanced welding campaign showed short surface defects at the end of the weld and they are mainly located in lead-out tabs. The measured surface defect length of the first friction stir weld was 13.7 mm. The welding machine deflection and deflection variation along the tool traveling direction causing inconsistent tool and coupon engagement during the FSW were considered as two of the highest possibilities for such welding defect appearance. Therefore, Further tool plunge in which should result more tool shoulder engagement with the welded material could be a solution to get rid of such defect. In the current FSW of irradiated 304D-5 coupon, the tool plunged in 0.013” more than that in the first FSW of irradiated 304L SS. Major FSW parameters used in the 2nd advanced welding campaign are shown in Table 2. The 304D-5 friction stir weld is shown in Figure 2, where the surface defect is still clearly seen by the end of the weld.

Table 2 FSW parameters of the irradiated 304D-5 coupon

Parameter	*Value*	*Units*
Starting Position	4.500 (x), 0.000 (y), 2.747 (z)	inch
Tool Rotation Rate	+400 (counter clockwise)	rev/min
Tool Tilt Angle	0	degrees
Welding Speed	0.033	inch/sec
Weld Path Z Travel	0.355 (0.013" more than the 1st FSW)	inch
Plunge Speed	0.004	inch/sec
Weld Length	4.0	inch

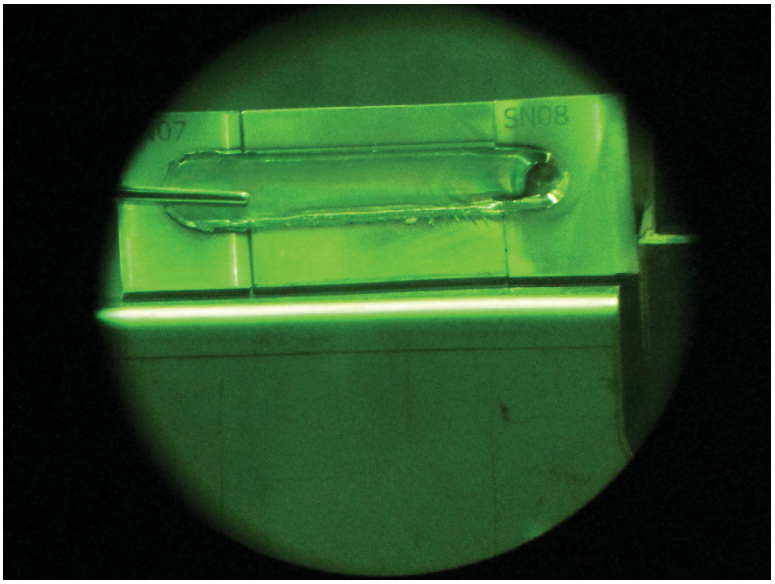


Figure 2 Friction stir weld of the irradiated 304D-5 coupon

Since the FSW tool has a convex shoulder, the more tool plunge into the material will result wider weld width on the material surface. To study the tool shoulder and the irradiated coupon engagement, weld widths of the 1st irradiated material weld and the current irradiated material weld were measured at four locations, the interface between the lead-in tab and the irradiated coupon, in the middle of the coupon length direction, the interface between the irradiated coupon and the lead-out tab, and at the tool exit hole. Moreover, the length of the surface defect by the end of the weld was also measured. Measured weld width of the current irradiated material friction stir weld and the 1st irradiated material friction stir weld are shown in Table 3. From Table 3, a slightly weld width drop along the welding length is seen inside the irradiated coupon, and a sharp weld width drop is presented in the lead-out tab, see Figure 3 for trends. Further study is needed to identify reasons of the weld width change along the tool traveling direction and to eliminate the surface defect. Moreover, comparing weld widths at similar locations of the current weld and the 1st weld, it is clear that the additional 0.013” tool plunge in during the current FSW created more tool and coupon contact and resulted wider weld width than the 1st weld, and the surface defect is shorter than that of the 1st weld, see Table 3 and Figure 3.

Table 3 Irradiated material friction stir weld width variation along the welding direction and the surface defect length at the weld end

Irradiated 304L SS friction stir weld	Weld width at the beginning of the coupon, mm	Weld width in the middle of the coupon, mm	Weld width at the end of the coupon, mm	Weld width at the tool exit hole on the lead-out tab, mm	End weld surface defect length, mm
The current weld (0.013” more tool plunge in than the first weld)	22.4	19.4	17.1	15.2	10.1
The first weld	17.2	16.8	14.3	10.9	13.7

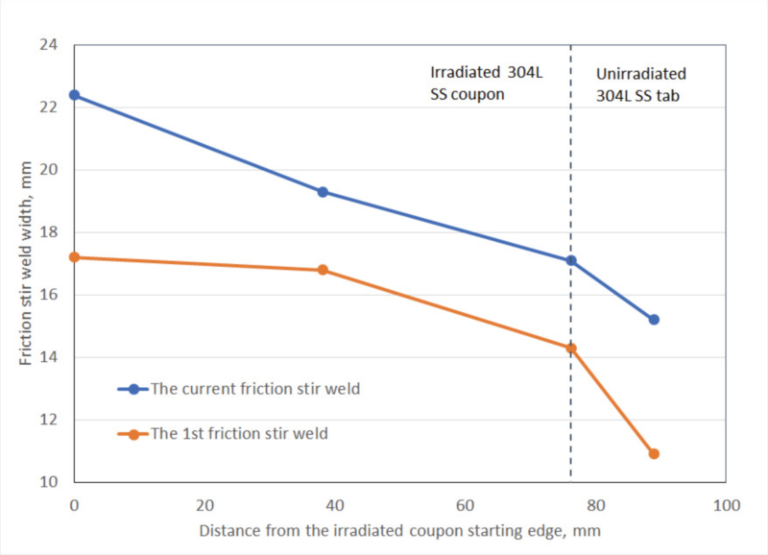


Figure 3 Irradiated 304L SS friction stir weld width variation along the longitudinal direction

The other two irradiated coupons, 304C-5 and 316C-7, which are irradiated 304L SS and 316L SS targeted for 10 appm helium, were welded with LW. Each laser weld was comprised of three layers of multiple passes, with layer 1 containing 10 passes, layer 2 containing 7 passes, and layer 3 containing 4 passes, for a total of 21 passes per weld. Four welds were made on each irradiated coupon (two welds per side) with high and low welding heat input, with and without the scanning laser. In addition to the four weld overlays on the two irradiated coupon, single-pass welds were made between the edge of the coupon and the side of the weld overlay. Two single-pass laser welds were made beside the weld 1 and the weld 2 respectively on the first LW coupon 304C-5, but the formation of the single weld beside the weld 1 was not as good as the one beside the weld 2, probably because it was too close to the clamping fixture. Therefore, only one single-pass weld was made on each side of the rest surfaces/coupons, either beside the weld 2 on one surface or beside the weld 3 on the other surface of a coupon. The layout of laser welds for irradiated coupons is shown in Figure 4.

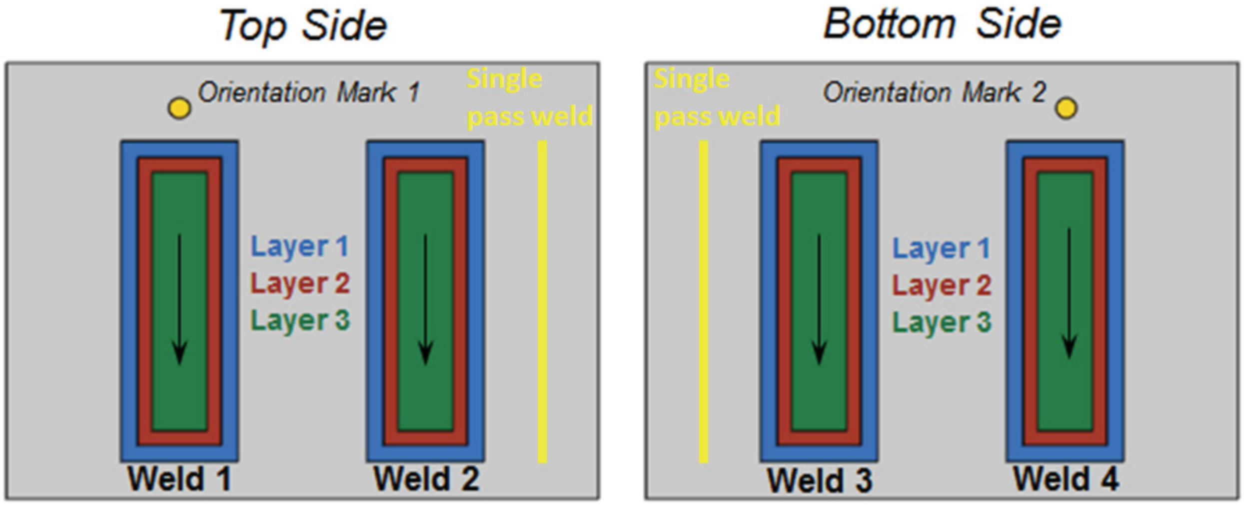


Figure 4 Laser weld layout for irradiated coupons

LW parameters and conditions of each weld and layer of each coupon are shown in Table 4, and welded irradiated coupons are shown in Figure 5.

Table 4 Laser welding parameters of irradiated 304C-5 and 316C-7 coupons

	Weld 1*	**Weld 2***	**Weld 3**	**Weld 4**
Welding Type	CV: conventional, ABSI, FW: filler wire (TURBALOY 308L)			
	CV, FW	ABSI, FW	CV, FW	ABSI, FW
Layer 1, No. of Passes: 10				
Pass Length (inch)	1.375	1.375	1.375	1.375
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	15 - 17	17 - 20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5
Layer 2, No. of Passes: 7				
Pass Length (inch)	1.250	1.250	1.250	1.250
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	17	20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5

Layer 3, No. of Passes: 4				
Pass Length (inch)	1.125	1.125	1.125	1.125
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	17	20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5

*, Weld 1 and Weld 2 on the 304C-5 coupon are reversed.

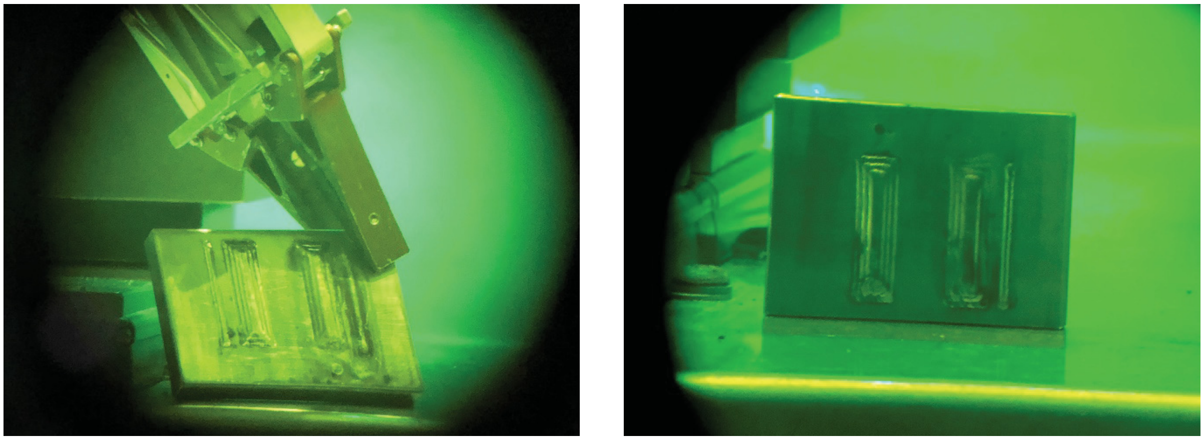


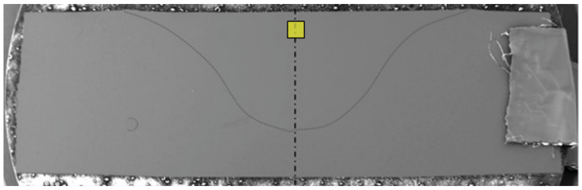
Figure 5 Advanced laser welds on the irradiated 304C-5 coupon (left) and 316C-7 coupon (right)

From Figure 2 and Figure 5, we can see that there is no helium induced welding defects such as cracks and voids appeared on surfaces of the irradiated 304L SS friction stir weld coupon, irradiated 304L SS laser weld coupon and irradiated 316L SS laser weld coupon.

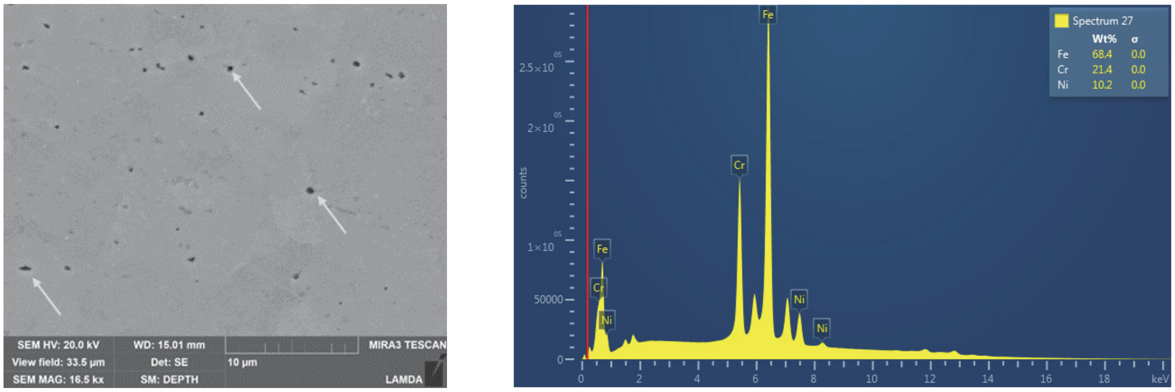
3. IRRADIATED 304L SS FRICTION STIR WELD DETAILED MICROSTRUCTURE CHARACTERIZATION

During the previous microstructure characterization of the irradiate 304C-6 friction stir weld, black objects with micrometer or sub-micrometer sizes were observed close to the weld top and weld root. Locations and introduction of those features were summarized in milestone report M2LW-18OR0406014 “Complete Report on Development of Weld Repair Technology.” In this study period, SEM/EDS was used to further characterize and identify those features close to the top and at the root of the 1st irradiated 304L SS friction stir weld on the 304C-6 coupon, which was measured 26 appm helium by Laser Ablation Mass Spectroscopy (LAMS). This number is significantly higher than the expected value 10 appm and may require additional measurements on samples from other coupons of the same heat material in the future when available.

Multiple dark/black objects close to the weld top surface were analyzed by SEM/EDS, and the analyzed area is marked with a yellow square in Figure 6(a). Those dark/black objects under SEM high magnification are shown in Figure 6(b) and it can be seen that most of them are smaller than one micrometer. For thirty objects detected with SEM/EDS at the spot shown in Figure 6(a), twenty-nine of them had similar chemical compositions with 304L SS, and a typical result is shown in Figure 6(c). Therefore, most of those dark/black objects observed in the weld close to the top surface are voids, and they were possibly generated by helium accumulation during the FSW process.



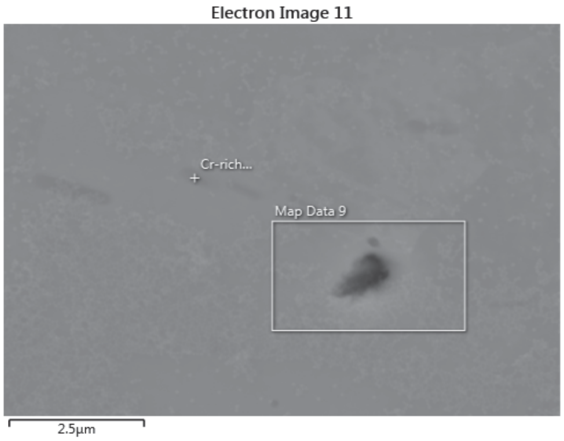
(a) Irradiated 304C-6 friction stir weld cross section and the SEM/EDS analysis spot close to the top (Yellow square)



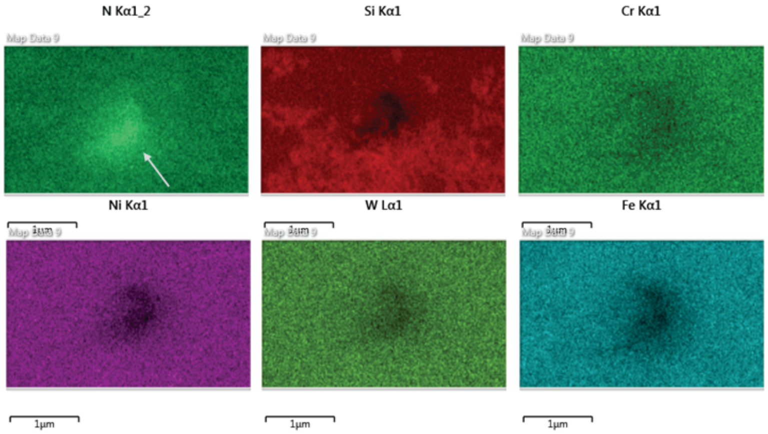
(b) Black object close to weld top (c) Detected chemical composition of a typical black object

Figure 6 Black objects in the irradiated 304C-6 friction stir weld close to the top surface

There is only one spot out of the thirty SEM/EDS analyzed spots close to the weld top showed unusual enrichment of nitrogen, and this black object and corresponding element maps are shown in Figure 7. It is hard to draw conclusion with just one result, but considering the FSW tool material consists boron nitride, and the tool shoulder, which contacted the coupon surface during FSW and experienced the highest temperature, it is possible that the detected nitrogen at that spot came from the tool shoulder wear during the FSW process. However, no corresponding boron peak was detected at this spot.



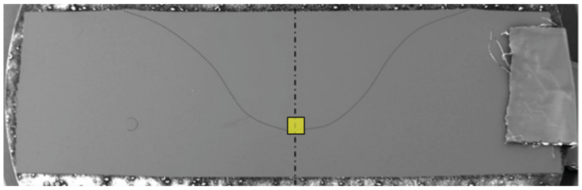
(a) One SEM/EDS detecting spot close to the 304C-6 friction stir weld top



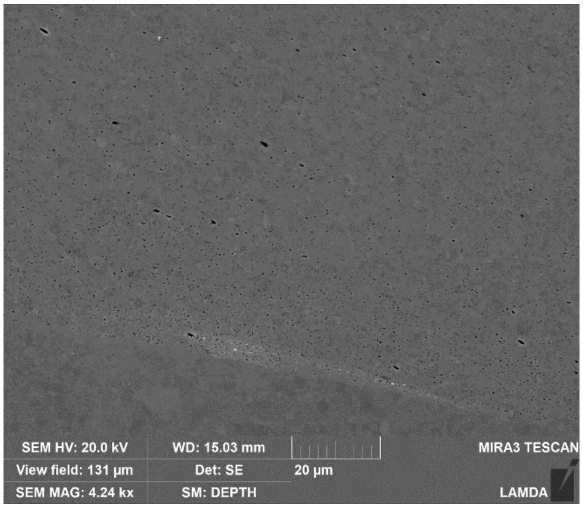
(b) SEM/EDS chemistry mapping

Figure 7 SEM/EDS element maps of one black object close to the weld top revealed possible tool shoulder wearing during FSW

SEM/EDS was also carried out on the other end of the weld, i.e. weld root. The location of the analyzed spot is marked with a yellow square in Figure 8(a), and a high magnification SEM picture at this location is shown in Figure 8(b), where black objects with sizes from sub-micrometer to a couple of micrometers are clearly seen. Two phenomena can be observed from Figure 8(b), 1, black objects are presented in friction stir weld only and they are not seen in the heat affected zone (HAZ) right outside of the weld boundary, and 2, inside the weld zone, the black objects density is high at regions close to the weld zone/HAZ boundary, and the it drops when locations move into the weld zone from the boundary.



(a) Irradiated 304C-6 friction stir weld cross section and root SEM/EDS analysis spot



(b) High magnification SEM picture at the bottom of the weld

Figure 8 Black objects at the root of the irradiated 304C-6 friction stir weld

Through SEM/EDS, different element maps at the weld root area are shown in Figure 9, where complex mix of parent steel and tool material elements are illustrated. W-enriched layer with W-enriched particles and nitrogen-rich objects, which both elements can be found in the FSW tool, are widely presented in the weld zone root region, as well as 304L SS base metal element Cr-rich spots. Furthermore, Si-clusters are also visible in the weld root but no B-enrichment appears. Chemical compositions of representative spots inside the weld zone and one spot in the HAZ are shown in Figure 10. The detected spot in the HAZ, which is located at the left bottom corner in Figure 10, showed typical 304L SS chemical composition. The rest detected spots are located in the weld zone, and significant amount of W, N and Re were detected, see Figure 10. All W, N and Re elements are not 304L SS original elements, and they can be found in the FSW tool as materials or material binders. This indicates tool pin wearing during the FSW process.

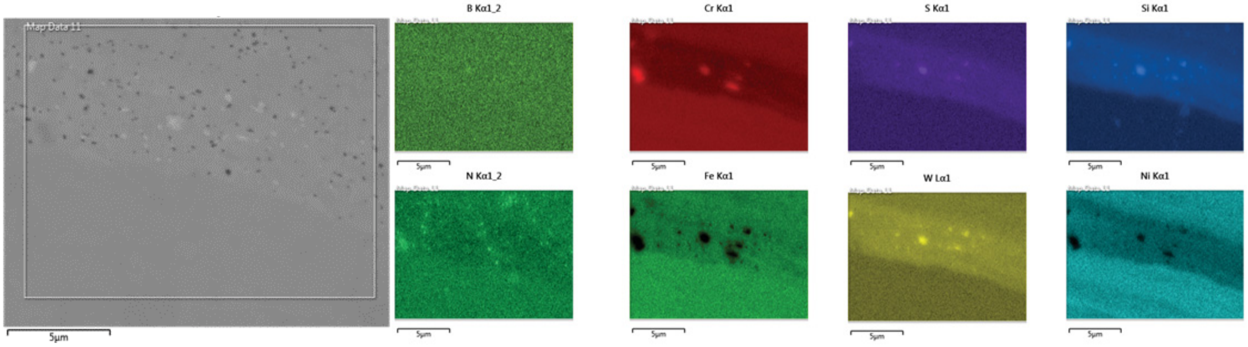
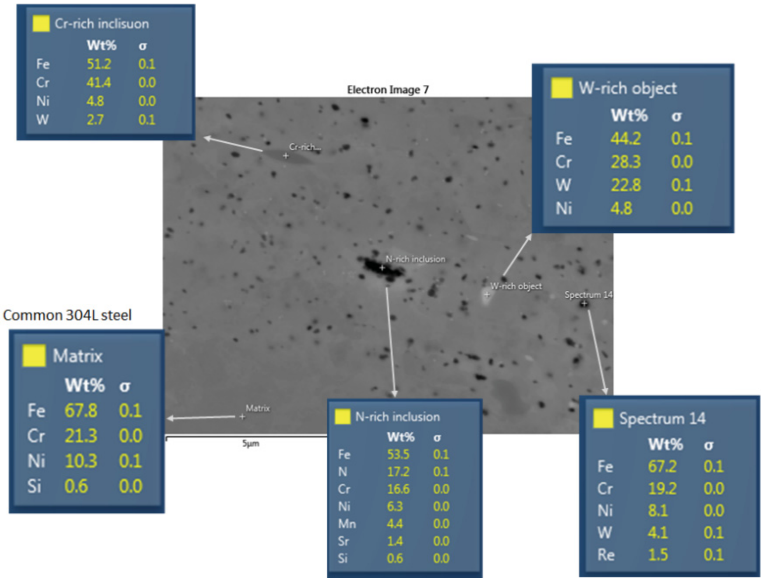


Figure 9 Irradiated 304C-6 friction stir weld root element maps



Cr-rich inclisuon

	Wt%	σ
Fe	51.2	0.1
Cr	41.4	0.0
Ni	4.8	0.0
W	2.7	0.1

W-rich object

	Wt%	σ
Fe	44.2	0.1
Cr	28.3	0.0
W	22.8	0.1
Ni	4.8	0.0

Matrix

	Wt%	σ
Fe	67.8	0.1
Cr	21.3	0.0
Ni	10.3	0.1
Si	0.6	0.0

N-rich inclusion

	Wt%	σ
Fe	53.5	0.1
N	17.2	0.1
Cr	16.6	0.0
Ni	6.3	0.0
Mn	4.4	0.0
Sr	1.4	0.0
Si	0.6	0.0

Spectrum 14

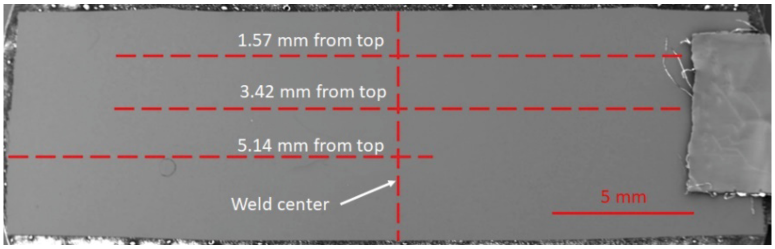
	Wt%	σ
Fe	67.2	0.1
Cr	19.2	0.0
Ni	8.1	0.0
W	4.1	0.1
Re	1.5	0.1

Figure 10 Irradiated 304C-6 friction stir weld root inclusions chemical element detected by SEM/EDS

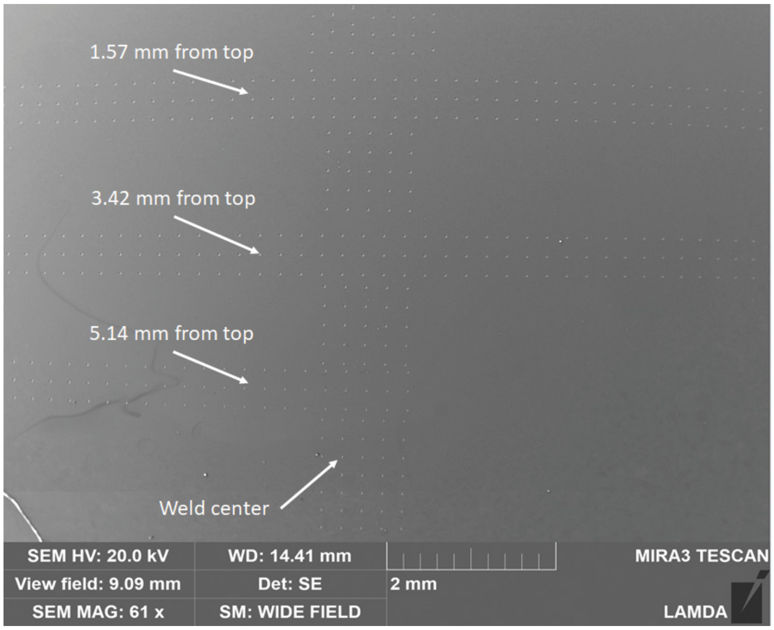
Through the SEM/EDS characterization and analysis, micrometer-level size of black/dark spots observed close to the top of the irradiated 304C-6 friction stir weld are mostly voids which have close or identical chemistry with the 304L base metal, and only 1 out of 30 spots showed unusual enrichment of nitrogen, probably due to tool shoulder wear in the FSW. At the weld root, black/dark objects showed very sophisticated microstructure by SEM/EDS: complex mix of multiple phases, grain boundaries, etc. mixed with micrometer-level W-enriched clusters, N-enriched clusters and Cr-enriched particles, as well as Re/W-enriched objects appeared in some spectra. All additional chemical elements other than the base metal's such as N, W, and Re can be found in FSW tool as material or material binders. Therefore, FSW tool pin wear happened during the FSW.

4. IRRADIATED 304L SS FRICTION STIR WELD MICROHARDNESS MEASUREMENT AND DISTRIBUTION

Material hardness is one of its mechanical properties and it is closely related to the material chemical composition and microstructure. Unlike homogenous materials, welded joint's hardness values generally are different in different metallurgical zones because of different heat received during the welding. Therefore, hardness testing along specific lines and in specific areas are always used to reveal mechanical properties variation in a weld. In this report, Vickers microhardness tests along specific directions/lines were carried out on the irradiated 304C-6 friction stir weld specimen. Three horizontal measurement levels were followed in this study, horizontal level close to weld top (1.57 mm from the top), in the middle (3.42 mm from the top), and at the bottom (5.14 mm from the top), and results are used to represent microhardness distributions at the top, middle and bottom of the weld. Hardness tests along the top and middle horizontal lines were carried out from the weld center and extend to both sides of the weld for about 10 mm, and the hardness tests along the bottom horizontal line were carried out from the weld center and only extend to one side of the weld for about 15 mm. In addition to horizontal hardness tests, vertical hardness tests were carried out from top to bottom at the weld center. Schematic of all hardness measurement directions and levels are shown in Figure 11(a). The Vickers microhardness test was carried out using a Tukon 3100 Knoop/Vickers hardness tester with 200 grams load and 10 sec dwell time, and representative indentations following various directions/levels are shown in Figure 11(b). As they are shown in Figure 11(b), three lines of microhardness tests were carried out at each horizontal level, and five lines of vertical microhardness tests were carried out at the center of the weld. For all microhardness tests, the distance between two neighbored indentation in the same line and at different lines (at the same level) are 250 µm.



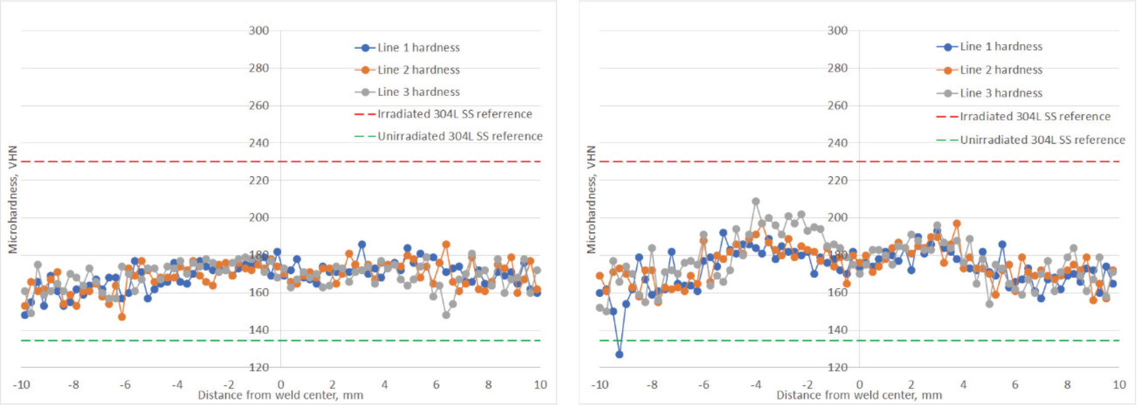
(a) Vickers microhardness measurement lines



(b) Vickers microhardness indentations

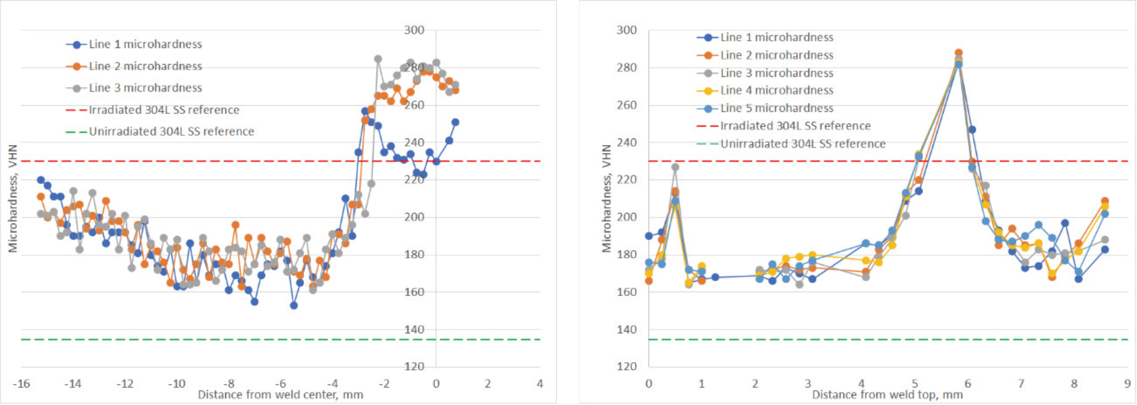
Figure 11 Vickers microhardness test on the irradiated 304C-6 friction stir weld

All Vickers microhardness measurements at different directions/levels, and the 304L SS coupon reference hardness before and after the irradiation, are shown in Figure 12. The reference hardness test before the irradiation was performed on a coupon which had the same heat and chemical composition with the welded coupon 304C-6. As it is shown in Figure 12, the 304L SS coupon hardness prior to irradiation was 130 VHN, which corresponding to a fully tempered 304L SS hardness value. The reference hardness value after the irradiation was taken on the 304C-6 weld cross section at the left bottom corner, where is far away from the FSW heat source. As it is shown in Figure 12, the irradiated 304L SS coupon reference microhardness increased to about 230 VHN because of the irradiation-induced hardening effects. From Figure 12(a) and Figure 12(b), microhardness values in the weld and the HAZ at top and middle levels of the specimen dropped 60 – 70 VHN from the irradiated 304L SS coupon reference value. This is because the friction stir welding heat input released some irradiation-induced hardening effects. It also can be observed from these two figures that the friction stir weld is marginally harder than the HAZ at the top and middle levels. However, microhardness at the bottom level of the weld showed different distribution pattern. The HAZ microhardness values close to the weld at the bottom level are similar to those at the top and middle levels, and they are increasing towards the irradiated 304L SS reference value when the measurements extend further away from the weld. However, microhardness values inside the weld zone at the bottom level are much higher than those measured weld hardness values at the top and middle levels, and they are even higher than the irradiated 304L SS reference value, especially for measurements close to the weld root, i.e. line 2 and line 3 in Figure 12(c). We have always observed higher microhardness (~250 VHN) at roots of unirradiated 304L SS friction stir welds due to lower welding heat input at the weld root, but not as high as 280 VHN. There are reasons other than the FSW effects contributed to the weld root hardness increase of the irradiated coupon, and further study is needed to explain this phenomenon. A direct comparison of microhardness values at different horizontal levels, drawn with their average values, are shown in Figure 13(a).



(a) Horizontal distributions at weld top

(b) Horizontal distributions at weld middle

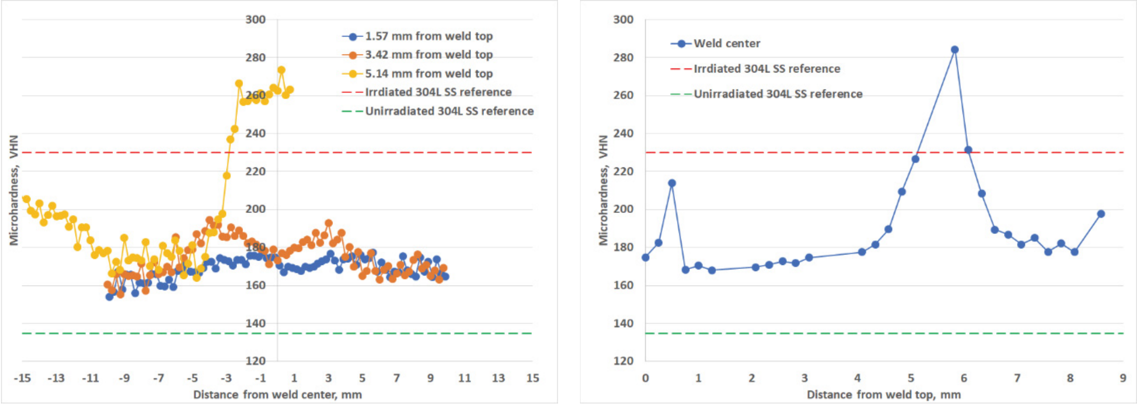


(c) Horizontal distributions at weld bottom

(d) Vertical distributions at weld center

Figure 12 Irradiated 304C-6 friction stir weld microhardness distributions

The microhardness vertical distributions in Figure 12(d) show similar trends with the horizontal measurements. The first 2/3 height of the weld exhibited relatively low microhardness values comparing with the irradiated 304L SS reference value, except a small hardness peak located at about 0.5 mm below the top surface. However, weld microhardness values increased at the bottom 1/3 of the height, and the measured peak (may not the real hardness peak of the weld) exceeded the irradiated 304L SS hardness reference value. After the measurement extended into the HAZ (The weld height is about 6 to 7 mm following the FSW tool geometry), the microhardness dropped back to the normal HAZ values. The hardness distribution with average values along the vertical direction is shown in Figure 13(b).



(a) Horizontal average hardness distribution

(b) Vertical average hardness distribution

Figure 13 Irradiated 304C-6 friction stir weld average microhardness distributions

5. SUMMARY

The 2nd irradiated materials advanced welding campaign was carried out successfully in October 2018. Advanced laser welding was carried out on an irradiated 304L SS coupon (304C-5) and an irradiated 316L SS coupon (316C-7), and both coupons were targeted for 10 appm helium contents after the irradiation. Friction stir welding was carried out on an irradiated 304L SS coupon (304D-5) which targeted for 20 appm of helium content after irradiation. Initial visual inspection showed no helium induced welding cracks or voids in the weld and surrounding areas on the surfaces.

In-depth SEM/EDS characterization revealed more details of the 1st friction stir weld made with the irradiated 304L SS coupon 304C-6. In the weld zone close to the top surface, up to one micrometer size voids were identified. In the weld root area, up to a couple of micrometer size inclusions were recognized at locations close to the weld zone/HAZ boundary, and elements of FSW tool material and tool material binder were detected in some of those inclusions. In general, these micro-size voids or inclusions are too small to cause a significant change in weld properties. Codes and standards wouldn't consider these voids and inclusions as reportable indications if they could be detected. The mechanisms for this developed micro-level voids/inclusions and the effect on weld properties are being evaluated.

Microhardness testing along horizontal directions with three height levels and along the vertical direction at the weld center were carried out on the irradiated 304C-6 friction stir weld. At the top and middle levels along the horizontal direction, weld and the HAZ hardness values are lower than the irradiated 304L SS reference hardness value, however, weld hardness values at the root are higher than the irradiated 304L SS reference hardness value. Further investigation is needed to identify and confirm reasons for the hardness changes and effects of the hardness variation.

REFERENCES

[1] Zhili Feng, Wei Tang, Roger Miller, Jian Chen, Scarlett Clark, Brian Gibson, Mark Vance, Gregory Frederick, Jonathan Tatman, Benjamin Sutton, Complete Report on Development of Weld Repair Technology. U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, ORNL/SPR-2018/1035, September 2018.

[2] Z. Feng, R.G. Miller, J. Chen, W. Tang, et al., Complete Report of Progress of Weld Development of Irradiated Materials. U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, ORNL/SPR-2018/833, April 2018.

[3] Wei Tang, Zhili Feng, Artie Peterson, Greg Frederick, Friction Stir Welding of Helium Content 304 Stainless Steel. Febtech 2016, Las Vegas, NV, November 16 – 18, 2016.

PUBLICATIONS

1. Wei Tang, Keith Leonard, Zhili Feng, Scarlett Clark, Roger Miller, Jian Chen, Brian Gibson, Mark Vance, Jonathan Tatman, Greg Frederick, Benjamin Sutton, Irradiated Material Advanced Repair Welding. Molten Salt Reactor Workshop 2018 – Creating a Self-Sustaining Environment of MSR Success, October 3 – 4, 2018, ORNL.
2. Jian Chen, Zhili Feng, Roger Miller, Wei Tang, Maxim Gussev, Keith Leonard, Jonathan Tatman, Benjamin Sutton and Greg Frederick, Auxiliary Beam Stress Improved Laser Welding for Repair of Irradiated Light Water Reactor Components. ASME 2019 Pressure Vessels & Piping Conference, July 14 – 19, San Antonio, Texas (Manuscript accepted)
3. Wei Tang, Maxim Gussev, Zhili Feng, Brian Gibson, Roger Miller, Jian Chen, Scarlett Clark, Keith Leonard, Jon Tatman, Ben Sutton, Greg Frederick, Friction Stir Welding and Preliminary Characterization of Irradiated 304 Stainless Steel. ASME 2019 Pressure Vessels & Piping Conference, July 14 – 19, San Antonio, Texas (Manuscript Accepted)

APPENDIX A
MOLTEN SALT REACTOR WORKSHOP 2018 – AGENDA

OAK RIDGE
National Laboratory

AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Molten Salt Reactor Workshop 2018—*Creating a Self-Sustaining Environment for MSR Success*
Sponsored by: GAIN, NEI, and ORNL

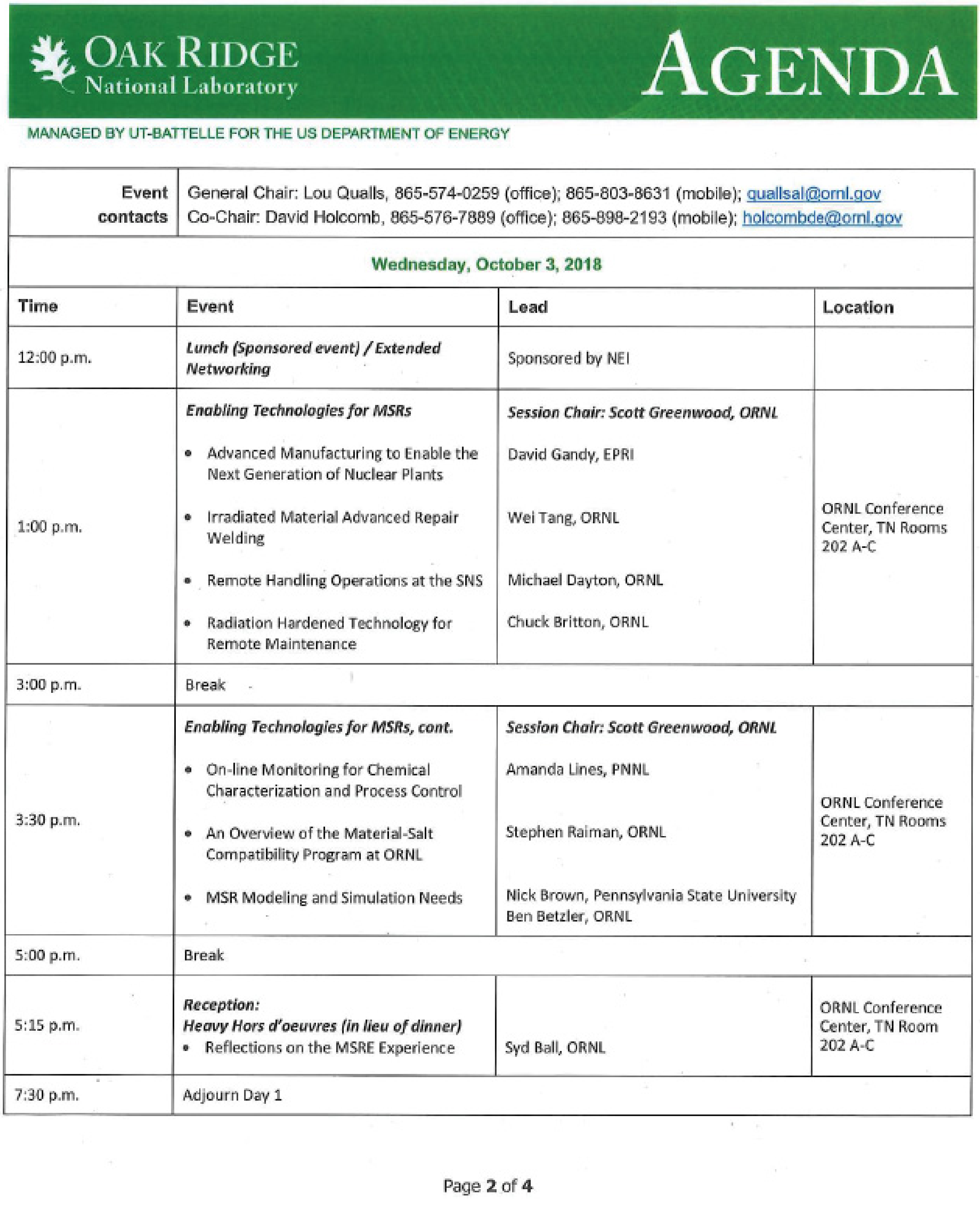
Workshop Objectives: *Understanding the opportunities, hearing the objectives, and addressing the challenges*

Agenda as of October 3, 2018

Event contacts	General Chair: Lou Qualls, 865-574-0259 (office); 865-803-8631 (mobile); quallsal@ornl.gov Co-Chair: David Holcomb, 865-576-7889 (office); 865-898-2193 (mobile); holcombde@ornl.gov

Wednesday, October 3, 2018

Time	Event	Lead	Location
7:00 a.m.	ORNL Visitor Center Check-in		ORNL Conference Center, TN Rooms 202 A-C
8:00 a.m.	***Welcome***		
	• ORNL Welcome	Alan Icenhour, ORNL	
	Keynote Talks (Working Breakfast)		
	• Opening Remarks	Alice Caponiti, DOE-NE	
	• U.S. IMSR Commercialization Before 2030	David Hill, Terrestrial Energy USA	
	• Advanced Nuclear Economics – MIT's Recently Released Future of Nuclear Energy in a Carbon-Constrained World	John Parsons, Massachusetts Institute of Technology	
9:30 a.m.	Break		
10:00 a.m.	***Perspectives on Advanced Nuclear Power***	***Session Chair: Jordan Rader, ORNL***	ORNL Conference Center, TN Rooms 202 A-C
	• A Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Licensing Non-Light-Water Reactors	William Reckley, NRC	
	• Canadian Regulatory Framework and MSR Technology Reviews	Marcel de Vos, CNSC	
	• Modeling Deployment Scenarios for Fast MSR Fleet	Eva Davidson, ORNL	
	• Advanced Reactor Fuel Cycle Issues	Everett Redmond, NEI	



OAK RIDGE National Laboratory

AGENDA

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	Wednesday, October 3, 2018		
Time	**Event**	**Lead**	**Location**
12:00 p.m.	***Lunch (Sponsored event) / Extended Networking***	Sponsored by NEI	
1:00 p.m.	***Enabling Technologies for MSRs***	***Session Chair: Scott Greenwood, ORNL***	ORNL Conference Center, TN Rooms 202 A-C
	• Advanced Manufacturing to Enable the Next Generation of Nuclear Plants	David Gandy, EPRI	
	• Irradiated Material Advanced Repair Welding	Wei Tang, ORNL	
	• Remote Handling Operations at the SNS	Michael Dayton, ORNL	
	• Radiation Hardened Technology for Remote Maintenance	Chuck Britton, ORNL	
3:00 p.m.	Break		
3:30 p.m.	***Enabling Technologies for MSRs, cont.***	***Session Chair: Scott Greenwood, ORNL***	ORNL Conference Center, TN Rooms 202 A-C
	• On-line Monitoring for Chemical Characterization and Process Control	Amanda Lines, PNNL	
	• An Overview of the Material-Salt Compatibility Program at ORNL	Stephen Raiman, ORNL	
	• MSR Modeling and Simulation Needs	Nick Brown, Pennsylvania State University Ben Betzler, ORNL	
5:00 p.m.	Break		
5:15 p.m.	***Reception:*** ***Heavy Hors d'oeuvres (in lieu of dinner)*** • Reflections on the MSRE Experience	Syd Ball, ORNL	ORNL Conference Center, TN Room 202 A-C
7:30 p.m.	Adjourn Day 1		

Page **2** of **4**

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Thursday, October 4, 2018

Time	**Event**	**Lead**	**Location**
8:00 a.m.	• Day 2 Welcome and Overview *(Working Breakfast)*	Lou Qualls, ORNL	ORNL Conference Center, TN Rooms 202 A-C
	• Advanced Reactor Development: Molten Salt Reactors	Brian Robinson, DOE-NE	
8:15 a.m.	***International Activities***	***Session Chair: David Holcomb, ORNL***	
	• MSR Research in China	Hongjie Xu, Shanghai Institute of Applied Physics	
	• MSR Research in the Czech Republic	Jan Uhlíř, Research Centre Rez	
	• MSR Irradiation Program at NRG Petten	Ralph Hania, NRG-EU	
	• Development of Molten Salt Capabilities at Canadian Nuclear Laboratories	Krishna Podila, CNL Dan Cluff, CNL	
10:15 a.m.	Break		
10:45 a.m.	***MSR Research at Universities***	***Session Chair: Ben Betzler, ORNL***	ORNL Conference Center, TN Rooms 202 A-C
	• MSRE Criticality Benchmark: Progress and Challenges	Massimiliano Fratoni, University of California, Berkeley	
	• Qualification of Alloys for Structural Applications in Fluoride High Temperature Reactors	Preet Singh, Georgia Institute of Technology	
	• Development and Application of a Molten Salt Chemistry Database in Modeling MSR Performance	Ted Besmann, University of South Carolina	
12:15 p.m.	Break		

OAK RIDGE National Laboratory

AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Event contacts	General Chair: Lou Qualls, 865-574-0259 (office); 865-803-8631 (mobile); qualIsal@ornl.gov Co-Chair: David Holcomb, 865-576-7889 (office); 865-898-2193 (mobile); holcombde@ornl.gov

Thursday, October 4, 2018

Time	Event	Lead	Location
12:30 p.m.	***Working Lunch:*** • Critical Infrastructure Resilience and rNPPs – A Case for MSRs? • Getting to Market: The Good, the Bad, and the Ugly	***Moderator: Gary Mays, ORNL (retired)*** Sherrell Greene, Advanced Technology Insights Dan Ingersoll, NuScale Power	ORNL Conference Center, TN Rooms 202 A-C
1:30 p.m.	***Developer Forum***	***Moderator: Nick Smith, Southern Company***	
3:15 p.m.	Break		
3:45 p.m.	***MSR Community Panel Discussion*** Opportunities and Issues Toward Success	***Moderator: Lou Qualls, ORNL*** MSR community stakeholders	ORNL Conference Center, TN Rooms 202 A-C
4:45 p.m.	***Closing Remarks***	Dan Vega, DOE-NE Alan Icenhour, ORNL	
5:00 p.m.	Adjourn the Workshop	Lou Qualls, ORNL	

APPENDIX B
MOLTEN SALT REACTOR WORKSHOP 2018 – ATTENDEE

FINAL 10/01/2018

2018 MOLTEN SALT REACTOR WORKSHOP
Creating a Self-sustaining Environment for MSR Success
October 3-4, 2018 – Oak Ridge National Laboratory, Oak Ridge, TN, USA

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