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TITLE

STRESS ANALYSIS OF BULK EFFLUENT
SYSTEM COMPONENTS IN B AND C REACTORS

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STRESS ANALYSIS OF BULK EFFLUENT
SYSTEM COMPONENTS IN B AND C REACTORS

INTRODUCTION

This report presents a study of the stresses induced in the elbow and downcomer of the B and C Reactors (bulk effluent systems) by flow momentum and pressurization effects. It is desirable to ascertain the limitations on the bulk outlet temperatures and flow rates from a stress viewpoint; the elbow, top coverplate of downcomer, and top baffle plate being the most severely stressed components.

SUMMARY

Calculations of static stresses show that the bulk outlet temperatures may be raised to 102.4°C in B-Reactor and 105°C in C-Reactor without causing a weld failure at either the elbow or top coverplate of the downcomer. The top baffle plates in both of these reactors are safe under static loading conditions (due to momentum effects) under the aforementioned temperature limits. The plate itself is welded to edge supports consisting of three angle sections welded along their length to the downcomer liner and a beam that is welded at both ends to the liner. These welded connections have been analyzed on the basis of shear failure and have been assumed to be of continuous length. Before conducting any experimental runs this latter assumption should be verified and, if this condition is not satisfied, then these connections should be made continuous. In addition, it would be advisable to further shore up the beam support using some of the techniques outlined in the steel construction manual⁽¹⁾ and if possible anchor these to the next lower baffle. Although these beams have been analyzed under dynamic loading conditions (transient flow-start-up) and found to be safe, considerable doubt remains concerning the behavior of the welded connections at the ends of the beams and around the edge of the plate under this type of loading. Furthermore, the stresses which would result from such dynamic conditions as bulk temperature surges or cavitation have not been considered in this document.

(1) "Steel Construction Manual", A.I.S.C., Fifth Edition, 1949, P. 336-338 and P. 286.

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NOMENCLATURE

p	= Internal pressure, psig
P_o, P_i	= Maximum and minimum internal pressures (outside and inside curves) - psig
V	= Flow velocity - ft./sec.
v	= Specific volume of fluid - ft ³ /lb.
a, b	= Internal radius of approach section and radius of curvature
r_c	= Radius from center of curvature to center line of elbow.
r_o	= Radius of circle perpendicular to axis of elbow - inches
r_1	= Radius of curvature of shell in meridional plane, in.
$N_\varphi, N_\theta, N_{\varphi\theta}$	= Membrane forces per unit length of axial section and a section perpendicular to the axis of a cylindrical shell - lbs./inch.
$\sigma_\varphi, \sigma_\theta, \sigma_{\varphi\theta}$	= Respective membrane stresses - psi
p_1, p_2	= Pressure components ($p = p_1 \sin \varphi + p_2$) - psig
σ_1, σ_2	= Principal stresses - psi.
σ_{wt}, σ_{wc}	= Allowable working stresses in tension and compression, respectively, psi.
l	= Length of cylindrical tube.
R, R_x, R_y	= Resultant wall force and its components lbs.
x, φ	= Coordinates of cylindrical shell.
$N_x, N_{x\varphi}, N_\varphi$	= Membrane forces per unit length of axial section and a section perpendicular to the axis of a cylindrical shell.
$\dot{m}$	= Mass rate of flow - lbs./sec.
T	= Size of fillet in a fillet weld.
σ_c	= Normal stress in the direction of the c dimension of a rectangular plate.
W'	= Total load on a beam - lbs.

- w = Load intensity on a plate - psi.
 θ = Polar coordinate for elbow - degrees
 z = Load intensity acting on surface of shell (equals internal pressure) - psi.

ANALYSIS

In the determination of stresses caused by momentum effects it becomes necessary to determine the velocity of flow. This is done by assuming a throttling process in which saturated water at same bulk outlet temperature in excess of 100°C expands down to 100°C such that vaporization takes place. Employing the continuity of flow conditions, and knowing the mass rate of flow, cross sectional area, and specific volume of the mixture (liquid and vapor), one can then compute the resulting velocity.

A. Approach section to Downcomer (Elbows)

The approach section at the B-Reactor effluent system (see Figure 1) has been treated as a toroidal shell, while the approach section in the C-Reactor (see figure 2) has been treated as a cylindrical shell. Throughout these analyses the following assumptions have been made:

- (1) Membrane theory of shells applies (neglects bending stresses); good approximation at some distance from ends of shell.⁽²⁾
- (2) Every cross section experiences the same pressure distribution ($p = p_1 \sin \phi + p_2$)
- (3) Pressures can never be less than 10 psig on the inside surface (surfaces B_1 C_1 Figures 1 & 2).

1. B-Reactor Approach Section

From the results of a paper by Lansford,⁽³⁾ the pressure differential, (for B-elbow - Figure 1) $p_o - p_i$, can be determined corresponding to a particular velocity using the expression:

$$p_o - p_i = \frac{4 a}{r_c} \frac{v^2}{2 g v} \quad (1)$$

Making use of assumption (3) pressure components p_1 and p_2 , can be calculated from expression, $p = p_1 \sin \phi + p_2$, and equation (1) where

$$\begin{aligned}
 p_o &= p_1 + p_2 \\
 p_i &= p_2 - p_1
 \end{aligned} \quad (2)$$

(2) Timoshenko, S. - "Theory of Plates and Shells" - p.355-356, p. 373-374

(3) Lansford, W.M., "The Use of an Elbow in a Pipe Line for Determining Flow in the Pipe", Bull. 259, Dec. 1936, University of Illinois Experimental Station.

To obtain the force equations, the equilibrium equations⁽²⁾ must be satisfied.

$$\begin{aligned}\frac{\partial (r_0 N_\varphi)}{\partial \varphi} - N_\theta r_1 \cos \varphi &= 0 \\ \frac{\partial (r_0 N_\theta)}{\partial \varphi} + N_\theta \varphi r_1 \cos \varphi &= 0 \\ N_\varphi r_0 + N_\theta r_1 \sin \varphi &= p r_1 r_0\end{aligned}\quad (3)$$

Using the last of these equations N_θ can be eliminated so that from the first of equations (3) we obtain the differential equation

$$\frac{dN_\varphi}{d\varphi} + \left(\frac{1}{r_0} \frac{dr_0}{d\varphi} + \cot \varphi \right) N_\varphi = p r_1 \cot \varphi \quad (4)$$

Substituting in Equation (4) $p = p_1 \sin \varphi + p_2$, $r_0 = b + a \sin \varphi$, and $\frac{dr_0}{d\varphi} = a \cos \varphi$ and then solving; one finds that

$$N_\varphi = \frac{p_1 a \left[\frac{b}{2} \sin \varphi + \frac{a \sin^2 \varphi}{3} \right] + p_2 a \left[b + \frac{a}{2} \sin \varphi \right]}{(b + a \sin \varphi) + \frac{C_1}{\sin \varphi (b + a \sin \varphi)}} \quad (5)$$

Since all values of N_φ should be finite for all values of φ , C_1 vanishes. Simplifying Equation (5) and substituting $\frac{r_0 - b}{a} = \sin \varphi$ we obtain

$$N_\varphi = \frac{p_1}{6r_0} \left[(2r_0 + b)(r_0 - b) \right] + \frac{p_2 a}{2r_0} (r_0 + b) \quad (6)$$

Substituting N_φ into the third of Equations (3) and simplifying we find that

$$N_\theta = p_1 \left(\frac{4r_0 - b}{6} \right) + \frac{p_2 a}{2} \quad (7)$$

The shear force, $N_\theta \varphi$, may be obtained from the second of Equations (3). This equation may be simplified by substituting $r_1 = a$, $r_0 = b + a \sin \varphi$, and $\frac{dr_0}{d\varphi} = a \cos \varphi$ so that finally we obtain the solution:

$$N_\theta \varphi = \frac{C_2}{(b + a \sin \varphi)^2} \quad (8)$$

To determine the constant of integration C_2 , take the sum of the components of all forces acting on the half elbow in the direction of the horizontal radius in the plane $\theta = 0$ (Figure 3). This gives

$$\begin{aligned} & \int_0^{\pi/2} (N_{\theta\phi})_1 (a+b) \sin \phi \, d\theta + \int_0^{\pi/2} (N_{\theta\phi})_2 (b-a) \sin \theta \, d\theta \\ &= \int_0^{\pi/2} \int_{-\pi/2}^{\pi/2} a p \sin \phi \cos \theta (r_c) \, d\theta \, d\phi \\ \text{or } C_2 &= \frac{\pi}{4} \frac{a}{b} (p_1 b + p_2 a) (b^2 - a^2) \end{aligned} \quad (9)$$

Substituting this value into Equation (8), we obtain

$$N_{\theta\phi} = \frac{\pi a}{4b} \frac{(p_1 b + p_2 a) (b^2 - a^2)}{(b + a \sin \phi)^2} \quad (10)$$

Knowing the force equations one can compute stresses merely by dividing the forces by the shell thickness. However, in order to determine whether the elbow is safe from a stress viewpoint, one must first compute the principal stresses which may be calculated by means of the expression⁽⁴⁾

$$\sigma_1, \sigma_2 = \frac{\sigma_\phi + \sigma_\theta}{2} \pm \sqrt{\left(\frac{\sigma_\phi - \sigma_\theta}{2}\right)^2 + \tau_{\phi\theta}^2} \quad (11)$$

Employing the internal friction theory of failure,⁽⁴⁾ it is possible to determine whether the component is safe. In applying this criterion it is assumed that the welded joints may begin to fail before the rest of the structure, consequently, the working stresses for a weld (11,300 psi in tension and 15,000 in compression) are used. The expression is

$$\frac{\sigma_1}{\sigma_{wt}} = \frac{\sigma_2}{\sigma_{wc}} = 1 \quad (12)$$

Where σ_{wt} = working stress in tension

σ_{wc} = working stress in compression

According to the calculations, the maximum stress occurs on the inside surface of the elbow (B₁ C₁ Figure 1). Sample computations for locations at this surface are given in Appendix I corresponding to 102.4°C bulk outlet temperature.

(4) Marin, J., "Engineering Materials" - Prentice Hall - pp. 121, 142-144.

2. C-Reactor Approach

Since this component is a cylindrical shell, the pressure differential expression in Lansford's paper no longer applies. To arrive at an approximate pressure differential, momentum equations may be written and the resultant wall force, R , determined. By summing up pressures in the direction of R . (The reactor operating on only one downcomer)

$$\int_0^{2\pi} l p \cos \phi \, d\phi = R$$

$$\text{where } p = p_1 \cos \phi + p_2$$

$$\text{we find that } p_1 = \frac{R}{\pi l a} \quad (13)$$

This expression together with assumption (3) determines pressure components, p_1 and p_2 .

Force equations are obtained by solving the equilibrium equations⁽²⁾

$$\begin{aligned} \frac{\partial N_x}{\partial x} + \frac{1}{r} \frac{\partial N_{x\phi}}{\partial \phi} &= 0 \\ \frac{\partial N_{x\phi}}{\partial x} + \frac{1}{r} \frac{\partial N_\phi}{\partial \phi} &= 0 \\ N_\phi &= -Z r \end{aligned} \quad (14)$$

These forces are:

$$\begin{aligned} N_\phi &= p_2 a + p_1 a \cos \phi \\ N_{x\phi} &= -p_1 \left(\frac{l}{2} - x \right) \sin \phi \\ N_x &= \frac{p_1 x (l-x)}{2a} \cos \phi \end{aligned} \quad (15)$$

The calculations show that the maximum stress occurs at the locations D_1 and E_1 of Figure 2. Sample computations for locations at this surface are given in Appendix I corresponding to 105°C bulk outlet temperature. Again the same failure theory as used on the B-Reactor elbow was employed here.

3. Downcomer Components

a. Top Cover Plate

This component was treated as a plate with all edges built in or fixed.⁽²⁾ Maximum pressures were determined that induced stress at the weld equal to the working stress in tension. Sample computations are given in Appendix II for the plate in B-Reactor.

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b. Top Baffle Plate (or tray)

In order to determine pressures exerted on the plate due to momentum effects an impulsive force equal to $\frac{m}{g} V$ was assumed to act where V , is the velocity the instant before impact. This velocity includes not only the velocity in the approach section but the velocity of free fall from the approach section to the baffle. The same stress expressions encountered in the top cover plate analysis were used here. Sample computations are given in Appendix II for the baffle plate in B-Reactor.

c. Baffle Plate edge supports1. Beam

The beam has been assumed to carry approximately one-half the total load on the plate and to act like a beam fixed at both ends with a uniformly distributed load. The loading to which this beam may be safely subjected to is that loading giving a stress at the built in ends equal to the working stress of a weld in tension.

A method has been developed by Frankland⁽⁵⁾ for investigating the dynamic behavior of a structure. According to the method an equivalent static moment is defined as the product of a dynamic load factor (max. value of the ratio of actual moment to the static moment) and the peak impact load. The value of dynamic load factor (under a step function application of the load) for a simple beam was applied to the supporting beam to get an approximate idea of its behavior.

Sample calculations are shown in Appendix II.

2. Welded Connections

The welded joints supporting the beam appear to be the most critically loaded connections of the baffle. These welds have been assumed to fail in shear through the weld throat. Fillet weld capacity in shear (static loading) may be calculated by means of the expression

$$(13,600)(0.707)(T)l$$

Where T = size of fillet

l = length of weld

13,600 = shearing working stress⁽¹⁾

However, as a note of caution these joints have been assumed to be continuous in length. Sample calculations of a beam connection in B-Reactor is given in Appendix II.

(5) Frankland, J.M., "Effects of Impact on Simple Elastic Structures" S.E.S.A. Vol. VI, No. 2, 1948, p. 7-27.

APPENDIX I
Downcomer Approach Sections
Sample Computations

B-Reactor Approach Section:

102.4°C bulk outlet temperature
71,000 gal./min. - mass rate of flow

$$p_o - p_i = \frac{4a}{r_c} \frac{v^2}{2gv} = \frac{(4)(3.50)}{(3.70)} \frac{(138.3)^2}{(64.4)(144)(0.135)}$$

$$= 28.94 \text{ psig}$$

$$p_1 + p_2 = p_o, \quad p_2 - p_1 = p_i$$

$$p_o - p_i = 2p_1$$

$$p_1 = 14.47 \text{ psig}$$

$$p_2 - p_1 = 10 \text{ psig}$$

$$p_2 = 24.47 \text{ psig}$$

stresses on surface B₁ C₁:

$$\sigma_\phi = \frac{1}{t} \left[\frac{p_1}{6r_o} (2r_o + b)(r_o - b) + \frac{p_2 a}{2r_o} (r_o + b) \right]$$

$$= \frac{1}{3/16} \left[\frac{14.47}{(6)(23.4)} (46.8 + 44.4)(23.4 - 44.4) + \frac{(24.47)(21)}{(2)(23.4)} (23.4 + 44.4) \right]$$

$$\sigma_\phi = 2,917.6 \text{ psi}$$

$$\sigma_\theta = \frac{1}{t} \left[p_1 \frac{(4r_o - b) + p_2 a}{6} \right] = \frac{16}{3} \left[(14.47) \left(\frac{(4)(23.4)}{6} - 44.4 \right) + \frac{(24.47)(21)}{2} \right]$$

$$\sigma_\theta = 2,003.1 \text{ psi}$$

$$\tau_{\theta\phi} = \frac{1}{t} \left[\left(\frac{\pi a}{4b} \right) \left(\frac{p_1 b + p_2 a}{b - a} \right) (b + a) \right]$$

$$= \frac{16}{3} \frac{(\pi)(21)}{4(44.4)} \frac{(14.47)(44.4) + (24.47)(21)}{44.4 - 21} (44.4 + 21)$$

$$\tau_{\theta\phi} = 6,402.3 \text{ psi}$$

Principal stresses:

Equation (11)

$$\sigma_1, \sigma_2 = \frac{2,917.6 + 2,003.1}{2} \pm \sqrt{\left(\frac{2,917.6 - 2,003.1}{2} \right)^2 + (6,402.3)^2}$$

$$\sigma_1, \sigma_2 = 8,878.9, -3,958.3 \text{ psi}$$

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Failure criterion - Internal Friction Theory applied to Welds:

Equation (12)

$$\frac{8,878.9}{11,300} - \frac{-3958.3}{15,000} = 1$$

$$1.05 \approx 1$$

C-Reactor Approach Section:

105°C bulk outlet temperature, 96,000 gal./min. - mass rate of flow. (Operating on one downcomer). Wall force, R:

$R_x = 97,580$ lbs. from momentum equations (6)

$R_y = 97,570$ lbs.

$R = \sqrt{2}(97,580) = 138,000$ lbs.

Pressures:

Equation (13)

$$p_1 = \frac{138,000}{\pi (53.6) \frac{(53.625)}{2}} = 30.6 \text{ psi}$$

$$p_2 = 10 + p_1 = 40.6 \text{ psig}$$

stresses on surface B_1C_1 :

Equations (15) divided by shell thickness

$$\sigma_\phi = \frac{16}{3} \left[26.81 (40.6 + 30.6 \cos -90^\circ) \right] = 5,800 \text{ psi}$$

$$\tau_{x\phi} = -p_1 \left(\frac{l}{2} - x \right) \sin \phi = -\frac{16}{3} \left[(30.6) \frac{(53.6)}{2} \sin (90^\circ) \right]$$

$$= 4,370 \text{ psi}$$

$$\sigma_x = 0$$

Principal stresses:

$$\sigma_1, \sigma_2 = \frac{5,800}{2} \pm \sqrt{\left(\frac{5,800}{2} \right)^2 + (4,370)^2} = 8,140 \text{ psi},$$

$$-2,340 \text{ psi}$$

Failure Criterion

Equation (12)

$$\frac{8,140}{11,300} - \frac{-2,340}{15,000} = 0.876 < 1$$

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APPENDIX II
Downcomer Components

Top Cover Plate

B-Reactor

$$d/c = \frac{6.96}{5.15} = 1.35$$

$$\sigma_c = \frac{6 M_c}{t^2}$$

$$M_c = 0.0706 w c^2$$

$$= \frac{(6)(0.0706) w (5.15)^2 (144)}{(1/2)^2}$$

$$\sigma_c = 6,500 w \text{ (direction of dimension } c \text{)}$$

$$\sigma_c \leq \sigma_{w_t}$$

$$w = \frac{11,300}{6,500} = 1.74 \text{ psi (max. pressurization allowed - gage)}$$

Top Baffle Plate (or tray)

B-Reactor

$$\text{Applied force exerted on top plate} = \frac{\dot{m} V}{g}$$

$$= \frac{(9860)(141)}{32.2}$$

$$= 43,200 \text{ lbs.}$$

$$\text{Pressure on plate} = \frac{43,200}{5,311.9} = 8.14 \text{ lb/in}^2$$

$$\text{Stress in plate: } d/c = \frac{63.6}{14.52} = 4.38$$

$$\sigma_c = \frac{(6)(0.1003) w (14.52)^2}{(3/8)^2}$$

$$= 905 w$$

$$w = \frac{11,300}{905} = 12.5 \text{ psi}$$

∴ The capacity of plate is greater than the applied pressure.

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Baffle Plate Edge Supports:

1. Beam

$$\sigma = \frac{M}{Z} = \frac{W'}{12} \frac{(6.96)(12)}{175.4} = 11,300 \text{ psi.}$$

$$W' = 2.85 \times 10^5 \text{ lbs}$$

$$Z = 175.4 \text{ in}^3 \text{ section modulus}$$

$$\begin{aligned} \text{Load capacity of plate, } W &= 2(2.85 \times 10^5 - 529) & W' &= \text{Uniform load (capacity)} \\ & & & \text{transmitted to beam} \\ &= 568,900 \text{ lbs.} & M &= \text{Bending moment} \end{aligned}$$

$$529 = \text{wt. of beam}$$

$$\text{Pressure capacity of plate, } w = \frac{568,900}{5,311.9} = 107 \text{ psi}$$

∴ The capacity of beam is greater than the load applied.

Dynamic study of beam:

$$\text{dynamic load factor} = 2$$

$$\text{Applied loads } W_{eq.} = (2) W'$$

$$\text{Equivalent pressure on plate} = (2) (8.14) = 16.28 \text{ psi}$$

The capacity of beam 107 psi, is greater than the applied dynamic load.

2. Welded Connection:

At ends of beam

$$\begin{aligned} \text{Capacity} &= (13,600) (0.707) (3/16) (82.88) \\ &= 149,000 \text{ lbs.} \end{aligned}$$

$$\text{Subtracting wt. of beam} = 2 (149,000) - 529 = 297,471 \text{ lbs.}$$

$$\text{Capacity of plate, } w = \frac{(2) (297,471)}{5,311.9} = 112.0 \text{ psi}$$

The capacity of this connection is greater than the applied load.

Similar calculations have been made for the downcomer components in C-Reactor. (Operating on one downcomer).

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Figure 1. B Reactor Approach Section

Figure 3. B Reactor Approach Section

SECTION A-A

Figure 2. C Reactor Approach Section

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