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CURRENT RESULTS FOR THE NRC'S SHORT CRACKS IN PIPING AND PIPING WELDS RESEARCH PROGRAM

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INTRODUCTION

The overall objective of the Short Cracks in Piping and Piping Welds Program is to verify and improve engineering analyses to predict the fracture behavior of circumferentially cracked pipe under quasi-static loading with particular attention to crack sizes typically used in LBB or flaw evaluation criteria. Other specific efforts focus on clarification of technical issues that evolved during the NRC's Degraded Piping Program - Phase II. The program consists of 8 technical tasks as listed below.

- Task 1 Short through-wall-cracked (TWC) pipe evaluations
- Task 2 Short surface-cracked (SC) pipe evaluations
- Task 3 Bi-metallic weld crack evaluations
- Task 4 Dynamic strain aging and crack instabilities
- Task 5 Fracture evaluations of anisotropic pipe
- Task 6 Crack-opening-area evaluations
- Task 7 NRCPIPE Code improvements
- Task 8 Additional efforts

This paper reflects changes made to the program since its conception through February 1993. Task 8 contains various new efforts. Some new efforts or changes in efforts are also in the first 7 tasks.

SUMMARY OF RESEARCH PROGRESS

Technical efforts in the NRC's Short Cracks in Piping and Piping Welds research program started in May of 1990. Because of the number of activities in the program, only a few of the more recent ones can be summarized in this paper. Further details are given in References 1 through 5. The full-scale pipe experimental efforts involve conducting pipe fracture experiments at LWR conditions. These data will then be used to validate and/or develop improved analysis procedures for leak-before-break or in-service flaw inspection criteria such as the ASME Section XI Article IWB-3640 and 3650 criteria.

TASK 1 - SHORT THROUGH-WALL-CRACKED (TWC) PIPE EVALUATIONS

This task involves conducting a number of pipe experiments and making improvements to the current J-estimation schemes as needed. All the pipe experiments have been completed and details are given in past reports, see References 2 through 4.

Much of the analysis has been conducted and improved GE/EPRI functions developed, see Reference 3. More significant errors were found in the plastic rotation function h_4 as opposed to the h_1 function relating J to load. An additional analytical development was the incorporation of the weld metal strength into the LBB.ENG2 J-estimation scheme. This is the only J-estimation scheme that incorporates the effect of weld metal strength. The development of the method is given in Reference 2, and a critical evaluation using past data on solution annealed and as-welded, stainless steel weld, cracked-pipe experiments from the Degraded Piping Program is underway.

TASK 2 - SHORT SURFACE-CRACKED PIPE EVALUATIONS

This task involves conducting smaller diameter pipe experiments with short surface cracks, to determine effects of R/t ratio and crack size on the Net-Section-Collapse analysis, and large diameter pipe experiments to assess the effect of toughness on the failure loads. The smallest flaw size that would ensure a non-buckling-type failure was chosen. Hence uncracked pipe buckling analyses were also conducted to design the experiments. The fracture analyses involve making modifications to the SC.TNP analysis (Reference 6), development of a J-estimation scheme for surface cracks based on a similar approach used in the LBB.ENG method, and finite element analyses of the experiments to verify the estimation schemes.

All the small diameter pipe experiments have been completed. These were conducted using stainless steel pipe, so that with the high toughness and the small pipe size, the pipes should fail under limit-load conditions. The experimental loads were compared to the Net-Section-Collapse analysis loads, see Figure 1. This showed that the R/t effect determined from the long crack experiments in the Degraded Piping Program was similar to the short crack experiments from this program. Hence, the Net-Section-Collapse analysis should have an R/t correction to it that appears to be independent of the flaw size.

All but one of the large diameter pipe experiments have been conducted. These results are currently being analyzed, and the details of the experiments can be found in References 2 through 4. Much of the fracture analyses is just starting and will be reported in future meetings.

TASK 3 - BI-METALLIC WELD CRACK EVALUATIONS

The objective of this task is to conduct experiments and assess the current analytical engineering J-estimation schemes to assess the behavior of through-wall cracks in bi-metallic welded pipe. This work has just begun and will be presented in the future.

TASK 4 - DYNAMIC STRAIN AGING AND CRACK INSTABILITIES

The objective of this task is to predict the effect of crack instabilities, believed to be due to dynamic strain aging (DSA), on the fracture behavior of ferritic pipe. Specific objectives are to establish a simple screening criterion to predict which ferritic steels may be susceptible to unstable crack jumps, and to evaluate the ability of current J-based analysis methodologies to assess the effect of unstable crack jumps on the fracture behavior of ferritic steel pipe at LWR temperatures.

Much of the past work concentrated on developing a screening criterion to determine if a given ferritic steel is sensitive to DSA. An elevated temperature hardness test method was developed as a DSA screening criterion, see References 3 and 4. Recent work concentrated on obtaining dynamic load, displacement, and crack growth data during a crack jump. It was found the average crack velocity of one of these crack jumps was 0.5 meters/second, which is orders of magnitude slower than a cleavage fracture instability, but 40,000 times faster than the stable crack growth in C(T) tests.

One disconcerting fact that was found was that these crack instabilities were more likely to occur in pipe experiments than in C(T) specimens. Furthermore, detailed metallurgical examination of fracture surfaces where crack jumps occurred showed no microstructural evidence of why a DSA crack instability started or arrested. The occurrence of DSA crack instabilities appears to be probabilistic, and the best we can do at this time is to use the elevated temperature hardness screening test to determine if a material is susceptible to DSA at LWR temperatures.

TASK 5 - FRACTURE EVALUATIONS OF ANISOTROPIC PIPE

The objective of this subtask is to assess if anisotropic fracture properties (where the toughness is typically lower in the helical or axial direction than in the circumferential direction for ferritic seamless pipe) together with having high principal stresses in a helical direction can lead to a lower failure stress than the longitudinal stress for a circumferential crack. Information about the effects of tensile test and C(T) specimen orientation can be found in References 3 and 4.

TASK 6 - CRACK-OPENING-AREA EVALUATIONS

The objective of this subtask is to make improvements in the crack-opening area predictions for circumferentially cracked pipe, with particular attention to cracks in welds. The crack-opening-area analyses will be incorporated into the NRCPIPE code, and the SQUIRT leak-rate code. The major effort undertaken most recently was a probabilistic LBB analysis specifically to provide guidance to the NRC for changes to NRC's Reg. Guide 1.45 on leakage detection systems.

Quantifying Leak-Rates for Updating Reg. Guide 1.45

The objective of this effort was to perform analyses to support changes to the NRC's current Regulatory Guide 1.45, ''Reactor Coolant Pressure Boundary Leakage Detection Systems". Regulatory Guide 1.45 was published in May, 1973, and is undergoing revision. The NRC currently wants to update this procedure taking into account the current leak-detection instrumentation capabilities, experience from the accuracy of leak-detection systems in the past, and current analysis methods to assess the significance of the detectable leakage relative to the structural integrity of the plant. Leak-detection capabilities at normal operating conditions are used in current leak-before-break (LBB) analyses. The consistency of the LBB procedures needs to be considered in any changes to Regulatory Guide 1.45. Additionally, the impact of such changes on structural integrity of piping not approved for LBB needs to be considered.

The probabilistic analysis undertaken was a significant effort to provide conditional probabilities of PWR and BWR plants, with both austenitic and ferritic piping material. The LBB.ENG2 J-estimation schemes in NRCPIPE for maximum load predictions and the leak-rate analyses in the SQUIRT code were used as the basic deterministic models. Failure is defined to occur when the N+SSE stresses reached or exceeded the maximum stresses predicted by the LBB-ENG2 J-estimation scheme. Statistical data involved the following.

- The parameters for Ramberg-Osgood curves and power-law fits to the J_d-R curves were determined from the PIFRAC database and other data at Battelle. Cross correlations were established between the strength and toughness for base metals.

- The locations of cracks in either weld metal or base metal was determined by examining available reports on crack removed from service. About 1/3 of the crack were in welds.

- For the leak-rate parameters such as surface roughness, an examination of various cracks removed from service showed that the past leak-rate models were too simple to reflect actual cracks geometries. For instance, the past leak-rate models assumed that cracks grew straight through the thickness, and accounted for the pressure drops due to the number of turns but didn't account for the turns making the flow path longer. Also, the surface roughness was assumed to be a constant value, where in reality if the crack is tight there may be a large number of turns, but the effective surface roughness is the roughness of the grain boundaries. For large crack openings, the number of small turns becomes less, but the surface roughness increases to reflect, for instance, the growth of the crack along grain boundaries. A new leak-rate model was developed to determine the effective surface roughness, number of turns, and flow path length as a function of the crack opening. Statistics of these parameters were developed by examining the fracture surfaces for IGSCC, corrosion fatigue, and thermal fatigue cracks removed from service.

- Perhaps one of the most difficult statistical variables was the level of stress in the "generic" piping systems of plants throughout the United States. Numerous contacts were made with NRC staff, various researchers in the U.S., and examination of published reports. The normal operating stresses were taken as conservatively 50 percent of the ASME Service Level A limit. The normal plus SSE loads were found to be conservatively bounded by the ASME Service Level B limit, see Figure 2. Initially, Service Level D limits were to be used, but the stresses from various sources showed that a much lower stress level existed. Future changes to plant piping designs, such as snubber reductions, could change the normal plus SSE stresses.

The probabilistic analysis involved evaluating the failure probability as a function of leak rate. It was assumed that a leak occurred, and the a seismic event would also occur. "Average" probabilities of seismic events of 10^{-4} per year are frequently quoted and would increase the conditional failure probabilities calculated, however, the SSE stresses correspond to a plant specific probability of occurrence. Furthermore, the failure probability should also consider the time from when a leak starts and the plant is shut down for inspection or repair.

Due to the large number of calculations, advanced probabilistic analysis rather than Monte Carlo simulations was used. Figure 3 shows a comparison of the FORM/SORM advanced analytical probabilistic results to Monte Carlo analyses for one case. Figure 4 shows the ratio of the computational time of the FORM and SORM methods compared to Monte Carlo simulations as a function of the failure probability. The computational efficiency of the FORM/SORM methods is significantly better than Monte Carlo simulations at the low failure probabilities, which with the over 300 probabalistic analyses conducted made this study possible. The results of this work are published in Reference 5. Figure 5 shows a summary comparison of conditional failure probabilities as a function of pipe diameter for austenitic and ferritic BWR pipe at a 1 gpm leak rate and for a normal operating stress of 50 percent of the ASME Service Level A limit.

TASK 7 - NRCPIPE CODE IMPROVEMENTS

The main objective of this task is to incorporate the analysis improvements from Tasks 1, 2, and 6 into the NRCPIPE code. A secondary objective is to make the NRCPIPE code more efficient and user friendly.

To date, a new version of the through-wall-crack version of NRCPIPE Version 1.4f has been released. This incorporated numerous user-friendly changes and a few technical changes. Any future changes to the J-estimation schemes due to improvements in analyses from the work performed in this program will be incorporated into Version 2.0.

We have also developed a finite length circumferential surface-cracked pipe J-estimation scheme code called NRCPIPES. Version 1.0 of this code incorporated the SC.TNP and SC.TKP J-estimation schemes developed in the Degraded Piping Program (6). It will include the ASME Section XI criteria in the future, and currently Version 1.0 is being tested.

TASK 8 - ADDITIONAL EFFORTS

This task was created specifically for efforts undertaken during the course of the program to assess aspects discovered during the program. To date there are 5 specific additional efforts being undertaken. These are:

Subtask 8.1 - Validation of J_m Resistance Curves
Subtask 8.2 - Evaluation of Fusion Line Toughness of Stainless Steel Flux Welds
Subtask 8.3 - Improvements and Addition to the PIFRAC Database
Subtask 8.4 - Development and Expansion of a Pipe Fracture Database
Subtask 8.5 - Archiving of Past Degraded Piping Program Pipe Fracture Digital Data

The efforts in Subtask 8.1, Validation of J_m-Resistance Curves, involve a theoretical evaluation of the limits on J_m. This effort is currently being undertaken by Professor Fong Shih at Brown University.

Subtask 8.2 entitled "Evaluation of Fusion Line Toughness of Stainless Steel Flux Welds" is currently being undertaken as a result of numerous pipe fracture experiments where a crack initially in the center of a weld, grew to the fusion line and continued to propagate there. The implication is that the fusion line offers a lower resistance to fracture than the weld metal. Since the flux welds are generally considered the lowest toughness in the ASME code and regulatory evaluations, this work could have significant impact on past evaluations. C(T) specimens prepared from a special weld so that the fusion line is perpendicular to the specimen surface, and with a standard single-Vee weld so that the notch is slanted through the specimen thickness will be tested. The slant notch specimens are typical of the full-scale pipe fracture behavior, but add the complication of mixed-mode fracture.

Subtask 8.3 involves improvements and additions to the PIFRAC database. This is a database initially created by MEA for the NRC to compile piping material property data. This database will be expanded by adding data from the final year of the Degraded Piping Program, the IPIRG program data, data from this program, and data from other sources in the U.S. and Canada. The size of the database is expected to triple. To date, quality assurance checks to the current data in PIFRAC.2, a dBase III+ version of PIFRAC, and some improvements to the format of the database has been made.

Subtask 8.4 entitled "Development and Expansion of a Pipe Fracture Database", involves compiling all the circumferential surface crack data into a common Lotus spread sheet. Currently, Version 1.0 of this database, CIRCUMCK.WK1, contains 146 pipe fracture experiments from past EPRI and NRC programs conducted at Battelle, as well as data from DTRC pipe fracture programs for the NRC. Data from numerous international programs will also be added to the database, with the number of experiments expected to reach over 300 in the final version. In addition to the pipe data, detailed material property data are also included, i.e., Ramberg-Osgood parameters, power-law fitted J_d-R curves, and Charpy data. These data are to be made readily available upon request, specifically for use to ASME Section XI pipe flaw evaluation task group efforts.

Subtask 8.5 involves archiving past Degraded Piping Program pipe fracture digital data files. Past data files were in an older HP computer format and are being translated into PC ASCII files for easy importation into spread-sheet programs.

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(6) Scott, P. M., and Ahmad, J. A., "Experimental and Analytical Assessment of Circumferentially Surface-Cracked Pipes Under Bending", NUREG/CR-4872, April 1972.

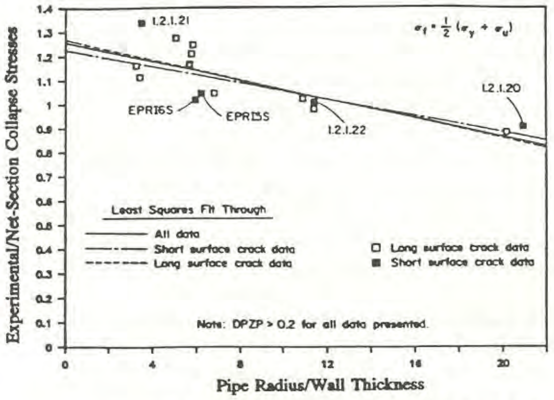

Fig. 1. Ratio of experimental stress to predicted stress as a function of pipe radius to thickness ratio (R/t)

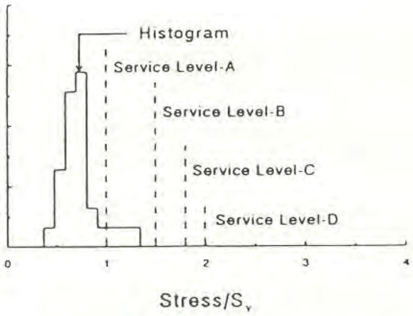

Fig. 2. Comparisons of actual N + SSE stresses with various service limits

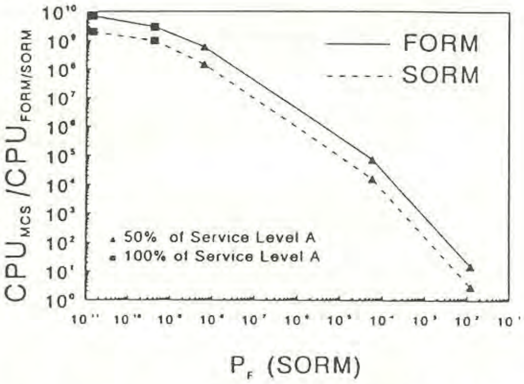

Fig. 4. Computational efficiency of FORM/SORM (BWR-1)

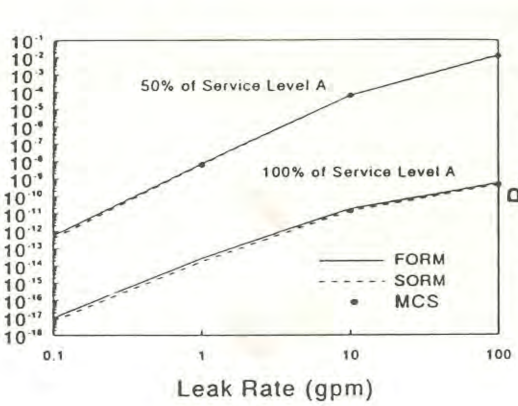

Fig. 3. Conditional probability of failure by various methods (BWR-1)

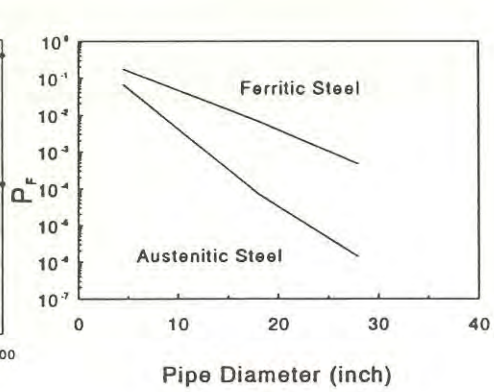

Fig. 5. Conditional failure probability as a function of diameter in BWR pipes at 1 GPM and normal operating stress equal to 50 percent of Service Level A