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Jet Mixing Long Horizontal Storage Tanks

J. J. Perona
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E. L. Youngblood
R. L. Cummins

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Chemical Technology Division

JET MIXING LONG HORIZONTAL STORAGE TANKS

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NOMENCLATURE

C_c = concentration at centerline of developed jet

C_n = concentration of fluid leaving jet nozzle

D_n = jet nozzle diameter

h = height of jet nozzle centerline above the floor

L = length of developed jet

L_{eff} = effective length of developed jet calculated by Eq. (4)

L_t = distance from nozzle to end of tank

N = number of jets

Q_e = flow rate of fully developed jet

Q_n = volumetric flow rate through jet nozzle

Re = jet Reynolds number = $D_n \rho v_n/\mu$

t_m = mixing time

t_R = recirculation time constant = V_T/Q_n

v_c = velocity of jet at centerline

v_n = velocity at jet nozzle

V_T = tank volume

z = distance from jet nozzle

β = empirical factor = f(Re)

ρ = density of fluid

μ = viscosity of fluid

JET MIXING LONG HORIZONTAL STORAGE TANKS

J. J. Perona, T. D. Hylton, E. L. Youngblood, and R. L. Cummins

Abstract

Large storage tanks may require mixing to achieve homogeneity of contents for several reasons: prior to sampling for mass balance purposes, for blending in reagents, for suspending settled solids for removal, or for use as a feed tank to a process. At Oak Ridge National Laboratory, mixed waste evaporator concentrates are stored in 50,000-gal tanks, about 12 ft in diameter and 60 ft long. This tank configuration has the advantage of permitting transport by truck and therefore fabrication in the shop rather than in the field. A survey of the literature revealed no information on mixing large storage tanks with a length-to-diameter ratio greater than 2.

Jet mixing experiments were carried out on two model tanks: a 230-gal (1/6-linear-scale) Plexiglas tank and a 25,000-gal tank (about 2/3 linear scale). Mixing times were measured using sodium chloride tracer and several conductivity probes distributed through the tanks. Several jet sizes and configurations were tested. In the 1/6-scale tank, jet diameters of 0.62, 0.87, and 1.61 in. were used. In the 2/3-scale tank, jet diameters of 1.38 and 1.94 in. were used. One-directional and two-directional jets were tested in both tanks. Mixing times for each tank were correlated with the jet Reynolds number. Mixing times were correlated for the two tank sizes using the recirculation time for the developed jet. When the recirculation times were calculated using the distance from the nozzle to the end of the tank as the length of the developed jet, the correlation was only marginally successful. Data for the two tank sizes were correlated empirically using a modified effective jet length expressed as a function of the Reynolds number raised to the 1/3 power.

Mixing experiments were simulated using the TEMPEST computer program at Battelle Pacific Northwest Laboratories. The simulations predicted trends correctly and were within the scatter of the experimental data with the lower jet Reynolds numbers. Agreement was not as good at high Reynolds numbers except for single nozzles in the 25,000-gal tank, where agreement was excellent over the entire range.

1. INTRODUCTION

Large storage tanks may require homogenization of contents for several reasons: for sampling of the tank contents for inventory purposes, for blending in additives or reagents, for suspending settled solids for tank cleaning, or for use as a feed tank to a process. The use of mechanical mixers is often not practical for large tanks, and jet mixing is a common choice. In this method the tank contents are recirculated through a pump, often located external to the tank, and then back into the

tank through a jet. The jet flows into the bulk liquid at a high relative velocity near the nozzle and expands as it flows away from the nozzle, entraining and mixing bulk fluid. In one of the earliest accounts of this method, Fossett and Prosser (1949) studied the blending of tetraethyl lead in underground gasoline tanks 118 ft in diameter by 20 ft deep.

At Oak Ridge National Laboratory (ORNL), mixed waste evaporator concentrates are stored in 50,000-gal tanks about 12 ft in diameter by 60 ft long. Wastewaters are neutralized with sodium hydroxide prior to evaporation, and the concentrates produce a hydroxide sludge upon cooling. The tanks contain a sludge layer typically 1 to 2 ft deep. The tank contents are highly radioactive, and the tanks must eventually be emptied. Work at the Savannah River Laboratory showed that similar sludges can be suspended into the supernate using jets in close proximity and parallel to the tank floor (Churnetski, 1981). The resulting slurry can then be pumped out of the tank. Alternately, the sludge might be dissolved by an acid addition before pumping out the tank contents. Work at ORNL is being carried out in two stages: (1) mixing in the absence of sludges (reported in this report) and (2) studies of sludge mobilization.

The literature on jet mixing of tanks has been surveyed by Revill (1985) and by Maruyama (1986). Most of the studies reported have been done with tanks having the cylindrical surface oriented vertically and flat bottoms. This is also the geometry of radioactive waste storage tanks at Savannah River and Hanford. Most commonly, in the published literature on mixing, a single jet or multiple jets are located near the tank floor oriented at an angle to the vertical, but some studies have been published for jets oriented vertically at the tank axis. Published mixing data for vertical jets covered only short tanks (i.e., liquid height/tank diameter ratios of 0.3 to 1). Results in the present study are reported for tanks with length/diameter ratios of 4 and 5. An experimental study was carried out to provide mixing times for horizontal cylindrical tanks.

2. EXPERIMENTAL METHOD

Experiments were performed on two model tanks. The smaller tank was 1/6 linear scale (i.e., 2 ft in diameter by 10 ft long) and had a capacity of 230 gal. The tank was constructed of Plexiglas to permit flow visualization studies. A photograph of the Plexiglas tank is shown in Fig. 1. The larger tank, which was 10 ft in diameter by 40 ft long (~2/3 linear scale) and had a capacity of 25,000 gal, is shown in Fig. 2. Two jet configurations were tested. Data were taken with a single jet placed 1/4 tank length from one end, pointed toward the center of the tank. This configuration was chosen because of the most accessible port on the actual tanks. Jet nozzles were straight pieces of pipe or tubing 10 diameters long. Jet diameter and velocity were varied with this configuration. Tests were also made with two-directional opposed jets at this location and also at the center of the tank lengthwise. In all cases the jet was positioned close to the bottom of the tank, in the range of one to four jet diameters. Tests were made with the suction to the pump loop at the opposite end of the tank from the jet and also at the tank center. A schematic of the Plexiglas tank and single-jet piping arrangement is shown in Fig. 3. Detailed dimensions for the piping loops are shown in the Appendix.

The pump for the 230-gal tank was a canned rotor chempump (Crane model GA-1K-1S), which gave flow rates in the recirculation loop up to 36 gal/min. For the 25,000-gal tank, a Gardner-Denver triplex plunger pump was used, which gave flow rates up to 200 gal/min. Flow rates in the recirculation loops were measured with magnetic flowmeters (Magflo).

Each test began with the tank contents in a quiescent condition. A section of the piping loop, isolated with ball valves, was drained and filled with a concentrated solution of sodium chloride. The ball valves were opened, and then the pump and clock were started simultaneously. Sodium chloride concentration was measured in the tank at four locations using conductivity probes. The probes were

Fig. 1. Photograph of 230-gal Plexiglas tank.

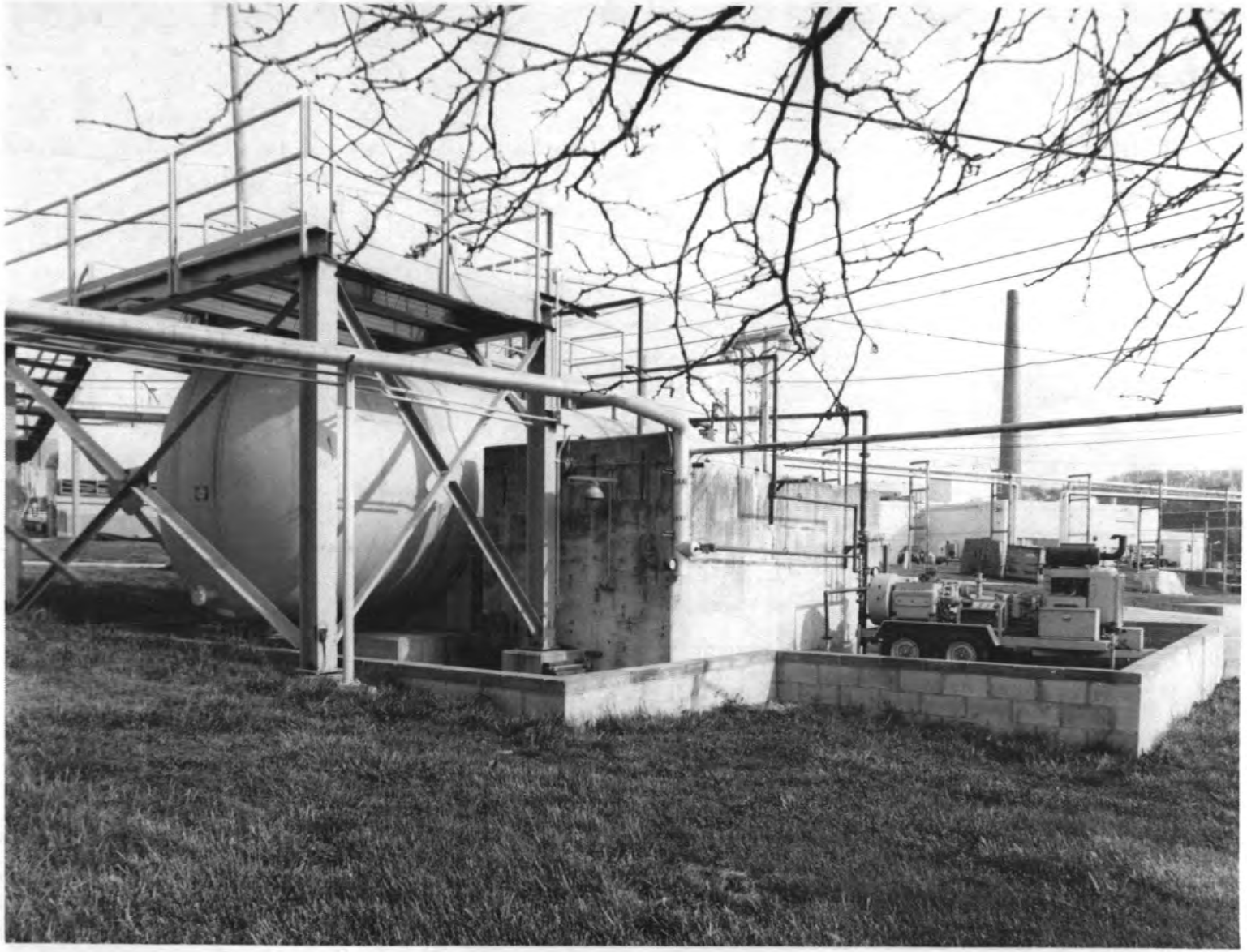

Fig. 2. Photograph of 25,000-gal tank.

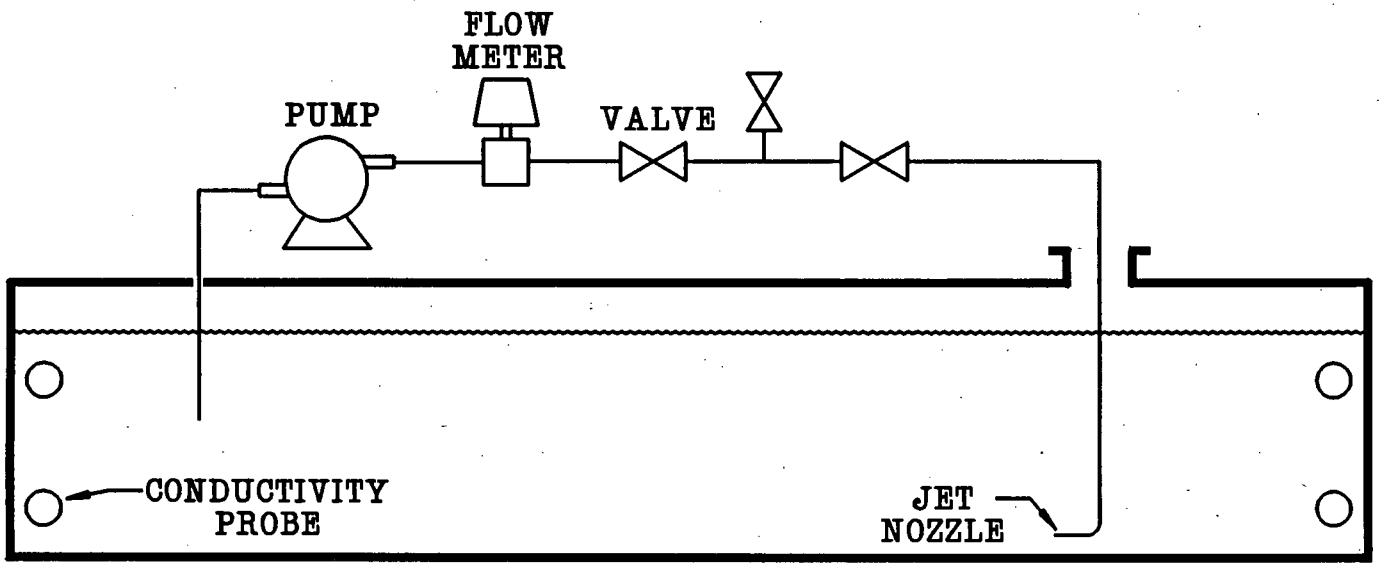

Fig. 3. Sketch of Plexiglas tank and piping loop.

toroidal flow-through sensors manufactured by Rosemount Analytical (model number 228). Signals from the conductivity cells are fed to Rosemount model 1054A microprocessors, which provide digitized data at 5-s intervals to Genesis software. Conductivity versus time data were analyzed both manually and by computer for determination of mixing times. An example of a conductivity-time plot is shown in Fig. 4. The mixing time was taken as the time when the last probe had reached a horizontal orientation, indicating no long-term concentration changes, and short-term fluctuations were within $\pm 5\%$.

3. RESULTS

Mixing times in the 1/6-scale tank are shown in Fig. 5 and are in the range of 5 to 30 min as the flow rate was varied from 35 to 5 gal/min. In these experiments, single jets were located 1/4 tank length from one end, discharging toward the middle of the tank. Jet diameters of 0.62, 0.87, and 1.61 in. were tested with the jet located 1.25 in. above the tank floor for the two smaller diameters and 1.75 in. above the floor for the largest diameter jet. Values of h/D_n were 2.0, 1.4, and 1.1, respectively. The results in Fig. 5 show that the mixing times for the various jet diameters can be correlated with jet Reynolds number ($D_n \rho v_n/\mu$). The 0.87-in.-diam jet was raised from near the tank bottom to the tank axis, and a series of mixing times was measured. The mixing times were not greatly different. With the jet at the tank axis, mixing times were about 15% lower at a Reynolds number of 100,000 and about 20% higher at a Reynolds number of 20,000 than with the jet near the tank floor. Attempts were made to obtain mixing times with double-direction jets in the 1/6-scale tank using this range of flow rates, but the results were chaotic and not reproducible.

Mixing times in the 25,000-gal tank were measured with single and double jets located 1/4 tank length from one end using jets with inside diameters of 1.38 in. (1.25-in. schedule 40 pipe) and

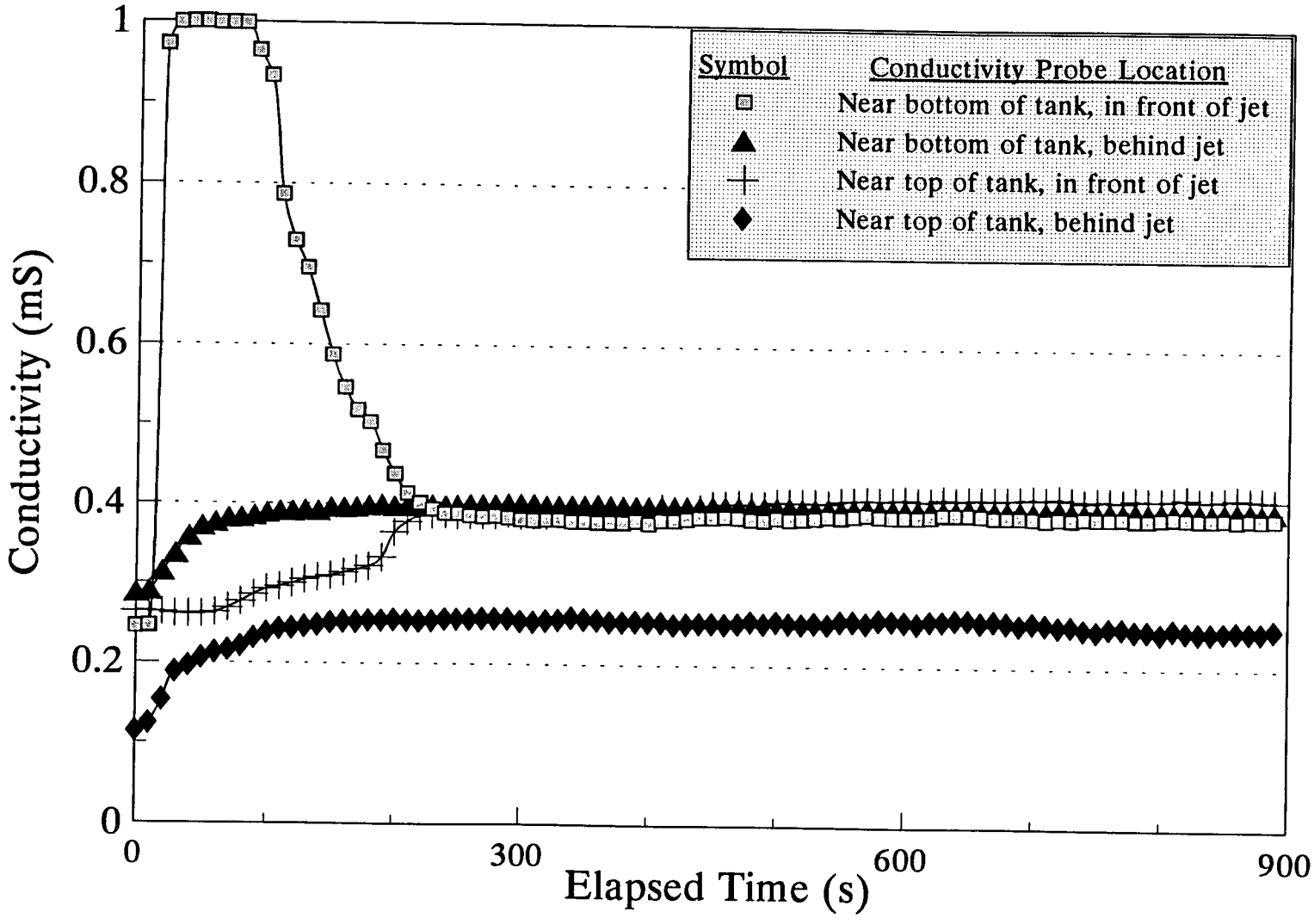

Fig. 4. Example of a conductivity-time plot.

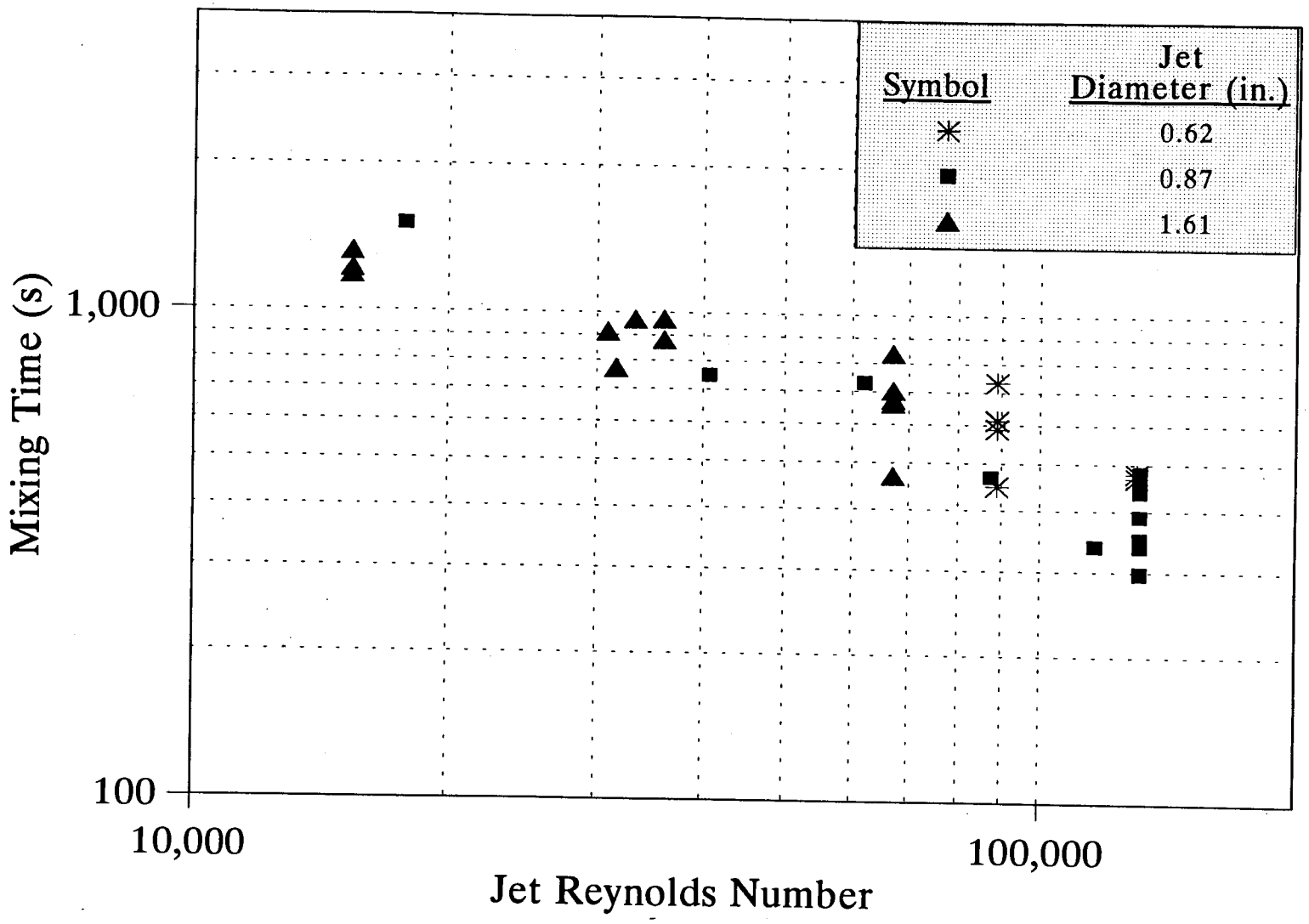

Fig. 5. Correlation of mixing times in 1/6-scale tank with one-directional jets. The jets were located 1/4 tank length from one end near the bottom.

1.939 in. (2-in. schedule 80 pipe). Experiments were also made with a double jet in the center of the tank lengthwise. All mixing tests in the 25,000-gal tank were performed with the jets positioned 6 in. from the bottom of the tank, giving h/D_n values of 4.3 for the smaller jet and 3.1 for the larger jet. For the single jet, mixing times ranged from 14 to 75 min as the flow rate was varied from 200 to 50 gal/min (Fig. 6). For the double jet of the same size and location, mixing times were within 15% of those for the single jet at the same flow rates, although the jet velocities (and Reynolds numbers) were half of those of the single jet. At a given flow rate, mixing times were significantly lower with the 1.38-in. jet than with the larger jet. Mixing times for the different sizes of double jets at the 1/4-tank-length location were correlated by the jet Reynolds number (Fig. 7).

The 1.38-in. double jet was moved to the center position of the tank (lengthwise). A series of tests was made over the velocity range of 50 to 150 gal/min. The mixing times are compared in Fig. 8 with those obtained with the jet located 1/4 tank length from the end of the tank. Mixing times are around 20 to 25% longer with the jet in the center of the tank. Mixing time data are presented in Table 1.

4. CORRELATION OF MIXING TIMES

Lehrer (1981) developed a theoretical model for mixing in free turbulent jets, which he applied to the tank mixing time data of Fosset and Prosser (1949) and of Fox and Gex (1956). Lehrer defined an entrainment ratio as the mass flow rate in the fully developed jet to the mass flow rate of the injected stream. His thesis was that the time required for jet mixing a tank is inversely proportional to the entrainment ratio. The ratio of entrained liquid flow rate to jet flow rate is as follows (Revill, 1985):

$$\frac{Q_e}{Q_n} = \beta \frac{z}{D_n} . \qquad (1)$$

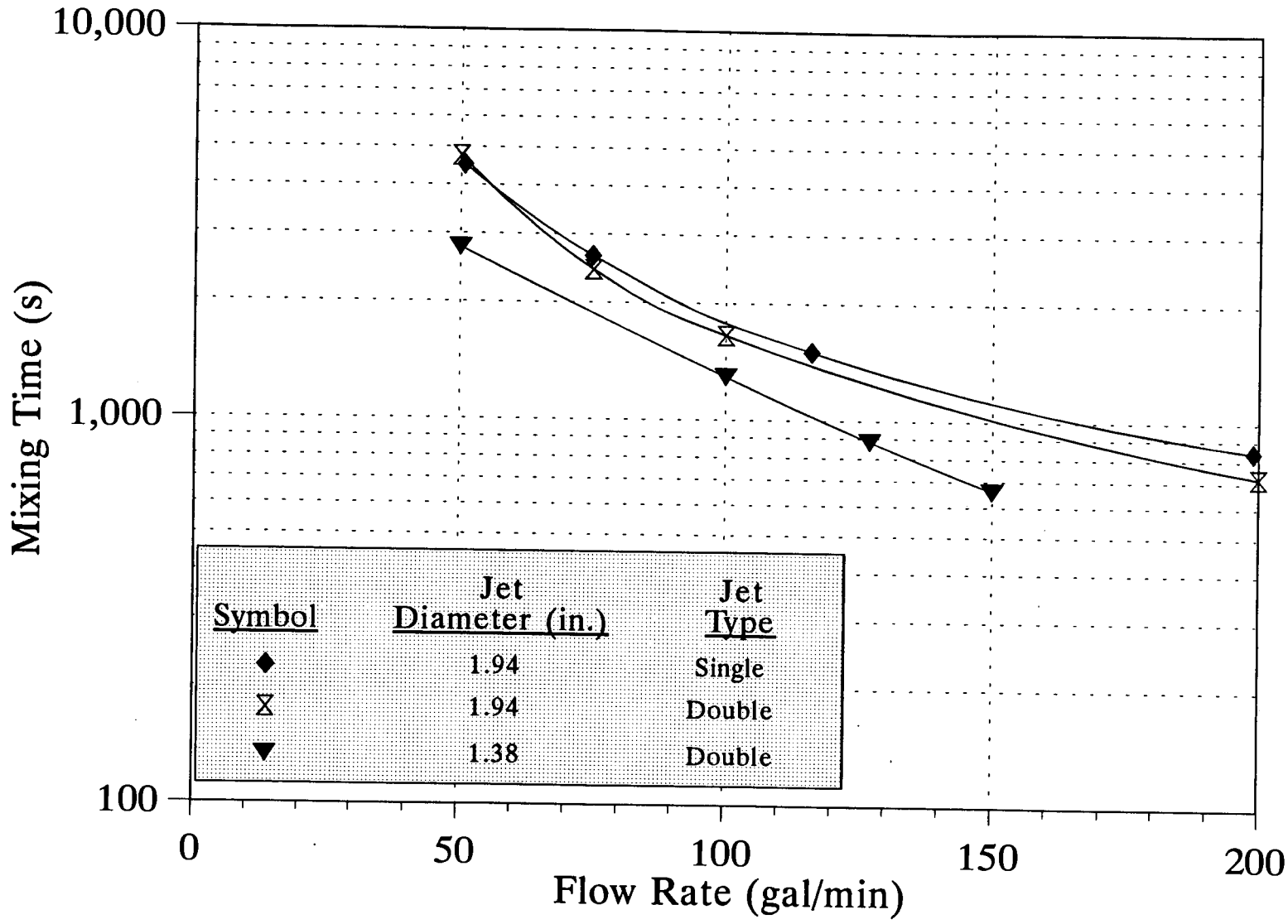

Fig. 6. Mixing times in 25,000-gal tank.

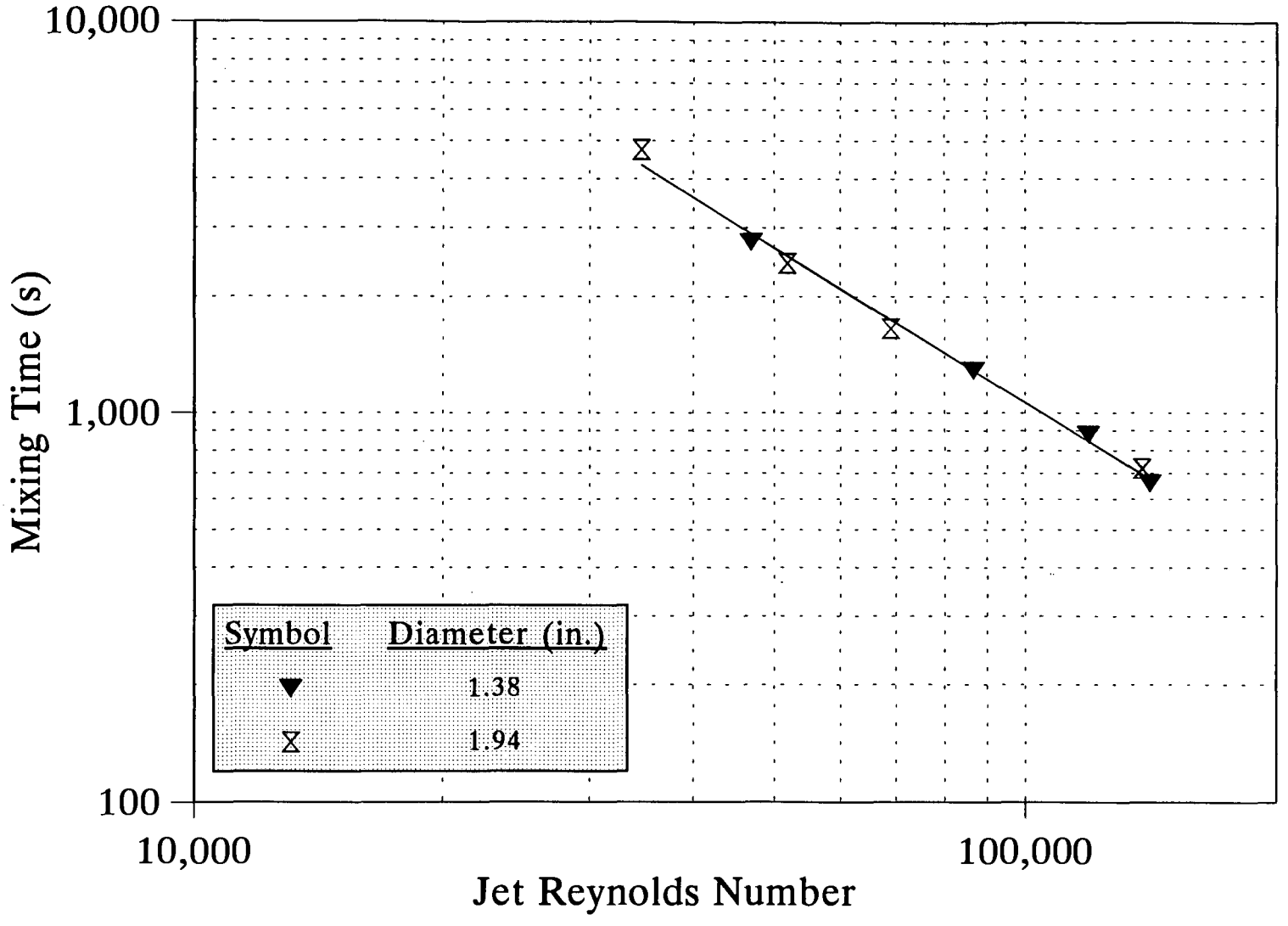

Fig. 7. Correlation of mixing times for double jets in 25,000-gal tank.

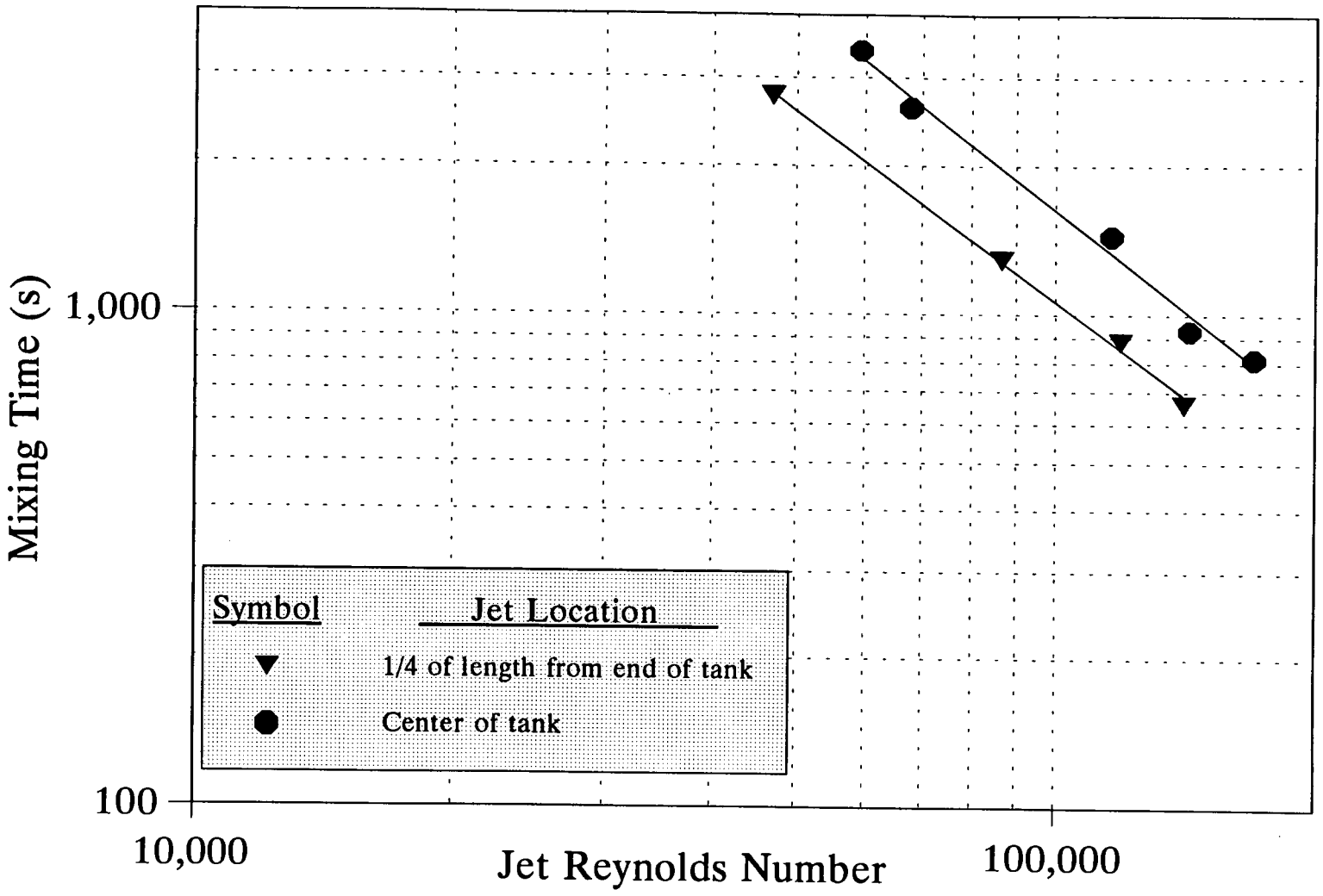

Fig. 8. Comparison of mixing times for 1.38-in. double jets at two locations in 25,000-gal tank.

Table 1. Mixing time data

D_n (in.)	Flow rate (gal/min)	Jet velocity (ft/s)	Jet Reynolds number (thousands)	Mixing time (s)
1/6-scale tank, single jet, 1/4 tank length from end*				
0.62	17.4	18.5	89.0	590
0.62	25.4	27.0	130	473
0.87	4.85	2.62	18.0	1510
0.87	11.1	6.00	40.7	748
0.87	17.0	9.16	62.0	728
0.87	23.9	12.9	87.0	468
0.87	31.7	17.1	116	338
0.87	35.7	19.3	131	366
1.61	7.80	1.23	15.4	1218
1.61	16.9	2.66	33.3	898
1.61	34.1	5.38	67.0	672
25,000-gal tank, single jet, 1/4 tank length from end				
1.939	50.7	5.51	80.0	4500
1.939	74.8	8.13	110	2640
1.939	116	12.6	182	1500
1.939	199	21.6	311	840
25,000-gal tank, double jet, 1/4 tank length from end				
1.38	50	5.36	46.9	2760
1.38	100	10.7	86.7	1290
1.38	127	13.6	119	882
1.38	127	13.6	119	882
1.38	150	16.1	141	660
1.939	50	2.72	34.6	4740
1.939	75	4.08	51.9	2430
1.939	100	5.43	69.0	1650
1.939	200	10.9	138	720
25,000-gal tank, double jet in center of tank (lengthwise)				
1.38	51.7	5.55	59.2	3390
1.38	61.6	6.61	67.9	2610
1.38	101	10.9	116	1440
1.38	125	13.4	143	930
1.38	150	16.1	170	815

*To conserve space, only a representative selection of points for the 1/6-scale tank is presented. All the data points are shown in Fig. 5.

A nomenclature list is located at the beginning of this document on page ix. The empirical factor β depends on the jet Reynolds number in the laminar region but is only a weak function of Re for the turbulent jets of interest in this work. When Q_e is large compared with Q_n, the ratio approximates the entrainment ratio. The recirculation time for the developed jet is equal to the recirculation time calculated with the flow rate through the jet nozzle multiplied by the factor D_n/L. If the time required to mix a tank is proportional to the recirculation time for the developed jet, a correlation of the following form is indicated (Maruyama, 1986):

$$t_m = (constant)\ t_R \frac{D_n}{L} . \tag{2}$$

Determination of the length L of the fully developed jet is not straightforward. The turbulent jet entrains liquid and expands as it moves away from the nozzle, and its velocity slows until at some point it no longer entrains liquid. The centerline jet velocity and concentration can be approximated as follows (Revill, 1985):

$$\frac{v_c}{v_n} \approx \frac{6\ D_n}{z} ; \quad \frac{C_c}{C_n} \approx \frac{4.5\ D_n}{z} . \tag{3}$$

Equations (3) show that velocity and concentration fall in inverse proportion to the distance from the nozzle. The mixing effect of a turbulent jet is generally considered insignificant after about 400 jet diameters (Revill, 1985). When the jet impacts the end of a tank, it may be considered to be broken up and no longer a jet. In our experiments with the 1/6-scale tank, the smallest single jet (0.62-in. diameter) was about 150 diameters from the end of the tank. With the 1.38-in. jet in the 25,000-gal tank, the distance to the end was about 260 diameters. In all other cases the jets were located fewer jet diameters from the ends of the tanks (Table 2).

In most of the experiments reported in this paper, the jet is located near the floor of the tank. The developing jet contacts the floor of the tank a short distance away from the nozzle and

Table 2. Developed jet lengths

Tank size (gal)	Jet location	D_n (in.)	Distance to end of tank (ft)	Number of D_n's to end of tank
230	1/4 from end	0.62	7.5	145
230	1/4 from end	0.87	7.5	103
230	1/4 from end	1.61	7.5	56
25,000	1/4 from end	1.38	30	260
25,000	1/4 from end	1.94	30	185
25,000	Center	1.38	20	174

is affected by it. Several investigators have reported studies of jets developing from a circular nozzle above a plane surface (e.g., Newman et al., 1972; Rajaratnam and Pani, 1974; Davis and Winarto, 1980). These studies show that the influence of the wall is to cause the jet to spread laterally (parallel to the wall) to a much greater extent than vertically. Davis and Winarto (1980) report experiments on velocity distributions and turbulent properties of jets for h/D_n values of 0.5 to 4. The ratio of spreading rates approaches 8.5 at large distances from the nozzle. Measurements of turbulence and Reynolds stress were generally consistent with the spreading rates. The drop in maximum jet velocity with distance from the nozzle was not quite as fast for the wall jets as for a free jet. The shear on the floor is not a large factor in the overall momentum balance. Entrainment ratios could not be obtained from these studies. In the present tank experiments, the jets were developing not above a plane surface but above a cylindrical surface. The effects of the curvature of the surface on the spreading rates and turbulence properties are not known.

By using the distances from the jet nozzles to the ends of the tanks for values of L, the data were plotted as indicated by Eq. (2) as shown in Fig. 9. The points in Fig. 9 indicate some general validity to the correlation, but the agreement is marginal for quantitative purposes. The data from the 230-gal tank are better fit by a curve that is concave downward than by a straight line indicated by Eq. (2), while the single-jet data for the 25,000-gal tank indicate a curve that is concave upward.

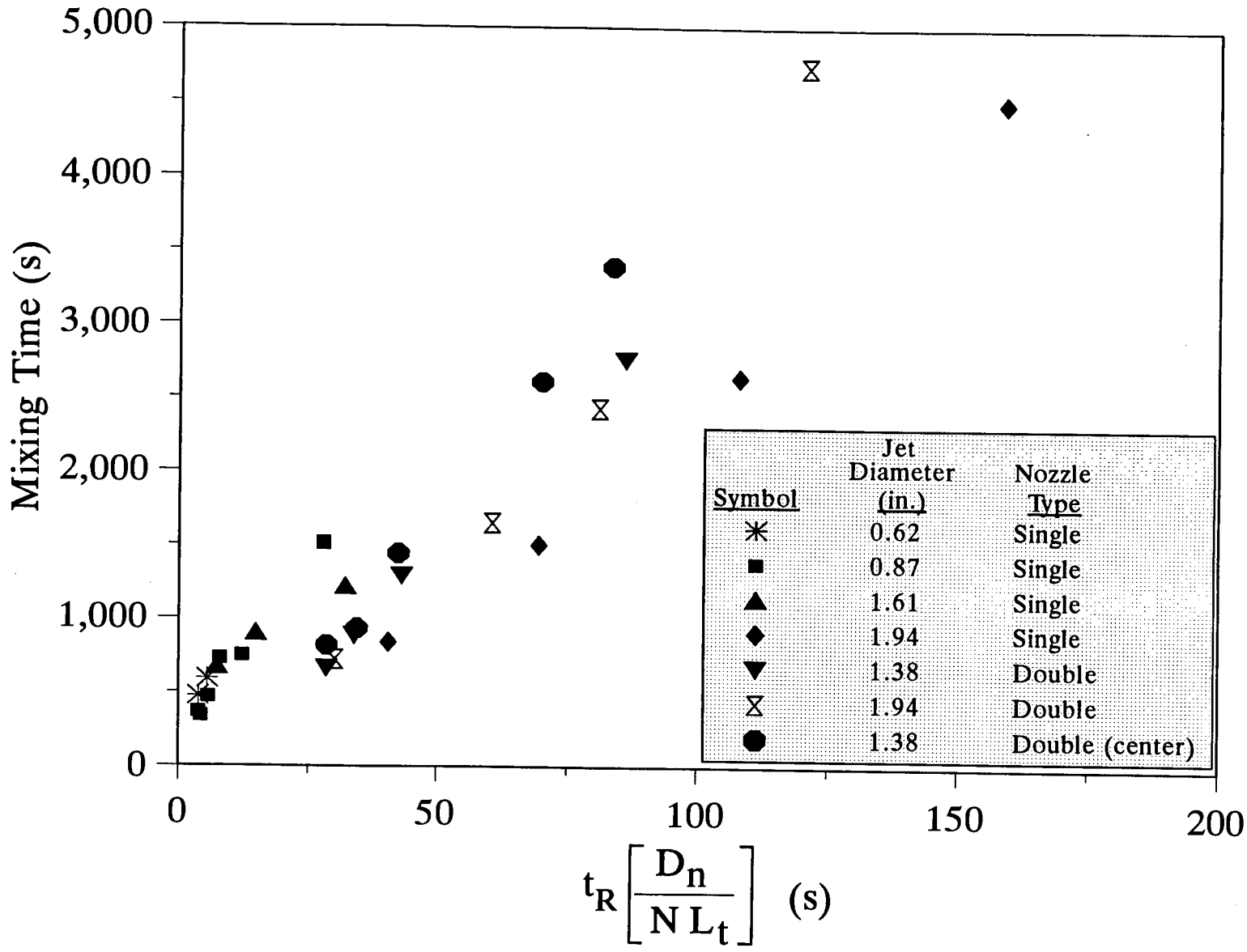

Fig. 9. Correlation of mixing times for both model tanks. Length of developed jet is calculated as distance from nozzle to end of tank.

Data for the double jet in the middle of the 25,000-gal tank are more consistent with the data from the 230-gal tank. The slope of the straight line drawn through the points is 33, while similar plots for vertical tanks have slopes generally in the range of 2 to 10 (Maruyama, 1986). For a given value of the abscissa, mixing takes longer in the horizontal tanks of this investigation. The reason is not clear at this time but undoubtedly involves the proximity of the jet to the tank floor in the present work and perhaps the surface-to-volume ratios of the tanks.

An improved empirical correlation was obtained by expressing the "effective" jet length as a function of the Reynolds number:

$$L_{eff} = L_t \left(\frac{Re}{10^5} \right)^{1/3} . \tag{4}$$

By trial and error the functional relationship was found to provide a better fit. The resulting plot is shown in Fig. 10. The best line through the points does not quite pass through the origin. The slope of the line is about 25.

5. TEMPEST SIMULATIONS

Some of the mixing experiments were simulated at Battelle Pacific Northwest Laboratories (PNL) using the TEMPEST program developed there. The objective was to determine if TEMPEST might serve as a scale-up tool: that is, if TEMPEST successfully simulated experiments in model tanks, then simulations of the 50,000-gal Melton Valley Storage Tanks and the new 100,000-gal tanks could be accepted as reasonably accurate. TEMPEST (time-dependent, energy, momentum, pressure equation solution in three dimensions) has been developed and tested on similar applications at PNL over the last 15 or so years. The simulation work was subcontracted by ORNL to PNL. A full account of the simulation work is given by Terrones and Eyler (1993).

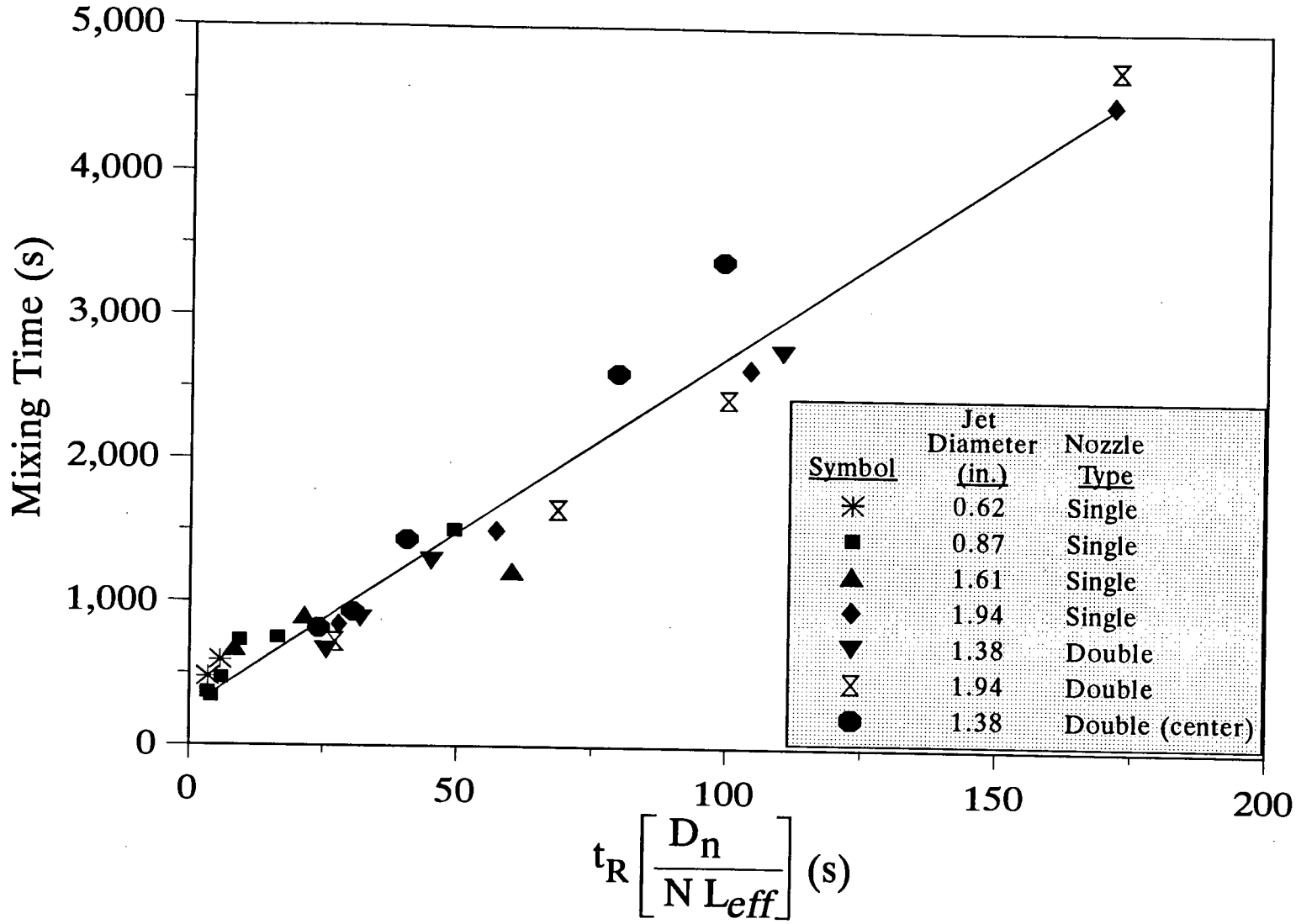

Fig. 10. Correlation of mixing times for both tanks using modified length of developed jet.

The TEMPEST computer program (Trent and Eyler, 1992) numerically solves a base set of governing transport equations for continuity, momentum, and species transport. Viscosity in the momentum equation is an effective viscosity determined from consideration of turbulence and concentration-dependent rheology. TEMPEST uses the k-ϵ turbulence model, in which the turbulent viscosity is related to the turbulence energy k and to its dissipation rate ϵ. The equations are solved numerically using a combination of explicit, semi-implicit, and implicit algorithms.

TEMPEST-simulated mixing times in the 230-gal tank with single jets are compared in Fig. 11 with the best line drawn through the experimental points. Agreement is very good at the lowest jet Reynolds number of 16,000. At the higher Reynolds numbers, TEMPEST predicts lower mixing times than those observed, although the experimental data exhibit a great deal of scatter as shown in Fig. 5. Experiments in the 25,000-gal tank showed much better reproducibility. Agreement between experiments and TEMPEST simulations for the single-nozzle system was excellent (Fig. 12). With two-directional jets the TEMPEST-predicted mixing times lie considerably above the experimental data, with a predicted mixing time about twice the experimental value at the jet Reynolds number of 140,000 (Fig. 13).

6. CONCLUSIONS

Jet mixing times were measured for long horizontal tanks with length-to-diameter ratios of 4 and 5. Mixing times in the 1/6-scale tank decreased from 30 to 5 min as the jet Reynolds number was increased from 15,000 to 130,000. Mixing times for various jet diameters were correlated with the jet Reynolds number. With the single jet in the 25,000-gal tank, mixing times decreased from 75 to 14 min as the jet Reynolds number was increased from 80,000 to 311,000. For a double jet of the same diameter and location, mixing times were not significantly different from those of the single jet

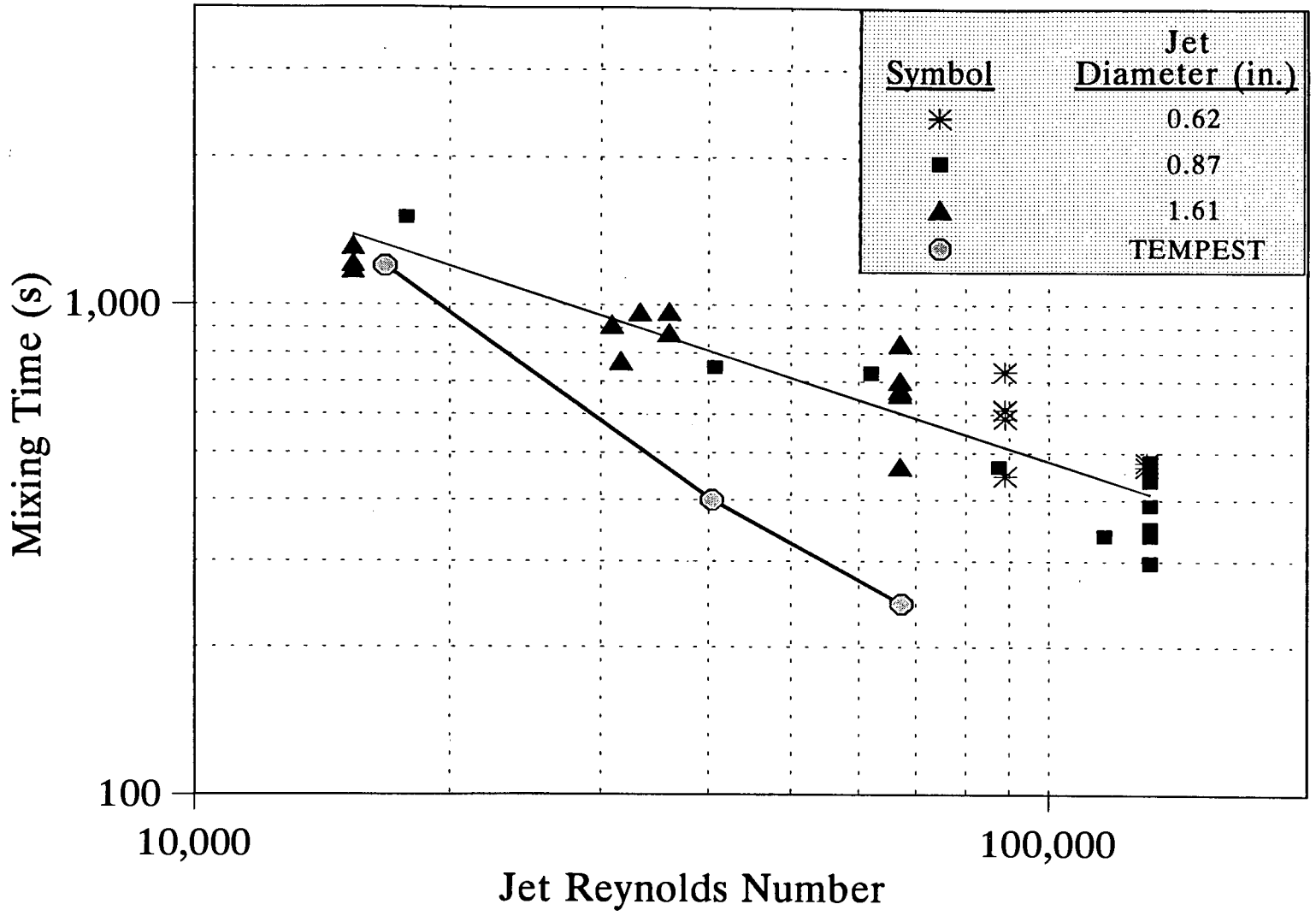

Fig. 11. TEMPEST-simulated mixing times in the 230-gal tank with single jets.

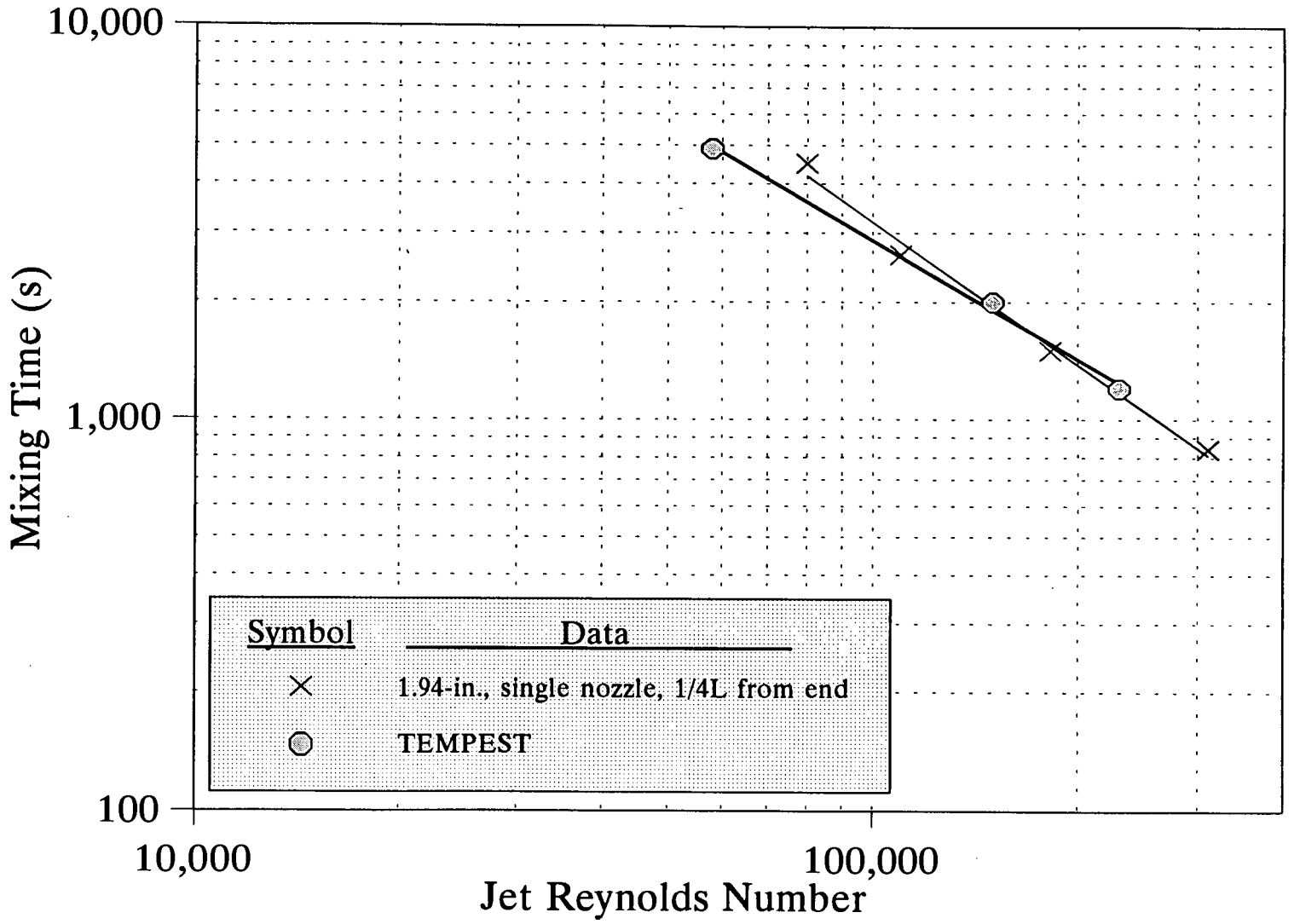

Fig. 12. Comparison of experimental data and TEMPEST simulations for the single-nozzle system.

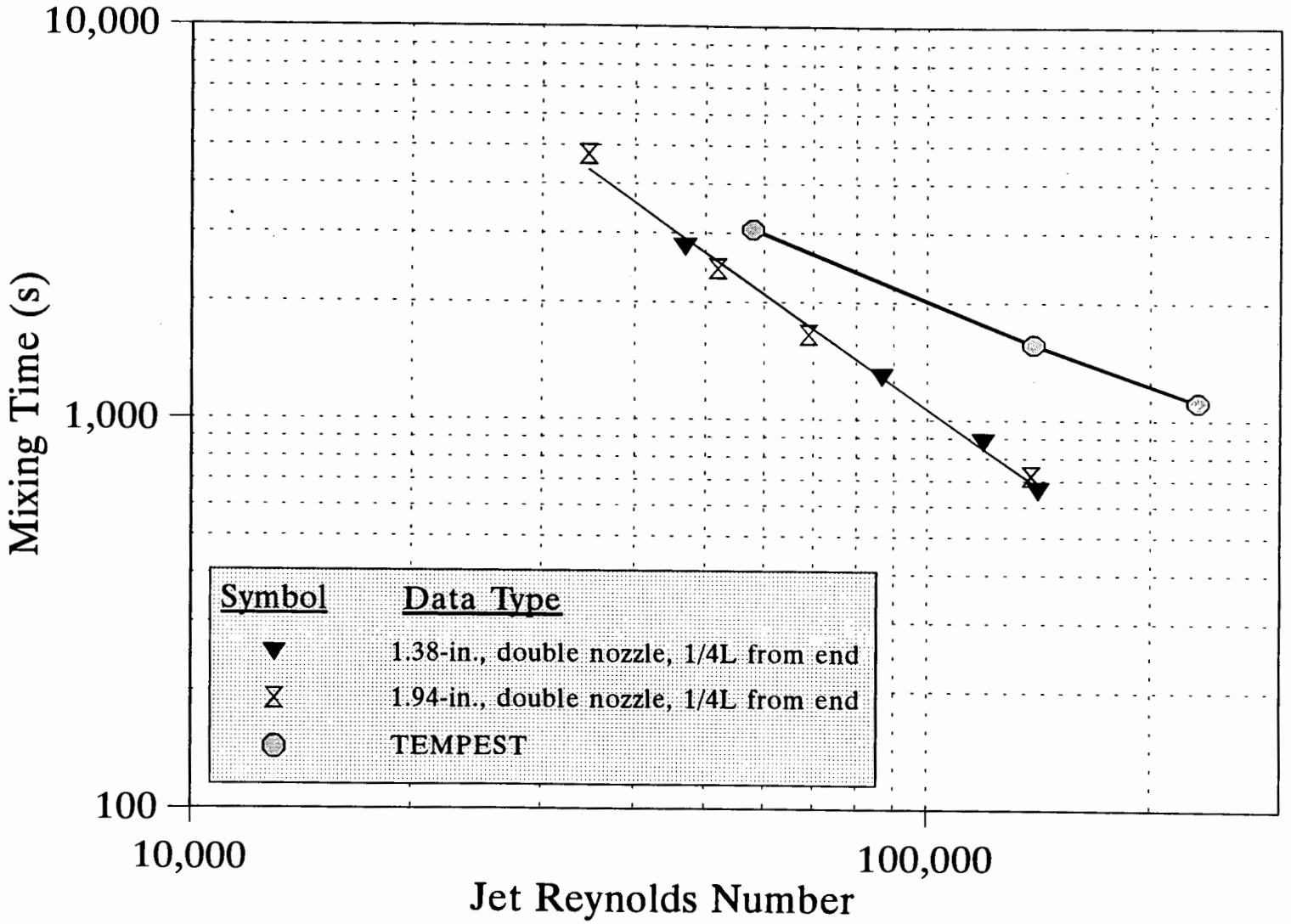

Fig. 13. Comparison of experimental data and TEMPEST simulations for the double-nozzle system.

at the same flow rate. At a given flow rate, mixing times were significantly lower with a 1.38-in. double jet than with a 1.94-in. double jet. The concept of correlating mixing times with the recirculation time of the developed jet was found to be valid. An empirical effective jet length was used to obtain an improved correlation. Comparison of experimental mixing times in the 25,000-gal tank with the TEMPEST simulations showed that TEMPEST can be used reliably for mixing time predictions for the full-scale tanks with single jets at all Reynolds numbers and also with double jets for jet Reynolds numbers below about 50,000. For most purposes, use of the empirical effective jet length correlation would probably be adequate and would require less time than a TEMPEST simulation run.

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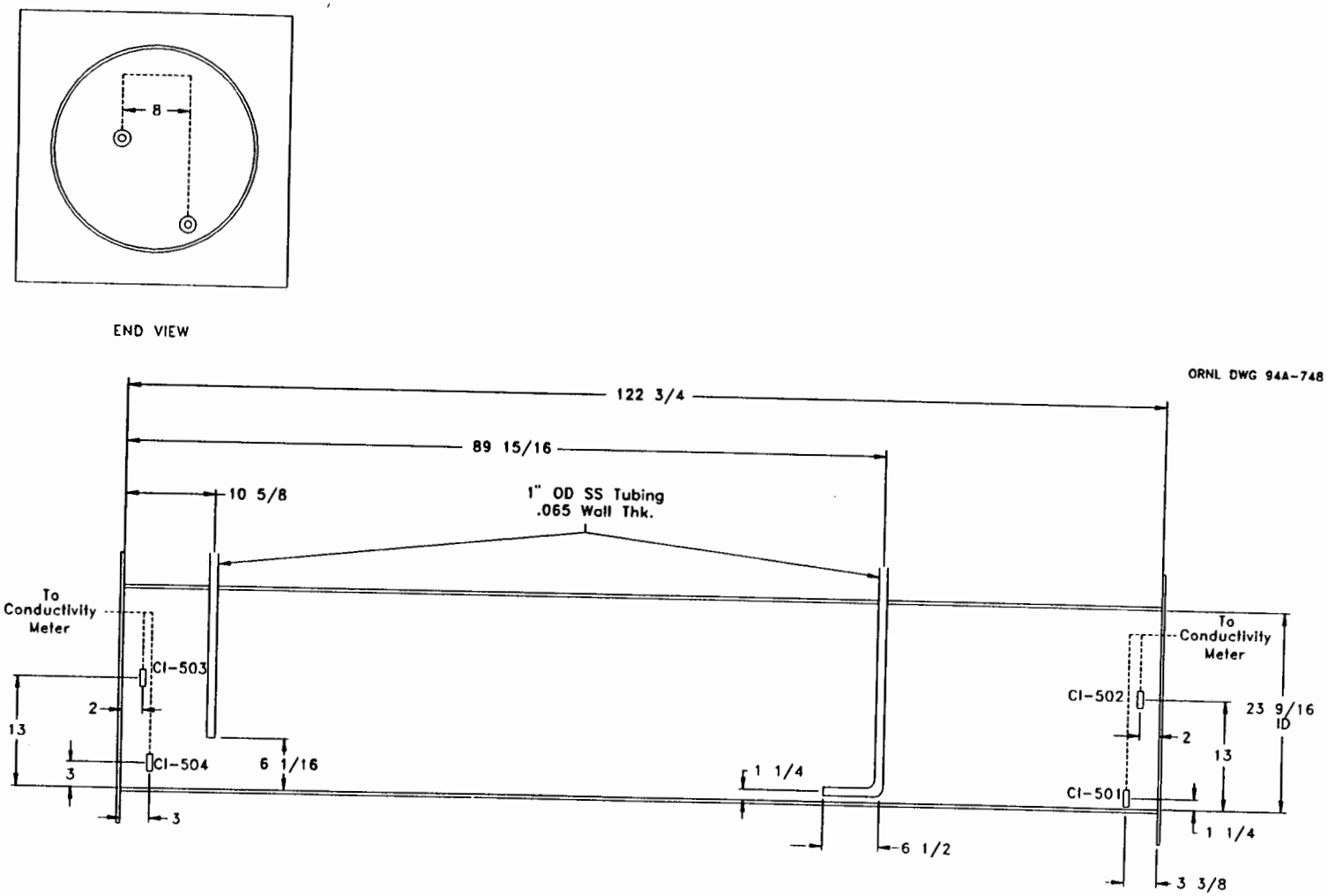
APPENDIX



All dimensions are in inches.

Fig. A.1. Sketch of the 230-gal tank illustrating a single nozzle located 1/4 tank length from the end of the tank.

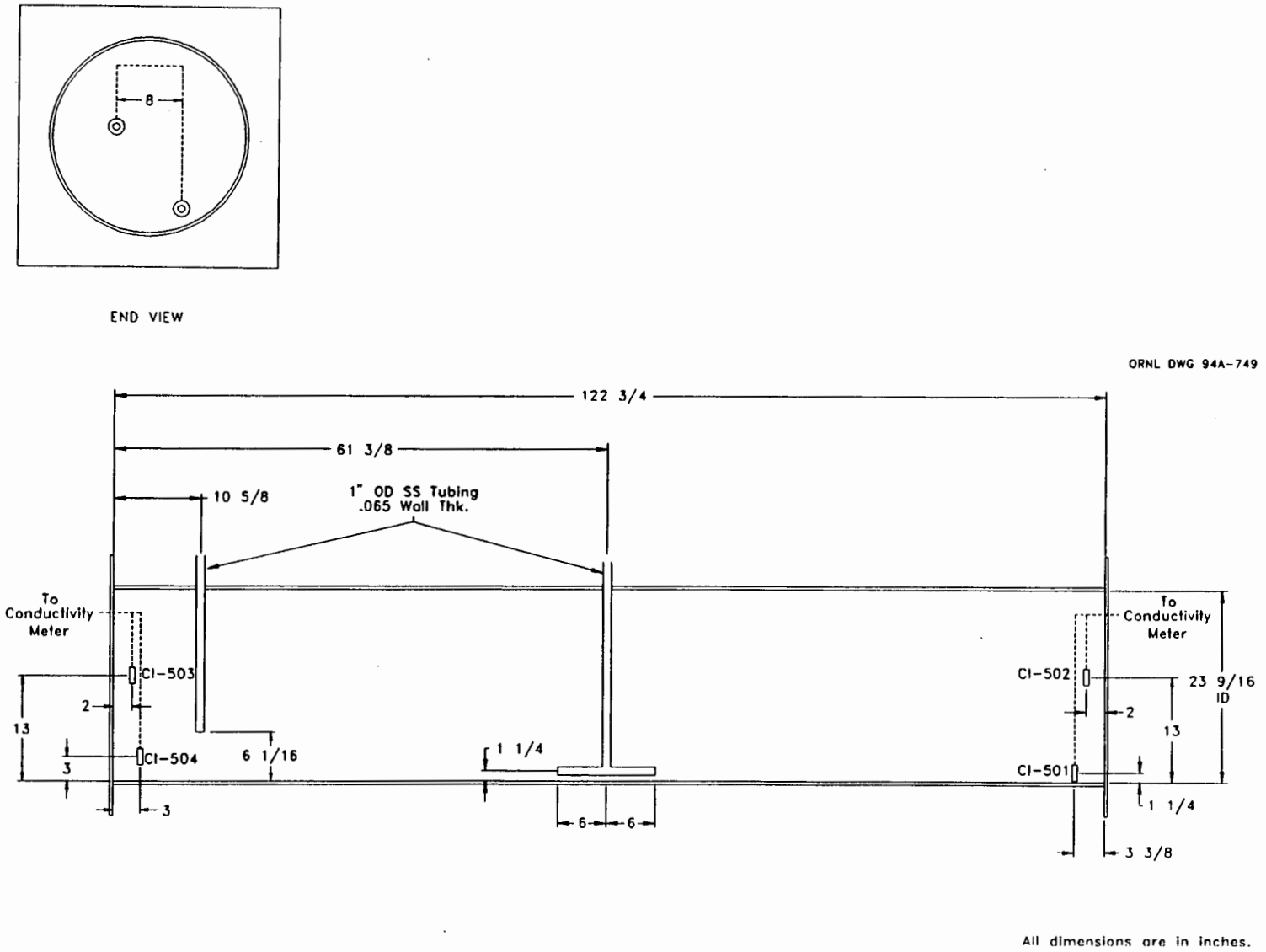


Fig. A.2. Sketch of the 230-gal tank with a double nozzle located in the center of the tank.

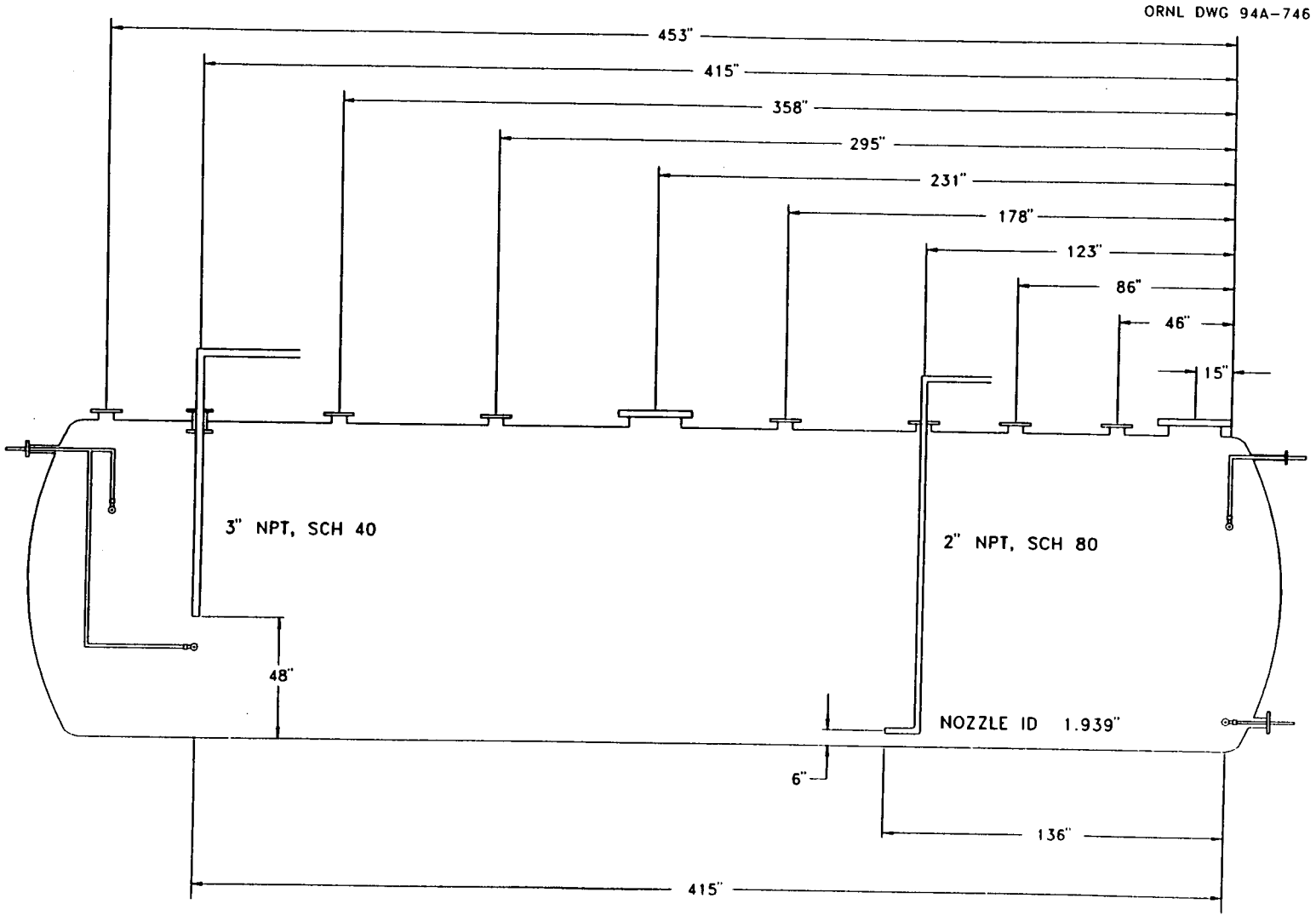


Fig. A.3. Sketch of the 25,000-gal tank illustrating a single nozzle located 1/4 tank length from the end of the tank.

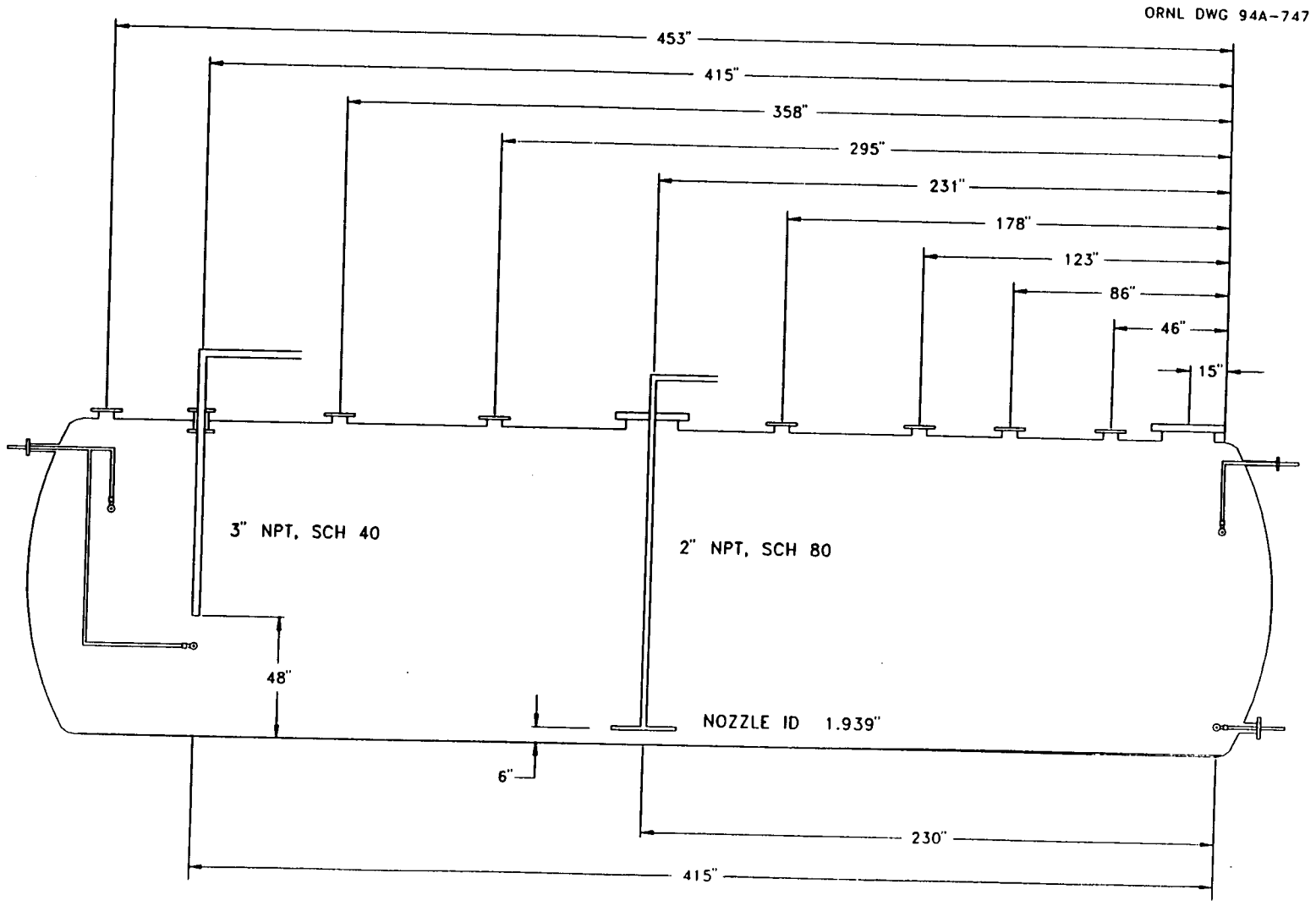


Fig. A.4. Sketch of the 25,000-gal tank with a double nozzle located in the center of the tank.

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