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SUBJECT: Responds to RA Hermann inquiry re C-E metallurgical exam rept of failed pressuizer nozzle.

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February 7, 1990

F. R. NANDY
MANAGER OF NUCLEAR LICENSING

TELEPHONE
(714) 587-5400

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, D. C. 20555

Gentlemen:

Subject: Docket Nos. 50-361 and 50-362
Pressurizer Nozzle Replacement
San Onofre Nuclear Generating Station
Units 2 and 3

This letter provides the Southern California Edison (SCE) response to an inquiry by Mr. Robert A. Hermann, Section Chief, Materials and Chemical Engineering Branch of the NRC, for a copy of a Combustion Engineering (C-E) metallurgical exam report of a failed San Onofre Unit 3 Pressurizer Nozzle. This request occurred during a recent telephone conversation between C-E and the NRC in which the pressurizer heater sleeve fabrication history for C-E plants was being discussed.

Following failure of a San Onofre Unit 3 Inconel-600 Pressurizer Nozzle in March, 1986, C-E performed a detailed metallurgical evaluation of the failed nozzle. C-E determined that the failure was due to a form of Intergranular Stress Corrosion Cracking (IGSCC) and that the most likely mechanism was Pure Water Stress Corrosion Cracking (PWSCC) but that the causative factor could not be positively identified. The nozzle met chemical specification requirements and its microstructure was normal and C-E considered this failure to be an isolated event.

Included as Enclosure 1 is a copy of a November 5, 1986, internal SCE Report on the Failed Pressurizer Nozzle. The main conclusion from the SCE Report confirms the basic results of the C-E evaluation that the San Onofre Unit 3 nozzle failed due to IGSCC but, contrary to the C-E Report results, SCE considers the failure to be due to PWSCC, and all nozzles fabricated from this heat of material are susceptible to PWSCC induced failure. Based on this conclusion, SCE replaced the San Onofre Unit 3 failed nozzle. The results of SCE's evaluation were reported to the NRC on November 13, 1986, as part of LER 86-003, Revision 1, which discussed the failed Pressurizer Nozzle. Four other nozzles (3 in Unit 3 and 1 in Unit 2) were identified as also being fabricated from this heat

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and were subsequently replaced with nozzles fabricated from PWSCC Resistant Inconel-600 material. Inspection of the four replaced nozzles indicated that three of them had crack indications which substantiates our conclusion that all nozzles fabricated from this heat are susceptible to PWSCC.

SCE has contacted C-E and they have committed to supply the NRC with a copy of the C-E Report on the San Onofre Unit 3 failed nozzle, including glossy photomicrographs of the nozzle microstructure, in the near future.

If you require additional information on this issue, please call me.

Very truly yours,

cc: J. B. Martin, Regional Administrator, NRC Region V
C. Caldwell, NRC Senior Resident Inspector, San Onofre Units 1, 2 and 3

AMC/PNR190:bec

November 5, 1986

MR. J. T. REILLY

SUBJECT: Corrective Action for the Unit 3 Pressurizer Nozzle Failure in March 1986

A failure analysis for the Unit 3 Pressurizer nozzle failure in March 1986 has been performed. The results of the analysis are documented in the attachment. This analysis, mainly concentrating on the metallurgical aspects of the failed nozzle, has been thoroughly reviewed by Dr. M. T. Simnad, an international well-known expert in corrosion science and currently teaching at the University of California, San Diego. His review letter is also attached for your information.

The failure analysis concludes that the heat which contains the failed nozzle has several metallurgical characteristics prone to pure water stress corrosion cracking (SCC). All nozzles made of the same heat (3 in Unit 3, 1 in Unit 2) should be replaced. However, due to a higher service temperature, two out of the three nozzles in Unit 3, which are located in the vapor space of the pressurizer, should be replaced in the upcoming outage. However, the remaining two nozzles, located in the water space of the Unit 2 and 3 pressurizers, could be replaced at a later date, but no later than three years from now. The specifications for a pure-water SCC resistant Inconel-600 are described in this report. They should be included in the material specifications for the future replacement nozzles.

The conclusion reached by this failure analysis rejects the recommendation from C-E stating that the Unit 3 failure is an isolated case. The rejection is mainly based on the fact that C-E's statement is not well supported by the established theories and data for Inconel-600 pure water stress corrosion cracking and C-E's field operation experience. Also, Mr. L. McKnight's extensive experimental work on this subject is not used in this failure analysis since the data he collected in strong acidic solution are not applicable to pure water SCC.

Chong Chiu
C. CHIU

CC:3870I/shg
Attachments

cc: Harold B. Ray
H. E. Morgan
K. L. Johnson
S. R. Gosselin
R. W. Krieger
D. E. Shull
W. C. Marsh
J. L. Reeder
M. P. Short
CDM Files

INTERIM FAILURE ANALYSIS FOR SAN ONOFRE UNIT 3 PRESSURIZER INSTRUMENT NOZZLE

C. Chiu, S. Gosselin

Introduction

On February 27, 1986, a vapor space leak was located on a pressurizer instrument nozzle as a result of a leak investigation. The investigation was prompted by a long suspected reactor coolant leak of 0.15-0.2 gpm from the vapor space of the pressurizer (Reference 1). Consequently, the plant was brought to cold shutdown and the broken nozzle was ground out. A replacement nozzle was then welded in place.

A small portion of the nozzle (1/4 x 1/8 x 1/8 inch) containing the fracture surface and the remainder of the removed nozzle were sent to Combustion Engineering, Inc., and L. McKnight and Associated for metallurgical analysis. Both of them submitted metallurgical examinations and/or failure analysis reports (References 2, 3 and 4). Subsequent to the review of C-E's report, Mr. L. McKnight proposed that certain metallurgical and laboratory tests be conducted on Inconel-600 material. The results of the test are documented in Reference 3.

Purpose

The purpose of this report is to review the conclusions and the supporting arguments contained in the C-E and McKnight's reports. Additionally, the experimental data performed by other scientists regarding Inconel-600 IGA or IGSCC are reviewed and an independent analysis was performed to study the feasibility of various failure scenarios hypothesized in the report.

C-E's Analysis

The results of C-E's laboratory examination as documented in Reference 2 are summarized below:

1) The cracking mode on the fracture surface of the small sliver was entirely intergranular, characterized by well defined grain facets. An intergranular crack mode is characteristic of Intergranular Stress Corrosion Cracking (IGSCC). There was no evidence of cracking in the larger piece of the nozzle. Because of the size of the sliver, it was not possible to tell where this cracking started.

2) There were no signs of cyclic/fatigue-induced failure.

3) The same design, material form, and fabrication techniques have been used with partial penetration instrument nozzles on other C-E supplied components including the San Onofre 3 pressurizer. The records do not indicate any anomalies during the fabrication of the San Onofre 3 pressurizer.

4) The failed nozzle was fabricated from an Inconel-600 forging and was stress-relieved at 1675°F for a period of 1 1/2 hours. Therefore, the stresses typically associated with a rolled tube do not exist.

5) The microstructure of the removed nozzle (not the sliver containing the crack) is characterized by very large grains, sizes 0-2 (ASTM Standard), with small grain boundary carbides, a lot of very fine intragranular precipitates, and a narrow denuded zone adjacent to the grain boundaries.

6) CE believes that Inconel-600 tubing with a high, greater than 55 Ksi, yield strength has been associated with poor resistance to pure water IGSCC. The heat of material for the cracked nozzle has a yield strength of 60.9 Ksi, well into the range that as tubing has poor resistance to IGSCC. This heat yields the highest yield strength among those of the five heats of material used at seven CE plants.

7) The same heat of material from which the failed nozzle was fabricated was also used to make three (3) other nozzles in the Unit 3 pressurizer, as well as one in San Onofre Unit 2 and five (5) at another C-E plant. No problems have been encountered at the other two plants which have operated longer than Unit 3.

Based upon the above findings, C-E concluded that the crack in the instrument nozzle of the SONGS Unit 3 pressurizer was due to a form of IGSCC. Since the nozzle is made of Alloy 600 material with a high yield strength, pure water IGSCC would be the most probable mechanism.

Further, C-E believes that since this same heat of material has been used without cracking in other plants with longer service, this Unit 3 nozzle had a unique set of conditions that resulted in the IGSCC. Hence, this crack is not believed to be a generic problem.

McKnight's Report & Test Data

The preliminary report by Mr. McKnight agreed to C-E's conclusion that the fracture mode is intergranular and suggested a series of tests be done to investigate the metallurgical property of Inconel-600 and the failed nozzle. The tests were subsequently performed by C-E under Mr. McKnight's supervision. The results of the test are summarized below.

1) The nozzle material was forged in accordance with SB166 and had been annealed at 1675°F with a carbon content of 0.065% to 0.07%. The carbon content is considered too high. As a result, a considerable amount of intragranular carbide precipitation was observed.

2) There is a chromium depletion zone adjacent to the grain boundaries. It is evidence of sensitization, probably during the processing sequences and due to the welding technique used to install the nozzle.

3) Contrary to C-E's belief, McKnight believes that it is impossible to identify any corroding media responsible for the observed failure on the fracture service because the material has been decontaminated and surface deposits has been removed.

4) The remaining position of the removed nozzle was used to prepare four specimens, i.e., 1, 2, 3 and 4. These four specimens were first pre-treated to yield different grain boundary morphology and then tested for their susceptibility to IGSCC. The pre-treatment, grain boundary carbide morphology, and the test results for these four specimens are tabulated in table 1. In addition, four more specimens made of standard Inconel-600 with a lower carbon content (0.03%) were prepared; two solution annealed and the other two solution annealed and then sensitized. The test results of these four additional specimens are also tabulated in Table 1, but in the parentheses.

5) Based on the results of Table 1 it appears that if the carbides tend to be larger size and less continuous in the grain boundary, there is less tendency for SCC.

In summary, Mr. McKnight believes that the material of the failure nozzle close to the weld may have been exposed to elevated temperature in the realm of 2000°F during welding. Upon cooling down from the welding temperature, some of the material may have been sensitized through the 1200 - 1600°F range. However, he stated that for IGSCC to happen, it would have been necessary the existence of a corrosion environment, a very high residual stress or applied stress, and an unfavored microstructure, as evident of the test results in Table 1. The mechanical properties of typical Inconel-600 as well as the failed nozzle are tabulated in Table 2.

Past Research on Inconel-600 IGSCC

Inconel-600 has been known to be susceptible to IGSCC in the caustic environment (References 5, 6 and 7), in the lead doped water (Reference 8), in the resin intrusion environment of H_2SO_4 solution (Reference 9), and in the pure water environment (References 9, 10 and 11). Significant findings in these references are summarized below.

1) After an extensive study on the microstructure effect on SCC resistance, Airey stated in Reference 12 that "the maximum improvement in SCC resistance correlates with a semi-continuous grain boundary carbide precipitation and phosphorous segregation to the grain boundaries." This maximum improvements is associated with annealing at 1200°F (10-100 hours) and 1300°F (10-24 hours).

2) When annealed at the top of the sensitization range (1200°F to 1600°F) in which carbides tend to precipitate at the grain boundaries, large discrete precipitates due to an agglomeration process were observed in a very short period of time. Low temperature annealing (1200-1300°F) generates fine, semi-continuous carbide precipitation and it does not agglomerate even after 100 hours (Reference 12).

3) Data taken by Bandy and Vanrooyen (Reference 13) regarding Inconel-600's performance in pure water have demonstrated the fact that under a slow strain rate (i.e., plastic deformation) condition, the crack growth rate is proportional to the system temperature. Moreover, it seems that the cold worked Inconel-600 with pure water is more susceptible to IGSCC than several other combinations of material and environmental condition. H_2 seems to accelerate the IGSCC process. The data by Randy and Vanrooyen is shown in Figure 1.

4) Bandy and Vanrooyen found that the crack growth rate in pure water seems to be independent of carbon content since the crack growth rate of one test with 0.05%C Inconel-600 is in good agreement with that of 0.01%C material.

5) Bandy and Vanrooyen's data show a lowering in crack growth rate due to an increase in pH of the primary water such as would result from the addition of lithium hydroxide to the test medium.

6) Page and McMinn (Reference 9) did an experimental comparison of Inconel-600 and Inconel-690 in the simulated BWR primary water environment. The microstructure examination has shown the three sensitizing treatments of Inconel-600 (1150°F for 24 hours, 840°F for 24 hours, and a combination of the former two treatments) do not produce a noticeable change in microstructure of Alloy-600. This fact suggests that mild degree of sensitization may have been present in all the mill annealed Alloy-600 specimens.

7) The data by Page and McMinn show that SCC did not occur in the uncreviced, slow-strain-rate test for Inconel-600 with a high purity water condition (200 ppb oxygen) at 600°F. However, when oxygen level increases to 16 ppm, SCC surface cracks were observed. Based on the data, it seems that the SCC occurrence is independent of whether or not it is sensitized at 1150°F or 840°F.

8) In 1978, at Duane Arnold BWR, cracks were found on an Inconel-600 safe-end (pipe connection) at the recirculation-inlet-nozzle. The root cause were determined to be the high residual stress, stress concentration caused by the existing crevice, and, probably, the corrosive enhanced material stayed in the sleeve area due to an earlier resin intrusion incident (Reference 10, NUREG-0531). Reference 14 also concluded that there is insufficient evidence to indicate that sensitization is a factor that contributed significantly to crack initiation or propagation.

9) A detailed study on the microstructure effects on primary water SCC of Inconel-600 has been performed by EPRI and Battelle Pacific Northwest Laboratories. The results of the study are summarized in Reference (15). The study explains when a semi-continuous intergranular carbide precipitation will improve SCC resistance. Based on a detailed examination of the fracture surface, it concludes that grain boundary carbides, because they are effective sources to generate dislocations, result in a reduction in crack-tip stress state. With this reduction, localized corrosion will be hindered (probably because of little strain rate exists to repeatedly rupture the localized oxidation film - based on the theory of film rupture SCC model).

10) The role of the tensile stress in the crack initiation time has been correlated by the mechanistic film-rupture model developed by EPRI. The predictions of time-to-crack initiation based on the model are calibrated against all available data related to primary water SCC. Based on the model, it is believed that the time-to-failure, beyond which SCC cracks will occur, is inversely proportional to the strain rate.

11) Based on the experiments by Bandy and Rooyen, and Coriou (Reference 16), EPRI Steam Generator Reference Book (Reference 17) stated that the stress threshold for cracking of mill annealed material in high temperature water is estimated to be 0.6 to 0.8 times the room temperature yield strength.

12) Based on the fact that IGSCC has been observed with no difficulty in non-sensitized (as well as sensitized) condition and in highly pure deoxygenated (as well as oxygenated) water, it appears that the effect of sensitization on SCC is minor or insignificant (Reference 17). This view is shared by S. M. Bruemmer et al after a review of the data documented in References 17, 18 and 19. They concluded that "Significant Chromium depletion or impurity segregation at grain boundaries is not essential for SCC." This observation is consistent with the mechanistic model developed by S. M. Bruemmer et al.

13) C-E believes that there are two common denominators that are characteristics of pure-water SCC prone tubing. A paragraph from the paper (Reference 21) by Mr. Owen of C-E is quoted below.

> "3.1 <u>Highly susceptible tubing</u>
>
> "There are two common denominators that are characteristic of 'Coriou' prone tubing. Cracked tubing removed from plants such as Obrigheim[1], Doel II, Ringhals II[2] and Trojan have exhibited a characteristic microstructure and yield strength. The high yield strength (~60KSI, 413MPa) is set by the fine grain size ASTM - 9 to 11). The fine grained microstructure is the result of a low temperature (1700°F, 926°C) final anneal which also dictates a very specific carbon inventory. 'Coriou' prone microstructures typically exhibit a preponderance of intragranular carbides, few if any intergranular carbides and little or no solid solution carbon.
>
> "The absence of grain boundary carbides has been shown to be undesirable for resistance to 'Coriou' type SCC. This undesirable microstructure, combined with the high yield strength where elastic stresses can build <u>and persist</u>, apparently above the threshold required for crack initiation, constitutes the ultimate metallurgical condition for 'Coriou' susceptibility. This condition develops as a direct result of employing low temperature at final anneal."

<u>Discussion</u>

Based on the current understanding of the phenomena and mechanism of pure-water stress corrosion cracking as briefly discussed in the previous section, several key points raised by CE and Mr. McKnight are discussed here.

1. <u>55 Ksi Yield Strength Limit</u>

As the understanding of the author, based on several conservations with CE's metallurgists, CE has a 55 Ksi upper yield strength limit for CE's steam generator tubes for many years. CE's believes (based on field experience) that a higher yield strength is associated with small grain size and high residual stress persisting in the material and, therefore, results in a higher susceptibility to SCC. This correlation has not been studied by other researchers but it is consistent with the current understanding in Inconel-600 susceptibility to SCC. One evidence to support the validity of this upper limit is that both W and Framatone steam generators have extensive pure-water SCC failure experience whereas CE steam generators have none (based on A. R. McIlree - EPRI's statistics). W and Framatone do not have this upper limit whereas CE does.

2. <u>Isolated vs. Non-isolated Case</u>

CE believes that the Unit 3 leakage is an isolated case because there are nine other nozzles used at three plants from the same heat with a yield strength of 60.9 Ksi and none of the others has exhibited symptoms of failure. These plants are SONGS-2, SONGS-3 and St. Lucie-2. The location of these nine nozzles are tabulated below.

3 nozzles	Unit 3 vapor space
1 nozzle	Unit 2 water space
4 nozzles	St. Lucie-2 vapor space
1 nozzle	St. Lucie-2 water space

Because the time-to-crack-initiation is both highly temperature and strain rate dependent (References 22, 23, 24), a nozzle submerged in the water at the bottom of the pressurizer tends to have a longer life because of axial temperature stratification. Also, a nozzle that has experienced fewer startups will last longer. Note that the strain rate is non-zero only during a startup and the time-to-crack-initiation is infinite when the strain rate is zero (References 22, 24).

Since St. Lucie-2 has only experienced about 17 startups (based on the data provided by St. Lucie-2 technical staff) since its commercial operation, whereas San Onofre Unit 3 has already experienced about 22 startups, it is not surprising that St. Lucie-2 has not experienced a similar failure. Meanwhile, since the nozzle from the same heat in Unit 2 is in an environment about 20-40°F lower than those for the nozzles in the vapor space of the pressurizer, the life is probably 2 to 4 times longer (based on Speidel's data, life increases by a factor of 2 for every 10°C reduction in solution temperature, Reference 23).

Based on the above discussion, it is expected that one of the three nozzles, from the heat of 60.9 Ksi yield strength, located in the vapor space of the Unit 3 pressurizer will fail first. Because this expectation is consistent with the established theories and data for Inconel-600 pure water SCC, treating the Unit 3 pressurizer nozzle failure incident as an isolated case is technically questionable.

3. Forging vs. Mill-Annealing

The failed nozzle was machined out of a forging, whose processing temperature is unknown and could be a little lower than the temperature typically used for mill annealing (1900°F~2000°F). The effect of a lower processing temperature would be that a smaller amount of intragranular carbon could be going into solution and diffuse to the grain boundary. As a result, the grain boundary carbide content is less and is more susceptible to SCC.

4. High Carbon Content of the Failed Nozzle

The carbon content of the failed nozzle is 0.07%, within the specification range of Inconel-600, but higher than what is typical for steam generator tubes. A high content of carbon greater than 0.03% may be associated with a high intragranular carbon content, thus reducing the resistance to IGSCC. The solubility of carbon content at about 1800°F is 0.03%. Therefore, for a low temperature forging, about 0.04% of carbon will not dissolve into Inconel solution and eventually migrate the grain boundaries.

However, this effect is considered minor by Bandy and Vanrooyen for Inconel with carbon content between 0.01% and 0.05%. Moreover, three out of six heats of CE's Inconel material used at its pressurizers have carbon content greater than 0.07% without any failures. Table 3 tabulates the properties of all the heats of Inconel material used by CE for the pressurizer nozzles. This fact also suggests that the effect of carbon content on SCC susceptibility in pure water is minor, if not negligible.

5. McKnight's Experiments at CE

The results of the experiments performed at CE under the supervision of McKnight, as tabulated in Table 1, are judged to be not useful or related to the understanding of the pure-water stress corrosion cracking problem at Unit 3. This is because that there is enough difference in the SCC process between an acidic solution and a pure-water (or primary water) solution such that the conclusion drawn from the data may not be applicable to the case of pure water SCC. This is evident that McKnight's data show that the sensitization reduces the SCC resistance in an acidic solution after solution annealed. Meanwhile, the sensitization process does not reduce the SCC resistance in pure water and caustic solution after mill-annealed at various temperatures (see data in Reference 17).

Relevant Data for Failure Analysis

The following data, in addition to what are stated in previous sections, are considered relevant to the failure analysis.

1) The outside diameter of the failed tube is 1.05 inches with thickness of 0.218 inches.

2) The configuration of the failed tube with respect to the pressurizer wall and the 1/8" stainless liner is shown in Figure 2.

3) The unit has been in operation since August, 1983. Total operation time at the system temperature of 650°F in pressurizer before failure is approximated 600 days. It has gone through about 22 pressurization cycles at a high temperature.

4) Typical mechanical properties of Inconel-600 are listed in Table 3.

5) According to Westinghouse, all the instrument nozzles in pressurizer are made of stainless steel-316, together with a SS-316 pressurizer liner. IGSCC has not been observed on these nozzles for some years.

Failure Analysis

As discussed in the previous sections, all laboratory and field data support the fact that a Inconel-600 tubing with high yield strength, relatively small grain size, and copious intragranular carbide precipitation is susceptible to pure-water SCC in a high strain rate and/or local stress enviroment.

Based on the data collected and analyses performed on the failed tube, we know that:

1) The yield strength 60.9 Ksi is beyond the acceptable limit (55 Ksi).

2) Copious intragranular carbides are precipitated inside the grain.

3) The location of the highest stress-point is at the six and twelve o'clock location of the tube end inside surface. With the residual stress from welding (estimated in Appendix B) and the pressurized hoop stress combined (estimated in Appendix C by elastic model), the actual stress level is probably 50% above the yield strength (based on a first-order estimation) if plastic deformation is considered. The nozzle hoop stress is considered very small as compared to other stress components (Appendix A). The crack observed at the nozzle end is at the five o'clock location, very close to the area with the highest stress.

4) The average strain rate during plant start-up is 4.8×10^{-8}/sec. If the tube is as susceptible to pure-water SCC as the mill annealed Inconel-600, the crack will initiate after about 17 to 18 times of start-up (Appendix D).

5) The grain size estimated by McKnight's SEM picture of the cracked sliver is about ASTM 2-3. This grain size is considered medium because it, by itself, will not reduce the susceptibility to pure-water SCC.

With the above information and the discussion in the previous sections, it seems reasonable to conclude that the failed nozzle has a material composition prone to pure-water SCC. Also, the nozzle failed after about 22 startups, whereas a tube with mill-annealed Inconel-600 (which is also prone to pure-water SCC failure) will have failed after about 17 startups. This conclusion, plus the fact that there is no sound evidence suggesting that the failed nozzle has been subjected to a different operation condition than the other three nozzles located in the Unit 3 pressurizer vapor space, implies that another nozzle failure is expected, probably, within one or two years.

The hypothesis of a pre-existing crack on the failed nozzle (which had propagated during operation until the March, 1986 incident) is possible but not likely. This is because that based on the observed crack configuration its origin seems to be at the inside edge of the tube, an area of the highest stress. It is believed that a pre-existing crack at this location would have been detected during the NDT of the weld after its completion.

Recommended Actions

To prevent recurrence, the following corrective actions should be taken:

1) Replacement of all nozzles from the same heat as the failed nozzle (Heat No. 54318). All three Unit 3 nozzles located in the vapor space should be inspected and then replaced as soon as possible within one year. The two other nozzles (one for each unit) submerged in the water should be replaced within about three years from now.

2) The replacement nozzle should have material characteristics proved to be resistant to pure-water SCC. Two candidates should be considered. One is Inconel-600 with low yield strength and a high annealing temperature (>1900°F) and can be selected from one of the heats which were provided to CE's plants in the past. The other is Inconel-800 which has been used in the KWU steam generators with no known pure-water SCC problem for more than 20 years (Reference 17).

TABLE 1

McKnight & CE Inconel - 600 IGSCC Test Results With the Removed Nozzle (0.07% C)

SPECIMEN	PRE-TREATMENT	MORPHOLOGY	SUBCEPTIBILITY: MAGNESIUM CHLORIDE 45 HOURS	SUBCEPTIBILITY: SULFUROUS ACID 24 HOURS	SUBCEPTIBILITY: SULFUROUS ACID 72 HOURS
1	As-received	Continues carbide at GB + Cr depletion	No	No	No
2	As-received + 1200°F sensitization for four hours	Semi-continuous Carbide at GB	No	No	No
3	Solution annealed at 2000°F + water quenched (2 more samples, 0.03%C)	Semi-continuous Carbide at GB	No	No (No)	No (No)
4	Solution annealed at 2000°F + water quenched + sensitization at 1200°F for 4 hours (2 more samples, 0.03%C)	Continuous Carbide at GB + larger grain size	No	Yes (Yes)	Yes (Yes)

TABLE 2

Typical (and the failed nozzle) Alloy-600 Properties

	Room Temperature	600°F
Yield Strength	50.4 Ksi (60.9 Ksi)*	40.9 Ksi
Tensile Strength	110.3 Ksi (108.0 Ksi)*	101.3 Ksi
Elongation	35.9% (36%)*	40.4%
Reduction In Area	56.9% (70%)*	53.3%

Note: The actual strength depends on the actual annealing temperature. The higher the annealing temperature, the lower the yield strength.

* Based on the data specified on the certified material test report.

TABLE 3

Inconel-600 Materials Used by C-E

Heat Group	Carbon %	Yield (psi)
1*	.07	60.9K
2	.05	36K
3	.06	38.5K
4	.08	52.7K
5	.09	38.5K
6	.09	51.6K

*Note that Group 1 contains the five suspect nozzles and the failed nozzle.

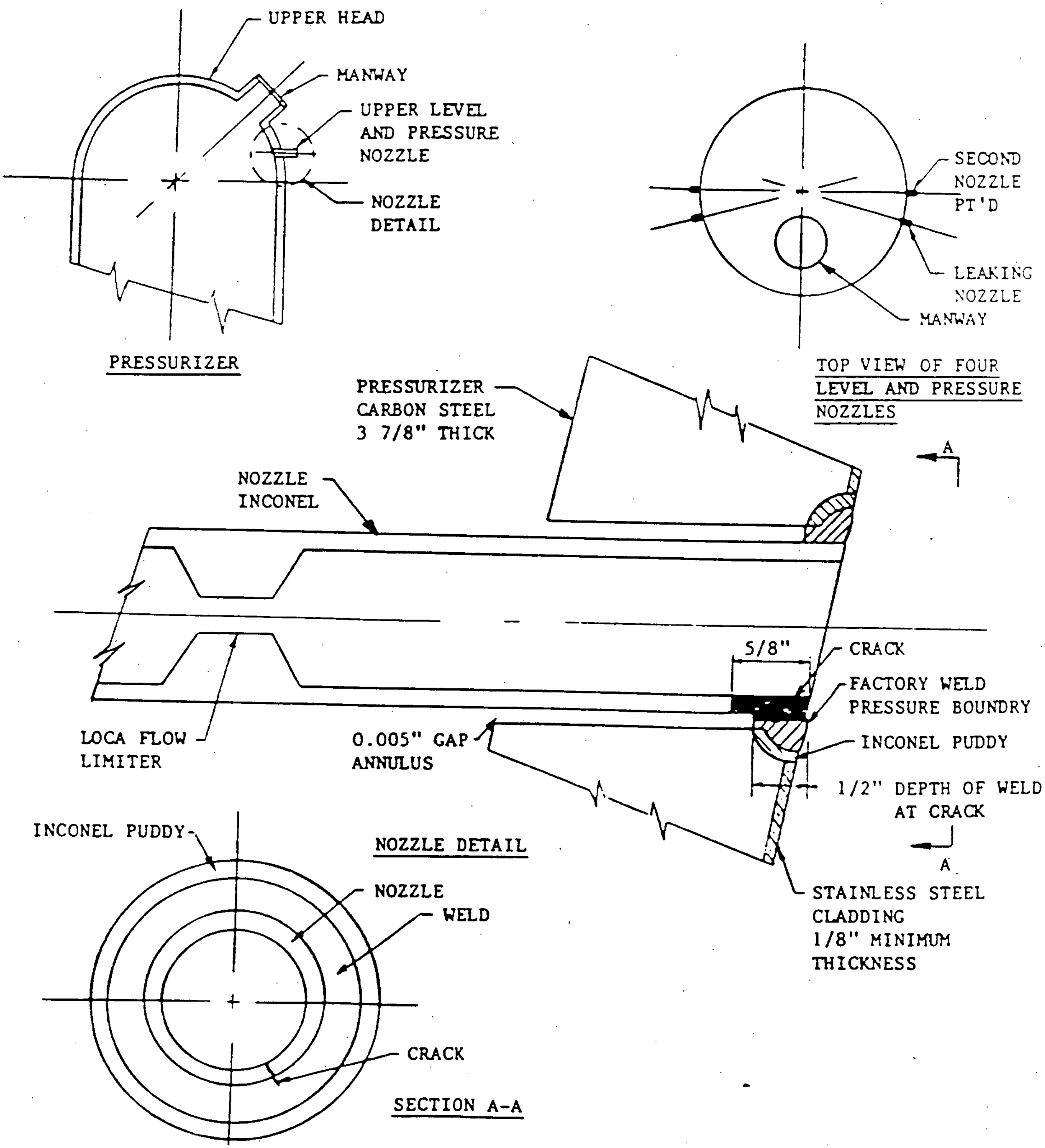
UPPER HEAD
MANWAY
UPPER LEVEL AND PRESSURE NOZZLE
NOZZLE DETAIL
PRESSURIZER
SECOND NOZZLE PT'D
LEAKING NOZZLE
MANWAY
TOP VIEW OF FOUR LEVEL AND PRESSURE NOZZLES
PRESSURIZER CARBON STEEL 3 7/8" THICK
A
NOZZLE INCONEL
5/8"
CRACK
FACTORY WELD PRESSURE BOUNDRY
LOCA FLOW LIMITER
0.005" GAP ANNULUS
INCONEL PUDDY
1/2" DEPTH OF WELD AT CRACK
A
INCONEL PUDDY
NOZZLE DETAIL
NOZZLE
WELD
STAINLESS STEEL CLADDING 1/8" MINIMUM THICKNESS
CRACK
SECTION A-A

FIGURE 1

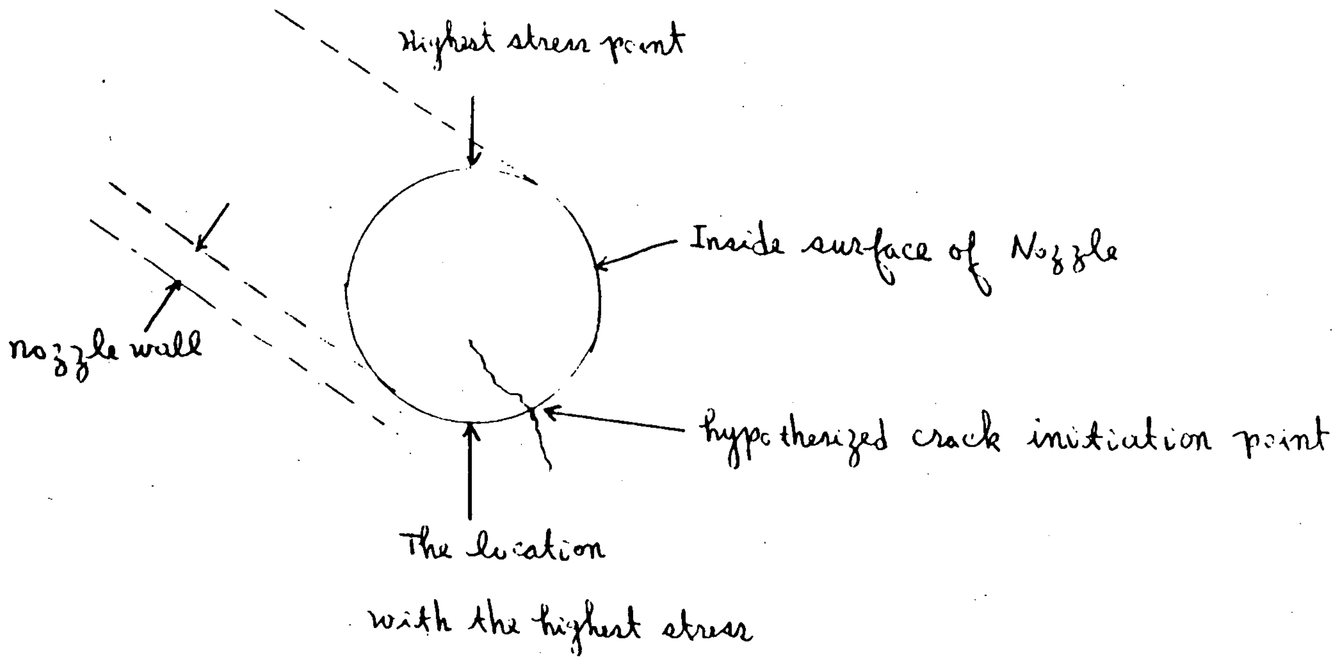

Figure 2 Front View of the Crack Configuration

Appendix A

Stress Distribution of Instrument Nozzle at Location Away From Welding

The tensile stress of a thick pipe when internal pressure P_i can be expressed by the following formula (Reference 25).

$$S_t = \frac{a^2 P_i}{b^2 - a^2} \left(1 + \frac{b^2}{r^2}\right) \qquad (A\bullet1)$$

where P_i = internal pressure = 2250 psi

a = inside radius = 0.307 inch

b = outside radius = 0.525

r = radial distance from center

The maximum S_t, occurring at the inside diameter, is:

$$S_{t_{max}} = \frac{(0.307)^2\ 2250}{0.525^2 - 0.307^2} \left(1 + \frac{0.525^2}{0.307^2}\right)$$

$$= 4588 \text{ psi} \qquad (A\bullet2)$$

The minimum S_t, occurring at the outside diameter, is:

$$S_{t_{min}} = \frac{2 \times 0.307^2 \times 2250}{0.525^2 - 0.307^2}$$

$$= 2338 \text{ psi} \qquad (A\bullet3)$$

Appendix B

Residual Tensile Stress Due to Welding

During welding, many passes of weldment were progressively applied to the butt weld recess. The average width of each pass is about 1/8 inch. The radial shrinkage of last pass at each vertical welding plane will generate a tensile hoop stress in the nozzle. Note that one side the weldment was attached to Inconel-butter which was welded to the thick wall and the other side of the weldment was connected to the tube. Because the wall is much stiffer than the tube, the shrinkage in the weldment will result in deformation in only the tube, not the wall. The residual tensile stress can be approximated by the linear approximation

$$S_R = \frac{\Delta T \bullet \alpha \bullet \ell}{R} \bullet E \qquad (B \bullet 1)$$

ΔT = temperature change of the weldment ~ (2300°F - 650°F)

$\alpha = 8.6 \times 10^{-6}$ in/in.°F, thermal expansion coefficient

ℓ = radial width of one pass weldment

R = mean radius of the nozzle

E = Young's modulus of Inconel-600

$$S_R = \frac{1650 \times 8.6 \times 10^{-6} \times \frac{1}{8}}{0.4} \times 29.5 \times 10^{6}$$

$$= 130.8 \text{ Ksi} \quad > 60.9 \text{ yield strength} \qquad (B \bullet 2)$$

Conclusion

Since the calculated residual stress with linear approximation is greater than the yield strength, the tube was plastically deformed during welding. However, after deformation the residual stress would reduce to a level approximately equal to the yield strength of 60.9 Ksi.

Appendix C

Stress Distribution and Strain Rate Around the Nozzle Inlet

The stress field around the nozzle inlet area can be determined by superimposing the following three stress components.

1) The tensile stress caused by the internal force applied to the pressurizer wall, which was subjected to a pressurizer pressure of 2250 psi. The stress is in both the circumferential and longitudinal directions of the pressurizer cylinder.

2) The residual stress induced by welding.

3) The tensile stress in circumferential and longitudinal directions of the tube due to the internal pressure of the nozzle. This stress is considered negligible as compared to the welding residual stress and the pressurizer hoop stress as described in (1).

The pressurizer hoop stress will result in a local high tensile stress at the sharp edge of the nozzle end. The highest tensile stress occurs at the sharp edge location which is perpendicular to the nominal hoop stress. In other words, it occurs at the 12 o'clock and 6 o'clock location of the nozzle inlet.

Meanwhile, the longitudinal stress of the pressurizer will also generate tensile stress on the sharp edge of the nozzle end. The highest concentration will be at the 3 o'clock and 9 o'clock locations. The numerical valves of the tensile stresses at 3, 6, 9 and 12 o'clock of the sharp-edge nozzle end are calculated below.

Nozzle End Tensile Stress at 6 and 12 o'clock Locations

Based on the analysis documented by R. Peterson (Reference 26), the stress concentration factor for a small hole in a large plate, which is in an uniaxial, circumferential tensile condition, is 3.0. Knowing that the inside radius of the pressurizer cylinder is 48.125" and the thickness of the wall is 3.875". The hoop stress at the inside surface of the pressurized is calculated as follows:

$$S_{t\ max} = \frac{(b^2 + a^2)}{b^2 - a^2} P_i \text{ (see Appendix A)}$$

$$= \frac{(48.125 + 3.875)^2 + 48.125^2}{(48.125 + 3.875)^2 - 48.125^2} \times 2250 = 29.1 \text{ Ksi} \qquad (C \bullet 1)$$

Including the stress concentration factors of 3, the maximum local stress at the 6 and 12 o'clock location of the sharp-edged, nozzle end is:

$S_{t\ max}$ at nozzle end = 87.3 Ksi

Nozzle End Tensile Stress at 3 and 9 o'clock Locations

Based on the data from Van Dyke, R. Peterson (Reference 26) stated that the stress concentration factor for a small hole in a large cylinder which is in an uniaxial longitudinal tension condition is also 3.0. The longitudinal tensile stress can be obtained by force balance.

$$S_\ell = \frac{(\pi\ a^2)\quad Pi}{(\pi\ b^2 - \pi\ a^2)}$$

$$= 13.4 \text{ Ksi} \qquad (C{\bullet}2)$$

Accounting for the stress intensity effect, the local tensile stress at the 3 and 9 o'clock locations of the nozzle end is:

$$S_{t\ max} \text{ at nozzle end} = 40.3 \text{ Ksi} \qquad (C{\bullet}3)$$

Superposition of Elastic Stresses by Linear Elastic Model

At the 12 and 6 o'clock locations of the nozzle edge, the principal stress at the 2250 psia can be calculated by the following formula:

$$S_p = ((87.3 + 60.9)^2 + 13.4^2)^{\frac{1}{2}}$$

$$= 148.8 \text{ Ksi} \qquad (C{\bullet}4)$$

The 8.0 and 16.0 Ksi are the minimum and maximum compressive, residual stresses caused by welding. The 13.4 Ksi is the tensile stress caused by the longitudinal force exerted to the pressurizer wall. Its direction is perpendicular to that of 87.3 Ksi, but on the same plane containing the inside pressurizer wall.

At the 3 and 9 o'clock locations of the nozzle edge, the principal stress is calculated by the same method as that for the 12 and 6 o'clock locations.

$$S_{p,\ min} = ((40.3 + 60.9)^2 + 29.1^2)^{\frac{1}{2}} = 105.3 \text{ Ksi} \qquad (C{\bullet}5)$$

Note the tensile stresses caused by the nozzle internal pressure in either its circumferential or longitudinal direction are neglected because of their small magnitude compared to the tensile stress generated by the pressurizer internal pressure at the tip of the nozzle edge.

Actual Stress

The actual local stress at the 6 and 12 o'clock locations will be lower than 148.8 Ksia, but greater than 60.9 Ksia, if plastic deformation is considered. The maximum stress level will actually be limited by the amount of the plastic deformation allowed by the surrounding elastic material. A first-order estimate of the actual stress is the average of the yield strength and the stress calculated from the linear elastic mode. That is, 105 Ksi.

Local Strain Rate In the High Stress Area

Based on the above analysis, the position of the highest stress is at the 12 and 6 o'clock location on the edge of the Inconel-600 tube end. The average strain rate is determined here.

Because the stress level drops exponentially with the distance from the highest stress point, the area of high stress will behave elastically, i.e., the local strain is almost linearly proportional to the local stress. Moreover, the maximum strain is limited by the elastic behavior of the surrounding material. With this relationship, the maximum local strain change during pressurization can be calculated as follows:

$$S_s = \frac{S}{E}$$

$$= \frac{29.1 \text{ Ksi}}{30 \times 10^6 \text{ psi}} = 0.97 \times 10^{-3} \qquad (C{\bullet}6)$$

The average strain rate, assuming an average of 8 hours of pressurization time, is:

$$S_s = \frac{0.97 \times 10^{-3}}{8 \times 3600} = 3.3 \times 10^{-8}$$

Appendix D

Time-To-Failure Prediction

Based on the model proposed by Y. G. Garud (Reference 22), the Inconel-600 pure water SCC failure model can be approximated by the following failure model.

$$a_t = \int_0^{t_f} A\dot{E}^P \, dt \qquad (D\bullet 1)$$

where a_t = critical value, beyond which SCC is considered in existence

A = constant

$\dot{E}$ = strain rate

t_f = time-to-crack-initiation

From the above equation, t_f is:

$$t_f = \left(\frac{a_t}{A} \right) / \dot{E}^P \qquad (D\bullet 2)$$

Based on Spiedel's data for mill-annealed Inconel-600 pure water SCC at 644°F, (a_t/A) is 8.547 second and P = 0.638.

$$t_f = 8.547/(3.3 \times 10^{-8})^{0.638} = 139.0 \text{ hours}$$

No. of Startups = 139/8.0 = 17.3 times

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LA JOLLA, CALIFORNIA 92093

30 October, 1986

Mr. John S. Steibel
Vice President
Torrey Tech Inc.
P.O.Box 786
Solana Beach, CA 92075

Dear John:

Re: Interim Failure Analysis for San Onofre Unit 3
Pressurizer Instrument Nozzle.

Per your request, I have reviewed the memo from C. Chiu and S. Gosselin on the examination of the cracked pressurizer instrument nozzle in San Onofre Unit 3. The supporting documents and papers related to this topic have also been included in my assessment, which is attached herewith.

I agree with the conclusions reached by C.Chiu and S. Gosselin in their report. Their analysis of the problem and the review of the background information is quite complete and accurate.

Sincerely,

Massoud T. Simnad

Massoud T. Simnad
Adjunct Professor
Materials Science & Engineering
and Nuclear Energy

encl:

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M T Simnad

COMMENTS ON INTERIM FAILURE ANALYSIS FOR SAN ONOFRE UNIT 3 PRESSURIZER INSTRUMENT NOZZLE

by

M. T. SIMNAD
University of California in San Diego

30 October, 1986

The following are my comments on the interim failure analysis for San Onofre Unit 3 pressurizer instrument nozzle:

1. The susceptibility of high nickel alloys, such as Inconel-600, to intergranular stress corrosion cracking in pure water at elevated temperatures has been well established since the pioneering work of Coriou over twenty years ago. The time to failure is governed by a number of variables, including the tensile stress level and the strain rate, the structure of the alloy resulting from prior heat treatments and forming operations, composition of the alloy, surface treatment, purity and oxygen content and pH of the water, and the temperature. Most of the experience has been obtained from PWR steam generator Inconel-600 tubing. There are also a number of cases of IGSCC failures in Swedish BWR Inconel instrumentation tubing and core screw components. No such failures have been observed with Incoloy-800.

2. The C-E conclusions are based upon the examination of the failed nozzle material, and upon the fact that a number of other nozzles made from the identical heat of material have not failed after longer exposures. The statement to the effect that "this crack is not believed to be a generic problem" is somewhat persuasive. However, it is unclear as to what were the postulated "unique set of conditions that resulted in the IGSCC in San Onofre Unit 3". The question is whether longer exposures in the San Onofre units will result in IGSCC in the undamaged nozzles too, if the stress levels or the relative susceptibilities of these nozzles are somewhat different. The accelerated stress corrosion tests in strong alkali and acid solutions are not relevant to this problem.

3. It is important to note that the heat of material for the cracked nozzle has too high a yield strength of 60.9 Ksi, well into the range where poor resistance to IGSCC is indicated by CE data. It has been observed that Inconel-600 tubing with yield strengths greater than 55 Ksi are most susceptible to IGSCC in pure water.

M.T. [illegible]

There is little doubt that the material of the failed nozzle close to the weld was exposed to sensitizing temperature range during the welding operation. The presence of high tensile stresses in the susceptible structure of the alloy could result in IGSCC in the Inconel-600 nozzle material.

5. The discussion of the nine intact nozzles made from the same heat of Inconel-600, operating in other units and locations, is well supported by the experimental evidence. The threshold time for IGSCC is both strain rate and temperature dependent. Hence, nozzles that have experienced fewer startups and/or lower temperatures will have correspondingly longer lifetimes. The cracked nozzle was exposed at the system temperature of 650'F for approximately 600 days and 22 pressurization cycles before it failed. The crack is located at the location close to where the stress is highest (estimated to be 50% above the yield strength), resulting from residual stresses from welding and the pressurized hoop stress.

6. In Germany (KWU) and Canada (for the boiling version of the CANDU reactors), the alloy Incoloy-800 was specified following its highly successful application in the Peach Bottom HTGR steam generator tubing (no leaks in 7 years of operation). Also, extensive studies in France during the past two decades on caustic stress corrosion and IGSCC in pure water of Inconel-600, Incoloy-800, and type 316 stainless steel have provided very useful information on the threshold stresses for stress corrosion cracking of these alloys. The tests were carried out at 350'C (662'F) on specimens under constant strain and under constant load. The results of these tests showed that for Incoloy-800 resistance to caustic stress corrosion, in NaOH solutions below 10% concentration, no cracking occurs even at stresses exceeding the yield strength (280 MPa, 40ksi). Inconel-600 showed susceptibility to stress corrosion cracking in all concentrations of caustic and in pure water at stresses as low as one-half the yield strength. Heat treatment improved the caustic stress corrosion cracking resistance of Inconel-600. The steam generator tubing for the Super Phoenix fast breeder reactor is all Incoloy-800. (Ph.Berge, et al, Corrosion 33(12), 425 (1977); Nucl. Energy 17(4), 291 (1978).

7. In the KWU steam generators Incoloy-800 tubing has been used very successfully since 1969 in about 20 PWRs. The specification complies with ASTM 163-66, with somewhat narrower compositional specifications toward higher mean nickel (32 to 35%) and Cr (20 to 23%) contents and lower permissible carbon contents (0.03%). The stabilization ratios of titanium-to-carbon and C+N are $\geq$12 and $\geq$8, respectively, to prevent sensitization at welds. All KWU steam generator tubes are shot-peened with glass balls on the outside diameter in order to generate compressive surface residual stresses to mitigate stress corrosion. The decision to continue to use Incoloy-800 in KWU reactors is based upon the results of extensive tests in laboratory experiments in a model steam

M.T. [illegible]

generator and the many years of excellent performance in operating PWRs with Incoloy-800 tubing. In contrast, Inconel-600 tubing in KWU reactors showed both internal and external intergranular cracks.

8. Canadian studies have shown that tests in pure water and in dilute NaOH solutions provide a better simulation of SCC than tests in concentrated caustic solutions which far exceed the maximum concentration of free hydroxide that can form in heated crevices. The latter concentration is governed by the available superheat (difference between the saturation temperature and the primary coolant temperature). In dilute caustic solutions and in pure water Incoloy-800 was found to be practically immune and far more resistant to SCC than Inconel-600. (R.S.Pathania and J.A.Chitty, Corrosion 34(11), 369 (1978).

9. The results of an extensive study of SCC of steam generator tubing materials in a cyclic steam environment were reported in 1975 by ORNL and Southern Nuclear Engineering. The tests were carried out in a loop in steam taken directly from a steam generator superheater (Bartow Plant, Florida Power). These tests yielded results that differed radically from the results of conventional laboratory tests conducted in boiling Mg-chloride. The alloys that resisted SCC contained at least 22% Cr (e.g., Incoloy-800). Nickel alloys that showed susceptibility to SCC all contained low amounts of Cr (e.g., Inconel-600, with 16% Cr). (J.P.Hammond, et al, ORNL-5031).

10. The EPRI "Steam Generator Reference Book" does not give a balanced assessment of the relative merits of Inconel and Incoloy-800 for PWR steam generator tubing.

Paine, et al, (p.4-4) state that " Incoloy-800 is less desirable than Inconel-690 due to a lesser corrosion data bank available to US utilities and to its susceptibility to caustic SCC," while acknowledging the excellent performance of this alloy in the KWU PWRs since 1969! The same authors also admit (p.4-3) that for Inconel-690 (their preferred alloy) "steam generator operating experience is lacking." (!). This data bank certainly is available to US utilities, as well as the long experience in the Peach Bottom and Ft.St.Vrain HTGRs. In contrast, both Inconel-600 and Inconel-690 have been found to be susceptible to IGSCC at 288'C in a resin intrusion water environment (Page & Minn, Met.Trans.AIME, 17A (May 1986) 877).

11. I concur with the actions recommended by C. Chiu and S. Gosselin, namely, that the nozzles made from the same heat as the failed nozzle (heat No. 54318) be replaced. The replacement nozzles should be Incoloy-800 alloy, or Inconel-600 selected from CE specified alloy that is resistant to IGSCC.

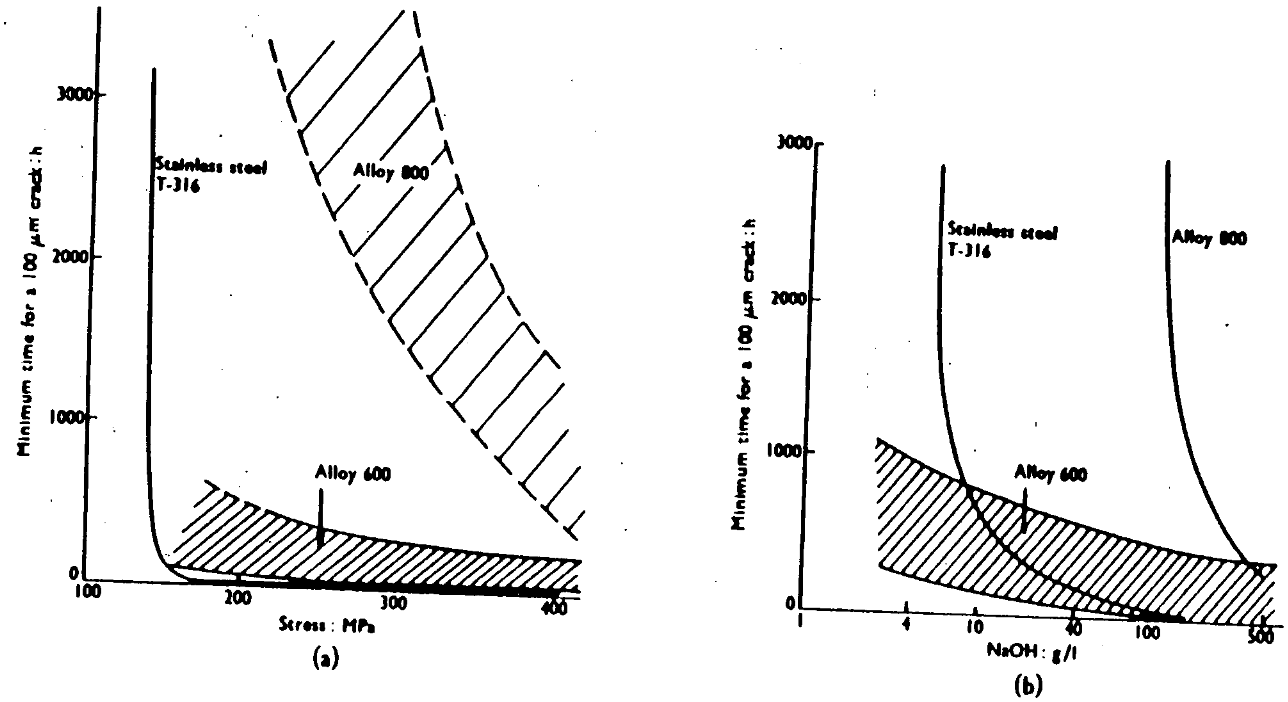

Fig. 26. Comparison of resistance to stress cracking of Alloy 600, Alloy 800, and T-316 stainless steel in deaerated caustic soda solutions at 350 C: (a) effect of stress (NaOH = 100 g/1); (b) effect of caustic soda concentration ($\sigma \approx 0.8\ E_{0.2}$) (Ref. 81) (Berge, et al)

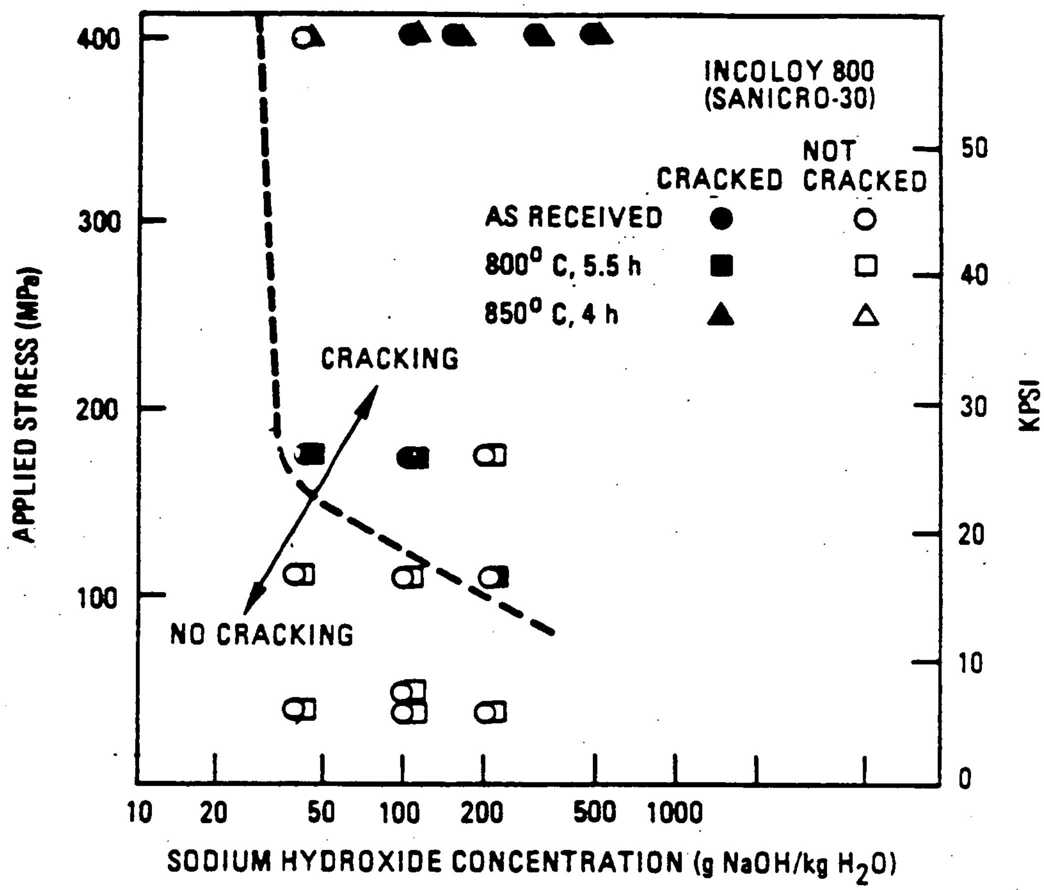

Fig. 27. Effect of applied stress and sodium hydroxide concentration on stress corrosion cracking of Incoloy 800 (Sanicro 30) C-rings and pressurized capsules at 290° to 300°C (554° to 572°F) (Ref. 115) Berge, et al

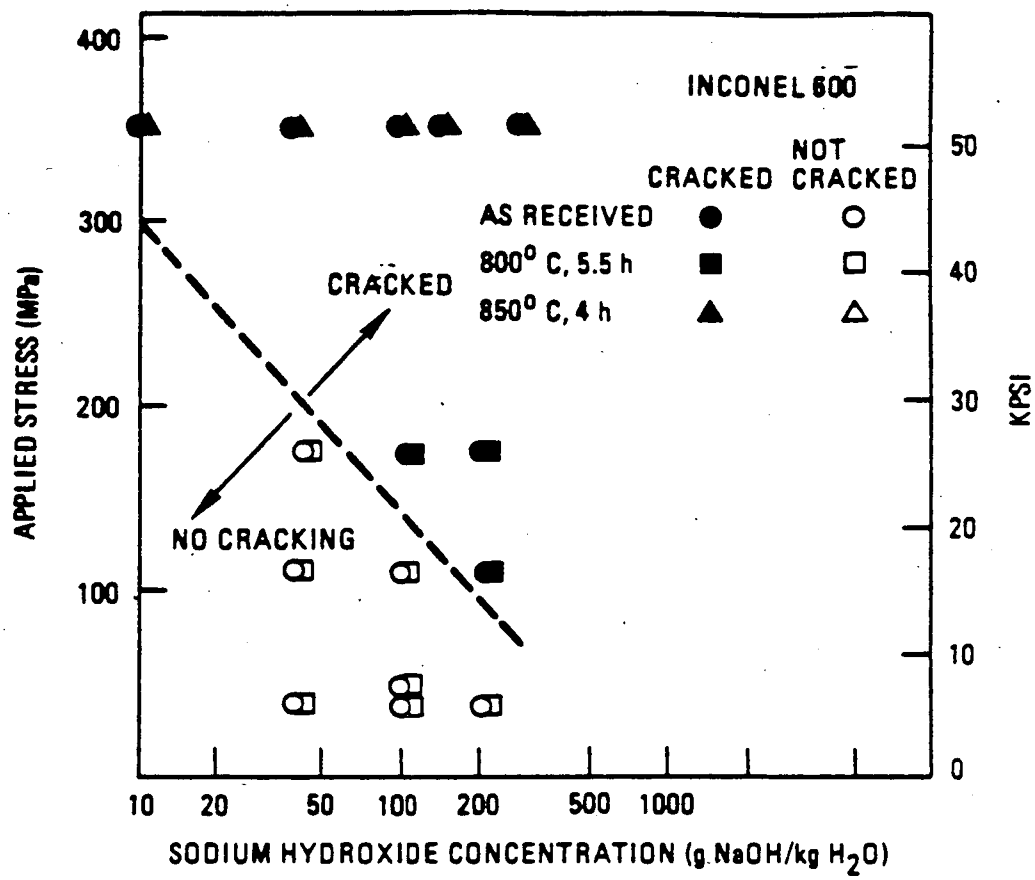

Fig. 28. Effect of applied stress and sodium hydroxide concentration on stress corrosion cracking of Inconel 600 C-rings and pressurized capsules at 290° to 300°C (554° to 572°F) (Ref. 115) Berge, et al