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Field Testing of Dielectric Steam Quality Sensor

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Abstract

Proper management of steamflood projects requires accurate information about the amount of heat input into the petroleum reservoir. A logical step toward obtaining this information is to meter the steam flow rate and quality directly at the injector wellhead. Numerous devices and methods have been developed and marketed over the past few decades to measure two-phase steam rate and quality.

Steam quality metering devices include a two-phase separator, orifice-choke in series, densitometers, dielectric sensors, and radiation detectors. Over the past ten years, with the exception of separator vessels, no steam quality metering device has proven to be commercially viable. However, recent application of dielectric (or impedance) sensor technology to steam quality measurement has shown promising results.

This paper presents results of field testing to evaluate the performance of a commercially available dielectric steam quality sensing device over an extended range of conditions. Overall accuracy of the device compared to separator vessel measurements is discussed. Recommended guidelines for sensor sizing and installation at injectors, to ensure reliable performance, are also presented.

Introduction

Monitoring steam flow to injection wells is an important element of steamflood management.[1-3] Injector steam quality and rate data are used to predict oil recovery, compute heat utilization efficiency, and optimize steamflood performance.

Various steam quality metering devices have been developed, field tested, and deployed in steamflood projects over the past ten years.[4-12] These devices range from a two-phase separator vessel to radiation detectors. In general, currently available steam quality metering devices can be grouped into two categories:

1. Intrusive devices that are either installed as part of the wellhead piping system or the piping system must be modified to allow for periodic hook up of the device. Intrusive steam quality devices include two orifice plates in series, orifice and choke in series, V-cone and vortex or turbine meter in series, densitometers, dielectric meters, and separator vessels.
2. Non-intrusive devices can be clamped onto the exterior pipe surfaces, eliminating the need for extensive piping modifications. Non-intrusive quality meters include neutron and gamma radiation detectors.

The effectiveness of the above mentioned metering devices has been previously reviewed.[13,14] This paper focuses on the evaluation of a commercially available dielectric-based steam quality sensor developed by Texaco.[12] Preliminary tests conducted by Chevron indicated that the dielectric sensor was in pretty good agreement with separator vessel measurements for qualities between 30% to 70%. However, more testing was needed to determine the overall reliability and accuracy of this device over a wide range of steam conditions.

Dielectric Steam Quality Sensor

Several years ago, Texaco developed a device that measures the electrical impedance of two-phase steam flowing through an annular cross-section between an electrode and housing, as shown in Figure 1. The device, called the *Dielectric Steam Quality Sensor* (DSQS), is currently manufactured and marketed by California Steam Service.[15]

Operating Principle. The application of electrical impedance measurement to determine the void fraction (or, inversely, the liquid volume fraction) of gas-liquid mixtures has been studied for over twenty years.[16-18] Measured impedance (conductance or capacitance) of a two-phase fluid depends upon the sensor geometry and the liquid volume fraction.

In its simplest form, a capacitance transducer consists of two parallel conducting plates separated by a dielectric medium such as water. The capacitance is proportional to the area of the plates, A, and inversely proportional to the distance between them, d. The constant of proportionality for the area of the plates is given by the product of the dielectric constant, κ, and the dielectric constant of a vacuum, ε_0.[19]

$$C = \kappa \varepsilon_0 A/d \tag{1}$$

For a given transducer geometry, the change in capacitance is directly proportional to the change in the dielectric constant of the medium between the plates. If the medium is a gas-liquid mixture, then dielectric constant, κ, is determined from the liquid volume fraction, λ, the dielectric constant of the gas phase, κ_G, and the dielectric constant of the liquid phase, κ_L.

$$\kappa = (1 - \lambda)\kappa_G + \lambda \kappa_L \tag{2}$$

Originally, the DSQS device was designed to measure the capacitance of deionized water vapor and liquid. Dionized water is a nonconducting liquid (i.e., infinite electrical resistance). However, oil field water contains dissolved solids that make the liquid phase conductive. Consequently, the commercially available DSQS device measures impedance, which is the vector resultant of capacitive reactance, X_c, and resistance, R.

$$Z_{\text{total}} = (X_c^2 + R^2)^{1/2} \tag{3}$$

The liquid phase of the steam has a much lower impedance than the vapor phase. As the volume fraction of the vapor phase increases or decreases, so does the measured impedance.

Each dielectric sensor system (mechanical components and electrical cable) has its own characteristic "background" impedance. Calibration of each sensor allows for the subtraction of "background" impedance from total impedance to give the impedance of the two-phase steam.

$$Z_{\text{steam}} = Z_{\text{total}} - Z_{\text{sensor}} \tag{4}$$

The liquid volume fraction, λ, is then determined from the steam impedance, Z_{steam}, the steam pressure, P, the water or liquid phase resistivity, ρ_w, and the impedance of the vapor phase, Z_v.

$$\lambda = \mathrm{K}\,(\rho_w * \mathrm{P})^{1/2}\,\mathrm{Log}(Z_v/Z_{\text{steam}}) \tag{4}$$

The empirical constant, K, takes into account the geometry and mechanical components of the sensor. The liquid volume fraction and specific volumes, ν_V and ν_L, are then used to compute steam quality, x, assuming the vapor and liquid phases flow through the sensor at equal velocities.

$$x = \left[1 + \left(\frac{\nu_V}{\nu_L}\right)\frac{\lambda}{1-\lambda}\right]^{-1} \tag{6}$$

The annular flow geometry of the DSQS device tends to promote mixing of the vapor and liquid phases. However, if the vapor and liquid velocities are not equal, then a slip velocity factor must be included in equation (6). Introduction of a slip factor, however, adds an unknown variable that must be determined by yet another measurement. Therefore, it is important that the steam flow conditions entering the DSQS device be as homogenous as possible.

Field Tests

The purpose of the field tests was to evaluate the performance of a commercially available DSQS device installed at an injection well for an extended range of steam conditions. A steam separator vessel, installed directly downstream of the device, was the primary means of validating the DSQS quality readings.

Equipment and Procedure. In recent years, the DSQS device has been modified to improve field performance and allow easier installation. Key components have been upgraded to ensure reliable operation at steam pressures up to 1000 psig (545 °F). The electrode length has been reduced from 18" to 12" and the housing ID reduced from 2" to 1.5". A schematic of a standard 2" nominal DSQS device for injector installation is shown in Figure 2. This "off-the-shelf" configuration was used throughout our testing.

A simplified schematic of a steam separator is shown in Figure 3. The liquid and vapor phases are separated in the vessel and a fluid level is maintained with a level indicator and control valve. The volume flow rate of each phase is measured using orifice plates or vortex meters. The same two separators were used throughout our testing.

The test setup, shown in Figure 4, was designed to take steam output from a 22 MMBtu/hr portable gas-fired generator. The total steam output from the generator was alternately directed through one of two side-branching tees and the split streams were injected into two nearby injectors. Generator steam quality was varied by adjusting the fuel and feedwater rates.

The steam flow rates to each injector were controlled using wellhead chokes. Thermocouples were installed upstream and downstream of each choke to monitor steam temperatures (and saturation pressures). Critical flow was achieved at each choke to maintain stable flow conditions during testing. A DSQS device and separator vessel were installed downstream of each choke to measure quality (and rate) at each injector. Data were collected for at least 30 minutes (under stable conditions) before changing to the next test case.

Data Analysis. The separator vapor and liquid flow rates were analyzed to determine the steam flow rates and qualities exiting each branch of the tee. The separator data were adjusted to pressure conditions upstream of the choke to correct for liquid flashing as a result of the large pressure drop. Isenthalpic throttling across each choke was assumed to obtain steam qualities at upstream pressure conditions. The total adjusted liquid and vapor rates exiting the tee were then compared to the generator outlet data to ensure that the steam mass flow rate and thermal energy were balanced for the system.

The separator steam quality measurements were used as the primary means of evaluating the performance of each DSQS device. Liquid and vapor volume flow rate measurements, Q_V and Q_L, at each separator were also used to estimate the superficial vapor and liquid velocities and the liquid volume fraction entering each DSQS device.

$$V_{SV} = Q_V/(A_C * 3600) \qquad (7)$$

$$V_{SL} = Q_L/(A_C * 3600) \qquad (8)$$

$$\lambda_{sep} = (1-x_{sep})v_L/[(1-x_{sep})v_L + x_{sep}v_V \qquad (9)$$

The superficial velocities and liquid volume fraction provide additional information for evaluating DSQS performance at different inlet flow conditions.

Test Results. Test data are summarized in Tables 1 - 4. The tests were conducted in different Phases (I through IV) over several months. Different pairs of DSQS devices, designated Sensor 1 and Sensor 2, were used during each phase of testing. Sensor 1 and Sensor 2 data depict the DSQS qualities measured at injectors 1 and 2, respectively.

Inlet steam conditions for Sensor 1 ranged from 150 to 380 psia, 75 to 650 b/d cwe, and 20 to 100% quality. Inlet steam conditions for sensor 2 ranged from 180 to 450 psia, 315 to 900 b/d cwe, and 20 to 90% quality. The vapor velocity and liquid volume fraction entering Sensor 1 ranged from 30 to 100 ft/sec and 0.001 to 0.01, respectively. The vapor velocity and liquid volume fraction entering Sensor 2 ranged from 40 to 150 ft/sec and 0.001 to 0.04, respectively.

Figures 5 through 8 show comparisons of DSQS and separator quality measurements. With few exceptions, the DSQS qualities were within +/- 10% (quality percentage units) of separator qualities for the entire range of inlet flow conditions. The DSQS and separator measurements were even closer for qualities above 40%. At lower qualities, the DSQS measurements were consistently lower, but for the most part were still within -10% quality units of separator measurements.

Additionally, the effects of meter orientation can be seen from a comparison of Phase I data (sensors positioned vertically) to Phase II through IV (sensors positioned horizontal). The DSQS devices, that were positioned so that the steam flowed vertically up through the electrode-housing annulus, consistently measured lower qualities than the separator. This effect, which was especially pronounced at low steam rates and qualities seen at Sensor 1, was reduced significantly once the DSQS devices were installed horizontally.

Discussion

There are various reasons for the differences between the DSQS and separator quality measurements. First, uncertainty is inherent in any measurement process and needs to be considered when comparing DSQS and separator steam qualities. Second, the DSQS device is more sensitive to inlet flow conditions than the separator. Third, the DSQS device is sensitive to changes in water resistivity, whereas the separator is not.

Measurement Uncertainty. As a rule of thumb, all metering devices should be reviewed carefully for inherent errors associated with the measurement process and to determine the impact of simplifying assumptions applied to governing principles or equations on overall reliability and accuracy. Sensitivity studies were conducted to estimate the relative error contributions of various measurement parameters on overall measurement uncertainty for a two-phase separator and a DSQS device. A PC Windows application called **UncertaintyAnalyzer** greatly facilitated the process. Heuristic estimates of error limits and confidence levels were entered into the program and weighted error contributions were computed.[20]

Steam Separator. The two-phase separator is considered to be the most reliable method for measuring both steam rate and quality. It measures the liquid and vapor rates separately using well-established single-phase flow technology. The total steam mass flow rate, m_{steam}, is determined from the vapor and liquid flow rates, Q_V and Q_L and the phase specific volumes, v_V and v_L. The steam quality is determined by dividing the vapor mass flow rate by the total mass flow rate.

$$m_{steam} = Q_V / v_V + Q_L / v_L \qquad (10)$$

$$x = \frac{Q_V / v_V}{Q_V / v_V + Q_L / v_L} \qquad (11)$$

A rigorous uncertainty analysis would of course include meter factors, pulsed signal output from the vortex meters, and steam pressure. However, for the purposes of this study, uncertainty analysis of separator quality measurements were conducted using estimated error limits, and associated confidence levels, for the volume flow rates and specific volumes given in equation (11).

The overall uncertainty in separator quality measurement was estimated to be 1.5% (quality percentage units). The error limits, based on a 95% confidence level, is +/- 3.0%. The percent contribution of each input variable to overall uncertainty is shown in Figure 9. As expected, the liquid volume rate contributes the largest source of error because of periodic fill-up and dumping associated with fluid level control within the separator vessel.

DSQS Device. The DSQS device measures impedance and converts it to liquid volume fraction using equation (5). In turn, the liquid volume fraction is converted to steam quality using equation (6). Therefore, both equations were used in the estimation of DSQS quality measurement uncertainty. Error limits, and associated confidence levels, were estimated for each variable.

The overall uncertainty in DSQS quality measurement was estimated to be 1.7% (quality percentage units). The error limits, based on a 95% confidence level, is +/- 3.4%. The percent contribution of each variable to overall uncertainty is shown in Figure 10. The liquid phase resistivity contributed the largest source of error. In most applications, frequent adjustment of ρ_w to account for generator output variations may not be practical. Therefore, error limits for ρ_w were estimated assuming a nominal value of ρ_w and generator quality variation of +/- 5%.

Inlet Flow Conditions. The DSQS device measures changes in impedance resulting from changes in the liquid volume fraction. However, impedance electrodes are sensitive to the different flow regimes or patterns that can occur during gas-liquid flow.[16] Typical two-phase flow regimes in horizontal pipes are shown in Figure 11. The occurrence of a particular flow regime depends on the amount of vapor and liquid present in the pipe, their velocities, and their densities.

Both DSQS Sensors tended to indicate low steam qualities when a combination of low inlet vapor velocities and high liquid volume fractions. At these conditions, intermittent slugging was apparent at Sensor 2. Stratified and stratified-wavy flow conditions were also likely at Sensors 1 and 2 at low vapor velocities and high liquid volume fractions.

When a slug of liquid passes through the DSQS device, the measured impedance will reflect 100% liquid even if the slug does not fill the entire device. This effective "shorting" of the impedance device results in a much lower estimated quality than is actually present. This "shorting" effect also occurs when the flow entering the DSQS device is stratified, provided the liquid level is high enough to bridge the gap between the bottom of the electrode and the housing.

For slug flow, this problem can be minimized by increasing the data sampling frequency and reducing the electrode length. For semi-annular and stratified flow, increasing the gap width between the electrode and the housing would further reduce the problem.

Water Resistivity. The resistivity of the liquid phase must be known to convert the DSQS impedance measurements to steam quality. Liquid phase resistivity, ρ_w, is a function of the total dissolved solids (TDS) in the feedwater and the steam quality exiting the generator. As generator quality decreases the TDS concentration in the liquid phase decreases and, correspondingly, ρ_w increases. Since feedwater TDS is typically uniform for a given field, actual values of ρ_w can be measured for generator qualities ranging from 20% to 90%. The value of ρ_w used by the DSQS device would then depend upon the quality coming out of the steam generator plant.

The DSQS data plotted in Figure 4 through 7 were based on ρ_w values for three generator qualities (30%, 50% and 75%). Figure 12 shows the effect of using a single, nominal value of ρ_w, based on 75% generator quality. The largest effect can be seen when the actual generator quality is much lower than that used for the nominal value of ρ_w. Since, the nominal resistivity is much lower than the actual liquid phase resistivity, the DSQS device will tend to underestimate the amount of liquid present. Consequently, the DSQS quality readings will be higher than expected.

Low DSQS quality measurements, caused by inlet flow regime effects, tend to be offset by high quality measurements, caused by using low water resistivities. This can be seen in Figure 12, for inlet qualities below 30%. When the actual (higher) water resistivities are used, the DSQS qualities are much lower than separator qualities. When the nominal (lower) water resistivity is used, the DSQS qualities track separator qualities more closely. It is not safe, however, to assume that the errors occurring from these effects will always offset one another.

Installation Guidelines

As with any metering device, special consideration must be given to installation. Often, unsatisfactory meter performance can be attributable to problems associated with initial installation of the device.

Meter Orientation. As previously discussed, installing the DSQS device in a vertical orientation can result in erroneously low quality readings. The primary reason is believed to be electrode "shorting" caused by liquid hold-up or accumulation.

The preferred installation of a DSQS device at an injector is shown in Figure 13. The device should be positioned horizontally in the steam line, downstream of a wellhead choke or other flow control device.

Inlet Flow Conditions. Ideally, the flow entering the DSQS device should be in the annular-mist regime. High vapor velocities and low liquid volume fractions observed downstream of a wellhead choke often result in annular flow. The DSQS device should be located at least three to four feet downstream of the choke to ensure that stable flow conditions have been establish.

In other installations, where flow chokes are not used, the vapor velocity can be increased by reducing the diameter of the steam piping directly upstream of the DSQS device. A flow straightener or mixing device can be installed upstream of the DSQS to improve inlet flow conditions.

Meter Sizing. As previously mentioned, reducing the electrode length and increasing the gap width between the electrode and the housing can minimized adverse flow regime effects. Although, there are limits to which the electrode length can be reduced and the gap width increased and still achieve a strong impedance signal.

Phase IV testing included evaluation of a DSQS device with a shortened electrode length. Two devices were installed in series at Injector 1 to obtain a direct comparison of quality readings. The results, shown in Figure 14, indicate that shortening the electrode improves DSQS measurements at qualities below 40%. Additional calibration is required to improve the measurements over the entire range of qualities.

Conclusions

Multiple DSQS devices were installed at injector wellheads and tested over a wide range of flow conditions. The following conclusions are based on the evaluation of the data:

1. DSQS qualities were consistently within +/- 10% of separator qualities for steam rates ranging from 90 b/d to 900 b/d cwe and qualities ranging from 20% to 95%.
2. In most cases, the DSQS and separator qualities were well within expected measurement error limits.
3. The measurement accuracy of the DSQS is comparable to that expected from a separator (roughly +/- 3% to 4% quality).
4. Reliable DSQS quality measurements can only be obtained using representative water resistivity data for a given field.
5. Correction for water resistivity changes is required for steam plant output variations greater than +/- 10% quality.
6. Proper installation of the DSQS devise is important to ensure reliable operation.

Nomenclature

A = surface area of plate
A_C = $\pi D_i^2/4$ = pipe cross-sectional area, ft^2
C = capacitance, ohms
d = distance between plates
D_i = pipe inner diameter, ft
I = current, milliamps
K = sensor constant
m = mass flow rate, lb/hr
P = steam pressure, psia
Q = volume flow rate, ft^3/hr
R = resistance, ohms
X_c = capacitive reactance, ohms
x = steam quality (vapor mass fraction)
V = voltage
V_{SV} = superficial vapor velocity, ft/sec
V_{SL} = superficial liquid velocity, ft/sec
W = flow rate, B/D cwe
Z = impedance, ohms
ε_0 = permittivity or dielectric constant of vacuum
λ = liquid volume fraction
κ = dielectric constant
ρ = resistivity, ohms
θ = phase angle
ν = specific volume, ft^3/lb

Subscripts

G = gas phase
L = liquid phase
DSQS = dielectric sensor measurement
sep = separator measurement
v = vapor phase
w = water

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Table 1a Phase I Tests - Sensor 1

Inlet Conditions

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 70% to 80%					
1	340.3	403.3	91.5	0.24	0.003	84.4	81.4	-3.0
2	342.5	415.8	93.5	0.25	0.003	84.1	86.5	2.4
3	430.0	550.0	90.4	0.48	0.005	77.2	75.3	-1.9
4	278.9	299.0	89.1	0.10	0.001	91.2	83.6	-7.6
5	271.3	293.6	88.1	0.12	0.001	89.4	83.5	-5.8
6	195.2	157.7	61.7	0.09	0.001	84.7	78.2	-6.5
7	195.8	157.1	63.5	0.07	0.001	87.7	81.0	-6.7
8	194.7	162.0	66.5	0.07	0.001	88.7	81.1	-7.6
9	202.6	174.0	69.6	0.06	0.001	89.7	88.2	-1.6
10	181.9	112.7	45.4	0.07	0.002	81.5	76.9	-4.5
11	172.2	114.9	53.9	0.04	0.001	90.0	87.4	-2.5
12	342.2	426.1	88.1	0.36	0.004	77.3	76.2	-1.2
13	346.7	431.7	91.2	0.33	0.004	80.0	82.1	2.1
14	428.0	571.0	87.9	0.62	0.007	72.0	69.1	-2.8
15	265.6	301.3	78.5	0.27	0.003	76.0	74.9	-1.0
16	275.9	299.1	83.5	0.17	0.002	84.5	79.5	-5.1
17	277.1	298.0	84.0	0.16	0.002	85.7	80.4	-5.2
18	199.4	164.9	58.8	0.13	0.002	78.8	72.8	-5.9
19	195.4	166.1	63.4	0.10	0.002	82.6	74.9	-7.7
20	196.0	164.5	61.9	0.11	0.002	81.7	75.2	-6.5
21	194.6	167.9	66.0	0.09	0.001	84.8	77.0	-7.8
22	191.3	169.4	67.6	0.09	0.001	84.7	85.1	0.4
			Generator Quality = 45% to 55%					
23	321.4	394.5	81.5	0.40	0.005	72.6	67.1	-5.5
24	385.0	494.4	84.4	0.53	0.006	71.8	60.4	-11.3
25	240.9	269.2	76.4	0.24	0.003	75.3	71.8	-3.5
26	177.3	143.7	57.8	0.11	0.002	79.3	72.3	-6.9
27	180.0	144.3	58.0	0.10	0.002	80.5	73.2	-7.3
28	179.1	142.0	56.8	0.10	0.002	79.7	71.6	-8.0
29	173.5	91.7	37.6	0.07	0.002	79.2	68.8	-10.4
30	159.0	89.9	37.2	0.08	0.002	73.6	75.1	1.5
31	165.0	94.1	41.7	0.06	0.001	81.5	80.7	-0.9
32	327.7	402.3	80.0	0.43	0.005	71.3	64.8	-6.5
33	381.0	516.7	82.2	0.66	0.008	66.2	56.7	-9.4
34	242.4	280.2	75.1	0.29	0.004	71.5	67.8	-3.7
35	180.5	148.6	54.6	0.14	0.003	73.8	67.5	-6.3
36	184.9	150.3	55.1	0.13	0.002	75.3	68.1	-7.2
37	182.7	147.9	50.5	0.16	0.003	69.8	63.2	-6.6
38	179.0	151.9	55.9	0.15	0.003	73.2	67.2	-6.0
39	170.1	91.8	38.6	0.07	0.002	79.7	69.2	-10.5
40	158.7	89.0	38.0	0.08	0.002	75.8	77.4	1.6
			Generator Quality = 33% to 38%					
41	210.4	254.0	67.5	0.35	0.005	61.8	59.3	-2.5
42	169.0	124.3	49.1	0.11	0.002	74.4	69.5	-4.9
43	170.7	126.2	45.6	0.14	0.003	68.8	66.9	-1.9
44	157.2	85.4	33.2	0.10	0.003	68.3	60.4	-7.9
45	169.2	137.9	47.9	0.17	0.004	65.5	66.5	1.0
46	170.9	131.5	43.8	0.17	0.004	63.4	62.9	-0.5
47	170.0	133.7	43.7	0.18	0.004	62.0	62.4	0.3
48	157.4	83.0	34.0	0.08	0.002	72.2	67.5	-4.7

Table 1b Phase I Tests - Sensor 2

Inlet Conditions

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 70% to 80%					
1	274.7	471.0	108.2	0.53	0.005	69.2	73.6	4.4
2	207.0	334.9	108.1	0.32	0.003	73.9	78.4	4.5
3	328.8	594.3	115.6	0.67	0.006	69.9	72.8	2.9
4	344.6	590.7	123.1	0.48	0.004	78.5	77.9	-0.6
5	378.9	725.2	116.4	0.92	0.008	66.4	68.3	1.8
6	395.1	734.9	126.3	0.72	0.006	74.1	76.2	2.0
7	397.3	713.1	131.6	0.54	0.004	80.0	78.1	-1.9
8	445.3	798.3	129.8	0.65	0.005	79.1	79.5	0.4
9	441.9	801.7	128.9	0.69	0.005	77.6	78.5	0.9
10	422.0	789.4	128.7	0.75	0.006	75.1	76.6	1.5
11	274.1	456.3	111.0	0.45	0.004	73.2	77.1	3.9
12	207.3	321.1	111.8	0.23	0.002	79.9	83.3	3.4
13	325.3	583.8	115.6	0.65	0.006	70.5	73.6	3.1
14	353.7	581.0	121.6	0.42	0.003	80.9	79.9	-1.0
15	380.6	718.6	119.4	0.85	0.007	69.0	71.0	2.0
16	407.4	720.7	127.8	0.58	0.005	78.9	78.7	-0.2
17	395.5	725.9	128.1	0.66	0.005	76.2	78.8	2.6
18	402.1	726.2	138.1	0.46	0.003	83.5	80.3	-3.2
			Generator Quality = 45% to 55%					
19	441.1	787.4	126.5	0.69	0.005	77.4	77.6	0.2
20	422.9	792.4	129.5	0.75	0.006	75.5	77.4	1.9
21	244.7	492.0	94.9	0.86	0.009	52.0	54.9	3.0
22	194.3	358.7	79.6	0.67	0.008	47.8	53.4	5.6
23	301.0	614.2	96.2	1.10	0.011	51.7	51.2	-0.5
24	357.2	744.7	103.0	1.29	0.012	54.0	49.7	-4.2
25	360.7	745.8	104.4	1.26	0.012	55.2	50.5	-4.6
26	355.2	745.8	103.7	1.30	0.012	53.9	48.5	-5.4
27	384.7	787.3	105.2	1.31	0.012	56.1	50.3	-5.9
28	374.7	801.5	105.8	1.40	0.013	54.0	47.6	-6.4
29	249.8	474.7	98.7	0.75	0.007	57.1	59.9	2.8
30	191.9	361.2	80.6	0.68	0.008	47.5	53.4	5.9
31	304.6	606.4	98.9	1.03	0.010	54.4	54.2	-0.2
32	357.5	737.9	104.6	1.24	0.012	55.4	50.6	-4.7
33	364.6	734.8	105.5	1.19	0.011	57.2	53.1	-4.1
34	340.0	765.0	95.5	1.54	0.016	46.4	40.2	-6.1
35	358.1	732.9	104.3	1.23	0.012	55.7	51.6	-4.0
36	382.6	794.7	106.1	1.34	0.012	55.8	49.6	-6.2
37	355.4	793.3	117.3	1.28	0.011	57.4	51.7	-5.7
38	374.8	799.0	106.0	1.38	0.013	54.3	48.5	-5.8
			Generator Quality = 33% to 38%					
39	251.4	632.8	79.6	1.51	0.019	34.8	31.5	-3.3
40	302.8	746.8	88.9	1.68	0.019	39.5	32.2	-7.3
41	295.1	748.1	85.7	1.75	0.020	37.1	29.2	-7.8
42	312.2	795.0	86.8	1.86	0.021	37.3	29.2	-8.1
43	305.2	744.9	90.6	1.65	0.018	40.7	33.4	-7.2
44	298.4	719.7	86.3	1.63	0.018	39.2	32.8	-6.4
45	295.5	740.4	85.9	1.72	0.020	37.6	30.5	-7.1
46	313.2	803.5	87.2	1.88	0.021	37.2	28.7	-8.5

Table 2a Phase II Tests - Sensor 1

Inlet Conditions

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 70% to 80%					
1	331.6	422.1	93.2	0.32	0.003	80.0	79.9	-0.2
2	398.8	522.8	90.3	0.50	0.005	75.2	75.3	0.1
3	432.9	564.1	90.8	0.52	0.006	76.1	74.9	-1.2
4	265.6	311.3	90.4	0.18	0.002	84.6	86.3	1.7
5	172.5	162.2	77.6	0.05	0.001	92.0	92.0	0.0
6	139.9	100.3	58.8	0.03	0.000	92.3	92.3	0.0
7	330.6	443.2	90.5	0.44	0.005	73.8	72.3	-1.5
8	434.3	577.4	89.9	0.58	0.006	73.8	71.5	-2.3
9	435.7	577.4	90.2	0.57	0.006	74.3	71.6	-2.7
10	398.7	537.2	88.8	0.57	0.006	72.0	72.0	0.0
11	264.8	325.7	82.8	0.31	0.004	73.9	73.0	-0.9
12	177.7	179.2	69.5	0.15	0.002	76.7	79.9	3.2
13	142.4	115.9	55.7	0.09	0.002	76.9	77.7	0.8
			Generator Quality = 50% to 55%					
14	304.5	375.3	87.0	0.32	0.004	77.3	75.6	-1.7
15	370.6	487.5	88.7	0.49	0.005	73.6	70.7	-2.9
16	248.5	273.7	81.6	0.19	0.002	81.5	82.3	0.8
17	223.5	254.7	83.6	0.18	0.002	80.9	80.5	-0.5
18	167.5	136.6	64.5	0.06	0.001	88.2	86.9	-1.4
19	141.4	87.6	47.5	0.04	0.001	86.2	89.4	3.2
20	307.5	391.4	83.9	0.41	0.005	72.1	69.1	-3.1
21	370.3	492.4	87.7	0.52	0.006	72.0	69.7	-2.3
22	224.1	266.1	79.9	0.25	0.003	74.3	71.5	-2.8
23	251.7	289.7	75.8	0.29	0.004	72.4	72.9	0.5
24	223.9	264.0	80.3	0.24	0.003	75.2	71.1	-4.0
25	168.8	146.4	59.7	0.12	0.002	76.7	75.6	-1.1
26	142.4	94.0	44.0	0.08	0.002	75.0	75.0	0.0
			Generator Quality = 25% to 35%					
27	237.5	277.2	78.8	0.26	0.003	74.4	72.0	-2.4
28	288.9	402.4	72.9	0.64	0.009	57.4	55.6	-1.8
29	193.0	199.8	72.8	0.16	0.002	78.1	76.4	-1.7
30	206.1	217.3	73.6	0.18	0.002	77.2	76.3	-0.9
31	148.4	110.5	54.1	0.07	0.001	81.4	81.9	0.5
32	132.9	64.9	34.0	0.05	0.001	78.5	77.8	-0.7
33	250.4	300.9	77.8	0.32	0.004	71.2	66.6	-4.6
34	238.9	284.5	77.6	0.29	0.004	71.8	69.6	-2.2
35	280.0	374.6	76.8	0.51	0.007	63.0	60.3	-2.6
36	207.0	240.1	71.6	0.28	0.004	68.3	70.5	2.2
37	193.7	210.0	70.9	0.21	0.003	72.5	71.6	-0.9
38	193.8	210.2	70.6	0.21	0.003	72.2	71.2	-1.0
39	149.9	117.2	50.4	0.11	0.002	72.4	70.9	-1.5
40	135.1	74.6	34.8	0.08	0.002	71.0	68.1	-3.0

Table 2b Phase II Tests - Sensor 2

Inlet Conditions

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 70% to 80%					
1	284.5	465.4	105.1	0.51	0.005	70.4	71.7	1.3
2	254.9	379.5	107.8	0.28	0.003	79.6	79.9	0.4
3	220.9	319.6	110.3	0.18	0.002	84.2	84.5	0.3
4	320.1	581.5	118.5	0.62	0.005	71.4	72.0	0.6
5	393.0	730.9	127.4	0.70	0.005	74.8	75.3	0.5
6	422.5	798.0	133.8	0.70	0.005	77.3	77.9	0.6
7	282.2	450.3	108.6	0.42	0.004	74.6	76.4	1.8
8	217.9	314.6	114.5	0.14	0.001	87.6	86.1	-1.5
9	216.5	325.0	116.1	0.17	0.001	85.4	87.9	2.5
10	247.9	374.5	114.9	0.22	0.002	83.6	85.9	2.3
11	319.4	558.2	123.8	0.47	0.004	77.5	78.0	0.5
12	376.7	711.1	135.5	0.58	0.004	78.4	79.3	0.9
13	423.1	786.8	135.6	0.62	0.005	79.6	79.8	0.2
			Generator Quality = 50% to 55%					
14	255.9	508.5	83.0	1.01	0.012	46.0	46.6	0.6
15	208.5	402.6	72.4	0.85	0.012	41.5	43.3	1.8
16	295.9	619.1	96.4	1.14	0.012	50.5	48.0	-2.5
17	297.3	632.3	90.8	1.25	0.014	46.8	45.5	-1.3
18	345.2	743.6	100.0	1.38	0.014	50.7	45.3	-5.5
19	367.9	806.2	102.7	1.49	0.014	51.2	45.3	-5.9
20	254.1	492.1	87.3	0.91	0.010	49.6	49.9	0.4
21	208.2	387.6	72.7	0.80	0.011	43.2	45.6	2.4
22	297.4	616.8	94.3	1.15	0.012	49.8	47.9	-1.9
23	295.8	595.4	99.8	1.01	0.010	54.3	52.2	-2.2
24	299.0	612.3	94.9	1.12	0.012	50.8	49.8	-0.9
25	344.4	721.2	103.7	1.25	0.012	54.1	49.6	-4.5
26	365.8	787.4	105.0	1.39	0.013	53.3	48.3	-5.0
			Generator Quality = 25% to 35%					
27	203.1	593.9	55.2	1.69	0.030	20.9	10.7	-10.2
28	185.0	469.9	41.1	1.38	0.032	18.0	8.1	-9.9
29	255.5	650.7	59.8	1.77	0.029	25.8	15.4	-10.4
30	274.0	665.3	64.2	1.74	0.026	29.0	19.3	-9.7
31	288.6	766.2	74.2	1.97	0.026	30.6	23.3	-7.4
32	291.2	811.9	69.9	2.18	0.030	27.5	19.2	-8.3
33	218.4	547.1	59.7	1.46	0.024	26.4	16.2	-10.2
34	204.5	577.2	56.4	1.62	0.028	22.2	12.3	-9.9
35	180.8	486.0	38.5	1.46	0.037	15.9	6.7	-9.2
36	277.9	638.1	66.9	1.60	0.023	32.0	24.3	-7.7
37	245.6	647.2	66.2	1.71	0.025	27.7	20.2	-7.5
38	248.2	654.0	65.5	1.74	0.026	27.3	19.2	-8.2
39	289.3	754.4	75.3	1.91	0.025	31.7	23.8	-7.9
40	303.2	800.9	75.9	2.04	0.026	31.5	23.1	-8.3

Table 3a Phase III Tests - Sensor 1

			Inlet Conditions					
Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 65% to 75%					
1	317.1	481.7	106.8	0.41	0.004	76.9	70.5	-6.5
2	319.7	519.7	102.7	0.60	0.006	69.1	69.3	0.2
3	320.4	517.5	99.8	0.63	0.006	67.6	68.5	0.8
4	385.4	608.3	110.6	0.54	0.005	76.5	72.0	-4.5
5	370.2	611.9	107.5	0.67	0.006	71.1	66.3	-4.7
6	250.0	349.4	97.0	0.30	0.003	76.3	73.0	-3.3
7	173.7	172.9	66.6	0.16	0.002	74.5	75.1	0.6
8	166.2	171.9	72.5	0.13	0.002	78.2	75.0	-3.2
9	141.6	110.2	53.1	0.09	0.002	76.7	73.3	-3.4
10	334.0	576.0	101.8	0.77	0.007	64.5	66.1	1.6
11	316.4	516.2	101.5	0.62	0.006	68.1	67.8	-0.2
12	387.0	650.0	103.9	0.80	0.008	67.5	63.4	-4.1
13	368.1	646.1	102.3	0.89	0.009	63.6	62.9	-0.7
14	250.0	352.8	95.6	0.33	0.003	74.5	72.4	-2.2
15	170.0	165.3	66.9	0.14	0.002	76.7	75.2	-1.5
16	166.2	169.3	72.8	0.12	0.002	79.7	75.2	-4.5
17	151.8	105.2	48.6	0.08	0.002	78.5	75.0	-3.5
			Generator Quality = 40% to 50%					
18	274.5	513.4	87.4	0.92	0.010	51.3	46.3	-5.0
19	286.7	510.3	88.2	0.86	0.010	54.3	48.2	-6.2
20	302.7	512.2	92.0	0.77	0.008	59.5	56.3	-3.2
21	311.6	598.0	88.1	1.11	0.012	50.3	42.9	-7.4
22	311.7	591.9	91.9	1.04	0.011	52.9	43.8	-9.1
23	228.6	343.9	88.6	0.44	0.005	64.9	63.3	-1.6
24	148.3	172.5	53.9	0.29	0.005	51.9	61.0	9.1
25	157.9	194.0	60.5	0.31	0.005	55.1	62.8	7.7
26	148.1	174.4	54.6	0.30	0.005	52.0	61.6	9.6
27	132.1	116.3	37.4	0.21	0.006	47.9	55.1	7.3
28	276.7	444.3	98.0	0.54	0.005	67.0	65.7	-1.2
29	287.4	466.2	98.9	0.57	0.006	66.8	64.7	-2.1
30	311.6	527.9	97.1	0.73	0.007	62.7	60.8	-1.9
31	322.8	552.0	101.0	0.73	0.007	64.6	61.1	-3.5
32	208.7	293.3	85.5	0.35	0.004	67.3	67.7	0.4
33	151.7	150.5	59.4	0.18	0.003	67.0	69.0	2.0
34	156.7	167.6	64.4	0.19	0.003	67.4	68.9	1.4
35	148.6	147.6	58.8	0.18	0.003	66.4	69.4	3.0
36	133.8	81.4	43.4	0.06	0.001	80.5	67.0	-13.5
			Generator Quality = 25% to 30%					
37	242.6	489.2	77.9	0.99	0.012	45.1	39.0	-6.1
38	240.9	488.7	77.3	1.00	0.013	44.4	38.6	-5.8
39	259.9	583.7	74.7	1.32	0.017	38.6	30.9	-7.7
40	175.5	327.1	66.8	0.67	0.010	43.0	45.3	2.3
41	130.7	165.5	40.5	0.35	0.009	39.9	48.7	8.8
42	123.5	169.0	46.8	0.34	0.007	43.2	52.7	9.5
43	103.4	112.9	32.5	0.24	0.007	38.4	42.0	3.6
44	232.7	386.0	90.1	0.51	0.006	63.6	61.0	-2.6
45	239.8	453.3	85.1	0.79	0.009	52.5	48.8	-3.8
46	178.4	260.3	76.8	0.35	0.004	63.1	64.0	1.0
47	128.7	130.6	46.9	0.20	0.004	57.7	61.9	4.2
48	121.0	108.7	48.5	0.12	0.003	68.0	61.2	-6.7
49	116.2	74.9	32.0	0.10	0.003	63.2	58.3	-4.9

Table 3b Phase III Tests - Sensor 2

			Inlet Conditions					
Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 65% to 75%					
1	288.0	497.4	115.7	0.49	0.004	73.4	74.6	1.2
2	245.1	471.8	112.7	0.61	0.005	64.4	67.9	3.6
3	242.2	471.9	111.4	0.64	0.006	62.9	66.4	3.5
4	225.4	366.2	106.6	0.37	0.003	72.4	76.1	3.8
5	211.4	372.6	106.0	0.45	0.004	66.5	69.7	3.2
6	343.2	635.1	122.1	0.67	0.005	72.1	71.4	-0.7
7	421.4	815.3	127.8	0.87	0.007	72.1	68.4	-3.7
8	421.4	820.1	133.1	0.80	0.006	74.6	71.1	-3.5
9	447.0	870.0	133.7	0.84	0.006	75.0	71.1	-3.9
10	271.1	432.2	117.9	0.30	0.003	81.1	81.7	0.5
11	250.0	432.8	117.5	0.40	0.003	74.7	77.7	3.0
12	230.1	323.9	115.9	0.11	0.001	90.8	87.5	-3.3
13	215.8	334.1	110.9	0.25	0.002	79.1	81.6	2.5
14	343.2	635.6	123.6	0.65	0.005	72.9	72.3	-0.7
15	421.6	813.3	124.3	0.92	0.007	70.4	66.5	-3.8
16	421.3	823.1	132.7	0.82	0.006	74.1	69.9	-4.3
17	451.6	877.3	124.6	1.02	0.008	70.0	64.6	-5.4
			Generator Quality = 40% to 50%					
18	202.6	479.3	95.1	0.96	0.010	44.5	47.4	2.9
19	216.0	478.5	94.0	0.92	0.010	46.9	49.5	2.6
20	223.9	477.2	102.6	0.81	0.008	53.1	54.2	1.1
21	181.7	394.3	82.1	0.82	0.010	42.0	47.2	5.2
22	205.7	392.5	74.9	0.80	0.011	43.5	48.2	4.8
23	299.6	638.2	116.5	0.95	0.008	59.9	55.4	-4.5
24	338.6	821.0	108.8	1.57	0.014	49.1	41.4	-7.7
25	336.7	801.2	113.0	1.45	0.013	51.9	44.5	-7.5
26	335.3	813.6	111.9	1.51	0.013	50.4	42.2	-8.2
27	350.7	879.9	111.8	1.70	0.015	48.7	40.2	-8.4
28	203.8	539.9	88.2	1.23	0.014	36.9	39.2	2.3
29	216.4	523.7	91.0	1.11	0.012	41.5	43.8	2.3
30	180.6	463.3	74.4	1.12	0.015	32.3	32.9	0.7
31	190.2	437.3	81.0	0.96	0.012	39.1	44.0	4.9
32	255.8	695.5	99.9	1.52	0.015	40.4	37.1	-3.3
33	347.0	831.5	105.3	1.63	0.015	48.0	39.7	-8.3
34	330.3	825.2	107.5	1.64	0.015	47.1	39.4	-7.7
35	326.5	847.9	107.0	1.74	0.016	45.1	37.5	-7.6
36	362.4	900.9	110.9	1.75	0.016	48.7	39.9	-8.8
			Generator Quality = 25% to 30%					
37	190.9	497.2	84.4	1.14	0.013	36.0	35.3	-0.7
38	189.9	497.4	82.4	1.16	0.014	34.9	34.3	-0.7
39	185.7	425.5	55.9	1.11	0.020	27.1	16.9	-10.1
40	225.9	662.4	90.0	1.59	0.017	33.9	29.4	-4.5
41	277.8	824.6	95.1	1.98	0.020	35.1	26.0	-9.2
42	299.1	826.6	98.9	1.87	0.019	39.2	30.9	-8.3
43	291.2	890.3	93.1	2.20	0.023	33.4	24.5	-8.9
44	188.7	604.2	70.6	1.64	0.023	24.5	19.1	-5.3
45	189.5	539.0	41.1	1.62	0.038	16.1	6.4	-9.6
46	220.8	731.8	83.5	1.92	0.022	27.8	22.4	-5.4
47	271.8	866.1	88.5	2.22	0.024	30.5	21.8	-8.7
48	262.4	838.9	88.6	2.15	0.024	30.4	22.4	-8.1
49	281.7	917.1	88.8	2.38	0.026	29.9	21.2	-8.7

Table 4a Phase IV Tests - Sensor 1

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Inlet Conditions Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality = 70% to 75%					
1	170.9	106.8	54.6	0.01	0.000	97.5	95.3	-2.1
2	173.8	127.5	50.6	0.11	0.002	76.8	79.8	3.0
3	173.8	165.1	42.1	0.30	0.007	49.6	51.4	1.8
4	177.6	201.0	36.1	0.46	0.013	35.5	24.3	-11.1
5	177.7	121.1	48.6	0.09	0.002	79.5	79.4	0.0
6	198.2	177.8	78.5	0.02	0.000	97.0	94.7	-2.2
7	203.9	201.4	71.2	0.15	0.002	79.8	83.9	4.1
8	202.5	272.4	56.3	0.53	0.009	46.4	54.4	8.0
9	204.1	209.1	70.8	0.18	0.003	76.5	82.1	5.7
10	252.7	315.1	106.9	0.07	0.001	94.2	94.4	0.1
11	260.4	340.7	96.5	0.24	0.002	81.0	83.9	2.9
12	259.2	418.6	80.8	0.69	0.008	55.0	59.0	4.0
13	260.8	346.3	94.5	0.28	0.003	78.2	81.5	3.3
14	293.7	424.3	124.3	0.09	0.001	94.3	93.4	-1.0
15	308.5	437.9	118.1	0.15	0.001	91.0	93.2	2.1
16	324.0	530.9	93.9	0.74	0.008	62.6	62.5	-0.1
17	324.0	464.3	106.8	0.32	0.003	81.5	82.7	1.2
18	317.7	463.6	105.1	0.37	0.003	78.8	80.8	2.0
19	323.2	468.8	105.6	0.36	0.003	79.7	81.5	1.9
			Generator Quality = 45% to 55%					
20	255.0	354.3	118.0	0.09	0.001	93.4	94.2	0.8
21	275.0	376.1	102.2	0.25	0.002	82.0	83.9	1.9
22	330.3	502.7	66.2	0.99	0.015	47.6	45.2	-2.4
23	288.5	464.7	83.1	0.75	0.009	56.6	57.9	1.3
24	306.9	462.6	75.0	0.78	0.010	54.5	54.1	-0.4
25	306.6	465.1	119.3	0.24	0.002	86.1	90.7	4.6
26	323.1	475.0	108.5	0.34	0.003	80.7	81.9	1.2
27	354.8	645.3	81.2	1.25	0.015	48.8	42.0	-6.8
28	307.8	603.8	82.9	1.21	0.014	46.3	46.0	-0.3
29	220.5	266.6	105.0	0.04	0.000	95.9	94.3	-1.5
30	231.7	308.4	93.1	0.26	0.003	77.1	80.7	3.6
31	239.8	375.1	77.1	0.63	0.008	54.3	58.5	4.2
32	241.4	417.9	68.5	0.86	0.012	43.5	47.0	3.5
33	234.9	340.8	76.9	0.52	0.007	58.4	64.2	5.8
34	168.2	137.3	70.9	0.02	0.000	96.9	95.6	-1.3
35	177.1	166.8	61.1	0.17	0.003	72.4	80.9	8.5
36	178.3	198.0	51.7	0.34	0.007	51.8	62.0	10.2
37	215.1	254.8	33.4	0.64	0.019	31.1	22.0	-9.1
38	177.7	190.6	54.4	0.30	0.005	56.5	67.0	10.5
39	153.2	93.7	49.7	0.03	0.001	91.1	93.9	2.8
40	155.3	105.9	45.3	0.10	0.002	74.3	77.8	3.5
41	162.5	136.8	35.7	0.26	0.007	47.3	45.1	-2.2
42	227.2	200.4	17.1	0.57	0.032	21.4	7.9	-13.6
43	155.3	129.7	38.7	0.22	0.006	51.8	55.8	4.0
			Generator Quality = 25% to 30%					
44	156.6	84.8	48.4	0.00	0.000	99.9	95.2	-4.7
45	159.0	101.2	42.8	0.09	0.002	75.1	77.3	2.2
46	170.0	125.8	35.2	0.21	0.006	53.0	53.7	0.7
47	191.6	226.1	20.6	0.66	0.031	19.4	7.4	-12.0
48	157.2	148.5	34.7	0.31	0.009	41.1	39.7	-1.3
49	178.6	102.8	51.7	0.00	0.000	100.0	92.0	-8.0
50	166.2	150.7	52.2	0.19	0.004	64.3	80.0	15.7
51	166.4	168.7	43.0	0.32	0.007	47.3	55.0	7.7
52	174.0	247.1	31.5	0.66	0.021	24.7	14.0	-10.7
53	170.0	180.2	38.4	0.38	0.010	40.4	43.8	3.5
54	199.0	194.8	83.6	0.04	0.000	94.7	91.1	-3.7
55	207.2	214.4	74.5	0.16	0.002	79.7	83.1	3.4
56	223.1	263.3	59.6	0.42	0.007	55.8	62.7	7.0
57	253.6	363.0	38.4	0.94	0.024	29.8	23.2	-6.6
58	203.8	322.7	59.5	0.68	0.011	41.6	49.2	7.6
59	279.2	421.4	94.5	0.49	0.005	68.8	71.4	2.7
60	291.4	469.1	83.9	0.75	0.009	57.1	57.0	-0.2
61	364.3	572.9	53.2	1.37	0.025	37.0	25.8	-11.2
62	370.1	553.0	54.7	1.26	0.022	40.0	26.7	-13.3
63	225.1	256.6	100.3	0.03	0.000	97.1	90.6	-6.5
64	231.3	274.6	96.9	0.10	0.001	90.0	88.4	-1.6
65	234.9	297.5	92.7	0.21	0.002	80.7	84.1	3.5
66	254.7	377.0	73.7	0.63	0.008	54.7	58.1	3.4
67	288.0	460.8	56.4	1.05	0.018	38.6	36.1	-2.6
68	275.5	448.3	62.4	0.96	0.015	42.9	40.5	-2.3

Table 4b Phase IV Tests - Sensor 2

Test Case	Steam Pressure (psia)	Steam Rate (b/d cwe)	Inlet Conditions Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Liquid Volume Fraction	Separator Steam Quality (%)	DSQS Steam Quality (%)	Quality Difference (%)
			Generator Quality ≈ 70% to 75%					
1	417.1	856.2	138.3	0.87	0.006	73.6	74.2	0.7
2	421.4	846.5	141.1	0.76	0.005	76.7	77.5	0.8
3	421.4	835.4	147.6	0.60	0.004	81.4	83.5	2.1
4	418.2	805.1	152.2	0.42	0.003	86.3	87.4	1.1
5	413.8	852.1	141.5	0.81	0.006	75.0	76.2	1.2
6	371.4	794.1	136.6	0.91	0.007	69.8	71.4	1.6
7	375.5	777.5	139.0	0.79	0.006	73.3	74.7	1.4
8	374.8	712.1	151.6	0.35	0.002	87.3	85.9	-1.5
9	369.9	796.4	140.4	0.87	0.006	71.2	75.6	4.4
10	316.5	667.7	129.3	0.82	0.006	67.1	69.7	2.7
11	316.7	645.1	135.5	0.66	0.005	72.9	77.1	4.3
12	313.2	583.3	150.9	0.25	0.002	88.7	88.1	-0.6
13	317.7	656.3	136.9	0.67	0.005	72.5	78.5	6.0
14	265.4	558.2	118.8	0.78	0.006	62.2	68.2	6.0
15	265.7	554.5	119.6	0.76	0.006	62.9	68.4	5.5
16	259.8	455.6	143.1	0.17	0.001	89.7	91.5	1.8
17	262.4	515.7	124.4	0.58	0.005	69.7	76.4	6.8
18	271.2	515.9	129.4	0.48	0.004	74.6	80.8	6.2
19	271.2	507.6	130.7	0.44	0.003	76.6	81.2	4.6
			Generator Quality ≈ 45% to 55%					
20	232.2	634.8	80.7	1.56	0.019	32.6	36.7	4.2
21	230.4	583.1	86.3	1.32	0.015	37.6	42.0	4.3
22	253.9	462.8	99.0	0.68	0.007	59.7	66.0	6.3
23	244.1	537.1	95.5	1.03	0.011	47.8	57.1	9.3
24	234.8	500.6	96.1	0.92	0.009	49.7	55.3	5.7
25	186.0	543.9	63.1	1.48	0.023	24.0	28.9	4.9
26	181.9	488.2	70.1	1.24	0.017	29.1	36.3	7.2
27	194.8	353.7	88.6	0.58	0.007	54.3	68.4	14.1
28	206.6	387.6	66.8	0.85	0.013	39.4	50.5	11.0
29	294.2	715.7	94.5	1.53	0.016	42.6	40.7	-1.9
30	298.4	655.4	104.8	1.16	0.011	52.3	48.9	-3.4
31	305.2	596.9	116.2	0.78	0.007	65.1	67.2	2.1
32	305.2	555.3	121.7	0.55	0.005	73.2	75.9	2.6
33	306.6	621.8	97.9	1.09	0.011	52.9	47.6	-5.3
			Generator Quality ≈ 25% to 30%					
34	312.0	886.5	80.3	2.28	0.027	31.2	22.6	-8.6
35	298.5	870.6	84.3	2.21	0.025	32.1	25.4	-6.8
36	305.3	837.0	85.4	2.05	0.023	34.1	27.2	-6.9
37	314.1	714.7	91.4	1.49	0.016	44.1	37.4	-6.8
38	299.6	822.5	90.9	1.95	0.021	36.3	29.8	-6.5
39	272.7	858.4	81.5	2.27	0.027	28.5	23.4	-5.1
40	276.4	842.4	83.4	2.18	0.025	30.0	25.4	-4.7
41	282.9	794.9	90.0	1.91	0.020	35.6	31.0	-4.5
42	289.8	722.1	96.4	1.54	0.016	42.6	38.8	-3.9
43	278.6	798.2	88.6	1.95	0.021	33.9	29.7	-4.2
44	225.6	762.1	73.9	2.10	0.028	24.2	21.9	-2.3
45	225.8	743.0	75.9	2.01	0.026	25.5	24.2	-1.3
46	227.9	673.5	79.3	1.72	0.021	29.7	28.9	-0.8
47	233.7	599.2	87.3	1.36	0.015	37.6	39.3	1.6
48	236.3	646.7	86.0	1.54	0.018	34.6	35.3	0.7
49	166.3	532.4	51.1	1.56	0.029	18.2	16.9	-1.3
50	167.1	506.2	55.7	1.43	0.025	20.5	25.0	4.5
51	169.4	392.7	66.7	0.95	0.014	32.1	43.0	10.9
52	170.0	393.4	66.8	0.95	0.014	32.2	42.4	10.2
53	208.0	720.0	53.1	2.16	0.032	20.3	15.7	-4.6
54	194.7	698.9	60.3	2.05	0.032	18.9	17.7	-1.2
55	194.5	679.8	63.7	1.95	0.030	20.2	20.6	0.3
56	198.7	587.8	72.1	1.55	0.021	27.1	31.7	4.6
57	202.8	509.0	80.6	1.18	0.014	35.6	42.0	6.5
58	198.1	516.8	82.8	1.21	0.014	35.2	41.1	5.9

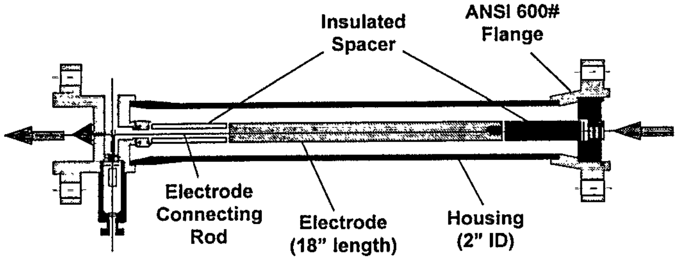

Figure 1 Dielectric Steam Quality Sensor (DSQS)

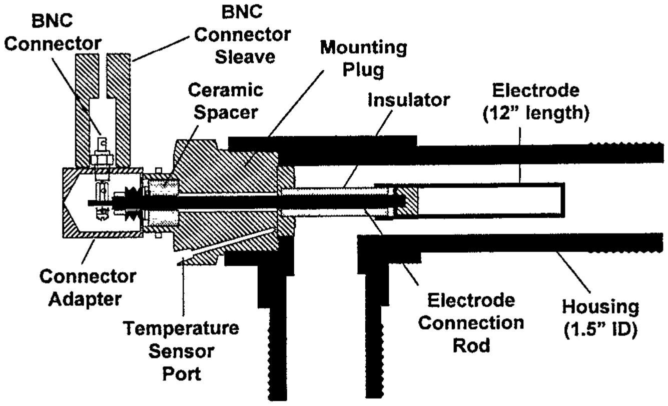

Figure 2 Cut Away View of Commercial DSQS Device

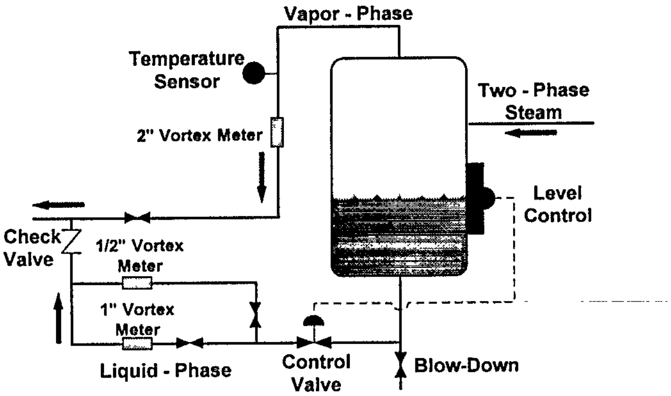

Figure 3 Two-Phase Separator Vessel

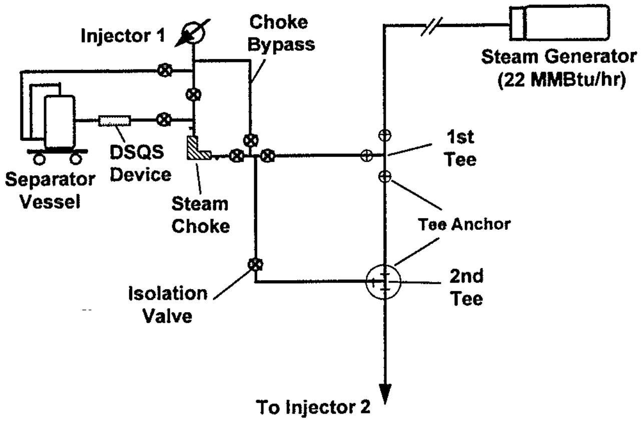

Figure 4 Schematic of Test Setup

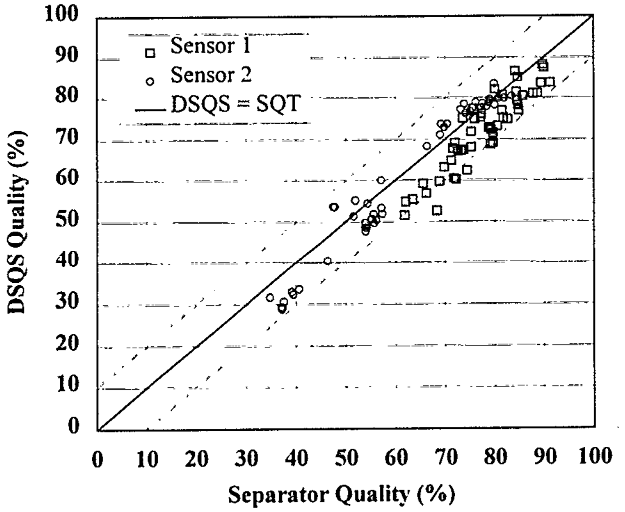

Figure 5 DSQS vs Separator (Phase I Tests)

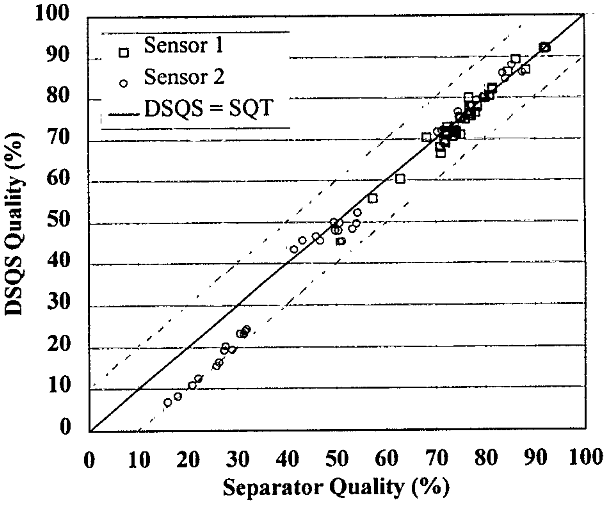

Figure 6 DSQS vs Separator (Phase II Tests)

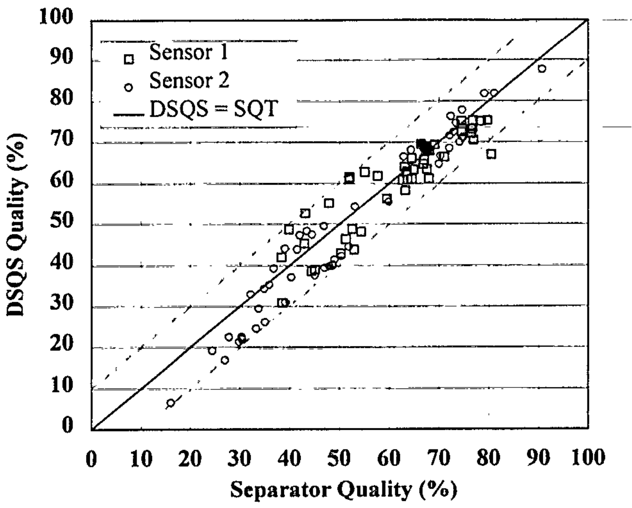

Figure 7 DSQS vs Separator (Phase III Tests)

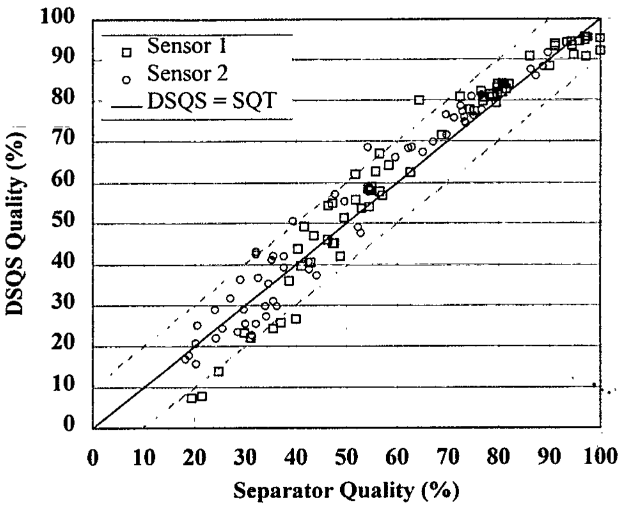

Figure 8 DSQS vs Separator (Phase IV Tests)

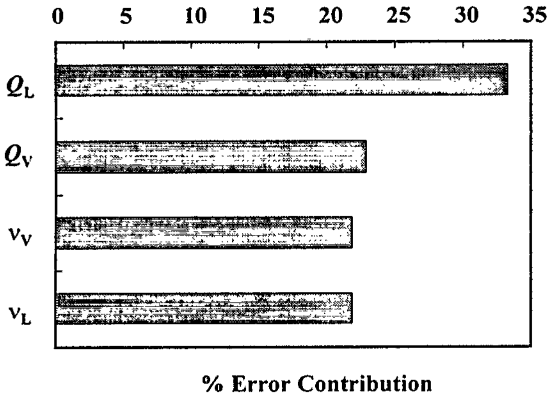

Figure 9 Error Contribution for Separator Quality

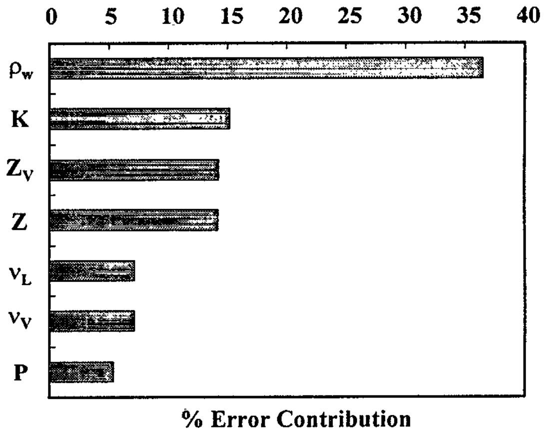

Figure 10 Error Contribution for DSQS Quality

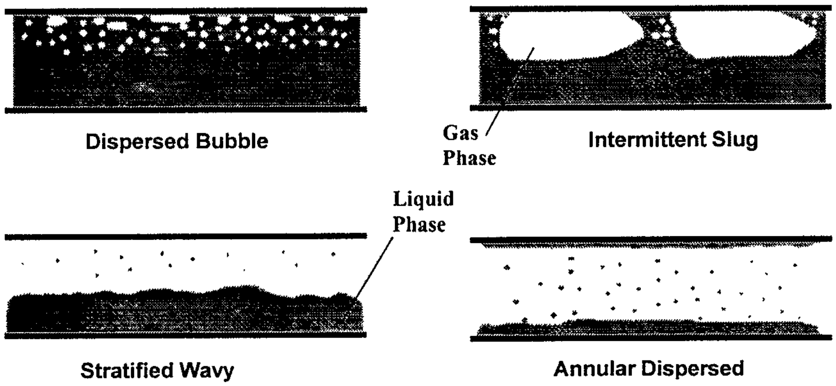

Figure 11 Two-Phase Flow Regimes for Horizontal Flow

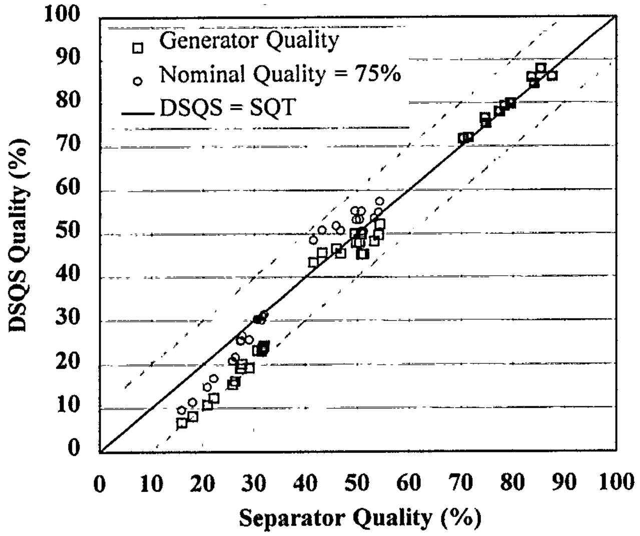

Figure 12 Effect of ρ_w (Phase II Tests - Sensor 2)

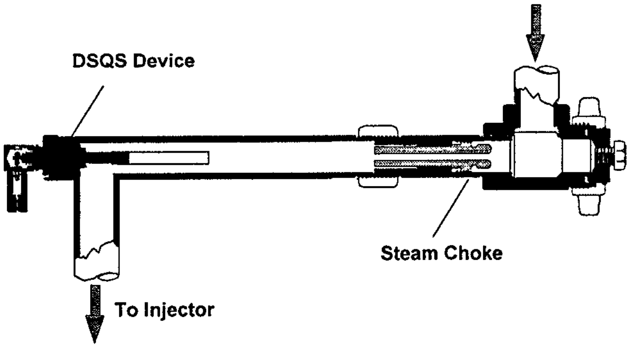

Figure 13 Preferred DSQS Injector Installation (top view)

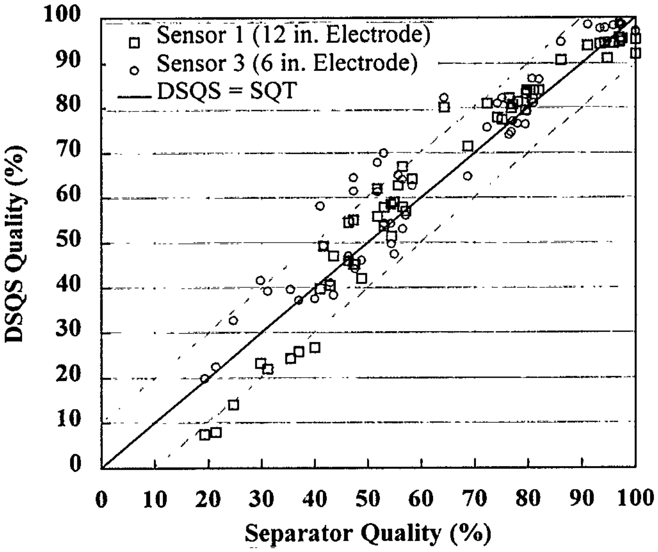

Figure 14 Effect of Electrode Length (Phase IV Tests)