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June 22, 1984

Docket Nos. 50-277
50-278

Dr. Thomas E. Murley, Administrator
Office of Inspection and Enforcement
U.S. Nuclear Regulatory Commission
Region I
631 Park Avenue
King of Prussia, PA 19406

SUBJECT: Final Report of the Fracture Mechanics Analyses for Weld Acceptability on the Weld Imperfections Identified by Philadelphia Electric Company in Licensee Event Report 2-83-24/1T

REFERENCE: 1. Letter to Dr. T. E. Murley, NRC, from W. T. Ullrich, PECo, dated March 30, 1984 (Preliminary Report of the Fracture Mechanics Analyses for Weld Acceptability)
2. Letter to Dr. T. E. Murley, NRC, from W. T. Ullrich, PECo, dated April 10, 1984 (Supplement to Preliminary Report of the Fracture Mechanics Analyses for Weld Acceptability)

Dear Dr. Murley:

The attached "Fitness-for-Service Evaluation of Radiographic Indications in Piping Systems at the Peach Bottom Atomic Power Station - Units 2 and 3", prepared by Stone and Webster Engineering Corporation under contract to Philadelphia Electric Company, is the final report on the fracture analyses of the welds whose radiographs were discovered to contain unacceptable indications as reported in Licensee Event Report 2-83-24/1T Attachment to Dr. T. E. Murley from M. J. Cooney, PECo, dated November 7, 1983.



IE 22

As stated in the referenced March 30, 1984 letter, Philadelphia Electric Company discovered that certain Class I piping radiographs were improperly read by Eastern Testing and Inspection, Inc. (ETI) during previous outage modification work. A review of the 131 welds that had been radiographed by ETI in safety-related systems discovered twenty-three welds with unacceptable indications. These unacceptable indications are located in four systems of the plant as follows:

| Peach Bottom Unit | No. of Welds | System |
|---|---|---|
| 2 | 3 | Scram Discharge Volume |
| 2 | 1* | Reactor Water Cleanup |
| 2 | 5 | Core Spray |
| 2 | 2 | Feedwater |
| 3 | 8 | Scram Discharge Volume |
| 3 | 3 | Reactor Water Cleanup |
| 3 | 1 | Core Spray |

*Note: This weld and its associated piping will be replaced as part of the Recirculation Pipe Replacement modification which is in progress for Peach Bottom Unit 2.

Subsequent to these findings, conference calls were made to the Regional Office of the NRC reporting on the preliminary fracture mechanics evaluation performed on the 'worst case' weld imperfections in each of the four systems. These preliminary findings revealed that the weld imperfections would not propagate to an unacceptable condition within the design life of the plant (40 years) for either the Scram Discharge Volume, Core Spray, or Reactor Water Cleanup Systems. The preliminary fracture analyses performed on the Feedwater System, which were based on code allowable stresses rather than the actual stresses, discovered that the 'worst case' feedwater system imperfection was suitable for 240 cycles (approximately 18 years of cycles).

Prior to submission of the March 30, 1984, preliminary report, the NRC requested that Philadelphia Electric Company perform microdensitometer readings of the radiographs to confirm the size and depth of the weld imperfections as identified by a Philadelphia Electric Company NDE Level III. The

microdensitometer readings were performed on radiographs of five welds that were selected by PECo and the NRC (after NRC film review, per Inspection Notice 50-277/84-05; 50-278/84-05, T. T. Martin, NRC, to S. L. Daltroff, PECo, dated February 17, 1984). As stated in the referenced April 10, 1984 letter, Philadelphia Electric Company has concluded, based on densitometer readings of these five radiographs, that the defect characteristics observed by the NDE Level III are valid.

The attached report describes each of the twenty-three welds, the basis of the fatigue analysis and the findings of these analyses for all these welds. The findings of the report are summarized therein in Table 2, 'Results of Fatigue Analysis'. Code calculations indicate that the number of loading cycles that the weld with the worst defect can sustain safely, considerably exceeds the estimated total number of cyclic events for each system over the plant lifetime. On this premise, Philadelphia Electric Company concludes that the weld defects within these systems are acceptable for the design life of the plant.

Submission of this final report completes the corrective actions as described in Licensee Event Report 2-83-24/1T Attachment dated November 7, 1983 (Dr. T. E. Murley, NRC, from M. J. Cooney, PECo).

Should you require additional information, please do not hesitate to contact us.

Very truly yours,

R. H. Logue, Superintendent
Nuclear Services
Nuclear Genera[illegible]ion Division

Attachment

cc: A. R. Blough, Site Inspector
NRC Document Control Desk

PHILADELPHIA ELECTRIC COMPANY

PEACH BOTTOM ATOMIC POWER STATION

UNITS 2 AND 3

FITNESS-FOR-SERVICE EVALUATION

OF RADIOGRAPHIC INDICATIONS IN PIPING SYSTEMS

DOCKET NUMBERS 50-277 AND 50-278

Submitted to

THE UNITED STATES NUCLEAR REGULATORY COMMISSION

June 1984

## SUMMARY

During the period between 1980 and 1982 Philadelphia Electric Company (PECO) performed modification work on several piping systems at Units 2 and 3 of Peach Bottom Atomic Power Station. These systems contained a number of welds which were radiographed and accepted at that time. PECO re-examined these radiographs in 1983, and concluded that some radiographic indications in the scram discharge volume, reactor water clean-up, core spray and feedwater startup bypass systems were not acceptable. Stone & Webster Engineering Corporation evaluated these indications using a fitness-for-service approach based on the methods and requirements of ASME Boiler and Pressure Vessel Code, Section XI, 1983 Edition, and Winter 1983 Addenda.

The indications detected during re-examinations of the radiographs were identified by PECO as weld cracks, lack of fusion, lack of penetration, and slag inclusions. An analysis of the effect of these crack-like flaws indicated that fatigue crack growth is the only relevant failure mechanism under the operating conditions. A fatigue analysis was performed using the methods of linear elastic fracture mechanics consistent with Section XI of ASME Code.

Several conservative assumptions were made in the analysis. The major ones are 1) the flaws are modeled as cracks with a postulated depth significantly greater than the reported depth, 2) all applied stresses act concurrently, 3) welding residual stress is tensile and has its maximum value at the location of the flaw, 4) all flaws could grow regardless of their initial size.

The results of the analysis showed that the number of loading cycles required to propagate the postulated flaws to an unacceptable limit considerably exceeds the estimated total number of cyclic events over the plant lifetime.

TABLE OF CONTENTS


| Section | Title | Page |
|---|---|---|
| 1 | INTRODUCTION | 1-1 |
| 2 | TECHNICAL ANALYSIS | 2-1 |
| 2.1 | DESCRIPTION OF THE SYSTEMS | 2-1 |
| 2.1.1 | Reactor Water Cleanup System | 2-1 |
| 2.1.2 | Scram Discharge Volume System | 2-2 |
| 2.1.3 | Feedwater Startup Bypass System | 2-3 |
| 2.1.4 | Core Spray System | 2-3 |
| 2.2 | EFFECT OF INDICATIONS ON FITNESS FOR SERVICE | 2-4 |
| 2.3 | FATIGUE ANALYSIS | 2-5 |
| 2.3.1 | General | 2-5 |
| 2.3.2 | Stress Intensity Factor | 2-6 |
| 2.3.3 | Crack Growth | 2-7 |
| 2.3.4 | Material Constants | 2-9 |
| 2.3.5 | Acceptance Criteria | 2-10 |
| 2.4 | ANALYSIS AND RESULTS | 2-11 |
| 2.4.1 | Reactor Water Cleanup System | 2-11 |
| 2.4.2 | Scram Discharge Volume System | 2-11 |
| 2.4.3 | Feedwater Startup Bypass System | 2-12 |
| 2.4.4 | Core Spray System | 2-12 |
| 2.5 | DISCUSSION | 2-13 |
| 3 | CONCLUSIONS | 3-1 |
| 4 | REFERENCES | 4-1 |

## LIST OF TABLES


| Table | Title |
|---|---|
| 1 | Locations and Sizes of Radiographic Indications |
| 2 | Results of Fatigue Analysis |


## LIST OF FIGURES


| Figure | Title |
|---|---|
| 1 | RWCU Pipes and Welds |
| 2 | RWCU Pipes and Welds |
| 3 | SDV Pipes and Welds |
| 4 | SDV Pipes and Welds |
| 5 | SDV Pipes and Welds |
| 6 | FW Pipes and Welds |
| 7 | CS Pipes and Welds |
| 8 | CS Pipes and Welds |
| 9 | CS Pipes and Welds |
| 10 | CS Pipes and Welds |
| 11 | CS Pipes and Welds |
| 12 | CS Pipes and Welds |
| 13 | Typical Fatigue Stress Cycles |

# SECTION 1

# INTRODUCTION

During the period between 1980 and 1982, several systems were modified at Units 2 and 3 of Peach Bottom Atomic Power Station (PBAPS). Modifications included a number of pipe welds. These welds were radiographed and accepted at that time. Philadelphia Electric Company (PECO) re-examined these radiographs in 1983, and concluded that some radiographic indications in the scram discharge volume, reactor water clean-up, core spray and feedwater startup bypass systems were not acceptable. PECO asked Stone & Webster Engineering Corporation (SWEC) to evaluate the effect of these indications on the performance of these systems.

SWEC evaluated the indications using a fitness-for-service approach based on the methods and requirements of ASME XI. This report summarizes the results of these evaluations; details are given in References 1-8. The report discusses the effect of indications on different postulated rupture modes with an emphasis on fatigue crack growth that could be initiated by the indications.

## SECTION 2

## TECHNICAL ANALYSIS

### 2.1 DESCRIPTION OF THE SYSTEMS

Basic characteristics of the systems containing the unacceptable indications are briefly described in the following four subsections as given in Ref. 9 and 10. A detailed description of the indications and their locations are given in Section 2.4.

#### 2.1.1 Reactor Water Cleanup System (RWCU) - Modification 686

The RWCU provides for the continuous mechanical and chemical filtration and demineralization of a portion of reactor water that is not circulated through the condensate demineralizers. Reactor water is removed from the suction side of the recirculation loop via shutdown cooling suction piping or from the bottom drain line on the vessel. This flow is cooled in the regenerative and nonregenerative heat exchangers, filtered and demineralized, and returned to the feedwater system through the regenerative heat exchanger.

The RWCU system is designed to support the following reactor operations:

1. Normal or Reactor Power Operation

2. Startup Operation

3. Blowdown Operation

4. Refueling Operation

5. Hot Standby Operation

The welds of Modification 686 are located on the RWCU recirculation pump suction piping inside the Primary Containment (See Figures 1 and 2). The following process parameters are applicable to these welds (maximum values):

| Operation | Temperature ($^oF$) Initial | Final | Pressure (psig) Initial | Final | Flow (gpm) | Frequency |
|---|---|---|---|---|---|---|
| Reactor Power*) | 522 | 531 | 1018 | 1035 | 477 | - |
| Startup | 100 | 522 | 0 | 217 | 411 | 4/year |
| Blowdown | 100 | 545 | 0 | 1018 | 189 | 4/year |
| Refueling (or shutdown) | 522 | 545 | 1000 | | 364 | 4/year |
| | 545 | 375 | | | 364 | 4/year |
| | 375 | 330 | | | 364 | 4/year |
| | 330 | 100 | | 0 | 364 | 4/year |
| Hot Standby | 531 | 545 | 1000 | 1018 | 364 | 4/year |

*) Not used in fatigue calculations due to small temperature and pressure changes, resulting in $\Delta K \ll \Delta K_{th}$ (see Section 2.3).

The maximum temperature used in the fatigue calculations was 545F. The maximum pressure used in the calculations was 1135 psig as given in Reference 10.

The pipe material is ASTM A312 TP-316L and the weld material is 308L. Pipe size and other characteristics are given in Table 1.

### 2.1.2 Scram Discharge Volume (SDV) System - Modification 655

The scram discharge volume is used to limit the loss of and contain the reactor vessel water from all the drives during a scram. This volume is provided in the scram discharge header. During normal plant operation, each discharge header is empty (temp. = 70$^oF$) and the drain and two vent valves are open. Upon receipt of a scram signal, the drain and vent valves close. During a scram the control rod drives inject 3.34 gal (at 280$^oF$) each into the SDV through approximately 100 ft of 3/4 in. and 12 ft of 1 in. sch. 80 stainless steel pipe in about 30 sec. Unit 2 SDV is 6 in. sch. 80 pipe (775 gal volume plus 53 gal Instrument Volume) and Unit 3 SDV is 8 in. sch. 80 pipe (930 gal volume plus 53 gal Instrument Volume).

Subsequently the SDV will continue to fill at a rate between 185 gal/min. and 550 gal/min. depending on the condition of the drive seals until SDV pressure equals reactor pressure. When the scram signal is cleared (usually less than 20 min.) the SDV scram signal is overridden and the SDV is automatically drained.

The locations of the modification welds containing indications are shown in Figures 3, 4 and 5.

The pipe material is ASTM A106, Gr. B and the weld material is E 7018. Pipe sizes and other characteristics are shown in Table 1.

### 2.1.3 Feedwater Startup Bypass System (FW) - Modification 381

The feedwater startup valve provides a flowpath around the reactor feedpump (RFP) discharge gate valve to allow control of feedwater to the reactor for startup, shutdown and hot standby operations. The objectives are to provide better control of reactor water level and minimize thermal cycling of feedwater nozzles on the reactor vessel.

#### Normal Startup

Startup valve (AO-8091) and associated piping is placed in service when reactor pressure reaches about 600 psig (flow is about 250-300 gpm and feedwater temperature is 100 to 120$^{o}$F). The startup valve remains in service until reactor power reaches about 10-15 percent power, which is prior to placing any of the feedwater heaters in service. Flow conditions at this point are 1500 to 2000 gpm at a temperature of 100-120$^{o}$F.

At this point the startup valve (AO-8090) and the startup block valve (MO-8090) are closed and all feedwater flow to the reactor passes through the RFP discharge gate valve (MO-2149C). Feedwater temperature begins to increase as the heat cycle feedwater heaters are placed in service. The temperatures typically increase from 100$^{o}$F to a maximum of 376$^{o}$F (full power) over a time period of at least 24 hours. However, the feedwater startup bypass system temperature does not exceed 120$^{o}$F. The latter temperature is used in the calculations.

#### Normal Shutdown

Normal shutdown is much the same as the startup, except the events occur in reverse order. Feedwater temperature decreases as the power level is gradually reduced and the heat cycle is removed from service. The startup valve would only be placed in service after feedwater temperatures have dropped to below 150$^{o}$F.

#### Hot Standby

The startup valve could be used during hot standby conditions to maintain reactor vessel water level (feedwater temperatures 100-120$^{o}$F).

The assumed number of transients is:

| | |
|---|---|
| Startups and Shutdowns | 4/year |
| Hot Standby | 9/year |

The locations of the welds containing indications are shown in Figure 6.

The pipe material is ASTM A106 Gr. B, the weld material is E7018. Pipe sizes and other characteristics are given in Table 1.

### 2.1.4 Core Spray System (CS) - Modification 389

The purpose of the core spray system is to prevent overheating and melting of the fuel during a loss-of-coolant accident.

The core spray system consists of two completely independent spray loops. The equipment for each loop consists of two 50 percent core-spray pumps, a sparger ring, a spray nozzle, and the necessary piping, valves, and instrumentation. Each pump will take water from the suppression chamber by suction and will spray the water through the sparger ring into the plenum chamber above the core.

The welds in question are located between the core spray isolation valves and the reactor vessel (Figures 7 through 12). This portion of the system is without flow during all conditions except loss-of-coolant accidents and system flushing during shutdown. In case of no flow conditions, with reactor operating, for the piping between the isolation valve and the reactor normal operating pressure is 1025 psig, and design pressure is 1135 psig. The temperature gradient along the pipe is such that the temperature greater than 6 ft from the reactor vessel nozzle is drywell ambient (135°F) and less than 6 ft is 575°F. During full injection the system is at a pressure of 127.7 psia, a temperature of 210°F, and a flow of 6250 gal/min.

The pipe material is ASTM A312/TP316L and the weld material is 308L and 309L. Pipe sizes and other characteristics are given in Table 1.

## 2.2 EFFECT OF INDICATIONS ON FITNESS FOR SERVICE

Indications detected during the re-examination of the radiographs for the four systems were identified as cracks, lack of fusion, slag inclusions and lack of penetration. According to para. IWA-2110 and A-1100 of ASME XI lack of fusion or lack of penetration flaws are classified as cracks. The locations and sizes of indications as reported by PECO (Ref. 10) are shown in Table 1. Cracks and crack-like flaws can cause failure of metal components through the following mechanisms:

a. rupture caused by unstable crack propagation,

b. fatigue crack growth resulting in unstable rupture or leak,

c. enhanced corrosion (stress corrosion cracking (SCC) and/or corrosion fatigue).

The failure modes, except for SCC, can be analyzed using the methods of fracture mechanics described in Appendixes A and C of ASME XI. SCC is not a problem in the cases analyzed in this report for the following reasons:

a. ASTM A106 Gr. B pipe and E7018 weld metal used in the SDV and feedwater systems are carbon steels which are not sensitive to SCC in the reactor water environment

b. Reactor Water Clean-up system and Core Spray System are made of low carbon stainless steel (316L) and 308L and 309L weld metals which are not sensitive to intergranular SCC due to low susceptibility of these materials to sensitization during welding. Chloride induced transgranular SCC is not considered as a problem since the water chemistry in both systems is controlled.

ASME XI requires fracture mechanics analysis of indications if they exceed certain size relative to the component thickness. Most of the indications shown in Table 1 would not have to be analyzed applying the ASME XI criteria if the <u>reported</u> indication depth were used. However, the size of indications was determined by interpreting radiographs. Due to inherent uncertainties of such interpretations, for the purpose of the analysis we assumed that the depth of the postulated cracks is 1/16 in. for all indications with reported depth up to 0.025 in. and 1/8 in. for all indications with reported depth greater than 0.025 in. and up to 0.060 in. (Ref. 5). When this is assumed more indications listed in Table 1 have to be analyzed.

References 5 through 8 show that the <u>initial</u> size of the postulated flaws cannot cause unstable rupture. This can be concluded from the fact that the fatigue analyses in these references show that the welds containing the postulated flaws must be exposed to a large number of cycles before reaching a critical size. Therefore, the only failure mechanisms that has to be analyzed is fatigue crack growth. The effect of environment on fatigue crack growth was taken into account by using the appropriate materials constants (see Subsection 2.3.4). The fatigue analysis is presented in the next section.

## 2.3 FATIGUE ANALYSIS

### 2.3.1 General

As pointed out in the previous section, the rules of ASME XI consider the indications analyzed in this report to be cracks. The most convenient way to analyze the effect of such flaws on the initiation of fatigue cracks and their propagation is through the use of the methods of linear elastic fracture mechanics (LEFM). This particular application of LEFM is now universally accepted. Its theoretical background and practical applications are described in numerous books and articles (see for example Refs. 11 and 12).

The rate of fatigue crack growth can be expressed by the Paris equation:

$$\frac{da}{dN} = C_o(\Delta K_I)^n \qquad (1)$$

where a is the crack size (the depth for surface and edge cracks)

N is the number of cycles

$C_o$ and n are material constants

$K_I$ is the stress intensity factor range:

$$K_I = (K_I)\ \max - (K_I)\ \min \qquad (2)$$

Where $(K_I)$ max and $(K_I)$ min are values of the stress intensity factor, $K_I$, calculated for the maximum and minimum stress during the fatigue cycle. The stress intensity factor used in fatigue calculations almost always corresponds to the crack opening mode (or mode I, where crack surface

displacement is normal to the crack plane). A general expression for the mode I stress intensity factor is:

$$K_I = FS\sqrt{\pi a} \quad (3)$$

and $$\Delta K_I = F\Delta S\sqrt{\pi a} \quad (4)$$

where S is the applied stress, and $\Delta S$ = (max. stress) - (min. stress)

F is a parameter that depends on the shape and size of the crack and geometry of the body containing the crack.

The above methodology is accepted by ASME XI (see Appendices A and C of ASME XI - Winter 1983). Fatigue analysis of the indications discussed in this report is consistent with the requirements of ASME XI (see Refs. 5 through 8). The following subsections summarize the details of these calculations

2.3.2 Stress Intensity Factor

To calculate the stress intensity factor range, $\Delta K_I$, in Eq. (4) it is necessary to know the crack size, stress range during a cycle, and the parameter F.

As stated in Section 2.1 it was assumed for the purpose of the analysis that the depth of the postulated cracks is 1/16 in. for all indications with reported depth up to 0.025 in. and 1/8 in. for all indications with reported depth greater than 0.025 in. and up to 0.060 in. The length of the postulated cracks corresponds to the reported length (See Table 1). All the indications were modeled as semielliptical cracks of depth a and length L. The orientation of the postulated cracks was based on the orientation of the reported indications. In most cases the plane of the indication was normal to the axis of the pipe (circumferential orientation). When the orientation was non-circumferential both orientations, circumferential and longitudinal, were considered in the analysis.

The following cyclic stress contributions are evaluated where applicable:

1. Stresses due to the restraint of the free end displacement caused by thermal expansion.

2. Internal pressure stress.

3. Transient through wall thermal stress due to fluid temperature change (the linear part ($\Delta T_1$)).

These stress contributions are conservatively considered to act concurrently.

The stress components normal to the face of the indications are evaluated. These stresses are separated into membrane and bending components.

Since the welded joints containing indications were not post-weld heat treated welding residual stresses act on the postulated cracks. These stresses are static and do not directly affect $\Delta K_I$ value in Eq (4). However, a static stress affects the mean stress value, which has an effect on crack growth rate, da/dN. As will be shown later in Section 2.3.4 this indirect effect of residual welding stresses was included in the calculations.

The total stress intensity factor range that includes effects of all the stresses can be written as:

$$\Delta K_I = (\Delta S_m + H \Delta S_b) F \sqrt{\pi \frac{a}{Q}} \qquad (5)$$

Where $S_m$ is the uniform tension stress
$S_b$ is the outer-fiber bending stress
Q is the crack shape factor.

Factors H, F and Q are given in Ref. 13 for elliptical surface cracks in flat plates. The values of these factors depend on:

- o a/t = crack depth/plate thickness,
- o a/L = crack depth/crack length,
- o $\varphi$ = angle defining the position at the crack tip
- o ($\varphi$ = 90° at the tip of the crack, and 0° at the point where the crack intersects the surface).
- o type of loading (uniform tension or bending)

Similar solutions are available for cracks in cylindrical bodies (Ref. 14). A comparison with Eq (5) showed that differences between flat plate and cylindrical solutions were insignificant when those solutions were applied to the cases discussed in this report. It was decided to use Eq (5) since factors H and F are given in Ref. 13 in an analytical form, while those for cylindrical bodies are tabulated, and thus less convenient for numerical integration of Eq (1) (See 2.3.3 below).

### 2.3.3 Crack Growth

The analysis usually begins with an evaluation of the initial stress intensity factor range. If the latter is below a threshold level, $\Delta K_{th}$, there will be no crack growth. $\Delta K_{th}$ is a material property and the values for the steels in question have been reported in the literature. In a few cases the reported $\Delta K_{th}$ values, obtained under the conditions similar to those discussed in this report, were higher than some of the calculated K values. But due to uncertainties in measuring $\Delta K_{th}$ and limited amount of data it was assumed that the calculated $\Delta K$ values in all the cases exceeded the reported threshold values, so it was necessary to determine the crack growth rate by solving Eq. (1).

The usual method is to calculate the number of cycles needed to grow a crack from its initial depth, $a_i$, to the final depth, $a_f$, by integrating Eq (1):

$$N = \int_{a_i}^{a_f} \frac{da}{C_o \ (\Delta K)^n} \qquad (6)$$

This integral can be solved analytically if factor F in Eq (4), or factors H and F in Eq (5) do not change when a crack grows. However, these factors are dependent on crack depth and other related parameters, (see 2.3.2), so the direct integration is possible only for a small crack growth, when the factors will be practically constant due to a small change in the crack depth. In this work piece-wise integration was applied. The integral was solved for a small crack increment, $\Delta a = a_1 - a_i$; where $a_1$ takes place of $a_f$ in Eq (6). The number of cycles, $N_1$, needed to cause crack growth a was recorded. The new crack value was then obtained by adding $\Delta a$ to $a_i$ resulting in the new initial crack depth $a_2 = a_i + \Delta a$. This was again integrated in the same range a to obtain a corresponding number of cycles, $N_2$. The process was then repeated until the final crack depth, $a_f$, was reached, and the sum of all the cycles is obtained:

$$N = \sum_{i=1}^{n} N_i \cong \int_{a_i}^{a_f} \frac{da}{C_o \ (\Delta K)^n} \qquad (7)$$

(The final crack depth was based on the acceptance criteria described in 2.3.5).

The above integration process was performed in this work in two ways. 1) A simplified calculation method based on the following assumption was used: a) the maximum stress intensity factor value is at the maximum depth point of the crack and, b) the crack depth/length ratio stays constant during the growth ("self similar growth"). 2) A more accurate method that takes into account the variation of the stress intensity factor along the crack front was also applied. This variation depends on the a/L ratio and the relative magnitude of the bending load. For a/L = 0 to approximately 0.25 the maximum stress intensity factor occurs at the maximum depth point; for cracks with a/L > 0.25 exposed to bending the maximum value of the stress intensity factor is at the point where the crack intersects plate surface. From this point of view the assumption made in the simplified calculation method that the stress intensity factor is constant and corresponds to the value at the maximum crack depth point is conservative, at least when a/L ratios are less than 0.25. As can be seen in Table 1 a/L is less than 0.25 in most cases. However, conservatism of the assumption about the "self similar growth" and its effect on N was tested by performing calculations taking into account change of the stress intensity factor along the crack front. As will be shown later this more refined method gave higher N values in most cases, so the simplified method is usually more conservative, at least for the cases discussed in this report.

### 2.3.4 Material Constants

Eq(1) includes two material constants, $C_o$ and n, which depend on type of material, environment and the ratio of the minimum to the maximum stress in a cycle (or $^{Kmin}/Kmax$). In this work we discuss two materials: carbon steel and austenitic stainless steel. The materials constants, $C_o$ and n, for ferritic steels in air and in light-water reactor environment are given in Appendix A of ASME XI. Fig. A-4300-1 of that Appendix shows fatigue crack growth curves for reactor water environment at different values of R = min. stress/max. stress. Data for austenitic stainless steels were obtained from Ref. 15. These data were developed from tests performed in boiling water reactor environment.

As mentioned in 2.3.2 welding residual stresses affect the value of the mean stress, which has an effect on fatigue crack growth curves. Since it is an important factor it will be discussed here in some detail. This discussion is based on Ref. 16 which gives an excellent treatment of this subject. The fatigue terms and their algebraic relationships are defined below and in Figure 13:

$$\text{Amplitude} = Sa = \frac{Smax - Smin}{2} \quad (8a)$$

$$\text{Mean stress} = Sm = \frac{Smax + Smin}{2} \quad (8b)$$

$$R = \frac{Smin}{Smax} = \frac{K_{Imin}}{K_{Imax}} \quad (8c)$$

Smax is the sum of external and internal (residual) stresses. When Smax is less than the yield strength of the material, R is calculated from Eq (8c) and an appropriate da/dN curve is selected from Fig A-4300-1 of ASME XI or another source. However, the tensile residual stress in the weld region of an as-welded structure can be as high as the yield stress (YS). Therefore, during the first cycle Smax will exceed YS. In order to preserve the internal stress equilibrium, the excess stress over YS, equal to Smax - YS, will be redistributed to the areas that are still elastic. (This argument applies to an elastic-ideal plastic body, which does not strain harden; a more realistic case is discussed later.) When the external loads are removed, or become compressive, elastic unloading occurs throughout the affected areas resulting in a modified residual stress distribution. The maximum magnitude of the remaining residual stress is now equal to Smin = YS - Sext., where Sext is the sum of external stresses. Reapplication of the external stresses results in Smax = YS and after removal of the external stresses Smin is again equal to YS - Sext. So after the first cycle the weldment will be subjected to pulsating type of cycling between YS and the difference between YS and Sext. For example, if the stress cycle based on external stresses is $S_1$ to $-S_2$, the nominal stress range is $S_1 - (-S_2) = S_1 + S_2$. The actual stress range will be the difference between YS and $YS-(S_1 + S_2)$, that is:

$$(Smax - Smin) = YS - \left[YS - (S_1 + S_2)\right] = S_1 + S_2$$

So the stress ratio with residual stresses is:

$$R = \frac{Smin}{Smax} = \frac{YS-(S_1 + S_2)}{YS} = 1 - \frac{S_1 + S_2}{YS} \quad (9)$$

Without residual stresses:

$$R = -\frac{S_2}{S_1} \quad (10)$$

which is a smaller number than R with residual stresses. Since fatigue crack growth is faster for higher R values welding residual stresses may have a significant effect on the number of cycles calculated from Eq (6).

The above discussion is based on the assumption that plastic deformation is ideal, that is, that there is no strain hardening. To account for the strain hardening effect we used the flow stress instead of YS in Eq (9). Flow stress is given by:

$$FS = \frac{YS + UTS}{2} \quad (11)$$

Where UTS is ultimate tensile strength. In this analysis, the cyclic stress is expressed as $(S_m + HS_B)$, where H accounts for nonuniformity of the bending stress. Accordingly,

$$R = \frac{FS - (S_m + HS_b)}{FS}$$

2.3.5 Acceptance Criteria

For carbon steel under normal operating conditions the acceptance criterion of IWB-3612 (a) of ASME XI

$$K_I < K_{Ia} / \sqrt{10} \quad (12)$$

was used as suggested in paragraph IWB-3620.

Here $K_I$ is the maximum stress intensity factor for normal conditions for the flaw size $a_f$ and $K_{Ia}$ is the crack arrest toughness. The maximum stress intensity factor was calculated using all stresses (cyclic and static), including the seismic loads. However, due to the redistribution of residual stresses the maximum stress is always equal to the flow stress (see 2.3.4 above), so the acceptance criterion depends on the material properties (flow stress and fracture toughness), pipe geometry and crack depth ($a_f$).

All the indications were reported to be in the weld metal; therefore fracture toughness of the weld metal, SFA5.1 E7018, was used in the analysis for all indications at the inner surface (ID). Due to the weld configuration, indications at the outer surface (OD) could grow into the base metal, if they are near the weld-base metal interface. Therefore, for these indications fracture toughness of the base metal was used. The temperature difference, $T-RT_{NDT}$, was estimated and the crack arrest

fracture toughness, $K_{Ia}$, was found from Fig. A4200-1 of ASME XI - Winter 1983. The criterion expressed by Eq (12) was modified in those cases where its application would allow deep cracks. The acceptable number of stress cycles was calculated on the basis that the crack would not grow deeper than half of the wall thickness, even if the $K_I$ value was less than that allowed by Eq (12). (See also the following discussion on stainless steel.)

For austenitic stainless steel the acceptance criterion is given in IWB-3640 of ASME XI (1983 Winter Addenda). According to this criterion, the maximum allowable flaw depth to thickness ratio is 0.75. However, we use a more conservative criterion of $a/_t \leq 0.5$, which is in agreement with the present NRC's staff criterion that crack depth should not exceed two-thirds of the code allowable limit. (Reference 17).

## 2.4 ANALYSIS AND RESULTS

Using the above described methods, the crack depth of the propagating postulated crack was evaluated as a function of a number of the load cycles for constant and variable crack depth to length ratios. Calculations were performed for all the welds, but results are shown only for the worst case flaws when more than one flaw is postulated in a given weld.

The results are presented in the following subsections. Details are given in Refs. 5 through 8.

### 2.4.1 Reactor Water Cleanup (RWCU) System

The RWCU system of Unit 2 contains one pipe to existing penetration weld with two indications (Table 1).

The RWCU system of Unit 3 contains three welds with five indications (Table 1). Two of these welds are pipe/ 90 deg elbow girth butt welds and the third is a girth butt weld joining two 45 deg L.R. elbows. This system is exposed to RPV pressure cycling and expansion stresses. The results of the crack growth analysis are shown in Table 2.

Using the acceptance criterion described in 2.3.4 above, it was found that at least 7,900 cycles are required for a postulated flaw 0.0625 in deep to grow to the maximum allowable depth of 0.22 in., i.e., to 50 percent of the thickness.

### 2.4.2 Scram Discharge Volume (SDV) System

Unit 2 contains three welds with a total of six indications (Table 1). Two of the welds are girth butt welds joining 90-deg L.R. elbows to straight pipe, and the third is a girth butt weld joining straight pipe members.

Unit 3 contains 8 welds with a total of 19 indications (Table 1). Five of the welds are girth butt welds joining 90-deg L.R. elbows to straight pipe, two join 45-deg elbows to straight pipe, and one is a butt weld joining and 8 in. x 12 in. weldolet to a tank.

The following cyclic stresses were considered in the analysis of this system:

1. Stresses due to the restraint of the free end displacement caused by thermal expansion.

2. Internal pressure stress.

3. Transient through wall thermal stress due to fluid temperature change (the linear part ($\Delta T_1$)).

These stress contributions are considered to act concurrently.

The fatigue crack growth analysis showed that in the worst case (a 0.125 in. deep postulated flaw) it would take more than 7,580 cycles to exceed the acceptance criterion given in Eq. (12). (See Table 2.) The $K_{Ia}$ value in Eq. (12) for the flaws at the inner surface was based on fracture toughness of the weld metal.

$$K_{Imax} = \frac{K_{Ia}}{\sqrt{10}} = \frac{200}{\sqrt{10}} = 63 \text{ ksi } \sqrt{in}$$

2.4.3 Feedwater Startup Bypass System

The Unit 2 bypass contains two welds with four indications (Table 1). One weld is at a girth butt weld joining a welded end valve to the large end of a 10 in. x 8 in. schedule 100 concentric reducer. The other weld is a pipe/elbow girth butt weld.

The cycling stresses acting on these indications are generated by the pressure and expansion.

Postulated cracks with an initial depth of 0.0625 in. (reported depth was 0.010 to 0.015 in.) are expected to grow due to the cyclic loading into the weld metal. The acceptance criterion expressed by Eq (12) was applied using fracture toughness of the weld metal to calculate the $K_{Ia}$ value. Due to a lower operating temperature, $K_{Ia}$ is less than in 2.4.2:

$$K_{Imax} = \frac{126}{\sqrt{10}} = 39.8 \text{ ksi } \sqrt{in.}$$

Based on these results it was shown that the postulated cracks would remain within the allowable limits of Eq (12) for at least 27,000 cycles. (See Table 2.)

2.4.4 Core Spray (CS) System

The Unit 2 CS contains five welds with eight indications (Table 1). Three of these welds are pipe-to-pipe girth butt welds, one is a pipe to elbow weld and the fifth is a girth butt weld adjacent to the RPV nozzle safe end (on the pipe side).

The Unit 3 CS contains one weld with one indication (Table 1). The weld is a pipe/elbow girth butt weld.

The CS system does not experience any operating transients (cyclic stress) due to CS operation. The CS system experiences RPV pressure cycling and free end expansion stresses caused by RPV expansion/contraction while the CS pipe remains essentially at ambient temperature.

The depth of the reported indications varied between 5 and 60 mils. Initial postulated crack depths of 0.625 and 0.125 in. were assumed in this analysis.

Using the acceptance criterion for stainless steel (the maximum allowable flaw depth equal to 50 pct of thickness) it was found that the minimum number of cycles was 21,000 in Unit 2 and 3,950 cycles in Unit 3 (Table 2).

## 2.5 DISCUSSION

Indications detected in the examined welds were identified as cracks, lack of fusion, lack of penetration, and slag inclusions. It was shown in Section 2.2 that fatigue crack growth is the only failure mechanism that these indications could cause under the operating conditions.

The fatigue analysis described in previous sections is based on a number of conservative assumptions. To understand better our conclusions relative to the fitness-for-service evaluation of the analyzed piping systems we will first summarize those assumptions.

1. The depth of the postulated flaws is 2 to 6 times greater than the depth of the reported indications. This increases the factor of safety in Eq (12) by about 1.4 to 2.6 times.

2. The postulated flaws are assumed to be located at the point of maximum applied stress. For example, thermal expansion produces bending moment resulting in a through-diameter stress distribution from a maximum tensile stress to a maximum compressive stress. It is assumed that the postulated flaw is at the point of the pipe circumference exposed to the maximum tensile stress.

3. It is assumed that all applied stresses act concurrently.

4. Welding residual stress is assumed to be tensile and has its maximum value at the location containing the flaw. Since the maximum stress is assumed to be the flow stress:

$$FS = \frac{UTS + YS}{2} = \text{(Applied Stress)} + \text{(Redistributed Residual Stress)}$$

   this can result in an assumption that residual stress is above the YS value if applied stresses are low.

5. It was assumed that all the postulated flaws would grow, although in at least some cases the calculated $\Delta K$ values were lower than a reasonable estimate of $\Delta K_{th}$.

6. Crack growth was analyzed by two techniques:

a/L = constant and a/L variable. In almost all the cases the latter more realistic technique, gave a higher acceptable number of cycles, but in the final evaluation, the lower results were used.

- The following table gives the minimum number of loading cycles for propagation of postulated cracks to an acceptable limit as calculated in Refs. 5 through 8 and reported in 2.4 above.

| System | Unit | Lowest Calculated Number of Cycles to Acceptable Limit | Estimated Number of Cycles per year | Estimated Number of Cycles over 40 years |
|---|---|---|---|---|
| Reactor Water Cleanup | 2 | 3,700,000 | 28 | 1100 |
| | 3 | 7,900 | 28 | 1100 |
| Scram Discharge Volume | 2 | 8,090 | 15 | 600 |
| | 3 | 7,580 | 15 | 600 |
| Feedwater Startup Bypass | 2 | 27,000 | 13 | 520 |
| Core Spray | 2 | 21,000 | 13 | 520 |
| | 3 | 3,950 | 13 | 520 |

The calculated number of cycles by far exceeds the estimated number of cycles.

## SECTION 3

## CONCLUSIONS

Based on the results obtained in this work the following is concluded:

1. Radiographic indications observed in welds in the reactor water cleanup, scram discharge volume, feedwater startup bypass, and core spray systems may cause fatigue crack growth.

2. The number of loading cycles required to propagate postulated flaws to an acceptance limit considerably exceeds the estimated total number of cyclic events over the plant lifetime.

# FIGURES AND TABLES

Welds analyzed in this report are identified by three groups of numbers:

(Modification) - (Unit) - (Weld)

For example: 686-3-7 represents Modification 686 in Unit 3, Weld No. 7.

Modification numbers are related to the systems as follows:

| System | Modification No. |
|---|---|
| RWCU | 686 |
| SDV | 655 |
| FW | 381 |
| CS | 389 |

The welds in Figures 1 through 12 are identified by the same code, except that in some cases only the last number (Weld No.) is shown in the square box.

To identify the analyzed welds compare Tables 1 and 2 with the figures.

SECTION 4

REFERENCES


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2. SWEC Calculation 14006.24-NP(B)-2

3. SWEC Calculation 14006.24-NP(B)-3

4. SWEC Calculation 14006.24-NP(B)-4

5. SWEC Calculation 14006.24-MED-1

6. SWEC Calculation 14006.24-MED-2

7. SWEC Calculation 14006.24-MED-3

8. SWEC Calculation 14006.24-MED-4

9. Letter E.A. Clymer (PECO) to L.B. Hirst (SWEC), January 30, 1984

10. Weld Characteristic Summary - MOD 1366, PBAPS, Units 2 and 3, Eastern Testing and Inspection

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12. S. T. Rolfe and J. M. Barsom, Fracture and Fatigue Control in Structures, Prentice-Hall, Inc., 1977

13. J. C. Newman, Jr. and I. S. Raju, Engineering Fracture Mechanics, vol. 15, No. 1-2, pp 185-192, 1981

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15. R. Huet et al., SCC of 304 Stainless Steel in High-Purity Water, EPRI Report NP-2423-LD, 1982

16. T. R. Gurney, Fatigue of Welded Structures, Second Edition, Cambridge University Press, (p. 233)

17. Memorandum from W. V. Johnston, NRC to F. J. Miraglic, NRC, "Safety Evaluation of the Confirmation Order Inspection and Repairs on the Dresden Unit 3 Reactor Coolant Piping Systems" (p. 3 of the Attachment), March 13, 1984

18. ASME Boiler and Pressure Vessel Code, 1983 Edition and Winter 1983 Addenda.

TABLE 1 LOCATIONS AND SIZES OF RADIOGRAPHIC INDICATIONS

| System | Unit | Pipe Characteristics (dia-schedule) | Max t-re, °F | Max Pressure, psi | Pipe Mat'l | Weld Mat'l | Weld Number | $t_{nom}$, in. | Film View | Indication Number | Type of 1) Defect/Location | Max Reported Depth $a_r$, in | Postulated Depth $a_p$, in | Total Length, L, in | $a_r$/L | $a_p$/L | $\frac{a_r}{t_{nom}}$ | $(\frac{a}{t})_{xi}$ 2) | $\frac{a_p}{t_{nom}}$ | $(\frac{a}{t})_{xi}$ 2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RWCU | 2 | 6-80 | 545 | 1135 | 316L | 308L | 686-2-15A | 0.432 | 2-3 | 1 | IF/ID | 0.05 | 0.125 | 0.1875 | 0.27 | 0.67 | 0.116 | 0.099 | 0.289 | 0.1 |
| | | | | | | | | | 3-4,4-1 | 2 | IF/ID | 0.015 | 0.0625 | 0.5 | 0.03 | 0.125 | 0.035 | 0.093 | 0.145 | 0.096 |
| | 3 | 6-80 | 545 | 1135 | 316L | 308L | 686-3-7 | 0.432 | 1-2 | 1 | IF/ID | 0.01 | 0.0625 | 1.5 | 0 | 0.04 | 0.023 | 0.094 | 0.145 | 0.096 |
| | | | | | | | | | 2-3 | 2 | IP/ID | 0.01 | 0.0625 | 2.625 | 0 | 0.02 | 0.023 | 0.094 | 0.145 | 0.096 |
| | | | | | | | | | 4-1 | 3 | IF/ID | 0.015 | 0.0625 | 1.5 | 0.01 | 0.04 | 0.035 | 0.094 | 0.145 | 0.096 |
| | | | | | | | 686-3-8 | 0.432 | 2-3 | 1 | CRACK/ID | 0.01 | 0.0625 | 0.4 | 0.02 | 0.16 | 0.023 | 0.094 | 0.145 | 0.096 |
| | | | | | | | 686-3-11 | 0.432 | 2-3 | 1 | IF/ID | 0.025 | 0.0625 | 1.75 | 0.01 | 0.036 | 0.058 | 0.094 | 0.145 | 0.096 |
| SDV | 2 | 6-80 | 280 | 1375 | A106B | E7018 | 655-2-39 | 0.432 | 2-3 | 1 | IF/ID | 0.060 | 0.125 | 1.125 | 0.05 | 0.11 | 0.139 | 0.078 | 0.289 | 0.096 |
| | | | | | | | | | 2-3 | 2 | IF/ID | 0.015 | 0.0625 | 0.5 | 0.03 | 0.125 | 0.035 | 0.076 | 0.145 | 0.096 |
| | | | | | | | 655-2-40 | 0.432 | 4-1,1-2 | 1 | IF/ID | 0.025 | 0.0625 | 5.25 | 0 | 0.012 | 0.058 | 0.074 | 0.145 | 0.096 |
| | | | | | | | | | 4-1 | 2 | CRACK/ID | 0.010 | 0.0625 | 0.25 | 0.04 | 0.25 | 0.023 | 0.092 | 0.145 | 0.096 |
| | | | | | | | 655-2-12 | 0.432 | 1-2 | 1 | IF/ID | 0.010 | 0.0625 | 0.5 | 0.02 | 0.125 | 0.023 | 0.092 | 0.145 | 0.096 |
| | | | | | | | | | 1-2 | 2 | CRACK/OD | 0.025 | 0.0625 | 0.75 | 0.1 | 0.25 | 0.058 | 0.087 | 0.145 | 0.096 |
| | 3 | 8-80 | 280 | 1375 | A106B | E7018 | 655-3-3 | 0.500 | 1-2 | 1 | CRACK/ID | 0.010 | 0.0625 | 0.125 | 0.08 | 0.5 | 0.02 | 0.082 | 0.125 | 0.097 |
| | | | | | | | 655-3-4 | 0.500 | 4-1 | 1 | CRACK/MW | 0.015 | 0.0625 | 0.375 | 0.04 | 0.17 | 0.03 | 0.075 | 0.125 | 0.097 |
| | | | | | | | 655-3-5 | 0.500 | 3-4 | 1 | LF/ID | 0.010 | 0.0625 | 1 | 0.01 | 0.06 | 0.02 | 0.073 | 0.125 | 0.078 |
| | | | | | | | | | 3-4 | 2 | CRACK/ID | 0.010 | 0.0625 | 0.4 | 0.02 | 0.16 | 0.02 | 0.073 | 0.125 | 0.090 |
| | | | | | | | 655-3-8 | 0.687 | 1-2 | 1 | CRACK/MW | 0.025 | 0.0625 | 0.75 | 0.1 | 0.25 | 0.04 | 0.085 | 0.09 | 0.097 |
| | | | | | | | | | 2-3 | 2 | CRACK/MW | 0.020 | 0.0625 | 0.3125 | 0.06 | 0.2 | 0.03 | 0.078 | 0.09 | 0.097 |
| | | | | | | | | | 2-3 | 3 | SLAG TAILS/MW | 0.020 | 0.0625 | 0.125 | 0.16 | 0.5 | 0.03 | 0.095 | 0.09 | 0.097 |
| | | | | | | | | | 2-3 | 4 | SLAG TAILS/MW | 0.025 | 0.0625 | 0.1875 | 0.13 | 0.33 | 0.04 | 0.09 | 0.09 | 0.097 |
| | | | | | | | 655-3-16 | 0.500 | 1-2 | 1 | LF/ID | 0.015 | 0.0625 | 3 | 0 | 0.02 | 0.03 | 0.072 | 0.125 | 0.074 |
| | | | | | | | | | | 2 | LF/ID | 0.012 | 0.0625 | 1.5 | 0.01 | 0.04 | 0.024 | 0.073 | 0.125 | 0.076 |
| | | | | | | | | | 3-4 | 3 | LF/ID | 0.015 | 0.0625 | 2 | 0.01 | 0.03 | 0.03 | 0.073 | 0.125 | 0.075 |
| | | | | | | | 655-3-24 | 0.500 | 2-3 | 1 | CRACK/MW | 0.010 | 0.0625 | 0.25 | 0.04 | 0.25 | 0.02 | 0.083 | 0.125 | 0.097 |
| | | | | | | | 655-3-27 | 0.500 | 1-2 | 1a | LF/ID | 0.010 | 0.0625 | 1.375 | 0.01 | 0.05 | 0.02 | 0.073 | 0.125 | 0.077 |
| | | | | | | | | | | 1b | LF/ID | 0.010 | 0.0625 | 0.625 | 0.02 | 0.1 | 0.02 | 0.074 | 0.125 | 0.085 |
| | | | | | | | | | 2-3 | 2 | POROSITY & CRACK/MW | 0.025 | 0.0625 | 0.1875 | 0.13 | 0.33 | 0.05 | 0.089 | 0.125 | 0.097 |
| | | | | | | | | | 3-4 | 3a | POROSITY & CRACK/MW | 0.015 | 0.0625 | 0.375 | 0.04 | 0.17 | 0.03 | 0.076 | 0.125 | 0.097 |
| | | | | | | | | | | 3b | POROSITY & CRACK/MW | 0.015 | 0.0625 | 0.125 | 0.12 | 0.5 | 0.03 | 0.088 | 0.125 | 0.097 |

TABLE 1 LOCATIONS AND SIZES OF RADIOGRAPHIC INDICATIONS (Cont)

| System | Unit | Pipe Characteristics (dia-schedule) | Max t-re, °F | Max Pressure, psi | Pipe Mat'l | Weld Mat'l | Weld Number | $t_{nom}$, in. | Film View | Indication Number | Type of Defect/Location [1)] | Max Reported Depth ar, in | Postulated Depth ap, in | Total Length, L, in | ar /L | ap /L | $\frac{ar}{t_{nom}}$ | $(\frac{a}{t})_{xI}$ [2)] | $\frac{ap}{t_{nom}}$ | $(\frac{a}{t})_{xI}$ [2)] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 8-80 | 280 | 1375 | A106B | E7018 | 655-3-27 | 0.500 | 4-1 | 4 | LF/ID | 0.010 | 0.0625 | 1.25 | 0.01 | 0.05 | 0.02 | 0.073 | 0.125 | 0.077 |
| | | | | | | | 655-3-30 | 0.500 | 3-4 | 1 | LF/ID | 0.010 | 0.0625 | 2.5 | 0 | 0.025 | 0. | 0.072 | 0.125 | 0.075 |
| FW | 2 | 10-100 | 120 | 1575 | A106B | E7018 | 381-2-8 | 0.718 | 1-2 | 1a | LF/ID | 0.015 | 0.0625 | 0.875 | 0.02 | 0.07 | 0.02 | 0.072 | 0.09 | 0.077 |
| | | | | | | | | | | 1b | LF/ID | 0.010 | 0.0625 | 0.625 | 0.02 | 0.1 | 0.01 | 0.072 | 0.09 | 0.083 |
| | | | | | | | | | 2-3 | 2a | LF/ID | 0.010 | 0.0625 | 1 | 0.01 | 0.06 | 0.01 | 0.071 | 0.09 | 0.076 |
| | | | | | | | | | | 2b | LF/ID | 0.010 | 0.0625 | 2.125 | 0 | 0.03 | 0.01 | 0.07 | 0.09 | 0.073 |
| | | | | | | | 381-2-14 | 0.718 | 1-2 | 1 | LF/ID | 0.010 | 0.0625 | 1 | 0.01 | 0.06 | 0.01 | 0.072 | 0.09 | 0.076 |
| CS | 2 | 10-80 | 575 | 1135 | 316L | 308L | 389-2-1 | 0.593 | 1-2 | 1 | SLAG/MW | 0.025 | 0.0625 | 0.375 | 0.07 | 0.17 | 0.04 | 0.092 | 0.105 | 0.096 |
| | | 12-80 | 575 | 1135 | 316L | 308L | 389-2-4 | 0.687 | 2-3 | 1 | CRACK/ID | 0.005 | 0.0625 | 0.25 | 0.02 | 0.25 | 0.01 | 0.092 | 0.091 | 0.096 |
| | | | | | | | | | 2-3 | 2 | CRACK/MW | 0.020 | 0.0625 | 0.2 | 0.125 | 0.31 | 0.06 | 0.093 | 0.091 | 0.097 |
| | | | | | | 309L | 389-2-7 | 0.687 | 1-2 | 1 | LF/ID | 0.010 | 0.0625 | 1.75 | 0 | 0.04 | 0.01 | 0.088 | 0.091 | 0.090 |
| | | | | | | 308L | 389-2-11 | 0.687 | 1-2 | 1 | SLAG/MW | 0.060 | 0.125 | 0.375 | 0.16 | 0.33 | 0.09 | 0.093 | 0.182 | 0.096 |
| | | | | | | | | | 4-1 | 2 | LF/ID | 0.015 | 0.0625 | 2.25 | 0.01 | 0.03 | 0.02 | 0.088 | 0.091 | 0.090 |
| | | | | | | 309L | 389-2-15 | 0.687 | 2-3 | 1 | LF/ID | 0.015 | 0.0625 | 2.5 | 0.01 | 0.025 | 0.02 | 0.088 | 0.091 | 0.089 |
| | | | | | | | | | 4-1 | 2 | LF/ID | 0.010 | 0.0625 | 7 | 0 | 0.01 | 0.01 | 0.088 | 0.091 | 0.089 |
| | 3 | 12-80 | 575 | 1135 | 316L | 308L | 389-3-7 | 0.687 | 3-4 | 1 | CRACK/MW | 0.020 | 0.0625 | 0.5 | 0.04 | 0.12 | 0.03 | 0.09 | 0.091 | 0.094 |

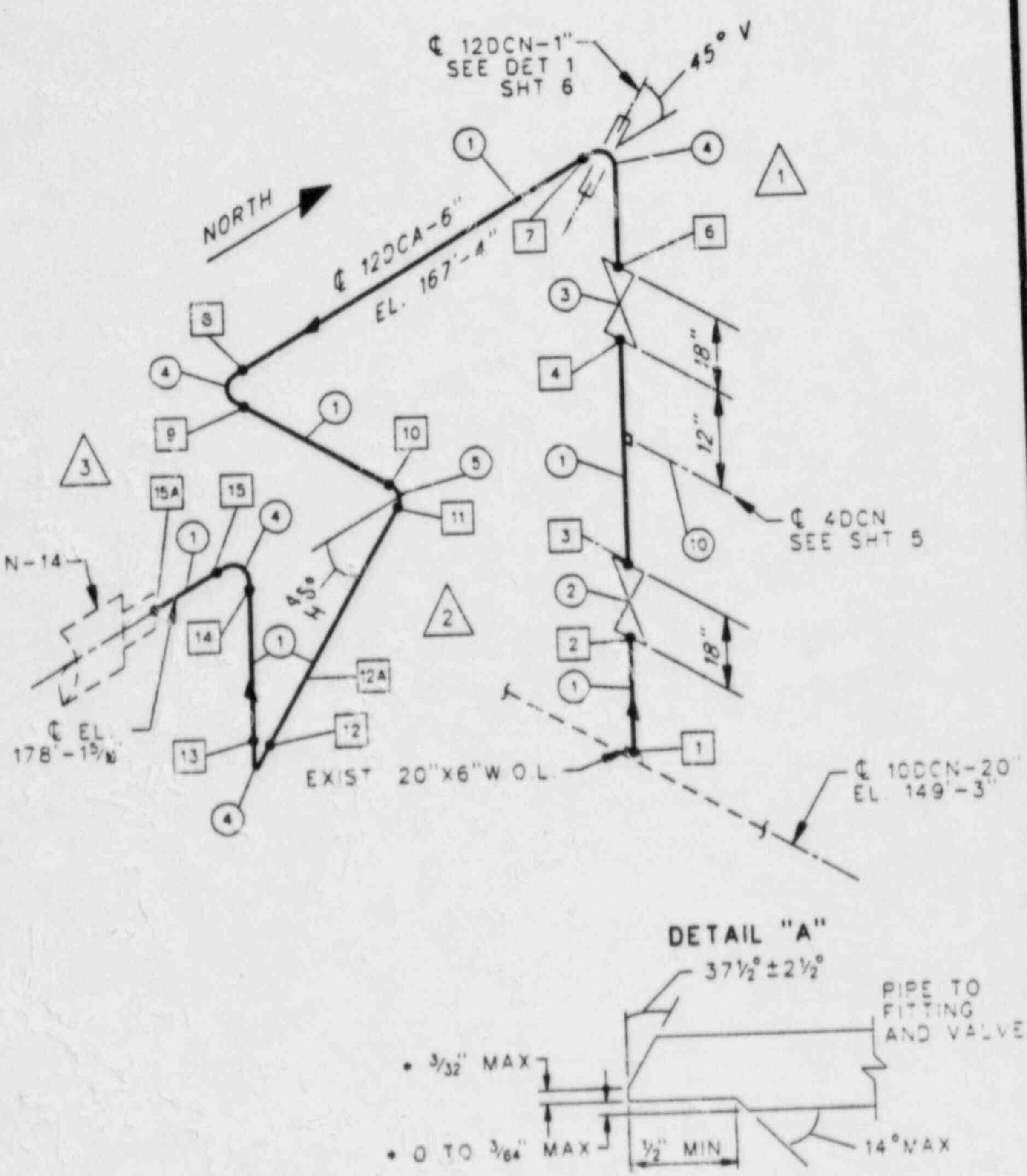
1) IF - incomplete fusion;
IP - incomplete penetration;
LF - lack of fusion;
ID - indication at the inner surface;
MW - indication at the mid-wall (for the purpose of the calculation all the MW indication were considered to be at the surface, ID or OD);
OD - indication at the outside surface

2) $(\frac{a}{t})_{xI}$ - flow depth/norminal thickness for allowable planar indications in ASME XI

## TABLE 2 RESULTS OF FATIGUE ANALYSIS[1)]

| System | Unit | Pipe Characteristics (dia-schedule) | Pipe Mat'l | Weld Material | Weld Number | Date Welding Performed | $t_{nom}$, in. | Indication Number | Max Reported Depth $a_r$, in | Postulated Depth $a_p$, in | Constant a/L $a_f$, in | $L_f$, in | $N_f$, cycles | Variable a/L $a_f$ | $L_f$ | $N_f$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RWCU | 2 | 6-80 | 316L | 308L | 686-2-15A | 4/82 | 0.432 | 1 | 0.050 | 0.125 | 0.22 | 0.32 | 3,700,000 | 0.22 | 0.46 | 17,000,000 |
| | 3 | 6-80 | 316L | 308L | 686-3-7 | 6/81 | 0.432 | 2 | 0.010 | 0.0625 | 0.20 | 9.0 | 9,100 | 0.22 | 2.6 | 7,900 |
| | | | | | 686-3-8 | 8/81 | 0.432 | 1 | 0.010 | 0.0625 | 0.22 | 0.7 | 130,000 | 0.22 | 0.6 | 390,000 |
| | | | | | 686-3-11 | 8/81 | 0.432 | 1 | 0.025 | 0.0625 | 0.22 | 6.0 | 41,000 | 0.22 | 1.75 | 48,000 |
| SDV | 2 | 6-80 | A106B | E7018 | 655-[illegible]-39 | 4/82 | 0.432 | 1 | 0.060 | 0.125 | 0.16 | 1.4 | 8,090 | 0.20 | 1.1 | 16,000 |
| | | | | | 655-2-40 | 4/82 | 0.432 | 1 | 0.025 | 0.0625 | 0.11 | 9.4 | 475,000 | 0.12 | 5.2 | 590,000 |
| | | | | | | | | 2 | 0.010 | 0.0625 | 0.22 | 0.86 | 390,000 | 0.22 | 0.5 | 920,000 |
| | | | | | 655-2-12 | 4/82 | 0.432 | 1 | 0.010 | 0.0625 | 0.16 | 1.3 | 1,600,000 | 0.22 | 0.67 | 3,000,000 |
| | 3 | 8-80 | A106B | E7018 | 655-3-3 | 6/81 | 0.500 | 1 | 0.010 | 0.0625 | 0.25 | 0.5 | 34,000 | 0.25 | 0.6 | 69,000 |
| | | | | | 655-3-4 | 8/81 | 0.500 | 1 | 0.015 | 0.0625 | 0.2 | 1.2 | 70,000 | 0.25 | 0.6 | 80,000 |
| | | | | | 655-3-5 | 6/81 | 0.500 | 2 | 0.010 | 0.0625 | 0.25 | 0.6 | 160,000 | 0.25 | 0.6 | 270,000 |
| | | | | | 655-3-8 | 7/81 | 0.687 | 2 | 0.020 | 0.0625 | 0.24 | 1.2 | 38,000 | 0.34 | 1.4 | 68,000 |
| | | | | | 655-3-16 | 7/81 | 0.500 | 1 & 4 | 0.015 | 0.0625 | 0.125 | 6.0 | 35,000 | 0.15 | 3.0 | 40,000 |
| | | | | | 655-3-24 | 7/81 | 0.500 | 1 | 0.010 | 0.0625 | 0.25 | 1.0 | 540,000 | 0.25 | 0.6 | 1,280,000 |
| | | | | | 655-3-27 | 7/81 | 0.500 | 3 | 0.015 | 0.0625 | 0.20 | 1.2 | 15,800 | 0.25 | 0.6 | 39,000 |
| | | | | | 655-3-30 | 6/81 | 0.500 | 4 | 0.010 | 0.0625 | 0.13 | 5.2 | 7,580 | 0.15 | 2.5 | 8,850 |
| FW | 2 | 10-100 | A106B | E7018 | 381-2-8 | 4/82 | 0.718 | 2b | 0.010 | 0.0625 | 0.07 | 2.4 | 38,000 | 0.07 | 2.1 | 49,000 |
| | | | | | 381-2-14 | 4/82 | 0.718 | 1 | 0.010 | 0.0625 | 0.075 | 1.2 | 27,000 | 0.08 | 1.0 | 36,000 |
| CS | 2 | 10-80 | 316L | 308L | 389-2-1 | 5/80 | 0.593 | 1 | 0.025 | 0.0625 | 0.25 | 1.5 | 130,000 | 0.25 | 0.55 | 330,000 |
| | | 12-80 | 316L | 308L | 389-2-4 | 6/80 | 0.687 | 1 | 0.005 | 0.0625 | 0.34 | 1.1 | 30,000 | 0.34 | 0.86 | 30,000 |
| | | | | 309L | 389-2-7 | 5/80 | 0.687 | 1 | 0.010 | 0.0625 | 0.34 | 9.4 | 27,000 | 0.34 | 1.75 | 30,000 |
| | | | | 308L | 389-2-11 | 6/80 | 0.687 | 1 | 0.060 | 0.125 | 0.34 | 1 | 78,000 | 0.34 | 0.74 | 81,000 |
| | | | | 309L | 389-2-15 | 5/80 | 0.687 | 2 | 0.010 | 0.0625 | 0.29 | 29 | 21,000 | 0.34 | 7 | 22,000 |
| | 3 | 12-80 | 316L | 308L | 389-3-7 | 6/81 | 0.687 | 1 | 0.020 | 0.0625 | 0.34 | 2.7 | 3,950 | 0.34 | 0.9 | 6,300 |

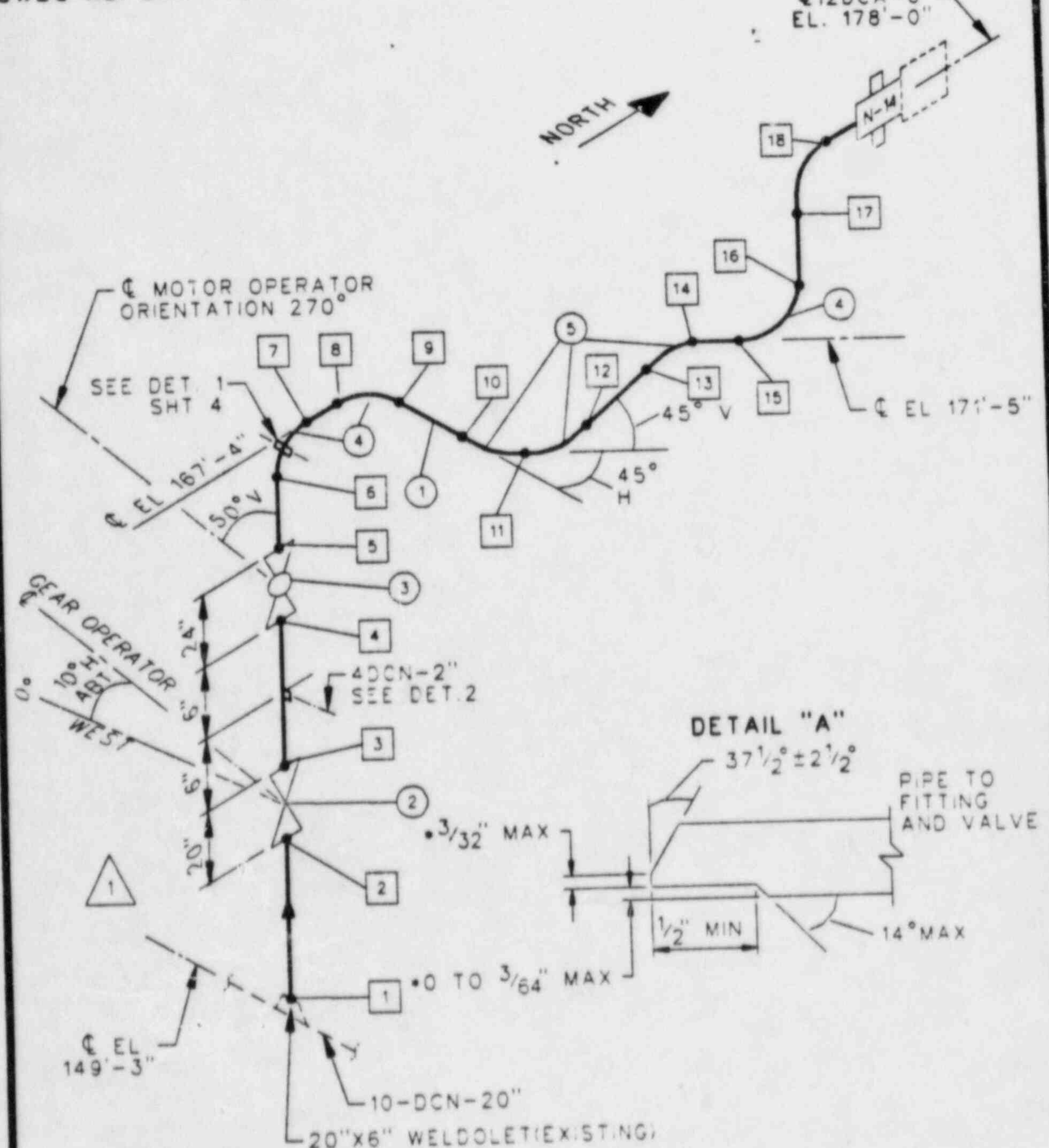
1) Only the worst case indication in each weld is included in this table.




* DIMENSIONS TO MATCH THE SPECIFIC END PREP OF EXISTING TIE-IN POINTS

FIG 1
RWCU PIPING & WELDS - UNIT 2

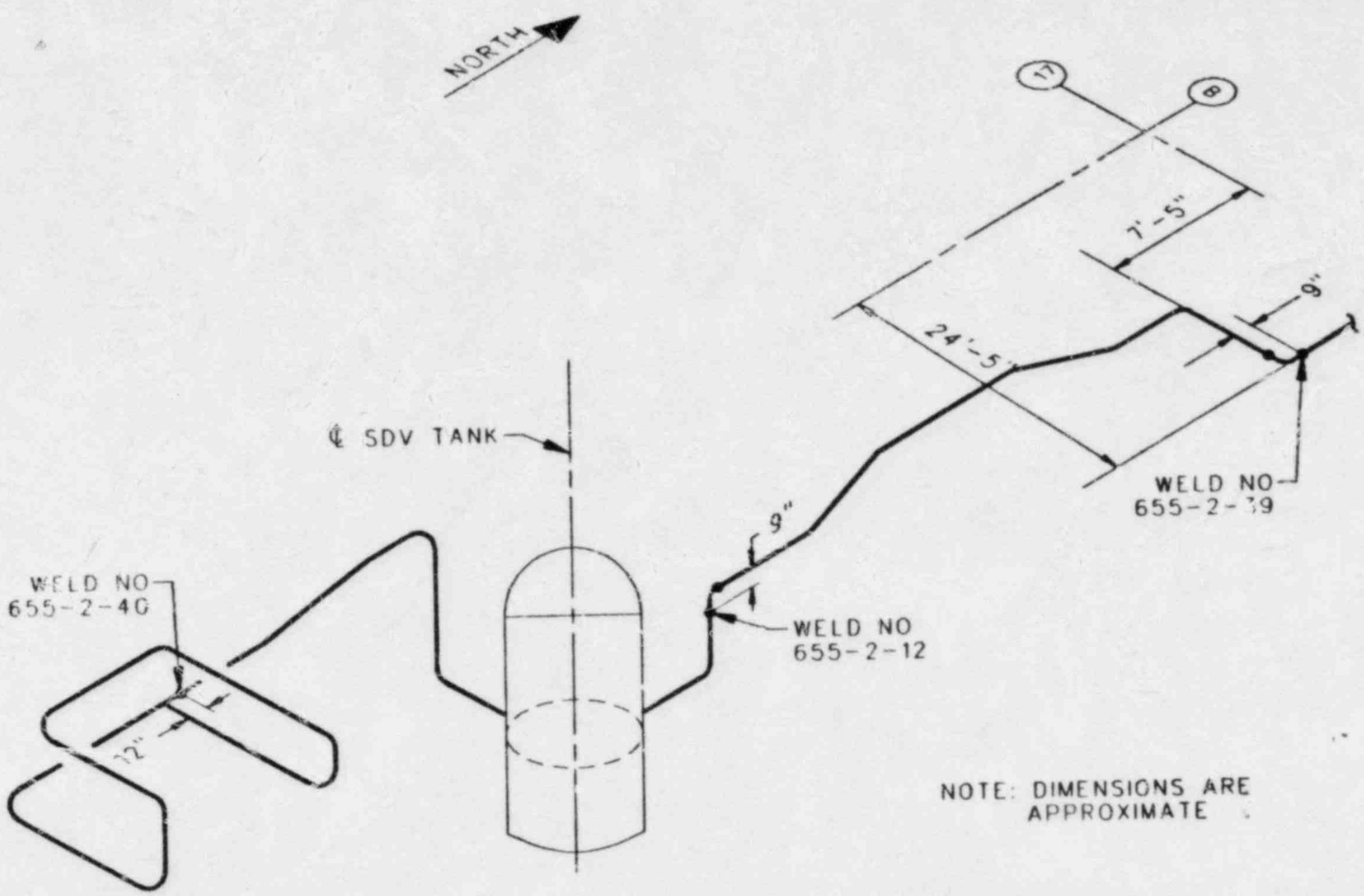
SWEC REPORT 14006.24-J(B)-133




• DIMENSIONS TO MATCH THE SPECIFIC END PREP OF EXISTING TIE-IN POINTS

FIG 2
RWCU PIPING & WELDS - UNIT 3

SWEC REPORT 14006.24-J(B)-133




NOTE: DIMENSIONS ARE APPROXIMATE

FIG 3
SDV PIPING & WELDS - UNIT 2

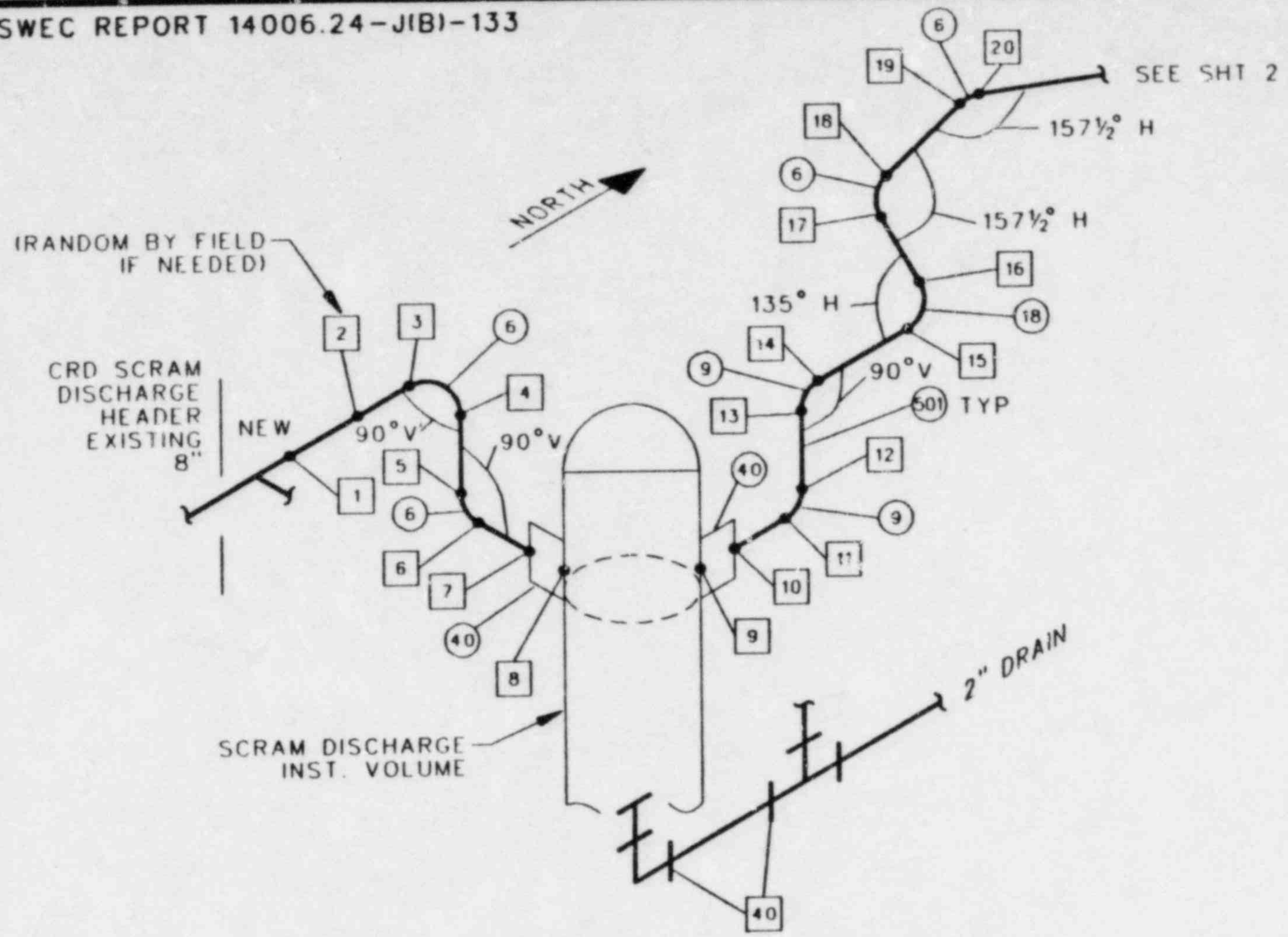
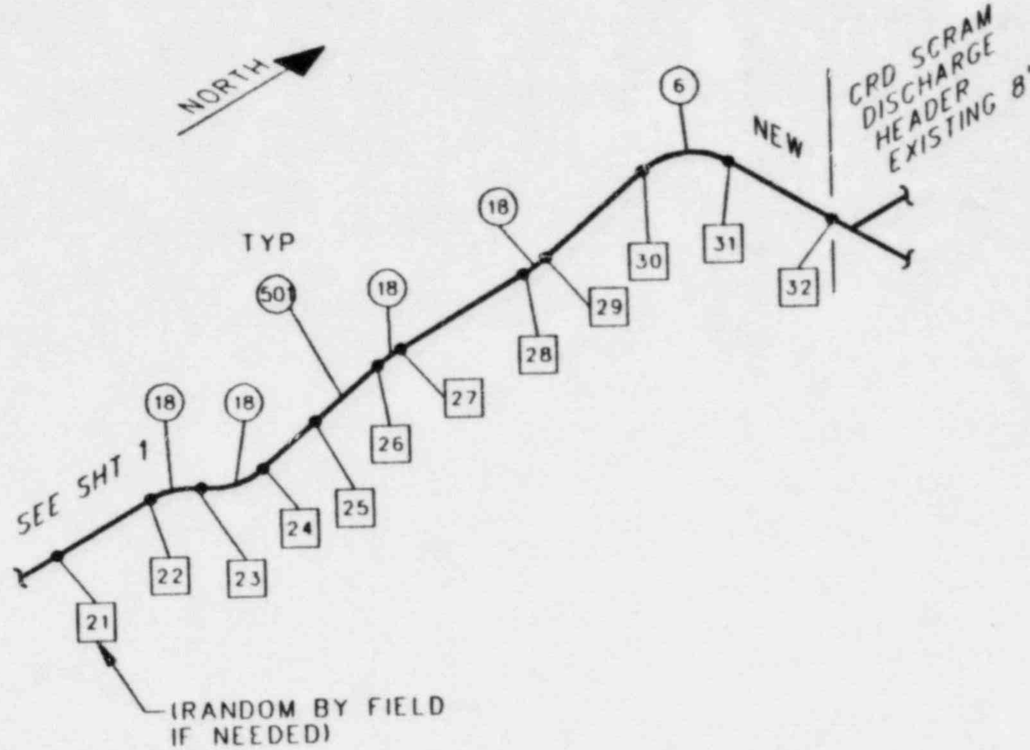



FIG 4
SDV PIPING & WELDS - UNIT 3
(SHEET 1)

SWEC REPORT 14006.24-J(B)-133

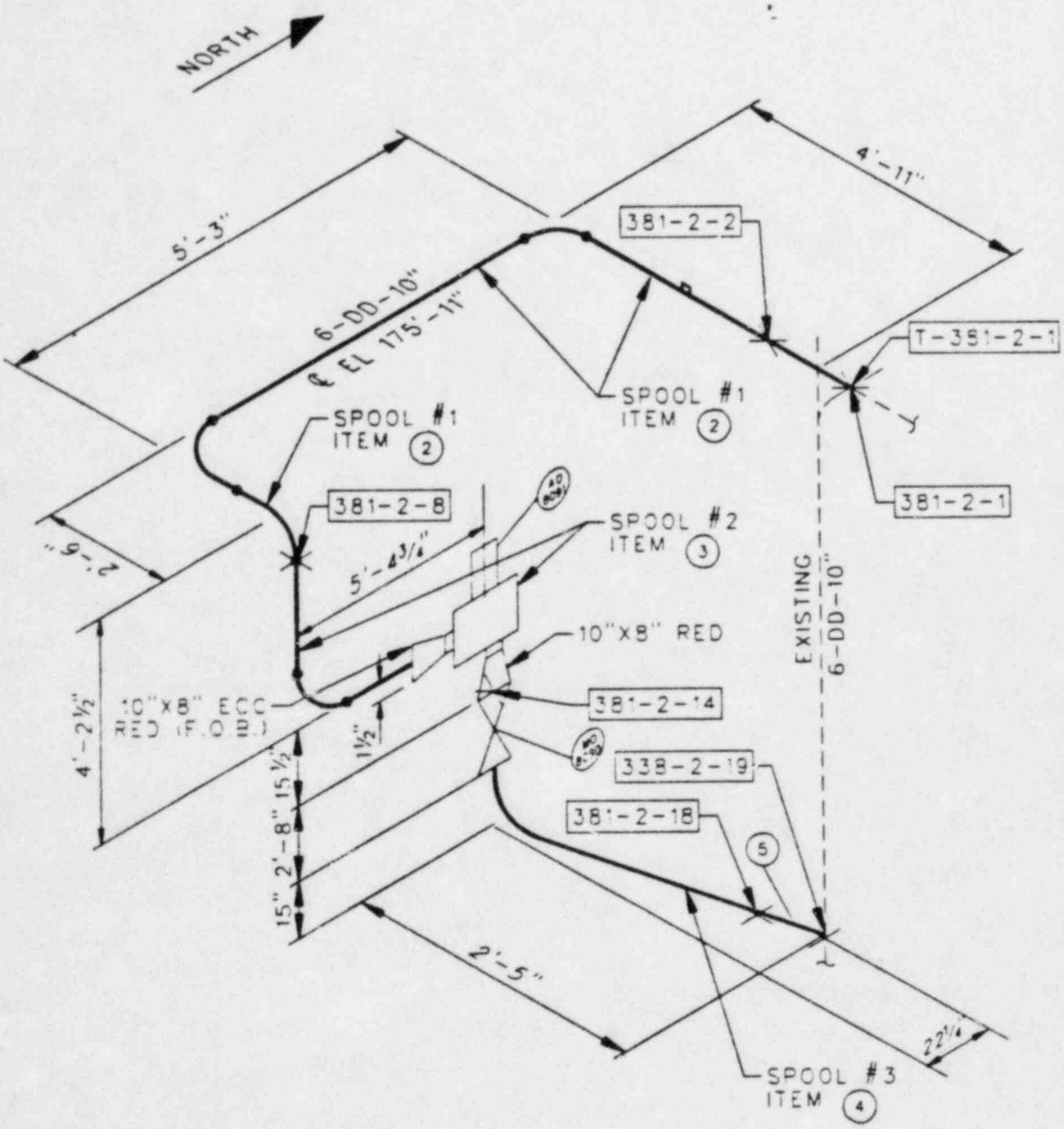



☐ WELD NO. (PRE-FIXED BY 655-3-)

○ ITEM NO. (SEE M.D.R. ENCL. 1.5.1)

FIG 5
SDV PIPING & WELDS - UNIT 3
(SHEET 2)

SWEC REPORT 14006.24-J(B)-133




DENOTES ITEM NO
SEE ENCL 15

DENOTES WELD NO
SEE ENCL 154

FIG 6
FW PIPES & WELDS – UNIT 2

SWEC REPORT 14006.24-J(B)-133

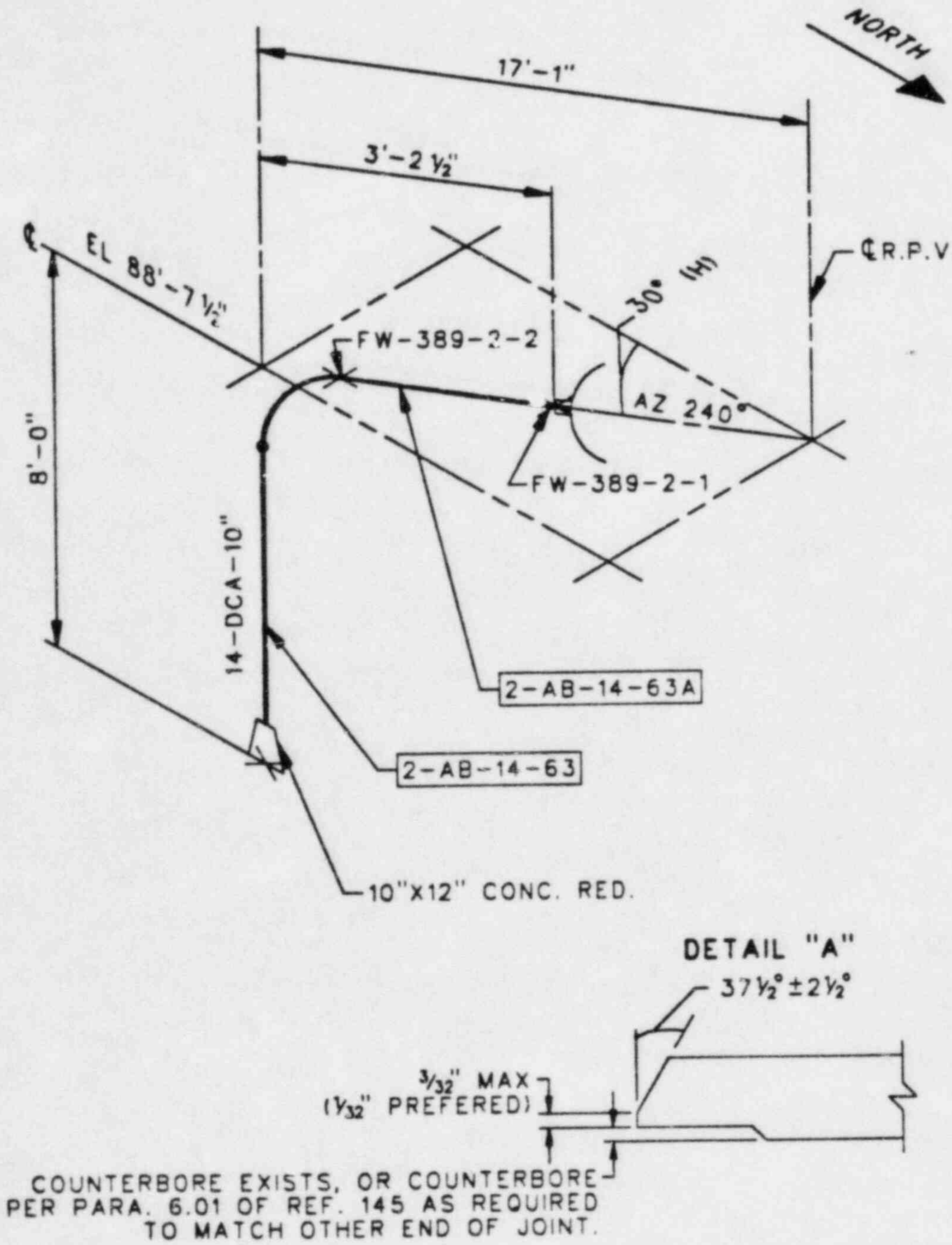



FIG 7
CS PIPES & WELDS - UNIT 2

SWEC REPORT 14006.24-J(B)-133

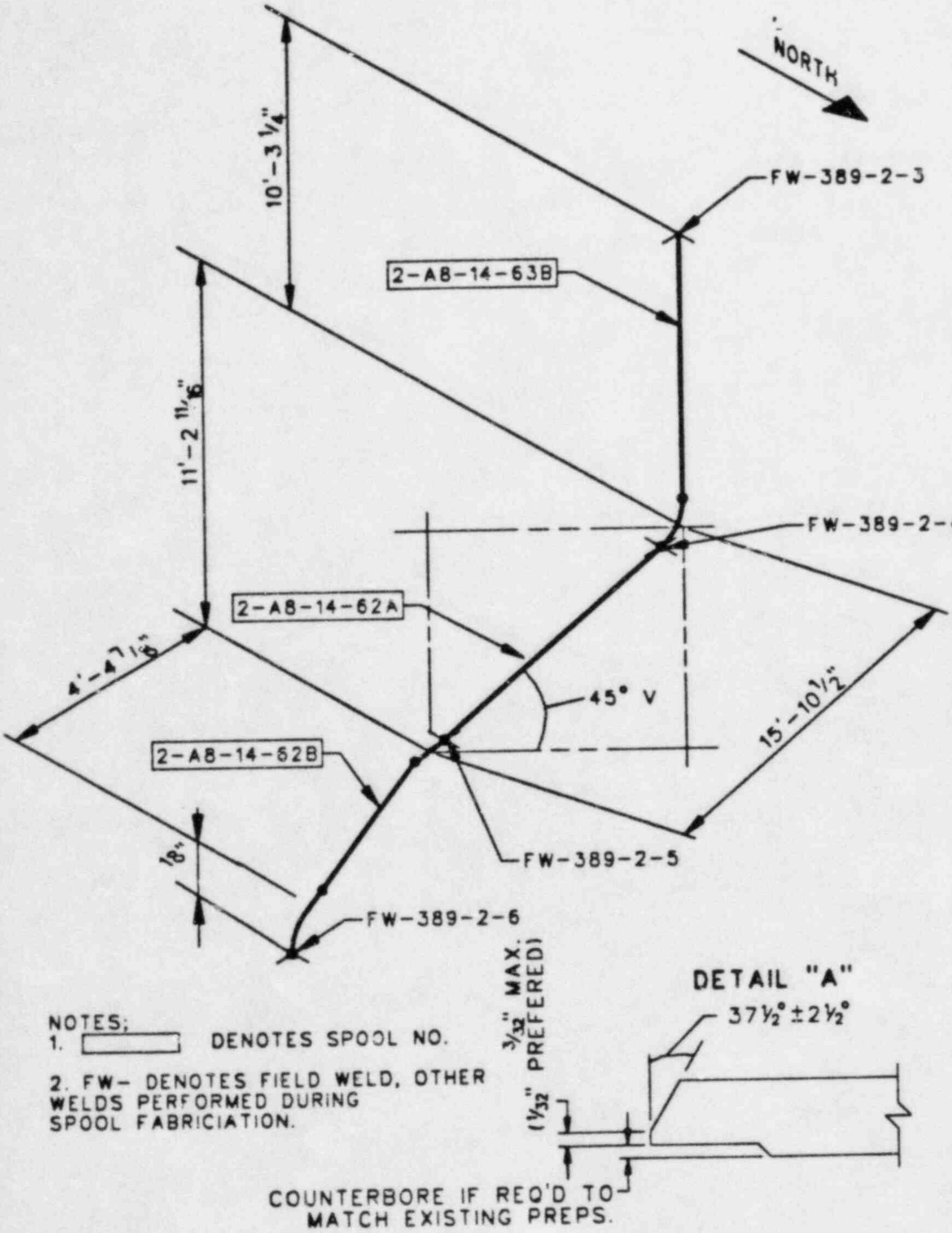



FIG 8
CS PIPES & WELDS - UNIT 2

SWEC REPORT 14006.24-J(B)-133

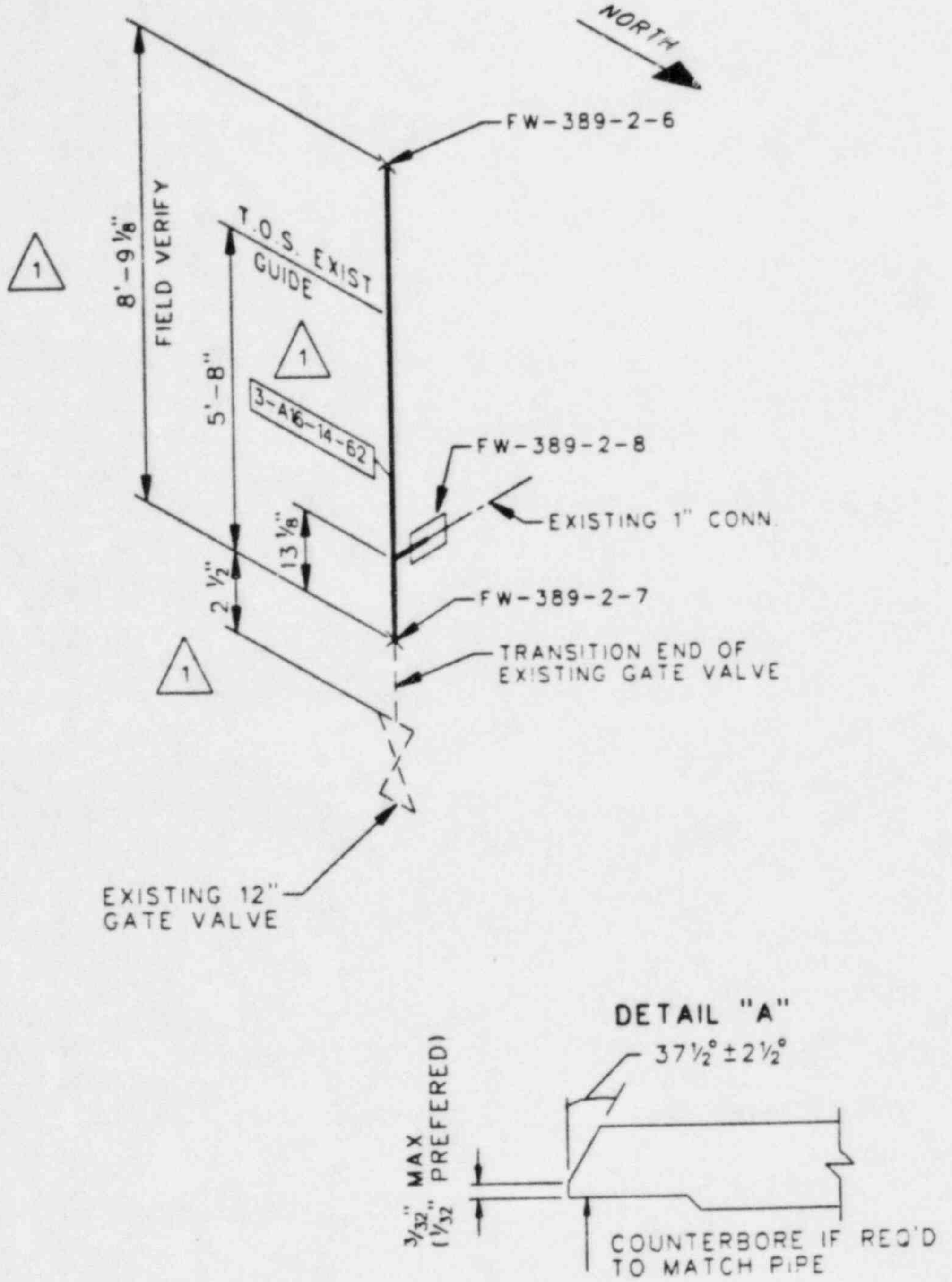



FIG 9
CS PIPES & WELDS - UNIT 2

SWEC REPORT 14006.24-J(B)-133

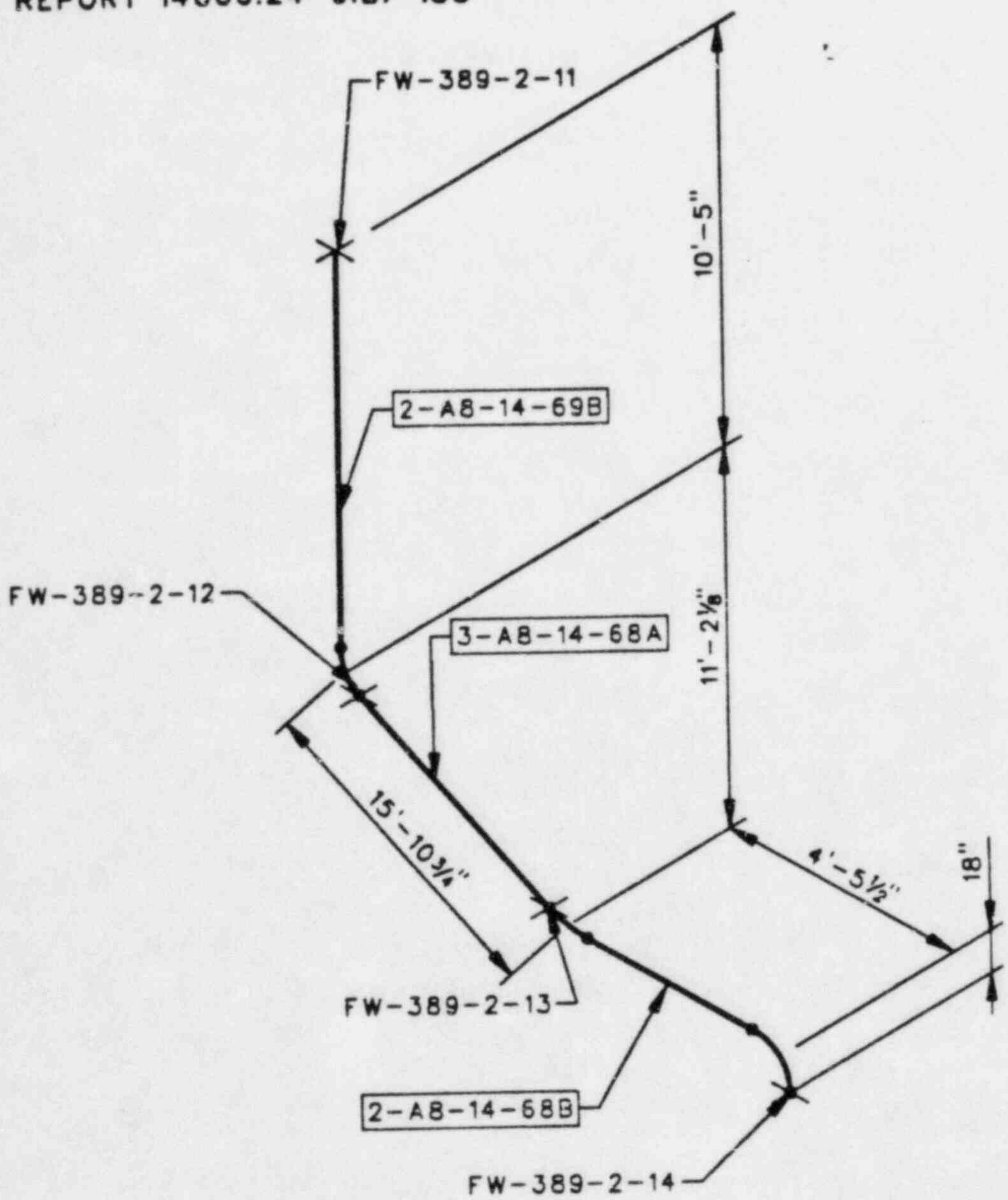
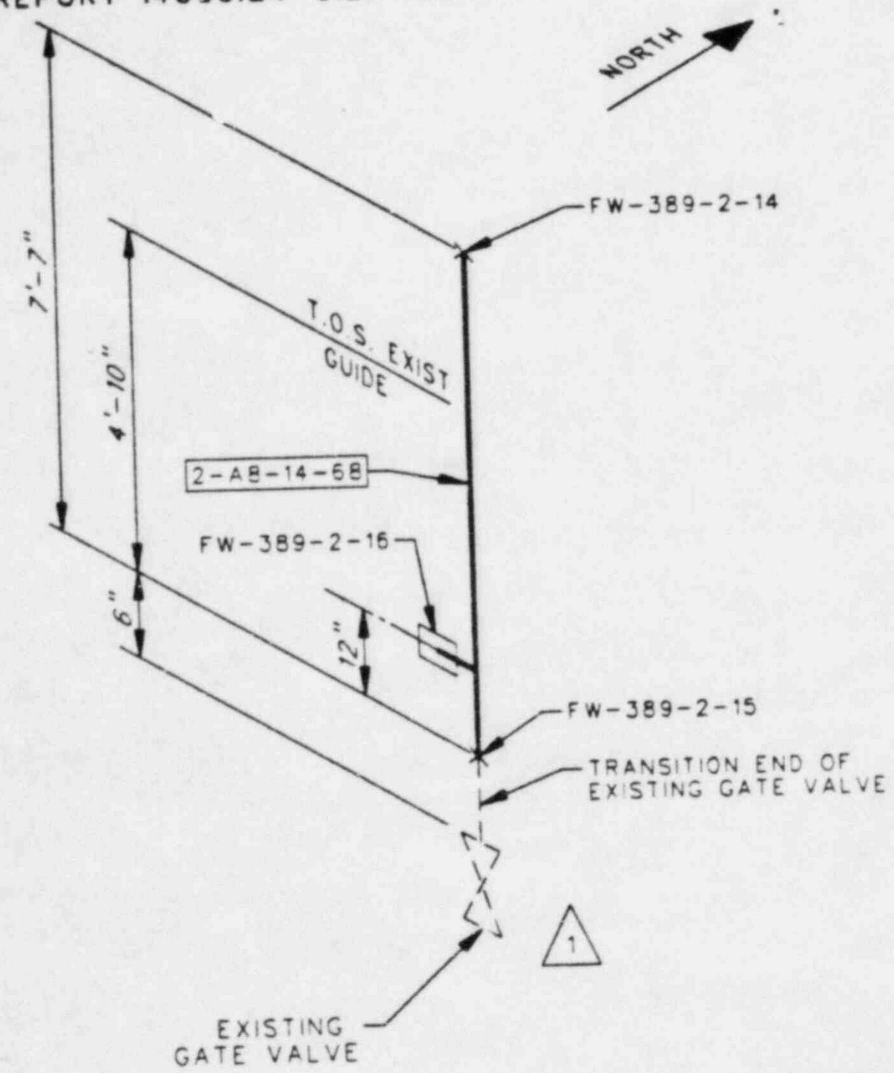
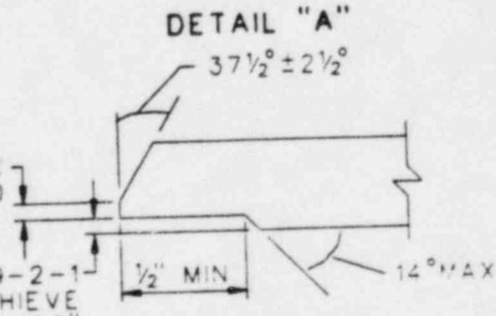



FIG 10
CS PIPES & WELDS - UNIT 2

SWEC REPORT 14006.24-J(B)-133




NOTES:
1. [ ] DENOTES SPOOL NO.
2. FW- DENOTES FIELD WELD

COUNTERBORE BOTH ENDS OF WELD FW-389-2-1
TO A NOMINAL I.D. OF 11.505" TO ACHIEVE
WELD PREP THICKNESS OF APPROX 0.623"
(MAX=0.644; MIN=0.58)
COUNTERBORE UPPER END IF REQ'D TO
MATCH SPOOL 63B

FIG 11
CS PIPES & WELDS - UNIT 2

SWEC REPORT 14006.24-J(B)-133

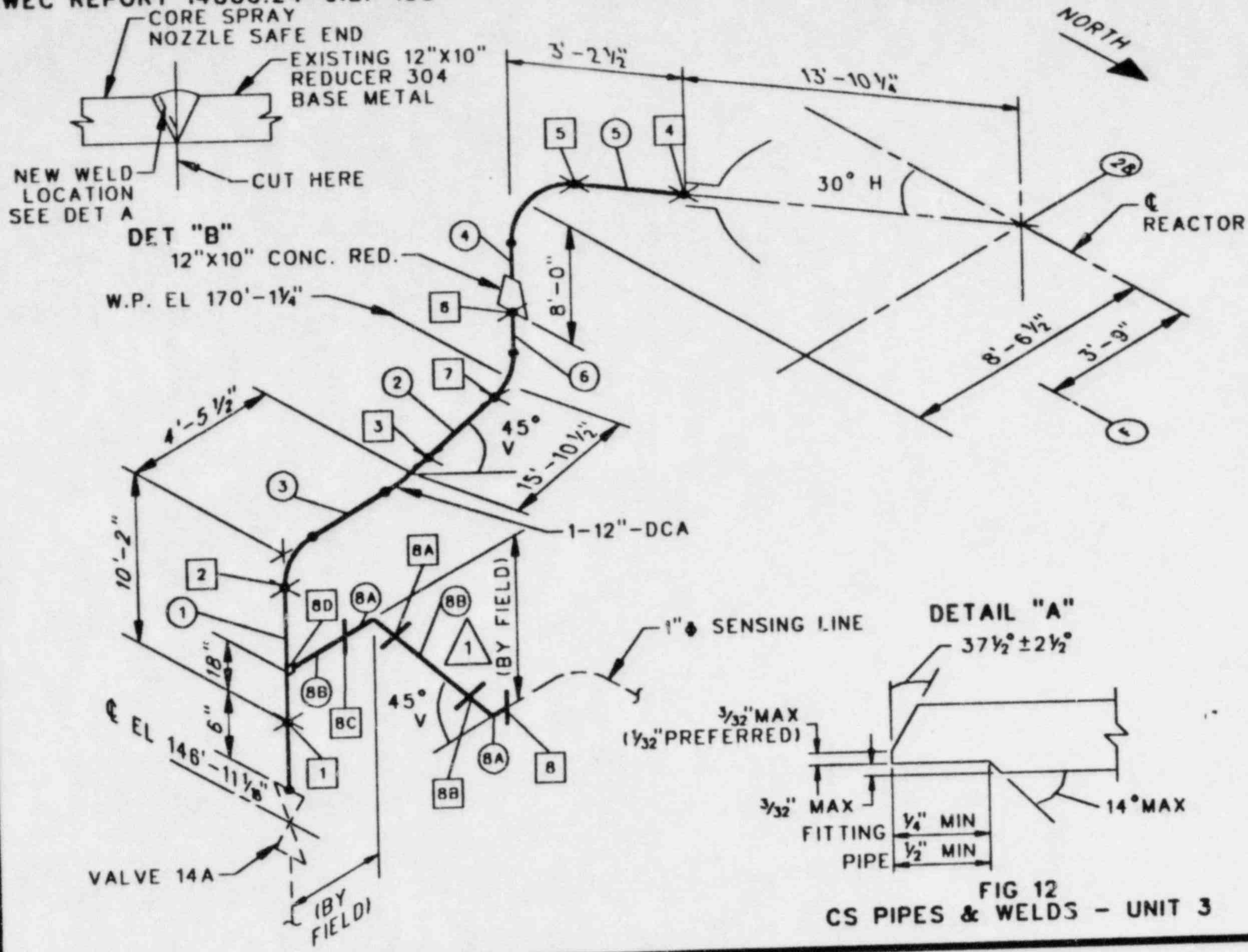



FIG 12
CS PIPES & WELDS - UNIT 3

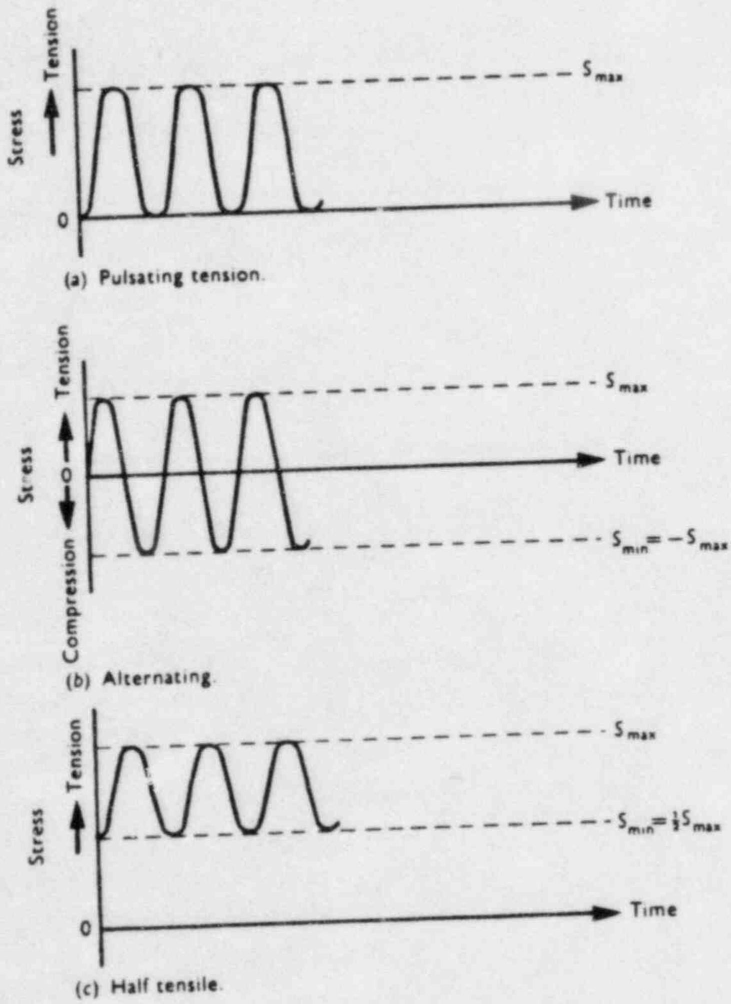



Fig.13 Typical Stress Cycles (Ref.16)