# ACCEPTABILIT OF CLASS 1
# 24-INCH FEEDWATE CHECK VALVES

Report for

Limerick Generating Station (Units 1 & 2)

Prepared for W. C. McDaniel

By ____________________
Y. Chung

Approved ____________________
R. A. White
Coatings and Corrosion Group Manager

Approved ____________________
R. A. Manley
Manager

Materials and Quality Services Department
Research and Engineering
BECHTEL GROUP, INC.
SAN FRANCISCO

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# ABSTRACT

Toughness properties of A352 Grade LCB castings were evaluated to determine the acceptability of 24 inch Class 1 feedwater check valves for a 40°F lowest service temperature. A review of the foundry material test reports, deoxidation practice, heat treatment, and microstructures indicated sufficient grounds for acceptance of the valves to not only the ASME Section III Code requirements but also NRC's Standard Review Plan concerning fracture prevention. Various metallurgical effects on material toughness properties in terms of Charpy V-notch (CVN) impact values and nil ductility transition temperatures (NDTT) were discussed. The NDTT data on steel castings in NUREG-0577 were found to be inappropriate for a generic evaluation of steel castings. Using other published NDTT data on steel castings and estimated NDTTs based on actual CVN data for the check valves, this report shows that the toughness of the 24-inch Class 1 feedwater check valve body castings satisfies the requirements of General Design Criteria concerning brittle fracture. A fracture mechanics analysis provided further confirmation that a brittle fracture is unlikely in all of the eight 24-inch Class 1 feedwater check valves in the Limerick Generating Station Units 1 and 2.

ACCEPTABILITY OF CLASS 1
24-INCH FEEDWATER CHECK VALVES

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## 1.0 INTRODUCTION

General Design Criterion (GDC) 51 requires that "The reactor containment boundary shall be designed with sufficient margin" against brittle fracture. During a preliminary review of reactor pressure boundary materials for compliance to the GDC 51 requirements in June 1983, an NRC staff member calculated permissible lowest service metal temperatures (PLSMT) for various components including 24-inch Class 1 feedwater check valves (1F074 A and B, 1F010 A and B, 2F074 A and B, 2F010 A and B). Using the nil ductility transition temperature (NDTT) data in NUREG-0577 (Issued for Comment in October 1979)[1], his calculations showed +80°F as the PLSMT for the 24-inch feedwater check valve body castings in the Limerick Generating Station Units 1 and 2. This report presents the results of our assessment of the toughness of the particular valve castings using the material test reports from the foundry, published data in addition to those in NUREG-0577, and in-situ metallographic examination of four of the eight 24-inch Class 1 feedwater check valve body castings in Units 1 and 2 (Appendix A). The "new" data we have collected and the results of our analysis of these data showed that the PLSMT for these valves is lower than +40°F. This is the lowest service temperature (LST) anticipated for the check valves during the life of the plant.

## 2.0 CONCLUSIONS AND RECOMMENDATIONS

(1) The basic toughness requirements that the 24-inch feedwater check valves must comply with are those in the 1977 Summer Addenda of the ASME Section III Code according to NRC's Standard Review Plan 6.2.7. The toughness of the check valve castings satisfies these requirements as well as those of the current Code.

(2) In addition, an evaluation of nil ductility transition temperatures for the check valve castings indicates that these valves would meet a 40°F permissible lowest service metal temperature.

(3) Brittle fracture is highly unlikely in these valves under an upset or normal conditions.

(4) The toughness properties of these valves comply fully with the requirements of GDC 51.

(5) It is recommended, therefore, that no system modification be made to raise the lowest service temperature from 40°F.

## 3.0 MATERIALS

### 3.1 Description of Feedwater Check Valves

The following data were extracted from the design report of the 24-inch feedwater check valves prepared by Atwood & Morrill.

(a) Valve Type: Swing check valve (Class 1). See Fig. 1.
(b) Valve Nominal Size and Pressure Rating: 24 inch - 775#
(c) Valve Inlet Diameter: 21 inches
(d) Body Material: SA352 Grade LCB
(e) Body Minimum Thickness: 2.083 inches including 0.120 inch corrosion allowance
(f) Actual Minimum Body Wall Thickness: 2.313 inches

(g) Bonnet Thickness $t_R$: 3.5 inches
(h) Disc Thickness t: 3.75 inches
(i) Design Stress Intensity Valves $S_m$: 23.3 ksi at room temperature
18.9 ksi at 500°F
(j) Standard Calculation Pressure $P_s$: 2100 psi
(k) Lowest Initial Temperature: 40°F (1180 - 875 psi)

## 3.2 Properties of Valve Body Castings

The valve bodies were cast in 1975 by Quaker Alloy to the requirements of SA352 Grade LCB. Table 1 is a compilation of data from Quaker Alloy's "Material Test Report" for six heats of the eight valve body castings. In addition to the chemical compositions and tensile properties, it shows Charpy V-notch (CVN) impact test results at 30°F. The contents of residual elements not in the original material test report were obtained only for Heat No. F6137 from the microfilm records in file at Quaker Alloy.

The Quaker Alloy documentation revealed that the eight valve body castings received the following heat treatment:

(1) Heated to 1690/1720°F, hold 4 hours 25 minutes, air cooled (4/18/75)*

(2) Heated to 1630/1650°F, hold 6 hours, furnace cooled
to 1440/1460°F, hold 2 hours, furnace cooled
to 1420/1430°F, hold 40 minutes, and water quenched (4/22/75)

(3) Tempered at 1200°F for 4 hours 15 minutes (4/25/75)

(4) Stress relieved (after weld repairs) at 1200°F for 4 hours 15 minutes (7/15/75)

The castings were examined using an X-ray source (for the Class II shrinkage acceptance level) and a magnetic particle method.

# 4.0 EVALUATION PROCEDURE

## 4.1 Toughness Requirements

NRC's Standard Review Plan[2)] 6.2.7 "Fracture Prevention of Containment Pressure Boundary" states the following acceptance criteria.

> "To meet the requirements of GDC 1, 16 and 51, ferritic containment pressure boundary materials should meet the fracture toughness criteria for Class 2 components identified in the Summer 1977 Addenda of Section III of the ASME Code."

This is the basic requirement that these Class 1 feedwater check valves must comply with. Where a pressure boundary component was not "fracture toughness tested", "the staff's assessment of the fracture toughness of materials" is "based on the metallurgical characterization of these materials and fracture toughness data presented in NUREG-0577."

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*The dates apply to Heat No. F6137.

### 4.1.1 ASME Section III Requirements

The toughness requirements for valves in ASME Section III are grouped according to the nominal wall thickness of the connecting pipe. This is 1.812 inches for the 24-inch check valves. For the nominal pipe wall thickness between 1-1/2 to 2-1/2 inches, the following requirements apply.

| | | 1977 Summer | 1983 NC Subsection |
|---|---|---|---|
| CVN impact testing at the lowest service temperature (LST) or lower | Energy ft-lbs | --- | 35 average/30 min |
| | Mils Lateral Expansion | 40 min | 35 average/30 min |
| OR | | | |
| NDTT ($T_{NDT}$) (Appendix R) | | --- | LST - $T_{NDT}$>30°F |

Thus, the only requirement for the check valves in the 1977 Summer Addenda of the Code is the 40 mils minimum lateral expansion in CVN tests at the lowest service temperature (LST)* or lower. The material test reports (Table 1) show that this requirement was satisfied. $T_{NDT}$ was not a requirement then. It is an option even in the 1983 Code. (For pressure retaining materials with a nominal wall thickness of connecting piping exceeding 2-1/2 inches, the (LST - $T_{NDT}$ >A) criterion applies.)

### 4.1.2 $T_{NDT}$ Requirements

The valve castings were CVN tested with results that satisfy the toughness requirements of the 1977 Summer Addenda of the Code. Still, the NRC staff used the $T_{NDT}$ data in NUREG-0577 in calculating the PLSMT. The acceptance criterion is basically the same as that in Appendix R of ASME Section III: the material temperature is at or above the $T_{NDT}$ plus the thickness correction (A) given in Figure 2. The $T_{NDT}$ of a material can be determined as follows according to NRC's Standard Review Plan PSRP-5.3.4[3].

(1) Use the $T_{NDT}$ values in Table NF-2311(b)-1 in the Winter 1982 Addenda to the ASME Code.

A352 Grade LCB is not included in this table or Table II of the review plan.

(2) The $T_{NDT}$ may be determined by testing.

The check valve castings were not tested for $T_{NDT}$.

(3) The $T_{NDT}$ may be estimated using the correlation given below.

For materials with a minimum specified yield strength between 35 ksi and 45 ksi, each of three Charpy specimens broken at $T_{NDT}$ should exceed 20 ft-lbs. We have used this method in estimating a $T_{NDT}$ along with other data not presented in NUREG-0577.

*40°F for Limerick

## 4.2 $T_{NDT}$ Data for Steel Castings

### 4.2.1 NUREG-0577 Data

Table 2 of this report represents a portion of the table in NUREG-0577 (or NUREG CR-3009) applicable to the $T_{NDT}$ of steel castings. According to this table, an average $T_{NDT}$ (or NDT) for A-27 and A-216 castings with thickness greater than 1-inch is 35°F and NDT+1.3σ is 57°F. We determined that this is based on the results of two heats (R3 and R4) of A-216 Grade WCB casting from one foundry in an investigation conducted by Banks et al[4]. Table 3 of this report reproduced pertinent data from the paper by Banks et al. It will be shown later that these data should not be used for a generic evaluation of A352 Grade LCB or other castings which were fracture toughness (CVN) tested.

### 4.2.2 SFSA Reports, MPC-13, and Steel Castings Handbook

The Steel Founders' Society of America (SFSA) issued two reports[5,6] on $T_{NDT}$ of steel castings. Some of the $T_{NDT}$ data in NUREG-0577 are referenced to SFSA (as personal communication rather than to any specific reports). The above two reports present the results of systematic laboratory tests as well as industry data. Although a large amount of data is presented in these reports, only a few are directly comparable to the check valve castings. Some of the highlights of these reports are as follows.

(1) A typical $T_{NDT}$ is -10°F for carbon steel castings in a normalized and tempered condition. The range was -75°F to +90°F.

(2) The best toughness was obtained in the quenched and tempered condition.

(3) "Double normalized and tempered steels averaged 57 degrees lower in NDTT than comparable normalized and tempered counterparts."

(4) Deoxidation with aluminum or aluminum-bearing alloy is beneficial to toughness, yielding fine grains. In the double normalized and tempered condition, aluminum lowered NDTT by about 12°F for every 0.01% up to 0.035% aluminum.

(5) "Small amounts of phosphorus and sulfur can significantly increase the NDTT."

(6) "No loss in NDTT due to section size was observed for LCB steel."

(7) Producer "A" reported -60°F to -75°F as $T_{NDT}$ for 8 heats of A352 Grade LCB in a double normalized and tempered condition.

Wallace et al[7] investigated the effects of section size on the toughness of various cast steels. Their results are presented in MPC-13. They found that "the toughness of normalized and tempered steels was only slightly affected by increasing mass." (The size effect was apparent in quenched and tempered cast steels with a high hardenability). The $T_{NDT}$ data for carbon steel castings in the report by Wallace ranged from -26°F for 5-inch thick WCB by one foundry to +32°F for both 1-inch thick WCA by another foundry and for 5-inch thick WCB by a third foundry (all in a normalized and tempered condition). This indicates the difficulty in generalizing the size effects on the toughness of steel castings.

Several $T_{NDT}$ data in the Steel Castings Handbook and its Supplement 5 were quoted from the above sources.

### 4.2.3 Quaker Alloy Data

As mentioned before, Quaker Alloy did not conduct $T_{NDT}$ tests for the eight check valve castings as it was not a requirement in 1975. They conducted a few $T_{NDT}$ tests, however, for comparable grades (e.g. WCB) for Navy and Military requirements. Their records for nine heats of castings in the 1970s showed that the tests were conducted to satisfy a +10°F maximum $T_{NDT}$ requirement without actually determining a $T_{NDT}$. For two heats, however, additional tests determined $T_{NDT}$ at 0°F and -10°F, respectively. More recent data by Quaker Alloy showed -50°F and -60°F $T_{NDT}$ for arc melted heats as in the 1970s and even -70°F and -90°F for arc melted and AOD refined heats, all for normalized and tempered WCB.

### 4.3 In-Site Metallography of Valve Body Castings

The valve body castings were metallographically examined in-situ by the Philadelphia Electric Company (Peco). The purpose was to verify the microstructures in relation to the chemical compositions and heat treatment. The results are presented in the Appendix A.

## 5.0 RESULTS OF EVALUATION

### 5.1 Conformance to Toughness Requirements

It is clear that the 24-inch check valve castings produced by Quaker Alloy in 1975 complied with the toughness requirement in effect in 1975, 1977 Summer, and even 1983. The only toughness requirement that these castings needed to comply with is the 40 mil minimum lateral expansion in CVN tests. The material test reports for the castings list CVN properties at 30°F, which is 10°F lower than the lowest service temperature (40°F). The CVN values in the material test reports exceed the minimum requirements. This should satisfy the acceptance criteria of NRC's Standard Review Plan 6.2.7 for fracture toughness as well as ASME Section III. As discussed below, the toughness of these castings satisfy even the $T_{NDT}$ criteria.

### 5.2 A352 Grade LCB vs Other Casting Grades

Table 4 of this report presents a comparison of several carbon steel casting specifications. The grades of castings compared in this table have a specified minimum yield strength from 35 ksi to 45 ksi. A352 is one of only two steel casting specifications that are specifically designated for low temperature applications. They have a distinction of requiring CVN impact tests. Drop weight tests for $T_{NDT}$ are included in supplementary requirements which may be specified in a purchase order in addition to the "regular" requirements which include CVN tests. Neither A-27 nor A-216 has a requirement for toughness. As will be elaborated later, therefore, A352 castings do not belong to the same category as regular A-27 and A-216 castings.

### 5.3 Applicability of $T_{NDT}$ Data in NUREG-0577

In NUREG-0577, A-216 Grade WCC is grouped together with A-27 Grade 70-40 for $T_{NDT}$ data presentation, simply because their chemical composition requirements are "virtually identical." In the case of these two grades, this kind of generalization may be reasonable merely based on chemical compositions. It would be, however, not reasonable to apply $T_{NDT}$ data from A-27 and A-216 castings to A352 Grade LCB.

The two major variables on toughness of castings are heat treatment (or microstructures) and deoxidation in addition to chemical composition. Foundrymen would pay extra attention to chemical composition control and deoxidation practices well beyond what is apparent from ASTM chemical composition requirements when the castings are made for low temperature applications. None of the ASTM specifications on carbon steel castings have any stipulations on deoxidation practices. A wide variation in deoxidation practices and other controls among foundries is reflected on a wide variation in toughness data. The $T_{NDT}$ data in NUREG-0577 have only a narrow base and biased to the high side of $T_{NDT}$ for castings, particularly for those with thickness greater than 1 inch as explained below.

As pointed out in Section 4.2.1 of this report, the $T_{NDT}$ data in NUREG-0577 for castings with thickness greater than 1-inch are based on the results of 12 tests from two heats of castings produced by one foundry. These are heat codes R3 and R4 in a normalized and tempered condition in Table 3 (a) of the report by Banks et al [4]. The $T_{NDT}$ ranged from 0°F to +60°F with an average of 35°F. A review of other data [Table 3(b)] indicates that R3 and R4 happen to be the worst two heats of the 22 heats investigated by them. Other comparable heat codes (D, K, and L) showed $T_{NDT}$ much lower than those for R3 and R4 for a comparable heat treatment condition (NWQT)*. The chemical compositions showed higher phosphorus and sulfur contents for R3 and R4 than other heats. Thus, the $T_{NDT}$ data for castings with thickness greater than 1-inch in NUREG-0577 are biased toward the high side.

One of the conclusions by Banks et al was that an "increase in section size has a generally degrading effect on NDTT when the current results are compared with other industry data for 1-in thick plate." This view is reflected in the data presented in NUREG-0577: -6°F as an average $T_{NDT}$ for 1-inch thick casting and 35°F as an average $T_{NDT}$ for thicker casting. A comparison of their data for various thicknesses (from 2-1/2 to 5-inches in 1/2-inch increments) show no size effects. In fact, in their later paper[8], Banks et al stated that "no discernable effect of plate** thickness (1 to 3-inch) on toughness was noted" for steels including A352 Grade LCC. The SFSA reports and the MPC data support this latter view that the $T_{NDT}$ of steel castings is affected little by section size. Therefore, thicker castings should not be "penalized" as much as the data in NUREG-0577 dictate.

The paucity of toughness data for steel castings, particularly in terms of $T_{NDT}$, and variations in deoxidation and other foundry practices make a statistical analysis difficult. It is inappropriate to apply the small $T_{NDT}$ data base in NUREG-0577 for generic applications. The above discussion presents a sufficient evidence why the $T_{NDT}$ data in NUREG-0577 should not apply to the A352 Grade LCB check valves. The $T_{NDT}$ of this casting may be estimated from the CVN data in the material test reports and comparison with $T_{NDT}$ data for comparable grades in sources other than NUREG-0577. Some of these data are considered "new", as they have been published after NUREG-0577 was issued and have not been incorporated into NUREG/CR-3009.

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*NWQT = normalized, water quenched, and tempered

**cast plate samples

## 5.4 Estimation of $T_{NDT}$ for A352 Grade LCB Check Valve Body Castings

Since the castings were not tested for $T_{NDT}$ and no samples are available for direct measurements, $T_{NDT}$ was estimted "based on the metallurgical characterization of this grade"2).

### 5.4.1 Effect of Quaker Alloy's Heat Treatment on $T_{NDT}$

The heat treatment condition of a material has a major effect on its toughness. The heat treatment for the check valves is given in Section 3.2 of this report. It is essentially equivalent to an NWQTT condition (normalizing, water quenching, and double tempering). The temperature step-down (from 1630/1650°F to 1420/1430°F) before water quenching is somewhat unorthodox for low carbon steel castings. This was done perhaps to minimize quench cracking in a relatively thick and complex casting according to Quaker Alloy. The NRC staff considers that this is equivalent to normalzing rather than water quenching. Then, the castings should be considered as being equivalent to a double normalized and double tempered condition, which according to the SFSA reports, relates to low $T_{NDT}$ values.

Dilatometer studies in the SFSA reports indicated that the $AR_3$ temperature is 1440°F for a low carbon steel casting with 0.16%C. The $AR_3$ temperature for the check valve containing 0.20%C should be slightly lower. The final temperature (1420/1430°F) before water quenching in the Quaker Alloy's heat treatment would be just about the upper critical temperature. The effect of austenite decomposition should have been minimal. Therefore, the effect of the temperature step-down on the microstructure from water quenching should have been minimal. Thus, the comparison of the water quenching to a normalizing is conservative from the point of its effect on toughness.

### 5.4.2 Effects of Microstructures

The micrographs in the Peco report (Appendix A) show fine grains. The beneficial effects of fine grains on the toughness of steels have been well recognized. The finer the grains, the higher the toughness or the lower the nil ductility transition temperature (NDTT). The fine grain structure of the valve castings is directly tied to the aluminum deoxidation practice as pointed out in 4.2.2 (4) and the heat treatment used. The grain size is 8 or finer for these four valve castings according to the micrographs in the Appendix A. Reference 6 of the report cited the following NDTT for 0.2%C-1.0%Mn steel castings: -10°F for grain size 8 and -40°F for grain sizes 9.5 to 10.

### 5.4.3 $T_{NDT}$ Estimation

Banks et al4) determined CVN transition curves for heat code R4. This is reproduced as Figure 3 in this report. At +30°F, the highest curve indicates 35 ft-lbs for 3 inch thick R4 in an NWQT condition and the lowest at 15 ft-lbs for an NT condition. The data in Table 3(b) indicate $T_{NDT}$ of 0°F and 30°F, respectively, for these conditions. Therefore, for the check valve castings with an average CVN value of 34* ft-lbs at +30°F, the $T_{NDT}$ should be also 0°F. This is the lowest CVN values of all eight castings (Table 1). Therefore, this would correspond to the highest $T_{NDT}$. This is supported by Quaker Alloy's data. Their other castings which are comparable to the check valve castings in the same period satisfied +10°F $T_{NDT}$ when the castings were produced with a low

*Average of 32-33-38 ft-lbs for Heat No. F6161.

temperature toughness requirement, presumably using the same deoxidation and other foundry control practices. Some of their heats in the 1970s showed 0°F and -10°F $T_{NDT}$ and some recent heats -50°F and -60° $T_{NDT}$. These data demonstrate low $T_{NDT}$ for steel castings produced by Quaker Alloy.

One of the methods provided by the US NRC Standard Review Plan (PSRP-5.4.3) for $T_{NDT}$ determination is given in Section 4.1.2(3) of this report. Assuming that the CVN transition curve of the check valve castings follows the trend given in Figure 3, the temperature at which CVN values of 20 ft-lbs are expected is about -15°F and -40°F for Heat No. F6161 and F6137, respectively. These are the $T_{NDT}$ for these castings according to this method.

The SFSA report[6] derived regression equations for calculating $T_{NDT}$ based on chemical compositions. It provided the following (tentative) equations.

(1) NNT Condition: $T_{NDT} = -9.5 - 26Ni - 46Mn + 53Mo + 56Si$

(2) NQT Condition: $T_{NDT} = -48.2 - 32Ni - 305C - 1303Al + 78Si - 17Cr$

"These equations have been established with 99% confidence. Their standard error is 22°F and 29°F respectively." For the composition given in the material test report for Heat No. F6137, Equation (1) gives -20°F ± 22°F and Equation (2) -80°F ± 29°F. Since the heat treatment condition of the check valves is considered to be between the two, $T_{NDT}$ would be between -20°F and -80°F according to these regression equations. All of the above $T_{NDT}$ estimates, although not perfect, provide a measure of conservatism, if one picks 0°F or -10°F as the $T_{NDT}$ for all of the eight check valve castings.

## 5.5 Permissible Lowest Service Metal Temperature

Figure 2 provides the following temperature correction values.

30°F up to 2-1/2 inch in thickness
40°F for 3-inches in thickness
46°F for 3-1/2 inches in thickness
48°F for 3-3/4 inches in thickness

These are the temperatures that must be added to $T_{NDT}$ to determine the permissible lowest service metal temperature (PLSMT). According to ASME Section III, the nominal wall thickness of the connecting pipe should be used for determining the minimum CVN requirements or the PLSMT (Appendix R). Since the nominal wall thickness of the connecting pipe to the check valves is 1.812 inches, the PLSMT is 30°F for the check valves if their $T_{NDT}$ is 0°F. Even for the thickest portion of the casting which is 3-3/4 inches for the cover, a $T_{NDT}$ of -10°F would give a 38°F PLSMT. All of these temperatures would satisfy the lowest service temperature of 40°F.

## 5.6 Fracture Mechanics Evaluation

The $T_{NDT}$ approach to designing against brittle fractures was originally developed for ship hull plate in the 1960s. When this method is applied to castings of various heat treatment conditions without considering stress levels and flaw sizes, the results would become too restrictive. All three factors, toughness, stress level, and flaw size should be evaluated together when considering a brittle fracture potential.

The data presented in this report and discussion given would satisfy the minimum toughness requirement stipulated by ASME Section III and NRC's review plans. Let us now consider the other two factors, namely stress and flaw size.

Since the check valves were tempered and stress relieved at 1200°F for 4 hours 15 minutes each, residual stresses should be low. Therefore, only the applied stresses are considered as an approximation. The check valves were designed to the Class 1 requirements using an $S_m$ value of 18.9 ksi. This is less than 50% of the actual yield strength of the casting at 40°F. Also, during an upset condition, the maximum internal pressure is only 1180 psi as compared with the 2130 psi standard calculation pressure used. Therefore, the applied stresses from the internal pressure should be much lower than the design stresses. The following stress assumptions for calculating a stress intensity factor ($K_I$) should be, then, much higher than actual stresses: $\sigma_m$ (membrane stress) = 20 ksi and $\sigma_b$ (bending stress) = 20 ksi.

Using the stress intensity factor ($K_I$) equation in ASME IX, Appendix A, $K_I$ was calculated for an assumed surface flaw which is 3.5-inch long and 1-inch deep. The Class II shrinkage criteria for X-ray examination was conservatively equated to a 3.5-inch long surface crack for purpose of calculating $K_I$. This is an unlikely flaw size, since the castings were X-rayed and magnetic particle examined. A $K_I$ value of 90 ksi$\sqrt{in}$ was obtained for the above flaw under the assumed stress levels much higher than the maximum stresses expected during an upset condition.

The fracture toughness ($K_{Ic}$) of the check valves may be estimated using its CVN data and an approximate correlation between $K_{Ic}$ and CVN. For the transition zone, this correlation is given by the following equation.

$K_{Ic}{}^2 = 2 \times E \times (CVN)^{3/2}$, where E is Young's modulus

A CVN energy absorption of 34* and 74* ft-lbs is equivalent to 110 and 190 ksi$\sqrt{in}$, respectively, according to the above equation. This means that a flaw as large as postulated above under high membrane and bending stresses would not lead to a brittle fracture.

## 5.7 Acceptability of Check Valves

From the point of preventing brittle fractures, the 24-inch Class 1 feedwater check valves fully meet the acceptance criteria of not only the ASME Section III Code but also the criteria in NRC's review plans. The foregoing discussions provide sufficient evidence that

(1) The check valve castings meet the material toughness requirements of the 1977 Summer Addenda of ASME Section III,

(2) The $T_{NDT}$ evaluation satisfied the permissible lowest service metal temperature, and

*The lowest and the highest average CVN energy absorption values in Table 1.

(3) Brittle fractures are highly unlikely as indicated by a fracture mechanics analysis.

Therefore, the 24-inch Class 1 feedwater check valves satisfy the acceptance criteria of GDC 51 concerning fracture prevention of the containment pressure boundary.

References:

1. NUREG-0577 (For Comment): Potential for Low Fracture Toughness and Lamellar Tearing on PWR Steam Generator and Reactor Coolant Pump Supports, October 1979

2. NUREG-0800 Standard Review Plan 6.2.7 Fracture Prevention of Containment Pressure Boundary, Rev. 0 - July 1981

3. NUREG-0800 Standard Review Plan PSRP-5.3.4 (Proposed New SRP Section) Fracture Toughness of Steam Generator and Reactor Coolant Pump Supports, Rev. 0

4. W. C. Banks, K. F. Skidmore, H. Schwartzbart: Mechanical Properties of Cast Carbon Steel in Heavy Sections, Journal of Pressure Vessel Technology, v. 96, n.2, (May 1974), pp. 73-80

5. Steel Founders' Society of America: Research Report No. 75, The Nil Ductility Transition Temperature of Cast Steels, August 1971

6. Steel Founders' Society of America: Research Report No. 80, The Toughness of Cast Steels - NDTT, Charpy V-Notch and Dynamic Tear Tests, May 1974

7. R. Maino, J. Gomez-Gallardo, J. F. Wallace: Section Size Effects on Toughness of Various Cast Steel, in the Metal Properties Council MPC-13 Fracture Toughness of Wrought and Cast Steels, pp. 1-67, 1980

8. R. A. Douty, W. C. Banks, H. Schwartzbart: Mechanical Properties of Welded Cast Steels for Arctic Service, Welding Journal, v.55, n.8, (August 1976), pp. 661-670

TABLE 1

Chemical Compositions, Tensile Properties, and CVN Impact Values for the Check Valve Body Castings

| Heat No. *** | Chemical Compositions wt % | | | | | Tensile Properties | | | | CVN Impact Properties at +30°F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | P | S | T.S. ksi | Y.S. ksi | Elong % | RA % | Energy ft-lbs | Lateral Expansion mils | Shear Area % |
| F5178-7 | 0.18 | 0.70 | 0.40 | 0.016 | 0.019 | 79.0 | 53.5 | 29.0 | 66.2 | 55-58-56 | 42-44-42 | 40-40-40 |
| F5178-8 | 0.18 | 0.70 | 0.40 | 0.016 | 0.019 | 79.0 | 53.5 | 29.0 | 66.2 | 64-67-62 | 53-55-48 | 90-90-80 |
| F6137-1 | 0.20 | 0.76 | 0.46 | 0.017 | 0.013 | 71.5 | 42.5 | 30.0 | 53.3 | 43-45-42 | 41-44-43 | 40-40-40 |
| F6140-2 | 0.21 | 0.79 | 0.48 | 0.018 | 0.012 | 71.5 | 42.5 | 31.5 | 59.4 | 68-57-56 | 59-50-45 | 30-30-30 |
| F6152-1 | 0.19 | 0.82 | 0.50 | 0.021 | 0.015 | 93.0 | 61.0 | 28.0 | 63.8 | 47-58-57 | 41-47-45 | 40-40-40 |
| F6161-1 | 0.22 | 0.72 | 0.48 | 0.017 | 0.015 | 71.0 | 42.0 | 31.5 | 50.5 | 32-33-38 | 40-45-43 | 40-40-40 |
| F6589-5 | 0.22 | 0.95 | 0.49 | 0.020 | 0.011 | 78.0 | 48.0 | 31.0 | 66.7 | 69-65-69 | 65-54-58 | 99-80-90 |
| F6589-8 | 0.22 | 0.95 | 0.49 | 0.020 | 0.011 | 78.0 | 48.0 | 31.0 | 66.7 | 69-65-69 | 65-54-58 | 99-80-90 |
| SA 352 Gr. LCB | 0.30 max | 1.00 max | 0.60 max | 0.04 max | 0.045 max | 65.0 90.0** | 40.0 min | 24 min | 35 min | | | |
| ASME III 1977 Summer | | | | | | | | | | -- | 40 min | -- |

* Residual elements: 0.24% Cr, 0.19% Ni, <0.001% Mo, 0.10% Cu, 0.04% Al

** 90.0 ksi maximum after A352-74.

*** The last digit (e.g. -7) denotes the casting number.

Table 2

$T_{NDT}$ Data for Cast Steels in NUREG-0577*

| Material | | $\overline{NDT}$ | $\sigma$ | $\overline{NDT} + 1.3\sigma$ | $\overline{NDT} + 2\sigma$ |
|---|---|---|---|---|---|
| Cast Steels | | | | | |
| A-27, A-216 | 1" | - 6°F | 12°F | 10°F | 18°F |
| (heat treated condition) | >1" 2½" | 35 | 17 | 57 | 69 |
| A-352 (LC3) | | | | | max. -20 |

*Corrected as revised in NUREG/CR-3009

Table 3

$T_{NDT}$ Data for Various Heats of Carbon Steel Casting*

(a)

**Charpy V-notch impact energy and nil-ductility transition temperatures of the cast steels in the normalized and tempered condition**

| Code No. | Section Thickness, in. | Heat Treatment | CVN Impact Energy at -20F, ft-lbs Range | Average | NDTT, F |
|---|---|---|---|---|---|
| ● D2 | 1 | NT | 9 to 18 | 13.8 | ---- |
| ● R3 | 2-1/2 | NT-2 | | 4.0 | +40 |
| | 3 | " | | 4.0 | +50 |
| | 3-1/2 | " | | 4.0 | +50 |
| | 4 | " | | 3.0 | +60 |
| | 4-1/2 | " | | 4.0 | +50 |
| | 5 | " | | 3.0 | +40 |
| ● R4 | 2-1/2 | " | | 6.0 | 0 |
| | 3 | " | | 5.0 | +30 |
| | 3-1/2 | " | | 5.0 | +30 |
| | 4 | " | | 26.0* | +30 |
| | 4-1/2 | " | | 5.0 | +20 |
| | 5 | " | | 6.0 | +20 |
| R5 | 5 | NNTSR | 17 to 22 | 19.3 | -40 |
| R6 | 3 | " | all 11.5 | 11.5 | -10 |
| | 5 | " | 9 to 20 | 13.7 | --- |
| R7 | 5 | " | 5 to 6 | 5.0 | 0 |
| R8 | 3 | " | 12 to 23 | 16.0 | -10 |
| | 5 | " | 4 to 4.5 | 4.0 | -30 |
| R10 | 5 | " | 5 to 6 | 5.5 | 0 |
| R11 | 5 | " | 3 to 3.5 | 3.1 | +30 |
| R12 | 3 | " | 32 to 46 | 38.0 | -50 |
| | 5 | " | 9 to 11 | 10.3 | -20 |
| R13 | 3 | " | 12 to 31 | 21.1 | -30 |
| | 5 | " | 90 to 99.5 | 96.3** | -40 |
| R14 | 3 | " | 20 to 37 | 31.5 | -20 |
| | 5 | " | 11 to 26 | 17.7 | -20 |

* Doubtful energy because lateral expansion values were low.

** Not included in Figure 6 because of its unusually high value.

(b)

**Charpy V-notch impact energy and nil-ductility transition temperatures of the cast steels in the quenched and tempered condition**

| Code No. | Section Thickness, in. | Heat Treatment | CVN Impact Energy at -20F, ft-lbs Range | Average | NDTT, F |
|---|---|---|---|---|---|
| ● D1 | 1 | WQTSR | 26 to 39 | 31.0 | ---- |
| | 2 | " | 18 to 35 | 30.0 | -40 |
| | 3 | " | 15 to 30 | 22.7 | -40 |
| | 5 | " | 19 to 27 | 24.5 | -30 |
| ● D2 | 1 | NNQT | 60 to 62 | 61.0 | ---- |
| | 2 | " | 50 to 72 | 59.2 | -60 |
| | 3 | " | 44 to 76 | 56.0 | -60 |
| | 5 | " | 44 to 70 | 57.5 | -50 |
| ● D2 | 1 | NNQTSR | 45 to 71 | 55.0 | --- |
| | 2 | " | 40 to 57 | 48.7 | -60 |
| | 3 | " | 36 to 59 | 48.7 | -50 |
| | 5 | " | 33 to 51 | 43.0 | -50 |
| ● D3 | 1 | WQTASR | 44 to 49 | 47.0 | --- |
| | 2 | " | 30 to 44 | 36.0 | -40 |
| | 3 | " | 23 to 56 | 37.3 | -40 |
| | 5 | " | 7 to 39 | 20.7 | -40 |
| G1 | 10 | AWQTSR | | 38.0 | -20 |
| ● K1 | 1 | NWQTSR | 45 to 50 | 48.0 | --- |
| | 3 | " | 22 to 36 | 28.5 | -30 |
| ● L1 | 3-1/2 | NWQTSR | 23 to 27 | 25.3 | -20 |
| | 4 | " | 12 to 22 | 17.2 | -10 |
| L2 | 3-1/2 | " | 17 to 30 | 21.3 | -30 |
| | 4 | " | 15 to 22 | 19.0 | -30 |
| L3 | 3-1/2 | " | 24 to 33 | 27.3 | -20 |
| | 4 | " | 19 to 35 | 28.2 | -10 |
| R1 | 3-1/2 | NWQTSR | 41 to 76 | 58.5 | -20 |
| ● R2 | 3-1/2 | " | 59 to 72 | 65.5 | -20 |
| | 4 | " | 16 to 34 | 26.5 | -20 |
| | 5 | " | 55 to 56 | 55.5 | -20 |
| ● R3 | 2-1/2 | NWQT | 9 to 9.5 | 9.0 | 0 |
| | 3 | " | 8 to 10 | 9.0 | +20 |
| | 3-1/2 | " | 5 to 10 | 8.0 | +30 |
| | 4 | " | 8 to 33 | 23.8* | +20 |
| | 4-1/2 | " | 7 to 8.5 | 7.5 | +30 |
| | 5 | " | 5 to 8 | 6.1 | +40 |
| ● R4 | 2-1/2 | " | 12 to 16.5 | 14.3 | 0 |
| | 3 | " | 12 to 14 | 13.5 | 0 |
| | 3-1/2 | " | 16 to 18 | 17.5 | 0 |
| | 4 | " | 13 to 19 | 16.0 | -10 |
| | 4-1/2 | " | 9 to 23 | 14.5 | +10 |
| | 5 | " | 9 to 12 | 10.8 | +10 |
| R5 | 5 | NWQTSR | 41 to 47 | 44.3 | -50 |
| R6 | 3 | " | 17 to 22 | 20.1 | -30 |
| | 5 | " | 16 to 35 | 25.0 | -50 |
| R7 | 5 | " | 5 to 5 | 5.0 | -50 |
| R8 | 3 | " | 21 to 36 | 30.3 | -40 |
| | 5 | " | 23 to 38 | 28.0 | -30 |
| R9 | 5 | " | 15 to 23 | 17.8 | --- |
| R10 | 5 | " | 12 to 15 | 13.5 | -40 |
| R11 | 3 | " | 12 to 49 | 31.0 | -10 |
| R12 | 3 | " | 33 to 48 | 39.0 | -40 |
| | 5 | " | 25 to 38 | 33.8 | -40 |
| R13 | 3 | " | 32 to 42 | 37.0 | -40 |
| | 5 | " | 28 to 64 | 42.3 | -50 |
| R14 | 3 | " | 37 to 40 | 38.7 | -50 |
| | 5 | " | 15 to 29 | 20.2 | -20 |

* Doubtful energy value because lateral expansion values were low.

*From Reference (4), which is the basis for Table 2.
Code numbers with ● indicate chemical compositions equivalent to WCB.

## Table 4

### A Comparison of ASTM Specifications for Steel Casting*

| End Use | ASTM Specification | Grade | Heat Treatment[1] | Required Charpy V-Notch Energy ft·lb. (J) |
|---|---|---|---|---|
| General Application | A-27 | U70-40 | A,N,NT, or QT | None |
| High Temp. Service | A-216 | WCC | A,N, or NT | None |
| Pressure Vessels at | A-352 | LCB | N, NT or QT | 13 at -50°F |
| Low Temperature | A-352 | LCC | N, NT or QT | 15 (20) at −50°F (−46°C) |
| Pressure Service | A-487 | C | NT | None |
| | | CN | NT | None |
| | | CQ[2] | QT | None |
| Heavy Section Pressure Vessels | A-643 | A1 | NT or QT | None |
| Pressure Vessels and Low Temperature | A-757 | A2Q | QT | 15 (20) at −50°F (−46°C) |

[1]A = Annealed, N = Normalized, NT = Normalized and Tmpered, QT = Quenched and Tempered.
[2]Grade CQ requires a tensile strength of 80 ksi (550 MPa). All other grades require 70 ksi (485 MPa). Yield and tensile ductility requirements are identical for all.

*From Steel Castings Handbook, Table 15-31

A27: Specification for Mild- to Medium-Strength Carbon-Steel Castings for General Application

A216: Specification for Carbon-Steel Castings Suitable for Fusion Welding for High-Temperature Service

A352: Specification for Ferritic Steel Castings for Pressure-Containing Parts Suitable for Low-Temperature Service

A487: Specification for Steel Castings Suitable for Pressure Service

A643: Specification for Steel Castings, Heavy-Walled, Carbon and Alloy, For Pressure Vessels

A757: Specification for Ferritic and Martensitic Steel Castings for Pressure-Containing and Other Applications for Low-Temperature Service

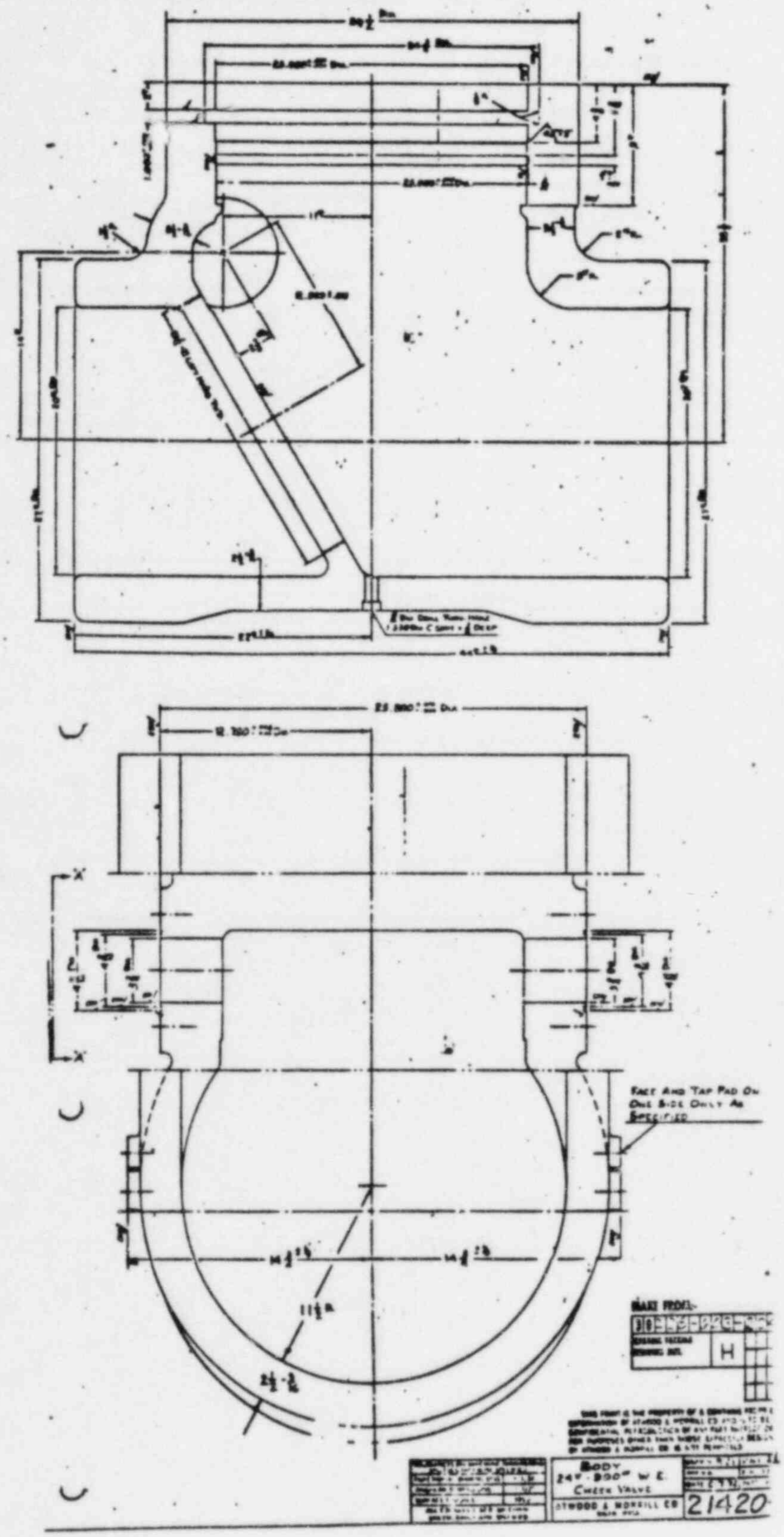


Fig. 1  Atwood & Morrill's 24 inch feedwater check valve

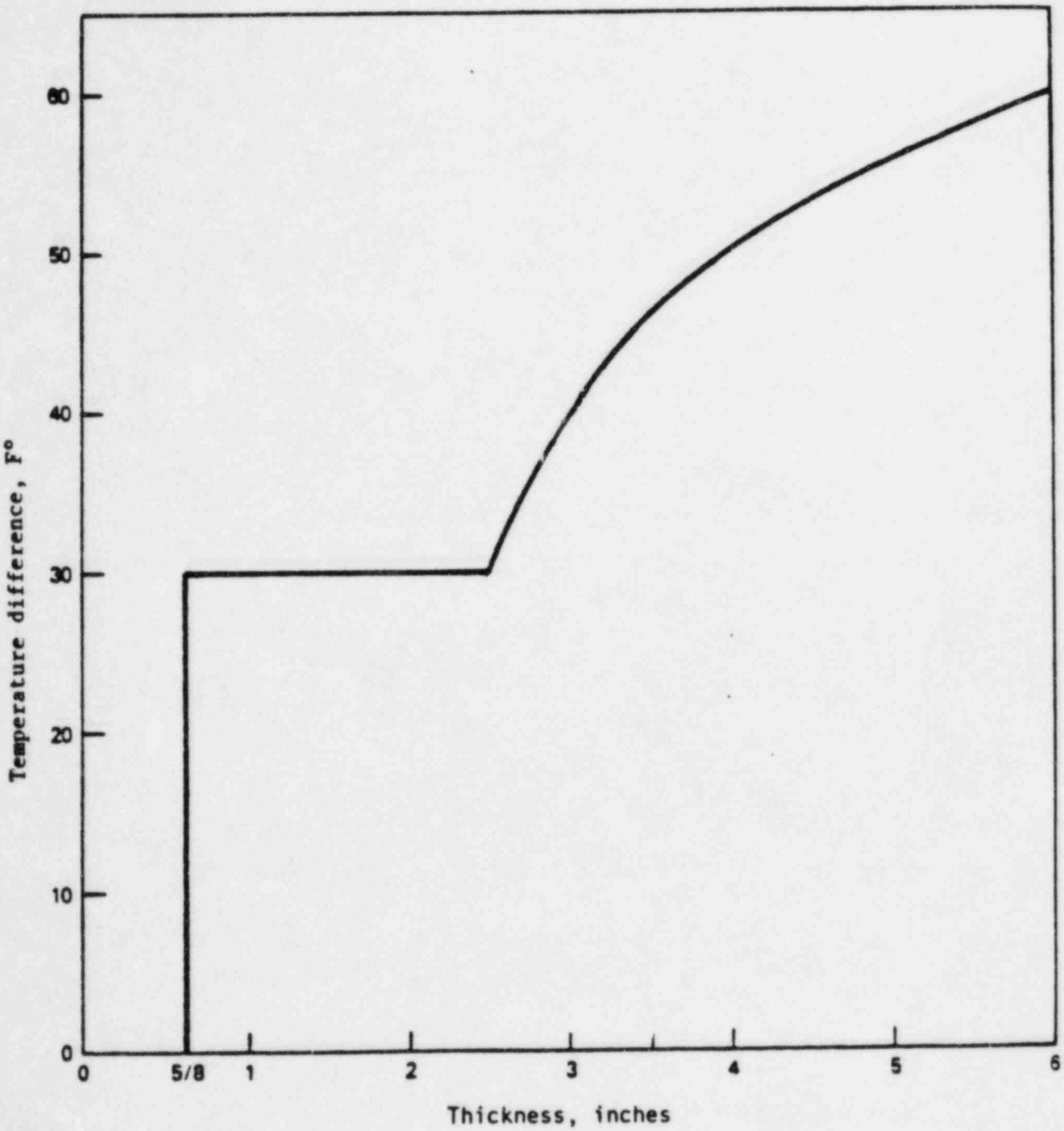


Fig. 2 A temperature correction curve as a function of metal thickness (Reproduced from NUREG-0577 Rev.0, Fig. 1)

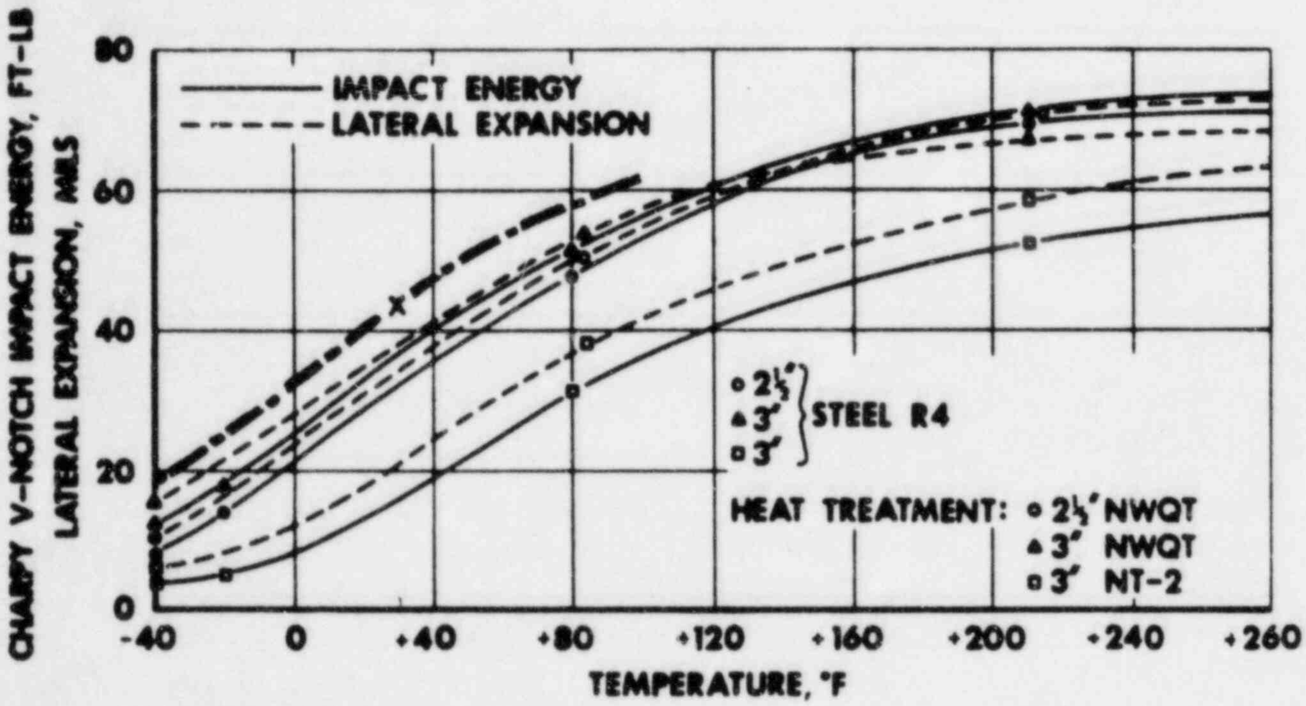


Fig. 3 Charpy V-Notch Transition Temperature Curves. (Reproduced from Reference 4)

x indicates the CVN Energy for the check valve.

—·— A transition curve postulated for the valve body casting Heat No. F6137.

# APPENDIX A

## MICROSTRUCTURES OF CLASS 1 FEEDWATER CHECK VALVE BODY CASTINGS

In January 1984, Phildelphia Electric Company (PECo) performed an in-situ metallographic examination of the four Class 1 feedwater check valve body castings in Unit 1. This Appendix contains the results of that examination, Metallurgical Laboratory Note No. 84-758, February 6, 1984. The microstructures of the four valve body castings support the conclusions of the body of this report.

Energy Conversion Research Section
S10-1, 2301 Market Street

February 6, 1984

FROM: J. F. DeLong

TO: R. A. Mulford

SUBJECT: Metallurgical Examination for Microstructure and Hardness of Four 24-Inch Feedwater Check Valves, Limerick Generating Station Units 1 and 2
METALLURGICAL LABORATORY NOTE NO. 84-758

Per your request, the four valves were examined for microstructure and hardness.

The attached metallurgical laboratory note details the results of the examination.

John F. DeLong

John F. DeLong

JFD/jm

Attachment

cc: J. P. Gibbons
E. C. Kistner
J. Moskowitz
G. M. Leitch
J. J. Clarey
J. M. Corcoran
J. W. Spencer
P. R. Boyles
R. H. Logue

Energy Conversion Research Section
S10-1, 2301 Market Street

February 6, 1984

## METALLURGICAL LABORATORY NOTE NO. 84-758

Metallurgical Examination for Microstructure
and Hardness of Four 24-Inch Feedwater Check Valves,
Limerick Generating Station Units 1 and 2

### Purpose:

To determine the microstructure and hardness of each valve.

### Background:

The following request was received from the Lime ick Project Manager:

"In June 1983 the NRC reviewed Limerick carbon steel containment and pressure boundary components for conformance with GDC-51. That review identified a potential problem with the feedwater system isolation valves (1F074A and B and 1F010A and B).

The NRC contended that the lowest acceptable operating temperature for these valves is 80°F. This would cause a problem when drawing HPCI and RCIC water from the condensate storage tank. The NRC contentions are based on generic data from an unpublished version of NUREG 0577 which has been greatly extrapolated to cover our valves. Please note that the specification and code acceptability of these valves is not in question. PECO requested Bechtel to investigate the specific metallurgical aspects of our valves and they have provided us with a report which establishes the acceptability of our material at much lower temperatures. This report is an attachment to BLP-31318 dated 12-3-83. We intend to use this report as a basis for resolving the NRC concern.

Bechtel and PECO metallurgists strongly feel that our position before the NRC can be greatly enhanced by knowledge of the actual grain structure of our valves. For this purpose, we request that arrangements be made to allow the PECO Metallurgical Lab to examine the four valves, which we understand have been turned over. This examination would involve the polishing of a small area of the outside surface, then applying an etching solution and then a facsimile impression tape. Upon completion of the examination, the results will be incorporated into our report and submitted to the Commission for their evaluation. It is necessary that this examination be completed in early January so that the licensability of these valves can be confirmed with the Commission."

The check valve material is ASTM A352 grade LCB with the following chemical percent composition:

| Carbon | Manganese | Silicon | Phosphorus | Sulfur |
|---|---|---|---|---|
| 0.20% | 0.76 | 0.46 | 0.017 | 0.013 |

| Chromium | Nickel | Molybdenum | Copper | Aluminum |
|---|---|---|---|---|
| 0.24 | 0.19 | less than 0.001 | 0.10 | 0.04-0.05 |

The valves, as reported by Quaker Alloy Heat Treatment, were heat-treated as follows:

| | | |
|---|---|---|
| | 1690-1720°F | 4 hrs. 25 mins., air-cool |
| | 1630-1650°F | 6 hrs. 20 mins. |
| Furnace Cool to: | 1440-1460°F | 2 hrs. |
| Furnace Cool to: | 1420-1430°F | 40 mins., then water quench |
| Temper: | 1200°F | 4 hrs. 15 mins. |

The NRC stated that the heat treatment is not sufficient to produce a quench and tempered microstructure but is equivalent to a double normalized and tempered heat treatment.

The following microstructures were recorded on the feedwater check valves using the replica-tape technique and portable hardness equipment.

Conclusions:

| Valve No. | Microstructure | Hardness |
|---|---|---|
| 1F010A | Fine pearlite in a ferrite matrix | RB 79 |
| 1F010B | Ferrite, pearlite and some upper bainite | RB 81 |
| 1F074A | Ferrite, upper bainite, some pearlite | RB 85 |
| 1F074B | Ferrite, upper bainite, some pearlite | RB 87 |

The microstructures consist of ferrite and pearlite, or a combination of ferrite, pearlite and upper bainite. These microstructures would be expected for a 0.20% carbon steel ASTM SA352 grade LCB water quenched from 1420-1430°F temperature.

The following critical point temperatures are recorded for 1020 material in two source books:

| | | |
|---|---|---|
| Grade 1020 | AR3 | 1515°F[1] |
| | AR1 | 1270°F |
| Grade 1020 fine grain | AR3 | 1470°F[2] |
| | AR1 | 1340°F |

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(1) "Practical Data for Metallurgists", The Timken Roller Bearing Company Canton, OH, May 1964, p. 50.

(2) "Modern Steels and Their Properties", Bethlehem Steel, Sixth Edition, 1966, p. 52.

The field metallography and hardness measurements were prepared by G. P. Monahan of the Materials Test Laboratory.

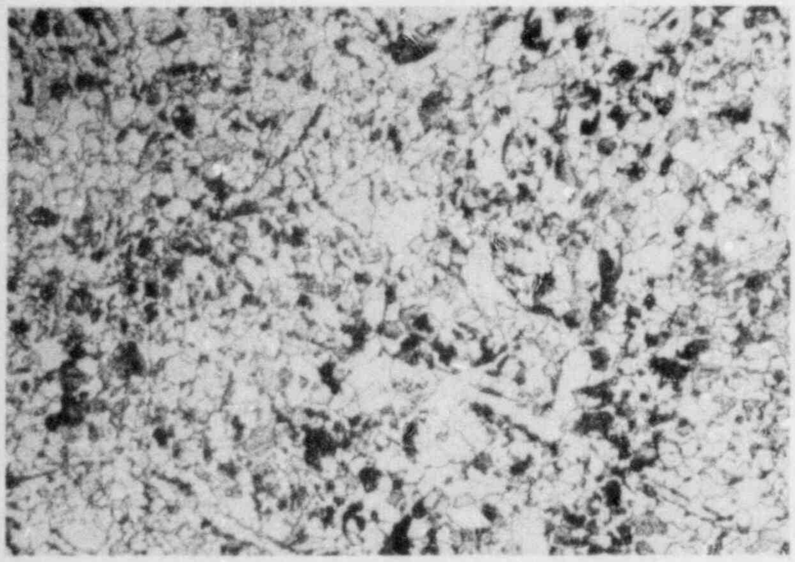
John F. DeLong

JFD/jm

Attachment

Microstructure:

FEEDWATER CHECK VALVE 1F010A - PHOTOMICROGRAPHS OF MICROSTRUCTURE



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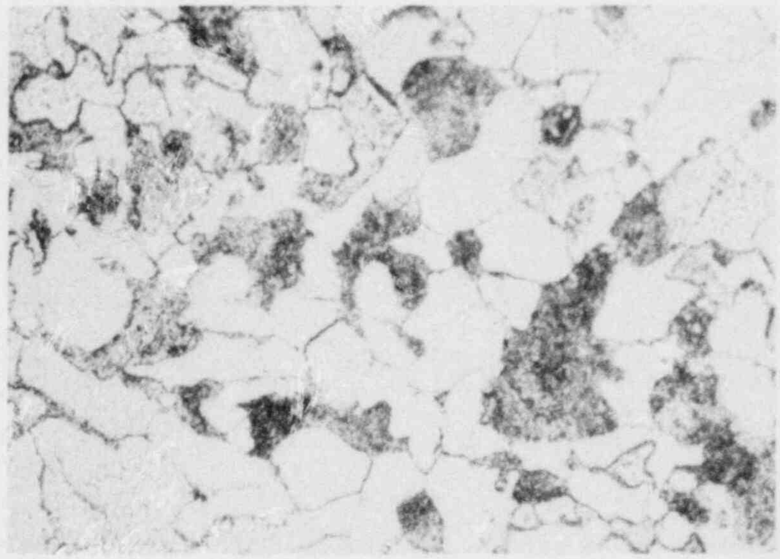

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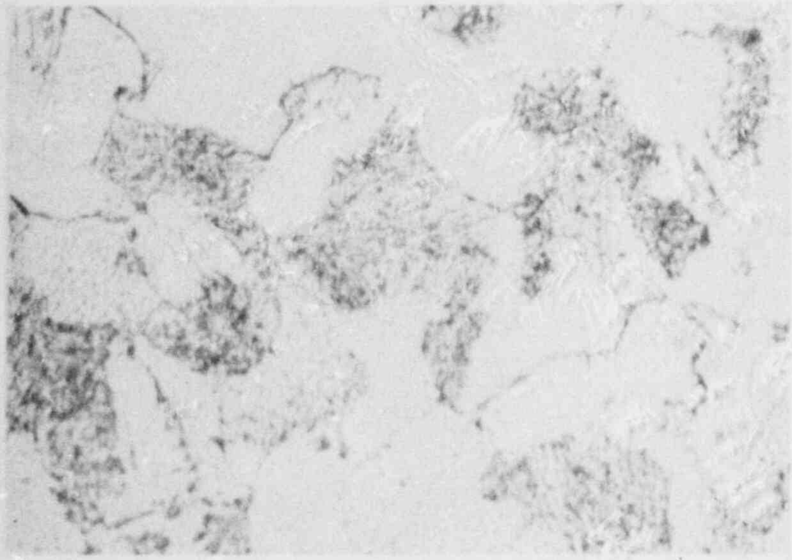
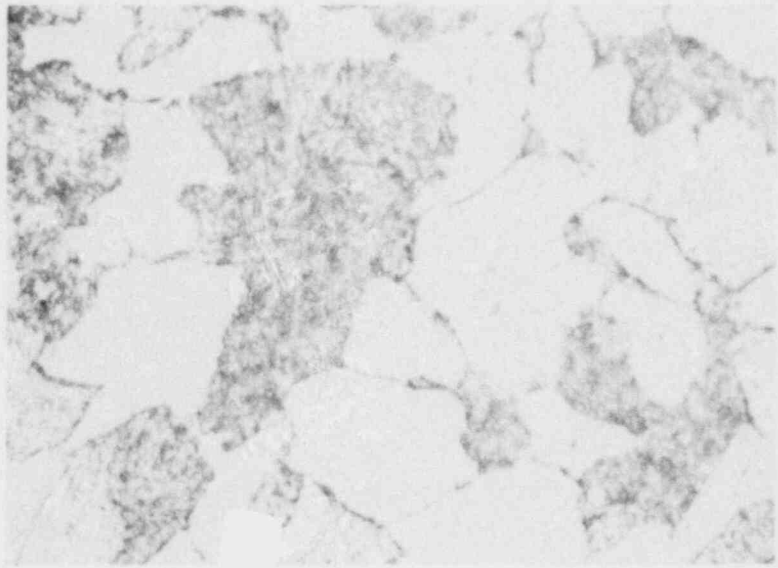


Magification: 800X



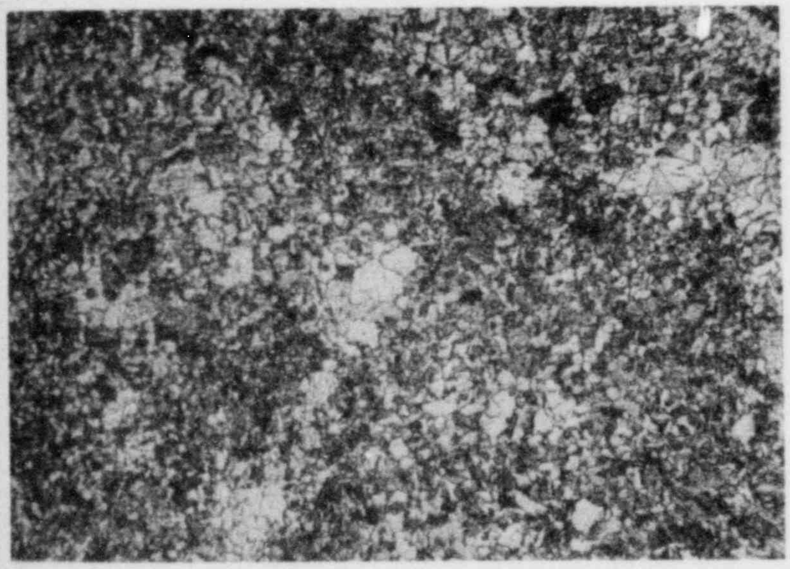
agnification: 1000X

Etch: 2% Nital

Hardness: RB 79

MICROSTRUCTURE: Fine Pearlite and Ferrite

FEEDWATER CHECK VALVE 1F010B - PHOTOMICROGRAPHS OF MICROSTRUCTURE



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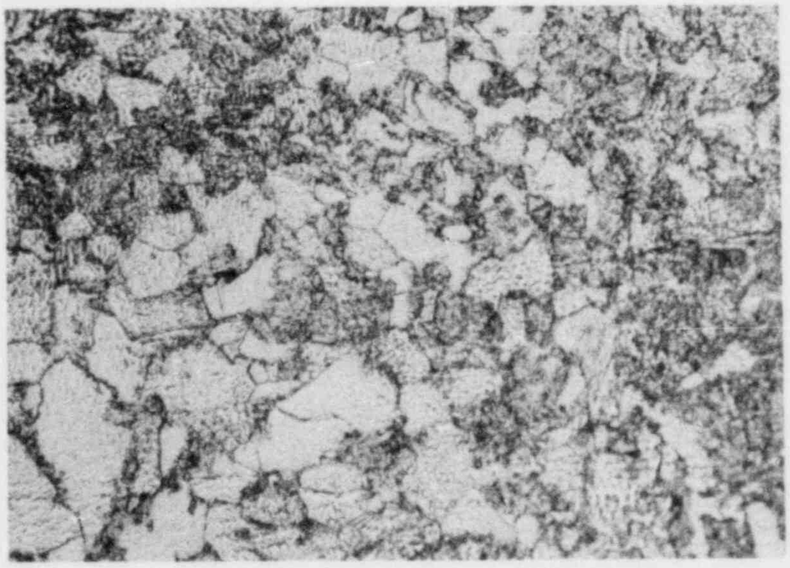

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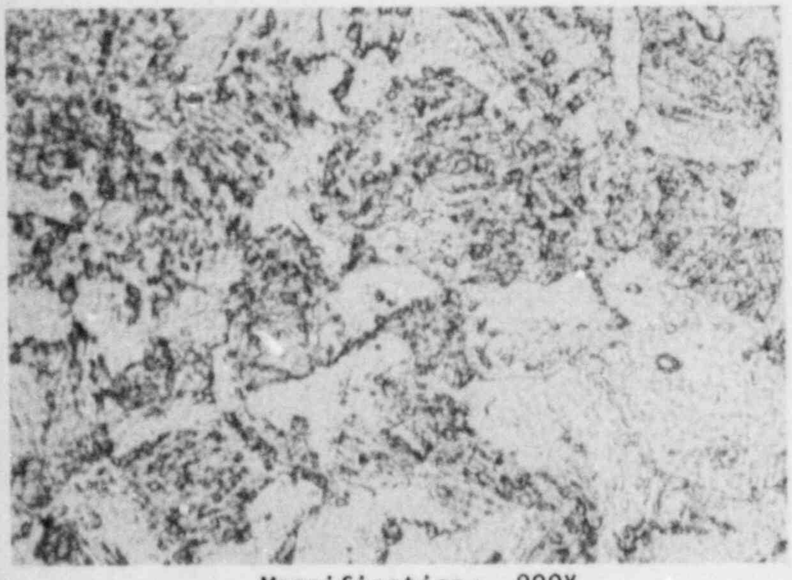

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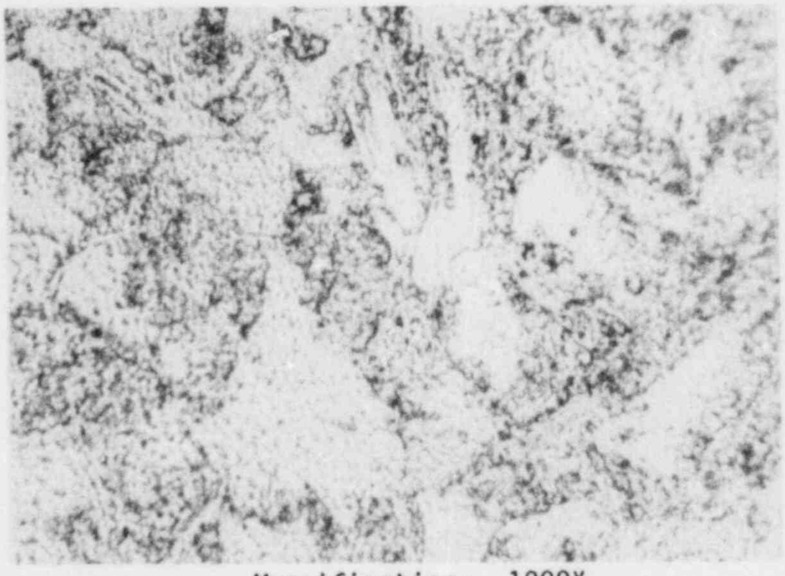


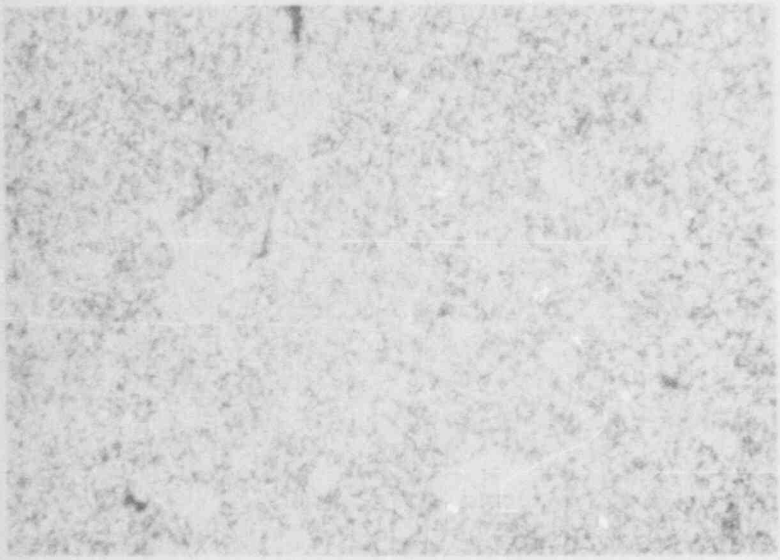
Magnification: 1000X

Etch: 2% Nital

Hardness: RB 81

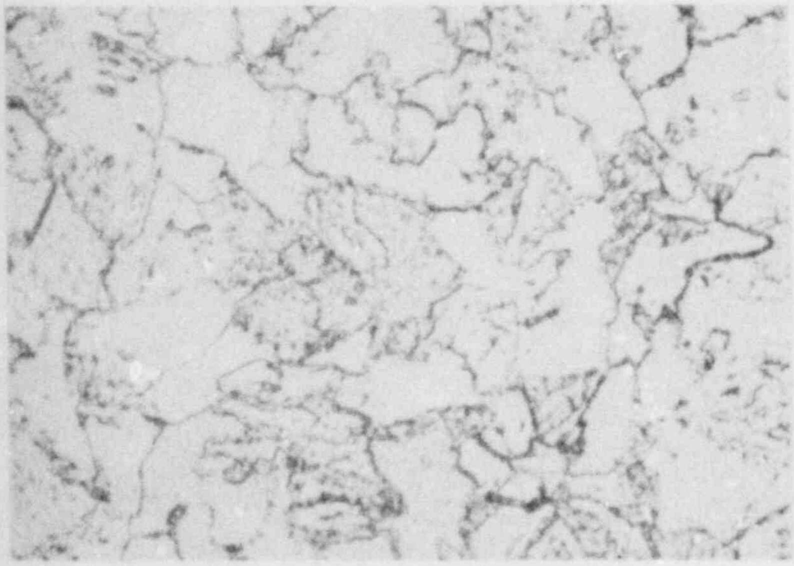
MICROSTRUCTURE: Ferrite, pearlite, some bainite.

FEEDWATER CHECK VALVE 1F074A - PHOTOMICROGRAPHS OF MICROSTRUCTURE



Magnification: 100X

Magnification: 400X



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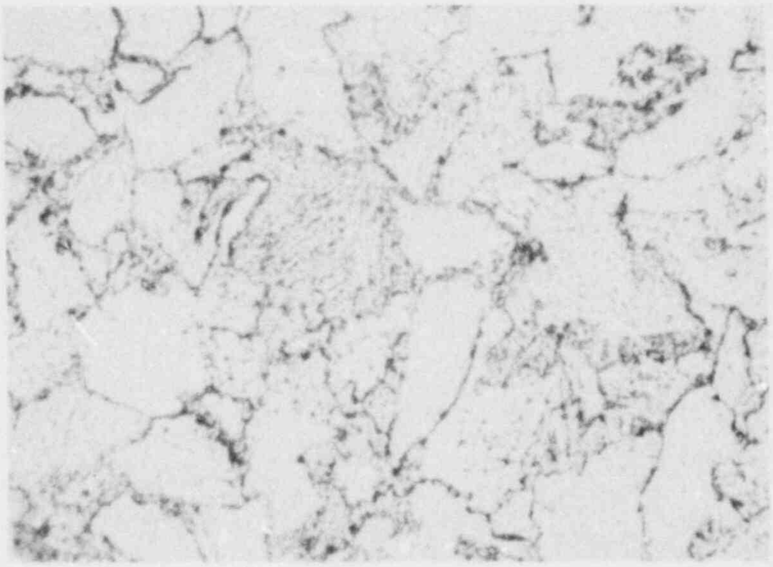


Magnification: 1000X

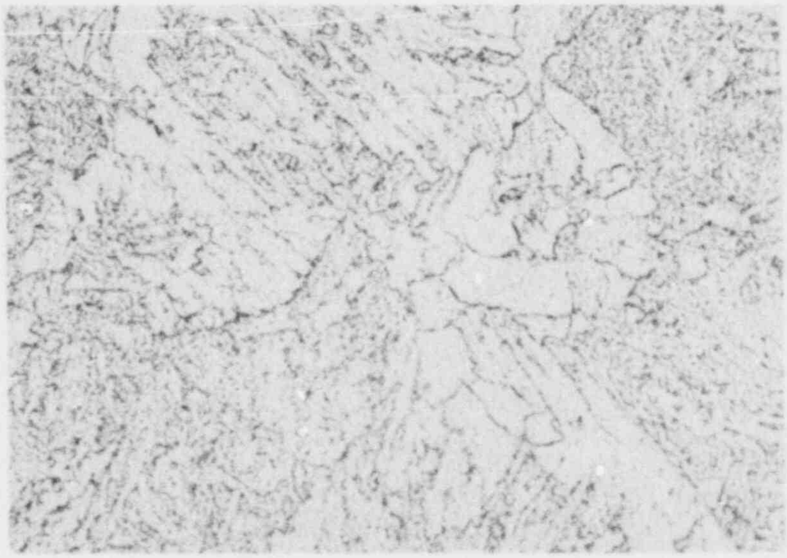
Etch: 2% Nital

Hardness: RB 85

MICROSTRUCTURE: Ferrite, upper bainite, some pearlite

FEEDWATER CHECK VALVE 1F074B - PHOTOMICROGRAPHS OF MICROSTRUCTURE

Magnification: 100X



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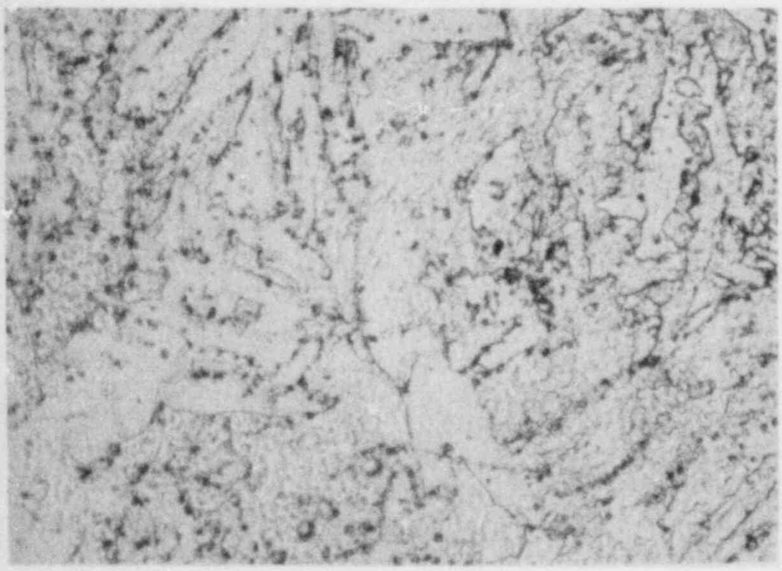

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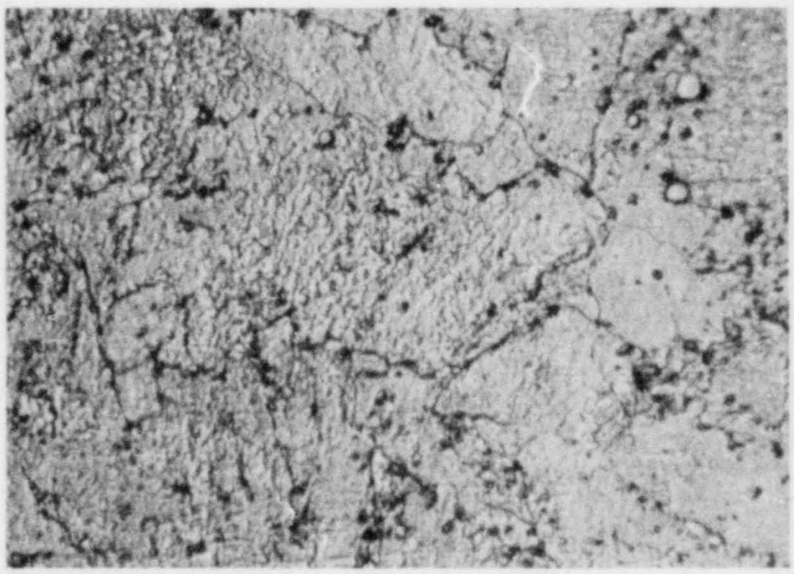

Magnification: 1000X

Etch: 2% Nital

Hardness: RB 87

MICROSTRUCTURE: Ferrite and bainite, some pearlite