Engineering Evaluation of Erosion/Corrosion in Piping Systems

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NOMENCLATURE

A	Additional thickness requirements, according to table 104.1.2(a)1 of [3]
a	Flaw depth
D_o, D	Outside diameter of a pipe
d	Inside pipe diameter based on the projected thickness (t_{proj})
f	Coefficient dependent on the number of thermal cycles
i	Stress intensification factor
l_c	Flaw length in circumferential direction
l_a	Flaw length in axial direction
M_b	Resultant gravity/thermal bending moment
M_t	Resultant gravity/thermal torsional moment
P	Internal design pressure
P_m	Primary longitudinal membrane stress
P_b	Primary bending stress
S_g	Gravity stress
S_h	Allowable stress at the hot temperature
S_c	Allowable stress at the cold temperature
S_m	Allowable design stress intensity
S_T	Thermal stress
SE	Maximum allowable stress for the material at the design temperature
T_{min}	Minimum wall thickness for given pressure and temperature based on Code [3]
T_{meas}	Measured minimum wall thickness
T_{proj18}	Projected thickness in 18 months
T_{init}	Initial thickness
T_{nom}	Nominal thickness
T_{orig}	Original thickness
t_{oper}	Operating time, conservatively estimated
$(T_{proj})_{avg}$	Projected average thickness at the end of 18 months
$(T_{min})_{avg}$	Minimum average thickness at a particular axial distance using the large, small or the combination of grids
y	Parameter obtained from table 104.1.2(a)2 of [3]
Z_{proj}	Mean section modulus of a pipe
a/l	Aspect ratio of a flaw
$(a/t)_{allow}$	Allowable depth-to-thickness ratio
$(a/t)_{proj}$	Projected depth-to-thickness ratio in 18 months

INTRODUCTION

Wall thinning in carbon steel piping systems, caused by erosion/corrosion

(E/C), has recently raised both safety and economical concerns in the nuclear industry. In several power plants, this thinning has created a safety hazard for plant personnel due to catastrophic pipeline rupture, and as a result, significant operational costs have been incurred due to unexpected forced outages. Therefore, the systematic checking of wall thickness in various piping components during scheduled refueling outages and determining whether to repair, replace, or continue to use those components have become an important factor in optimizing maintenance plans for power plants.

This paper presents a systematic approach for evaluating the acceptability of wall thinning (depth and extent) caused by erosion/corrosion in carbon steel piping. Development of the E/C evaluation procedure, which is based on references [1] through [5], includes an inspection program for wall thinning detection in the most susceptible piping components by means of Ultrasonic Testing (UT). The factors considered in the selection of inspection locations are: piping material, fluid velocity, piping configuration, oxygen concentration, water chemistry, and temperature. The systems that were found to be most susceptible to E/C were: condensate, condensate booster, reactor feed, heater drains, and fuel pool cooling. Data generated from wall thickness measurement were used at all stages of the detailed engineering evaluation. The evaluation, described next, determines the level of acceptability and the life of a particular piping component.

E/C EVALUATION PROCEDURE

The three-stage evaluation procedure is presented in the flow chart shown in Fig. 1.

A Stage I evaluation was performed for each component inspected. The inspection grid networkwas comprised of 2", 4" and 6" grid sizes. The grids extended approximately one diameter upstream and two diameters downstream from the component. Ultrasonically measured thicknesses were compared to nominal wall thickness. If the lowest UT measurement would reach the pipe minimum fabricated thickness (about 87.5% of nominal wall thickness) by the next refueling outage (18 months), using a conservative wear rate, the area around the low readings was examined again using a reduced grid pattern and a Stage II engineering evaluation was performed.

The Stage II engineering evaluation was performed to ensure that the thinned components were acceptable until the next refueling outage. A three-step procedure was followed to determine whether or not a more rigorous analysis was required to evaluate piping component stresses near the points of interest. The evaluation considers the effects of pressure, sustained loads, and flaw geometry on each of the piping components. The criteria used in this evaluation process are given subsequently.

Pressure Criterion

In this first step it is determined whether

$$T_{proj18} \geq T_{min}, \qquad (1)$$

where

$$T_{proj18} = T_{meas} - \text{wear rate x 18 months} \qquad (2a)$$

$$T_{min} = \frac{P\,D_o}{2(SE + P\,y)} + A \qquad (2b)$$

$$y = 0.40 \text{ at temperatures less than 900F} \qquad (2c)$$

$$A = 0.0 \quad \text{for } D_o \geq 4 \text{ inches} \qquad (2d)$$

Parameter A accounts for material removed in threading, corrosion or erosion allowance, and material required for structural strength of the pipe during erection. The above expression for minimum wall thickness of a pipe is based on B31.1 Code of record [3].

Wear rate and projected life are calculated as follows:

$$\text{Wear rate} = \frac{T_{init} - T_{meas}}{t_{oper}}, \tag{3}$$

where

$$T_{init} = 1.125\ T_{nom} \tag{4a}$$

or $T_{init} = T_{orig}$, if justified by measurement (4b)

$$\text{Projected Life} = \frac{T_{meas} - T_{min}}{\text{wear rate}}. \tag{5}$$

As an operating time is used either of two time frames:

- (month & year plant started operation - month and year of inspection) x 0.7
- documented reactor operating time.

It should be noted that the rate of wear is in reality not uniform, and can accelerate or slow down depending on the environmental conditions existing in the pipe. However, in view of the conservative assumption related to initial wall thickness as being the maximum fabricated wall thickness, the linear expression for wear rate is acceptable.

Stress Criterion

In the second step the following is determined

$$(T_{proj})_{avg} \geq 0.875\ T_{nom} \tag{6}$$

where

$$(T_{proj})_{avg} = (T_{min})_{avg} - \text{wear rate x 18 months}. \tag{7}$$

If the equation (6) is satisfied, the projected life is calculated here as

$$\text{Projected Life} = \frac{(T_{min})_{avg} - 0.875\ T_{nom}}{\text{wear rate}} \tag{8}$$

and the minimum value between equation (5) and equation (8) is considered.

Flaw Criterion

The third step of Stage II procedure is used to ensure that the size and depth of a flaw meet IWB-3500 standards [2], i.e., the following condition has to be satisfied

$$(a/t)_{allow} \geq (a/t) \tag{9}$$

where

$$a = T_{nom} - T_{meas} \tag{10a}$$

$$t = T_{nom} \tag{10b}$$

and the $(a/t)_{allow}$ value is taken from Table IWB-3514-1 for an aspect ratio which is the minimum of (a/l_c) and (a/l_a) ratios. If equation (9) is not satisfied, further evaluation is required using the procedure outlined in [5]. Based on this procedure, the new value of an allowable (a/t) ratio is calculated, and it is compared with projected (a/t) ratio, i.e.,

$$(a/t)_{allow} \geq (a/t)_{proj} \tag{11}$$

where

$$(a/t)_{proj} = \frac{T_{nom} - T_{proj18}}{T_{nom}} \tag{12}$$

If the component does not meet the requirements of any of the three criteria mentioned above, a detailed stress analysis is performed which includes the use of the finite element piping program SUPERPIPE [6].

Refined Stress Evaluation in E/C Areas

A finite element analysis of a piping subsystem is conducted in order to more accurately determine the component stresses in the E/C areas under consideration. For a particular computer model the actual gravity, pressure, and thermal load conditions are determined at the tested components. Stresses for these locations are calculated using a section modulus based on the thinnest UT measurement. These stresses are evaluated per piping Code of record [3], as shown below.

A) Sustained Loads (Pressure and Gravity)

The piping stresses resulting from sustained loads must satisfy the allowable stress specified in [3]

$$\frac{Pd^2}{(D^2 - d^2)} + S_g \leq S_h \qquad (13)$$

where

$$S_g = \frac{\sqrt{(iM_b)^2 + (M_t)^2}}{Z_{proj}} \qquad (14a)$$

$$Z_{proj} = \pi \left(\frac{D - T_{proj}}{2}\right)^2 T_{proj} \qquad (14b)$$

$$d = D - 2T_{proj} \qquad (14c)$$

B) Thermal Loads

Thermal Stresses induced in a piping component must satisfy the following condition

$$S_T \leq S_a \qquad (15)$$

where

$$S_a = f(1.25\ S_c + 0.25\ S_h) \qquad (16)$$

and S_T has the same form as equation (14a)

If equation (15) is not satisfied, the combination of stresses is evaluated using the condition

$$\frac{Pd^2}{(D^2 - d^2)} + S_g + S_T \leq (S_a + S_h) \qquad (17)$$

The projected life of the component is calculated for the wall thickness iteratively in order to satisfy equations (12) or (16).

The Stage III evaluation is performed whenever a particular piping component cannot be qualified in the previous stages of the evaluation. At this stage, the remaining life of degraded components is estimated based on fracture mechanics and limit load analysis ([2], [5], [7]). Both analyses are required to evaluate plausible failure mechanisms: unstable crack extension or plastic collapse. Stage III represents a multi-step approach involving a detailed flaw analysis.

EXAMPLE PROBLEM

A heater nozzle to be evaluated for E/C is located in Extract Steam Piping System and has the following features: Material Type: A335 Grade P11, Schedule Number: Standard, D_o = 12.75 in, T_{nom} = .375 in, T_{meas} = .129 in, $(T_{min})_{avg}$ = .314 in, SE = 15,000 psi for design temperature of 400F, P = 150 psig.

Based on these data, T_{min} = .064 in. This piping component requires Stage II evaluation, since $T_{meas} < .875\ T_{nom}$.

- Pressure Criterion
  Using equations (4b), (3), (2a), and (5) have: $T_{init} = .563$ in, wear rate $= 3.05 \times 10^{-3}$ in/month, $T_{proj18} = .074 > .064$ in, and the projected life = 21 months.
- Stress Criterion
  Equation (7) gives a value of $(T_{proj})_{avg}$ as .259 in, which is smaller than $.875\ T_{nom} = .438$ in. Therefore, a refined stress evaluation is required.

The insulated piping sub-system, with the configuration shown in Fig. 2, has been modeled using the SUPERPIPE finite element program [6]. Nodes 5 (condenser nozzle) and 65 of the model were subjected to thermal movements of the condenser and heater respectively. Stresses in the nozzle are checked according to equations (13) through (17) for the following data: $M_b = 12{,}247$ lb/in (gravity), $M_t = 5{,}105$ lb/in (gravity), $M_b = 139{,}283$ lb/in (thermal), $M_t = 139{,}471$ lb/in (thermal), $S_h = 15{,}000$ psi, $S_a = 22{,}500$ psi, $i = 1.3$.

The nozzle stresses of 8,053 psi due to sustained loads satisfy equation (13). However, the thermal stresses of 24,473 psi violate equation (15). The combined stresses satisfy the condition (17), and therefore projected life is calculated based on this stress combination.

At first, assume that $T_{life} = T_{min} = .064$ in, and check the combined stresses for

$$Z_{life} = \pi\left(\frac{12.75 - .064}{2}\right)^2 (.064) = 8.09\ in^3$$

The resulting stresses of 37,680 psi slightly exceed the allowable value of 37,500 psi. Therefore, the stresses are calculated for such projected thickness d_{life}, which corresponds to projected life of 21 months obtained from pressure criterion above. The value of d_{life} is calculated based on equation (7), i.e.,

$$T_{life} = .314 - (3.05 \times 10^{-3})(21) = .25\ in,$$

which gives a new value of $Z_{life} = 30.68\ in^3$

Now, the total combined stresses of 15,353 psi satisfy the allowables and thus the projected life of the nozzle under consideration is 21 months.

CONCLUSIONS AND RECOMMENDATIONS

The systematic approach to erosion/corrosion evaluation in piping systems presented in this paper proves to be a very effective tool in predicting the life of any piping component. As this E/C evaluation procedure indicates, the Code minimum wall thickness criterion, used in industry, is not the only criterion which should be used to determine the life of piping components.

Of the piping components evaluated due to erosion/corrosion, 47% were acceptable during the initial evaluation. Piping analysis was required on 41%, and 12% required repair or replacement. In general, the most severe degrading by erosion/corrosion has been observed in two-phase components where flashing occurred after an orifice, and on Extraction Steam heater nozzles. No severe wall thinning was evident in the single-phase components.

Based on the evaluation results, it is recommended that the carbon steel piping components be systematically checked and analyzed for erosion/corrosion degradation. By estimating the safe service life of these components, plant maintenance planning may be organized more efficiently and economically, but more importantly, the safety of plant personnel will be enhanced.

REFERENCES

[1] 1986 ASME Code Section III Division 1 Appendices.
[2] 1986 ASME Code Section XI Division 1 Standards: IWA-3300, IWB-3400, IWB-3500.
[3] ANSI/USAS B31.1-1967, "Power Piping".

[4] EPRI Report No. NP-5911SP, "Acceptance Criteria for Structural Evaluation of Erosion/Corrosion Thinning in Carbon Steel Piping", July 1988.
[5] EPRI Report No. NP-4824M, "Evaluation of Flaws in Carbon Steel Piping", October 1986.
[6] Impell Corporation Computer Program "SUPERPIPE", Cyber Version 22C.
[7] Tada H., Paris P.C., Gamble R. M., "A Stability Analysis of Circumferential Cracks for Reactor Piping Systems", in <u>Fracture Mechanics</u>: Twelfth Conference, ASTM STP 700, 1980.
[8] Bergen-Paterson Catalog 82R, "Pipe Supports".

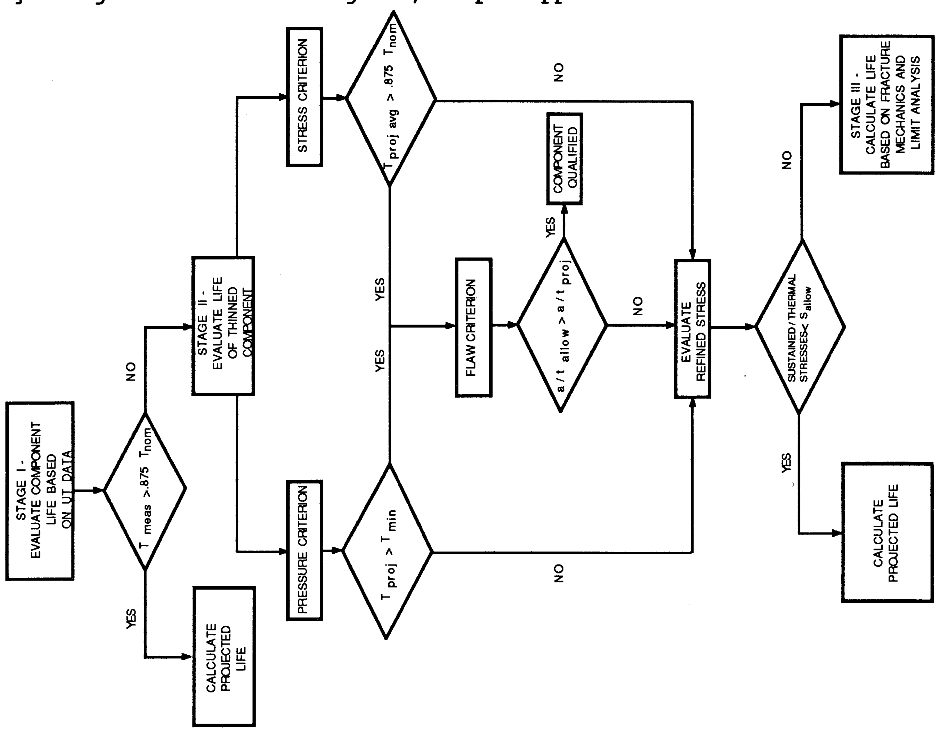

Fig. 1 Erosion/corrosion evaluation procedure.

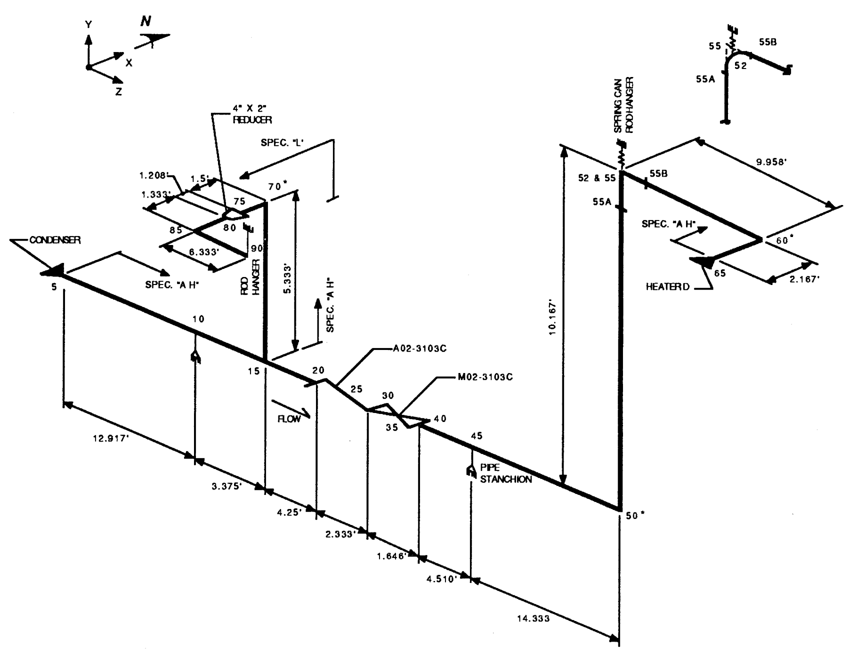

Fig. 2 SUPERPIPE model of piping sub-system.