ANL--82-86

DE83 016716

ANL-82-86

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

FAILURE ANALYSIS OF CRACKED HEAD SPRAY PIPING FROM THE DRESDEN UNIT 2 BOILING WATER REACTOR*

by

D. R. Diercks and G. M. Dragel

Materials Science and Technology Division

July 1983

MASTER

*Work performed under EPRI Contract No. T-114-2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FAILURE ANALYSIS OF CRACKED HEAD SPRAY PIPING FROM THE DRESDEN UNIT 2 BOILING WATER REACTOR

by

D. R. Diercks and G. M. Dragel

ABSTRACT

Several sections of Type 304 stainless steel head spray piping, 6.25 cm (2.5 in.) in diameter, from the Dresden Unit 2 Boiling Water Reactor were examined to determine the nature and causes of coolant leakages detected during hydrostatic tests. Extensive pitting was observed on the outside surface of the piping, and three cracks, all located at a helical stripe apparently rubbed onto the outer surface of the piping, were also noted. Metallographic examination revealed that the cracking had initiated at the outer surface of the pipe, and showed it to be transgranular and highly branched, characteristic of chloride stress corrosion cracking. The surface pitting also appeared to have been caused by chlorides. A scanning electron microprobe x-ray analysis of the corrosion product in the cracks confirmed the presence of chlorides and also indicated the presence of calcium. The helical stripe appears to have been produced during piping fabrication, possibly in the straightening step, and the mild surface deformation associated with this stripe apparently provided the residual tensile stresses necessary to initiation of the cracks. It is recommended that the source of the chlorides be located, if possible, and that consideration be given to removing from service any other piping in the system that is found to exhibit such helical striping.

I. INTRODUCTION

Commonwealth Edison Company's Dresden Nuclear Power Plant, located near Morris, Illinois, consists of three independent boiling water reactor (BWR) units, the first rated at 200 MW(e) and the latter two at 800 MW(e) each. Unit 2 began commercial operations in 1970. On April 26, 1981, a primary system hydrostatic test conducted at 7.9 MPa (1150 psi) on Unit 2 revealed the presence of a "weeper-type" leak in the 6.25-cm (2.5-in.)-dia. Schedule 40, Type 304 stainless steel head spray line. The leak was located at a short tight linear indication on the line (as observed ultrasonically), approximately 20 cm (8 in.) from the nearest weld. After replacement of a 74-cm (29-in.) section containing this leak, the line was retested on May 3. This test revealed two additional leaks in a portion of the line approximately 71 cm (24 in.) below the section replaced. A 250-cm (100-in.) length of the line, which included the 74-cm (29-in.) section previously replace, was then removed and replaced. Subsequent tests revealed no further leakage.

The 250-cm (100-in.) length of head spray line that had been removed was sent to Argonne National Laboratory for failure analysis. The failed line was shipped as four lengths of piping, ranging from about 56 to 74 cm (22 to

29 in.) long plus two short samples each about 5 cm (2 in.) long containing circumferential welds at the center. Two of the four longer pieces of piping also contained circumferential welds. Before detailed examination, the samples were decontaminated to radiation levels of less than 1 mR/h, using a solution of acetic, nitric, phosphoric, and hydrochloric acid.

II. EXPERIMENTAL OBSERVATIONS AND DATA

A. Visual Examination

A visual examination of the outer surface of the failed head spray piping revealed a number of interesting features. The first was the presence of a helical "stripe" observed visually on the outer surfaces of three of the four longer piping samples and oriented several degrees off the axial direction. This stripe, which was about 1-2 mm (40-80 mils) wide, had also been noted in the field by Commonwealth Edison personnel. Cracks apparently associated with the stripe were visible at three locations. Two of these cracks, one of which appears to have been peened with a hammer, are shown in Figs. 1 and 2. (According to Commonwealth Edison, the peening was probably done during hydrostatic testing; a leak detected during such testing is frequently peened shut temporarily to facilitate the subsequent detection of other leaks.) At other locations at and away from the stripe, surface grinding marks were clearly seen, as shown in Fig. 3. These grinding marks had also been observed previously by Commonwealth Edison personnel. The final surface feature noted in the visual inspection was the presence of surface pitting both at and away from the helical stripe. The most severe pitting, in fact, was present in a 66-cm (26-in.)-long piping piece that did not exhibit the stripe. An example of this pitting is shown in Fig. 4. It is not known whether Commonwealth Edison personnel had also observed this pitting in the field.

The helical stripe, or flaw, on the piping was examined visually in some detail in an attempt to determine its cause. There was no perceptible variation in surface contour at the stripe, as would be present for a lap or gouge, nor did the stripe appear to be caused by etching or similar chemical attack. From all appearances, the stripe was the indication of a local variation in surface roughness, such as would be produced by rubbing or sliding against another metal object.

B. Chemical Analysis

After visual examinations were completed, a sample of material was removed from one section of piping and subjected to chemical analysis. The results of this analysis are presented in Table I. The material composition as shown corresponds to that for Type 304 stainless steel, the specified material for this component. No significant impurity levels are noted, although the sulfur concentration very slightly exceeds the specified maximum of 0.030 wt %.

C. Metallographic Examination

Several of the features observed visually at the outer surface of the failed piping were examined metallographically in more detail. These include the helical stripe, the associated cracking, and the surface pitting. The

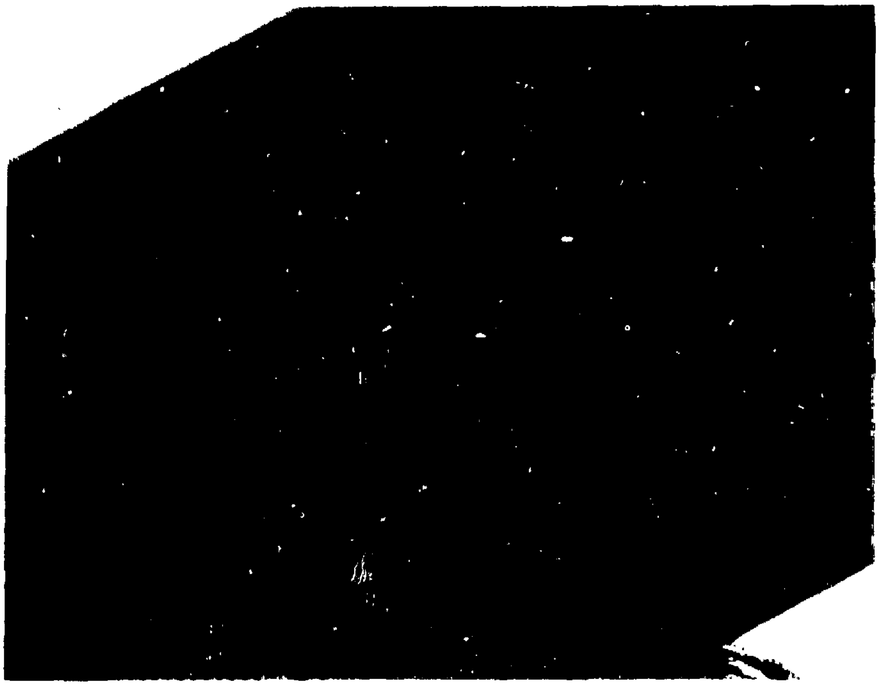

Fig. 1. Macroscopic View of Crack Observed at Helical Stripe on Outside Surface of Failed Head Spray Piping.

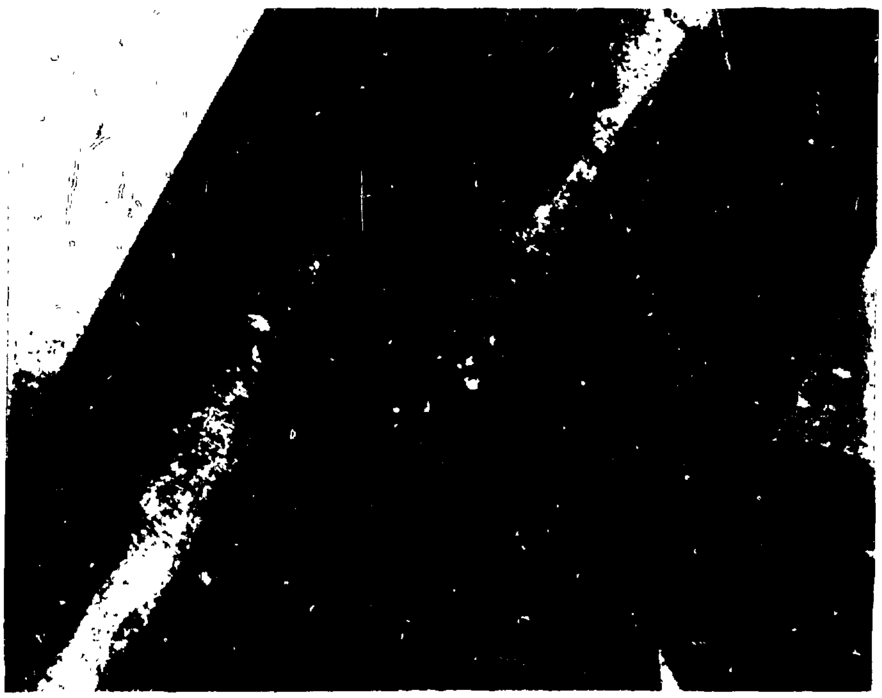

Fig. 2. Macroscopic View of Second Crack at Helical Stripe on Outside Surface of Failed Head Spray Piping. The cracked region appears to have been peened with a hammer.

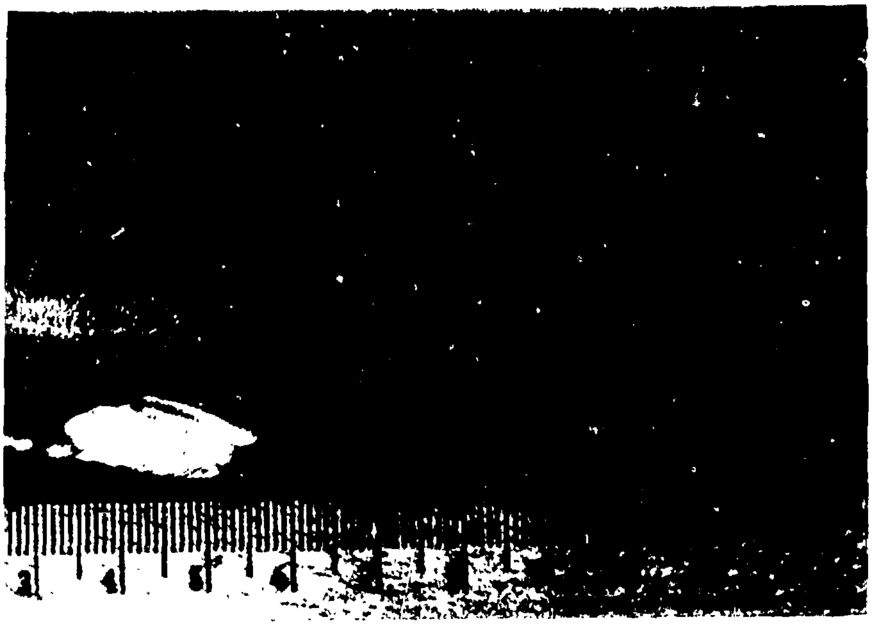

Fig. 3. Surface Grinding at Helical Stripe on Outside Surface of Failed Head Spray Piping.

Fig. 4. Pitting on Outside Surface of Failed Head Spray Line.

TABLE I. Results of Chemical Analysis of Dresden Unit 2 Head Spray Piping Material. All compositions are given in wt %

	Head Spray Piping	Specifications for AISI Type 304 Stainless Steel
Fe	bal.	bal.
Cr	18.52	18-20
Ni	10.11	8-12
Mn	1.42	2.00 max
Si	0.39	1.00 max
P	0.025	0.045 max
S	0.031	0.030 max
C	0.05	0.08 max
Mo	0.34	-
Cu	0.18	-
V	0.03	-
Cb + Ta	<0.01	-
Ti	<0.01	-

metallographic sections to be discussed here are normal to the outer surface of the pipe and are oriented in either the axial or circumferential direction. Except as otherwise noted, all the samples were electrolytically etched in a solution of 10% oxalic acid in water.

Figure 5 shows the microstructure present under the helical stripe at the outer surface. No cracking is present at this location, but the slip bands seen in the austenite grains near the surface indicate that this region was cold worked. The deformation is relatively light, however, and extends no more than a few grains into the interior of the specimen. Similar deformation was seen at locations on the outer surface away from the stripe, but it was generally not as extensive.

The appearance of several cracks that do not extend through the pipe wall and one crack that does extend through the wall, present on the outer surface of the head spray line, is shown in Figs. 6-9. The cracks are all transgranular, tend to be highly branched, and in some cases (see Fig. 9) have associated surface pitting. All of the cracks observed, including the leaking cracks, appear to have originated at the outer surface of the piping. The microstructural features associated with the cracking strongly suggest chloride-induced stress corrosion cracking as the cause of failure.

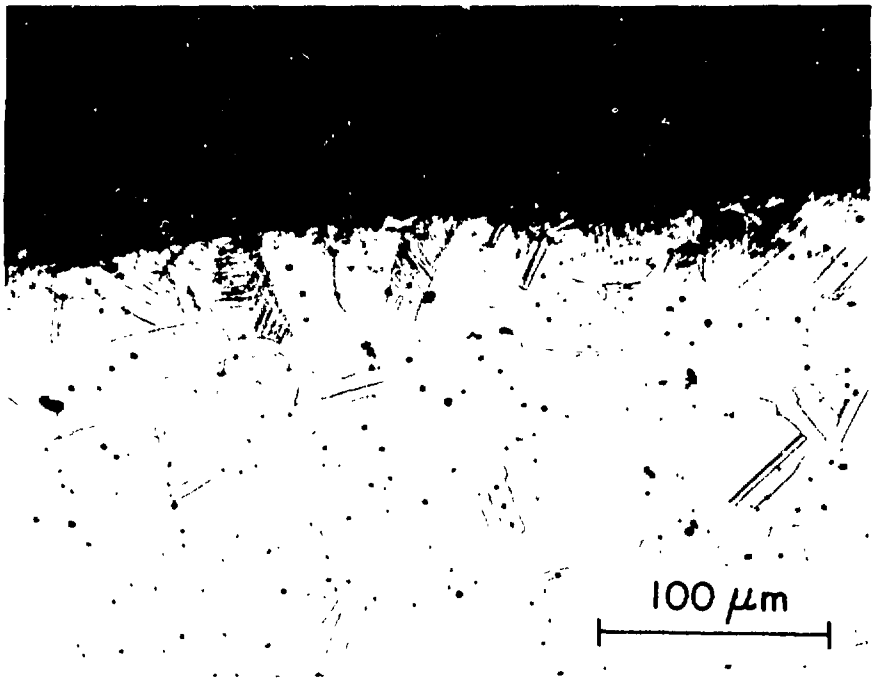

Fig. 5. Microstructure Under Helical Stripe on Outside Surface of Piping.

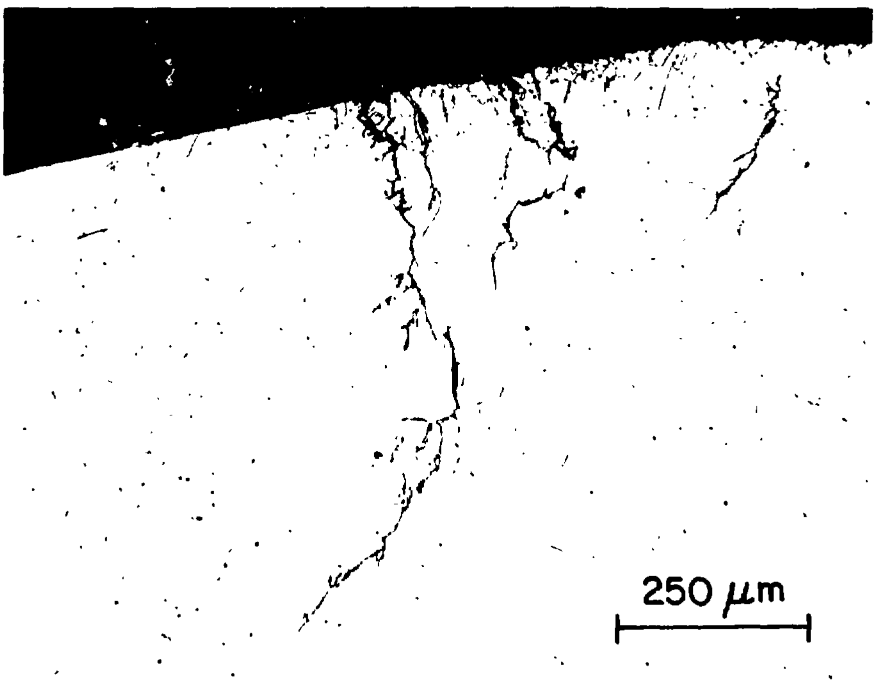

Fig. 6. Section through Transgranular Cracking on Outer Surface of Piping.

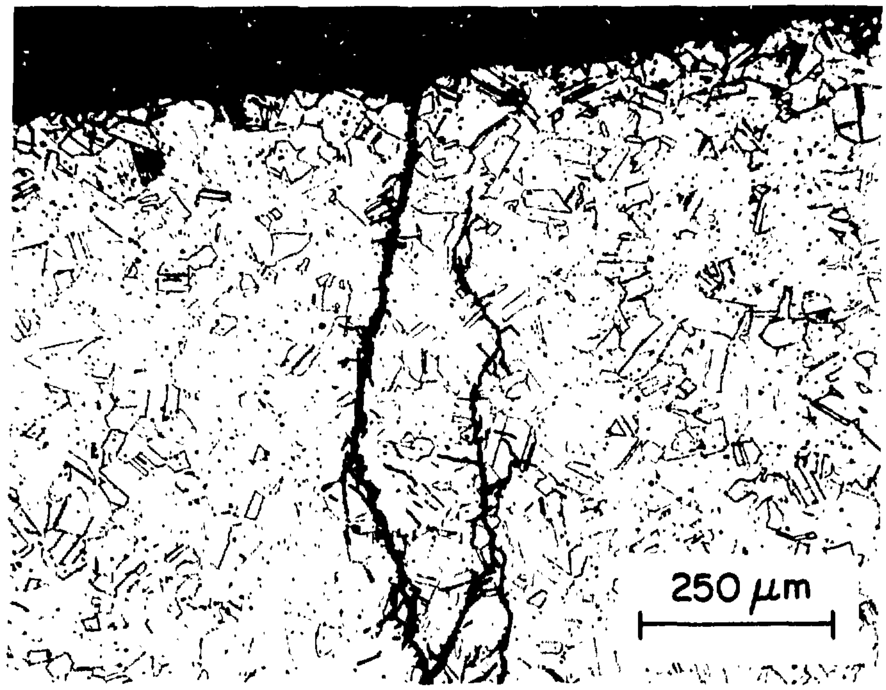

Fig. 7. Transgranular Cracking on Outer Surface of Piping.

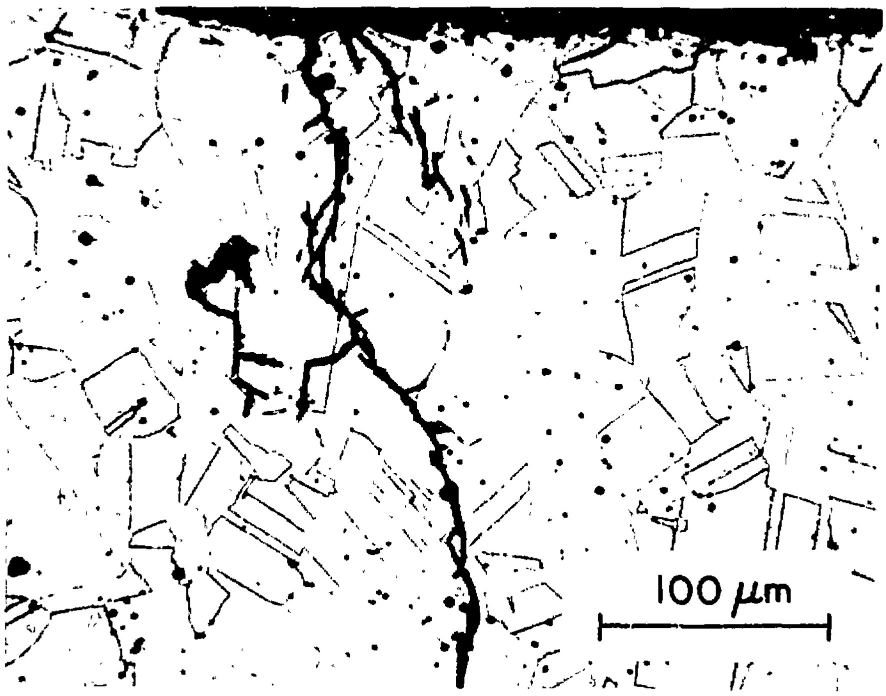

Fig. 8. Higher Magnification View of Cracking on Outer Surface of Piping.

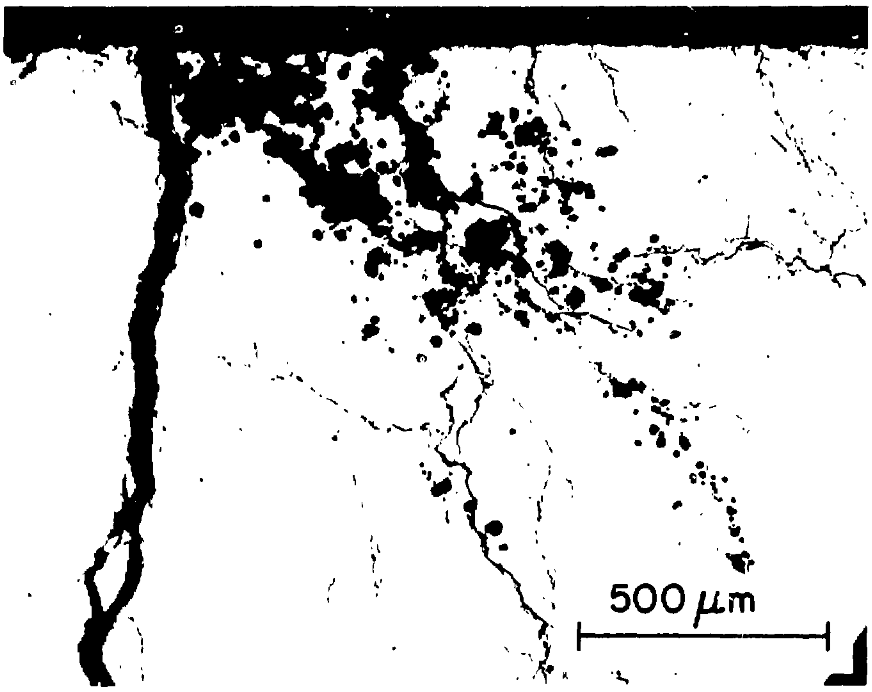

Fig. 9. Surface Pitting and Cracking on Outer Surface of Piping. The wide crack at left penetrated through the wall of the piping.

A profile through one of the surface pits is shown in Fig. 10 at low magnification. Unlike the pitting seen in Fig. 9, no cracking is associated with the relatively large, isolated pit. However, the extensive undercutting and the interconnected "cavern" appearance again suggest the presence of chlorides at the outer pipe surface.

One microstructural feature observed but not satisfactorily explained can be seen at the surface of the specimen shown in Fig. 6, immediately to the left of the longest crack. This dark etching surface layer is shown in more detail in Fig. 11. This feature was seen on only one of the specimens and extended for a distance of several millimeters on the outer surface. It did not appear to be directly associated with either the helical stripe on the outer surface or with the cracking. Although the needle-like appearance of this surface feature is somewhat suggestive of a martensitic structure, its exact nature and cause remain unexplained.

D. Scanning Auger Microprobe Analysis

Selected cracked regions of the piping were examined in the scanning Auger microprobe in an attempt to identify the corrosion product present. Typical results are shown in Fig. 12. The cracked region shown in the Auger electron image of Fig. 12a was mapped for the selected elements Fe, Cr, and O, by adjusting the Auger electron detector to detect electrons only at the appropriate energy intervals. The results clearly indicate a relatively high oxygen concentration in the corrosion product present in the crack, and also indicate Fe and Cr to be somewhat depleted. The Cl concentration was below the detection capabilities of the instrument.

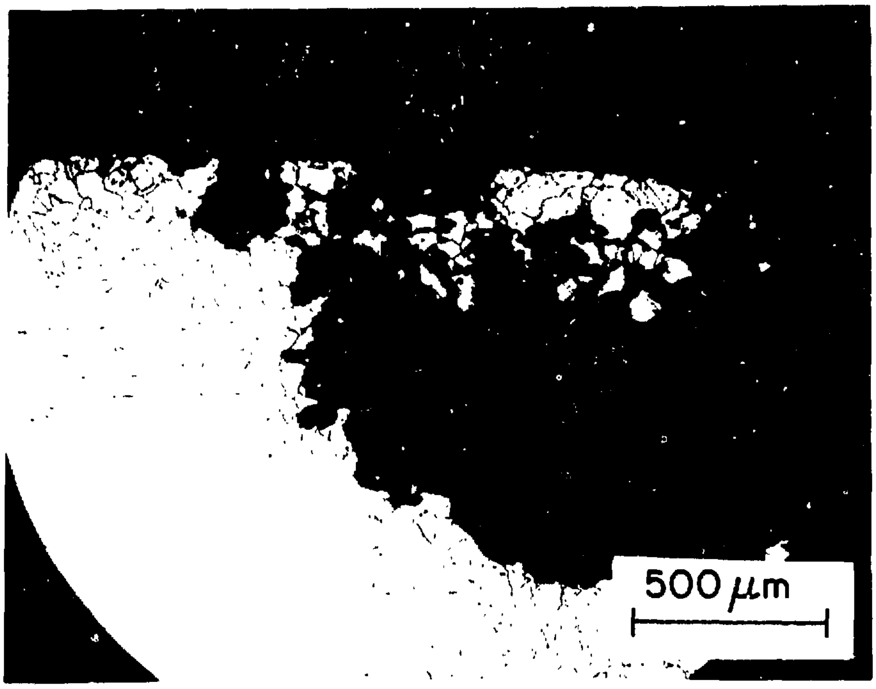

Fig. 10. Profile through Surface Pit on Outside Surface of Failed Piping.

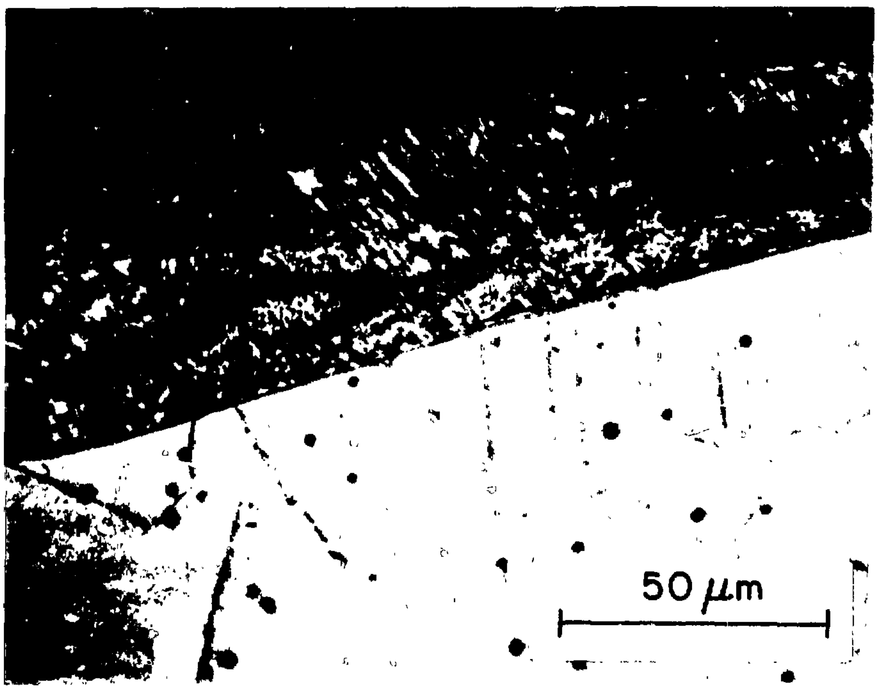

Fig. 11. High-magnification View of Dark Etching Surface Layer Present on a Portion of One Failed Piping Sample.

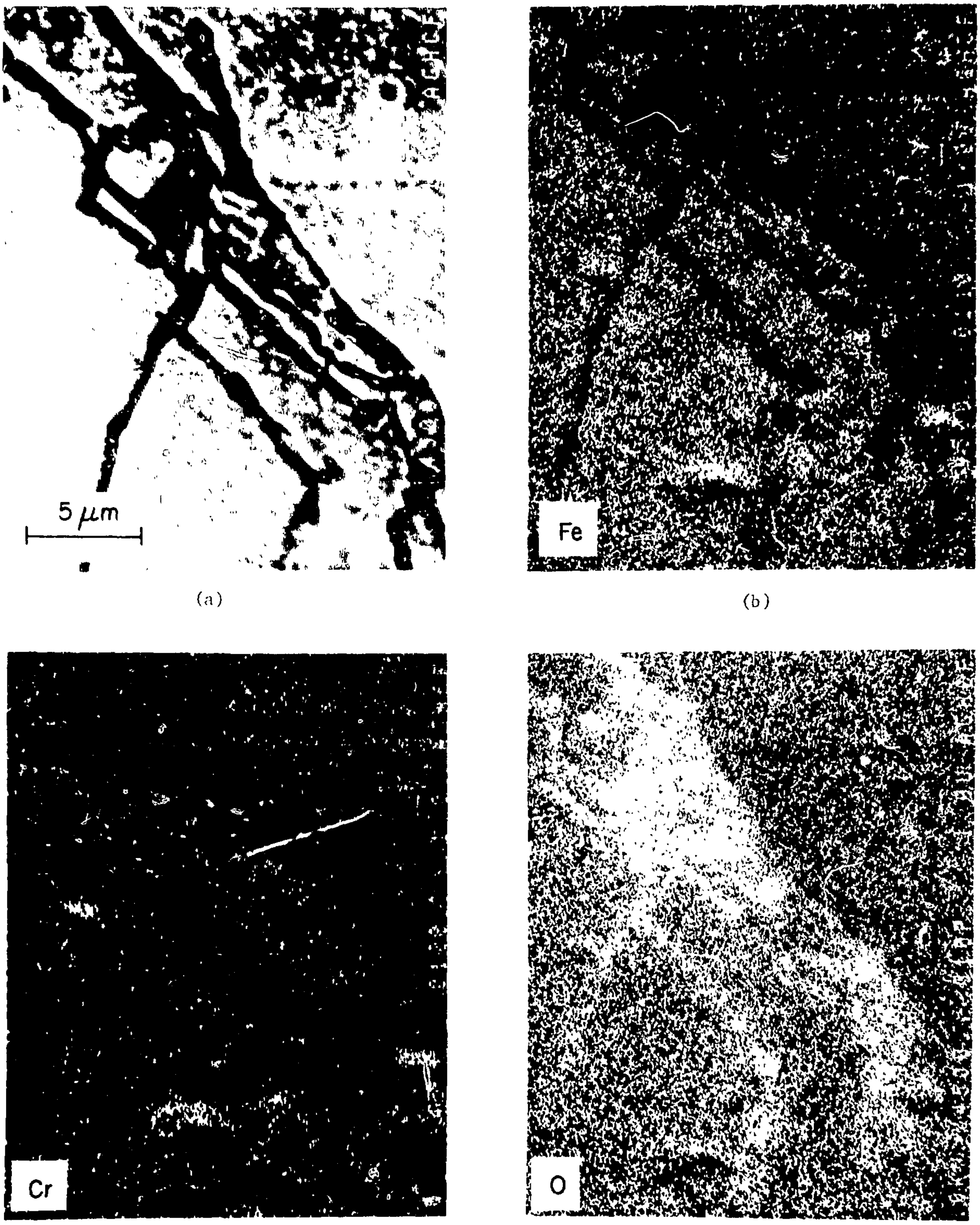

Fig. 12. Scanning Auger Microprobe Auger Electron Image (a) and Fe, Cr, and O Elemental Maps (b)-(d) At and Near Transgranular Crack in Piping.

E. Scanning Electron Microprobe Analysis

In addition to the metallographic and scanning Auger microprobe analyses performed, selected samples from the failed head spray line were also examined in the scanning electron microprobe (SEM), using both secondary electron imaging and x-ray elemental analysis techniques. Because the initial examinations revealed no unusual features, additional analyses were conducted using unusually long x-ray count times in an attempt to detect chlorine. The resulting x-ray spectra for a region at and away from a crack are shown in Figs. 13 and 14, in corresponding order.

The spectrum from the corrosion product in the crack (Fig. 13) shows strong Fe, Cr, and Ni peaks, as expected, and also Si, an impurity in the alloy, and Au and Pd, which were applied to the mounted sample as a thin coating to provide electrical conductivity across the bakelite mounting material. Of particular interest, however, is the presence of well-defined peaks at about 2.6 keV, corresponding to the energy of characteristic Cl Kα radiation, and 3.7 keV, corresponding to the energy of characteristic Ca Kα radiation. These same two peaks are absent from the x-ray spectrum obtained from the piping material away from the crack (Fig. 14), even though the x-ray count time was even longer in the latter case. Hence, the presence of Cl ($\lesssim$1 wt %) in the cracks is clearly indicated.

III. DISCUSSION AND CONCLUSIONS

The results of this investigation indicate that the observed failure of the Dresden Unit 2 head spray line was caused by chloride-induced stress corrosion cracking. The branched transgranular cracking observed and the pitting seen at the outside surface of the piping are consistent with this hypothesis, and the presence of Cl in the crack, as detected in SEM analyses, provides additional strong supporting evidence. The tensile stresses required for stress corrosion cracking to occur appear to have originated as a result of the cold work present at the outer surface of the piping, particularly at the helical stripe present on this surface.

It is conceivable that the chlorides detected in the cracks were introduced during decontamination of the piping, because hydrochloric acid was present in the solution used to decontaminate the piping before examination. However, this would not explain the simultaneous presence of calcium in the cracks, because calcium was not detected in the material away from the cracks. In addition, the authors have never detected chlorides in previous investigations of components decontaminated using similar solutions, although the very long x-ray count times used here were generally not used in previous studies. The authors believe that the chlorides detected in this study contributed directly to the failure of the piping, and that they were not introduced during decontamination.

One can only speculate as to the source of the chlorides that led to the failure. Their origin is apparently external to the reactor coolant system, because all of the cracking and pitting observed was initiated at the outer surface of the piping. The simultaneous presence of Ca in the corrosion product suggests that the chlorides were introduced in the form of $CaCl_2$, a salt commonly used as a deicing agent on roads and walkways and as an additive

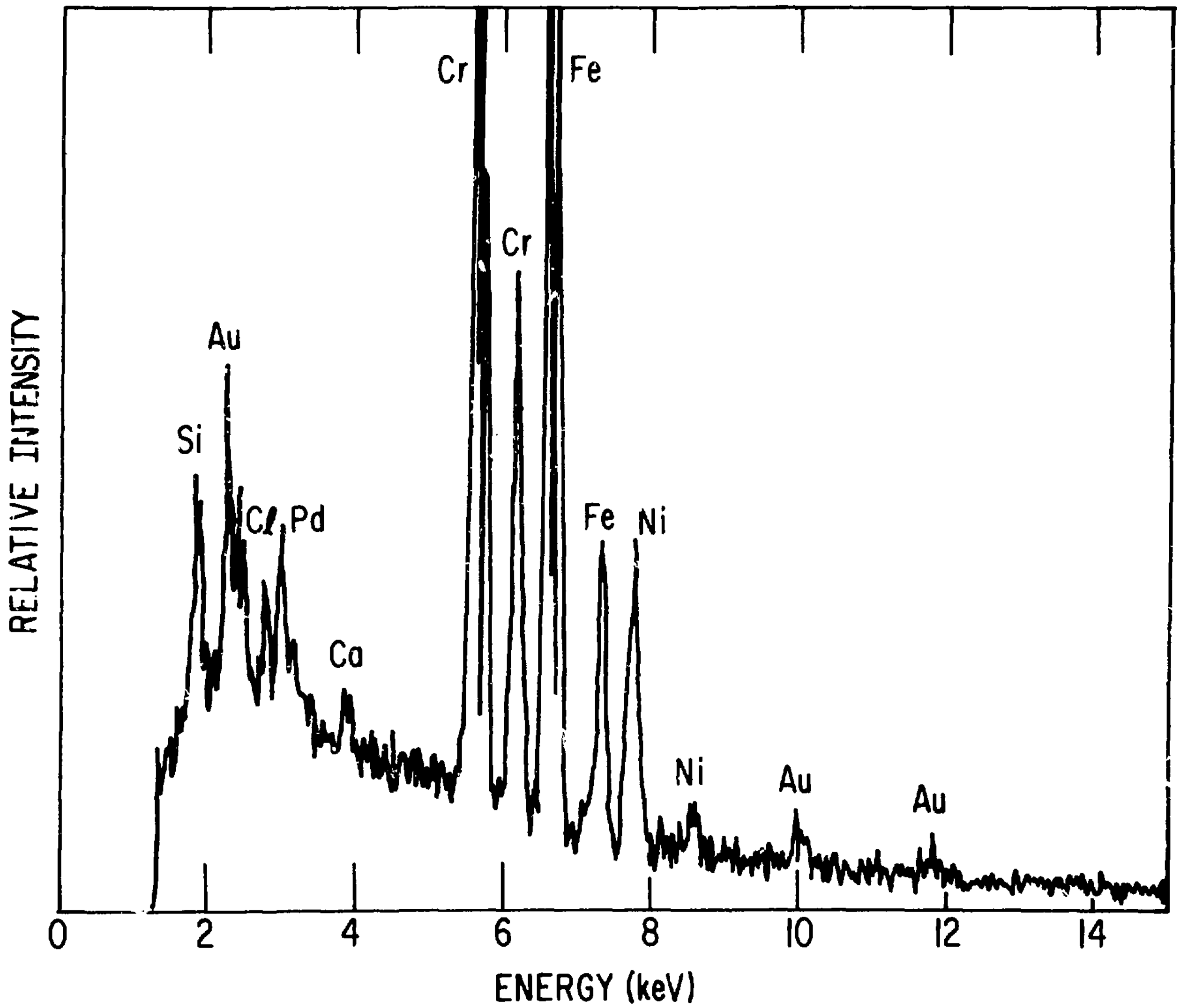

Fig. 13. SEM X-ray Spectrum Obtained from Corrosion Product in Crack in Failed Piping.

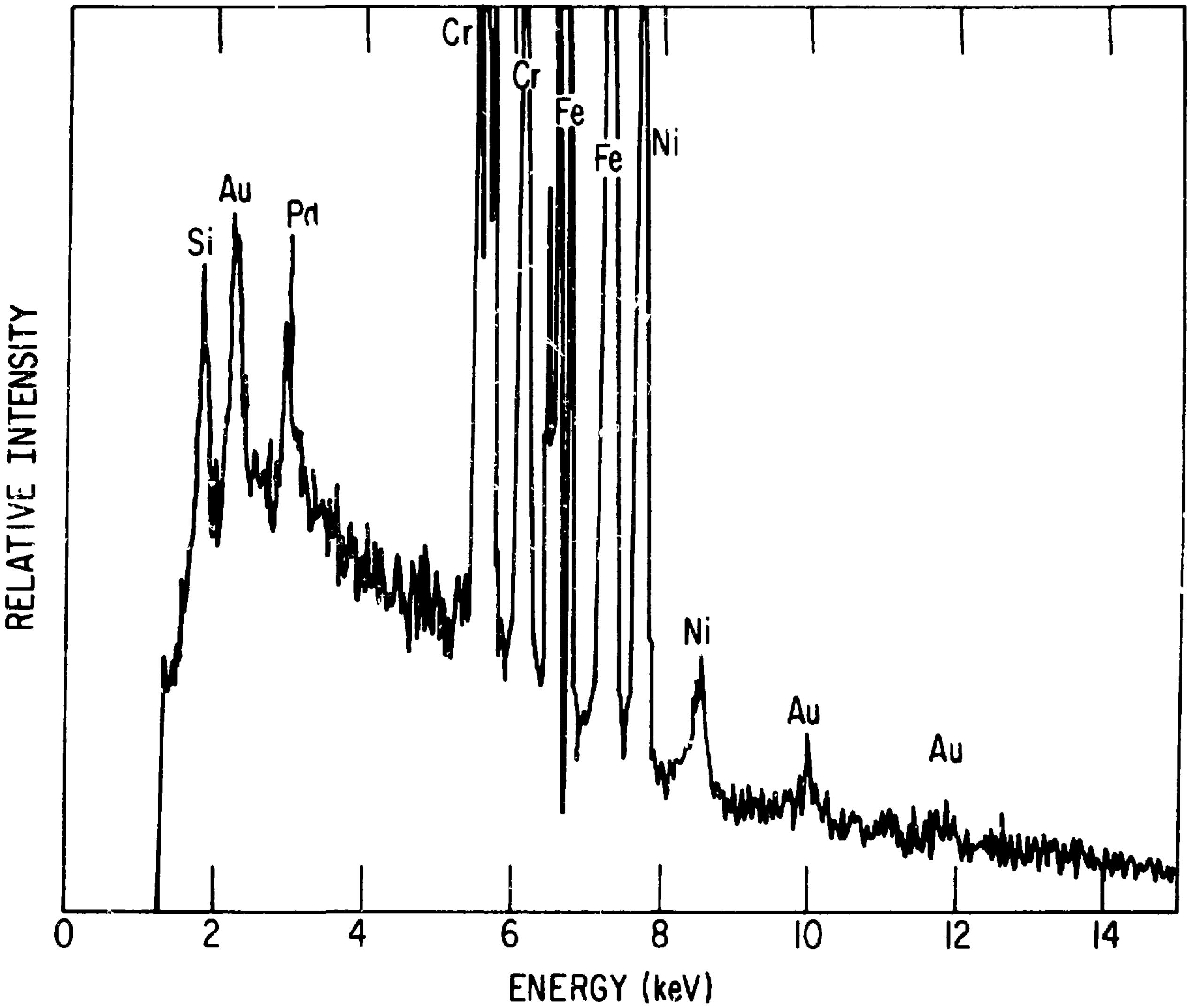

Fig. 14. SEM X-ray Spectrum Obtained from Base Metal Away from Cracking in Failed Piping.

to concrete to accelerate curing during cold weather. Hence, such possible sources as ice melting salt inadvertently carried into the building during the winter or leachant from the concrete containment building deposited on the piping should be investigated. It should also be noted that $CaCl_2$ is highly deliquescent, and small deposits of the salt on the piping surface could conceivably absorb enough moisture from the atmosphere, particularly during shutdown, to produce Cl^- ions in aqueous solution, a necessary condition for chloride-induced stress corrosion cracking.

The source of the helical stripe observed at the outside surface of some of the failed piping is also subject to speculation. Its general appearance and features suggest that it was introduced during fabrication, possibly during straightening of the piping in a multiple-roll rotary straightening machine. During such a process, slight misalignments can cause the workpiece to "skid" across one of rolls at the point of contact as it moves through the machine, thus creating a helical deformation stripe on the outer surface.

In summary, the failure of the Dresden Unit 2 head spray piping is attributed to chloride-induced stress corrosion cracking. The cracks and pitting observed originated on the outer pipe surface, and the chlorides were apparently introduced from the external environment, probably in the form of $CaCl_2$. The leaking cracks originated at a helical stripe apparently rubbed onto the piping during fabrication, and the slight surface deformation associated with this stripe appears to have provided the residual tensile stresses necessary to initiate the cracks. It is recommended that the source of the chlorides be located, if possible, and that consideration be given to removing from service any remaining piping in the system that exhibits the helical stripe.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation of Commonwealth Edison Company and, in particular, the assistance of Mr. Neil Mares, in carrying out this investigation. The scanning Auger microprobe analyses and SEM x-ray analysis were carried out by J. E. Sanecki of Argonne National Laboratory.

Distribution for ANL-82-86

Internal:

O. K. Chopra
H. M. Chung
D. R. Diercks (5)
G. M. Dragel
B. R. T. Frost
T. F. Kassner
K. L. Kliewer
D. S. Kupperman
Y. Y. Liu
P. S. Maiya
K. Natesan
L. Neimark
F. A. Nichols
J. Y. Park
R. B. Poeppel
K. J. Reimann
J. Rest
W. E. Ruther
W. J. Shack
E. M. Stefanski
R. W. Weeks
F. L. Yaggee
ANL Patent Dept.
ANL Contract File
ANL Libraries (2)
TIS Files (3)

External:

DOE-TIC (27)
Manager, Chicago Operations Office, DOE
W. Childs, Electric Power Research Inst., Palo Alto (60)
S. M. Gaitonde, Commonwealth Edison, Maywood, Ill. (20)
G. Gerzen, Commonwealth Edison, Maywood, Ill.
V. Stavropoulos, Commonwealth Edison, Chicago