CALIBRATION OF FLOW NOZZLES USING WATER WITH EXTRAPOLATION TO STEAM

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Introduction and Summary

This report presents the results of calibration tests performed on two steam flow nozzles at the Engineering Research Center of Colorado State University in accordance with Westinghouse Electric Corporation Purchase Order 56-IC-46472-G dated April 22, 1969. The aim of the calibration was to relate the steam flow rate through the nozzles to the difference in pressure sensed at the nozzle taps. The calibration was performed with water in place of steam and the results of the calibration were corrected for steam analytically. The primary results for water are presented in Table II as a set of data relating discharge coefficient to Reynold's number.

The Reynold's numbers for the tests with water are lower than those that will be experienced with steam. Figure 4 shows the empirical curve determined for the extrapolation of the data to the higher Reynold's numbers. The calibration data for the two nozzles were so close that one curve fits both sets.

The relationship between pressure difference and steam flow given in Table III and Figure 5 were obtained from the empirical curve of Figure 4 with analytically determined corrections for the thermal properties of steam.

The calibration of Nozzle I was performed May 8, 1969 and the calibration of Nozzle 2 was done on May 17, 1969. The calibration data was collected by Mike Wittington, and the data reduction was done by Ikram Ul-Haque, both graduate students in Engineering.

Theoretical Considerations

The basic differential equation for the flow of a compressible fluid in a pipe of varying cross section (as for example a flow nozzle), with negligible heat lost to the pipe walls, is

$$Jdu \div d(pv) + d(\frac{V^2}{2g}) = 0 \tag{1}$$

where: u is the internal energy

p is the absolute pressure

v is the specific volume

V is the mean velocity across the pipe

g is the acceleration of gravity and

J is the conversion from mechanical energy to heat.

The terms of Equation 1 represent changes in internal energy, flow work and kinetic energy in that order. The middle term of Equation 1 can be divided into two parts to give

$$Jdu + pdv + vdp + d(\frac{V^2}{2g}) = 0 \tag{2}$$

The first two terms of Equation 2 appear in the definition of entropy s

$$JTds = Jdu + pdv \tag{3}$$

The two terms on the left in Equation 3 are considered thermal terms and the two terms on the right are considered mechanical terms. Friction always causes a loss of energy from the mechanical terms to the thermal terms. There is no process in a flow conduit that can cause energy to flow in the reverse direction.

For frictionless flow, Equation 2 becomes

$$vdp + d(\frac{V^2}{2g}) = 0 \tag{4}$$

Under conditions of incompressibility v is constant and Equation 4 can be integrated to give

$$(p_2-p_1)v = \frac{V_1^2}{2g} - \frac{V_2^2}{2g} \tag{5}$$

Equation 5 can be expressed in terms of the flow rate F, the cross sectional areas A_1 and A_2, and a calibration coefficient K in the form

$$F = \frac{K\sqrt{2g(p_2-p_1)v}}{\sqrt{(\frac{v}{A_1})^2 - (\frac{v}{A_2})^2}} \tag{6}$$

Under ideal conditions, the coefficient K would be unity but in practice it is somewhat less. The major cause for this difference is the boundary layer which has the effect of making the nozzle seem smaller than it is (displacement thickness). Since the boundary layer thickness is less with higher flows, the coefficient characteristically approaches unity as the flow is increased. The boundary layer thickness can be shown to be a function of the Reynold's number R_e defined by

$$R_e = \frac{VD}{\nu} \tag{7}$$

where D is the pipe diameter and ν is the kinematic viscosity. It follows that K is basically a function of R_e. The primary calibration using water obtained related values of K and R_e.

As long as the expansion of steam is not great the boundary layer thickness is not materially affected and the $K - R_e$ relationship obtained for water will be applicable to steam as well. Once the ideal flow rate pressure difference relationship is obtained for steam the coefficient K can be applied.

To obtain the pressure difference for steam, Equation 4 must be integrated with the constraint that the entropy of the steam be constant. Integration of the left hand term cannot be performed unless the p-v relationship is known. However the mean value theorem for integrals states that there is a constant k between zero and 1 such that

$$(p_2-p_1)(v + k\Delta v) = \frac{V_1^2}{2g} - \frac{V_2^2}{2g} \qquad (9)$$

where Δv is the change in specific volume. Then to get an expression parallel to Equation 6 we can write Equation 9 as

$$F \doteq \frac{K\sqrt{2g(p_2-p_1)(v+k\Delta v)}}{\sqrt{(\frac{v}{A_1})^2 - (\frac{v+\Delta v}{A_2})^2}} \qquad (10)$$

If Δv is small enough the assumption can be made that v varies linearly with p meaning that $k = 0.5$. If Δv is too large the nozzle can be treated in steps with each step having a small enough change in area that the assumption of linearity is good.

To solve Equation 10, the following steps can be performed:

Step 1. Set $K = 1$

Step 2. Compute v corresponding to p_1 and the percent dryness x_1 from steam tables

Step 3. Set $\Delta v = 0$

Step 4. Compute p_2

Step 5. Compute the percent dryness x_2 for zero entropy change from steam tables.

Step 6. Compute Δv for p_2 and x_2

Step 7. Repeat steps 4 through 6 to convergence

Step 8. Correct F for coefficient K.

Description of Nozzles

The geometry of the nozzles are shown in Figure 1. The nozzles when received had identical markings:

W

S. O. #3395-1

Mil - S23194A C/S

HT #213060

To distinguish between them they were stamped 1 and 2 on the outside face of the pressure manifold. Micrometer reading of the throat diameter averaged 4.516 inches at room temperature (about 20°C) for both nozzles. The upstream pipe and tap was furnished by CSU and the diameter at the tap was measured as 6.081 inches. Under 1000 psia and 544°F it is estimated that the diameter would expand by 0.34 percent which would mean an increase in flow rate of 0.68 percent. This expansion was allowed for in the computations.

Description of the Test Facility

The tests were performed at the main flow calibration facilities of the Engineering Research Center which are shown diagrammatically in

Figure 2. The nozzles were installed in the 12-inch line as shown in Figure 3.

To find the flow rate, water from the nozzle is diverted into volumetric tanks for a specified period of time measured and controlled by a pulse counter operating off the AC power line. The volume of water collected in the tank is measured by a precision hook gauge. The water temperature is measured on samples collected from the flow diverter. The pressure difference was measured by two separate systems set up especially for these tests (Mercury manometers usually used were not allowed under the specifications). For high flows, a set of three differential manometers each 12 feet long with acetylene tetrabromide (S.G. 2.95) as the indicating fluid were provided. These were connected to the nozzle taps in series with each other. The tubes had large bores (9/16-inch) for accurate meniscus formation. For low flows, an inverted air-water manometer was used for larger manometer deflections.

The proposal for this study stated that open well hook guages would be used for low flows but these proved to be impractical. The air-water manometer is not quite as accurate as the open well system was predicted to be and, as a result, the data for the lowest flows show the most scatter.

Description of the Test Procedure

Each of the flow nozzles were calibrated for 15 discharges, adhering as close as possible to the quantities outlined in the pre-calibration data of Table I. The only difference was the

Table I. Pre-calibration Data for Calibration of Westinghouse Steam Flow Nozzles

Run No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Flow rate (gpm)	450	675	900	1125	1350	1575	1800	2025	2250	2475	2700	2925	3150	3375	3600
Run time (min)	10.0	7.0	5.0	4.0	3.5	3.0	2.5	2.5	2.0	2.0	1.75	1.75	1.5	1.5	1.5
Sample (gals)	4500	4725	4500	4500	4725	4725	4500	5062	4500	4950	4725	5120	4725	5060	5400
Volume error per rdg. (gals)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Number of readings	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Percent volume error	.09	.08	.08	.09	.08	.08	.09	.08	.09	.08	.08	.08	.08	.08	.07
Percent time error (Accuracy of 60 cps)	.00	.00	.00	.01	.01	.02	.03	.03	.04	.04	.05	.05	.06	.06	.06
Manometer system	Hook gauges				1 manometer					2 manometers				3 man.	
Total Man. Def. (ft)	0.87	2.0	3.5	5.5	4.0	5.5	7.2	9.1	11.2	14.1	16.9	19.0	22.1	25.2	28.8
Error per rdg. (ft)	.001	.001	.001	.001	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005
Number of readings (ft)	2	2	2	2	2	2	2	2	2	4	4	4	4	6	6
Percent pressure error	.22	.10	.06	.04	.25	.20	.14	.11	.09	.14	.12	.10	.09	.12	.10

substitution of an inverted air-water manometer for the hook guage arrangement indicated for Runs 1 through 4. The reading error for this manometer nominally would be .005 feet, as for the others, but the long run time for these runs allowed repeated readings for higher accuracy.

The step-by-step procedure adopted was as follows:

Step 1. With the pumps operating and with water recirculating through the nozzle but bypassing the volumetric tank, the valves were adjusted to obtain the desired flow rate as indicated by the precalculated manometer deflections of Table I.

Step 2. The following data was recorded:

a. the temperature of flowing water

b. the temperature of air

c. the temperature of water bled from manometer lines

d. the level of water in the volumetric tanks

e. the manometer levels.

For some runs the manometer lines were bled to check for air accumulation and the manometers were short circuited to check the null balance.

Step 3. The timer was started which automatically diverts the flow into the volumetric tanks,

Step 4. Manometer levels were measured repeatedly during the run to get as many readings as time allowed.

Step 5. The timer was stopped which automatically diverts the flow to the sump.

Step 6. Step 2 was repeated.

Step 7. The volumetric tanks were emptied by pumping into the sump and preliminary calculations were made to catch gross errors. Several runs were repeated on the basis that there were gross errors but only those for which the source of the error could be identified.

Evaluation of Systematic Errors

The calibration equipment has been designed to minimize or correct for most causes of systematic error. The sources of possible systematic error are:

1. calibration of the volumetric tank
2. variations in the 60 cycle AC current for the timer
3. non-uniformity of the flow diverting process
4. variations of the density and viscosity of the flowing water
5. variation of the specific weight of the fluid in the manometer and the connecting lines
6. inaccuracy of the manometer scales
7. meniscus effects
8. local variation of the acceleration of gravity
9. bouyancy of the fluids due to local barometric pressure
10. tank leakage and evaporation.

The evaluation and treatment of these error sources were as follows:

1. <u>Volumetric tank calibration</u> The tanks have been calibrated periodically by filling them with water in 240 pound increments weighed on a special scale calibrated by weights checked by the National Bureau of Standards in Boulder, Colorado. The depth volume relationship is known accurate to at least ±2 gallons over the 6000 gallon range.

2. Timer variations   The accuracy of the timer depends on the accuracy of the 60 cycle A.C. power supply. The power supply has been checked periodically against the government time signal from Station WWV in Fort Collins. The average error experienced has varied from .09 percent for a period of 1 minute to .0003 percent for 10 minutes.

3. Diversion process   The time required to complete the diversion from the sump to the volumetric tank, or vice-versa, is less than two seconds. The equipment is designed so that the amount of flow diverted varies linearly with time during that interval. If it is perfectly linear, there is no error introduced by the diversion process. However, there is no way to evaluate this possible source of error except to see if there is a systematic error associated with sampling time and none has been detected.

4. Density and viscosity of the flowing water   The density and viscosity of water was determined from the water temperature using standard tables*. Temperatures were read with a precision thermometer to 0.5° F. This permitted density to be computed to .02 percent and viscosity to about 1.0 percent. This accuracy for viscosity is acceptable since the discharge coefficient was found to vary about .01 percent for a one percent change in viscosity. Incidently, the mass density is the important property of the flowing fluid rather than the specific weight as far as the flow nozzle is concerned.

5. Specific weight of manometer fluid   The specific weight of the manometer fluid was determined from temperature readings of the

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*Meyer, C.A., McClintock, R.B., Siverstri, G.J. and Spencer, R.G. JR., Thermodynamic and Transport Properties of Steam, ASME Research Committee on the Properties of Steam. ASME, United Engineering Center, New York, 1967.

surrounding air. The relationship of the specific weight of the acetylene tetrabromide to temperature was evaluated from pycnometer determinations.

6. Manometers scales   The manometer scales were standard steel measuring tapes accurate to at least .002 feet over ten feet.

7. Meniscus effects   The capillarity associated with the meniscus is ideally balanced out in a differential manometer. Nevertheless, large tube diameters (9/16-inch) were used and the tubes were thoroughly cleaned and filled with fresh manometer fluid.

8. Acceleration of gravity   The variation of g over the United States is 0.2 percent. In Colorado the value differs about .04 percent from a value of 980.0 cm/sec^2.

9. Bouyancy of air   The bouyancy of the atmosphere affects the specific weight of water by about 0.13 percent. The difference in this bouyancy at Fort Collins (Elev 5000) and at sea level is about .02 percent.

10. Tank leakage and evaporation   The amounts of water lost due to tank leakage and evaporation are completely negligible.

Evaluation of Random Errors

Random errors are those that cause scatter of the data. They arise mainly from the determination of the volume of the sample and the deflection of the manometer.

The volume of water collected in the volumetric tanks is determined by measuring the height of the water surface with a hook guage before and after the run. The hook guage has a vernier which reads to 0.001 feet, equivalent to about 0.8 gallons of tank capacity. However, it is difficult to repeat readings to this accuracy and ±2 gallons is a reasonable estimate of the maximum random error for each measurement. Table I gives for each run the resulting percent error in volume expected from each of the two measurements required.

The manometer deflection is determined by measuring the elevation of the top of both meniscuses relative to the tape scale. The tapes are graduated in hundredths of a foot and readings are estimated to thousandths of a foot. However, fluctuation of the meniscus level and errors of parallax make .005 feet a reasonable maximum error for manometer readings. The last row of Table I shows the expected percent error in pressure for this order of accuracy. These figures are reasonable except for the first four runs which are based on hook guages readable to .001 inch. Without hook guages, the percent pressure error can be expected to be about five times the value given. It should be remembered that the square root of pressure is only one half as much as for pressure itself. Furthermore, the manometer deflections recorded were the average of a number of readings for these first runs, which should improve the accuracy.

Results for Water

The value of K and R_e obtained for the 15 runs for each flow nozzle are given in Table II. The values are also shown plotted in Figure 4. The scatter of the data is emphasized by the large scale chosen for K. The data for the two nozzles were so close that one curve could be fitted to both sets. The curve chosen was the exponential curve discussed earlier. The coefficients A and B were chosen to produce a least squares fit. With A = 0.35 and B = 0.45, the data of Nozzle 1 fitted with a root-mean-square error of 0.34 percent and Nozzle 2 with an error of 0.32 percent.

Table II

Discharge Coefficients and Reynold's Numbers for the Flow Nozzles

Nozzle 1 K	Nozzle 1 R_e	Nozzle 2 K	Nozzle 2 R_e
.9681	$1.94(10^5)$	.9778	$2.51(10^5)$
.9686	3.33	.9656	3.64
.9761	4.38	.9746	4.86
.9712	5.41	.9736	6.15
.9670	6.37	.9742	7.28
.9740	7.37	.9770	8.47
.9696	8.11	.9770	9.79
.9700	9.08	.9761	11.23
.9736	9.91	.9773	12.42
.9770	11.83	.9788	14.08
.9809	13.10	.9802	15.83
.9788	14.06	.9816	16.95
.9810	15.03	.9831	18.10
.9778	15.99	.9824	19.15
.9801	16.89	.9818	19.97

Results for Steam

Pressure differences and flow rates are related in Table III for dry saturated steam. The table covers flow rates from 30,000 to 300,000 pounds of steam per hour, with pipe line pressures varying from 500 to 1000 psia. The pressure difference values were determined by computer using the step-by-step procedure outlined earlier. Pressure differences assuming incompressibility are shown in brackets in Table III for comparison. The steam properties including viscosity were obtained from tables in the ASME publication referred to earlier. Key values of Table III are plotted in Figure 5 to provide a more convenient form for use.

Of course, the steam in the pipe line may not be in a dry saturation condition. Table IV shows, for comparison, pressure differences for steam which is 99 percent dry.

COLORADO STATE UNIVERSITY - CALIBRATION OF WESTINGHOUSE STEAM NOZZLE

STEAM QUALITY 100 PERCENT DRY

TABULATED VALUES ARE PRESSURE DIFF IN PSI FOR STEAM
BRACKETED VALUES ARE PRESSURE IN PSI ASSUMING INCOMPRESSIBILITY

PIPE PRESSURE PSIA	FLOW RATE IN POUNDS PER HOUR 30000	60000	90000	120000	150000	180000	210000	240000	270000	300000
500	.405	1.617	3.659	6.572	10.419	15.294	21.327	28.706	37.704	48.736
	(.404)	(1.607)	(3.604)	(6.396)	(9.979)	(14.355)	(19.521)	(25.477)	(32.223)	(39.759)
520	.389	1.553	3.512	6.302	9.979	14.624	20.351	27.314	35.738	45.956
	(.388)	(1.544)	(3.463)	(6.145)	(9.588)	(13.792)	(18.755)	(24.478)	(30.959)	(38.200)
540	.374	1.494	3.376	6.052	9.572	14.007	19.454	26.050	33.983	43.521
	(.373)	(1.485)	(3.332)	(5.912)	(9.225)	(13.270)	(18.045)	(23.551)	(29.788)	(36.754)
560	.360	1.438	3.249	5.820	9.197	13.440	18.636	24.900	32.393	41.339
	(.360)	(1.431)	(3.210)	(5.696)	(8.887)	(12.784)	(17.384)	(22.689)	(28.697)	(35.408)
580	.347	1.387	3.131	5.605	8.849	12.917	17.884	23.852	30.956	39.384
	(.347)	(1.380)	(3.096)	(5.494)	(8.572)	(12.330)	(16.767)	(21.883)	(27.678)	(34.151)
600	.335	1.339	3.021	5.405	8.526	12.433	17.190	22.888	29.643	37.617
	(.335)	(1.333)	(2.990)	(5.305)	(8.277)	(11.906)	(16.191)	(21.131)	(26.726)	(32.977)
620	.324	1.294	2.918	5.218	8.226	11.983	16.551	22.004	28.447	36.015
	(.324)	(1.288)	(2.890)	(5.128)	(8.000)	(11.508)	(15.649)	(20.425)	(25.833)	(31.874)
640	.314	1.251	2.822	5.043	7.945	11.564	15.955	21.185	27.344	34.553
	(.313)	(1.246)	(2.796)	(4.961)	(7.741)	(11.134)	(15.141)	(19.761)	(24.994)	(30.839)
660	.304	1.211	2.731	4.879	7.682	11.174	15.402	20.427	26.329	33.211
	(.303)	(1.207)	(2.708)	(4.804)	(7.496)	(10.782)	(14.662)	(19.136)	(24.204)	(29.864)
680	.294	1.174	2.646	4.725	7.434	10.807	14.884	19.721	25.388	31.977
	(.294)	(1.170)	(2.624)	(4.656)	(7.265)	(10.450)	(14.211)	(18.547)	(23.458)	(28.943)
700	.285	1.138	2.565	4.579	7.201	10.461	14.397	19.057	24.506	30.824
	(.285)	(1.135)	(2.545)	(4.516)	(7.047)	(10.136)	(13.784)	(17.990)	(22.753)	(28.074)
720	.277	1.105	2.489	4.441	6.982	10.136	13.939	18.435	23.681	29.748
	(.277)	(1.101)	(2.471)	(4.384)	(6.840)	(9.839)	(13.380)	(17.463)	(22.086)	(27.252)
740	.269	1.073	2.417	4.311	6.774	9.830	13.509	17.852	22.909	28.745
	(.269)	(1.070)	(2.400)	(4.259)	(6.645)	(9.558)	(12.997)	(16.963)	(21.455)	(26.472)
760	.262	1.043	2.348	4.188	6.578	9.541	13.104	17.304	22.187	27.811
	(.261)	(1.040)	(2.333)	(4.140)	(6.459)	(9.291)	(12.634)	(16.489)	(20.855)	(25.732)
780	.254	1.014	2.283	4.071	6.392	9.267	12.721	16.788	21.509	26.937
	(.254)	(1.011)	(2.269)	(4.026)	(6.282)	(9.036)	(12.288)	(16.038)	(20.284)	(25.028)
800	.248	.987	2.221	3.960	6.216	9.008	12.359	16.300	20.870	26.113
	(.247)	(.984)	(2.208)	(3.919)	(6.114)	(8.795)	(11.959)	(15.609)	(19.742)	(24.358)
820	.241	.961	2.163	3.854	6.048	8.761	12.016	15.840	20.268	25.341
	(.241)	(.959)	(2.151)	(3.816)	(5.954)	(8.564)	(11.646)	(15.199)	(19.224)	(23.719)
840	.235	.936	2.106	3.753	5.888	8.527	11.689	15.402	19.695	24.608
	(.235)	(.934)	(2.095)	(3.718)	(5.801)	(8.344)	(11.346)	(14.808)	(18.730)	(23.110)
860	.229	.912	2.053	3.657	5.736	8.303	11.379	14.985	19.152	23.914
	(.229)	(.910)	(2.042)	(3.624)	(5.655)	(8.133)	(11.060)	(14.435)	(18.258)	(22.527)
880	.223	.890	2.002	3.565	5.590	8.090	11.082	14.589	18.635	23.255
	(.223)	(.888)	(1.992)	(3.534)	(5.515)	(7.932)	(10.787)	(14.078)	(17.806)	(21.970)
900	.218	.868	1.953	3.477	5.451	7.887	10.800	14.211	18.145	22.630
	(.218)	(.866)	(1.944)	(3.449)	(5.381)	(7.740)	(10.525)	(13.737)	(17.374)	(21.437)
920	.213	.847	1.906	3.393	5.318	7.693	10.531	13.852	17.678	22.036
	(.213)	(.846)	(1.897)	(3.367)	(5.253)	(7.555)	(10.274)	(13.409)	(16.960)	(20.926)
940	.208	.827	1.861	3.313	5.191	7.507	10.273	13.508	17.232	21.471
	(.208)	(.826)	(1.853)	(3.288)	(5.130)	(7.379)	(10.034)	(13.096)	(16.563)	(20.437)
960	.203	.808	1.818	3.235	5.069	7.329	10.027	13.180	16.807	20.932
	(.203)	(.807)	(1.810)	(3.212)	(5.012)	(7.209)	(9.803)	(12.794)	(16.182)	(19.966)
980	.198	.790	1.776	3.161	4.952	7.158	9.791	12.865	16.400	20.417
	(.198)	(.789)	(1.769)	(3.139)	(4.898)	(7.046)	(9.581)	(12.504)	(15.815)	(19.514)
1000	.194	.772	1.736	3.090	4.839	6.994	9.564	12.564	16.010	19.923
	(.194)	(.771)	(1.730)	(3.069)	(4.789)	(6.889)	(9.367)	(12.226)	(15.463)	(19.079)

Table III

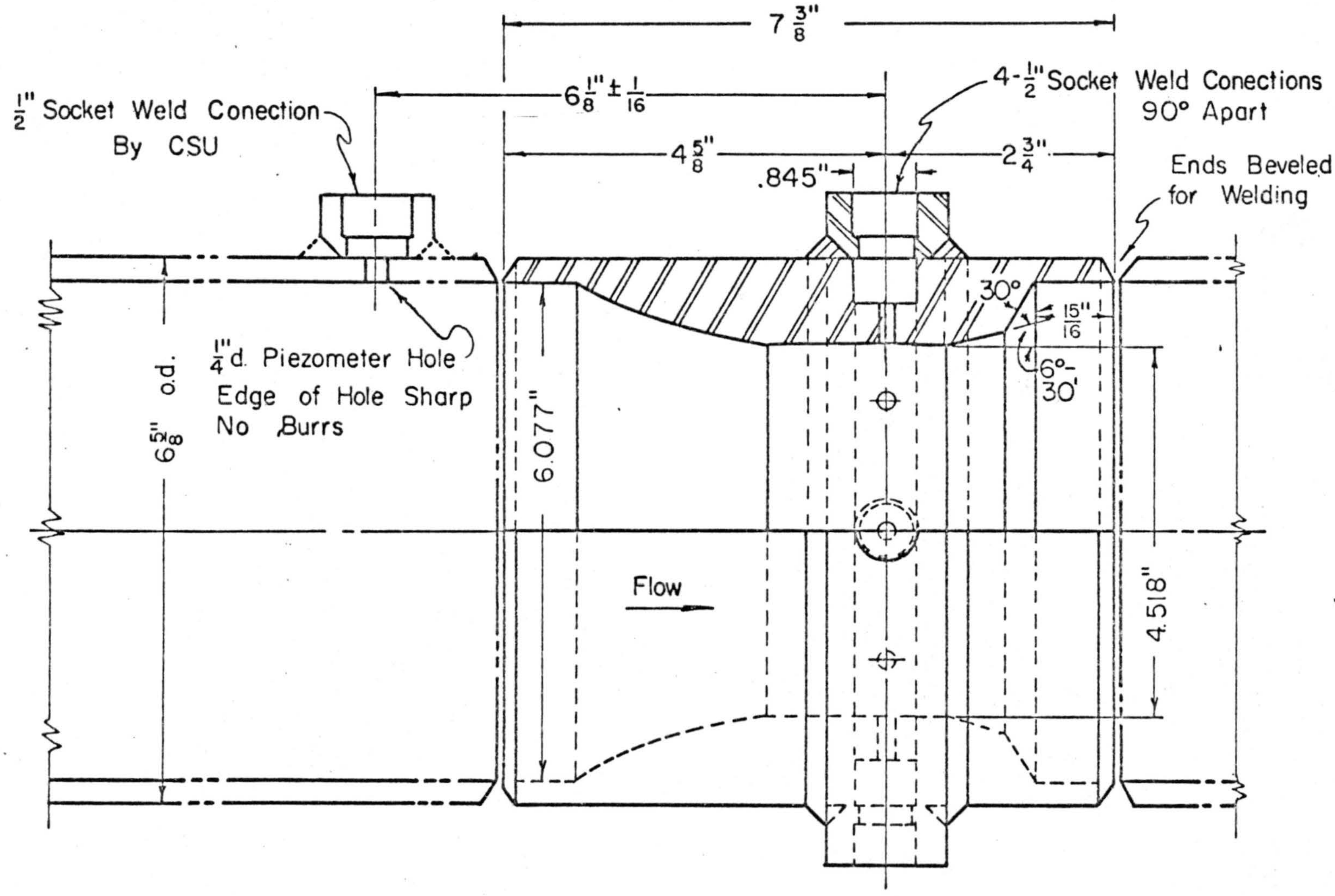
COLORADO STATE UNIVERSITY - CALIBRATION OF WESTINGHOUSE STEAM NOZZLE

STEAM QUALITY 99 PERCENT DRY

TABULATED VALUES ARE PRESSURE DIFF IN PSI FOR STEAM
BRACKETED VALUES ARE PRESSURE IN PSI ASSUMING INCOMPRESSIBILITY

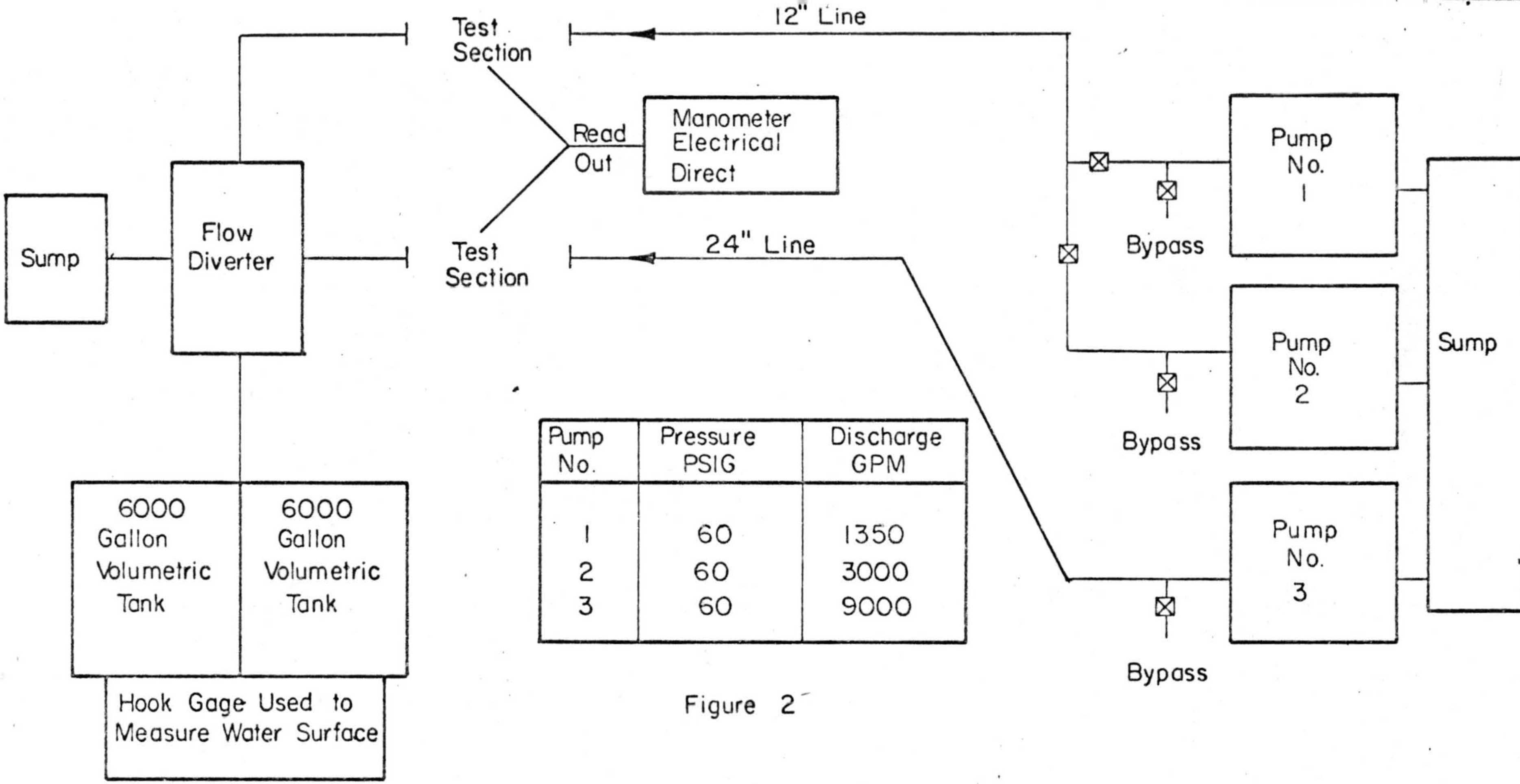
PIPE PRESSURE	FLOW RATE IN POUNDS PER HOUR									
PSIA	30000	60000	90000	120000	150000	180000	210000	240000	270000	300000
500	.401	1.602	3.623	6.506	10.314	15.136	21.102	28.394	37.278	48.155
	(.400)	(1.591)	(3.569)	(6.334)	(9.882)	(14.215)	(19.331)	(25.229)	(31.909)	(39.372)
520	.385	1.538	3.477	6.239	9.878	14.474	20.138	27.021	35.341	45.421
	(.384)	(1.529)	(3.429)	(6.085)	(9.495)	(13.657)	(18.573)	(24.240)	(30.658)	(37.828)
540	.370	1.479	3.342	5.992	9.476	13.864	19.252	25.773	33.610	43.024
	(.370)	(1.471)	(3.300)	(5.855)	(9.136)	(13.141)	(17.870)	(23.322)	(29.498)	(36.397)
560	.357	1.424	3.217	5.763	9.105	13.304	18.444	24.637	32.041	40.874
	(.356)	(1.417)	(3.179)	(5.641)	(8.801)	(12.660)	(17.216)	(22.469)	(28.418)	(35.064)
580	.344	1.373	3.100	5.550	8.761	12.787	17.701	23.602	30.624	38.948
	(.344)	(1.367)	(3.066)	(5.441)	(8.489)	(12.210)	(16.605)	(21.671)	(27.410)	(33.820)
600	.332	1.326	2.992	5.352	8.442	12.308	17.015	22.650	29.328	37.205
	(.332)	(1.320)	(2.961)	(5.254)	(8.197)	(11.791)	(16.034)	(20.926)	(26.468)	(32.657)
620	.321	1.281	2.890	5.167	8.144	11.863	16.382	21.777	28.146	35.625
	(.321)	(1.276)	(2.862)	(5.078)	(7.923)	(11.397)	(15.498)	(20.227)	(25.583)	(31.566)
640	.311	1.239	2.794	4.994	7.866	11.449	15.793	20.967	27.058	34.182
	(.310)	(1.234)	(2.769)	(4.913)	(7.666)	(11.027)	(14.995)	(19.570)	(24.752)	(30.541)
660	.301	1.200	2.705	4.832	7.606	11.063	15.247	20.218	26.055	32.858
	(.300)	(1.195)	(2.681)	(4.758)	(7.424)	(10.678)	(14.521)	(18.952)	(23.970)	(29.575)
680	.291	1.163	2.620	4.679	7.361	10.699	14.734	19.520	25.126	31.640
	(.291)	(1.158)	(2.599)	(4.611)	(7.195)	(10.349)	(14.074)	(18.368)	(23.231)	(28.664)
700	.283	1.127	2.540	4.534	7.131	10.358	14.253	18.864	24.254	30.501
	(.282)	(1.124)	(2.521)	(4.473)	(6.979)	(10.039)	(13.651)	(17.816)	(22.534)	(27.804)
720	.274	1.094	2.465	4.398	6.913	10.036	13.800	18.249	23.438	29.438
	(.274)	(1.091)	(2.447)	(4.342)	(6.775)	(9.744)	(13.251)	(17.295)	(21.874)	(26.989)
740	.267	1.063	2.393	4.269	6.708	9.733	13.375	17.672	22.676	28.448
	(.266)	(1.060)	(2.377)	(4.218)	(6.581)	(9.466)	(12.872)	(16.800)	(21.249)	(26.218)
760	.259	1.033	2.326	4.147	6.514	9.447	12.974	17.131	21.963	27.525
	(.259)	(1.030)	(2.311)	(4.100)	(6.397)	(9.201)	(12.513)	(16.331)	(20.655)	(25.485)
780	.252	1.005	2.261	4.032	6.330	9.176	12.596	16.621	21.292	26.661
	(.252)	(1.002)	(2.247)	(3.988)	(6.222)	(8.950)	(12.171)	(15.884)	(20.090)	(24.788)
800	.245	.978	2.200	3.922	6.155	8.920	12.237	16.138	20.660	25.848
	(.245)	(.975)	(2.187)	(3.881)	(6.056)	(8.710)	(11.845)	(15.459)	(19.552)	(24.125)
820	.239	.952	2.142	3.817	5.990	8.676	11.898	15.683	20.065	25.084
	(.239)	(.949)	(2.130)	(3.779)	(5.897)	(8.482)	(11.534)	(15.054)	(19.040)	(23.492)
840	.233	.927	2.086	3.717	5.831	8.444	11.575	15.249	19.498	24.360
	(.233)	(.925)	(2.075)	(3.682)	(5.745)	(8.264)	(11.238)	(14.667)	(18.551)	(22.889)
860	.227	.904	2.033	3.622	5.680	8.223	11.267	14.837	18.961	23.674
	(.227)	(.902)	(2.023)	(3.589)	(5.601)	(8.056)	(10.955)	(14.297)	(18.083)	(22.312)
880	.221	.881	1.983	3.531	5.536	8.012	10.974	14.445	18.451	23.022
	(.221)	(.879)	(1.973)	(3.501)	(5.462)	(7.857)	(10.684)	(13.944)	(17.636)	(21.761)
900	.216	.860	1.934	3.444	5.399	7.811	10.695	14.072	17.965	22.404
	(.216)	(.858)	(1.925)	(3.416)	(5.330)	(7.666)	(10.425)	(13.606)	(17.209)	(21.233)
920	.211	.839	1.888	3.361	5.267	7.618	10.429	13.716	17.504	21.817
	(.211)	(.838)	(1.879)	(3.335)	(5.203)	(7.484)	(10.177)	(13.282)	(16.799)	(20.727)
940	.206	.820	1.843	3.281	5.141	7.434	10.174	13.376	17.063	21.258
	(.206)	(.818)	(1.835)	(3.257)	(5.081)	(7.309)	(9.939)	(12.971)	(16.406)	(20.242)
960	.201	.801	1.800	3.205	5.021	7.258	9.930	13.052	16.642	20.725
	(.201)	(.799)	(1.793)	(3.182)	(4.964)	(7.140)	(9.710)	(12.673)	(16.028)	(19.777)
980	.196	.783	1.759	3.131	4.905	7.089	9.696	12.741	16.240	20.216
	(.196)	(.781)	(1.753)	(3.110)	(4.852)	(6.979)	(9.490)	(12.386)	(15.665)	(19.329)
1000	.192	.765	1.720	3.061	4.793	6.927	9.472	12.442	15.854	19.728
	(.192)	(.764)	(1.713)	(3.040)	(4.744)	(6.823)	(9.279)	(12.110)	(15.317)	(18.898)

Table IV



7 3/8"
6 1/8" ± 1/16
1/2" Socket Weld Conection By CSU
4-1/2" Socket Weld Conections 90° Apart
4 5/8"
2 3/4"
.845"
Ends Beveled for Welding
30°
15/16"
6°-30'
1/4"d. Piezometer Hole Edge of Hole Sharp No Burrs
6 5/8" o.d.
6.077"
4.518"
Flow

Figure 1



Pump No.	Pressure PSIG	Discharge GPM
1	60	1350
2	60	3000
3	60	9000

Figure 2

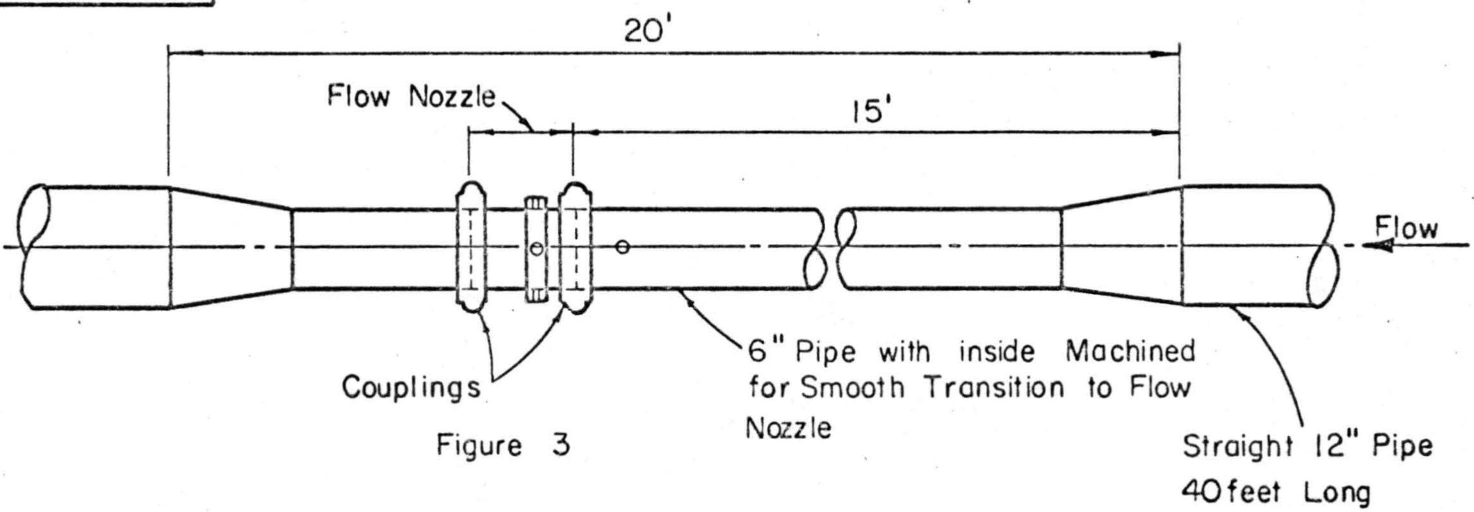


Figure 3

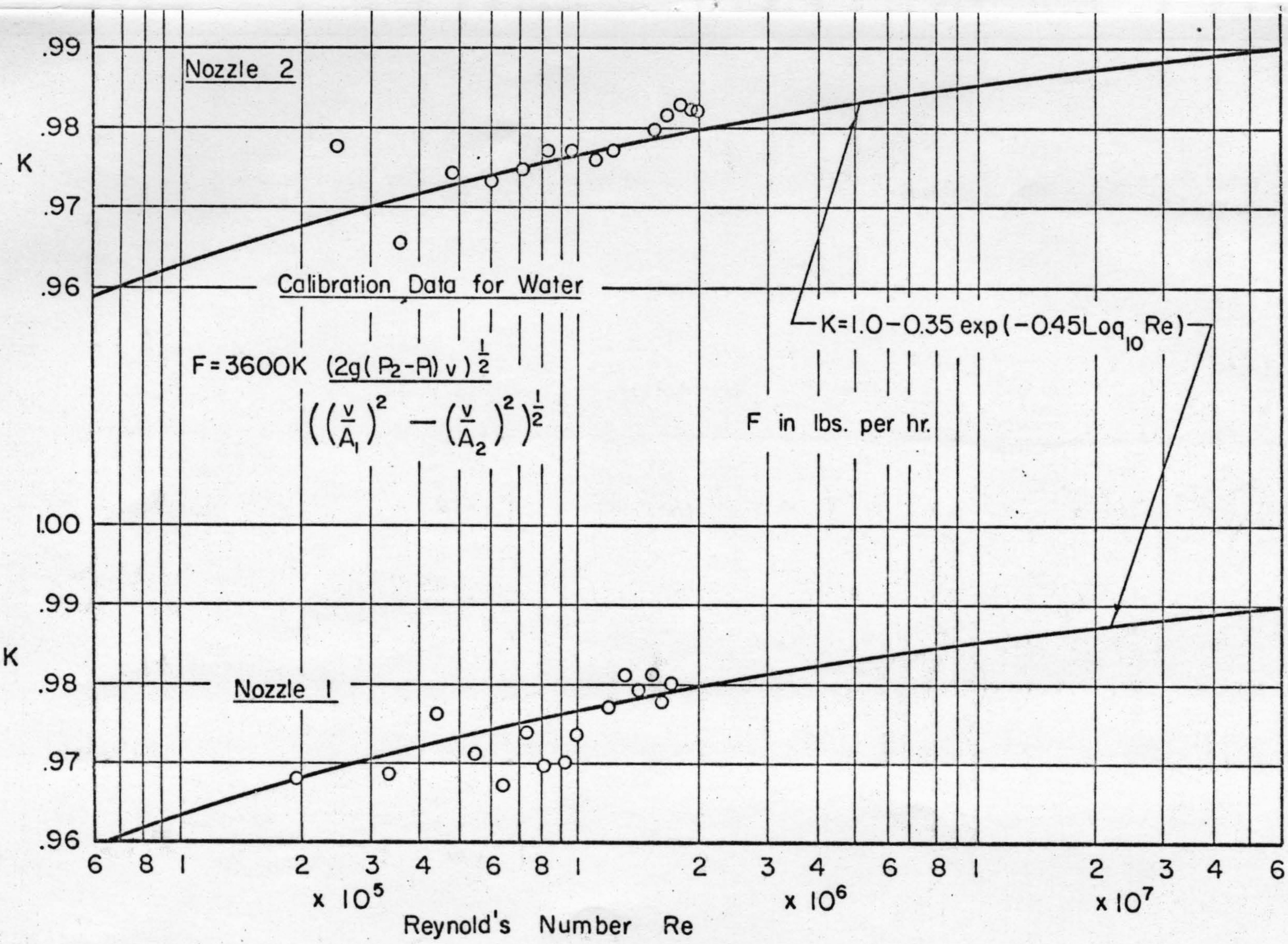
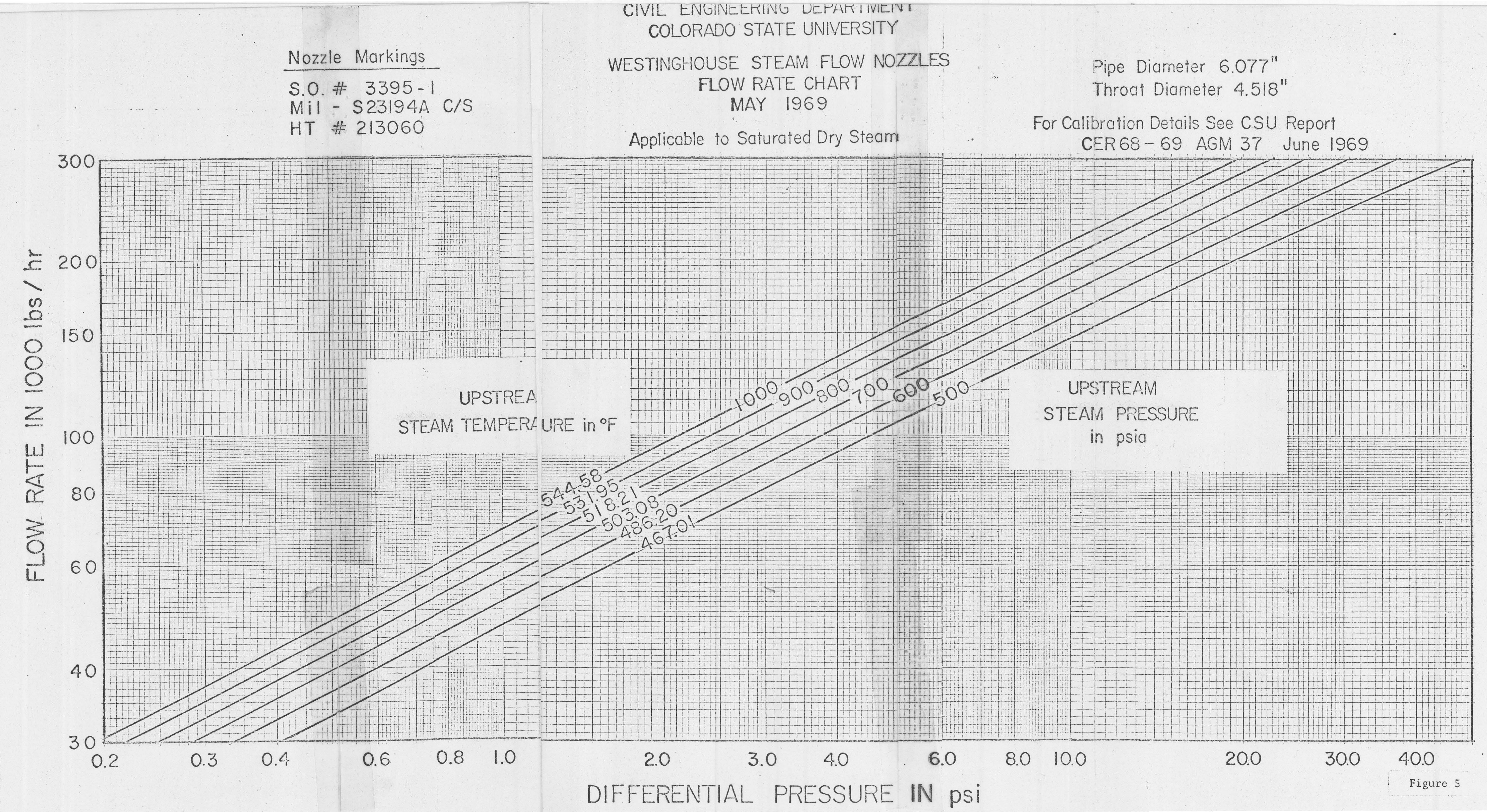

Nozzle 2
.99
.98
.97
.96
K
Calibration Data for Water
$K=1.0-0.35\exp(-0.45\,Log_{10}\,Re)$
$F=3600K\dfrac{(2g(P_2-P_1)v)^{\frac{1}{2}}}{\left(\left(\frac{v}{A_1}\right)^2-\left(\frac{v}{A_2}\right)^2\right)^{\frac{1}{2}}}$
F in lbs. per hr.
1.00
.99
.98
.97
.96
K
Nozzle 1
6 8 1 2 3 4 6 8 1 2 3 4 6 8 1 2 3 4 6
x 10^5
x 10^6
x 10^7
Reynold's Number Re

Figure 4


CIVIL ENGINEERING DEPARTMENT
COLORADO STATE UNIVERSITY
Nozzle Markings
S.O. # 3395-1
Mil - S23194A C/S
HT # 213060
WESTINGHOUSE STEAM FLOW NOZZLES
FLOW RATE CHART
MAY 1969
Applicable to Saturated Dry Steam
Pipe Diameter 6.077"
Throat Diameter 4.518"
For Calibration Details See CSU Report
CER 68 - 69 AGM 37 June 1969
UPSTREAM
STEAM TEMPERATURE in °F
544.58
531.95
518.21
503.08
486.20
467.01
1000
900
800
700
600
500
UPSTREAM
STEAM PRESSURE
in psia
FLOW RATE IN 1000 lbs / hr
300
200
150
100
80
60
40
30
0.2
0.3
0.4
0.6
0.8
1.0
2.0
3.0
4.0
6.0
8.0
10.0
20.0
30.0
40.0
DIFFERENTIAL PRESSURE IN psi
Figure 5