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A Research Report for Westinghouse Hanford Company

Test Plan

Characterization of Jet Forces Upon Waste Tank Components

J. A. Bamberger

January 1992

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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Richland, Washington 99352

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SUMMARY

Westinghouse Hanford Company plans to install mixer pumps in double-shell waste tanks to mobilize and suspend settled sludge to allow eventual retrieval for treatment and permanent storage. The mixer pumps produce high momentum, horizontally directed jets that impact and mobilize the sludge and mix it into slurry for removal. There is concern that the force of the jet may damage tank internal components in its path.

This test plan describes scaled experiments designed to characterize the velocity profiles of a near floor jet and to quantify the impact forces and drag coefficients of three tank components: radiation dry well, airlift circulator, and steam coil.

The experiments will be conducted in water, at approximately 1/6-scale, using one stationary nozzle to simulate the jet.

To measure and confirm the velocity profile of the free, submerged jet, the horizontal and vertical velocity profiles will be measured at several distances from the nozzle. The profile will also be measured after the jet impinges upon the tank floor to determine the extent of the change in the profile caused by impingement.

The jet forces upon the test articles will be measured at a maximum of four velocities and a variety of test article orientations. Each orientation will represent a unique position of the test article relative to the jet and the tank floor. In addition, the steam coil will be tested in three rotational orientations because it is not symmetric. The highest jet velocity will be selected so that the Reynolds number of the test article in the model will match that of the prototype when operating at design conditions.

The forces measured upon the model components will be used to calculate the force on the prototype components using geometric scaling factors. In addition, the model force measurements will be used to calculate the component's drag coefficient as a function of the component Reynolds number.

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1.0 INTRODUCTION

Double-shell tanks are used to store high-level radioactive wastes generated at Hanford. Eventually the waste will be removed from the tanks and processed into a containerized waste form suitable for long-term storage. Mixer pumps will be installed in the double-shell tanks to mobilize and suspend settled sludge layers as a first step towards retrieving the tank contents. The mixer pumps produce strong horizontally directed jets that resuspend the sludge and mix it into a slurry for removal. There is concern that the force of the high-velocity liquid jet from the pump nozzles may damage tank internal components that it impacts.

Several analyses to calculate the jet forces upon tank components have been conducted. In the most detailed, Pacific Northwest Laboratory (PNL)(a) analyzed the jet forces impacting the tank components using an integrated velocity profile that takes into account jet tangential impingement upon the tank floor and open literature drag coefficients. However, some questions still need to be answered to bound the uncertainty of this analysis, such as the level of turbulence intensity of the jet that affects the drag coefficient and the effect of the change in jet velocity profile after it tangentially impinges upon the tank floor.

To verify the approach and quantify the uncertainties associated with the force calculations, a set of scaled experiments will be conducted to measure jet velocity profiles, to quantify the forces upon tank components, and to calculate the tank component drag coefficients.

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1.1 OBJECTIVES

The objectives of this study are to

1. measure and confirm the velocity profile of a submerged liquid jet used in the test apparatus,
2. measure the steady jet forces upon four scaled tank components (test articles) at a specified number of distances and angular orientations from the jet origin,
3. determine the drag coefficients of the test articles over a range of Reynolds numbers,
4. use the test article force data and appropriate scaling factors to calculate the forces upon the prototype^(a) tank components, and
5. verify or adapt a mathematical model developed to estimate these jet forces as a function of component location and orientation in the submerged jet.

The waste tank components to be modeled through scaled experiments include the radiation drywell, airlift circulator with a thermocouple extension, steam coil, and thermocouple assembly.

1.2 SCOPE

The experiments will be conducted in water, at approximately 1/6-scale, using one stationary nozzle to simulate the jet.

To measure and confirm the velocity profile of the free, submerged jet, the jet horizontal and vertical velocity profiles will be measured at several distances from the nozzle. The profile will also be measured after the jet impinges upon the tank floor to determine the extent of the change in the profile caused by impingement. The flow rate, fluid properties, and flow turbulence intensity will be measured. In addition, the angle of expansion of the jet will be verified.

(a) In this test plan, "prototype" means the full-scale 75-ft diameter, double-shell tanks and associated equipment utilized to store waste at Hanford.

The jet forces upon the test articles will be measured at a maximum of four velocities and a variety of test article orientations. Each orientation will represent a unique position of the test article relative to the jet and the tank floor. In addition, the steam coil will be tested in three rotational orientations because it is not symmetric. The highest jet velocity will be selected so that the Reynolds number of the test article in the model will match that of the prototype when operating at design conditions. The other three velocities will be scaled at reduced nozzle $U_0 d$ (a) values over a range of four to one. Data will be analyzed as they are received, to determine whether the scope of the test matrix, i.e., the need to test at four jet velocities, can be reduced to include only two or three jet velocities.

The forces measured upon the model components will be used to calculate the force on the prototype components using geometric scaling factors. In addition, the model force measurements will be used to calculate the component's drag coefficient as a function of the component Reynolds number.

The component drag coefficients and force data obtained during the experiments will be used to update the assumptions used in the calculational code for the range of available data.

1.3 EXPERIMENT LIMITATIONS

The purpose of the test plan is to define the experiments required to accomplish the research objectives and scope defined in Sections 1.1 and 1.2. During the definition of the scope, additional items were addressed but excluded from the research scope presented here. These limitations to the scope are detailed briefly below.

Jet Angle. All experiments will be conducted with a horizontal jet. Prototype pump specifications permit the jet angle to vary from +0 degrees to -3 degrees from the horizontal. At a later time tests with a jet angle of -3 degrees may be of merit.

(a) $U_0 d$ is the product of nozzle exit velocity (U_0) and nozzle diameter (d).

Jet Visualization. Limited dye injection and photography may provide horizontal and vertical portraits of the jet shape, which may be useful to view the jet spreading configuration after it has impinged upon or grazed the model floor. No flow visualization is planned in this scope of work.

Jet Half Angle of Expansion. The jet half angle of expansion is a function of the fluid kinematic viscosity. By altering the fluid temperature or by changing the test fluid the dependence of jet half angle of expansion upon kinematic viscosity could be observed from the velocity profiles. This is not within the current scope.

Fluid Properties. The experiment is designed to model the provided prototype operating conditions. The results will only be applicable over the range of U_{0d} values investigated (7.5 to 29.4 ft²/s in the prototype). Because the experiments are being performed over a range of nozzle U_{0d} values, the results could be used over a range of kinematic viscosity (μ/ρ) from 25% to 100% of the current design point. This would address uncertainties in the prototype density and viscosity at the design point.

Model Temperature and Density Changes and Gradients. No attempt will be made to establish temperature or density gradients within the test tank. Fluid temperatures in the loop piping and tank will be stabilized using the cool down heat exchanger integral to the test loop.

Tank Flow Patterns. The model tank design is baffled to provide a stagnant pool simulation. No attempts to measure tank flow patterns or flow recirculation/entrainment will be made. To determine how recirculation patterns affect the jet forces upon the test articles, additional tests could be designed with the tank baffles removed and/or oriented to promote flow recirculation. These tests could be used to determine how recirculation patterns influence the jet. In addition numerical simulation of the jet dynamic interaction may be considered.

Model and Prototype Flow Rate to Volume Ratio. Calculations show that the ratio of tank entrainment to total volume for the model is encompassed by

that of the prototype because the prototype tank depth may vary from 30 to 4 ft. However, the model fluid has a greater flow/turbulence energy density than the prototype. This is not considered a serious experimental limitation because the energy is dissipated in the model through well placed flow baffles. In addition the model false floor divides the tank into two flow regions; this will permit additional energy dissipation in the lower tank section where the flow is directed by turning vanes.

Turbulence Intensity. The current test will limit turbulence intensity by designing the nozzle and supply piping to provide a uniform flow field. If required, a separate test could be conducted to increase the turbulence intensity of the jet by either placing a screen to distort flow from the nozzle, or by designing a very short radius nozzle, such as a hole in the side of the supply piping. The effects of turbulence intensity upon the component drag coefficient could be investigated.

Mechanical Cycling and Dynamic Forces. The current test configuration will only determine the static force on and drag coefficient of the test articles. An additional potential failure mode for the prototype components is dynamic stress caused by cycling. By designing a mechanically similar component as well as a geometrically similar component, the question of cycling failure could be addressed. Although no measurements of dynamic forces are planned, some idea of the frequency of dynamic force may be observed from the real time plots of the force measurement. However, because the velocity profile of the jet is three-dimensional, destructive interference may prevent oscillations from occurring.

Airlift Circulator End Effects. The model airlift circulator is located above the jet centerline. Because the airlift circulator is a hollow cylinder, end effects of flow rising into the center of the cylinder may affect the force upon the cylinder. To quantify this effect, a test configuration where the airlift circulator extends through the jet was proposed. This would be compared with a test in which the cylinder free end is at the center of the jet. This configuration is not in the current scope.

1.4 TEST PLAN ORGANIZATION

Modeling of the jet and the forces produced by the jet is discussed in Section 2.0. The experimental design and instrumentation requirements, and test conditions are presented in Sections 3.0 and 4.0, respectively. Data accuracy, analysis, and calculational code predictions are addressed in Sections 5.0 and 6.0. Quality assurance aspects are addressed in Section 7.0.

2.0 MODELING THE JET AND JET FORCES

Modeling the submerged jet and the forces it produces on internal tank components is addressed in this section. The physical problem is described in Section 2.1. Similarity issues, drag force, and submerged jet flow equations are presented in Sections 2.2, 2.3, and 2.4. The prototype and model parameters are defined in Section 2.5 and 2.6.

2.1 BACKGROUND

The waste storage tank retrieval system that will be installed and tested by Westinghouse Hanford Company (WHC) includes two pumps located near the floor of the cylindrical tank (offset from the tank vertical centerline). Each pump has two opposed jets. The pumps each rotate unsynchronized through a 190 degree arc. Suction occurs at the base of each pump.

The waste tanks contain many fixed components: airlift circulators, radiation drywells, thermocouple assemblies, and a steam coil. These components, at varied distances from the pump, are impacted by the jets if they are submerged in the liquid cone of the jet. The force with which the jet impacts these components must be quantified.

The jet is also influenced by its proximity to the floor. As the distance from the nozzle increases, the jet tangentially impinges on (grazes) the floor. The impingement changes the jet velocity profile and, therefore, alters the force at which it impacts the tank components.

Interaction of the four jets may cause fluid circulation patterns that enhance and/or interfere with the jet profile and the force each jet imparts upon the tank internal components. To complicate tank circulation patterns, the tank liquid volume is gradually decreased with time by removing liquid from the tank.

A scaled experiment is planned to model the jet forces upon the tank components. The data from this experimental model will be used to scale the forces upon the waste tank components and to determine the components' drag coefficients. The data will also be used to verify a calculational model.

Constraints to ensure equivalent drag coefficients between the experimental model and the prototype are not the same as those constraints required to ensure similarity between the experimental model and the computer code. The effects of jet interaction are currently not quantified for the prototype. The computer code models only one jet in a quiescent pool, thereby ignoring the influence of tank circulation patterns, and calculates the force on an object from one jet that flows through a quiescent fluid. The experimental model will limit the bulk fluid motion in the test vessel by using baffles to emulate the quiescent conditions assumed by the computer model.

2.2 SIMILARITY

Model studies are based on similarity between the model and the prototype. For complete similarity between the model and the prototype, geometric, kinematic, and dynamic ratios must be considered. Geometric similarity exists when the ratios of corresponding dimensions of the prototype and model are equal. Of major importance are the prototype and model component diameter and length, and the jet diameter at point of component impact. The ratio of the model and prototype tank volume is of lesser importance.

Kinematic similarity exists when the time aspects of the problem (flow streamlines of the prototype and model) are proportional. Kinematic ratios may be governed by acceleration, velocity, and volumetric flow rate and include oscillation frequencies.

Dynamic similarity exists between the model and the prototype when forces are proportional. Fluid forces include inertial, viscous, gravitational, pressure, centrifugal, elastic, surface, and vibrational.

For the jet forces analysis, inertial, viscous, and pressure forces are dominant. These forces can be characterized by the Reynolds number (Re), (inertia/viscous force ratio, $\rho U d/\mu$); pressure coefficient (C_p) [pressure/inertia force ratio, $P/(\rho U^2)$]; and by the Strouhal number (inertia/vibration force ratio). Because the jet velocity profile follows a Gaussian distribution instead of a constant velocity, no single Strouhal number is representative, so the Strouhal number is not expected to be of major concern.

Parameters to be considered in this analysis are summarized in Table 2.1.

2.3 DRAG FORCE

When a fluid impinges on an object, the undisturbed fluid pressure (P) and the velocity (U) change. The result of fluid impingement is to create a

TABLE 2.1. Parameters of Interest

<u>Test Factor</u>	<u>Geometric Parameters</u>
Nozzle exit:	nozzle diameter, d_0 nozzle centerline distance from the floor, h
Bulk flow:	size of the tank, volume jet half angle of expansion, θ
Test article:	diameter, d_{cyl} jet width, d_{jet} jet impingement area
<u>Test Factor</u>	<u>Kinematic Parameters</u>
Nozzle exit:	jet volumetric flow rate, Q
Bulk flow:	jet velocity profile, U fluid kinematic viscosity, μ/ρ
<u>Test Factor</u>	<u>Dynamic Parameters</u>
Bulk flow:	fluid density, ρ fluid dynamic viscosity, μ mass flow rate, m power imparted to bulk fluid
Test article:	force on test article, F

pressure acting normal to every point on the projected surface of the object. In addition, a frictional force, $F_f = \tau_0 A_s$, tangential to the entire surface area, A_s , opposes the jet motion. The sum of these forces gives the resultant force, R , acting on the object. The resultant force R is resolved into the drag component, F_d , parallel to the flow and lift component, F_l , perpendicular to the fluid motion.

Because the drag, F_d , and lift, F_l , forces may be considered independently,

$$F_d = C_d \rho U^2 A/2 \quad (1)$$

$$F_l = C_l \rho U^2 A/2 \quad (2)$$

where the drag coefficient, C_d , and the lift coefficient, C_l , are functions of Reynolds number; characteristic area, A ; and surface roughness. Because drag force arises from two sources the pressure or shape drag, F_p , and the skin-friction drag, F_f , caused by wall shear stress, τ_0 , the drag coefficient is made up of two parts

$$F_d = F_p + F_f \quad (3)$$

$$= C_d \rho A U^2/2 \quad (3a)$$

$$= C_p \rho A U^2/2 + C_f \rho A_s U^2/2 \quad (3b)$$

$$\text{or } C_d = C_p + C_f A_s/A \quad (4)$$

where C_p is the pressure coefficient, C_f is the skin-friction coefficient, and A_s is the characteristic area for shear. For cylinders or spheres in cross-flow, the frictional drag force is generally negligible relative to the pressure drag force.

For cylinders, the drag coefficient decreases at high Reynolds numbers. This reduction is attributed to the turbulence present in the fluid boundary layer. The increased level of turbulence delays the separation of the flow from the cylinder wall; therefore, the wake zone is smaller and more pressure recovery occurs behind the object. The wake converts flow energy into mixing turbulence and ultimately, heat.

The drag coefficient is also a function of the surface roughness and the free stream turbulence because these parameters affect the boundary layer separation mechanism. Literature data are not consistent with respect to the quantitative effects of free stream turbulence or its effect upon drag coefficient (Cheremisinoff 1986). Therefore, in this analysis the drag coefficient is assumed to be a function of Reynolds number, characteristic area, surface roughness, and turbulence intensity. This can be expressed as

$$C_d = f(Re, d, l, \epsilon/d, TI) \quad (5)$$

where Re = Reynolds number at the test article
 d = test article diameter in jet profile
 l = test article length in jet profile
 ϵ/d = relative roughness of test article
 TI = turbulence intensity.

Using Equation (3a) to describe the drag force, the ratio of the drag forces between the model, F_m , and the prototype, F_p , is

$$\frac{F_m}{F_p} = \frac{C_{dm} \rho_m U_m^2 A_m}{C_{dp} \rho_p U_p^2 A_p} \quad (6)$$

Fluid properties for the prototype and model are known at the design point, and test article dimensions can be scaled. The jet velocity profiles of the model and the prototype can be scaled by equating the Reynolds number at

relative model and prototype locations. Assuming that surface roughness can be scaled and that turbulence intensities in the model and prototype will be similar, the drag coefficient of the model can be assumed equal to that of the prototype ($C_{d_m} = C_{d_p}$), by equating the Reynolds number at the test article. This relationship allows a direct calculation of the force on the prototype from the measured force on the model without actually knowing the drag coefficients.

$$F_p = \frac{F_m \rho_p U_p^2 A_p}{\rho_m U_m^2 A_m} \quad (7)$$

2.4 SUBMERGED JET FLOW

A turbulent jet that discharges into and spreads through the same medium is said to be submerged. The jet discharges fluid with a relatively uniform initial velocity into a nonmoving surrounding fluid of the same density. The tangential shear layer at the jet boundary is a site of intense mixing and causes eddies to form and mix the two regions of fluid. The mixing produces an increase in the jet cross-sectional area. A submerged jet entrains surrounding fluid and expands as the entrained fluid becomes part of the jet. Momentum is transferred to the entrained fluid during the entrainment-mixing process. This decreases the average jet velocity and results in a distribution, or profile, of time-mean velocity across the jet. In the waste tank, the liquid flow past the test article is caused by a turbulent, submerged jet.

The jet, with nozzle diameter d_0 , can be characterized by three regions: 1) a potential core, within 4 to 8 nozzle diameters from the nozzle wherein the jet centerline velocity equals the nozzle exit velocity, 2) the mixing region where the jet flow is fully established and the jet diameter expands at a relatively constant angle, and 3) a transitional region between the other two regions where the jet diameter expands at a changing rate and angle

(Ivanov, Klochkov and Kozlov 1977) (see Figure 2.1). In the mixing region of the jet, the velocity profile remains similar as if the flow had originated from a point source at $x = -a$, behind the nozzle outlet.

In this analysis, the velocity at any point within the submerged, free jet (assuming no interaction with a component or wall) is assumed to be a function of Reynolds number, the jet angle of expansion, the distance from the nozzle, and the distance from the jet centerline. This can be expressed as

$$U = f(Re, \theta, x/d_0, r) \quad (8)$$

where θ = jet half angle of expansion
 x/d_0 = normalized distance from nozzle
 r = distance from jet centerline.

Three expressions are required to describe the turbulent, submerged jet:
 1) jet half angle of expansion, θ ; 2) the centerline velocity profile, U_c ;
 and 3) the radial velocity profile, $U_{r,c}$.

FIGURE 2.1. Diagram of Submerged Jet

2.4.1 Jet Half Angle of Expansion

An empirical expression relating the jet half angle of expansion and the kinematic viscosity of the jet fluid was observed by Donald and Singer (1959).

$$\tan \theta = 0.238 \nu^{0.133} \quad (9)$$

where θ is the jet half angle of expansion and ν is the kinematic viscosity of the fluid in Stokes. The relationship was deduced using data from four Newtonian fluids: water, sugar solution, air, and hydrogen flowing into air. Kinematic viscosities for these four fluids range from 0.01 to 1.0 Stokes, three orders of magnitude, and the fluids include both liquids and gases. Therefore, the relationship should be valid to quantify the angle of expansion of the prototype waste tank slurry (assumed Newtonian because of the large fraction of water in it) and the model fluid, water.

2.4.2 Jet Centerline Velocity Models

The centerline velocity of a jet can be described by a hyperbola, when the velocity is plotted as a function of the distance from the nozzle. The peak velocity beyond x_c , the point where the jet flow is fully established, can be calculated by the formulas listed in Table 2.2, where a = distance behind origin, d_0 = nozzle diameter, K = diffusion constant, x = distance from nozzle exit, and b = empirical constant usually $0.07 < b < 0.08$.

2.4.3 Jet Radial Velocity Models

Radial velocity profiles within the established flow region of the jet may be characterized by a Gaussian profile as presented in Table 2.3, where r = the radial distance from jet centerline and σ_x = the radial distance from the centerline to the point at which velocity U_x is equal to the root mean square of the jet velocity profile at point x along the centerline of the jet.

TABLE 2.2 Jet Centerline Velocity Equations

Centerline to Exit Velocity Ratio U_c/U_o	K Diffusion Constant	Reference
$K d_o/x$	--	Rouse 1958
$K d_o/(x + a)$	--	Hinze 1959
$K d_o/x$	6.325	Forstall and Gaylord 1955
$\frac{K d_o}{2 b x + 0.29 d_o}$	0.96	Abramavich 1963

TABLE 2.3 Jet Radial Velocity Equations

Radial to Centerline Velocity Ratio U_r/U_c	Reference
$\exp[-2(K r/x)^2]$	Rouse 1958
$\exp\{-2[K r/(x + a)]^2\}$	Hinze 1959
$\exp[(-r/\sigma_x)^2/2]$	Albertson et al. 1948

2.4.4 Jet Velocity Equations Used in the Analysis

To remain consistent with the analytical model, the same selection of centerline and radial jet velocity equations are used to determine the initial design specifications for the experimental investigation. The experimental data will be examined to determine the appropriate equation for the data analysis. After experimental data are available, this selection will be reevaluated.

2.4.4.1 Jet Centerline Velocity Equation

The diffusion constant, K, has been shown to range from 5.7 to 6.8 for air and water jets over a range of Reynolds numbers. Forstall and Gaylord

(1955) showed that a water jet peak velocity has the same form and follows closely the formula for air given by Rouse (1958).

$$\frac{U_c}{U_o} = 6.4 \frac{d_o}{x} \quad (10)$$

2.4.4.2 Jet Radial Velocity Equation

Theory indicates that the same K applies to both the jet centerline and to the jet radial velocity distribution formulas. The Gaussian distribution functions that correlate the jet radial velocity profile involve the diffusion constant in the term, $2K^2$. A large value of K represents a velocity profile that peaks more in the center. A low K value represents a velocity that spreads more widely. A velocity distribution with a low K value will produce higher forces on impinged objects than a distribution with a higher K because a higher average velocity is distributed onto the impacted area. Using a value of 6.4 for K, the resulting radial distribution is

$$\frac{U_r}{U_c} = \exp[-81.92(r/x)^2] \quad (11)$$

where $2K^2 = 81.92$. Equation (11) is used to predict the jet radial velocity distribution for the test conditions evaluated in this test plan.

2.4.4.3 Combined Centerline and Radial Velocity Profile

Equations (10) and (11) combine to form

$$\frac{U_r}{U_o} = 6.4 \frac{d_o}{x} \exp[-81.92(r/x)^2] \quad (12)$$

that predicts the radial velocity distribution as a function of the nozzle U_o and the distance from the nozzle and from the centerline.

2.5 PROTOTYPE

The waste tank and pump/jet configuration is presented in Figure 2.2. Each pump is to be designed to provide jet-like outlet flow with two jets; one on each side of the pump. The tank geometry and mixing pump specifications are listed in Table 2.4.

The tank internal components to be impacted by the rotating jets include radiation drywells, airlift circulators, mixer pumps, steam coil, and thermocouple assemblies. These components are located at various distances from the pump nozzle and at various heights above the tank floor. The configurations are listed in Table 2.5 and the Appendix.

2.5.1 Design Basis

The characteristics of the slurry during operation and the operating specification and design of the pump define the prototype design point. The slurry properties and jet design basis are listed in Table 2.6. No uncertainty intervals are specified for the slurry properties or for the jet design point. Although the prototype nozzle diameter may vary from 4 to 8 in., a nozzle

FIGURE 2.2. Tank, Pump, and Jet Arrangement

TABLE 2.4. Tank and Mixing Pump Data

Tank Geometry	
diameter	75 ft
distance, pump centerline to tank wall	15.5 ft
fluid depth	
final	4 ft
initial	30 ft
Mixing Pump Dimensions	
nozzle diameter	4 to 8 in.
distance, tank bottom to jet centerline	12 to 18 in.
distance, pump centerline to nozzle discharge	17.5 in.
diameter, pump intake	36 in.
distance, tank floor to pump intake	6 to 7 in.
Jet Properties	
U_{0d}	29.4 ft ² /s
discharge angle from vertical	90 degrees +3, -0

diameter of 6 in. was selected as the design value, because this diameter corresponds closely to the anticipated size of the actual pump nozzle. The selection of the nozzle diameter for the test is not critical, however, because fluid jets providing equivalent sludge resuspension can be produced from various nozzles by holding the U_{0d} product constant.

2.6 MODEL

To model the prototype jet force upon the test article, several criteria must be satisfied: 1) the Reynolds number of the model must equal that of the prototype at the test article, and 2) the following model/prototype ratios must remain constant: test article diameter to jet diameter, jet height above the floor to jet diameter, test article offset from jet centerline, and nozzle

TABLE 2.5. Tank Component Arrangement

Test Article	Height Above Floor, in.	Distance from Pump Centerline(a), ft	Article Configuration
Radiation drywell	3	12.80, 23.28, 25.30 26.14, 33.42, 51.96, 53.30, H-2-67314(b)	cylinder 6 in. Schedule 40 pipe diameter 6.625 ± 0.066 in.(c)
Airlift circulator (ALC)	30	5.05 to 48.99 H-2-67349(b)	cylinder 30 in. Schedule 10 pipe diameter 30.000 ± 0.300 in.(c)
ALC guide extension	3	3.71 to 50.29	cylinder 3/4 in. Schedule 40 pipe diameter 1.050 $+1/64$ $-1/32$ in.(c)
Mixer pump	3 at screen 6 at intake	44.00	cylinder 39 in. at nozzle 36 in. at body 16 in. at upper pump support
Steam coil	18	16.18, 38.81 H-2-68339(b)	three coiled cylinders, 2.375 ± 0.024 in. diameter coil 40 3/8 in. maximum diameter 22, 30, 38 ± 0.5 in. helix diameter, 4 in. staggered pitch, I-beam support framework
Thermocouple assembly	3 ^(d)	10.79 to 54.69 H-2-68339(b)	

- (a) The distance from the pump centerline to the nozzle outlet is 17.5 in. For additional information and tolerances see Appendix.
- (b) Reference drawing number.
- (c) Pipe diameter tolerance from ASME SA-53.
- (d) This distance varies with the assembly design.

TABLE 2.6. Prototype Design Basis

Slurry Properties	
density, ρ	1.2 g/cm ³ , 74.9136 lbm/ft ³
viscosity, μ	2 cP, 1.3439x10 ³ lbm/ft-s
jet half angle of expansion, $\theta^{(a)}$	7.86 degrees
Jet Design Basis	
U_{od}	29.4 ft ² /s
nozzle diameter, d_o	6 in.

(a) Calculated using Equation (9).

diameter to jet diameter. The parameters are defined in Figure 2.3 and the relationships are listed below:

$$Re_m = Re_p \quad (13)$$

$$\left(\frac{\rho U d}{\mu}\right)_m = \left(\frac{\rho U d}{\mu}\right)_p \quad (13a)$$

$$\frac{d_{cyl}}{d_{jet}} = \text{constant} \quad (14)$$

$$\frac{h}{d_{jet}} = \text{constant} \quad (15)$$

$$\frac{off}{d_{jet}} = \text{constant} \quad (16)$$

$$\frac{d_o}{d_{jet}} = \text{constant} \quad (17)$$

where h is the height and off is the offset from the jet centerline.

FIGURE 2.3. Model Diagram

To equate the Reynolds number of the model with that of the prototype, fluid properties and jet velocity may be varied. To minimize fluid handling problems, water was chosen as the test fluid. Because the viscosity of water and density, to a lesser degree, decrease as the temperature rises, testing at an elevated temperature increases the Reynolds number and reduces the total flow rate and pumping requirements. With a prototype nozzle diameter range of 4 to 8 in. and a 1/6-scale experiment, a number of operating conditions at temperatures from 60 to 111°F were reviewed. These operating conditions are summarized in Table 2.7. The preferred operating temperature still within safe operating limits is 111°F. If the loop pump heat is adequate, the experiments will be conducted at this temperature; if not, the temperature will be controlled in the range from 100 to 111°F. A separate heat exchange circuit will be used to maintain the operating temperature to within $\pm 1.0^\circ\text{F}$.

2.6.1 Design Point

Water and expected jet properties at the operating temperature of 111°F are listed in Table 2.8.

2.6.2 Methodology

The experimental approach will be to match the component Reynolds number of the prototype and the model at the component centerline (Equation 13 and

TABLE 2.7. Comparison of Operating Conditions at Various Temperatures for Prototype and 1/6-Scale Model Using Water

Temp., F	Nozzle diam., in.	Nozzle Reynolds Number	U d, ft/s	Exit Velocity, ft/s	Flow Rate, gpm	Pump Pressure 1/2 ρU^2 , psi	Nozzle Reaction Force, lbf	Pump Head at Temp, ft	Fluid Properties	
									Density, lbm/ft ³	Viscosity, lbm/ft-s
<u>Prototype</u>										
220	4.00	1638810	29.4	88.2	3456	62.9	1581	120.9	74.91	1.3439E-03
220	6.00	1638810	29.4	58.8	5182	28.8	1581	53.7	74.91	1.3439E-03
220	7.00	1638810	29.4	50.4	6046	20.6	1581	39.5	74.91	1.3439E-03
220	8.00	1638810	29.4	44.1	6909	15.7	1581	30.2	74.91	1.3439E-03
<u>Model</u>										
80	0.67	1789437	16.8	298	325	598	417	1383	62.22	5.7825E-04
80	1.00	1789437	16.8	199	487	286	417	615	62.22	5.7825E-04
80	1.17	1789437	16.8	170	568	195	417	452	62.22	5.7825E-04
80	1.33	1789437	16.8	149	649	149	417	346	62.22	5.7825E-04
100	0.67	1844649	13.8	245	266	401	280	931	62.00	4.5690E-04
100	1.00	1844649	13.8	163	399	178	280	414	62.00	4.5690E-04
100	1.17	1844649	13.8	140	466	131	280	304	62.00	4.5690E-04
100	1.33	1844649	13.8	122	532	100	280	233	62.00	4.5690E-04
111	0.67	1872473	12.3	222	241	329	230	768	61.85	4.0727E-04
111	1.00	1872473	12.3	148	362	148	230	340	61.85	4.0727E-04
111	1.17	1872473	12.3	127	423	107	230	250	61.85	4.0727E-04
111	1.33	1872473	12.3	111	483	82	230	191	61.85	4.0727E-04

13a), while using Equation (10) to calculate the jet centerline velocity from the nozzle conditions. Equation (18) provides the ratio of the model test component diameter to the scaled distance from the nozzle:

$$\frac{d_{cyl,m}}{x_m} = \frac{U_{op} d_{op} d_{cyl,p} \mu_m \rho_p}{U_{om} d_{om} x_p \mu_p \rho_m} \quad (18)$$

The diameter of the jet at the test component can be calculated from the jet half angle of expansion, θ .

$$d_{jet} = 2 \times \tan \theta \quad (19)$$

TABLE 2.8. Basis for Experimental Design

Fluid Properties	
temperature, T	111°F
density, ρ	0.9907 g/cm ³ , 61.8467 lbm/ft ³
viscosity, μ	0.6067 cP, 4.0727×10^{-4} lbm/ft-s
jet half angle of expansion, $\theta^{(a)}$	6.89 degrees
Jet Design Point	
Reynolds number at test article centerline	equal to that of prototype
nozzle diameter, d_0	1.00 in.

(a) Calculated from Equation (9).

Substitution of Equation (19) into Equation (14) yields:

$$\frac{d_{cyl,m}}{x_m} = \frac{d_{cyl,p}}{x_p} \frac{\tan\theta_m}{\tan\theta_p} \quad (20)$$

Equations (18) and (20) are combined to determine the model design condition

$$U_{om} d_{om} = \frac{U_{op} d_{op} \tan\theta_p \mu_m \rho_p}{\tan\theta_m \mu_p \rho_m} \quad (21)$$

The model operating flow rate is calculated from Equation (21).

The height of the model above the tank floor, h_m , and the offset distance of the test article past the jet centerline, off_m , can be scaled as shown below using Equations (19) and Equations (15) through (17):

$$\frac{h_m}{x_m} = \frac{h_p \tan\theta_m}{x_p \tan\theta_p} \quad (22)$$

$$\frac{\text{off}_m}{x_m} = \frac{\text{off}_p \tan \theta_m}{x_p \tan \theta_p} \quad (23)$$

$$\frac{d_{om}}{x_m} = \frac{d_{op} \tan \theta_m}{x_p \tan \theta_p} \quad (24)$$

2.6.3 Demonstration of Methodology

To demonstrate the effect of matching the Reynolds number of the model and the prototype at the centerline of the jet velocity profile comparisons of the Reynolds numbers and drag coefficients across the profile have been made for the three test articles. These comparisons are shown in Table 2.9. Fluid properties for the prototypes and models are listed in Tables 2.6 and 2.8. The Reynolds number for the prototype and the model are equal at the test article centerline; at the edge of the cylinders, the Reynolds number of the model is 44% greater than that of the prototype. Over most of the jet width, the drag coefficients for the prototype and the model match very well. The cumulative effect of the drag coefficient variation between the model and the prototype is very slight.

TABLE 2.9. Reynolds Number Comparison over the Test Article for Prototype and Model

Test Article		Radial Position		Reynolds Number		% Difference	Drag Coefficient (a)		% Difference
Radial Position, ft	Velocity, ft/s	Prototype	Model	Prototype	Model		Prototype	Model	
Prototype	Model	Prototype	Model	Prototype	Model	Prototype/Model	Prototype	Model	Prototype/Model
<u>Radiation Drywell, 2.89 ft from model nozzle</u>									
1.52	0.25	3.59	11.39	110446	159165	44	1.26	1.26	0
1.21	0.20	8.30	17.52	193773	244826	26	1.18	1.10	7
0.91	0.15	9.75	24.50	300040	342224	14	0.98	0.98	2
0.61	0.10	13.32	31.12	410028	434715	6	0.50	0.54	4
0.30	0.05	18.07	35.92	494531	501812	1	0.50	0.49	2
0.00	0.00	17.11	37.08	526406	526406	0	0.40	0.40	0
<u>Airlift Circulator, 2.89 ft from model nozzle</u>									
1.52	0.25	3.59	11.39	500135	720748	44	0.50	0.33	34
1.21	0.20	8.30	17.52	877461	1108645	26	0.36	0.36	0
0.91	0.15	9.75	24.49	1358673	1549691	14	0.36	0.36	0
0.61	0.10	13.32	31.11	1856730	1968521	6	0.36	0.36	0
0.30	0.05	18.07	35.91	2239386	2272358	1	0.36	0.36	0
0.00	0.00	17.11	37.07	2383723	2383723	0	0.36	0.36	0
<u>Steam Coil, 2.78 ft from model nozzle</u>									
2.02	0.34	2.70	8.58	507128	730825	44	0.50	0.33	34
1.61	0.27	4.74	13.20	889731	1124149	26	0.36	0.36	0
1.21	0.20	7.35	18.45	1377673	1571362	14	0.36	0.36	0
0.81	0.13	10.04	23.44	1882695	1996049	6	0.36	0.36	0
0.40	0.07	12.11	27.06	2270702	2304135	1	0.36	0.36	0
0.00	0.00	12.89	28.38	2417057	2417057	0	0.36	0.36	0
<u>Radiation Drywell, 4.76 ft from model nozzle</u>									
3.45	0.58	1.58	5.01	48598	70032	44	1.26	1.26	0
2.78	0.40	2.77	7.71	85260	107723	26	1.26	1.26	0
2.07	0.35	4.29	10.78	132018	150578	14	1.26	1.26	0
1.38	0.23	5.86	13.69	180412	191275	6	1.18	1.18	0
0.69	0.12	7.07	15.80	217594	220797	1	1.15	1.14	1
0.00	0.00	7.53	18.58	231618	231618	0	1.12	1.12	0
<u>Airlift Circulator, 5.71 ft from model nozzle</u>									
4.14	0.69	1.32	4.18	183383	264273	44	1.18	1.05	11
3.31	0.55	2.31	6.42	321736	406503	26	0.95	0.50	41
2.49	0.41	3.57	8.98	498100	560220	14	0.50	0.28	44
1.66	0.28	4.89	11.41	680801	721791	6	0.33	0.34	3
0.83	0.14	5.89	13.17	821108	833198	1	0.36	0.36	0
0.00	0.00	8.27	13.81	874032	874032	0	0.36	0.36	0
<u>Steam Coil, 5.71 ft from model nozzle</u>									
4.14	0.69	1.32	4.18	246003	355068	44	1.10	0.80	27
3.31	0.55	2.31	6.42	433003	547088	26	0.65	0.30	45
2.49	0.41	3.57	8.98	670467	764730	14	0.32	0.34	6
1.66	0.28	4.89	11.41	910245	971410	6	0.36	0.36	0
0.83	0.14	5.89	13.17	1105075	1121348	1	0.36	0.36	0
0.00	0.00	8.27	13.81	1176301	1176301	0	0.36	0.36	0

(a) Allemann, R. T. 1989. Analytical Evaluation of Jet Mixer Forces on Equipment in Waste Tanks. ESD-88-113
Pacific Northwest Laboratory, Richland, Washington, May.

3.0 EXPERIMENT DESIGN

The experimental design is presented in Section 3.0. The experimental facility, the tank configuration, and the instrumentation are described in Sections 3.1, 3.2, and 3.3, respectively. The models of the test articles are described in Section 3.4. Test article construction and placement specifications are listed in Section 3.5.

3.1 FACILITY DESCRIPTION

The experiments will be conducted in the 189D thermal hydraulic test facility, which includes a 3000-gal, 8-ft diameter recirculation tank. The facility provides three pumps: one with 500-gpm capacity at 1387 ft of head (600 psi), and two with 100-gpm capacity at 1155 ft of head (500 psi). The 500-gpm pump will be adequate for the tests. Operating conditions using a 1.00-in. diameter nozzle (1/6-scale experiment) show the flow rate will be about 360 gpm at 340 ft of head (see Table 2.7). A flow diagram for the facility is shown in Figure 3.1.

FIGURE 3.1. Experimental Facility Flow Diagram

The facility includes a cool down heat exchanger circuit to regulate the loop water temperature. Pump heat introduced to the closed loop will be used to elevate the loop temperature. The design point operating temperature is 111°F.

An in-line turbine flowmeter on the pump discharge line and an orifice flowmeter on the pump suction line will be used to monitor flow rate.

3.2 TANK CONFIGURATION

The 3000-gal tank is 8 ft in diameter and 9 ft high, with the tank overflow line 2 in. from the tank top and recirculation line at the tank bottom. To regulate flow circulation patterns, a test section floor will be installed 3 ft from the tank upper rim. The floor will be used to model the prototype tank floor. The model nozzle, suspended along the side of the tank, will be oriented toward the center of the tank. The distance between the nozzle and the tank floor will be varied from 2 to 3 in., by lowering the model false floor, to model the prototype nozzle elevations of 12 and 18 in. above the prototype tank floor.

The tank false floor will not be attached to the tank perimeter; an annular space around the edge of the tank will allow fluid to flow from the lower section of the tank for flow entrainment into the expanding jet. The annulus is sized to limit velocities to <3 ft/s. At the tank edge directly opposite from the nozzle, turning vanes will direct the jet to the lower portion of the tank.

3.2.1 Bulk Flow Baffling

To dissipate flow energy movable baffles will be placed in the upper portion of the tank. The baffles will be oriented to restrict circulation patterns with the upper portion of the tank and create a still pool around the jet to provide fluid for radial entrainment within the jet. The flow rate/tank volume ratio of the model is 360/3321, 0.108 gpm/gal. The ratio

for the prototype (two pumps, each with two nozzles) is $4(5182)/991435 = 0.0209$ gpm/gal. Therefore, the model will be baffled to dissipate flow energy and to restrict flow circulation patterns. To observe the effects of the still pool upon the jet characteristics, additional tests without the baffles could be planned to determine whether recirculation patterns influence the jet.

3.2.2 Nozzle and Jet

The model piping and nozzle are designed to provide uniform flow at the nozzle exit. The inlet piping is 4 in. Schedule 40 in OD followed by a 4 x 2 in. eccentric reducer, 2-in. long radius elbow and a 2 x 1 in. bell reducer; the nozzle, tapered at the inlet, is 1.00 in. ID. The jet velocity profiles obtained using this nozzle configuration can be compared to prior experiments in which the nozzle was fed through an annulus that modeled the mixer pump geometry to determine whether the uniformity of flow field effects jet behavior. One of the objectives of the jet forces experiment is to provide a well characterized, and therefore predictable, jet.

3.3 INSTRUMENTATION

3.3.1 Measurement and Test Equipment

A list of measurement and test equipment, its location, and accuracy is provided in Table 3.1.

3.3.2 Jet Velocity Measurement

The jet velocity profile will be characterized using a cone-shaped hot film anemometer. The sharp tip conical sensor provides a rugged contamination-resistant probe. Detail of the sensor tip is shown in Figure 3.2. The

TABLE 3.1. Instrumentation and Test Articles

Instrumentation	Accuracy		Location
	As Received	After Calibration	
Temperature thermocouple	$\pm 2^{\circ}\text{F}$	$\pm 0.5^{\circ}\text{C}$ $\pm 1.0^{\circ}\text{F}$	nozzle supply line mid-tank behind test article
Flow rate turbine flowmeter orifice ^(a)	$\pm 2\%$ $\pm 4\%$	$\pm 0.5\%$ $\pm 4\%$	pump discharge line only for indication pump suction line
Velocity hot film anemometer	$\pm 5\%$	No change	
Turbulence intensity ^(b) hot film anemometer	$\pm 20\%$	No change	
LVDT (Linear Variable Displacement Transformer)	± 0.075 in.	No change	
Axial load cell	$\pm 0.23\%$ full scale ^(c)		
Transverse load cell	$\pm 0.23\%$ full scale ^(c)		
Nozzle diameter	± 0.05 in.	± 0.001 in.	
Radiation drywell diameter	± 0.005 in.	± 0.005 in.	
Airlift circulator diameter	± 0.01 in.	± 0.005 in.	
Steam coil diameter	± 0.01 in.	No change	

- (a) The orifice flowmeter will be calibrated in place using the turbine flowmeter.
- (b) Uncertainty in turbulence intensity is estimated from voltage characteristics.
- (c) Factory calibration may reduce product literature uncertainty values.

anemometer system will include the components listed in Table 3.2. The conical probe and temperature compensating unit can be calibrated by TSI, Inc., the manufacturer, to an accuracy of $\pm 2\%$ at near ambient conditions. In the proposed operating temperature range for these experiments (100 to 111°F), empirical relationships are available to permit extrapolation to within $\pm 5\%$ accuracy. For comparison, a pitot probe would provide accuracy of $\pm 50\%$ because of the instability associated with the low pressure drops.

FIGURE 3.2. Conical Probe Tip Detail, mm (in.)

TABLE 3.2. Anemometer System Components

TSI Model
1231W platinum hot film 90 degree conical probe
1310W standard temperature compensating probe
1323W resistance network temperature compensation box
1054B linearized anemometer system
1076 RMS voltmeter

The velocity signal will be averaged using an integrating voltmeter. In addition to velocity, the turbulence intensity [root mean square (RMS) value of velocity fluctuation] will be measured using an RMS voltmeter. The turbulence intensity will be used to characterize the test articles' drag coefficients.

3.3.3 Force Measurement

The force of the jet as it impacts the test article produces a moment that will be measured using a load cell attached to the test article support frame. The reaction points of the forces upon the test articles will be scaled based upon Allemann's calculations. Tension/compression load cells will be used to measure the axial and side forces upon the test articles. Load cell information is summarized in Table 3.3. The load cells are interchangeable; therefore, if a more precise measurement of an axial load is required, the cells can be switched.

3.3.4 Position

The positions of the test articles (x and y) and the velocity probe tip (x, y, and z) will be monitored using an x-y translation stage, which produces a signal output. The z component (height) will be recorded manually using a scale scribed on the anemometer mount. Resolution of the translation stage is ± 0.02 in.

TABLE 3.3. Load Cell Characteristics

<u>Load Cell</u>	<u>Range</u>	<u>Accuracy</u>
axial component	0 to 500 lbf	$\pm 0.2\%$ full scale
side component	0 to 50 lbf	$\pm 0.2\%$ full scale

3.3.5 Signal Processing

Output from the process variables (temperature and flow rate); velocity profiles (velocity component, turbulence measurement and probe location); force measurement (axial and side force); and test article location will be recorded using a Fluke data acquisition system. Some data, such as z position during the velocity profile measurements, will be manually input to the data acquisition system.

3.4 TEST ARTICLES

Three of the four test articles will be evaluated in these experiments: radiation drywell, airlift circulator, and steam coil. These articles are basically cylindrical in shape. Forces upon the airlift circulator are asymmetric because of the thermocouple guide extension, and forces upon the steam coil are asymmetric because of the horizontal I-beam orientation. The test article positions vary in distance from the jet origin and in depth of submergence within the expanding jet. The dimensions for the scaled test articles are shown in Table 3.4. The distance from the nozzle to the test article, x_m , is calculated using Equation (20).

3.4.1 Radiation Drywell

The radiation drywell cross section is relatively small compared to the diameter of the expanded jet. The model radiation drywell is a 1.104-in. diameter circular cylinder. The radiation drywell extends through the jet below the centerline of the nozzle.

3.4.2 Airlift Circulator

The model airlift circulator is a 5.000-in. diameter cylinder; airlift circulators range in distance from the nozzle from 0.7 to 9.1 ft. The airlift circulator base is 5 in. above the floor, above the centerline of the nozzle; at close distances to the nozzle the jet will pass under the airlift circulator base, producing no impact force.

TABLE 3.4. 1/6-Scale Dimensions for Test Articles

Test Article	Height Above Floor, in.	Distance from Nozzle, ft	Article Configuration
Radiation drywell	0.5	2.16 to 9.87	cylinder diameter 1.104 in.
Airlift circulator (ALC)	5	0.684 to 9.05 ^(a)	cylinder diameter 5.000 in.
ALC guide extension	0.5	0.468 to 9.27 ^(a)	cylinder diameter 0.175 in.
Steam coil	3	2.80 to 7.11	three coiled cylinders 6.729-in. maximum diameter 3.667-, 5.000-, 6.333-in. helix diameter 0.667-in. staggered pitch I-beam support framework
Thermocouple assembly	0.5	1.48 to 9.84 ^(a)	unspecified

(a) Maximum distance to be measured in experiment is 30 ft in the prototype or 5.7 ft in the model.

A thermocouple guide is attached to the perimeter of the airlift circulators at random orientation. The thermocouple guides extend through the centerline of the nozzle; therefore, at distances close to the nozzle, the jet will impact the thermocouple guide.

3.4.3 Steam Coil

The steam coil consists of three concentric helical coils, supported by two central vertical I-beams and a horizontal support I-beam. The helix diameters of the model coils are 3.667, 5.000, and 6.333 in. Because of the orientation of the I-beams within the coil, the jet may impact either the perpendicular, parallel, or an intermediately positioned cross section of the horizontal I-beam. The steam coil is located 3 in. from the tank floor and 2.8 ft and 7.11 ft from the nozzle outlet.

3.4.4 Thermocouple Assembly

Two designs of thermocouple assemblies have been specified. One consists of three spaced cylinders; the other consists of a cylinder with three stiffener plates, arranged in a tri-star pattern. Because of the thermocouple assemblies' proximities to the jet and their inability to withstand jet forces, these thermocouple assemblies will be removed from the tanks and replaced by thermocouple assemblies of a new (unspecified) design.

3.5 TEST ARTICLE CONSTRUCTION AND PLACEMENT SPECIFICATIONS

The test articles will be constructed to approximately 1/6-scale, using information supplied by the prints listed in Table 3.5. The following specific items also apply.

- The model dimensions and locations will be based upon nominal prototype dimensions and locations obtained from the prototype prints.
- The test articles will be constructed within the following tolerances
 - 0.XXX = +0.005 in.
 - 0.XX = +0.01 in.
 - 0.X = +0.06 in.
 - angles = +0 degrees 30 minutesunless otherwise specified.
- The surface root mean square finish of the model will be scaled at 1/6-scale from the prototype. (The surface finish of the prototype components is assumed to be the handbook value for new carbon steel pipe.)
- As-built dimensions of the test articles will be used for all calculations.

3.5.1 Steam Coil

The purpose of the steam coil model is to physically represent the major components of the steam coil that provide the main source of the component drag within the jet. The major sources of steam coil surface area, and hence

TABLE 3.5. Drawings Providing Prototype Dimensions and Locations

<u>Drawing Number</u>	<u>Title and Application</u>
H-2-38620, rev. 1	Coil assembly (Steam coil dimensions)
H-2-67314, rev. 1	Plan tank 101 penetrations & schedule 241-AZ tank farm (Locations for steam coil, radiation drywell, and airlift circulator)
H-2-67349, rev. 1	Airlift circulator and riser extension details (Dimensions are airlift circulator and radiation drywell)
H-2-68339, rev. 3	Instrumentation in-tank temperature and pressure assemblies plan & details (Dimensions and locations for thermocouple tree)

drag, are the coils and horizontal and vertical I-beams. Other components have only a small effect upon drag.

Components to be included in the model are

- three concentric steam coils
- horizontal I-beam including the I-beam webs
- two vertical I-beams, modeled as square cross-section solid members
- two outer coil supports.

Because of structural integrity requirements of the model, the webs of the horizontal I-beam will be thickened slightly. The web width and spacing will be 1/6-scale. Other components of the steam coil will not be modeled because these components are inside the coils and, hence, do not contribute significantly to the steam coil drag.

4.0 TEST CONDITIONS

In Section 4.0 the experimental test conditions for the model studies are described. The jet characterization test matrix is presented in Section 4.1; the force characterization test matrixes for the three test articles are presented in Section 4.2.

The dynamic operating condition of the prototype that dictates the model operating condition is the U_{0d} of the jet. The specification of the prototype dictates a U_{0d} of 29.4 ft²/s at a nozzle diameter ranging from 4 to 8 in. The test conditions presented in this section are based upon a prototype nozzle diameter of 6 in. To simulate a range of pump operating conditions and the resulting forces upon the components as well as to document the change of drag coefficient with Reynolds number, a range of U_{0d} values will be investigated during the experiments. Proposed prototype U_{0d} values range from 7.5 to 29.4 ft²/s. The prototype and model operating conditions for a 1/6-scale experiment bracketed by this range of U_{0d} values are listed in Table 4.1.

TABLE 4.1. Prototype and Model Operating Conditions at Various U_{0d}

<u>Velocity</u>	<u>Reynolds Number at Nozzle</u>	<u>U_{0d}, ft²/s</u>	<u>Exit Velocity, ft/s</u>	<u>Flow Rate, gpm</u>	<u>Pump Pressure $1/2 \rho U^2$, psi</u>	<u>Nozzle Reaction Force, lbf</u>	<u>Pump Head at Temperature, ft</u>
<u>Prototype, full scale 6-in. diameter nozzle, slurry at 220°F</u>							
U1	1638810	29.4	58.8	5182	28.0	1581	53.7
U2	1254191	22.5	45.0	3966	16.4	926	31.5
U3	836127	15.0	30.0	2644	7.3	411	14.0
U4	418064	7.5	15.0	1322	1.8	103	3.5
<u>Model, 1/6-scale 1.00-in. diameter nozzle, water at 111°F</u>							
U1	1872473	12.3	148	362	146	230	340
U2	1433015	9.4	113	277	86	134	199
U3	955343	6.3	75	185	38	60	89
U4	477672	3.1	38	92	10	15	22

4.1 JET CHARACTERIZATION

To fully characterize the jet, the parameters listed in Table 4.2 must be defined.

4.1.1 Velocity Profile

A hot film anemometer will be used to measure the jet axial and radial velocity profiles. The probe position will be controlled using a traversing table. First the jet centerline will be verified and the centerline velocity

TABLE 4.2. Parameters Required for Jet Characterization

<u>Nozzle</u>	
diameter, d_0	
distance from floor, h	
<u>Fluid properties</u>	
temperature, T	
density, ρ	
viscosity, μ	
flow rate, Q	
<u>Jet</u>	
type of fluid, Newtonian or nonNewtonian	
jet half angle of expansion, θ	
centerline velocity profile as a function of distance, U_c	
horizontal and vertical velocity profiles, U_r	
location of half peak velocity ^(a)	
point of floor tangential impingement	
jet profile beyond point of tangential impingement	
turbulence intensity	

(a) The radial position where the velocity is one half of the centerline velocity.

will be measured as a function of distance from the nozzle. After the centerline profile is characterized, the radial velocity profile will be charted in the horizontal and vertical planes at several distances from the nozzle (see Table 4.3). The anemometer probe is limited to measuring velocities less than 40 ft/s. This limits the measurements to a distance of 2 ft or greater from the nozzle at velocity U1.

The jet profile will be most fully characterized at velocity U1, which models the prototype design point. The jet centerline velocity will be measured at U2, U3, and U4. In addition, efforts will be made to determine the position of the radial half peak velocity that is also used to characterize the center of the jet. In the vertical direction, measurements will be made to estimate the point of jet contact with the tank floor. Jet radial velocity and Reynolds number across the jet half width at prototype distances from 5 to 30 ft from the nozzle outlet are listed in Table 4.4.

Turbulence intensity will be measured with every velocity measurement.

4.2 FORCE CHARACTERIZATION

The test matrix velocity U1 was selected to match prototype and model Reynolds number ($Re_p = Re_m$) at the jet centerline velocity. In addition tests

TABLE 4.3. Velocity Profile Locations

<u>Distance from Nozzle outlet, ft</u>		<u>Centerline Velocity</u>	<u>Radial Velocity</u>
<u>Prototype</u>	<u>Model</u>		
11	2.09	U1, U2, U3, U4	U1, U2, U3
18	3.43	U1, U2, U3	U1, U2
25	4.76	U1, U2	U1
30	5.71	U1	

TABLE 4.4 Radial Velocity and Reynolds Number at Velocity U1

	Jet Radius ft	Velocity ft/s	Test Article Reynolds Number
<u>Orywell</u>			
Distance from nozzle: 5 ft prototype	0.12	25.06	350162
0.95 ft model	0.09	38.55	538617
	0.07	53.89	752892
	0.05	68.46	956373
	0.02	79.02	1103987
<u>Airlift Circulator</u>			
Distance from nozzle: 11 ft prototype	0.25	11.39	720746
2.09 ft model	0.20	17.52	1108645
	0.15	24.49	1549691
	0.10	31.11	1968521
	0.05	35.91	2272358
	0.00	37.67	2383723
<u>Steam Coil</u>			
Distance from nozzle: 14.6 ft prototype	0.34	8.58	730825
2.78 ft model	0.27	13.20	1124149
	0.20	18.45	1571362
	0.13	23.44	1996049
	0.07	27.06	2304135
	0.00	28.38	2417057
<u>Orywell</u>			
Distance from nozzle: 25 ft prototype	0.58	5.01	70032
4.76 ft model	0.46	7.71	107723
	0.35	10.78	150578
	0.23	13.69	191275
	0.12	15.80	220797
	0.00	16.58	231618
<u>Airlift Circulator</u>			
Distance from nozzle: 25 ft prototype	0.58	5.01	317128
4.76 ft model	0.46	7.71	487804
	0.35	10.78	681864
	0.23	13.69	866149
	0.12	15.80	999838
	0.00	16.58	1048838

will be made at three lower velocities (U_2 , U_3 , and U_4) to vary the prototype U_0 by a factor of four. The velocity range will provide drag coefficient versus Reynolds number data for code verification purposes.

At maximum velocity, U_1 , in addition to the centerline force measurements, the test articles will be offset radially from the jet axis and the force upon the test article will be measured. Radial position for the asymmetric steam coil orientations will include displacement in both positive and negative direction. Symmetric test articles will be tested in only one displacement direction after the jet centerline position is known.

Measurements at lower velocities (U_2 , U_3 , and U_4) will be made at the angle of maximum force, i.e., the jet centerline. The experimental configurations are listed in Table 4.5 and the number of tests are summarized in Table 4.6. The pump and test article elevations above the tank floor and the distance of the test article from the jet nozzle for both the models and the prototypes are listed. The distance from the nozzle to the test article is constrained by the 8-ft diameter of the tank. The nozzle entrance region and piping require a minimum of 12 in. and the flow baffles for flow diversion require another foot of length. That allows a maximum distance between the nozzle outlet and the test article of 76 in. This corresponds to 33 ft in the prototype. To permit flow around the rear of the test article, the maximum test distance shown corresponds to a distance of 30 ft between the prototype nozzle outlet and test article centerline. Details of the test matrices for each test article are presented in the following sections.

4.2.1 Radiation Drywell

Projected radiation drywell test conditions are listed in Table 4.7. The preliminary calculations show that at a prototype distance of 11 ft, the jet will miss the radiation drywell at a prototype azimuthal angle of 10 degrees; this will be verified during the tests.

TABLE 4.5. Model and Prototype Experimental Configurations

Test Article	Elevation from Floor				Distance from	
	Nozzle Centerline, in.		Test Article, in.		Nozzle outlet(a), ft	
	Prototype	Model	Prototype	Model	Prototype	Model
Radiation drywell	18	3	3	0.5	5, 11 18, 25	0.95, 2.09 3.43, 4.76
Airlift circulator	18	3	30	5	5, 11 18, 25 30	0.95, 2.09 3.43, 4.76 5.71
Steam coil ^(b,c)	12	2	18	3	14.6, 30	2.79, 5.71
	18	3	18, 54	3, 9	14.6, 30	2.79, 5.71
Thermocouple assembly	18	3	3	0.5	11, 18 25	2.09, 3.43 4.76

(a) The prototype nozzle outlet is 17.5 in. from the pump centerline.

(b) Three I-beam orientations, parallel, perpendicular, and 45 degree angle to the flow at velocity U1.

(c) At velocities U2, U3, and U4 the force measurements will be taken with the I-beam perpendicular to the flow.

TABLE 4.6. Number of Experimental Configurations

	Number of Combinations	
	U1	U2, U3, U4 ^(d)
Radiation drywell	4	12
Airlift circulator	5	15
Steam coil	<u>12</u>	<u>12</u>
Total	21	39

(d) Measurements made at angle of maximum force, approximately 0 degrees.

TABLE 4.7. Radiation Drywell Test Conditions

Distance From Nozzle, ft		Azimuthal Angle, degrees		Jet Half Width, ft	Test Article Radius, ft	Jet Offset Centerline, ft	Azimuthal Test Article Jet Overlap, ft		Height Above Floor, ft		Vertical Test Article Jet Overlap, ft		Jet Impacts Test Article
Prototype	Model	Prototype	Model	Model	Model	Model	Model	Y/N	Model	Model	Model	Y/N	Y/N
5	0.95	0	0.00	0.12	0.0460	0.00	0.16	yes	0.25	0.0417	0.32	yes	yes
5	0.95	5	4.38	0.12	0.0460	0.07	0.09	yes	0.25	0.0417	0.32	yes	yes
5	0.95	10	8.77	0.12	0.0460	0.15	0.01	yes	0.25	0.0417	0.32	yes	yes
5	0.95	-5	-4.38	0.12	0.0460	-0.07	0.09	yes	0.25	0.0417	0.32	yes	yes
5	0.95	-10	-8.77	0.12	0.0460	-0.15	0.01	yes	0.25	0.0417	0.32	yes	yes
11	2.09	0	0.00	0.25	0.0460	0.00	0.30	yes	0.25	0.0417	0.46	yes	yes
11	2.09	5	4.38	0.25	0.0460	0.16	0.14	yes	0.25	0.0417	0.46	yes	yes
11	2.09	10	8.77	0.25	0.0460	0.32	-0.02	no	0.25	0.0417	0.46	yes	no
11	2.09	-5	-4.38	0.25	0.0460	-0.16	0.14	yes	0.25	0.0417	0.46	yes	yes
11	2.09	-10	-8.77	0.25	0.0460	-0.32	-0.02	no	0.25	0.0417	0.46	yes	no
18	3.43	0	0.00	0.41	0.0460	0.00	0.46	yes	0.25	0.0417	0.62	yes	yes
18	3.43	5	4.38	0.41	0.0460	0.26	0.20	yes	0.25	0.0417	0.62	yes	yes
18	3.43	10	8.77	0.41	0.0460	0.53	-0.07	no	0.25	0.0417	0.62	yes	no
18	3.43	-5	-4.38	0.41	0.0460	-0.26	0.20	yes	0.25	0.0417	0.62	yes	yes
18	3.43	-10	-8.77	0.41	0.0460	-0.53	-0.07	no	0.25	0.0417	0.62	yes	no
25	4.78	0	0.00	0.58	0.0460	0.00	0.62	yes	0.25	0.0417	0.78	yes	yes
25	4.78	5	4.38	0.58	0.0460	0.36	0.26	yes	0.25	0.0417	0.78	yes	yes
25	4.78	10	8.77	0.58	0.0460	0.73	-0.11	no	0.25	0.0417	0.78	yes	no
25	4.78	-5	-4.38	0.58	0.0460	-0.36	0.26	yes	0.25	0.0417	0.78	yes	yes
25	4.78	-10	-8.77	0.58	0.0460	-0.73	-0.11	no	0.25	0.0417	0.78	yes	no

4.2.2 Airlift Circulator

The airlift circulator includes a thermocouple guide that extends along the side of the cylinder. The airlift circulator test matrix will include positions where either the circulator or thermocouple guide extension is impacted by the jet. Projected airlift circulator and thermocouple guide extension test conditions are listed in Tables 4.8 and 4.9. The preliminary calculations show that at a prototype distance of 5 ft the jet will pass under the airlift circulator. At a prototype distance of 25 ft the jet will miss the airlift circulator at a prototype azimuthal angle of 15 degrees. The preliminary calculations show that the jet will miss the thermocouple guide

TABLE 4.8. Airlift Circulator Test Conditions

Distance from Nozzle, ft		Azimuthal Angle, degrees		Jet Half Width, ft		Test Article Radius, ft	Jet Offset Centerline, ft	Test Article- Jet Overlap, ft		Height Above Floor, ft		Test Article- Jet Overlap, ft	Jet Impacts Test Article
Prototype	Model	Prototype	Model	Model	Model	Model	Model	Model	Y/N	Model	Model	Model	Y/N
5	0.95	0	0.00	0.12	0.4187	0.00	0.53	yes	0.25	0.4187	-0.05	no	no
5	0.95	5	4.38	0.12	0.4187	0.07	0.46	yes	0.25	0.4187	-0.05	no	no
5	0.95	10	8.77	0.12	0.4187	0.15	0.38	yes	0.25	0.4187	-0.05	no	no
5	0.95	15	13.15	0.12	0.4187	0.22	0.31	yes	0.25	0.4187	-0.05	no	no
11	2.00	0	0.00	0.25	0.4187	0.00	0.87	yes	0.25	0.4187	0.00	yes	yes
11	2.00	5	4.38	0.25	0.4187	0.18	0.51	yes	0.25	0.4187	0.00	yes	yes
11	2.00	10	8.77	0.25	0.4187	0.32	0.35	yes	0.25	0.4187	0.00	yes	yes
11	2.00	15	13.15	0.25	0.4187	0.40	0.18	yes	0.25	0.4187	0.00	yes	yes
18	3.43	0	0.00	0.41	0.4187	0.00	0.83	yes	0.25	0.4187	0.25	yes	yes
18	3.43	5	4.38	0.41	0.4187	0.28	0.57	yes	0.25	0.4187	0.25	yes	yes
18	3.43	10	8.77	0.41	0.4187	0.53	0.38	yes	0.25	0.4187	0.25	yes	yes
18	3.43	15	13.15	0.41	0.4187	0.80	0.03	yes	0.25	0.4187	0.25	yes	yes
25	4.78	0	0.00	0.58	0.4187	0.00	0.99	yes	0.25	0.4187	0.41	yes	yes
25	4.78	5	4.38	0.58	0.4187	0.35	0.63	yes	0.25	0.4187	0.41	yes	yes
25	4.78	10	8.77	0.58	0.4187	0.73	0.28	yes	0.25	0.4187	0.41	yes	yes
25	4.78	15	13.15	0.58	0.4187	1.11	-0.12	no	0.25	0.4187	0.41	yes	no

extension at a prototype azimuthal angle of 10 degrees; these calculations will be verified during the experiments. The combined test matrix for the airlift circulator-thermocouple guide extension tube combination is listed in Table 4.10. For this analysis, the extension tube is assumed to be located at the leading edge of the circulator. In actuality, it could be located at any angular orientation. However, at the leading edge it will receive the largest force.

4.2.3 Steam Coil

Projected steam coil test conditions at 14.6 ft from the prototype nozzle outlet are listed in Table 4.11. (Tests will also be conducted at 30 ft from the prototype nozzle outlet.) The preliminary calculations show that the jet will impact the steam coil at all projected test positions. Because the steam

TABLE 4.9. Airlift Circulator Thermocouple Guide Extension Test Conditions

Distance from Nozzle, ft		Azimuthal Angle, degrees		Jet Half Width, ft		Test Article Radius, ft		Jet Offset Centerline, ft		Horizontal Test Article-Jet Overlap, ft		Vertical Height Above Floor, ft		Test Article-Jet Overlap, ft		Jet Impacts Test Article	
Prototype	Model	Prototype	Model	Model	Model	Model	Model	Model	Y/N	Model	Y/N	Model	Model	Model	Y/N	Model	Y/N
3.75	0.71	0	0.00	0.09	0.0104	0.00	0.10	yes	0.25	0.0417	0.29	yes	yes				
3.75	0.71	5	4.38	0.09	0.0104	0.05	0.04	yes	0.25	0.0417	0.29	yes	yes				
3.75	0.71	10	8.77	0.09	0.0104	0.11	-0.01	no	0.25	0.0417	0.29	yes	no				
3.75	0.71	15	13.15	0.09	0.0104	0.17	-0.07	no	0.25	0.0417	0.29	yes	no				
9.75	1.88	0	0.00	0.22	0.0104	0.00	0.23	yes	0.25	0.0417	0.43	yes	yes				
9.75	1.88	5	4.38	0.22	0.0104	0.14	0.09	yes	0.25	0.0417	0.43	yes	yes				
9.75	1.88	10	8.77	0.22	0.0104	0.29	-0.05	no	0.25	0.0417	0.43	yes	no				
9.75	1.88	15	13.15	0.22	0.0104	0.43	-0.20	no	0.25	0.0417	0.43	yes	no				
16.75	3.19	0	0.00	0.39	0.0104	0.00	0.40	yes	0.25	0.0417	0.59	yes	yes				
16.75	3.19	5	4.38	0.39	0.0104	0.24	0.15	yes	0.25	0.0417	0.59	yes	yes				
16.75	3.19	10	8.77	0.39	0.0104	0.49	-0.10	no	0.25	0.0417	0.59	yes	no				
16.75	3.19	15	13.15	0.39	0.0104	0.75	-0.35	no	0.25	0.0417	0.59	yes	no				
23.75	4.52	0	0.00	0.55	0.0104	0.00	0.56	yes	0.25	0.0417	0.75	yes	yes				
23.75	4.52	5	4.38	0.55	0.0104	0.35	0.21	yes	0.25	0.0417	0.75	yes	yes				
23.75	4.52	10	8.77	0.55	0.0104	0.70	-0.14	no	0.25	0.0417	0.75	yes	no				
23.75	4.52	15	13.15	0.55	0.0104	1.06	-0.50	no	0.25	0.0417	0.75	yes	no				

TABLE 4.10. Combined Test Matrix for Airlift Circulator with Thermocouple Guide Extension

Distance from Nozzle, ft				Azimuthal Angle, degrees		Jet Impacts Thermocouple		Jet Impacts Airlift Circulator		Test at Position, Y/N	
Thermocouple Guide	Airlift Circulator	Prototype	Model	Prototype	Model	Tree, Y/N	Y/N	Y/N	Y/N	Y/N	Y/N
3.75	0.71	5	0.95	0	0.00	yes	no	yes			
3.75	0.71	5	0.95	5	4.38	yes	no	yes			
3.75	0.71	5	0.95	10	8.77	no	no	no			
3.75	0.71	5	0.95	15	13.15	no	no	no			
9.75	1.88	11	2.09	0	0.00	yes	yes	yes			
9.75	1.88	11	2.09	5	4.38	yes	yes	yes			
9.75	1.88	11	2.09	10	8.77	no	yes	yes			
9.75	1.88	11	2.09	15	13.15	no	yes	yes			
16.75	3.19	18	3.43	0	0.00	yes	yes	yes			
16.75	3.19	18	3.43	5	4.38	yes	yes	yes			
16.75	3.19	18	3.43	10	8.77	no	yes	yes			
16.75	3.19	18	3.43	15	13.15	no	yes	yes			
23.75	4.52	25	4.78	0	0.00	yes	yes	yes			
23.75	4.52	25	4.78	5	4.38	yes	yes	yes			
23.75	4.52	25	4.78	10	8.77	no	yes	yes			
23.75	4.52	25	4.78	15	13.15	no	no	no			

TABLE 4.11. Steam Coil Test Conditions

Distance from Nozzle, ft		Azimuthal Angle, degrees		Jet Half Width, ft	Test Article Radius, ft	Jet Offset Centerline, ft	Test Article- Jet Overlap, ft		Height Above Floor, ft		Test Article- Jet Overlap, ft		Jet Impacts Test Article
Prototype	Model	Prototype	Model	Model	Model	Model	Model	Y/N	Model	Model	Model	Y/N	Y/N
14.6	2.79	0	0.00	0.34	0.5600	0.00	0.93	yes	0.1667	0.33	0.21	yes	yes
14.6	2.79	10	0.77	0.34	0.5600	0.43	0.48	yes	0.1667	0.33	0.21	yes	yes
14.6	2.79	0	0.00	0.34	0.5600	0.00	0.93	yes	0.25	0.25	0.34	yes	yes
14.6	2.79	10	0.77	0.34	0.5600	0.43	0.48	yes	0.25	0.25	0.34	yes	yes
14.6	2.79	0	0.00	0.34	0.5600	0.00	0.93	yes	0.25	0.33	0.29	yes	yes
14.6	2.79	10	0.77	0.34	0.5600	0.43	0.48	yes	0.25	0.33	0.29	yes	yes
14.6	2.79	0	0.00	0.34	0.5600	0.00	0.93	yes	0.25	0.5	0.12	yes	yes
14.6	2.79	10	0.77	0.34	0.5600	0.43	0.48	yes	0.25	0.5	0.12	yes	yes

coil test matrix includes additional variables (such as pump elevation and I-beam orientation) that are not included in the test matrices of the other test articles, an additional table is provided that further defines the steam coil test conditions (Table 4.12).

4.2.4 Thermocouple Assembly

No tests of the thermocouple assembly are presently planned.

TABLE 4.12. Steam Coil Test Matrix, Prototype Dimensions

<u>Velocity</u>	<u>Elevation, in.</u>		<u>I-Beam Orientation</u>	<u>Nozzle Outlet, ft</u>
	<u>Pump</u>	<u>Test Article</u>		
U1	12	18	parallel perpendicular 45 degrees	14.6 and 30
	18	18	parallel perpendicular 45 degrees	
		54	parallel perpendicular 45 degrees	
U2	12	18	perpendicular	
	18	18	perpendicular	
		54	perpendicular	
U3	12	18	perpendicular	
	18	18	perpendicular	
		54	perpendicular	
U4	12	18	perpendicular	
	18	18	perpendicular	
		54	perpendicular	

5.0 DATA ANALYSIS

Data will be collected using a Fluke data logger. The data analysis will be automated through use of Lotus(a) spreadsheets.

5.1 VELOCITY PROFILES

The jet velocity profile data anticipated from these experiments are listed in Table 5.1.

The jet centerline velocity will be plotted as a function of distance from the jet nozzle to determine the validity of the jet centerline velocity expression (Equation 10) listed in Section 2.4.4.

Velocity component measurements will be plotted to determine the horizontal and vertical profiles of the jet at a variety of distances from the jet nozzle. Horizontal profile measurements taken after the jet tangentially impinges the floor of the tank will be plotted to determine the effects of impingement upon jet shape. This information will be used to develop the radial velocity profile equations.

In addition, velocity data will be examined to determine whether the edge of the jet agrees with the jet angle of expansion determined by Equation (9) presented in Section 2.4.1.

TABLE 5.1. Summary of Anticipated Velocity Profile Data

- jet centerline velocity profile data and comparison to published equations
- jet radial (horizontal) velocity profile data and comparison to published equations
- jet angle of expansion at test temperature
- jet bulk turbulence intensity
- effect of tangential floor impingement on jet vertical profile
- uncertainty intervals for measurements

(a) Manufactured by Lotus Development Corporation, Cambridge, Massachusetts.

If the velocity profile data does not agree with the profile equations presented in Section 2.4.4, the need to develop a more suitable equation to describe jet characteristics will be evaluated. If necessary, the model nozzle flow rate for the experimental test matrix will be adjusted to match model and prototype Reynolds number.

5.2 FORCE MEASUREMENT

The force and drag coefficient data anticipated from these experiments are listed in Table 5.2.

The force of the jet upon the test article is measured using two force transducers attached to the test article support frame. Both axial and side forces will be measured. The drag and lift forces upon the test article are related to the measured force as follows:

$$F_{\text{drag,model}} = \frac{F_{\text{axial}} L_{\text{test article}}}{L_{\text{moment arm}}} \quad (25)$$

TABLE 5.2. Summary of Anticipated Force Data

- drag coefficient for each test article as a function of Reynolds number
- lift coefficient for each test article as a function of Reynolds number
- drag force on each test article of model and prototype as a function of Reynolds number
- lift force on each test article of model and prototype as a function of Reynolds number
- total force on each test article of model and prototype as a function of Reynolds number
- uncertainty intervals for measurements

$$F_{\text{lift,model}} = \frac{F_{\text{side}} L_{\text{test article}}}{L_{\text{moment arm}}} \quad (26)$$

where $L_{\text{test article}}$ is the distance from the test article support to the center of force of the jet as it impacts the test article and $L_{\text{moment arm}}$ is the distance from the test article support to the force transducer. The length of the test article to the center of the force will be based upon Allemann's predictions. The total force upon the test article will be determined by the vector sum of the drag and lift forces.

$$F_{\text{total}} = F_{\text{drag}} + F_{\text{lift}} \quad (27)$$

The drag and lift coefficients will be calculated for each test article as a function of Reynolds number. The data can be presented graphically.

The force upon the prototype will be calculated from the measured data using Equation (7), Section 2.3.

5.3 UNCERTAINTY ANALYSIS

An uncertainty analysis was performed to quantify the uncertainty associated with the jet velocity profile measurements, the test article drag coefficients, and the forces upon the prototypes.

The model for uncertainty analysis (Hesson et al. 1985) can be defined as

$$\text{Result} = R = f(X_1, X_2, X_3, \dots, X_n) \quad (28)$$

The change in R resulting from changes in the variables (X_i 's) would be

$$dR = \frac{\delta R}{\delta X_1} dX_1 + \frac{\delta R}{\delta X_2} dX_2 + \dots + \frac{\delta R}{\delta X_n} dX_n \quad (29)$$

To account for negative or positive variables, dR is squared. When the variables are independent, cross product terms are zero and the variance of the result σ_R^2 is equal to

$$\sigma_R^2 = \left(\frac{\delta R}{\delta X_1}\right)^2 \sigma_{X_1}^2 + \left(\frac{\delta R}{\delta X_2}\right)^2 \sigma_{X_2}^2 + \dots + \left(\frac{\delta R}{\delta X_n}\right)^2 \sigma_{X_n}^2 \quad (30)$$

5.3.1 Jet Velocity Profile

The velocity of the submerged, free jet (assuming no interaction with a component or wall) is a function of Reynolds number at the nozzle, the jet half angle of expansion, the distance from the nozzle, and the distance from the jet centerline. The parameters, their functional relationships, and their sources of uncertainties (σ 's) are listed below:

θ = jet half angle of expansion

= $f(\rho, \mu) = f(T)$

σ_θ = f(thermocouple uncertainty)

x/d_0 = normalized distance from nozzle

= $f(\text{distance, nozzle diameter uncertainties})$

σ_{x/d_0} = $f(\text{position, nozzle diameter uncertainties})$

r = distance from jet centerline

= $f(\text{distance})$

σ_r = $f(\text{positioning uncertainty})$.

5.3.2 Velocity Measurement Uncertainty

The jet velocity profile will be measured using a hot film anemometer, connected to an x-y traversing mechanism. The hot film anemometer accuracy without temperature compensation is $\pm 5\%$ of the reading.

Parameters required to determine the jet velocity profile are

- jet axial velocity, $U_{c,r}$
- position of the anemometer, x , r (y and z).

5.3.3 Positioning Uncertainty

The position of the anemometer and the test articles will be determined using two LVDTs (linear variable differential transformer) for the x (distance from the nozzle) and y (radial) displacement. The LVDT positional accuracy is ± 0.075 in. The z (vertical) displacement will be measured using a scale attached to the test stand. For this analysis, uncertainties in measurement were assumed to be $1/8$ in. in each direction (x, y, and z); therefore, the uncertainty associated with position is 0.22 in.

5.3.4 Force

The force upon the test article is resolved into the drag component, F_d , parallel to the flow and lift component, F_l , perpendicular to the fluid motion; these may be considered independently [Equations (1) through (5), Section 2.3]. The parameters, their functional relationships, and their sources of uncertainties (σ 's) are listed below:

Re = Reynolds number at the test article

$= f(\rho, \mu, U, d) = f(T, Q, d)$

$\sigma_{Re} = f(\text{thermocouple, flowmeter, jet properties uncertainties})$

d = test article diameter in jet profile

$\sigma_d = f(\text{jet properties and test article diameter uncertainties})$

l = test article length in jet profile

$\sigma_l = f(\text{jet properties uncertainties})$

ϵ/d = relative roughness of test article

$\sigma_{\epsilon/d} = f(\text{test article surface finish uncertainty})$

TI = turbulence intensity

$\sigma_{TI} = f(\text{signal characteristics uncertainties}).$

5.3.5 Prototype Force Uncertainty

The uncertainty associated with calculating the force on the prototype, F_p , is estimated using Equation (7), Section 2.3. To differentiate between

experimentally-induced uncertainties and prototype-induced uncertainties, the uncertainties for the model and prototype parameters were calculated separately before being combined. This analysis was conducted for the three test articles at velocities U1 ($U_{0d\text{prototype}} = 29.4 \text{ ft}^2/\text{s}$) and U4 ($U_{0d\text{prototype}} = 7.5 \text{ ft}^2/\text{s}$), at the closest and farthest distances from the nozzle centerline. The parameters and uncertainties associated with them are listed in Table 5.3.

The majority of the uncertainty associated with force measurements is because of the uncertainty associated with the model and prototype jet velocity uncertainties. Uncertainties concerning the area of the test article exposed to the jet are the next dominant term.

5.3.6 Drag Coefficient Uncertainty

The drag coefficients for the test articles will be calculated from the measured moments upon the test frame load cell at a series of four velocities using the following equation:

$$C_d = \frac{2 F}{\rho U^2 A} \quad (31)$$

The uncertainty analysis for the drag coefficient is presented for the same range of conditions as the force uncertainty analysis. Drag coefficient uncertainties are listed in Table 5.4.

TABLE 5.3. Model, Prototype, and Combined Force Uncertainties for the Radiation Drywell, Airlift Circulator, and Steam Coil

	Radiation Drywell Force Uncertainty, %							
	U1				U4			
	Model	Prototype	Model	Prototype	Model	Prototype	Model	Prototype
Force	2.1	0.0	4.3	0.0				
Density	0.02	0.04	0.02	0.04				
Area	1.2	2.1	0.8	1.5				
Velocity	5.0	5.0	5.0	5.0				
Separate	9.1	9.1	9.8	9.1	9.1	9.1	9.8	9.1
Total	12.9		13.4		12.9		13.4	

Distance from Nozzle, ft	2.1	11.0	4.8	25.0	2.1	11.0	4.8	25.0
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	Airlift Circulator Force Uncertainty, %							
	U1				U4			
	Model	Prototype	Model	Prototype	Model	Prototype	Model	Prototype
Force	8.4 ^(a)	0.0	4.5	0.0				
Density	0.02	0.04	0.02	0.04				
Area	5.9	9.7	1.0	1.9				
Velocity	5.0	5.0	5.0	5.0				
Separate	12.0	11.7	11.8	10.8	12.0	11.7	11.8	10.8
Total	16.7		16.0		16.7		16.0	

Distance from Nozzle, ft	2.1	11.0	5.7	30.0	2.1	11.0	5.7	30.0
--------------------------	-----	------	-----	------	-----	------	-----	------

	Steam Coil Force Uncertainty, %							
	U1				U4			
	Model	Prototype	Model	Prototype	Model	Prototype	Model	Prototype
Force	1.8	0.0	1.6	0.0				
Density	0.02	0.04	0.02	0.04				
Area	1.6	2.9	0.8	1.8				
Velocity	5.0	5.0	5.0	5.0				
Separate	8.8	9.0	9.1	9.1	8.8	9.0	9.1	9.1
Total	12.6		12.9		12.6		12.9	

Distance from Nozzle, ft	2.8	14.6	5.7	30.0	2.8	14.6	5.7	30.0
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(a) Uncertainty estimated using 500 lbf load cell. The low reaction force, 14 lbf, at this orientation would permit additional measurements using the 50 lbf load cell if warranted.

TABLE 5.4. Estimate of Drag Coefficient Uncertainties for the Radiation Drywell, Airlift Circulator, and Steam Coil

	U1				U4			
	Uncertainty	Distance to	Uncertainty	Distance to	Uncertainty	Distance to	Uncertainty	Distance to
	%	Nozzle, ft	%	Nozzle, ft	%	Nozzle, ft	%	Nozzle, ft
Radiation drywell	10.3	2.1	10.9	4.8	10.3	2.1	10.9	4.8
Airlift circulator	14.3	2.1	11.0	5.7	14.3	2.1	11.0	5.7
Steam coil	10.3	2.8	10.2	5.7	10.3	2.8	10.1	5.7

6.0 COMPUTER PREDICTIONS

The jet velocity profile information, drag coefficient, and force data will be used to augment input to the analytical evaluation of the jet mixer forces.

7.0 QUALITY ASSURANCE

This testing will be performed in accordance with Impact Level II requirements as specified in the PNL Program QA Plan, WTC-051. Design work for the facility modifications will be performed as with Impact Level III in accordance with the Good Practices Standard and the applicable portions of PNL-MA-90, Design: Preparation, Control, and Implementation.

Minor modifications to the Test Plan that do not affect the scope, overall methods, or test parameters will be made by the Task Leader by recording the change in the working copy of the Test Plan and initialing and dating the entry. Significant changes will be made by revision of this Test Plan.

All staff that will perform testing are well versed in the operation of the equipment at 1890 and have extensive experience with the instrumentation. In addition, only a limited number of staff will be involved with the testing and all those were involved with the development of this Test Plan, the design, and the corresponding operating procedure. Therefore, no formal personnel training is required.

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APPENDIX

DISTANCE BETWEEN PUMPS AND TEST ARTICLES

APPENDIX

DISTANCE BETWEEN PUMPS AND TEST ARTICLES^(a)

Test Article	Location in Tank				Test Article-Pump		Test Article-Nozzle	
	Radius ft(b)	Angle degree(c)	x, ft	y, ft	Centerline, ft		Distance, ft	
pump1	22.00	0.00	22.00	0.00	to pump1	to pump2	to pump1	to pump2
pump2	22.00	180.00	-22.00	0.00	44.00	0.00	41.00	0.00
alc1	0.00	0.00	0.00	0.00	22.00	22.00	22.00	20.54
alc2	14.50	270.00	0.00	-14.50	20.35	20.35	24.89	24.89
alc3	14.50	220.59	-11.01	-9.43	34.33	14.48	32.87	13.02
alc4	14.50	167.14	-14.14	3.23	36.28	0.50	34.82	7.04
alc5	14.50	115.59	-8.26	13.00	31.14	20.46	29.68	19.00
alc6	14.50	64.29	8.29	13.00	20.43	31.16	18.97	29.70
alc7	14.50	15.65	13.96	3.91	0.94	36.17	7.48	34.72
alc8	14.50	310.63	10.88	-9.58	14.68	34.25	13.22	32.79
alc9	27.00	309.18	17.05	-20.94	21.51	44.31	20.06	42.85
alc10	27.00	282.86	0.01	-20.32	30.80	30.44	29.34	36.98
alc11	27.00	250.66	-6.23	-26.27	30.56	30.64	37.11	29.18
alc12	27.00	230.42	-17.20	-20.81	44.38	21.36	42.93	19.90
alc13	27.00	206.88	-24.08	-12.21	47.67	12.36	46.21	10.92
alc14	27.00	177.92	-26.96	0.98	48.99	5.00	47.53	3.62
alc15	27.00	154.29	-24.33	11.72	47.78	11.94	46.33	10.49
alc16	27.00	129.16	-17.05	20.94	44.31	21.51	42.85	20.06
alc17	27.00	102.86	-0.01	20.32	30.44	30.80	36.98	29.34
alc18	27.00	76.66	0.23	26.27	30.64	30.56	29.18	37.11
alc19	27.00	50.42	17.20	20.81	21.36	44.38	19.90	42.93
alc20	27.00	26.88	24.08	12.21	12.36	47.67	10.92	46.21
alc21	27.00	1.66	26.99	0.78	5.05	46.99	3.59	47.54
alc22	27.00	334.29	24.33	-11.71	11.94	47.78	10.49	46.33
rdw1	12.50	330.00	10.83	-0.25	12.80	33.42	11.35	31.96
rdw2	12.50	210.00	-10.83	-0.25	33.42	12.80	31.96	11.35
rdw3	12.50	90.00	0.00	12.50	25.30	25.30	23.84	23.84
rdw4	34.75	318.75	28.13	-22.91	23.28	53.30	21.82	51.84
rdw5	34.75	228.75	-22.91	-20.13	51.96	20.14	50.50	24.68
rdw6	34.75	138.75	-20.13	22.91	53.30	23.28	51.84	21.82
rdw7	34.75	48.75	22.91	20.13	20.14	51.96	24.68	50.50
sc1	20.00	135.00	-14.14	14.14	36.61	10.18	37.35	14.72

(a) Information summarized from Drawing H-2-67314 Plant Tank 101 Penetrations
& Schedule 241-AZ Tank Farm, Vitro, Hanford Engineering Services.

(b) Radial tolerances: $\pm 1/4$ in. from 0 to 10 ft radius
 $\pm 1/2$ in. from 10 to 20 ft radius
 ± 1 in. from 20 to 30 ft radius
 ± 2 in. from 30 to 40 ft radius

(c) Angular tolerance ± 0.25 degrees.

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