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PVRC JOINT INDUSTRY PROGRAM
PHASE II PROPOSAL

PREDICTION OF RESIDUAL STRESSES
EFFECTS OF WELDING, PWHT, LOCAL PWHT, AND ALTERNATIVE STRESS IMPROVEMENT TECHNIQUES

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INTRODUCTION

The PVRC Phase I **Residual Stress and Local PWHT** Joint Industry Project (JIP) has been completed. NEW and formers sponsors are invited to join Phase II. The major achievements of Phase I include:

- Validation of the PVRC JIP residual stress estimation procedure against a comprehensive collection of experimentally measured residual stress distributions for a wide range of materials and component geometries
- Development of a consistent set of procedures for characterizing for welds through-wall, transverse residual stress distributions in terms of (a) “global bending”, (b) “local bending”, and (c) “self-equilibrating”, as shown in Exhibit 1. For typical welds in pipe/vessel components, two important parameters have been identified. These govern the through-wall residual stress distribution from “global bending” to ‘self-equilibrating”. Key

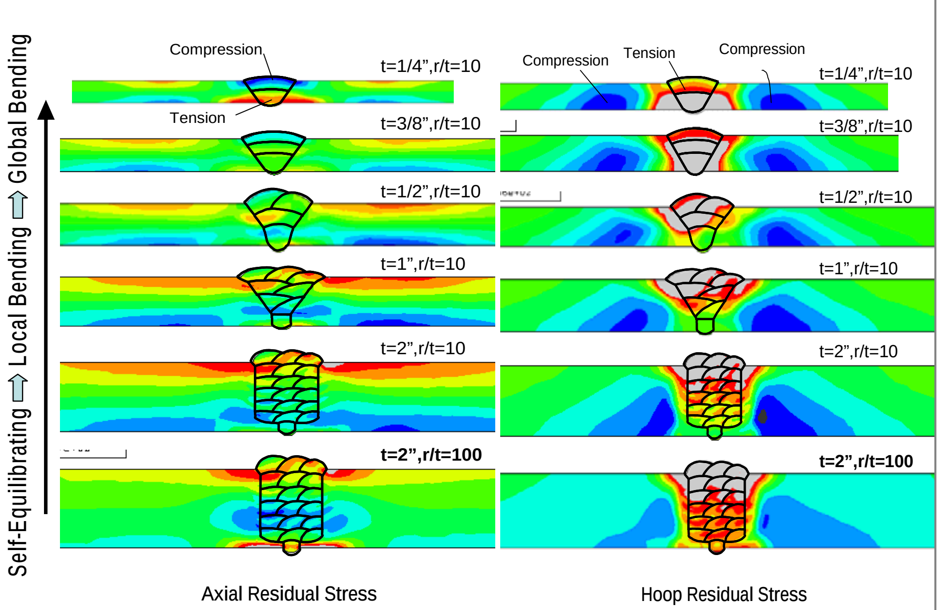

Exhibit 1

variables are simply the component radius (r), the ratio of radius to wall thickness (r/t) and the characteristic heat input $\hat{Q}$ (in units of KJ/mm^3). This residual stress characterization procedure has been adopted for welded components in the international standard API 579/ASME FFS-1 (formerly API 579) for fitness-for-service (FFS) based assessment.

- Improvement and demonstration of accurate and not unduly conservative procedures for incorporating residual stresses into fracture mechanics assessment FFS models. Conventional load-controlled K solutions are excessively conservative since residual stress relaxation due to crack propagation is not taken into account. It was shown that correct fracture mechanics treatment of residual stresses requires consideration of K solutions under displacement-controlled conditions. A simple K estimation scheme was developed and validated by finite element methods. Based on this consideration, a significant reduction in unnecessary conservatism can be realized, particularly for cracks with rather low aspect ratios.

- A simple, material specific, parametric, relationship for stress relief was developed. This concept considers Time Temperature and Thickness during Post Welding Heat treatment. The relations were shown to be convenient to use in practice. There can now be significant cost savings due to the greatly reduced holding time requirements to achieve a given degree of stress relief, as compared to current rules. The corresponding residual stress reduction can be obtained by simply scaling the as-welded residual stress profiles developed for the FFS assessments

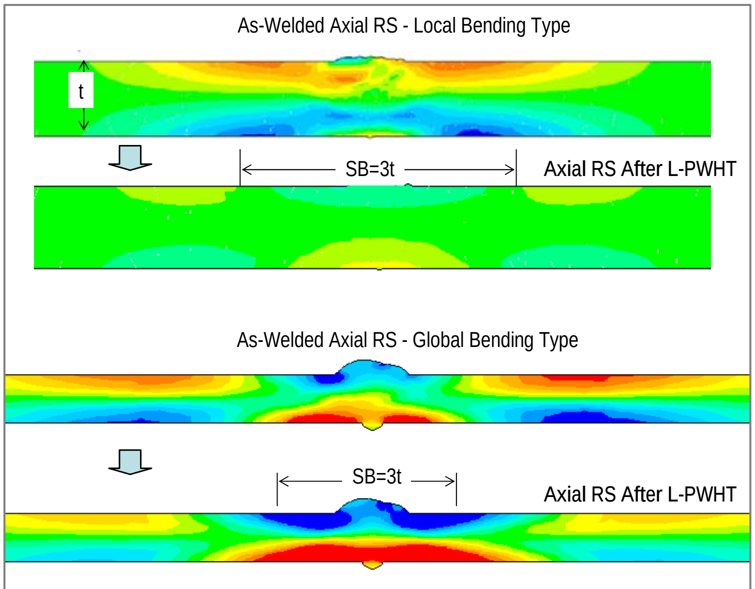

Exhibit 2

- Recommendations for local PWHT were provided. The case of uniform PWHT was used as a benchmark for residual stress reduction. “Harmful” temperature gradients, under both circumferential and spot heating, as identified in Codes and Standards can now be quantitatively identified for various pipe and vessel weld configurations. Detailed stress relief mechanisms and thermal-mechanical interactions during local PWHT were also identified for carbon and important low alloy steels. The limits for effectiveness in the code-specified local PWHT procedures was established in terms of geometric parameters in terms of either r/t or $\sqrt{rt}$ (which are also characteristic parameters for determining residual stress distribution types). As shown in Exhibit 2, when performing local PWHT against “local bending” type (or self-equilibrating type) of residual stress distributions in a girth weld, the soaking band (SB) can be as small as 2~3t. This gives significant residual stress reduction. However, for “global bending” types of residual stress distributions, the same local PWHT only enhances the original bending type residual stresses.

PHASE II OBJECTIVES/SCOPE

A large number of cases were analyzed during the PHASE I studies to establish the coherent framework for residual stress profile development for FFS assessment and to provide recommendations for performing uniform and local PWHT. However, there remain a number of areas that need to be investigated using the procedures developed during that work. These include:

1) Residual stress characterization:

- Welded components including complex geometries with thicknesses beyond what was investigated in Phase I, (i.e. >50mm)

- Weldments made of high alloy materials, such as austenitic stainless steels , duplex and super duplex stainless steels, solid solution nickel alloys and overlays and bimetallic welds with buttering layers

- Weldments with characteristic heat input $(\hat{Q})$ beyond the range investigated in Phase I. This will extend the coverage of the existing residual stress solutions to very low heat inputs (such as temper-bead welding) as well as to high heat input welding (such as electro-slag welding)

- Repair welds for which effective parametric descriptions of the residual stress distributions will require more comprehensive parametric residual stress analyses than those performed in Phase 2, particularly when dealing with high alloy or dissimilar weldments.

2) Uniform PWHT and local PWHT:

- The Time-Temperature-Thickness relationship developed in Phase I focused on carbon and low alloy steels. This relationship needs to cover a larger number of materials of interest to the sponsors

- The uniform and local PWHT analyses performed in Phase I focused on residual stress relief due to thermo-plasticity and creep relaxation. Material property changes during PWHT have not been investigated in detail. The MPC Omega method used to characterize material response for the analysis is capable of incorporating property changes such as tempering effects. If this is done the Method can lead to more effective prediction of susceptibility to stress relief or other cracking under conditions of restraint and thermal stress as well as cracking during long term service in the creep "embrittlement" range. In addition, Phase I results on local PWHT clearly showed that for some component configurations, e.g., in certain r/t ratio ranges, the current Code-specified local PWHT procedure is not only ineffective , but it can be detrimental (see comment on Exhibit 2 earlier). For such situations, more effective local PWHT procedures needs to be identified

3) Alternative stress improvement techniques:

There are situations in which PWHT or local PWHT cannot be applied, e.g. where weld repair is needed in aged components or local PWHT is not practical. For these, alternative stress improvement techniques can be cost-effective ways to mitigate weld residual stresses. The alternative methods include the well-known high-frequency induction stress improvement (HISI) technique and several others. As demonstrated in Phase I, advanced weld modeling techniques can study how various local heating configurations and heating source types can be used to mitigate detrimental residual stress effects. These techniques rely on local temperature gradients to achieve local mechanical over-loading. As a result, the peak temperature needed is much lower than that required by PWHT or local PWHT. Durations can be much shorter, e.g. in the order of minutes

4) <u>Technology Transfer- Training on JIP residual stress analysis procedures:</u> Although the detailed analysis procedures have been documented in the previous JIP reports, effective implementation of the complex thermal and thermo-mechanical analysis procedures requires detailed understanding of weld mechanics, process physics, thermo-plasticity theory and finite element analysis. A number of JIP Phase I participants and potential JIP II participants have suggested that training should be conducted so that JIP participants can perform residual stress estimates for their company's specific applications. In addition, effective interpretation of residual stress measurements requires understanding of the mechanics of weld residual stresses. The same is true for making cost-effective, appropriate residual stress measurements.

With the above in mind, the following scope of work is proposed for considerations by potential sponsors as a continuation for JIP Phase II.

Proposed Topics for Work in Phase II

The following specific major items toward the above objectives were compiled based on input from Phase I sponsors and suggestions from potential sponsors. Note that the list below is very likely more comprehensive than a single project can cover. They are listed here for the purpose of prioritizing by the Phase II sponsors. The detailed scope work for Year 1 will be determined based on the input at the Phase II kick off meeting and resources available at that time. Additional items may be added for later work, depending on Sponsors' preferences.

1) **<u>Residual stresses in thick components</u>**: Considering Sponsors' needs, the current girth and seam weld solutions will be extended to components with thickness larger than 50mm. Representative r/t ratios and heat inputs will be used. Complex geometries and narrow groove welds will be considered in this task

2) **<u>Residual stress in high alloy weldments</u>**: A series of representative high alloy materials will be identified for investigation, including bimetallic welds with typical material and buttering layer combinations. The material properties needed for the residual stress analysis will be taken from MPC resources and the literature. Stainless steel alloys not considered in Phase I will also be investigated

3) **<u>Consistent residual stress descriptions for FFS of both through-wall and surface situations</u>**: As a result of the Phase I investigation, a parametric description of the through-wall residual stress distributions was developed and adopted by API /ASME FFS-1. However, the parametric equations describing the residual stress distributions on weldment surfaces are not linked to the though-wall distributions at any given distance from either the weld centerline or the HAZ. Additional investigations of surface residual stress characteristics and their relationship to through-thickness distributions needs to be carried out to supplement the cases analyzed in Phase I. With these results, a

consistent residual stress distributions for both through-wall and surface locations can be constructed to achieve more comprehensive, parametric residual stress descriptions

4) **Effects on residual stresses of severe thermal and mechanical property mismatches**: The effects on residual stress distributions of mismatched thermo-physical or thermo-mechanical properties, as occur in bimetallic and high alloys welds, are expected to be more significant than for the cases analyzed in Phase I. These effects can change the "global bending" and "local bending" content of the residual stress distributions and need to be characterized for cycling applications.

5) **Residual stresses in weld repairs**: This task is to expand on the repair weld residual stress solutions developed by parametrically considering repair length, repair depth, and repair width as well as heat input. The effects of the first three geometric parameters on resulting residual stress distributions will be quantified with respect to the characteristic component geometric parameters such as r/t, t or other relevant geometric parameters for typical components

6) **Time-Temperature-Thickness relationship for PWHT of other materials**: Depending upon the Sponsors' interest, a new group of materials will be selected to establish stress relief behavior in the form of the Time-Temperature-Thickness relationship established in Phase I

7) **PWHT analysis with tempering effects**: For some materials property changes (including damage and softening) may occur. These effects can be evaluated l to quantify the benefit/detriment of PWHT. Simultaneous material tempering and creep damage will be considered in PWHT analysis. Propensity for reheat cracking governed by both creep damage and transient residual stress state can also be quantified

8) **Alternative stress improvement techniques**: For typical component geometries selected by the Sponsors, alternative stress improvement techniques using local heating with relative low temperatures (compared with the conventional PWHT temperature) and short durations will be examined. Existing data from literature and sponsors will be used for validation purpose. Validation tests may be conducted in this JIP if deemed necessary. Some of the promising techniques, depending upon component geometry and residual stress location of interest may include:

   - Heat sink welding
   - Induction heating with or without forced cooling
   - Controlled local heating with conventional heating sources with or without mechanical stressing, e.g., low pressurization

9) **Recommendations for performing uniform PWHT, local PWHT, and alternative stress improvement techniques for Sponsors and possible inclusion in Codes and Standards**: Based on the above investigations, a comprehensive set of recommendations for the sponsors , and , if desired, for inclusion in Codes and Standards will be developed. These will cover uniform and local PWHT, as well as alternative stress improvement techniques. These can include criteria for using each method and procedures, as well as for the sponsors, FE-based evaluation procedures for optimizing the procedures for adaptation to company specific applications

10) **Construction of a residual stress compendium database**: A large number of residual stress solutions were documented in the JIP Phase I report. Additional solutions will be generated during Phase II. It would be highly beneficial to document the residual stress solutions and corresponding

material properties used in performing the analyses in an easy to retrieve database format. This database should also include validated residual stress distributions based on various experimental measurement techniques. This database be can be made available to JIP sponsors via the PVRC website or other means so that any sponsors can query specific residual stress distributions and apply material properties relevant to their own applications

11) **Technology Transfer-Training for solving residual stress problems and database support**: During the course of Phase II, a training course will be offered to the sponsors in the form of residual stress modeling workshop. This may be conjunction with the periodic JIP review meetings. The course will cover the fundamentals of residual stress development, modeling and measurement procedures, well-documented residual stress case studies performed at Battelle and application of the database described in Item 10 above.

Duration and Cost

Phase II of the PVRC JIP is planed for a duration of 3 years after the start date. Sponsors that were not members of Phase I would make 3 payments of $16,000 (a total of $48,000). Sponsors that were members of Phase I will make 3 payments of $12,000 (a total of $36,000). Once a total of twelve sponsors have committed to the program, Phase II will be officially started and follow the prioritization of work items as agreed upon by the Sponsors at the launch meeting scheduled for Tuesday afternoon April 17, 2007 in Houston, Texas.

The meeting will be held in conjunction with a WRC meeting on High Alloy Welding at the same venue. See the accompanying brochure. Representatives of companies committing to participate in this JIP may attend the WRC conference at NO CHARGE (or will have there registration fee credited to the Project cost if they join at a later date).