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Experimental Plan for Primary Water Stress Corrosion Crack Initiation Testing

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September 29, 2015

ADAMS Accession No.:
ML

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Abstract

U.S. Nuclear Regulatory Commission and the EPRI Materials Reliability Program are undertaking a multiyear cooperative research effort to study crack initiation in primary water stress corrosion cracking (PWSCC) to generate data that can be used to validate and calibrate time-to-initiation models, and to calculate factors of improvement. The research is being conducted under a memorandum of understanding between EPRI and the NRC.

Two primary goals for this research program are 1) to quantitatively determine SCC initiation times for Alloy 182 welds as a function of microstructure, plastic deformation, and applied stress to characterize the uncertainty and verify the accuracy of SCC initiation models, and 2) to determine factor of improvement (FOI) for initiation times for Alloy 690 and its weld materials compared with Alloy 600 and its weld materials.

This report summarizes key aspects of the experimental plan, providing information about the testing approach; component purchases and test system assembly; materials and material conditions to be evaluated; proposed test matrix and expected schedule; and post-test specimen characterizations and analyses to interpret results.

1.0 Introduction

This letter report summarizes key aspects of the experimental plan for the stress corrosion crack (SCC) initiation project including: (a) testing approach; (b) component purchases and test system assembly; (c) materials and material conditions to be evaluated; (d) proposed test matrix and expected schedule and (e) post-test specimen characterizations and analyses to interpret results.

Two primary goals exist for the program. The first is to quantitatively determine SCC initiation times for alloy 182 welds as a function of microstructure, plastic deformation and applied stress to characterize the uncertainty and verify the accuracy of the SCC initiation models utilized in Version 2.0 of the xLPR Code. Version 2.0 of the xLPR Code utilizes three models to provide inputs for SCC crack initiation times that contain parameters to account for applied stress, plastic strain and temperature. Thus, an important consideration of this project is to develop SCC initiation data using testing conditions that are within the bounds of the parameters used by the various models. The second is to determine factor of improvement (FOI) initiation times for alloy 690 and its welds compared with alloy 600/182. Within the estimated 5 year lifetime of the program, it is desired to determine whether a >20x FOI is supported for alloy 690/152/52. To accomplish the second objective within this timeframe will require an accelerated test environment. Besides running at 360°C in simulated PWR primary water, the plan is for the test specimens to be in a cold worked condition. This is known to greatly accelerate SCC initiation times in alloy 600/182. A review of the available literature indicates that exposed surfaces in reactors may have a wide range of damage that spans from none to damage levels representative of ~30% cold work. A moderate level of cold work is proposed for this project for reasons that will be described below. The success of this program in determining initiation times as a function of stress and cold work level requires the ability to accurately know and control applied stress and plastic deformation in the test specimen. As is described in the following pages, careful consideration went into the selection of the type of test specimen, the level of cold work and the testing method. The proposed materials test matrix and estimated schedule for the program are also discussed.

2.0 Review of SCC Initiation in Alloy 600/182 PWR Service Components

The majority of the prior work on SCC initiation testing can be attributed to the French, namely AREVA, EdF, and CEA. Their observations point to primary water SCC initiation taking place on surfaces that have been cold worked in compression and subsequently strained in tension to produce a strain reversal. Examples that have been cited for alloy 600 components include 1) alloy 600 nozzles that were gun drilled with a coarse machining process and then strained during assembly by fit-up and welding stresses [1], 2) alloy 600 steam generator tubes that had a bead blasted interior surface finish prior to being bent and assembled [1], and 3) alloy 600 steam generator divider plates with ground finishes that were stressed in tension during the initial hydraulic pressure test [2].

For alloy 182/82, this two-step process of generating and then straining a cold work layer is not as clear-cut. It is well known that thick-section welds are ground to produce a desired profile. This coarse grinding process produces a cold worked layer up to 200 µm deep [3] or even 300 µm [2]. It has been implied that one means for subsequent application of strain is through the application of repair welds. Some of the first

observed cracks in thick section welds were in repair regions. The implication is that high residual stress and strains produced by the repair process [3] extended into the original weld. However, the exact location of initiation points relative to the repair welds was not given. Cracking has also been observed in non-repaired alloy 182 welds [4]. It has been suggested that sufficient heating during heavy grinding is produced to pull the cold worked layer into tension upon cooling [3]. Somewhat surprisingly, impact of loose parts with reactor internals has caused cracking in both alloy 600 [5] and alloy 182 [3]. The examples referenced here came from the same reactor. The impact of loose parts with the alloy 600 produced cold work to a maximum depth of 700 μm, while the maximum cold work damage depth was 310 μm for the alloy 182 [5].

Component analysis and laboratory studies indicate that this two-step combination of surface cold work and subsequent deformation can lead to secondary surfaces stresses that can reach 1000 MPa within this cold worked layer [1, 6]. Such levels of stress are achievable in alloy 600 and alloy 182 only by multi-axial loading where a substantial hydrostatic component is present, but presumably SCC initiation is sensitive to both deviatoric and hydrostatic stresses. Therefore, the scenario for SCC initiation in alloy 600/182 service components is one where accelerated crack formation takes place in this highly cold worked and stressed surface layer and eventually propagates into the bulk non-deformed component. SCC initiation in these materials has been described as the length of time needed to produce cracks that undergo rapid propagation [6, 7]. This is thought to occur by stress-assisted, intergranular attack (IGA) that transitions to open cracks that eventually become long enough to promote a local stress intensity sufficient to drive SCC growth at rates typical of well-developed cracks. The French believe that the critical stress intensity is ~9 MPa√m for SCC growth in mill-annealed alloy 600 [8], while a small number of recent tests at PNNL revealed that rapid propagation takes place in alloy 600 at a stress intensity closer to ~15 MPa√m [7]. It has been suggested that if the cold work layer is sufficiently shallow, i.e., below the crack depth needed to establish the critical stress intensity for long crack behavior, then cracks can form but not readily transition to established growing cracks in the non-cold worked bulk substrate.

3.0 Review of Existing Test Methods

A variety of different test methods and specimens have been used to measure SCC initiation times. These include, but are not limited to U-bend, bent beam, C-rings, blunt notch compact tension and tensile specimens.

3.1 U-Bend Test

The U-bend specimen **Figure 3-1** is the most common type, probably because it is self-contained and does not require any external loading. It is a simple design that allows specimens to be extracted from relatively small amounts of material, and it is amenable to application of different surface treatments. The specimen starts as a flat strip, or for the case of a reverse U-bend, as a half section of tubing produced by a lengthwise cut. The material is bent into a U-shape to build up stress and plastic strain near the apex of the bend. A half section of tubing is bent such that the interior surface of the tube becomes the outside of the U-bend specimen, thus producing a more complex shape than a standard U-bend. These are called reverse U-bend specimens. For the case of a flat strip of tubing, the amount of plastic strain (e_{pl}) developed at the outside of the apex can be estimated from:

$$e_{pl} = T/2R \quad (\text{for } T<<R)$$

where T is the specimen thickness, and R is the bend radius of curvature [9]. To illustrate the level of plastic strain developed, a typical specimen with a 3 mm thickness

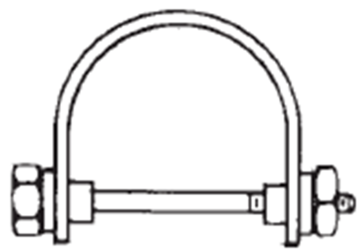


Figure 3-1 U-bend specimen. [9]

and 15 mm bend radius will have ~10% plastic strain at the apex of the exterior of the specimen. From a practical perspective, the smallest amount of strain that can be produced is ~5% plastic strain. This would require a rather large specimen with 30 mm bend radius. As a means to accelerate SCC initiation, a strain reversal can be created by bending the specimen slightly in one direction (typically ~2%) and then bending it in the opposite direction to produce the final U-bend shape. AREVA has concluded that this strain reversal method produces the most severe condition and results in shorter SCC initiation times than monotonic straining to higher total levels of plastic strain. For laboratory-polished (1200 grit) alloy 182 specimens given a -2% strain followed by a +6% strain, a longitudinal (along the length of the specimen) stress of 800 MPa was developed [10]. Such a stress is near the ultimate tensile strength (UTS) that can be achieved on alloy 182, and thus represents an extensive amount of strain at the surface of the U-bend specimen. The magnitude of the stresses and strains diminish into the depth of the specimen, and somewhere near the center of the thickness, the plastic strain is zero. However, it is important to recognize that the stresses and strains are not highly localized to the surface. To first order, they fall off in a linear dependence with depth into the center of the specimen thickness. By virtue of the process of producing the specimen, U-bend specimens are initially loaded to the yield strength of the strained material. During high temperature exposure, stresses can fall off due to creep relaxation. This is often mitigated by the use of a spring to maintain a constant stress on the specimen.

A major disadvantage of the U-bend specimen for this program is the inability to effectively decouple the applied stress and strain. This is important because one of the objectives of the program is to assess the effect of stress on initiation time for as-welded alloy 182. Measuring response for as-welded material is not possible with U-bend specimens where some strain must be generated. While it is conceptually possible to reduce the stress by reducing the load on a U-bend specimen, there is no simple relationship between the applied load and the stress. Other issues are that the stresses and strains cannot be determined in a straightforward manner. This is important to this program because of the goal to quantitatively establish test parameters and compare results to other published data.

3.2 Bent Beam and C-Ring Specimens

A bent-beam specimen **Figure 3-2**, typically in 4-point loading, has also been utilized for SCC initiation testing [10]. Like the U-bend specimen, it is a simple design that can be extracted from a relatively small amount of material and has an accessible surface for application of different surface finishes. Because the specimen does not have to be plastically deformed as part of the fabrication or loading process, there is better control over the level of plastic strain and stress applied to the specimen. While the detailed stress distribution is not easily calculated (compared to a tensile specimen), it can be more accurately estimated than for a U-bend specimen. Stress and strain can also be decoupled more easily than for a U-bend specimen. As with U-bend specimens, strains and stresses decrease as a function of depth into the specimen with a neutral stress point somewhere near the mid-thickness.

The experimental setup for an active, externally applied loading system is not overly complicated and methods for loading multiple specimens in series have been considered. Bent-beam geometries are also amenable to in-situ SCC initiation detection by direct current potential drop (DCPD) with a thinner specimen producing a stronger initiation signal.

C-ring specimens **Figure 3-3** are similar in concept to bent-beam specimens in that they are loaded to produce only slight amounts of deformation relative to a test such as a U-bend. Statically loaded C-ring specimens are simple to construct and test, but there is less control over stresses and strains than for an actively loaded bent-beam specimen. In general, an actively loaded C-ring design possesses the same pros and cons as a bent-beam specimen.

The bent-beam specimen was found to be a potential option for this program, particularly when considering the influence of complex surface deformation layers that often exist in service components. However, tensile specimens were determined to be more desirable for several reasons that will be described in a subsequent section.

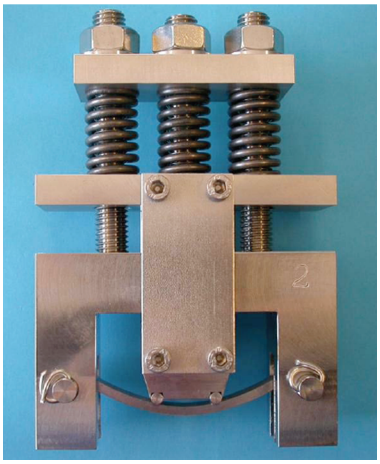


Figure 3-2 4-point bend devised by AREVA [10].

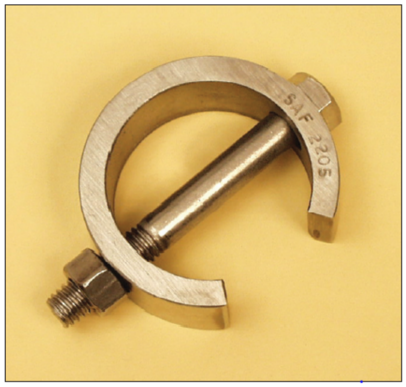


Figure 3-3 C-ring specimen from ASTM G38-01 (2013) [11].

3.3 Blunt-Notch CT Specimens

A blunt-notch CT specimen has a machined notch with a relatively large radius. This geometry produces a stress riser with a local stress that is given approximately by:

$$\sigma_{notch} = 2K / \sqrt{\pi\rho}$$

where K is the stress intensity assuming a sharp crack and ρ is the notch radius. As part of PNNL's research under the DOE-NE Light Water Reactor Sustainability (LWRS) program, stresses and strains in the region of the notch were calculated by FEM for materials having various yield strength levels. Not unexpectedly, stresses and strains are estimated to fall off rapidly as a function of depth into the specimen. Because much of the specimen never plastically deforms, stresses and strains are related in a complex way making it a challenge to decouple stress effects from strain effects. By virtue of the specimen design, SCC initiation is confined to a relatively narrow band of material in the notch. Also, inaccessibility to the surface of the notch regions makes it challenging to apply surface treatments. While fixturing for loading multiple blunt CT specimens in series is very simple to achieve, the complex stress state, the relatively small amount of surface that is under stress, and the complex relationship between stress and strain make this specimen undesirable for the needs of this test program.

3.4 Tensile Specimens

Tensile specimens have been used extensively for constant-load SCC initiation testing [6, 7, 12-17]. A wide range of specimen sizes and shapes are possible. For SCC initiation work that is ongoing with the LWRS program, PNNL adopted a round tensile geometry as shown in **Figure 3-4**. Tensile specimens provide the following desirable features: a simple uniaxial stress state that is easily determined, a gauge section that is physically accessible allowing control over the surface microstructure, various types of defects can be easily generated, and there are several ways to produce specimens with controllable amounts of uniform plastic strain. Cold worked surface layers can also be produced by grinding or peening and then put into tension through small, very controllable amounts of plastic strain. In addition, prior work at KAPL [12] and PNNL [7, 14, 15] has shown that DCPD can be effectively used to detect crack initiation. Stress, strain, and surface condition are believed to be key controlling factors for SCC initiation,

so the superior control over these variables combined with in-situ detection of crack initiation is considered to be highly advantageous.

Figure 3-4 PNNL 1.2" tall SCC tensile initiation specimen.

Several factors contributed to the specific design of the tensile specimens developed for the DOE-NE LWRS program; however the most important consideration was maximizing the ability of DCPD to detect crack initiation. This was accomplished by reducing gauge length and gauge diameter. A smaller gauge length reduces the creep signal while a smaller gauge diameter maximizes the DCPD sensitivity to cracking. In addition to maximizing DCPD-based initiation detection, a practical issue was the desire to have an initiation specimen size that fits within the dimensions of a 0.5T CT specimen such that any material prepared for SCC growth studies could also be used for SCC initiation studies. The final tensile design was refined to the point that a crack initiation specimen could be cut from an SCC-tested 0.5T CT specimen as long the crack length to width ratio (a/W) in the CT specimen did not exceed 0.7. This crack length is below the range of typical crack lengths in SCC studies conducted by PNNL, allowing routine extraction of crack initiation specimens as desired. Other factors that contributed to the design were the need to electrically isolate the specimen and eliminate any significant stress risers. In addition to these other considerations, the need to ensure that a sufficient number of exposed grain boundaries were at the applied stress remained a principal design criterion. A detailed design drawing is presented in **Figure 3-5**. Machining tolerances are kept to within ±0.001". Also, the reference DCPD measurement to correct for material resistivity drift is made in the larger diameter regions on either side of the gauge section. A gentle fillet radius is used to minimize stress risers. Gauge length is a nominal 4 mm, but for weld metal specimens, this may be increased to as much as 8 mm to increase the number of grain boundaries on the gauge section. The gauge diameter is selected based on the yield strength of the material, as measured using tensile tests in air conducted on the target material at the target SCC initiation test temperature. The range of gauge diameters possible with this specimen is ~2.8 to 4.5 mm. The exact diameter selected will depend on the strength of the material and, especially for weld metals, larger specimen diameters are desired to expose a larger number of grain boundaries. Prior to SCC testing, all specimens are given a surface treatment, e.g., a fine polish or a heavily ground finish. Procedures to produce various finishes have been refined, and the reduction in gauge diameter is consistently kept to

within 25-50 μm. This reduction is accounted for in the as-machined gauge diameter selected for specimen fabrication.

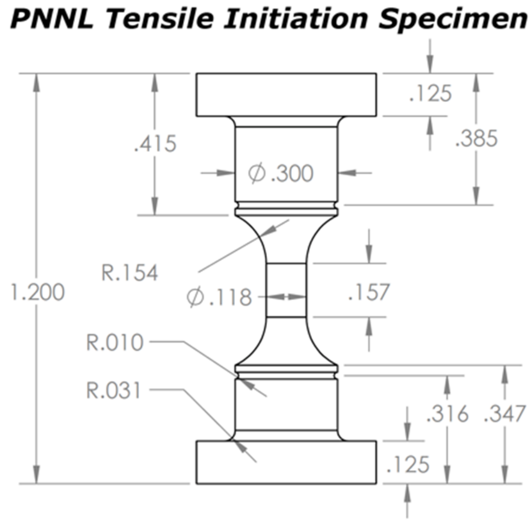


Figure 3-5 SAE dimensions of the PNNL 1.2" tall SCC tensile initiation specimen.

Surface damage can be applied to the gauge section using several different methods, with PNNL favoring grinding tools for its prior research. A controlled load is applied while systematically moving the tool across the gauge section. Grinding tools that have been used include wood-backed sandpaper of various grits and a rotary tool with grinding disks of different roughness [13, 14]. As part of DOE-funded research at PNNL, complimentary surface oxidation studies have been performed on small polished or ground coupons. The amount of surface damage (beyond a depth of ~5 nm) remaining was evaluated in cross-section using low kV, scanning electron microscopy (SEM) backscatter electron (BSE) imaging and determined to be negligible for the polished specimens. Near-surface damage in the ground specimens was evaluated by SEM, electron backscatter diffraction (EBSD), and microhardness techniques. These surface exposure specimens have been tested both concurrently with the initiation samples as well as in dedicated exposure autoclaves to better understand the inherent corrosion behavior of various materials and the effect of surface damage [7, 13, 14, 18, 19].

3.5 Discussion of Test Methods

It is useful to recall that a defining aspect of initiation events in service components often involves tensile loading of a highly cold worked surface layer. A key aspect of the increase in cracking susceptibility is suggested by the French to be due to a strain reversal process that produces very high stresses along with high levels of strain. Test specimens such as U-bends, bent beams, and even tensile specimens enable a highly stressed cold work layer on a mildly cold worked bulk substrate to be evaluated in a way that is relevant to service components. However, a critical consideration for SCC initiation testing is the associated relationship between the cold work layer thickness and the crack depth needed to produce a stress intensity level sufficient for rapid propagation. While the effect of cold work depth has been considered in phenomenological analysis of SCC initiation times [6], the effect of damage depth has not been generally addressed in the literature as a consideration for SCC test specimen design or test methodology even though it has a profound effect on the time to initiation.

Instead, experimental studies tend to only conclude that a tensile-strained, cold worked surface reduces SCC initiation time compared to polished (undamaged) surfaces [5, 20].

Uncertainties exist concerning the representative cold work depth and degree of damage in light-water reactor (LWR) service components. The depth of the cold work layer is variable as well as the applied stress and the component thickness that determines the stress intensity factor after the formation of a crack. The wide range of cold work layer depths that have been observed in alloy 600/182 service components suggests that a conservative approach would be to assume a worst case depth that could be as high as ~0.7 mm, based on direct observations [20]. Based on the available literature, this depth exceeds that needed to produce SCC initiation in susceptible alloy 600/182 service components and establish a condition where SCC growth controls the cracking behavior. This variability in the service cold work layer depth makes using this approach less desirable when similar stresses and strains can be achieved much more easily and in a more quantitative manner through homogeneous deformation of the bulk material.

Issues for evaluating surface cold work such as layer thickness and cold work level should also be considered with respect to alloy 690/152/52 service components. While modern day reactor assembly techniques strive to minimize the presence of surface damage, the production of some cold work may be unavoidable as illustrated by the loose part impact event that produced the deepest measured surface damage in a cracked in PWR component. As with alloy 600/182, a conservative approach would be to assume that a surface damage layer exists in alloy 690/152/52 that is sufficiently thick for SCC initiation to be controlled entirely by the response of cold worked material, and that if an SCC initiation benefit is to exist, it must be for comparing the susceptibility of similarly cold worked materials. Based on this perspective, PNNL believes that the most effective means to evaluate the material response is using a homogeneously cold worked specimen rather than a specimen with a complex cold worked surface layer. While it is clearly important to understand the effect of the cold work damage layer on SCC initiation for components in service, understanding the material response to cold work is a necessary first step for the joint NRC-EPRI SCC initiation program.

The only specimen type that allows assessing the effect of cold work independent of stress and strain gradients is a tensile specimen under constant load. This test method best enables the quantitative determination of initiation times as a function of applied stress for as-welded alloy 182 materials and measurement of FOIs for alloy 690/152/52 compared with alloy 600/182 in homogeneously deformed materials. The current plan is to cut specimens from cold forged material and then load them to their yield stress. Forging provides good control over the level of applied strain, and since loading to the yield stress produces small amounts of deformation, compressive forging followed by small amounts of tensile yielding should be replicative of the strain reversal process that the French indicate is important for SCC initiation in service components.

An important aspect to consider for this program is that it strives to measure SCC initiation times and not through thickness response. In service components where cold work may exist only in a surface layer, alloy 690 and its weld metals may exhibit crack initiation followed by very low growth as the crack extends into the softer base material. SCC initiation times measured in homogeneously cold worked tensile specimens are only meant to be an indicator of SCC initiation response and not an indicator of through thickness crack growth susceptibility.

Another potential concern is that cold worked specimens loaded to their yield stress may undergo extensive creep deformation and possibly promote mechanical cracking and/or SCC initiation. This is clearly possible if specimens are loaded to extremely high stresses or are tested under an increasing load that results in dynamic straining. Heavily cold worked alloy 600 loaded to its yield strength is known to undergo creep in air such as occurred for alloy 600 that failed after ~30,000 hours (~3 years) when loaded to 650 MPa [21]. In addition, recent testing at PNNL [7] and the University of Michigan [22] have shown that very slow constant extension rate testing of highly cold worked alloy 690 in 360°C PWR primary water can induce IG creep cracking on both the specimen surface and interior. However, long-term constant load SCC initiation tests on alloy 690 have yet to show creep failure. An approximately 1 year-long constant load SCC initiation test on 26% cold rolled alloy 690 loaded to its yield stress at 360°C showed no evidence of creep crack formation on either the specimen surface or within the interior [7]. The best evidence for the resistance of cold worked alloy 690 to constant load creep cracking is the long term testing of homogeneously deformed alloy 690 tensile specimens by MHI as reported in MRP-237 Rev. 2 [23]. Materials evaluated through long term constant load testing include alloy 690, alloy 152, and alloy 52 loaded to 500-550 MPa. These stress levels were achieved by tensile straining the specimens at the test temperature of 360°C. While this elevated temperature straining does not strictly qualify as cold working, the deformation structures produced at 360°C will be largely similar to that for room temperature tensile straining because the tensile and annealing properties for alloy 690 do not substantially change up to 450°C [24]. Recent testing at PNNL has revealed that rather than any softening occurring, alloy 690 undergoes hardening when exposed at 360°C due to unidentified microstructural changes [7]. MHI reported at the December 2014 Alloy 690 Expert Panel Meeting that no failures have occurred after more than 100,000 hours (~10 years) of exposure in any of the highly cold worked, high Cr materials despite their high stresses and high SCC growth susceptibility. These observations support the conclusion that for an appropriate selection of cold work level and applied stress, cracking due to creep deformation is not expected for the life of this project.

The selection of the appropriate level of cold work is an important aspect of this recommended test plan. It has been reported that highly damaged, cold work layers under very high stresses are relevant to plant SCC initiation conditions, however, it is important to keep in mind that these microstructures and stresses fade to bulk values as a function of depth into a plant component. Measurements of hardness or stress for field components are not readily available but examples of laboratory measurements [25, 26] and finite element modeling based predictions [21] show that the damage does decrease with depth, typically with an inverse dependence. To best represent this varying damage level, an intermediate strength has been chosen. Peak hardness levels of greater than 300 kg/mm^2 and peak stresses approaching 1000 MPa are representative of >30% cold work. This level of cold work would be associated with aggressive fabrication techniques (i.e., heavy grinding). Thus 15% cold work appears to be a reasonable intermediate level of damage. The choice of 15% cold work is also based on the expected maximum strain levels in heat affected zones and weld repairs [27]. From a practical perspective for assessing FOIs for alloy 690/152/52 materials, 15% cold work is expected to shorten the initiation time of susceptible alloy 600/182 to ~2000 hours or less, thus making it possible to determine a useful FOI within the time-frame of this project. Alloy 690/152/52 materials cold worked to 15% are expected to have a yield stress of ~450-550 MPa. Creep cracking should not be a concern for tests run at this stress.

3.6 Summary of SCC Initiation Testing Aspects and Specimen Selection

A principal consideration for the SCC testing program is assessing relevant microstructures and loading conditions. The French have shown that a cold worked surface layer with a compressive biaxial stress will become highly susceptible to SCC initiation in alloy 600/182 when tensile loaded to a level that produces strain reversal. Therefore, very high stresses are developed in a susceptible microstructure. This finding illustrates the importance of using cold worked materials loaded to their yield strength for assessing SCC initiation response. From the perspective that a range of surface damage conditions may exist on surfaces of plant components, homogeneous cold work can be viewed as a test accelerant, and indeed, the available data show that cold worked alloy 600/182 materials do show reduced SCC initiation times. Therefore, evaluation of cold worked materials is relevant to plant SCC initiation events and essential to accelerate SCC initiation response for FOI assessment.

The proposed plan is to cold forge all base metals and welds to a 15% reduction. Specimens will be cut from these forged materials so that the axis of the specimen is parallel with the forging direction. This will allow cracking to take place along the most susceptible plane of the cold forged material. All welds will be forged in the transverse direction with specimens aligned as shown in **Figure 3-6**, again resulting in the crack initiation plane being along the most susceptible orientation relative to the cold forging and the weld microstructure. The current plan for this project is to use a single surface finish enabling a large number of material heats and replicate specimens to be tested. A highly polished, 1 μm finish that allows much better identification of surface cracks has been selected.

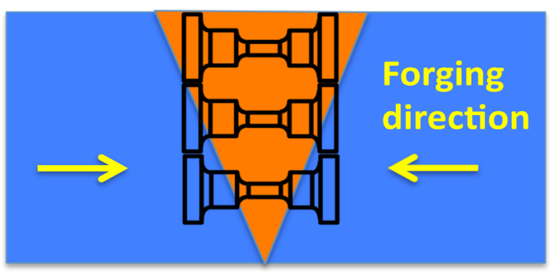


Figure 3-6 Orientation of tensile specimens cut from weldments.

4.0 Details on Test Systems

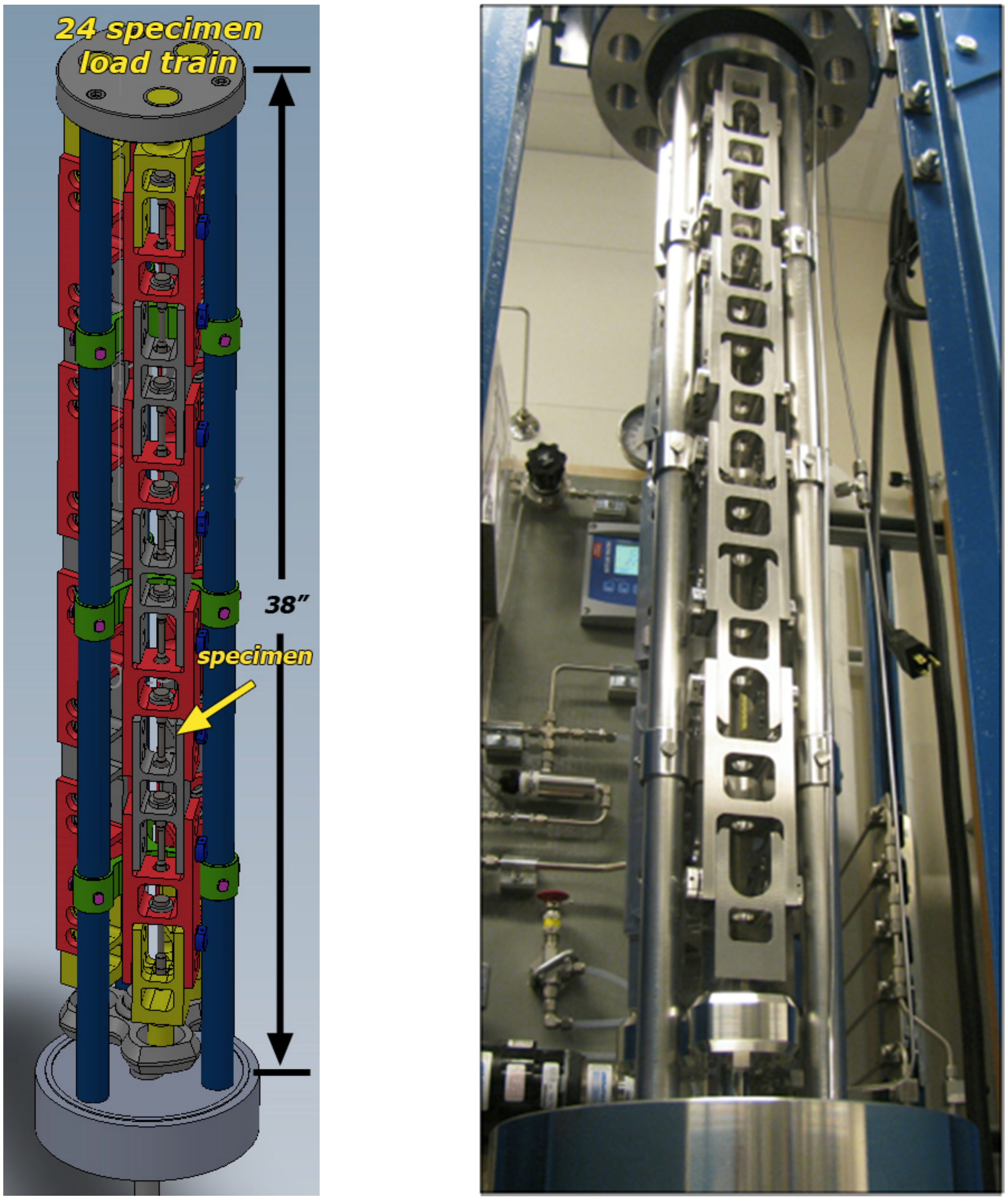
4.1 SCC Initiation Test System Design and Capability

Two 36-specimen test systems will be built to allow in-situ monitoring of crack initiation in an environment that provides a high degree of control over load (stress), applied strain, water temperature and water chemistry including B/Li content, dissolved gas content, and impurity content. These test systems are based on the system at PNNL constructed for the ongoing DOE-NE LWRS project [7, 13, 14] to investigate SCC initiation mechanisms in LWR pressure boundary component materials. The key components of these test systems are: (1) a servo-electric load control system capable of maintaining a stable constant load for very long periods of time and capable of providing a wide range of cyclic loading conditions, (2) a recirculating water system that is used to control water chemistry, (3) an autoclave for specimen exposure at high temperatures and pressures, (4) a DCPD system for in-situ monitoring of crack initiation, and (5) a continuous data

acquisition system. Careful consideration went into design and equipment selection to optimize control of all system variables. Some of the most important considerations were to: (1) use wetted components that release no contamination into the water, (2) have a sufficiently high water flow rate through the autoclave to maintain the target chemistry, (3) maintain uniform temperature and pressure at the specimens, (4) obtain highly accurate measurements of the test environment (temperature, conductivity, pH, load, dissolved gas content), and (5) create a sensitive DCPD-based crack initiation detection system. Each of the subsystems has been extensively discussed in detail within a recent DOE-NE report [14]. Tolerances on test parameters under normal operating conditions are as follows: Specimen load is maintained within ±1.5 kg (±3 lbs.). Water temperature along the length of the interior of the autoclave is maintained within ±0.5°C. Dissolved hydrogen is maintained at ±0.5 cc/kg H_2. Water pressure is maintained at ±1.5%. Boric acid and lithium hydroxide content are maintained at ±2%. Water purity under NWC conditions in our large initiation test system has not been verified, but for our smaller SCC test systems that are identical to the big systems with the exception of the large autoclave and load train, autoclave outlet water conductivity hovers between 0.07 and 0.08 µS/cm. A slightly higher value of ~0.1 µS/cm is to be expected for the large systems due to the larger wetted stainless steel surface area. The minimum detectable crack length for 10-20% CW alloy 600 has been found to be ~100 µm.

4.2 Test System Load Train

Load is applied using a servo-electric motor that can hold a steady load for indefinite periods of time while also providing the ability to perform cyclic loading in either displacement or load control up to about 3 Hz. Load from the servo-electric motor is transmitted into the autoclave with a pull rod inserted through the base of the autoclave. Specimens are supported from above by a top plate and multi-bar linkage that transmits load from the top plate to the base of the autoclave. The 36-specimen load train has three strings of 12 specimens. A sketch and a photo of an early 24 specimen design are shown in **Figure 4-1**, respectively. These system designs rely on series loading to allow multiple specimens to be tested with a single servomotor. All three strings are attached to the lower plate using ball joints. The lower plate is allowed to pivot around the central load rod on a ball joint. This equilateral triangle arrangement forces all three strings to carry 1/3 of the combined load generated by the servomotor and pull rod tare. Each string is designed so that if an individual specimen cracks to the point of failure, the string will pick up the load allowing the test to continue. When a specimen fails, temporary partial unloading of the remaining specimens will occur. An approximate 20% reduction in stress is expected to occur at the time of failure. The servomotor is set to move at a very slow speed so that reloading happens over a period of ~10 minutes.



(a) (b)

Figure 4-1 (a) Early design showing a 3-string 24-specimen load train. (b) Early version of the PNNL 3-string design capable of holding 24 specimens.

4.3 General SCC Testing Methodology

While specific test plans will be discussed later, the general testing approach is described here. It is expected that most SCC initiation tests will be performed on specimens at 360°C loaded to their yield stress or a controlled fraction of their yield stress. Individual materials will vary in strength and will require tailored gauge diameters to ensure that the proper applied stress is applied to each specimen. In order to accomplish this, 360°C air tensile tests will be performed on all materials prior to machining the initiation specimens. Gauge diameters are then machined based on this information and the desired specimen load, which is typically 455 kg (1000 lbs). At the

onset of an initiation test, specimens are brought up to their desired stress by constant extension rate, usually over a period of ~1 hour. The strain rate during this process is $\sim 1 \times 10^{-4}$ sec^{-1}. System load along with strain determined from DCPD is used to generate stress versus strain curves for each of the instrumented specimens during the loading process, thus providing direct evidence that the instrumented specimens have reached their yield stress. Some small variability in the yield load has been observed [7] among different specimens due largely to an always-present small variability in yield strength of materials. In prior tests performed for the DOE-NE LWRS program, specimens have yielded at loads that are within 5% of the target value. Since it is desired to have direct evidence that specimens have reached their target stress (i.e., the yield stress), the specimens that exhibit yielding first are typically allowed to undergo up to 0.5% plastic strain during the loading process so that yield can be observed in as many instrumented specimens as possible. After reaching the target stresses, the servo system is switched to constant load for the duration of the test. Small amounts of creep strain may occur during the time leading up to SCC initiation. When a test is stopped for any reason, stress versus strain curves are generated while the load is slowly returned to the original target load.

In addition to the temporary partial unloading that will occur when a specimen fails, specimens will be fully unloaded and reloaded when a test is stopped to swap out specimens or examine unfailed specimens. Although these will be purely elastic loading events that are thought to have little or no effect on initiation time, the events will be recorded in the datalogs for possible later comparison to SCC initiation times. It is also worthwhile to note that similar load changes occur in plant components during shutdown and restart activities.

SCC initiation will be actively monitored on at least 12 specimens while the remaining specimens will be monitored for failure using an open circuit technique. Since only a fraction of the specimens will be actively monitored, the difference between initiation and failure time will be established by letting a fraction of the actively monitored specimens run to failure.

5.0 Component Purchases, Test System Assembly and Validation

A critical first step for this project is the construction of two new SCC initiation test systems. Each test system requires the purchase of ~140 separate components that range from large items (such as the 12-liter autoclave and the Skala servo-electric loading system) to small items (such as bolts and electrical cabling). Ordering of longest lead-time items started in September 2014 and was completed in November 2015. All major components were delivered by June 2015.

In parallel, laboratory modifications were completed in the 3410 Building at PNNL to expand facilities and enable assembly of four new SCC initiation test systems (this includes two systems for another NRC-funded project). Test system assembly will require 3-4 months and should be completed in September 2015 followed by shakedown testing over the next month. Shakedown testing will include multi-specimen loading, partial instrumentation to evaluate the load train, and pre-oxidation of wetted components at 360°C in hydrogenated water. Performance capabilities will be established along with system monitoring during a ~500-hour test run. If all aspects remain on schedule, the two test systems will be ready for specimen loading and initial SCC experimentation in October 2015.

6.0 Materials and Material Conditions

The long-term objective of this program is to obtain PWSCC initiation data for reactor component nickel-base alloys including Alloy 600/182 and Alloy 690/52/152 materials. This data will support the development of the xLPR code and the technical basis for formulating in-service inspection requirements. As a result, there is a need to obtain alloy 600 and 690 base metal heats along with alloy 182, 152, 52, and 52M weldments in sufficient quantities for project requirements. These materials must have well documented processing histories, bulk compositions, and information on SCC susceptibility if possible. PNNL began interacting with the NRC and EPRI in September 2014 for the selection and acquisition of various materials and weldments. The goal has been to obtain four different heats or weldments for each class of material tested. For the 36 specimen test system, this allows for multiple specimens of each material to be tested. There is strong interest in obtaining materials having LWR-representative stress corrosion behavior. For alloy 600/182, selecting materials with known SCC response would facilitate this. For newly made or previously untested materials, SCC CGR testing could be conducted. For alloy 690 and its welds where no SCC has been observed in service, there is no LWR-representative response. In this case, the selection could be made based on laboratory SCC CGR testing response. For these reasons, SCC CGR testing has or will be conducted on all the materials that are being considered. Most all of the alloy 690/152/52 materials have already been tested for the NRC SCC CGR program, while testing is underway for the alloy 182 materials and will be followed by alloy 600 tests. If a wider range of materials response is needed, or if undesirable material response is observed, alternate materials will be procured and evaluated. The following sections briefly describe the current status of materials acquisition.

6.1 Alloy 600 Materials

The goal was to obtain two alloy 600 plate and two alloy 600 CRDM tube heats for the testing matrix. Only one CRDM material could be obtained, and therefore an alternative plan was established to obtain one CRDM and three plate heats with one of the plates being an older heat dating back to 2001 or earlier. All materials have now been obtained. The CRDM tube was extracted from a portion of a head salvaged from a PWR that never went into service.

6.2 Alloy 182 Welds

Alloy 182 is of particular importance to the xLPR model development and again the goal is to obtain four representative mockup welds for possible SCC initiation testing. Phase 2B and Flawtech alloy 182 mockup dissimilar metal pipe welds that were acquired by PNNL under other NRC programs have been obtained and can provide sufficient alloy 182 weld metal material for testing. In addition, EPRI has provided a large bead-on-plate build-up of alloy 182 build that was previously used for SCC testing at Studsvik. A fourth weldment has been fabricated by KAPL. It is a linear weld that is being shared between this program and the recently started NRC Peening program. A fifth weld may be obtained from EPRI.

6.3 Alloy 690 Materials

Extensive SCC testing of alloy 690 heats in the as-received and cold worked condition has been performed at PNNL [28-30]. As a result, many heats are available with information on their SCC susceptibility. Similar to alloy 600, the goal was to have two alloy 690 CRDM tube and two plate heats in the matrix. For this, PNNL has obtained

two Valinox CRDM heats (RE243 and WP142), and two plate heats (TK-VDM 114092 and ATI/Allvac B25K-2).

6.4 Alloy 152/152M/52/52M Welds

Due to the interest in several different high-chromium, nickel alloy welds, our initial goal was to identify one mockup weld along with four different weld metal variants. After considering the available options and sources, PNNL has obtained alloy 152, alloy 52, and alloy 52M mockups. The fourth material, an alloy 152M weldment from EPRI, was obtained in July 2015.

6.5 Material Characterization and Conditions to be Evaluated

All materials in the test matrix will be characterized to independently establish the alloy chemical composition, base microstructure and tensile properties. First steps will include optical metallography and microstructure analysis by scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). This will establish grain size characteristics and the distribution of second phases both at grain boundaries and in the matrix. Defect density in welds will also be evaluated during the metallography examinations. A weld will be removed from the test matrix if it has a high enough density of defects to cause concern that such defects may be present in a specimen gauge section.

As discussed earlier, it is proposed that all materials be cold forged to 15% reduction (via a single reduction step) to increase the yield strength of all alloys to ~500 MPa. For these nickel-base alloys, a cold worked condition is relevant to surface damage that is the primary precursor for SCC initiation in field components and is known to be more likely to induce SCC initiation and growth in PWR primary water. From the practical perspective of determining an FOI for alloy 690/152/52, laboratory tests [3, 5, 31, 32] have shown that applied stresses >350 MPa are required for SCC initiation for alloy 182, and stresses of ~450 MPa are needed to obtain reasonable nucleation times of <2000 hours (see **Figure 6-1**). Current results for SCC initiation tests by PNNL on alloy 600 in **Figure 6-2** also show a significant decrease in initiation time for stresses above 400 MPa resulting from ~10% cold work. Richey and co-workers at KAPL [12,33] have mapped behavior for alloy 600 heats and highlighted the importance of plastic strain (>5%) on SCC nucleation as illustrated in **Figure 6-3** where their data are plotted along with PNNL's most recent data.

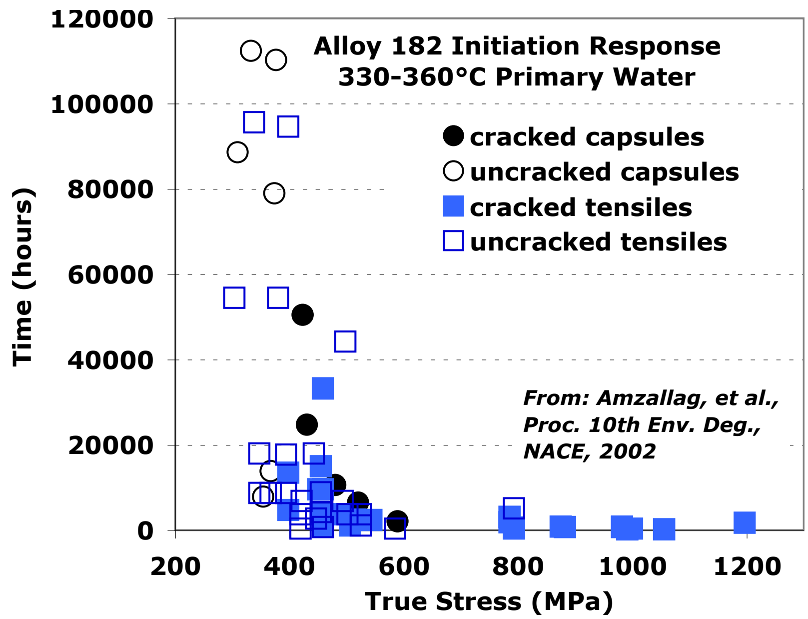


Figure 6-1 Alloy 182 SCC initiation test results by Amzallag, et al. [5]

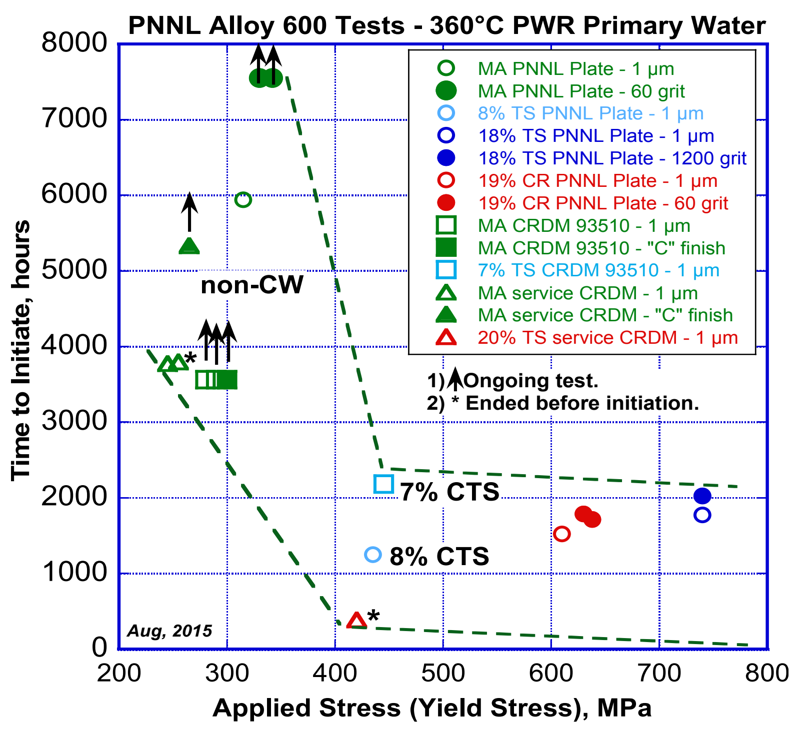


Figure 6-2 Recent PNNL alloy 600 SCC initiation test results. All specimens tested at their yield stress. Arrows indicate specimens that have not yet initiated. "C" finish is a heavily ground finish.

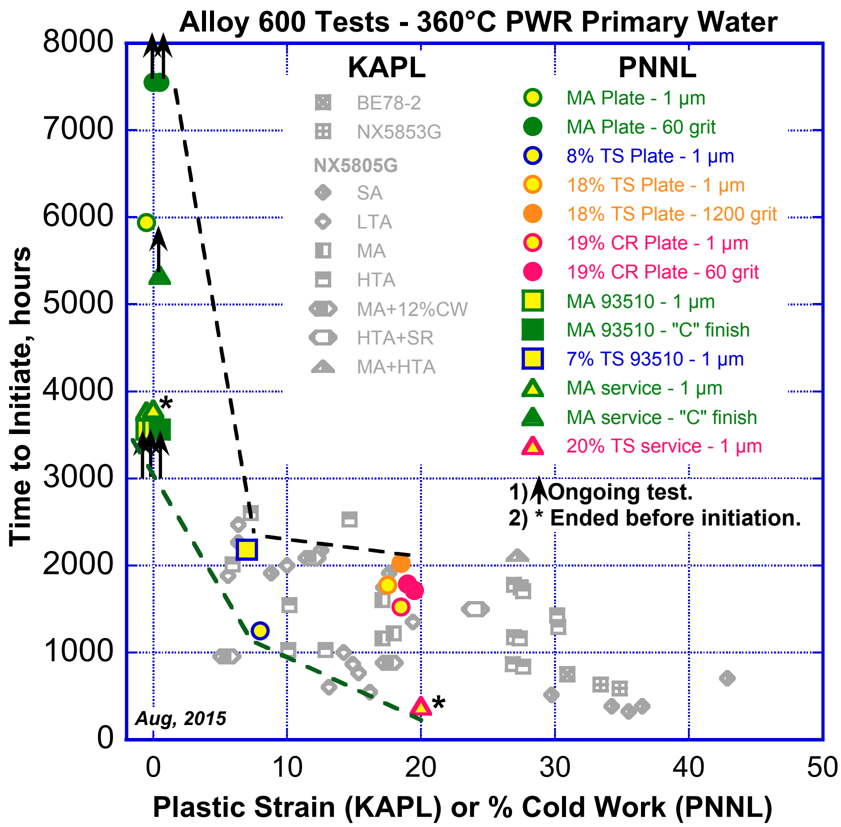


Figure 6-3 Alloy 600 SCC initiation test results by Richey, et al. [33] plotted with PNNL alloy 600 data.

As discussed earlier, constant-load, SCC initiation testing in this project will be conducted on cold forged materials at an applied stress equivalent to the material yield stress that will produce a small amount of plastic strain reversal that the French have shown to be highly conducive to SCC initiation. The application of a controlled 15% cold work by cold forging to the materials will produce relevant and reproducible alloy 600/182 and alloy 690/152/52 materials for laboratory SCC initiation testing in simulated PWR primary water. This level of cold work and the associated expected stress levels of ~500 MPa are below the 800-1000 MPa values known to exist in strained cold work surface layers in alloy 600/182 service components [3], but have been shown to readily produce SCC initiation in alloy 600/182. The time to SCC nucleation for susceptible alloy 600 and alloy 182 materials in the cold worked condition at 360°C is expected to be ~3 months based on prior work. This creates a situation where multi-year testing of alloy 690 and its weld metals can establish factors of improvement of approximately 20 within 5 years.

7.0 Proposed Test Matrix and Specific Materials

The primary objectives of establishing baseline SCC initiation response will be obtained by loading specimens to their yield stress and exposing them to 360°C simulated primary water. One autoclave will be loaded with alloy 690/152/52 specimens and is expected to run without failure for the estimated 5-year duration of the program. Experimentation on the SCC-resistant alloy 690/152/52 materials must start as early as possible to reach sufficient test times for desired factors of improvement over alloy 600/182 during this multi-year project. Therefore, a full set of 15% cold forged

specimens will be prepared, and testing will be started immediately after the test systems have been completed. At this time, we anticipate testing 3 specimens each of 4 alloy 690 heats (2 CRDM and 2 plate) and 6 specimens each of 4 alloy 152/52/52M welds. These results may be augmented by ongoing tests for the DOE-NE LWRS program on these heats and other. The final distribution of specimens may change as discussions are held with the NRC, EPRI, and an expert group. These 36 specimens will be loaded at an applied stress equal to the material yield strength of each material and will be exposed at constant load for the duration of the program, producing the highest possible factor of improvement when compared with cold worked alloy 600/182.

The second autoclave will cover all alloy 600/182 tests. The first goal will be to establish the SCC initiation response of Alloy 182 in support of near-term data needs for the xLPR program. Testing of alloy 182 is expected to occur in two phases. Phase 1 will assess weld-to-weld differences in SCC initiation susceptibility and provide a distribution of initiation times. Four separate welds will be evaluated with 6 specimens of each material in the 15% cold forged condition (Phase 1A) and 3 specimens in the as-welded condition (Phase 1B). It is anticipated that most of the cold worked alloy 182 specimens will exhibit crack nucleation within 3-4 months. When a significant fraction of these specimens have failed, the test will be stopped (likely in less than 6 months), and the failed Phase 1 specimens will be removed for characterization.

Phase 2 alloy 182 testing will overlap with Phase 1 testing and attempt to quantify the influence of applied stress of SCC initiation time with tests at 80% of the cold worked alloy 182 yield stress. The first group of Phase 2 specimens will replace the Phase 1 cold worked alloy 182 specimens that exhibited early failure times. After the first year (~10,000 hours) of alloy 182 exposure is complete, any Phase 1 specimens that have not undergone initiation will be replaced with the remaining Phase 2 specimens. The planned total exposure time allocated for Phase 1 and Phase 2 alloy 182 testing is two years. There will be options to modify the alloy 182 matrix during Phase 2 to best provide needed data for xLPR.

The next autoclave loading will be composed of cold worked alloy 600. These alloy 600 materials will include one CRDM and three plate heats. Based on prior work, it is expected that most of these specimens will exhibit SCC initiation within ~3 months. There is no plan to overlap exposure alloy 600 materials with the Phase 2 alloy 182 matrix because there is substantial data in the literature to suggest that initiation will not occur for any alloy 182 test run below the yield stress of the material.

The project scope beyond these series of exposures has been left open to give flexibility in evaluating other key material issues. Priority will be given to xLPR needs, but also under consideration are tests on 1) additional heats/welds of alloy 600/182 to better establish the range of material response, 2) dissimilar metal welds to assess SCC initiation in dilution regions for alloy 152/52 weld metal joined to low-alloy steel, 3) Alloy 152/52 welds with weld defects to assess the effect of ductility dip cracks, solidification cracks, and/or lack of fusion defects of SCC initiation. Decisions on testing priorities will be made in consultation with both NRC and EPRI project managers. A more detailed schedule is provided below based on the availability of two 36-specimen test systems for this project. It is possible that a third system may become available sometime in 2017. This would not alter the schedule for the long-term alloy 690/152/52 tests, but would impact the future matrices identified below as Options 1-3.

7.1 Estimated Schedule for Key Project Activities Based on Two Test Systems

The four major activities for this project are test system construction, specimen fabrication, SCC initiation testing, and post-test examination. The construction and specimen fabrication activity timeline is as follows:

(Pre-1) Acquire and Extract Materials
- Alloy 182: 4 primary and one alternate weld acquired
- Alloy 600: 3 plate heats and one CRDM heat acquired
- Alloy 690: 2 CRDM heats and 2 plate heats acquired
- Alloy 152/52: one each of alloy 152, alloy 52, alloy 52M, alloy 152M acquired

(Pre-2) Assess SCC Crack Growth Susceptibility of Alloy 182 Welds
- SCC crack growth rate testing of 2 CT specimens completed
- SCC crack growth rate testing of 2 remaining CT specimens has been started and will be completed by 10/15/15

(Pre-3) Cold Forging of Alloy 182/600/690/152/52/52M Materials
- All materials except the EPRI alloy 152M have been cold forged in sufficient quantity for the first autoclave loadings.
- 15% cold forged EPRI alloy 152M expected by 9/1/15

(Pre-4) Baseline Tensile Testing
- 360°C tensile testing of alloy 182 materials has been completed
- 360°C tensile testing of alloy 690/152/52 materials by 9/4/15

(Pre-5) Machine and Prepare SCC Initiation Tensile Specimens
- Machine and surface prep first loading of alloy 182 specimens by 9/30/15
- Machine and surface prep of alloy 690/152/52 specimens by 10/15/15

(Pre-6) Complete Assembly and Shakedown of SCC Initiation Test Systems
- Complete assembly of both test systems by 9/2/15
- Complete shakedown and validation testing by 9/30/15

Timing for the testing and analysis portion of the program is summarized in Table 1 and in the list below. Additional information on each test matrix is provided in Appendix 2.

Table 7-1 Alloy 600 SCC initiation test results by Richey, et al. [33] plotted with PNNL alloy 600 data.

Year	2015	2016		2017		2018		2019		2020	
Month	09	01-06	07-12	01-06	07-12	01-06	07-12	01-06	07-12	01-06	07-12
Time (Months)	1-4	5-10	11-16	17-22	23-28	29-34	35-40	41-46	47-52	53-58	59-64
A690/152/52											
A182 H-to-H (P1)											
A182 Stress (P2)											
A600 H-to-H											
O1 - TBD											
O2 - TBD											
O3 - TBD											

(Test-1) Alloy 690/152/52 SCC Initiation Testing

- Load and instrument CW alloy 690/152/52 by 10/19/15
- Start SCC initiation tests on CW alloy 690/152/52 by 10/29/15

(Test-2) Alloy 182 SCC Initiation Testing <u>Phase 1</u> (Heat-to-Heat, CF and AW, 100% YS)

- Load and instrument alloy 182 by 10/6/15
- Start SCC initiation tests on alloy 182 by 10/18/15
- Complete Phase 1A tests on CW alloy 182 by 5/1/16 [6 months total exposure, all specimens expected to initiate and fail]
- Optical and SEM examinations (Phase 1A), complete analysis by 7/1/16
- Restart test on remaining AW alloy 182 (Phase 1B) specimens by 6/1/16
- Interrupt test on Phase 1B AW alloy 182 specimens by 12/1/16 [12 months total exposure, expecting <50% initiation]
- Optical and SEM examinations on Phase 1B, complete analysis by 2/1/17
- *Submit technical report on Phase 1 alloy 182 by 4/1/17*

(Test-3) Alloy 182 SCC Initiation Testing <u>Phase 2</u> (Heat-to-Heat, CF and AW, 80% YS)

- Load and instrument Phase 2 alloy 182 (with remaining Phase 1B AW alloy 182 specimens) by 5/15/16
- Start SCC initiation tests on Phase 2 and Phase 1B alloy 182 by 6/1/16
- Complete Phase 2A (and 1B) set of tests on alloy 182 by 12/1/16 [6 months total exposure for Phase 2A and 18 months total exposure for Phase 1B].
- Optical and SEM examinations, complete analysis by 2/1/17
- Restart test on remaining (2B) alloy 182 specimens by 2/1/17
- Complete test on Phase 2B alloy 182 specimens by 8/1/17 [12 months total exposure]
- Optical and SEM examinations, complete analysis by 10/1/17
- *Submit technical report on Phase 2 alloy 182 by 2/1/17*

(Test-4) Alloy 600 SCC Initiation Testing (Heat-to-Heat Variability, 100% YS)

- Load and instrument CW alloy 600 (with remaining Phase 2B alloy 182 specimens) by 9/15/17
- Start SCC initiation tests on CW alloy 600 by 10/1/17
- Complete SCC initiation tests on CW alloy 600 by 3/1/18 [5 months exposure]
- Optical and SEM examinations, complete analysis by 6/1/18
- *Submit technical report on Alloy 600 Heat-to-Heat by 7/1/18*

(Test-5) Option 1 - Future SCC Initiation Testing

- Materials characterizations, forging, tensile testing and specimen preparation for Option 1 materials by 2/1/18
- Load and instrument alloy 600 and other specimens by 4/1/18
- Start SCC initiation tests by 4/15/18
- Complete tests by 1/1/19 [8.5 months exposure]
- Optical and SEM examinations, complete analysis by 3/1/19
- *Submit technical report on Phase 1 alloy 600 by 5/1/19*

(Test-6) Option 2 - Future SCC Initiation Testing

- Materials characterizations, forging, tensile testing and specimen preparation for Option 2 materials by 12/1/18
- Load and instrument specimens by 1/1/19
- Start SCC initiation tests by 3/15/19
- Complete next series of tests by 12/1/19 [8.5 months exposure]
- Optical and SEM examinations, complete analysis by 3/1/20
- *Submit technical report on Option 2 tests by 5/1/20*

(Test-7) Option 3 - Future SCC Initiation Testing

- Materials characterizations, forging, tensile testing and specimen preparation for Option 3 materials by 12/1/19
- Load and instrument specimens by 1/1/20
- Start SCC initiation tests by 2/15/20
- Complete tests by 9/1/20 [7.5 months exposure]
- Optical and SEM examinations, complete analysis by 11/1/20
- *Submit technical report on Option 3 tests by 12/31/20*

(Test-8) Alloy 690/152/52 SCC Test Completion

- Mid-term specimen examination (2 months) 7/1/17
- Mid-term specimen examination (2 months) 7/1/19
- Complete alloy 690/152/52 SCC initiation tests by 8/1/20
- Optical and SEM examinations, complete analysis by 10/1/20
- *Submit technical report on alloy 690/152/52 test results by 12/31/20*

8.0 Post-Test Examination

In order to better understand the SCC initiation response and potentially relate it to initiation behavior of in-service components, post-test examinations will be performed. The intent of the post-test examinations is to determine crack characteristics present when SCC initiation was detected by in-situ DCPD measurements. Most specimens will fail *in situ*, so crack morphology will have to be determined either from specimens that initiated near the end of an exposure cycle, or crack morphologies will be determined from observations of cracks in failed specimens. This information will help indicate the transition from precursor crack formation to active crack growth processes. We believe more detailed understanding of this stage of SCC initiation is important to the mechanisms of cracking for service components. Scanning electron microscopy (SEM) will be used to measure the surface length and depth of the cracks on the specimen. In order to accomplish this, full 360°C surface observations will be performed, and then the specimens will be sliced axially into 2-4 pieces that will be polished in cross-section for crack depth measurements. Hardness will also be measured in cross-section. EBSD may also be used to determine the misorientation of cracked and uncracked grain boundaries and the strains around them. The relationship between SCC initiation times and these post-test examinations will be considered. Many of the same materials are being tested and examined in the DOE-NE LWRS SCC initiation program at PNNL enabling some additional insights to be gained.

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Appendix A Proposed Materials

Alloy Class and Material Name	Top 4 Candidate?	Reason	Description/Form	Dimensions	Alloy Vendor	Heat Number	CMTR?	Weld Fabricator	WPS	At PNNL?	Number of Possible Specimens
Alloy 182											
PNNL/NRC Phase 2B Mockup	**yes**	**well-documented mockup**	LAS-SS DMW with alloy 182 butter and fill	circumferential pipe buttweld, 15" OD x 1.5" wall	TBD	TBD	TBD	EWI	yes	yes	50
PNNL/Flawtech/NRC Mockup	**yes**	**well-documented mockup**	LAS-SS DMW with alloy 182 butter and fill	circumferential pipe buttweld, 14" OD x 1.5" wall	Spec. Met.	844305	yes	Flawtech	yes	yes	90
Studsvik	**yes**	**well-documented mockup**	alloy 182 buildup	3"tall x 2.75" x 5"long	TBD	TBD	TBD	ENSA	yes	yes	64
KAPL	**yes**	**well-documented mockup**	alloy 182 U-groove	1.5"wide x 1.5"tall x 8"long	Techalloy	823030	yes	KAPL	yes	yes	25
EPRI weld		**under consideration**	alloy 182 groove	TBD	TBD	TBD	yes	TBD	yes	no	TBD
CRDM J-groove	**no**	**too challenging to forge and extract initiation specimens**	alloy 182 J-groove from dismantled partially built PWR	4.15" ID x 0.XX" thick x XX"tall	unknown	unknown	no	unknown	no	yes	none
Alloy 600											
PNNL Plate #1 (MA)	**yes**	**prior SCCI data from LWRS**	2" thick plate	9.6x15x2" thick	Spec. Met.	NX6016XK-11	yes	N/A	N/A	yes	300
PNNL Plate #3 (MA)	**yes**	**using for NRC Peening program**	3" thick plate	3x18x3" thick	ATI	522068	yes	N/A	N/A	yes	50
KAPL Plate (MA)	**yes**	**vintage material**	vintage 2" thick plate	4x12x2" thick	G.O. Carlson	33375-2B	yes	N/A	N/A	yes	50
CRDM Tube	**yes**	**service material**	From dismantled partially built PWR	4.15"OD x 0.70" wall x 8" long	unknown	unknown	no	N/A	N/A	yes	50
Foroni Bar	**no**	**under consideration**	6" dia. bar	6"OD x 12" long	Foroni	31907	yes	N/A	N/A	yes	100
PNNL Plate #2 (MA)	**no**	**other better candidates**	2" thick plate	6x24x2" thick	ATI	521616	yes	N/A	N/A	yes	300
Alloy 152/52											
MHI alloy 152 U-groove	**yes**	**have SCC CGR data**	U-groove weld joining SS	1.8"tall x 2"wide x 2.5" long	TK-VDM?	307380	yes	MHI	yes	yes	15
MHI alloy 52 U-groove	**yes**	**have SCC CGR data**	U-groove weld joining SS	1.8"tall x 2"wide x 2.5" long	Spec. Met.	NX2686JK	yes	MHI	yes	yes	15
ENSA DPM alloy 52M butter	**yes**	**sufficient material available**	Double bevel 690-LAS DMW, alloy 52M butter	0.75"tall x 2.7"wide x 4" long	unknown	unknown	no	ENSA	yes	yes	20
EPRI alloy 152M	**yes**	**favorable geometry, sufficient material**	TBD	TBD	TBD	TBD	yes	TBD	yes	yes	>40
KAPL alloy 52M NG	**no**	**too narrow**	narrow gap weld joining alloy 690	1.8"tall x 0.5"wide x 1.1" long	Spec. Met.	NX5285TK	yes	KAPL	yes	yes	6
EPRI alloy 52i	**no**	**not enough material**	V-groove weld	1.8"tall x 0.75-1.75"wide x 1.5" long	TK-VDM	187775	yes	unknown		yes	9
ENSA DPM alloy 52 fill	**no**	**alloy 52 with prior SCC experience already identified**	Double bevel 690-LAS DMW, alloy 52 fill	1.5"tall x 0.5-1.6"wide x 4" long	Spec. Met.	NX4196JK	yes	ENSA	yes	yes	20
NRC alloy 52MSS NG	**no**	**too narrow**	narrow gap weld joining alloy 690	2"tall x 0.4-0.6" wide x 2.8" long	Spec. Met.	NX77W3UK	yes	PCI	yes	yes	18
Alloy 690											
Valinox Alloy 690 CRDM RE243 (TT)	**yes**	**significant SCC CGR data**	CRDM	4.4"OD x 1.35"wall x 6" long	Valinox	RE243	no	N/A	N/A	yes	>20
Valinox Alloy 690 CRDM WP142 (TT)	**yes**	**have SCC CGR data, and substantial materal**	CRDM	4.56"OD x 1.20"wall x 4" long	Valinox	WP142	no	N/A	N/A	yes	>20
TK-VDM 114092 plate (TT)	**yes**	**have SCC CGR data**	plate	2"tall x 4"wide x 2.5" long	TK-VDM	114092	yes	N/A	N/A	yes	>20
ATI/Allvac B25K-2 (MA)	**yes**	**have SCC CGR data**	plate	3"thick x 5.5"wide x 2.2" long	ATI/Allvac	B25K-2	yes	N/A	N/A	yes	>20
Doosan CRDM bar (TT)	**no**	**insufficient material for additional tests**	CRDM	6"OD x 2.5" long	TK-VDM	133454	yes	N/A	N/A	yes	12
EPRI NX8625HG21 (TT)	**no**	**no SCC data, other better candidates**	plate	12x12x1.34" thick	Spec. Met.	NX8625HG21		N/A	N/A	yes	>20

Appendix B Proposed Test Matrix

Alloy 690/152/52 (Autoclave #1)
Goals: Heat-to-heat variability
Start: 11/2015
End: 08/2020
Total Exposure Duration: ~55 months
Comment: Autoclave will be opened once per year to selectively examine specimens.

Material	*Condition*	*Quantity*	*Pct YS*
MHI 152	15% CF	6	100
MHI 52	15% CF	6	100
ENSA 52M	15% CF	6	100
EPRI 152M	15% CF	6	100
VX RE243	15% CF	3	100
VX WP142	15% CF	3	100
TK-VDM	15% CF	3	100
Allvac B25K-2	15% CF	3	100

Alloy 182 Phase 1A/B (Autoclave #2)
Goals: Heat-to-heat variability, CF versus AW response
Start: 10/2015
End: 12/2016
Total Exposure Duration: 12 months
Comment: Autoclave will be opened after six months to replace failed specimens with alloy 182 Phase 2 specimens.

Material	*Condition*	*Quantity*	*Pct YS*
Phase 2B	15% CF	6	100
Flawtech	15% CF	6	100
Studsvik	15% CF	6	100
KAPL	15% CF	6	100
Phase 2B	AW	3	100
Flawtech	AW	3	100
Studsvik	AW	3	100
KAPL	AW	3	100

Alloy 182 Phase 2A/B (Autoclave #2)
Goals: Effect of stress for different heats and cold work level
Start: 06/2016
End: 08/2017
Total Exposure Duration: 12 months
Comment: Autoclave will be opened after six months to replace failed specimens with alloy 182 Phase 2B specimens.

Material	*Condition*	*Quantity*	*Pct YS*
Phase 2B	15% CF	6	80
Flawtech	15% CF	6	80
Studsvik	15% CF	6	80
KAPL	15% CF	6	80
Phase 2B	AW	3	80
Flawtech	AW	3	80
Studsvik	AW	3	80
KAPL	AW	3	80

Alloy 600 (Autoclave #2)
Goals: Heat-to-heat variability, CF versus AW response
Start: 10/2017
End: 03/2018
Total Exposure Duration: 5 months
Comment: All specimens expected to fail.

Material	*Condition*	*Quantity*	*Pct YS*
PNNL Plate #1	15% CF	9	100
PNNL Plate #2	15% CF	9	100
KAPL Plate	15% CF	9	100
WNP5 CRDM	15% CF	9	100

Option 1 (Autoclave #2)
Goals: TBD
Start: 04/2018
End: 12/2018
Duration: 9-10 months total
Comment: None

Material	*Condition*	*Quantity*	*Pct YS*
TBD			

Option 2 (Autoclave #2)
Goals: TBD
Start: 02/2019
End: 12/2019
Duration: 9-10 months total
Comment: None

Material	*Condition*	*Quantity*	*Pct YS*
TBD			

Option 3 (Autoclave #2)
Goals: TBD
Start: 02/2020
End: 09/2020
Duration: 7-8 months total
Comment: None

Material	*Condition*	*Quantity*	*Pct YS*
TBD			