The Battelle Integrity of Nuclear Piping (BINP) Program Final Report

Appendices

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Appendices

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ABSTRACT

Volume I of the final report for the Battelle Integrity of Nuclear Piping (BINP) program provided a summary of the results from this program and a discussion of the implications of those results. This volume (Volume II - Appendices) provides the details from the various technical tasks conducted as part of this program. Each individual appendix provides the details of a specific task conducted as part of the BINP program.

FOREWORD

Since 1965, the U.S. Nuclear Regulatory Commission (NRC) has been involved in research on various aspects of pipe fracture in nuclear power plant piping systems. The most recent programs are the Degraded Piping Program, Short Cracks in Piping and Piping Welds Program, and two International Piping Integrity Research Group programs. These programs have developed and validated "state-of-the-art" structural analysis methods and data for nuclear piping systems.

This report describes the results of the Battelle Integrity of Nuclear Piping (BINP) program, which was performed by Battelle Columbus Laboratories. The objective of the BINP program was to address the most important unresolved technical issues from the earlier research programs. The BINP program was initiated as an international program to enable fiscal leveraging and an expanded scope of work. Technical direction for the program was provided by a Technical Advisory Group composed of representatives from the funding organizations.

The BINP program was divided into eight independent tasks, each of which examined one of the unresolved technical issues. These eight tasks included both experimental and analytical efforts. The two pipe-system experiments examined the effects of secondary stresses (such as thermal expansion) and cyclic loading (such

as during a seismic event) on the load-carrying capacity of flawed piping. For these experiments, the pipe system had large flaws or cracks. The remaining six tasks were "best-estimate" analyses to examine the effects of other factors, such as pipe system boundary conditions, and weld residual stresses on the behavior of flawed pipes. Many of these analyses involved the use of finite element modeling techniques. One of these analytical tasks was to examine the actual margins that may exist in flawed pipe evaluations as a result of non-linear behavior. While the magnitude of these margins would vary on a case-by-case basis, the results of this task show that a potential for significant margins does exist.

In addition to developing a technical basis for more advanced inservice flaw evaluation procedures for use with Class 1 piping, as defined by the American Society of Mechanical Engineers (ASME), the BINP program considered the development of flaw evaluation procedures for ASME Class 2 and 3 piping and balance-of-plant piping.

This research supports the NRC's goal to improve the effectiveness and realism of the agency's regulatory actions.

Carl Paperiello, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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APPENDIX A

EVALUATION OF PROCEDURES FOR THE TREATMENT OF SECONDARY STRESSES IN PIPE FRACTURE ANALYSES

A.1 BACKGROUND

Currently, the flaw evaluation procedures embodied in ASME Section XI specify different safety factors for global secondary stresses, such as thermal expansion and seismic anchor motion (SAM) stresses, than they do for primary stresses, such as primary membrane or primary bending stresses. The ASME Code specifies a safety factor of 2.77 for Service Levels A and B, and 1.39 for Service Levels C and D for primary stresses. For cracks in ferritic materials (base metal and welds) and austenitic flux welds (submerge-arc and shielded-metal-arc welds), the Section XI procedures indicate that the thermal expansion stresses should be included, but with a safety factor of only 1.0. In addition, for cracks in austenitic base metals, the ASME Code indicates that thermal expansion stresses need not be considered. Furthermore, the current ASME Section XI procedures do not explicitly require SAM stresses to be considered, regardless of the material.

The R6 analysis classifies certain secondary stresses, such as thermal expansion and other displacement-induced stresses (SAM), as effectively being primary stresses if there is significant elastic follow-up at the crack section. These stresses will not generally be self-equilibrating as is typically assumed for secondary stresses, such as weld residual stresses.

In a similar view, the LBB procedures specified in draft Standard Review Plan (SRP) 3.6.3 have an option that allows the thermal expansion stresses to be considered in the stability analysis of cracks in austenitic submerge-arc and shielded-metal-arc welds, but not in the stability analysis of cracks in austenitic wrought base metals and TIG welds. For ferritic materials,

this option is not given so that secondary and primary stresses are combined.

A.2 RESULTS OF PRIOR PIPE-SYSTEM EXPERIMENTS

The results from the IPIRG pipe-system experiments indicate that for large cracks, where the failure stresses are below the general yield strength of the uncracked pipe, the thermal expansion and SAM stresses contributed just as much to fracture as did the primary stresses, see Figure A.1. Figure A.1 shows a plot of the maximum experimental stress normalized by the Net-Section-Collapse (NSC) stress for five quasi-static bend and five pipe-system experiments conducted as part of the IPIRG (Refs. A.1 and A.2) and related programs (Refs. A.3 and A.4). The crack sizes in each of these experiments were relatively large, such that the failure moments were low enough that plasticity was restricted to the crack section. The maximum experimental stresses have been normalized by the NSC stress to account for slight differences in pipe size and crack size. For each experiment, the maximum stress has been broken down into its various stress components, i.e., primary membrane, primary bending (inertial), seismic anchor motion, and thermal expansion (For the quasi-static bend companion experiments, the only stress components applicable are primary membrane and primary bending [quasi-static bending]). From Figure A.1 it can be seen that if the thermal expansion and SAM stresses are ignored in the stress terms for the pipe-system experiments, then the normalized failure stresses for the pipe-system experiments would only be 40 to 50 percent of normalized failure stresses for the quasi-static bend experiments. Consequently, it appears from these results that secondary stresses do contribute to fracture, at least for the case of large surface cracks where plasticity is limited.
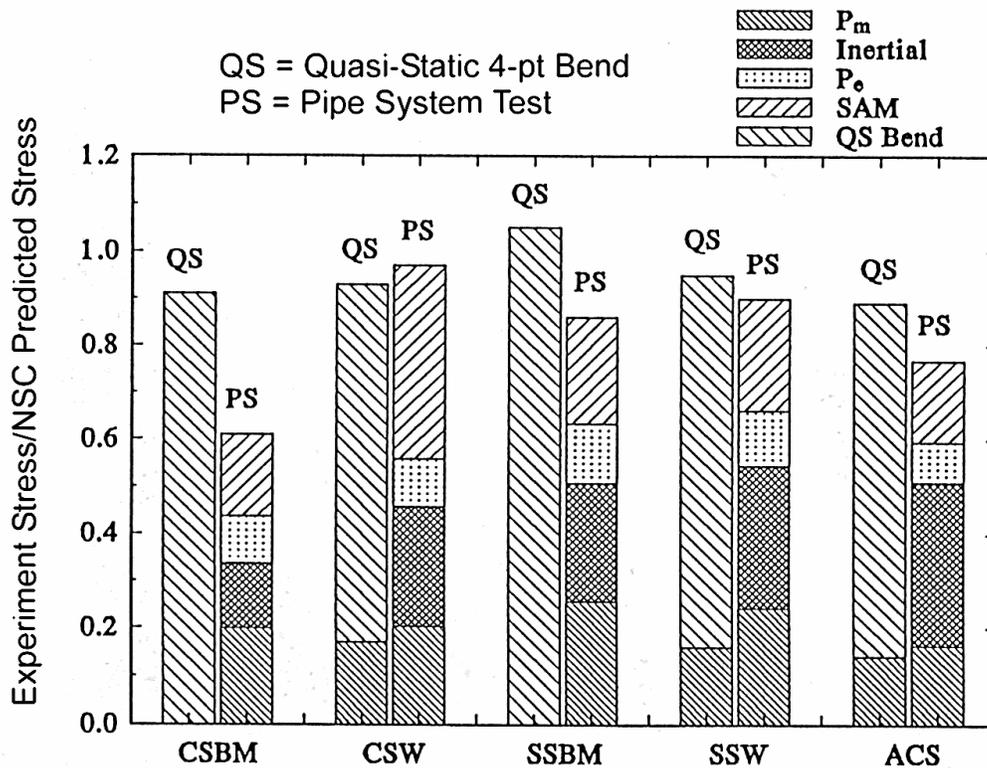
Figure A.1 Comparison of the results from the IPIRG-1 pipe-system experiments with companion quasi-static, four-point bend experiments demonstrating how global secondary stresses, such as thermal expansion and seismic anchor motion stresses, contribute to fracture

A.3 BINP TASK 1 EXPERIMENT

As part of this effort in the BINP program, another pipe-system experiment (BINP Experiment 1) was conducted. For this experiment the actuator was intentionally offset at the beginning of the experiment, prior to the application of the dynamic cyclic load history, to simulate a larger thermal expansion stress. Figure A.2 is a plot of the actuator time history for this experiment along with the actuator time history for its companion pipe-system experiment from the First IPIRG program, i.e., Experiment 1.3-5. The crack for both of these pipe-system experiments (1.3-5 from IPIRG-1

and BINP Experiment 1) was located in the center of a stainless steel submerge-arc weld. The crack sizes for both experiments were nominally the same, i.e., 50 percent of the pipe circumference in length and 66 percent of the pipe wall thickness in depth. From Figure A.2 it can be seen that the actuator for the BINP experiment was offset an additional 56 mm (2.2 inches) at the start of the experiment with respect to the actuator displacement for the IPIRG-1 experiment. This additional static offset in displacement resulted in an additional 255 kN-m (2,257 in-kips) of static moment at the crack section.
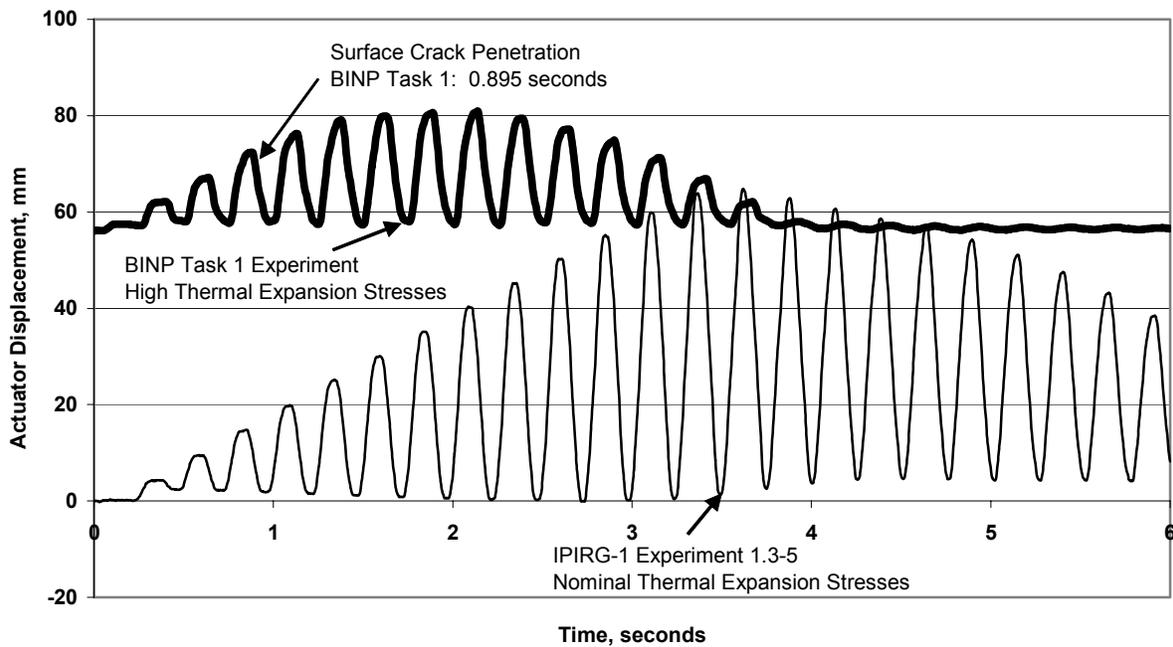
Figure A.2 Actuator time history for BINP Task 1 experiment and IPIRG-1 Experiment 1.3-5

Figure A.3 is a plot of the crack section moment as a function of time for these two pipe-system experiments up to the instant when the surface crack penetrated the pipe wall thickness. From this figure it can be seen that the total moment at the crack section at the instant of surface crack penetration was comparable for the two experiments. This further supports the contention that these global secondary stresses (thermal expansion and SAM stresses) contribute just as much to fracture as do the primary stresses, at least for the case where the stresses in the uncracked pipe are below the yield strength of the pipe. From Figure A.4, which is a similar plot as Figure A.1, except it shows the results for the four stainless steel weld experiments (Experiment 4141-4 from the Degraded Piping Program, Experiment 1.3-5 from IPIRG-1, Experiment 1-5 from IPIRG-2, and the BINP Task 1 experiment), it can be seen that the primary stresses for the BINP Task 1 experiment represented only 35 percent of the total stress at maximum load.
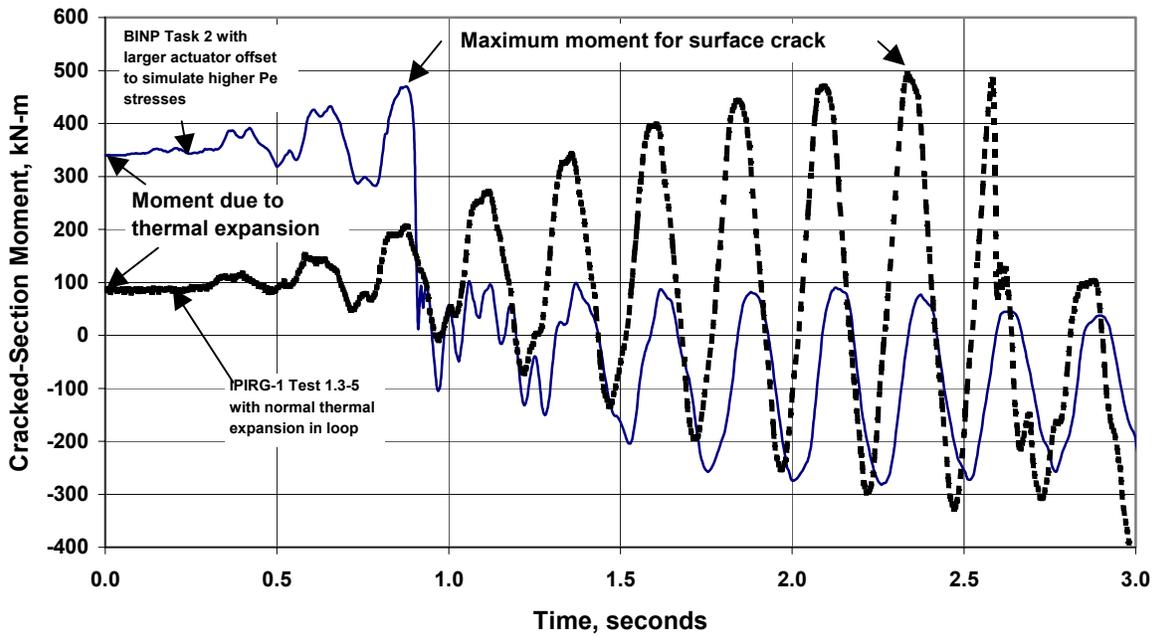
Figure A.3 Plot of crack section moment as function of time for BINP Task 1 experiment and IPIRG-1 Experiment 1.3-5
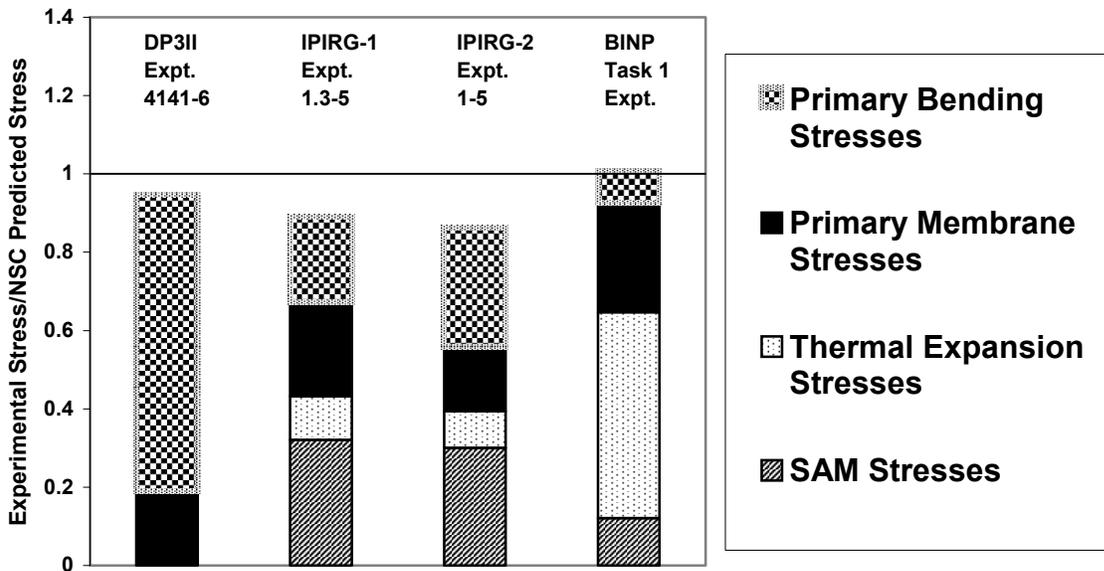
Figure A.4 Comparison of the results from four stainless steel weld experiments showing the contributions of the various stress components to pipe fracture

These findings support the contention that the thermal expansion and seismic anchor motion (SAM) stresses (secondary stresses) are as detrimental as the primary stresses, at least for these test conditions for which the stresses at failure for the uncracked pipe were less than the yield strength of the material.

For such conditions, there is the potential for elastic follow-up. Section III of the ASME code recognizes this potential in its local overstrain criteria in paragraph NC-3672.6(b). This paragraph implies that global secondary stresses, such as thermal expansion and seismic anchor motion stresses, can act as primary stresses under certain conditions, such as when the weaker or higher stressed portions of the piping system are subjected to strain concentrations due to elastic follow-up of the stiffer or lower stressed portions. One such obvious example of this is the IPIRG pipe system in which a large crack is introduced into a weaker material (lower yield strength) than the surrounding materials. Consequently, the resultant stresses for the uncracked pipe sections were less than the yield strength at the time of failure of the cracked section. The implication is that the safety margins for secondary stresses may be a function of the ratio of the failure stress to the yield strength. If the failure/yield stress ratio is less than 1.0, then global secondary stresses should probably be treated the same as primary stresses for fracture in the stability/critical crack size analyses. If the opposite holds true, then the global secondary stresses may become less important with some nonlinear function.

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