APPENDIX 6.2C

DECLASSIFICATION OF FAN COOLER DUCTWORK: HEAT AND STEAM REMOVAL AND CONTAINMENT MIXING

Objective

After a Design Base Accident (DBA), the fan cooler ductwork may not survive if it does not meet the requirement of Safety Class II and Seismic Class I. This investigation is to illustrate the capability of the fan cooler system to carry out the function of containment heat and steam removal without the consideration of ductwork.

Assumptions

The air steam mixture discharged from the fan cooler will be considered as submerged turbulent jet; the analytical treatment of the jet with regard to mixing and momentum transfer is based on the jet theories [1, 2, 3,]*. Furthermore, the containment spray enhances the mixing process by the wake action which will also be included in this analysis. Also assumed is a complete severance of the duct at the junction of the classified to nonclassifed ductwork following the fan exhaust.

Inputs [4]

Q	=	Fan cooler capacity after accident = 44000 CFM
A	=	Discharge opening area = 8 x 8 = 64 ft^2
R_f	=	Radius of containment space for unobstructed jet flow = 40 ft
R_c	=	Primary containment radius = 70 ft
R_d	=	Direct distance from the fan discharge to the containment wall = 98 ft
Q_w	=	Containment spray flow rate = 1750 gpm
d_w	=	Spray drop size = 700µ
V_w	=	Droplet terminal velocity = 8.36 fps
C_d	=	Drag coefficient = 0.5
θ	=	Angle between jet flow and spray flow = 45°
η	=	Spray coverage factor = 0.95

Analysis

We can assume a round jet at the discharge even if the initial cross-section is square [3]. So we have:

r_o = equivalent round jet radius, ft

Since

$$r_o^2 \pi = A$$

thus

$$r_o = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{64}{\pi}} = 4.51 ft.$$

*Reference numbers

We define:

x_H = length of the initial region, distance along the jet axis from the discharge plane to the point beyond which the jet velocity on the axis begins to change.

x_H can be calculated from [1]:

$$\frac{x_H}{r_o} = 8$$

or $x_H = 8 \; x \; 4.51 = 36.1 ft$. which is within the unobstructed zone.

Also we define:

U_o = initial jet veolictity

U_m = velocity on the jet axis

U_c = velocity based on the mass averaged over the entire jet cross – section

with:

$$Uc = \frac{\int_{\circ}^{A} \rho U^2 \; d \; A}{\int_{\circ}^{A} \rho U \; d \; A}$$

where:

ρ = density

U = velocity

At the end of the initial region where the main region is assumed to begin, the universal velocity profile is valid and that leads to: [1, 2,]:

U_c = .52 U_m

In the initial region

U_m = U_o

with

$$U_o = \frac{Q}{A} = \frac{44{,}000}{64 \text{ x } 60} = 11.46 \text{ fps;}$$

accordingly, at the end of the initial region

$U_C = 0.52 \times 11.46 = 5.96$ fps.

Due to the fact that the momentum and heat content of the jet remain unchanged, the following relation is obtained for turbulent jet [1]:

$$\frac{\Delta T_c}{\Delta T_o} = \frac{U_c}{U_o}$$

also from the similarity of heat and mass transfer [1]:

$$\frac{\Delta X_c}{\Delta X_o} = \frac{\Delta T_c}{\Delta T_o}$$

where

$$\Delta T_o = T_o - T_a$$
$$\Delta T_c = T_c - T_a$$
$$\Delta X_o = X_o - X_a$$
$$\Delta X_c = X_c - X_a$$

with

T_o = initial jet temperature
T_a = ambient gas temperature
T_c = mass averaged temperature over the jet cross-section
X_o = initial concentration of certain species of the jet
X_a = ambient concentration of the same species
X_c = mass averaged concentration over the jet cross-section

T_c and X_c are defined in a manner similar to U_c:

$$T_c = \frac{\int_\circ^A \rho\, U\, T\, d\, a}{\int_\circ^A \rho\, U\, d\, a} \qquad X_c = \frac{\int_\circ^A \rho\, U\, X\, d\, A}{\int_\circ^A \rho\, U\, d\, A}$$

with

T = temperature

X = concentration

We then conclude:

$$\frac{\Delta X_c}{\Delta X_o} = \frac{U_c}{U_o}$$

Since the containment atmosphere is made up of air and steam, the initial density of the jet differs from that of the surrounding medium by the effects of cooling and condensation through the cooler. The percentage decrease in density is found less than 15 percent which is based on the output from the containment analysis. This value represents approximately the initial steam concentration difference:

$$\Delta X = -0.15$$

the minus sign indicates defect. At the end of the initial region, one can find:

$$\frac{\Delta X_c}{\Delta X_o} = \frac{U_c}{U_o} = 0.52$$

Within the free space zone, the concentration deficiency is down to half of what it was initially. This is true also for the temperature defect. The effect of containment spray is investigated next.

B. Containment Spray

The interaction between the jet and the spray is studied here. Defining

N = drop number density

N can be found by the continuity relation between spray flow rate and pump rate:

$$N \frac{\pi}{6} d_W^{\pi} \; V_W \; \pi \; R_C^2 \; \eta = Q_W$$

or

$$N = \frac{Q_w}{\frac{\pi}{6} d_w^3 \; V_w \; \pi \; R_c^2 \; \eta}$$

$$= \frac{1750 \times 0.13368 / 60}{\frac{\pi}{6}\left(700 \times 10^{-6} \times 3.28\right)^3 \times 8.36 \times \pi \chi 70^2 \times 0.95}$$

= 5032 drops/ft^3

The interaction between the jet and the droplet motion can be found through the momentum exchange; the momentum flux gain by the jet in the transverse direction must be equal to the total drag force to the droplets in the same direction. The result is [2]:

$$V_s^2 = \frac{C_d}{2} \left(V_w \mathrm{Cos}\theta\right)^2 N \left(\pi \frac{d_w^2}{4}\right)$$

$$V_s = \left[\frac{0.5}{2} \times 5032 \times \pi \frac{\left(700 \times 10^{-6} \times 3.28\right)^2}{4}\right]^{1/2} \times 8.36 \times \cos 45^\circ = 0.427 \text{ fps}$$

where

V_S = transverse velocity gain by the jet

However, the momentum transfer is dissipative, namely, it contributes to the mixing of the jet with its surrounding through the wake of the drop. V_S represents approximately the turbulence fluctuation supplied to the jet by the spray.

$$\sqrt{\overline{V_s'^2}} \approx V_s = 0.427\,fps$$

where

$\sqrt{\overline{V_s'^2}} =$ turbulence fluctuation in the jet contributed by the spray; we also define:

$\sqrt{\overline{\ '^2}} =$ transverse turbulence fluctuation of the jet; it is observed that [1]:

$$\sqrt{\frac{\overline{V'^2}}{U_m}} \approx 0.1$$

In the initial region, $U_m = U_o$

therefore

$$\sqrt{\overline{V'^2}} \approx 0.1 \text{ x } 11.46 = 1.15 \text{ fps}$$

The ratio of the turbulence fluctuation due to spray to that due to the jet alone is

$$\frac{\sqrt{\overline{V_s'^2}}}{\sqrt{\overline{\ '^2}}} \approx \frac{0.427}{} = 0.37$$

Thus, the spray increases the mixing rate about 37 percent . At this point, it is felt that the mixing in the main region of the jet should also be considered since it can extend beyond the initial region. If the jet can reach to containment wall directly, the jet center velocity is found to be [1]:

$$\frac{U_m}{U_o} = \frac{12.4^{ro}}{R_d}$$

or Um = 12.4 x 4.51 x 11.46/98 = 6.54 fps

the turbulence fluctuation is

$$\sqrt{\overline{V'^2}} \approx 0.1\, x\, 6.54 = 0.654\,fps$$

and the ratio of fluctuations

$$\frac{\sqrt{\overline{V_S'^2}}}{\overline{V'^2}} \approx \frac{0.427}{0.6545} = 0.652$$

The spray can increase the mixing rate by 65.2 percent at this distance. Without the spray, the concentration ratio is

$$\frac{\Delta X_c}{\Delta X_o} = \frac{U_c}{U_o} = \frac{0.5U_m}{U_o} = 0.285$$

with the spray, the concentration ratio can be reduced to:

$$\frac{\Delta X_c}{\Delta X_o} \approx \frac{\left.\frac{\Delta X_c}{\Delta X_o}\right|_{\text{no spray}}}{1 + \frac{\sqrt{\overline{V_s'^2}}}{\overline{V'^2}}} = \frac{0.285}{1 + 0.653}$$

$$= 0.172$$

or $\Delta X_c \approx 0.172 \text{ x } (-0.15) = -0.026 \approx -0.03$

we can conclude that the concentration difference is reduced below 3 percent. This situation should be considered sufficiently mixed.

<u>Conclusion</u>

The fan cooler without ductwork will assure adequate mixing in association with the spray inside the containment. Interference between the fan cooler discharge and solid object in its path will result in further enhancement of mixing through wake action. Any form of natural circulation within the containment will also increase the mixing process. The arrangement of the fan cooler discharge without ductwork ring headers and the strength of the jet will assure the ejected cool air to be mixed well with the ambient air before it is drawn in the cooler inlet. We can conclude that the fan cooler will perform the heat and steam removal functions as designed.

<u>References</u>

1. Abramovich, G.N., "The Theory of Turbulent Jets", MIT Press, 1963

2. Schlichting, H., "Boundary Layer Theory," Mc Graw Hill, 1968.

3. duPlessis, M.P., Wang, R.L. and Kahawita, R.,"Investigation of the Near-Region of a Square Jet," Journal of Fluid Engineering, Trans. ASME, Vol. 96, 1974.

4. Drawings [LOU-1564] G-146, G-854, G-855, G-856 (6/15/76).