Commonwealth
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Braidwood Station—Units 1 and 2 Engineering Evaluation of the Pipe Corrosion Problem Identified in CECo NCR #633

Docket Nos. 50-456 and 50-457

January 1986

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Contents

I. Executive Summary

This report documents the conclusions reached by Commonwealth Edison Company (CECo) with respect to the corroded pipe problem identified in Nonconformance Report (NCR) 633, Revision 1. These conclusions are based on engineering evaluations and studies performed by Sargent & Lundy (S&L) and a consultant. CECo has evaluated S&L's conclusions and the bases for them and has determined that these conclusions provide an adequate basis for dispositioning NCR 633. This report is intended to serve as the basis for the final report for closure of 10 CFR 50.55(e) 84-10 and also to serve as the basis for closure of Item 2 in the Notice of Violation issued in connection with NRC Staff Inspection Report 84-17.

NCR 633, Revision 1, identifies certain nonconforming heats of small bore (2-inch, 1-1/2-inch, 1-inch, 3/4-inch, and 1/2-inch) carbon steel piping. (A "heat" refers to a batch of steel produced in the primary melt of the steelmaking process. A heat number is uniquely assigned to each batch of steel.) The heats identified in NCR 633, Revision 1, have areas below the wall thickness required by the material specification to which the pipe was fabricated, ASME SA-106 Grade B. (This material specification is identical to ASTM A-106, and the two are hereafter used interchangeably.) This wall thickness is the nominal wall thickness of the pipe minus a 12-1/2% manufacturer's tolerance to account for manufacturing variability.

The pipe found not to satisfy that material specification was believed to be affected by one or more of the following conditions:

- Corrosion resulting from unprotected outdoor storage

- Surface defects

- Potentially excessive chemical cleaning

This failure to uniformly meet the minimum wall thickness requirement of the material specification for a single heat was reported by CECo to the NRC, as required by 10 CFR 50.55(e). It was reported orally on June 21, 1984, and by letter on July 20, 1984, and was designated Report 84-10 for tracking purposes. On September 18, 1984, the notification was expanded to cover other heats and sizes of pipe.

The observed defects gave rise to two concerns regarding the adequacy of the pipe installed in safety-related systems. First, reduced wall thickness could potentially result in the piping not complying with the design requirements of the ASME code. Second, chemical residue on certain chemically cleaned pipe could induce further degradation of the material. Sargent & Lundy and CECo jointly developed a program to address both concerns and to provide an engineering disposition for NCR 633. The program consisted of a very conservative engineering evaluation, the results of which were confirmed by two additional measures: a material testing program and a statistically based wall thickness measurement sampling program.

The fact that pipe wall thickness does not meet the minimum required by the material specification does not mean that the pipe is unacceptable under the ASME code. The code is met if the code allowable stresses are not exceeded when the actual wall thickness and the design loads are used in the analysis.

In order to assess the corroded pipe, CECo personnel chose approximately 1000 feet of the affected pipe which appeared to exhibit the worst discrepancies in terms of pitting and other surface defects, measured the extent of the defects, and sent this data to S&L for further evaluation. Sargent & Lundy was asked to perform studies to determine whether the affected pipe continued to meet the minimum wall thicknesses required by the ASME code to accommodate the stresses resulting from the applicable pressure and mechanical loading. This evaluation established that even with the application of conservative stress increase factors to take account of reduced wall thicknesses from pitting and localized thinning, all the piping met the ASME code allowable stresses with the exception of six pipe segments. As a prudent measure, even though the evaluation was very conservative, those six segments were removed and replaced with new pipe. Subsequent measurements performed on these six segments confirmed that they were acceptable because they would, in fact, have met all code stress allowables.

In addition, it was subsequently observed that additional margin relative to ASME code allowable stresses could be obtained by replacing the next four most highly stressed pipe segments. Therefore, again as a prudent measure, these four pipe segments were also removed and replaced by new pipe, even though they met the acceptance criteria established by the conservative initial evaluation.

Thus, the 10 most highly stressed segments where the affected pipe could have been used have been removed from the plant and replaced with new pipe. This action ensures that the affected pipe will not be in service at locations of high calculated stress.

Samples of the affected pipe were then tested by a consultant to confirm the conservative nature of the engineering evaluation. The testing also confirmed the assumption, implicit in the evaluation, that the material properties of the affected pipe were typical of those expected in ASTM A-106 piping materials. Testing included provisions to determine the effects of corrosion on the chemical, mechanical, and metallurgical properties of this pipe. Testing also included provisions to determine whether corrosion-inducing chemicals were still present, and whether such chemicals could have an adverse effect on the pipe during its normal operating life. These tests demonstrated that the samples met or exceeded all applicable requirements and that no degradation in service life or performance should occur.

A confirmatory study was performed, based on actual wall thickness measurements of a statistically based sample of the affected pipe installed in Unit 1 and common systems and that remaining in storage in order to confirm that the piping met the code allowable stress levels. These evaluations confirm that at any location where the affected pipe was used in Unit 1 and common systems, the pipe still meets ASME code allowable stress levels. An engineering judgment was made that this evaluation applies equally to affected pipe installed in Unit 2.

On the basis of CECo's evaluation of S&L's studies, all the affected piping which has been installed will be allowed to remain. However, as a further prudent measure, CECo will not install the remaining affected pipe in safety-related applications.

The piping affected by NCR 633, Revision 1, was ordered by CECo on December 8, 1976, when CECo placed a purchase order for various sizes and schedules of SA 106 Grade B carbon steel small-bore piping (2 inches and under). The pipe was manufactured by Gulf States Tube Corporation to the ASME SA 106 material specification, certified as such, and shipped to the Braidwood site. As part of this order, the site received a total of approximately 341,000 feet of ASME Section III, Class 2 safety-related pipe on various dates from August 1977 to early 1978.

At that time, construction activities at the Braidwood site had not progressed to the point where small-bore pipe would be installed. The pipe was stored outdoors on open racks, uncovered and uncapped.

In 1981 construction had proceeded to the point where installation of the small-bore piping was initiated. By that time, rust and corrosion had formed on the inside and outside surfaces of the pipe from exposure to the elements, and it was decided to clean the pipe by immersion in a chemical bath before using it.

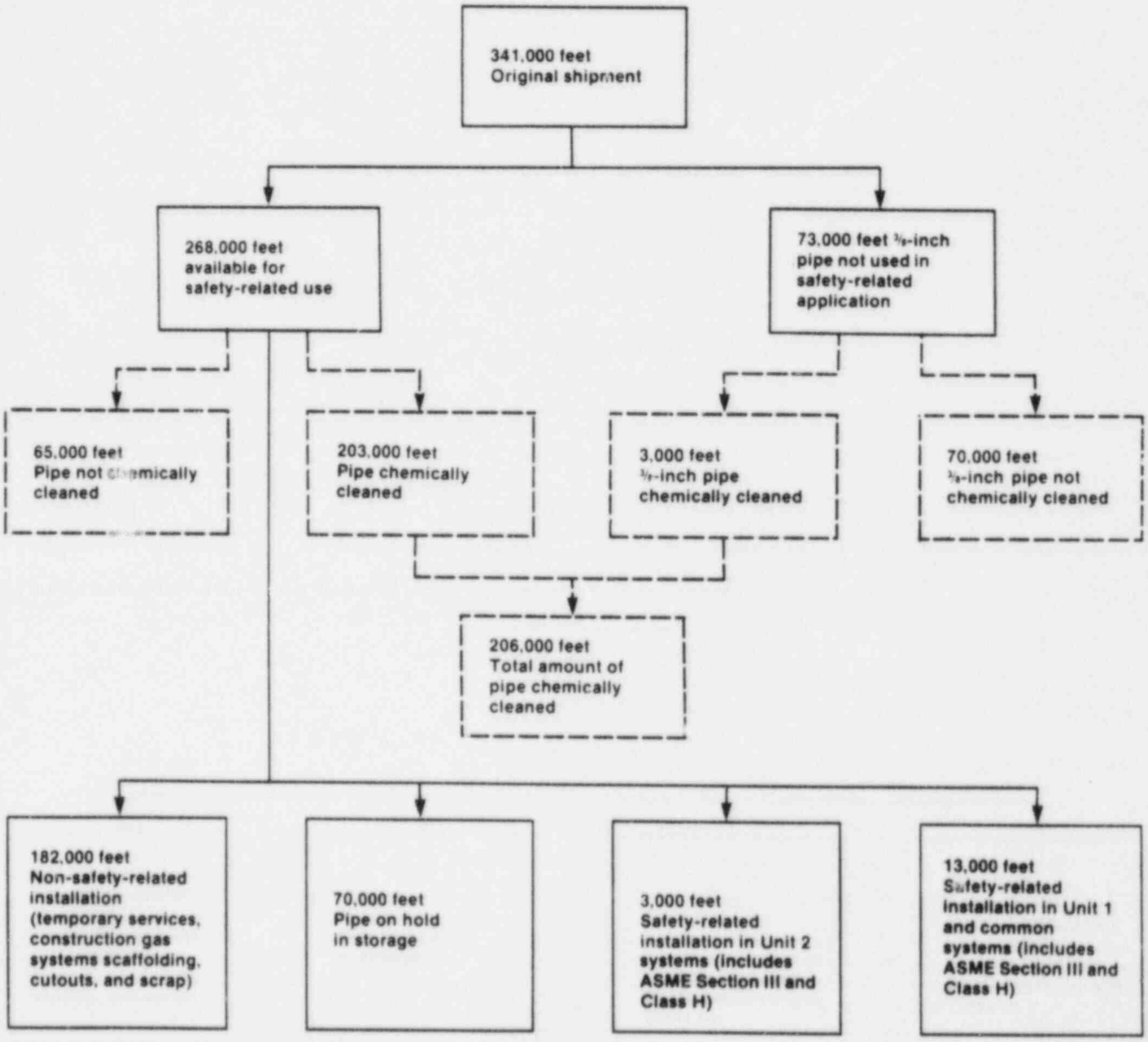
Two purchase orders, Nos. 254379 and 730091, were issued by CECo to the H. H. Howard Company. The purchase orders required that the chemical cleaning process follow designated steps. The methods of cleaning were standard commercial methods, and it was believed by CECo that they would not adversely affect the pipe. As a result, CECo believed the cleaning process itself was non-safety-related and accordingly issued the purchase orders to H. H. Howard, a non-safety-related vendor. Accordingly,

H. H. Howard was not required to have an approved QA program. In a letter to Braidwood Project Construction, H. H. Howard documented the chemical cleaning methods that would be used. This list of methods was forwarded to S&L for review prior to approval by CECo. A Field Change Request allowing the cleaning was then approved. In order to maintain required material heat traceability, each piece of pipe to be chemically cleaned was mechanically marked with a heat code identification.

As depicted on Exhibit 1, of the approximately 341,000 feet of pipe originally received, about 268,000 feet were available for installation in safety-related piping systems. The remaining 73,000 feet of piping are 3/8-inch diameter pipe, and no safety-related systems in the plant require use of this size pipe. Not all of the pipe received at the site in the original shipment was chemically cleaned. Of the approximately 268,000 feet of pipe available for installation in safety-related applications, about 203,000 feet were chemically cleaned by H. H. Howard Company. In addition to this 203,000 feet, approximately 3,000 feet of the 3/8-inch pipe were also chemically cleaned. Based on as-built drawing review, of the 268,000 feet of pipe available for installation, a maximum of about 13,000 feet was installed in safety-related applications in Unit 1 and common systems. A computerized status report indicates that an estimated 3,000 feet were installed in safety-related applications in Unit 2. Approximately 70,000 feet remain in

Quantity Breakdown of Pipe Under the Scope of CECo NCR 633, Rev.1

Exhibit 1



Note: Numbers on this chart are approximate.

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storage, and the remaining 182,000 feet have been used for plant temporary construction systems, scaffolding, and non-safety-related piping applications.

The pipe that had been chemically cleaned was returned from H. H. Howard between late 1981 and the middle of 1982. Upon return, the pipe was received and documented on CECo Material Receiving Reports, and a receipt inspection was performed. Dimensional checks were not performed as part of these inspections. The pipe was inspected for proper cleaning and for handling or shipping damage. Quality documentation was not required from H. H. Howard with the shipments. After receipt, the pipe was stored indoors in a warehouse and the ends were capped.

In December 1983, while performing dye penetrant tests on small-bore piping welds, Philips, Getschow Company (PGCo) observed axial surface indications on some installed 2-inch pipe from material heat number KD6751. PGCo issued an NCR and dispositioned it internally by undertaking to determine locations in which pipe from this heat was installed. This matter was brought to the attention of CECo Project Construction in late April 1984. CECo instructed PGCo to investigate further and issue reports. Upon further investigation it was observed that some pipe from this heat of material was pitted and corroded. PGCo measured wall thicknesses of the pitted and corroded pipe, both installed and in storage. Samples of pipe from heat KD6751 were discovered to be deficient, in that they did not meet material specification requirements for minimum wall thickness.

As a result of these reviews, a 10 CFR 50.55(e) notification was issued to the NRC on June 21, 1984. On June 28, CECo NCR 633 was issued to document the problem. All 2 inch schedule 80 pipe with heat number KD6751 was placed on hold. Further measurements were performed on other samples of stored pipe, and it was determined that carbon steel small-bore pipe from other heats and in other sizes from the original 341,000 foot shipment had similar problems. CECo issued Revision 1 to NCR 633, expanding the scope of the recognized problem, and similarly expanded the scope of the 10 CFR 50.55(e) notification.

In August 1984, CECo put a hold on all the pipe from the original shipment that had not yet been installed; this amounted to approximately 70,000 feet of pipe. CECo developed a program to determine whether the pipe installed in safety-related systems was adequate. The tasks performed by PGCo as a part of this program were controlled and documented in accordance with the PGCo quality assurance program. Certain detailed activities were performed as prescribed by approved PGCo Procedures PGCP-52.

Part of this program involved a PGCo engineering department review of the as-built isometric drawings to determine all locations in Unit 1 and common systems where this size and type of pipe could have been used. It was assumed that in any location on the drawing where suspects pipe could have been used, it was in fact used. By this method it was determined that a maximum of 13,000 feet of the pipe in question had been installed in Unit 1 and common safety-related systems. Because as-build isometric drawings were not yet available for Unit 2, PGCo based its estimate on a computerized status report that identified the small-bore carbon steel pipe installed in Unit 2 prior to August 1984. By this method it was determined that approximately 3,000 feet had been installed in Unit 2.

Samples of the affected pipe in storage selected by CECo engineers were sent to CECo's System Materials Analysis Department (SMAD). A metallurgical analysis performed by SMAD (summarized in Ref. 2) showed that the material was typical of A-106 Grade B carbon steel, but that a combination of pitting and localized thinning had resulted in wall thicknesses at certain localized locations of less than that required by the ASTM A-106 material specification. Minimum wall thickness under the material specification is defined as the nominal wall thickness specified in ANSI B36.10 minus the ASTM A-106 allowed manufacturer's tolerance of 12-1/2%.

In addition, contractor personnel under the direction of CECo performed detailed pit depth measurements and wall thickness measurements on other samples of the piping in storage using a pit depth gauge and a digital thickness meter. Pit depth measurements were made on both the ID and OD surfaces of split sections of pipe. These measurements were taken at locations which appeared to the inspectors to be the worst or deepest pits in the given segment of pipe. The sample consisted of 272 segments representing over 1000 feet of pipe which were considered by CECo engineers to be the most affected by pitting and corrosion. Out of 544 pit measurements on the 272 samples, the deepest pit found was 0.033-inch deep, while averaging the "worst" pit from each segment resulted in a depth of approximately 0.011 inch.

The results of these measurements were forwarded to S&L. Sargent & Lundy was requested to investigate the problem, to help develop a program to determine whether the installed piping still met ASME code requirements and could perform its intended design function.

On the basis of the above pit depth measurements, S&L performed a highly conservative engineering evaluation to determine whether the affected pipe met all ASME code allowable stress levels. CECo had concluded that the selection of the 1000 feet of corroded pipe from storage, which was based on engineering judgment, was representative of the worst corrosion that would be found in the pipe installed in Unit 1, Unit 2, and common systems. Based on these measurements, the S&L engineering evaluation made conservative assumptions regarding pitting and wall thinning. (The statistical based sample performed subsequently confirmed that the selection based on engineering judgement was representative and did result in an appropriately conservative evaluation.)

It was judged that the engineering evaluation would be applicable both to the chemically cleaned and the corroded uncleaned pipe. This was later confirmed by Dr. Steven Danyluk, a corrosion expert, who examined specimens of the corroded pipe and the pipe which was corroded and chemically cleaned, as well as specimens of new pipe. Dr. Danyluk concluded that there was no relevant difference in the corrosion behavior of the three categories of pipe (Ref.9).

Pipe with a wall thickness that does not meet the material specification is not necessarily unacceptable under the ASME code. The wall thickness requirements of the material specification are intentionally quite conservative. The code contains equations to be used in determining the minimum wall thickness required to meet the piping design pressure. (ASME code, section III, subsections NC and ND, paragraphs NC/ND 3641, equations (3) and (4)). In selecting a schedule of pipe, the designer adds various allowances (bend allowance, manufacturer's tolerances, etc.) to this minimum wall to determine the actual wall thickness required at the specified designed pressure. He then selects piping with the next highest commercially available nominal wall for that application. This was the procedure followed by S&L in selecting and specifying the small-bore piping to be installed at Braidwood. This procedure for selecting the nominal wall assures that the actual wall thickness less the manufacturer's tolerance will conservatively accommodate the design pressure. The installation of piping with wall thickness less than nominal wall minus manufacturer's tolerance, however, is acceptable under the code, provided that the code design equations are still satisfied.

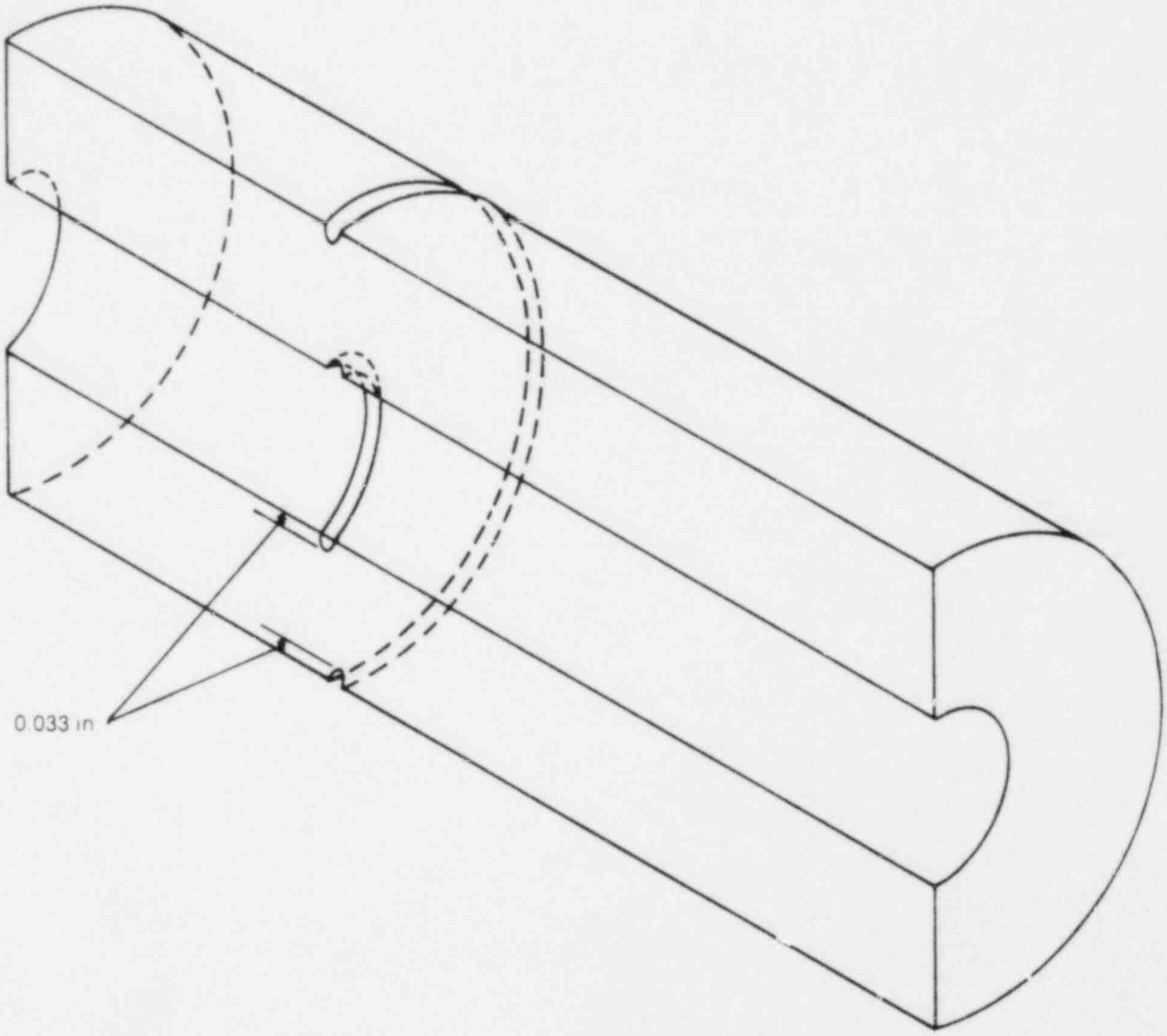
Sargent & Lundy analyzed the ability of the affected pipe to withstand the design pressure. A comparison was made between the minimum wall for pressure loads calculated using the applicable code equations, and the wall remaining after subtracting the maximum pit depth, the maximum mill tolerance, and the maximum bend allowance (for bends with radii equivalent to three pipe diameters) from the B36.10 nominal wall. This comparison showed that the associated pipe sizes in the potential pressure applications where this piping could have been used would still meet the minimum wall requirements for pressure.

In addition to withstanding the internal design pressure, piping must be adequate to meet externally applied design loads. The piping stress analysis is required by the ASME code to be performed for dead weight, thermal, and seismic loads as applicable, using the nominal wall thickness, by application of ASME code subsection NC/ND 3652, equations (8), (9), (10) and (11).

Therefore, after establishing conformance with the code minimum wall pressure requirements, S&L performed studies to conservatively evaluate the adequacy of the corroded pipe to withstand the applicable stresses resulting from operating pressures and mechanical loads. Since information on the density and the distribution of the pits was not available, conservative assumptions were made about the stress increases attributable to such pits. Sargent & Lundy determined the increased stress concentration by developing specific stress increase factors for each size and schedule of piping to account for notch effects and section modulus reduction postulated to occur as a result of the reported pitting and localized thinning. ("Section modulus" is a numerical representation of the strength of a component in bending which varies with the geometrical properties of the cross-sectional area of the component.)

The notch effect component of the stress increase factor was based on the mathematical model shown in Exhibit 2, in which it was assumed that the 0.033-inch "worst" pit existed on both the OD and ID of the pipe at the

Exhibit 2

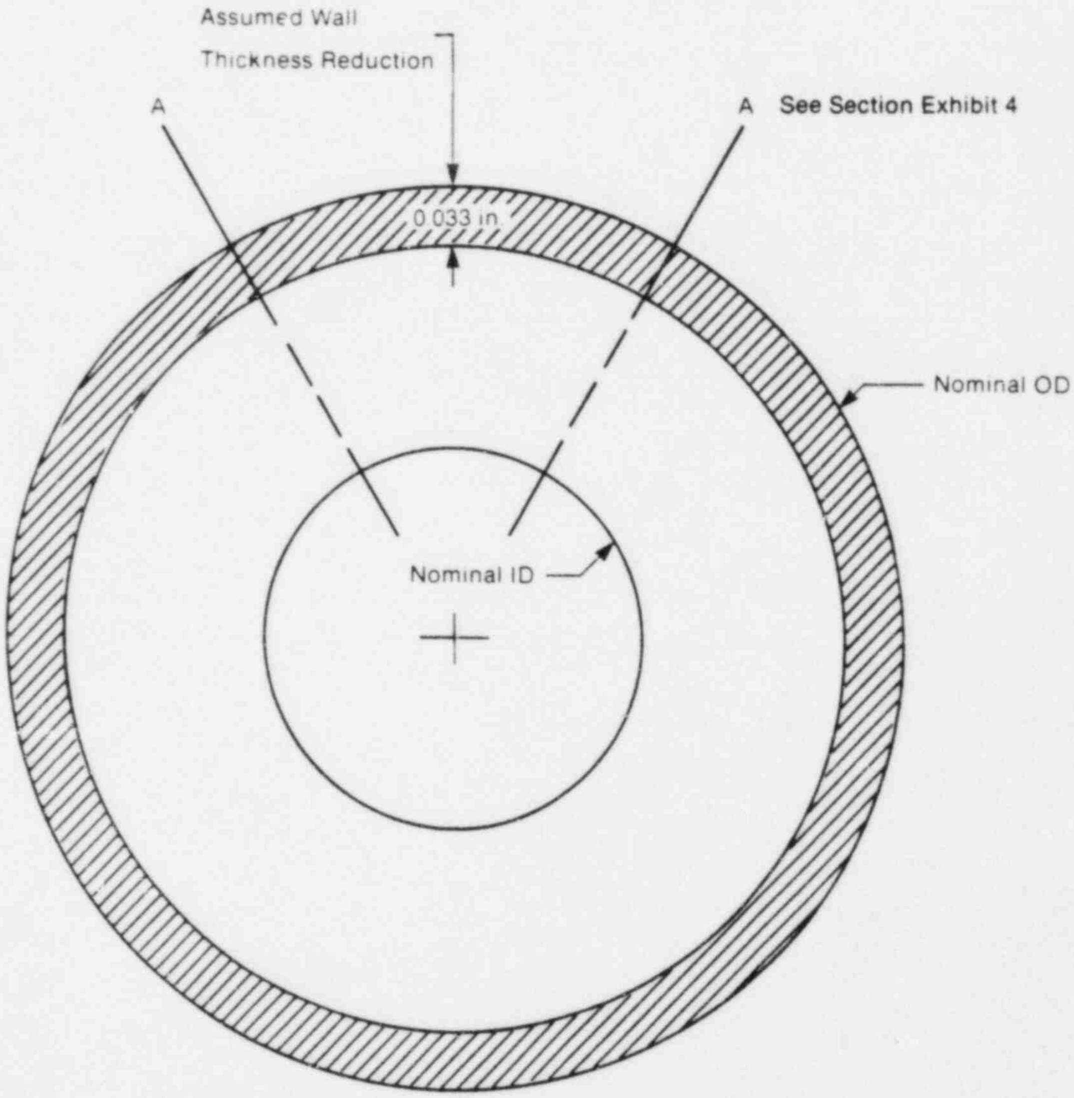


Mathematical Model for Calculation of "Theoretical" Notch Effect Stress Intensification Factor same axial location. This is a very conservative assumption because the actual observed pitting was random in depth and location around the circumference of the pipe, and only one pit measured 0.033-inch deep. Therefore, the probability of two pits of the maximum depth occurring exactly opposite one another on the ID and OD at the pipe and at the same longitudinal location is very low.

The reduction in section modulus was them calculated assuming that the worst pit (0.033-inch) wall reduction was not localized, but rather was represented as a uniform wall thickness reduction around the circumference of the pipe. In order to maximize the reduction in section modulus, this 0.033-inch wall thinning was assumed to occur entirely on the OD of the pipe as shown in Exhibit 3. Applying this reduction to the outside diameter is conservative in that it results in the greatest reduction of the available section modulus.

The assumptions relative to the notch effect calculations are conservative in light of the methods recommended to reduce stress concentration effects contained in standard mechanical design textbooks (e.g., Phelan, Fundamental of Mechanical Design, McGraw-Hill, New York, 1970, figures 6-7 and 6-8 on pages 113 and 114'; Shipley, Mechanical Engineering Design, McGraw-Hill, New York, 1972, figures 6-5 and 6-6 on pages 224 and 225). These texts indicate that the stress concentration effects of a groove can be decreased by making additional grooves on either side of the groove in question. These multiple

Exhibit 3



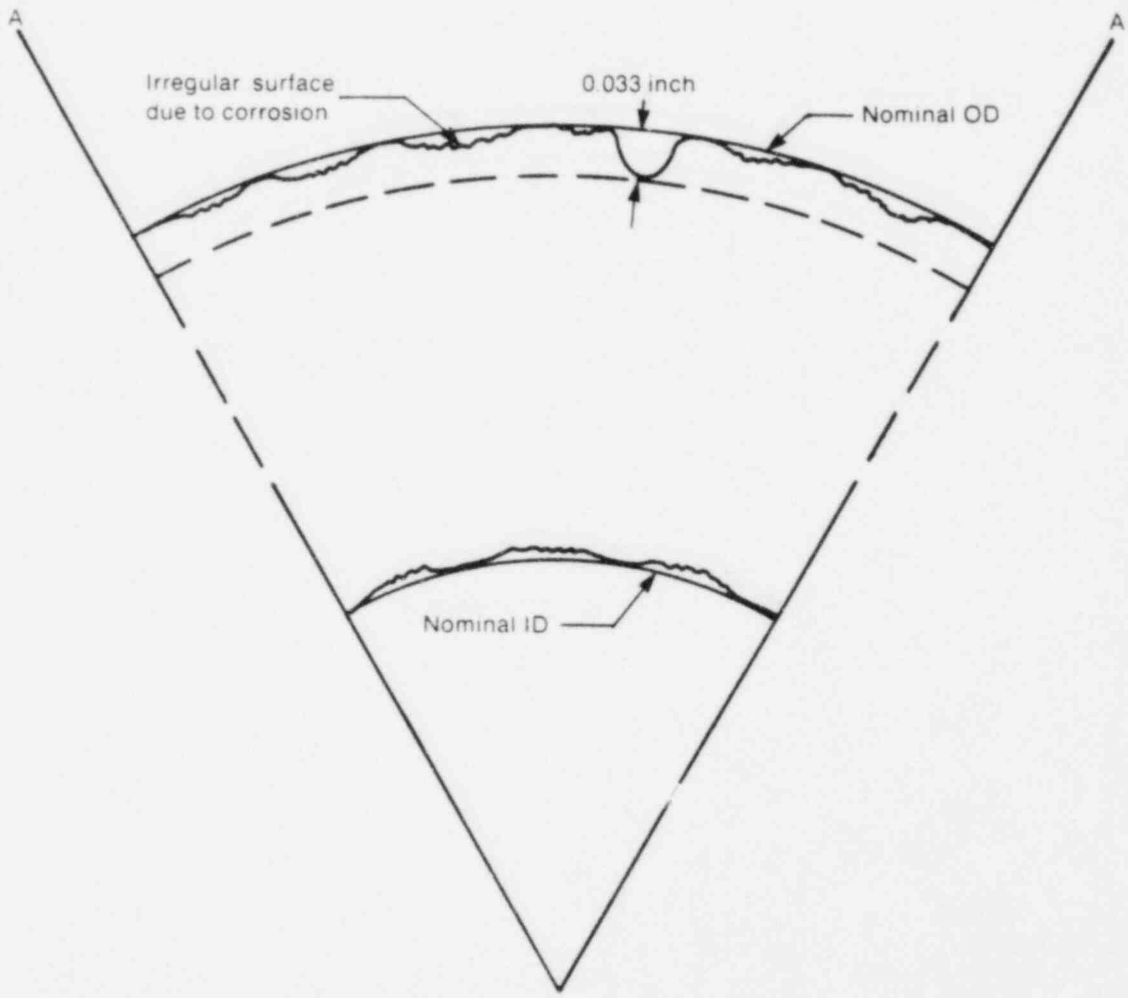
Mathematical Model for "Theoretical" Section Modulus Reduction
(Shaded area represents area of assumed metal loss.)

grooves of random depth reduce the stress concentration effect by decreasing the sharpness of bend of the "stress flow" lines in the member, In a similar manner, multiple pits on the surface of a pipe will tend to mitigate the stress concentration effects of any given single pit. (The conservatism of the analysis was later corroborated by the fatigue testing performed by Taussig Associates, Inc. (Ref. 6), as discussed in section IV of this report.)

The assumptions made concerning the section modulus reduction were also conservative. Exhibit 4 represents a typical cross-section of corroded pipe as found during the wall thickness sampling performed after the initial studies were completed. It can be seen from the figure that the reduction in section modulus due to the corrosion is negligible. Thus, the assumption of uniform metal loss based on the worst single point pit measurement is a very conservative assumption.

For these studies, then, two very conservative assumptions regarding increased stresses were applied simultaneously. The worst case notch effect stress increase factor was combined with the reduced section modulus stress increase factor to determine a "theoretical" overall stress increase factor. These conservatively estimated stresses were then applied to ASME section III, code subsections NC and ND, NC/ND 3652, equations (8), (9), (10) and (11) to determine the adequacy of the piping under the maximum stress increase which could be expected. Two separate evaluations were then performed.

Exhibit 4



Representation of a Typical Cross Section of Corroded Pipe.

In initially designing the pipe, S&L had employed two different methods of analysis. Sargent & Lundy designed the majority of the pipe using conservative simplified design rules that it had developed and that it regularly uses. (In this report such pipe will be referred to as the "simplified design pipe." In certain applications, however, where the pipe connected to large-bore pipe or where it would experience local loads not provided for in the simplified design rules, the pipe was designed with the assistance of computer analysis. (In this report such pipe will be referred to as the "computer analyzed pipe.")

In performing this stress evaluation, separate evaluations were performed for the simplified design piping for Class B, C (safety-related ASME class 2 and 3 piping) and H (safety-related instrumentation piping) applications and for the computer analyzed piping for Class B, C and D applications. Using the conservative stress increase factor calculated by S&L for each size and schedule of pipe, all locations where the pipe could have been installed in Unit 1 and common systems were evaluated.

Sargent & Lundy simplified design rules used a stress intensification factor throughout the original analysis. This factor represents a conservative approach to piping design and is utilized to reduce the need for mose costly detailed computer analysis. Therefore, simplified design pipe will not be potentially overstressed unless the theoretical overall stress increase factor exceeds the stress intensification factor used in the original design. The study considered all pipe in the plant which was designed by the simplified rules and showed that no piping exceeded the original factor. Therefore, all piping analyzed by the simplified method is acceptable and meets the ASME code allowable stresses.

Computer analyzed small bore piping was then evaluated, assuming that the stresses were increased by the theoretical overall stress increase factor calculated previously. The results of this evaluation (Ref. 5) showed that out of the approximately 38,000 node points in 324 subsystems (which included all Unit 1 and Common computer-analyzed piping), all nodes except for six met the code allowable stress levels when the conservatively-derived stress increase factor is uniformly applied to the applicable calculated stresses. (A node point is a mathematical representation of a specific physical location in the analytical model of a piping system used to define the point at which stresses are calculated.) If it could be determined, as it later was, that no stress increase factor due to notch effect was necessary, and that the actual wall thickness reduction was not as great as assumed, then these six nodes would also meet ASME code allowable stress levels. Nonetheless, as a prudent measure, since all the testing and wall thickness sampling was not yet complete, the six nodes were identified and cut out of the plant, and new pipe was installed in their place. It was later confirmed on the basis of the wall thickness sampling program and specific wall thickness measurements on these six nodes, that they did in fact meet all code allowable stresses and would have been acceptable had they remained in place.

In addition, in order to restore additional design margin relative to the ASME code allowable stresses, and to assure that the conservative initial evaluation would definitely bound any potential unforeseen variations in later tests and evaluations, the piping associated with the next four most highly stressed nodes of the computer analyzed piping was removed from the plant and replaced with new pipe.

Based on the results of this very conservative engineering evaluation, S&L concluded that, with the initial six nodes cut out, all of the pipe installed in Unit 1 and common systems met all applicable ASME code requirements and was capable of fulfilling its intended design function. As described more fully below, S&L made an engineering judgement that this conclusion applied equally to the pipe installed in Unit 2.

Sargent & Lundy established a testing program to confirm the conservatism of the engineering evaluation. The testing was also designed to confirm the assumption, implicit in the evaluation, that the material properties of the affected pipe are typical of those expected in ASTM A-106 piping materials. Finally, the testing was designed to address the additional concern that chemical residue left from cleaning might induce further corrosion in the pipe. Sargent & Lundy selected Taussig Associates, Inc., an independent testing laboratory, to perform the tests.

Three categories of tests were performed by Taussig Associates according to the requirements set forth in S&L Consultant Specification 121, "Metallurgical Testing Services." These categories were:

- **Fatigue Testing**
  Fatigue testing was performed on 11 samples of pipe to confirm that the notch effect component of the stress increase factor selected by S&L was conservative.

- **Other Confirmatory Testing**
  Six additional tests were performed to confirm that the general physical and chemical properties of piping material were within acceptable limits. These were:

  - Tensile Testing (9 samples)

  - Chemical Analysis (9 samples)

- Burst Testing (2 samples)

- Bend Testing (9 samples)

- Macro-Etch Examination (10 samples)

- Metallographic Examination (10 samples).

- **Testing for Chemical Residue**

  Three tests were designed to determine whether potentially corrosive residue remained on the piping material from chemical cleaning.

  - Deposit Analysis (OD Surface Deposits) (10 samples) by X-Ray Flourescence

  - Pit Residue Analysis (OD and ID Pits) (10 samples) by Energy Dispersion X-Ray (EDX)

  - Residual Chemical Acidity (pH) Testing (three samples)

The piping samples selected by CECo engineers for testing were chosen so as to be representative of the range of sizes and schedules of the heats affected by this corrosion problem. The specimens selected by CECo were those which were judged to exhibit significant pitting and corrosion. Samples of new pipe were also sent to be tested in order to establish a benchmark or a "control" sample for each test performed.

The results of this testing program are contained in Taussig Associates, Inc. Report No. 60493-2, dated 08-27-85 (Ref. 6). While the tests showed some minor differences between the corroded and new pipe samples, the corroded pipe was confirmed to have the same typical properties of, and to meet the ASTM material specification requirements for A-106 Grade B pipe.

1. Fatigue Testing

The fatigue tests were designed to confirm the conservatism of the assumption made regarding the notch effect stress increase factor in S&L's engineering evaluation. The tests consisted of the application of very large mecha[illegible]al loads (much beyond those levels expected during normal services of the pipe) in alternately opposing directions to determine the number of stress cycles that can be accommodated by the pipe. These tests establish a fatigue life (number of stress cycles) for the type of pipe involved. The ASME code addresses the fatigue life for the classes of pipe in question by requiring the application of certain stress intensification factors to certain configurations of piping. The stress intensification factors used in the ASME code are based on testing performed by Markl (Ref. 10).

Fatigue life of a particular component is significantly reduced by the presence of deep, narrow defects (notches). This so called "notch effect" results in a localized stress concentration and serves as a mechanism for more rapid failure of the component. The reason for performing the fatigue tests was to determine whether the pits in the affected pipe did result in this notch effect reduction in fatigue life and, if so, to determine whether the theoretical notch effect component of the stress increase factor calculated by S&L was adequately conservative.

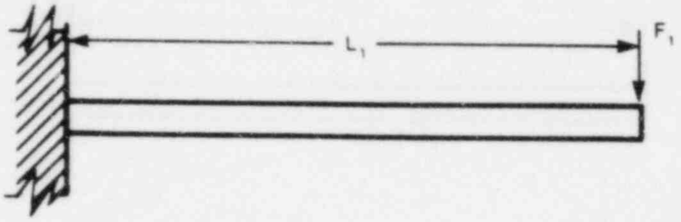
Fatigue testing was performed on 1/2-inch and 2-inch schedule 80 pipe sizes in order to bound the effect of the corrosion on the various sizes in question. The test was patterned after Markl's original fatigue tests which form the basis of the stress intensification factors used by the ASME code.

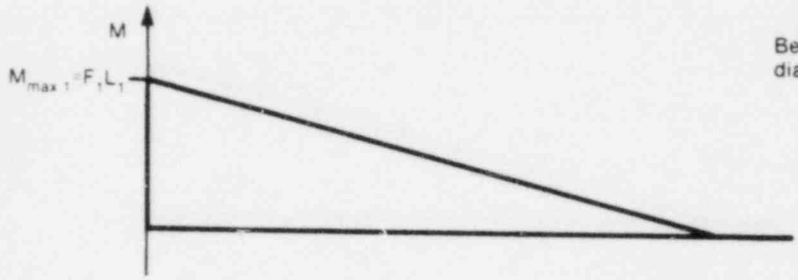
The samples selected for this fatigue testing were chosen from pieces significantly affected by corrosion and pitting. Markl's tests were limited to only one size of pipe (4-inch standard wall) and the results have since been extrapolated by the industry to cover other pipe sizes and schedules. In view of Markl's tests, the sample size selected for this testing program was judged to be adequate to obtain meaningful engineering results because their purpose was to verify that the range of values obtained were similar to those obtained by Markl. One variation from the Markl test methodology should be noted. A four-point bend was performed, rather than the cantilever beam bend utilized by the Markl method.

This four-point bend approach subjects a greater volume of pipe to the maximum moment, and thus is more conservative than the Markl test, which induced the maximum moment only at a single point. This can be seen by reviewing Exhibit 5. Because the four-point bend would distribute the maximum moment over a larger area of pipe, it provides increased assurance that the severely pitted areas on the pipe specimen are subjected to the maximum applied moment, thus yielding reliable results.

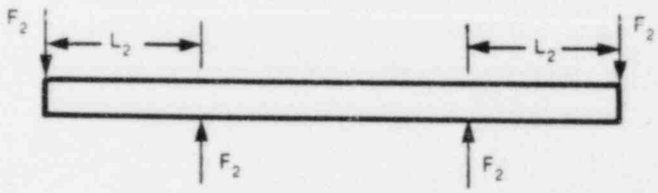
The results of these fatigue tests are shown plotted as S-N fatigue curves in Taussig's report as Figures 1 and 2. Superimposed on these curves are Markl's reference curves labeled "Not Clamped," which corresponds to a stress intensification factor of $i = 0.64$, and a second reference curve labeled "clamped," which corresponds to a stress intensification factor of $i = 1.0$. By inspection of these curves, it can be seen that all of the test data points plot above the $i = 1.0$ reference line, which means that the actual stress intensification of the pipe samples in less than 1.0. While minor differences exist between the curves for the "new" and "corroded" pipes, all curves fall within or above the bounds predicted by Markl for straight pipe sections. This means that the assumption of a stress intensification factor of $i = 1.0$ for all straight sections of corroded pipe is a valid and conservative assumption. It also establishes the conservatism in the initial evaluation, which utilized stress increase factors greater than 1.0, and eliminates the need to include the notch effect component of the stress increase factor in sequent evaluations.

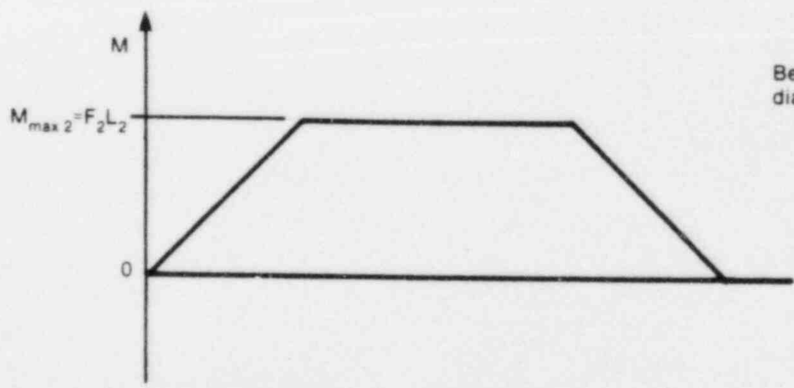
Cantilever Beam Bending (used in Markl's original tests)





Four Point Beam Bending (used in fatigue tests)





$$\boxed{M_{max1} = M_{max2}}$$

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2. Other Confirmatory Tests

A variety of tests was performed to confirm that the general physical and chemical properties of the piping material were within acceptable limits. This had been implicitly assumed by the engineering evaluation, because the evaluation was based on typical ASTM A-106 Grade B material properties. These tests verified this assumption, and therefore the tests support the conclusions reached based upon that evaluation.

Tensile tests were done on pipe samples which included the pitted ID and OD surfaces. The test results showed that the tensile strength, yield strength and elongation values met or exceeded the requirements for A-106 Grade B piping products.

The chemical analysis tests showed that the corroded pipe contained no significant amounts of contaminants or unusual alloying elements and that the samples were in conformance with the chemical requirements of ASTM A-106.

Both new and corroded pipe samples were subjected to hydrostatic burst tests. Again, there were minor differences between the test results; however, these variations are typical for experimental data scatter. All samples exceeded the ASTM minimum burst pressures by a factor of 3.5 or greater.

Bend tests were performed to verify ductility during the bend forming process. The test samples were bent over dies which had a much sharper radius (equivalent to 5 pipe diameters or less) than that required by ASTM A-106 (12 pipe diameters for standard bends and 8 pipe diameters for close bends) in order to assure conservative test results and to be consistent with the bend radius normally used by the piping contractor. The bent pipes were then visually examined by a qualified Level III Visual Examiner. These test samples met the bend test acceptance requirements of ASTM A-106 as no indications or other defects were noted on the nine pipe samples.

Macro-etch testing was performed on samples of the corroded pipe. Visual examination of the samples revealed no evidence of inherent defects or weld seams. Though no requirements are specified by A-106 for Macro-etch Testing, the samples observed were confirmed to be typical for A-106 type materials.

Metallographic examinations were performed on 10 samples of the corroded pipe. The samples exhibited microstructures which are typical of low carbon steel products such as A-106. The pitting on the ID and OD surfaces was observed to be broad and shallow. Surface imperfections which are shallow and rounded have a lower stress concentration effect than that associated with sharp notches and grooves. None of the samples displayed evidence of other unacceptable surface conditions such as intergranular or grain boundary attack, stress corrosion cracking, or indications of embrittlement. While A-106 has no specific requirements for this type of examination, the results were confirmed to be typical of A-106 type materials with the exception of the visible surface pitting.

3. Chemical Residue Tests

A series of tests was performed to determine whether chemical residues from the cleaning process might be present on the pipe and might cause or accelerate further corrosion. As noted above, the chemical analysis showed that no significant contaminants were present and that the samples were in conformance with the chemical requirements of A-106. These tests confirmed an assumption inherent in the S&L engineering evaluation, which did not account for the potential of future chemical attack.

A surface deposit analysis was performed by the x-ray flourescence test method as a part of the corrosive residue evaluation. No measurable amounts of chlorine or sulfur, possible corrosive agents, were identified. Other trace elements which were identified by these analyses would not be expected to either cause or accelerate corrosion.

An energy dispersion x-ray (EDX) analysis was also performed on the residue in the pitted areas and the results were found to be in good correlation with the surface deposit analysis. The most common trace elements were found to be aluminum, sulphur, and silicon. None of these represent any threat to the life of the pipe.

The outer surface of the piping was checked for corrosive chemical residue by adding deionized water to the outside surface of the pipe and checking the resultant pH. The acidity of the water was checked after letting the water stand for several minutes. No measurable change in the pH of the deionized water was noted. This test indicated that the sulphur and chlorine on the pipe surface are not in sufficient quantity or are not adequately chemically active to cause significant amounts of sulphuric or hydrocholoric acids to be formed when exposed to water. Therefore, this test indicated that there were no detrimental chemical residues remaining on the pipe surface, and the piping was not under chemical attack.

Dr. Steven Danyluk, a corrosion expert, examined specimens of the corroded pipe and the pipe which was corroded and chemically cleaned, as well as specimens of new pipe. Dr. Danyluk concluded that there was no relevant difference in the corrosion behavior of the three categories of pipe. (Ref. 9.)

4. Conclusion

Based on the test results, it was concluded by Taussig that, while the corrosion has caused some variation in properties of the piping materials when compared with new pipe, the samples all met or exceeded the requirements and expected values for the specified materials. Taussig expects no degradation in service performance or lifetime beyond what would be expected for uncorroded A-106 materials.

As indicated above, the Taussig testing confirmed the conclusions of the S&L engineering evaluation in three ways. First, it confirmed that the notch effect stress increase factor used in the evaluation was extremely conservative and that in fact no notch effect stress increase factor was necessary for a valid and conservative stress analysis of the affected pipe. Second, the testing confirmed S&L's assumption that the material properties of the affected pipe were typical of those expected in ASTM A-106 Grade B piping materials. Third, the testing and Dr. Danyluk's evaluation confirmed S&L's assumption that no significant chemical residues from the cleaning process were present on the pipe which might cause or accelerate further corrosion.

In order to provide an additional assessment of the acceptability of the affected pipe and to further confirm the engineering evaluation, a random sampling program for both installed and uninstalled pipe was established. The program was designed to confirm, on a statistical basis, that the wall thinning observed would not result in pipe cross-sections with inadequate strength. The population for this statistical sampling was considered to be "pieces" of small-bore pipe. For the installed pipe, a piece was defined as a section of pipe between connections, usually welded. For uninstalled pipe, a piece was defined as a section equal to the average length of an installed piece, approximately 3 feet. There were 4,586 such installed pieces of pipe in Unit 1 and common systems, and 24,137 equivalent stored pieces, for a total population of 28,723 pieces. These pieces were each uniquely identified by assigning sequential numbers for purposes of random selection for examination. For purposes of satisfying a 95% confidence/99% reliability criterion, 300 samples from the above population were examined for wall thickness. The 300 randomly selected pieces were identified in a letter dated April 4, 1985, from S&L to CECo.

Samples were cut and obtained from both field-installed and storage locations and were uniquely identified throughout the measurement process. PGCo was responsible for obtaining and measuring the designated sample in accordance with PGCo Procedure PGCP-52. Each piece was subdivided into 6-inch long sections and one end of each 6-inch section was measured for wall thickness with a point micrometer at eight points equally spaced around the circumference. One additional measurement was taken between each of the eight points at a location where localized thinning was apparent. All measurements were performed by qualified and certified PGCo quality control inspection personnel using calibrated inspection equipment. The CECo Quality Assurance Department performed audits and surveillances of the above activities to assure compliance with the requirements of procedure PGCP-52.

The previously discussed fatigue testing confirmed that no stress intensification did in fact occur at the pit locations. Therefore, there was actually no need to apply the notch effect stress increase factor, as was done in the engineering evaluation. The piping from the wall thickness sampling program could be evaluated based solely on the reduction in section modulus resulting from the pits and localized thinning. Thus, all the affected piping could now be evaluated using the code design allowable without imposing a stress factor to account for the notch effect.

Sargent & Lundy developed conservative criteria for evaluating the wall thickness measurements. If the measured wall thickness of the pipe met the industry standard tolerances of nominal thickness minus the manufacturer's tolerance of 12-1/2%, the piping required no further evaluation because it was within the standard limits established for new piping. If the measured wall thickness of the pipe did not meet the industry standard tolerance, the pipe was evaluated by applying the worst case reduction in wall thickness measured for pipe of that size in the statistically based sample to the most highly stressed node for that size pipe, excluding cut-outs. In all cases, the measured wall thickness resulted in larger section moduli and cross-sectional area than those used in the engineering evaluation.

The pipe thickness data based on these actual field measurements was transmitted from CECo to S&L. The measurements were then evaluated by S&L. The 300 samples taken represent 28,112 wall thickness measurements. Only 82 of the samples contained one or more locations (for a total of 497 locations out of the 28,112 points measured) where the measured wall thickness was below the nominal wall thickness minus the 12-1/2% manufacturer's tolerance allowed by ASTM A-106. Therefore, 218 samples were within standard industry tolerances and required no further evaluation. The remaining 82 samples were then evaluated against ASME code allowable stresses and were found to be acceptable.

The wall thickness measurements taken on this statistical sample confirmed the conclusions of the S&L engineering evaluation. The measurements confirmed that for each size and schedule of pipe, the measured available wall resulted in a section modulus and cross-sectional area greater than that used in the engineering evaluation. In addition, the measurements confirmed that the available wall was in all cases sufficient to enable the pipe to meet all ASME code allowable stresses.

When both the notch effect and section modulus stress increase factors are considered for the engineering evaluation with the 10 cutouts removed, all pipe meets the ASME code allowable stresses. In addition, when the worst case section modulus reduction from any size pipe from the wall thickness sample program is combined with the most highly stressed node from any size pipe remaining after the 10 cutouts were removed, the ASME code allowable stresses were met even in this "worst/worst" case.

As previously indicated, a quantity of the affected pipe has been installed in Unit 2. At the time the hold was placed on further installation of the affected pipe, virtually no safety-related small-bore piping stress analyses had been done on Unit 2. As a result, the methodology used in the engineering evaluation (i.e., stress increase factor applied to calculated stress) could not be directly applied to the Unit 2 piping because calculated stresses were not available for comparison. Therefore, although the engineering evaluation does not specifically address the pipe installed in Unit 2, the results obtained and the conclusions reached can still be applied to the Unit 2 pipe with high confidence for the following reasons.

The majority of the Unit 2 piping will be subject to the simplified analysis approach which has been shown to be generically acceptable when evaluated against the engineering evaluation acceptance criterion. In addition, the design and installation approach being utilized on Unit 2 is to duplicate the Unit 1 design and installation where possible. Thus, in the majority of cases, the Unit 1 results will be directly applicable to Unit 2.

It should also be noted that even though the wall thickness sampling program did not specifically include any potentially affected pipe from Unit 2 as part of the sample population, the results obtained are still applicable to Unit 2. First, there is no reason to believe that the piping that may have been installed in Unit 2 is any different from that installed in Unit 1. The Unit 2 piping has been subjected to the same conditions of cleaning and storage as the Unit 1 pipe. In addition, the wall thickness sampling program did draw many of its samples from the piping in storage. This is the same location where the Unit 2 piping would have been stored. Therefore, CECo believes the statistically based sampling results should apply equally to Unit 2 and to Unit 1.

The engineering evaluation concluded that with the exception of the six previously discussed computer analyzed node points (cut-outs), all pipe installations would meet ASME code allowable stress limits notwithstanding the use of corroded pipe. The confirmatory testing and wall thickness sampling program indicate that all pipe locations (including the six cut-outs) would meet the ASME code allowable stress limits and that the methodology used in the engineering evaluation was very conservative. The maximum stress which can occur at any location where this pipe has been or could have been used was shown to be less than the code allowable design stress.

In addition, based on the evaluations, testing, and wall thickness sampling performed, it has been demonstrated that, while some minor degradation of mechanical properties has occurred due to corrosion, the corroded pipe still has adequate strength to perform its intended design function in the same manner as new pipe. Chemical tests have indicated no surface residue which would tend to cause additional corrosion in the future, beyond what would be expected due to normal service. The service conditions to which this piping is subjected and the indoor environment in which the majority of the piping is installed are normal power plant applications and are neither highly corrosive nor highly corrosion-inducing. Therefore, considering the design margin available in the piping, and the vast amount of experience of using carbon steel piping in similar applications, this pipe is expected to perform in the same manner as new pipe during its service life. Therefore, the safety-related piping which has been installed will be allowed to remain installed. However, as a further prudent measure, the existing quantities of uninstalled corroded pipe will not be installed in safety-related applications.

1. "Stress Intensification Factors for 1/4- to 2-Inch Schedule 80 Pitted and Corroded Pipe," EMD-049664, 10-01-84.

2. "System Materials Analysis Department Report on Seamless Carbon Steel Pipe at Braidwood Station," M-2525-84, 08-20-84.

3. "Stress Check of 1/2- and 3/4-Inch Schedule 80 Pickled Pipe," EMD-049655, 11-16-84, Addendum A, 09-18-85.

4. DIT-BR-PMDF-0025-0, 10-05-84, and DIT-BR-PMDF-0025-1, 09-03-85.

5. "Evaluation of the Corrosion Problem Applicable to Small Bore Carbon Steel Piping Subsystems," EMD-051333, 07-10-85, Addendum A, 08-06-85; Addendum B, 08-28-85; Addendum C, 09-17-85.

6. "Metallurgical Testing of Pipe Samples Per Consultant Specification No. 121," Taussig Associates, Inc., Report No. 60493-2, 08-27-85.

7. "Acceptance Criteria for Corroded Pipe Wall Thickness Measurements," EMD-054207, 09-03-85.

8. "Evaluation of Wall Thickness Measurement Samples for Corroded Pipe," EMD-054246, 09-13-85.

9. Letter from Dr. Steven Danyluk to C. Berger of Taussig Associates, Inc., dated 11-26-85, transmitting his report dated November 1985.

10. ASME Transactions, 1952, pp. 402-418.