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Wake Deficit Measurements on the Jess and Souza Ranches, Altamont Pass

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PREFACE

This report is the ninth in a series of documents presenting the findings of field tests under the Department of Energy's (DOE) Cooperative Field Test Program (CFTP) with the U.S. wind industry. The report provides the results of a project conducted by Altamont Energy Corporation (AEC) to measure wake deficits on the Jess and Souza Ranches in Altamont Pass, Calif. This study complements a second study conducted by AEC under the CFTP Free-Flow Variability on the Jess and Souza Ranches, Altamont Pass, (SERI/STR-217-3404), which investigated the terrain effects on wind speed at the two ranches. This research enhances and complements other DOE-funded projects to refine estimates of wind turbine array effects. This project will help to explain turbine performance variability caused by wake effects.

Three wind turbine arrays, located in the Altamont Pass east of San Francisco, Calif., were instrumented with anemometers, communications devices, and a central monitoring computer. Each array consisted of three or four rows of Nordtank 65/13-kW wind turbines with about 20 turbines in each array. Rows of turbines were switched on and off to measure the energy and speed deficits at the downwind rows. The measurements were analyzed to determine array wake effects.

ACKNOWLEDGMENTS

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SUMMARY

Three arrays of Nordtank 65/13-kW turbines on the Jess and Souza Ranches in Altamont Pass, Calif., were operated in a number of scenarios to quantify wake energy and speed deficits. Spacing between rows varied from 6.8 to 10.2 rotor diameters (D) but averaged about 8.5 D. Turbine spacing within rows was about 2 D. This spacing is typical of many commercial windfarm arrays.

Various test scenarios were used to measure the effect of one to three rows of turbines on a downwind test row. There were also scenarios to measure the effects of a single turbine. In addition, data were analyzed during days when winds blew parallel to the rows. In this situation, spacing between turbines was only 2 D.

Seven test scenarios were used. In the basic scenario, to test the effect of one row on another (separated by about 8.5 D), average wake energy deficits of approximately 12% were measured. The deficits ranged from 16% at 20 mph down to 4% at 33 mph, and an inverse relationship between wind speed and energy deficits was established. A positive relationship was established between energy deficits and two turbine performance parameters: thrust coefficient and system coefficient of power. The energy deficits were a function of the combination of wind speed and turbine performance.

In more complex scenarios with additional, more distant upwind rows switched on, the incremental energy deficits from the second upwind row were almost 50% of the single row deficits.

A surprising finding was the large row-to-row deficits measured in 16-D tests. In spite of the greater distance between rows, the energy deficits were approximately 12%, which is essentially the same as in tests with 8-D spacing. The inverse relationship between wind speed and energy deficits was also present. However, regression analysis of the 16-D test data showed that the deficits decreased more steeply as the wind speed increased, than they did in the 8-D test analysis.

Wind speed deficits were also examined and found to be on the order of 1% to 7%. The wind speed data were collected at 35 ft above ground level (AGL), which is about half of the hub-height. These data were collected at a level that was probably below the wake centerline, which would explain their smaller magnitude compared to the energy deficits. In some tests, power density (W/m^2) deficits were calculated from the wind speed data. The power density deficits were sometimes equivalent to the energy deficits and at times were much smaller.

The magnitude of the energy deficits was inversely proportional to wind speed. Because of this relationship and the speed variability caused by the uneven terrain within rows, deficits usually varied significantly within a row. A clear pattern was present in most tests. Turbines at lower elevation sites or less exposed sites had the largest deficits within a test row. Thus, the effects of terrain are compounded by wake effects. A site with marginal exposure that has a naturally lower wind resource will suffer more severe wake deficits.

Wake deficits in winds blowing parallel to the rows were inferred from energy production data. Turbine spacing within rows was 1.9 D. In these parallel wind cases, the energy deficits were approximately 50%. As the wind direction became oblique, in winds that were 22 1/2 (one compass point) off axis, the energy deficits were approximately 33%. The energy deficits were higher at night than during the day, and they were lower in high winds than in low winds.

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1.0 INTRODUCTION

Thousands of turbines have been installed in arrays in the Altamont Pass in northern California as well as the Tehachapi and San Gorgonio Passes in southern California. Windfarm developers/operators and researchers have been amazed at the variability in individual turbine energy production within these arrays. Sources of variability could include (1) individual turbine characteristics, (2) free-flow variability caused by terrain effects and (3) array wake effects. Two studies were undertaken by Altamont Energy Corporation (AEC) to address the last two items above. This report focuses on array wake deficits whereas a previous report by Nierenberg (see Bibliography) addresses the issue of free-flow variability.

Three groups of Nordtank NTK 65/13-kW wind turbines were used in this study. Two groups were on the Jess Ranch in the east-central portion of Altamont Pass. These two arrays are installed on gently sloping terrain by Altamont Pass standards. The third array was located on the Souza Ranch in northern Altamont Pass. This array has moderately complex terrain.

A variety of test scenarios were undertaken to make direct measurements of the wake speed and energy deficits within these arrays. The term energy deficits is used rather than power deficits because the basic data measured and analyzed were 10-min mean energy production in kWh at the test turbines. It should be noted that the energy deficits were not measured over the entire spectrum of wind conditions, and the results should therefore not be construed to be annual energy deficits. The results are believed, however, to be representative energy deficits that can be expected at these sites.

In most scenarios, the downwind or back row of turbines remained on line at all times whereas various combinations of upwind turbines and turbine rows were turned on and off. The energy production in the downwind row of turbines was analyzed by comparing output during periods with no wakes (upwind rows off line) to times with expected wakes (upwind rows on line). The decrease in energy output in the downwind row is defined as the deficit.

SECTION 2.0 STUDY METHODOLOGY

2.1 Test Arrays

The Jess Ranch is in the east-central portion of the Altamont Pass. It is on relatively flat terrain, by Altamont Pass standards, with elevation dropping gently to the northeast. There are two test arrays on the Jess Ranch. The Jess-A array consists of four rows of turbines with four to five turbines in each row. The Jess-C array consists of three rows of six turbines each. The Jess-B array (not shown) was not used because of mechanical availability problems. Elevations in the Jess-A array range from 570 ft mean sea level (msl) in the northwest corner to 470 ft msl in the southeast corner. Elevations in the Jess-C array range from 520 ft msl in the western portion to 465 ft msl in the eastern portion. Figure 2-1 is a topographic map of the Jess Ranch test arrays. The contour intervals are five (lighter lines) and 25 ft.

The Souza Ranch test array is in the northern portion of the Altamont Pass about six miles north-northwest of the Jess Ranch. The Souza area terrain is more complex than the Jess area. The study area is on moderately rolling terrain. Elevations in the test array range from 420 ft msl in the western portion to 330 ft msl in the eastern portion. Figure 2-2 is a topographic map of the Souza-C test array. The Souza-A and -B arrays (not shown) were not used because of availability. The contour interval is 20 ft.

Turbines in the perimeter of the test arrays were designated as buffer turbines that would remain inoperative during testing. After a few tests were conducted, the data analysis suggested that end turbines in many rows were experiencing less deficits than turbines in the middle of a row. During discussions with project managers, it was suggested that the buffer turbines along the sides of the array might be providing an artificial "wind corridor" that could be reducing wake deficits at the end turbines in each row. It was decided that buffer turbines on the sides of rows would be operated in the same fashion as the rest of the row. The upwind buffer turbines would remain off during testing.

The Nordtank turbines are mounted on 72-ft tubular towers. The rotor diameter (D) is 52.5 ft. Spacing between turbine rows varies from array to array. Lateral spacing between turbines within rows is 100 ft in all three arrays. This is equivalent to 1.9 D. Spacing between rows varies considerably and is plotted on Figures 2-1 and 2-2. The figures show that spacing between rows varies from 6.8 D to 10.2 D. Mean spacing is about 8.5 D between rows. The Jess test arrays are on flatter terrain, which might explain why the developer installed these turbines with more uniform spacing on this ranch.

Table 2-1 lists characteristics of the test arrays, which include buffer turbines, spacing, and approximate orientation of the array with respect to the upwind wind direction.

2.2 Monitoring Equipment

2.2.1 Anemometry

The reference anemometer for both test arrays on the Jess Ranch was site J08. J08 is a 50-ft tower located approximately 2 D upwind of turbine L4 in

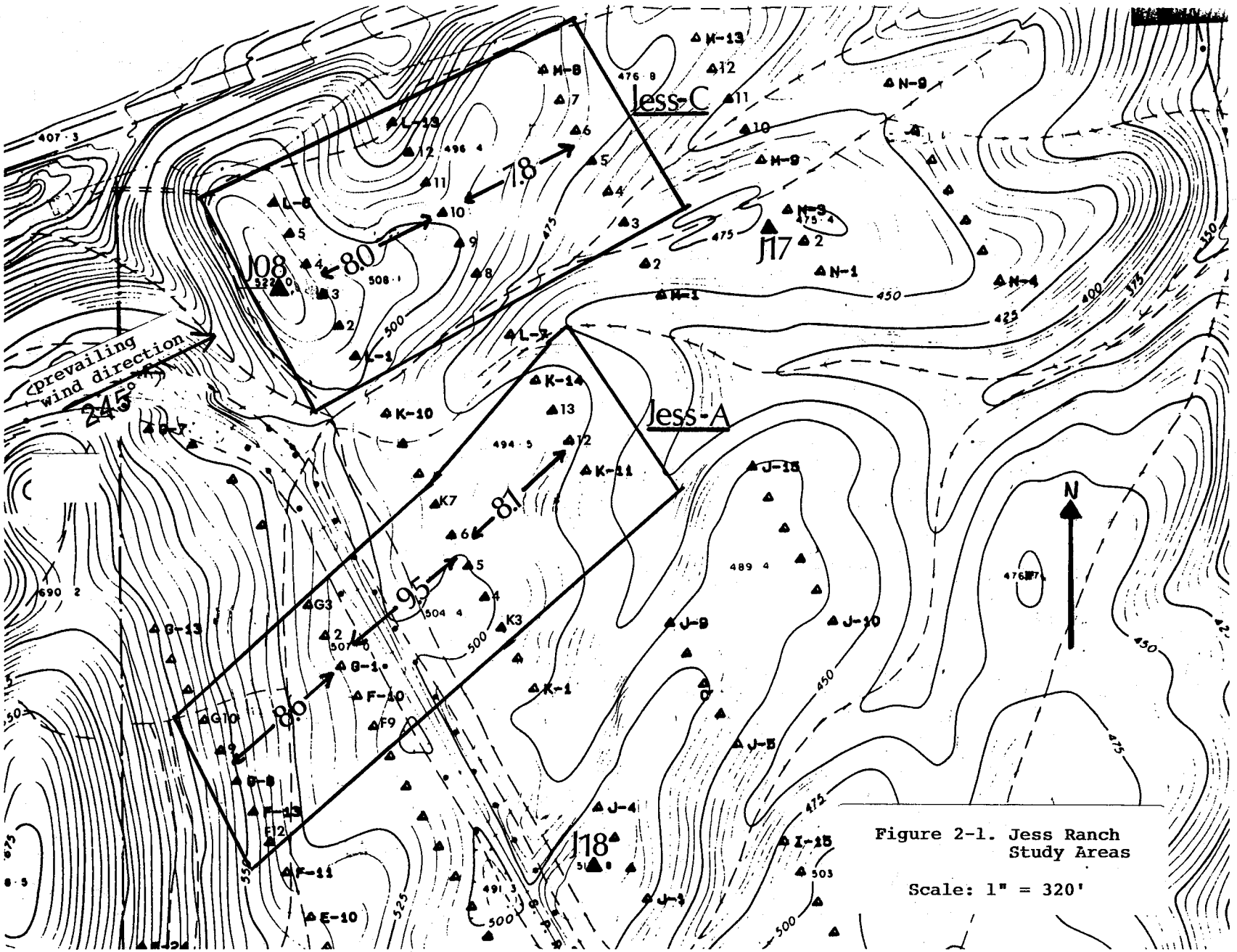

Figure 2-1. Jess Ranch Study Areas

Scale: 1" = 320'

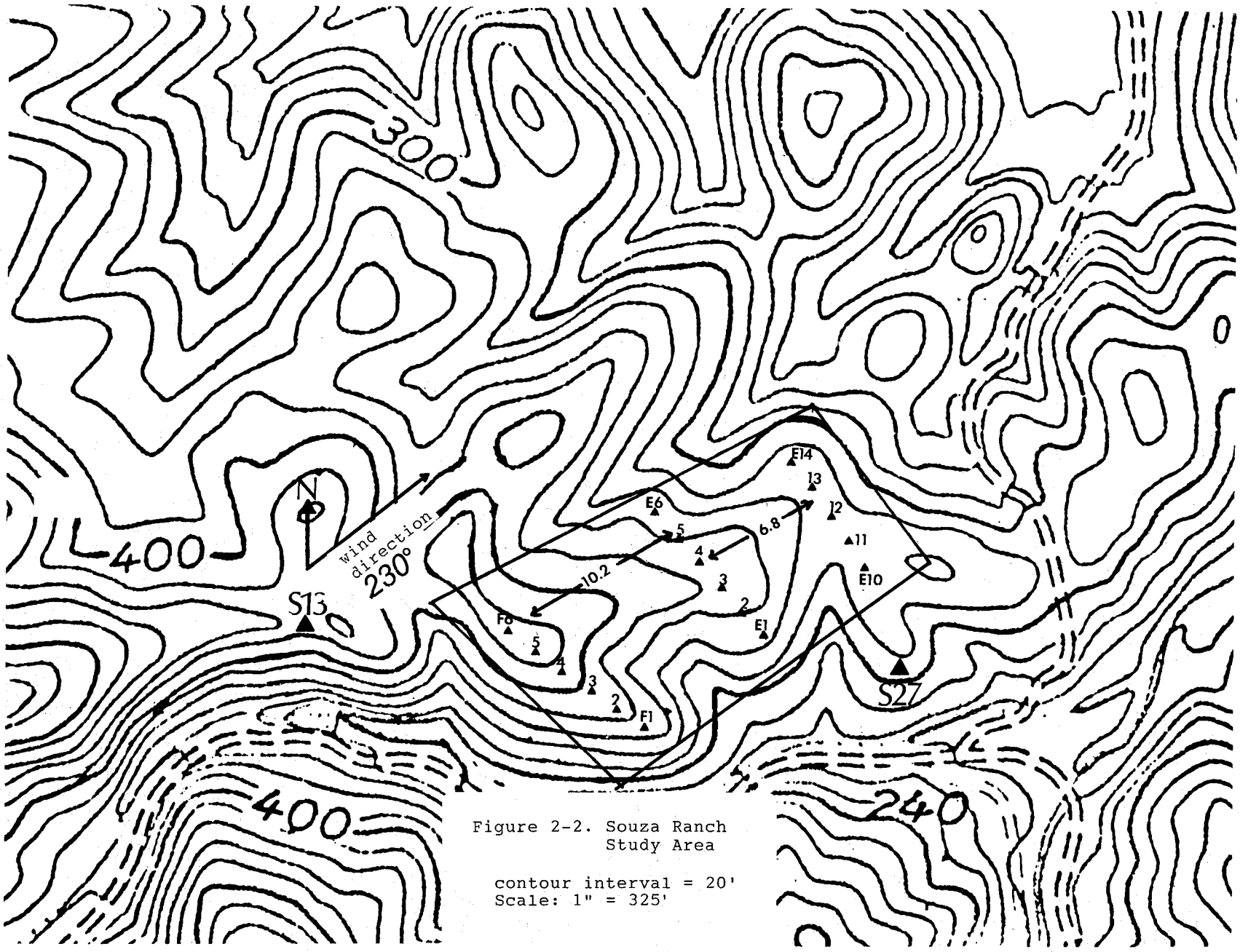

Figure 2-2. Souza Ranch Study Area

contour interval = 20'
Scale: 1" = 325'

Table 2-1. Test Array Characteristics

Test Array	Configuration (row 1=upwind)	Spacing Between Rows (RD)	Orientation	Buffer Turbines
Jess-A	4 rows; 5 turbines in row 1 5 " " " 2 5 " " " 3 4 " " " 4	8.6 between 1 & 2 9.5 " 2 & 3 8.1 " 3 & 4	230°	F11,G11, G12,G4,L7 K1,K2,K8, K9,F7,F8
Jess-C **	3 rows of 6	8.0 between 1 & 2 7.8 " 2 & 3	245°	K10, L6, L7, L13 M3
Souza-C	3 rows; 6 turbines in row 1 6 " " " 2 5 " " " 3	10.2 between 1 & 2 6.8 " 2 & 3	240°	F5, E1, E6, E10

the Jess-C array. The sensor was an R. M. Young "Wind Monitor" Propvane for the tests conducted in 1987. A problem was discovered with this sensor, which is discussed in Section 2.3.1. The sensor was replaced with a Maximum cup for the tests conducted in 1988. Two 70-ft towers with anemometers at 35 ft and 70 ft above ground level (agl) were installed for the free-flow study to measure vertical wind shear. These sites, J17 and J18, as well as J08, are plotted on Figure 2-1.

Because of the relatively flat terrain on the Jess Ranch, the turbines are laid out in straight rows approximately normal to the west-southwest flow. Anemometers were installed on every other turbine as part of the free-flow variability study, so that the spacing between sensors is 200 ft, crosswind, by about 450 ft downwind. Anemometers were installed on the Nordtank turbines on 12-ft booms at 35 ft agl. The boom orientation was north-northwest, which is normal to the flow, so there was no tower shadow. On the Nordtank turbines, 35 ft agl is about 11 ft below the bottom of the rotor. The effects of the operating rotor on the anemometer were examined at one turbine. Speed ratios between this test turbine and two adjacent turbines were calculated for two periods when the test turbine was turned off and on. There were no differences in speed ratios between the test turbine and the two adjacent turbines for the two time periods. Because the ratios remained constant, it is assumed that the operating rotor had no measurable effect on the anemometer.

The reference anemometer for the Souza array was site S13, a 70-ft tower located about 2 D upwind of turbine G5. The sensor was an R. M. Young Propvane. A second tower was also available. Site S27 is an 80-ft tower located 2 D crosswind (south) of turbine E7. The sensor was a Maximum cup. Both sites are plotted on Figure 2-2.

The Souza Ranch terrain is more complex than that of Jess. On Souza, the turbine rows follow the local ridgelines to some extent. The rows are not as straight nor are they all parallel. Spacing between anemometers and sensor height is the same as on Jess. However, the boom orientation is northwesterly because the prevailing wind direction is southwesterly.

Except for the two reference towers, all sensors were Maximum type 40-cup anemometers. The sensors are constructed of three molded lexan cups. The transducer is an alternating current (ac) generator that produces a sine wave signal. The signal frequency is proportional to wind speed. The manufacturer specifies the accuracy to be ± 2.5%, and the distance constant to be 9.7 ft.

The two reference towers, J08 on Jess and S13 on Souza, had R. M. Young "Wind Monitor" Model #05103 Propvane anemometers. Wind direction was measured with a potentiometer and wind speed was measured with an ac sine wave generator. The manufacturer specifies the distance constant to be 7.4 ft and the accuracy to be ± 2.0%.

Approximately 60 of the Maximum cups and both propvanes were wind-tunnel tested at the University of California Davis wind tunnel. The wind tunnel test procedure called for approximately 30 samples for each sensor in wind speeds ranging from 10 to 60 mph. Almost all cups tested read 1% to 2% below tunnel speed, and the mean speed of all cups tested was 98.7% of tunnel speed. The two propvanes read about 1% above tunnel speed.

2.2.2 Central Monitoring Computer and Communicating Turbine Monitors (CTM)

The Second Wind, Inc., monitoring system on each ranch has two main components: (1) the central computer and (2) the CTMs. Each individual turbine has a CTM that monitors turbine status, turbine power, and wind speed and direction (if there are wind sensors installed). Turbine power is measured by two current transducers and two power transducers manufactured by Ohio Semitronics, Inc. The manufacturer specifies their accuracy to be + 1.0%. The CTMs operate on a 1-s scan interval, and calculate and store 10-min averages of wind speed, as well as turbine status and 10-min integrated energy output. The CTMs are connected via cable to the central computer, which interrogates all turbines once a minute. The central computer performs many functions, but of particular importance to this study is the data archiving function. The 10-min data are stored on a Bernoulli disk drive, which permits these data to be accessed by other computers.

2.2.3 Nordtank NTK 65/13-kW Turbine

The Nordtank turbine is mounted on a 72-ft tubular tower and has an upwind rotor with a diameter of 52.5 ft. It has an active yaw system. The turbine has two generators, 13 and 65 kW, and rotates at two speeds. In winds below 15 mph, the rotor rotates at 38 rpm and is connected to the 13-kW generator. Tip speed is approximately 70 mph. In higher winds, it switches automatically to the 65-kW generator and rotates at 48 rpm. Tip speed is approximately 89 mph. Power regulation in high winds is controlled passively with stall-regulated blades.

Figure 2-3 is a plot of the system power curve and system coefficient of power (Cp) versus wind speed. Because the slope of the power curve is steepest at

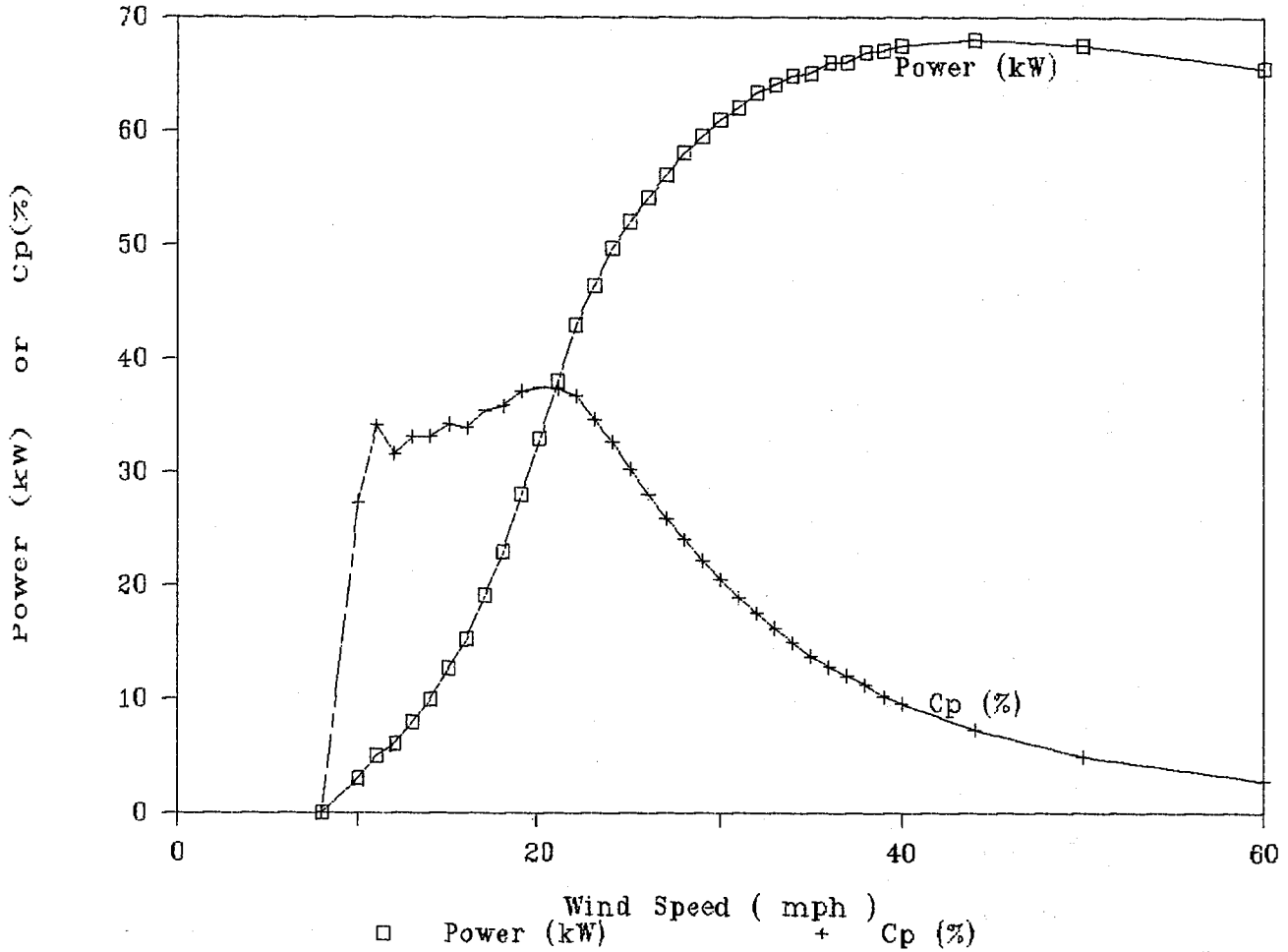

Figure 2-3. Nordtank 65/13 Power Curve and Coefficient of Power vs. Wind Speed

about 20 mph, and one would expect maximum wake deficits to occur in this region of the curve. At about 30 mph, the slope of the power curve changes rapidly. It becomes much flatter as it approaches the "rated" speed of about 35 mph.

Because a given change in speed will produce a smaller change in power, one would expect smaller wake deficits above 30 mph.

The second curve shows that the maximum Cp occurs at 20 mph, where it reaches 38%. A secondary maximum of 34% is found at 11 mph. This maximum occurs when the system is operating on the low-speed generator. The Cp curve falls off very steeply above 22 mph. As mentioned in the previous paragraph, maximum deficits are expected at about 20 mph, at the maximum Cp and steepest part of the power curve. Deficits should decrease above this speed as the power curve flattens and Cp decreases.

Figure 2-3.a is a plot of thrust coefficient (Ct) versus wind speed. The figure shows that in 10- to 30-mph winds, the plot is nearly a straight line with a negative slope. The linear correlation coefficient between these two variables is nearly perfect at -0.997. Because of this relationship, either variable is a suitable surrogate for the other.

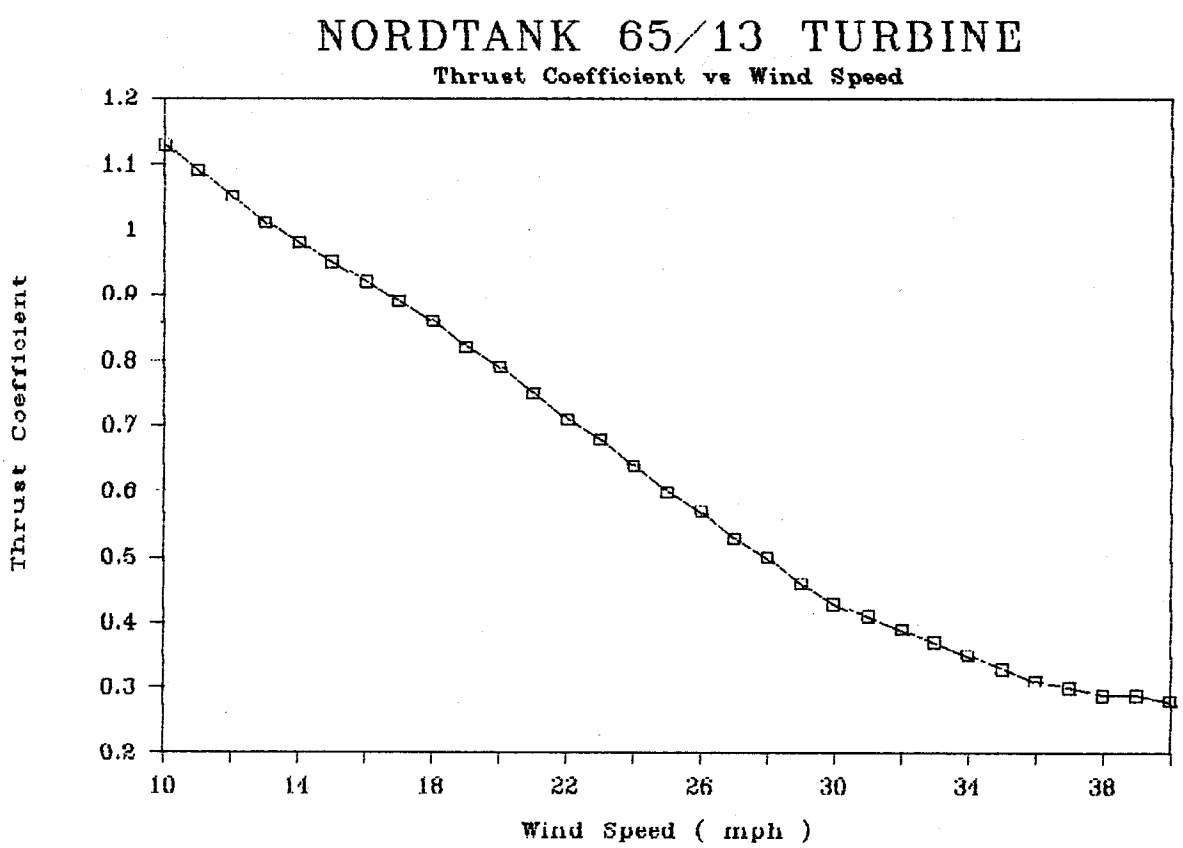

Figure 2-3.a. Thrust Coefficient vs Wind Speed

Figure 2-3.b is a plot of tip speed ratio versus Cp. The curve shows the two peaks in Cp, also shown on Figure 2-3.

Table 2-2 lists the Nordtank power output, Cp, Ct, and tip speed ratio. These have been calculated for ambient air density, approximately 97% of sea level. Ct is calculated for the high-speed generator only. Therefore, the table entries of Ct up to 14 mph are not absolutely correct.

2.3 Data Processing and Quality Assurance

The Second Wind, Inc., central monitoring computer stores the 10-min averages. These data are transferred to the office computer on a Bernoulli disk. The office computer has several programs that were used to access this data. One program is a Data Dump, which allows the user to specify a start and end time and a range of parameters. It creates a file that can be printed out or imported into a Lotus spreadsheet for review of the 10-min records.

The Data Dump program was used to extract all the 10-min records of speed, direction, energy, and turbine status from all test turbines and reference anemometers. This raw data file was then compared with test operator's field notes to assign each 10-min record to the appropriate turbine configuration. Turbine configurations generally fall into three categories: upwind turbines off (i.e., no wakes), upwind turbines on (wakes), or transition periods. The 10-min records collected during the transition periods were then deleted.

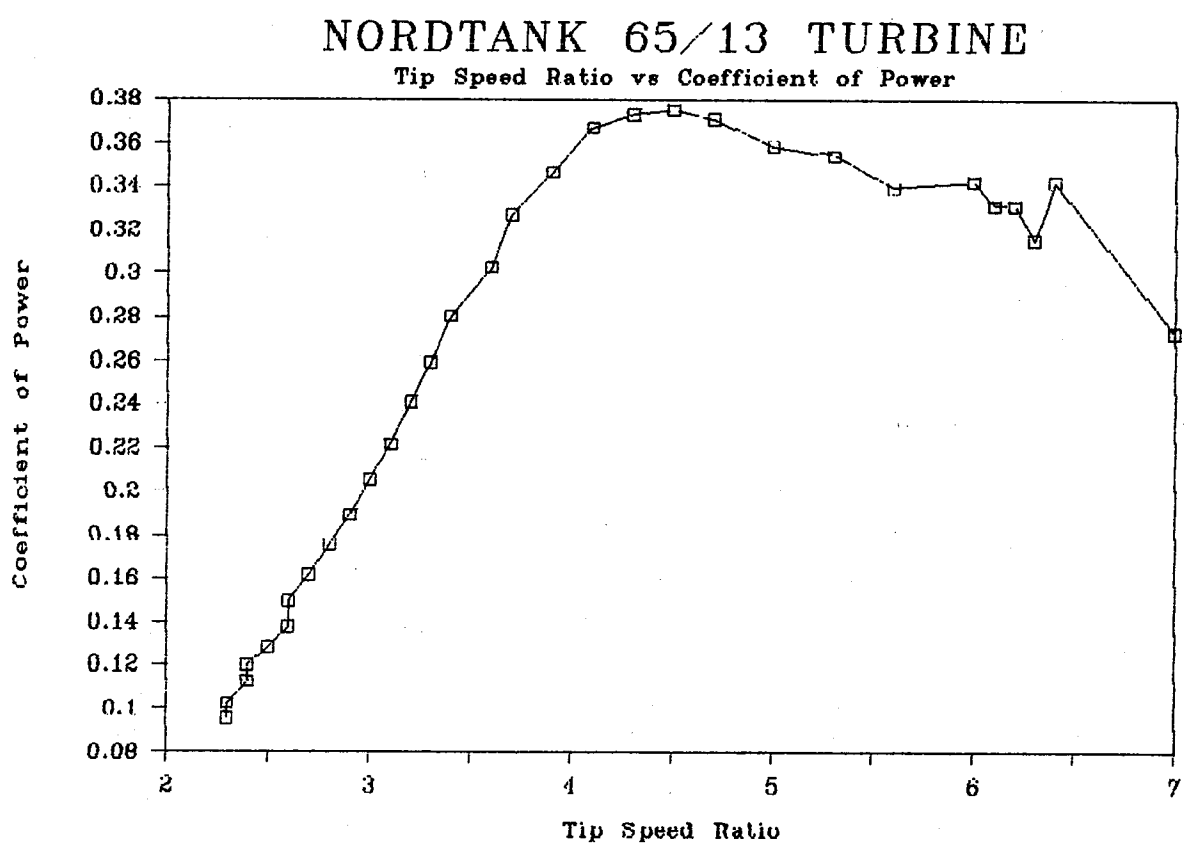

Figure 2-3.b. Tip Speed Ratio vs Coefficient of Power

Table 2-2. Nordtank NTK 65/13 Power Curve and Other Statistics

Speed (mph)	Power (kW)	Cp	Ct[a]	Tip Speed Ratio
10	3	.27	e 1.13	7.0
11	5	.34	e 1.09	6.4
12	6	.32	e 1.05	5.9
13	8	.33	e 1.01	5.5
14	10	.33	e .98	5.1
15	12	.34	.95	6.0
16	15	.34	.92	5.6
17	19	.35	.89	5.3
18	22	.36	.86	5.0
19	27	.37	.82	4.7
20	32	.38	.79	4.5
21	37	.37	.75	4.3
22	42	.37	.71	4.1
23	45	.35	.68	3.9
24	48	.33	.64	3.7
25	50	.30	.60	3.6
26	53	.28	.57	3.4
27	54	.26	.53	3.3
28	56	.24	.50	3.2
29	58	.22	.46	3.1
30	59	.21	.43	3.0
31	60	.19	.41	2.9
32	61	.18	.39	2.8
33	62	.16	.37	2.7
34	63	.15	.35	2.6
35	63	.14	.33	2.6
36	64	.13	.31	2.5
37	65	.12	.30	2.4
38	66	.11	.29	2.4
39	67	.10	.29	2.3
40	67	.10	.28	2.3

[a] Calculated for high speed generator only.
e = estimate (see text)
All calculations for 97% sea-level density.

The test operators' notes included references to turbine problems that might have occurred during a test. For the entire duration of the tests, there were only ten occasions when a turbine faulted or went off line. The 10-min energy production values for these incidents were flagged because the turbine was not producing power for the entire 10-min period. Later, during data analysis, these records were edited to normalize the energy to a full 10 min. These records are flagged with an "e" for estimate in subsequent data listings.

In addition to these ten data records, there were 70 missing records. These were due to turbines that were either unavailable or the production data were suspect for an entire test. These records were detected in visual scans of the data listings, and energy values during these scans were clearly invalid.

Typically, the energy production values were off by nearly an order of magnitude from adjacent turbine values. These data were deleted and no attempt was made to estimate or fill in these data records. Approximately 7500 valid 10-min data records were recorded and analyzed. Therefore, overall data recovery was approximately 99%.

The 10-min data files for each test were analyzed using Lotus 1-2-3 software. These files are contained in Section 3.0, the Data Analysis Section. The format for all the data listings is the same and a description follows.

The data are usually presented in two separate blocks. Each block of data contains the 10-min records for one of the test configurations such as upwind rows off or on. The data records within each block are sorted by increasing wind speed or by wind direction at the upwind reference anemometer.

Column 1 lists the start time (hour:minute) of each 10-min data record. Column 2 shows the turbine configurations, such as the number of turbines or rows of upwind turbines on or off. Column 3 lists the mean speed in mph from the reference anemometer. Column 4 lists the wind direction in degrees, at the reference anemometer. The next few columns list the 10-min energy production from the test turbines. The next column is the sum of energy production from these test turbines. In many of the tests, wind speed data were available from every other turbine. These data are listed to the right of the sum of energy. Wind speed data were not analyzed in the Lateral Induction Test or the Meandering Wake Effect Test.

At the bottom of each block of data, the column means for that particular configuration have been calculated. At the bottom of the table, ratios are calculated between the mean speeds and energies for the two periods. Ideally, the speed ratios between periods at the upwind anemometer should be near unity, indicating that the two periods had similar conditions. If they are different, a second set of means may be calculated. The new set of means will eliminate the highest or lowest wind speed record (the first or last record). This "normalized" mean is compared to the other block mean to see if the two periods are closer to unity. This process reduces "bias" between the two data sets. Ideally the mean speeds at the upwind reference should be equal so there is no bias. Then, one can assume that differences in energy production are due to wakes and not temporal differences. The ratios of energy (calculated by dividing the period with turbines on by the period with them off) indicate the decrease between the periods. The energy deficit in percent can be calculated by subtracting this ratio from 100.

Although not contained on the data listings, standard deviations of the 10-min means were also calculated. The means and standard deviations were used to determine the statistical level of significance of the test results. The statistical test used was the "Student's" t distribution. The test was used on all cases except the Meandering Wake Test and the Parallel Case Studies. The level of significance is given at the end of each test discussion in Section 3.0.

2.3.1 Site J08 Sensor Problems

Two problems were detected with the R. M. Young sensor at site J08. This sensor was installed on September 7, 1987. Previous to this installation,

three years of data had been collected at this site and at site J04. Site J04 is at the southwest edge of the Jess Ranch, one mile from J08. The established speed ratio between these sites for the previous three Septembers was 98.8% (J08 = 98.8% of J04). After installation of the R. M. Young sensor, this ratio jumped 2.8%, to 101.6% of J04. It was felt that the J08 sensor might have a positive bias. To determine if this were true, in the field, a calibrated Maximum cup was installed at J08 at the same level, in January 1988. Three months of concurrent wind speed data were collected by these two sensors. Correlation of all concurrent wind speed data, in winds of 10 mph or greater, showed that the R. M. Young sensor was reading 2% higher than the Maximum cup. The correlation was perfect. As a result, all wind speeds collected in 1987 at J08 were reduced by 2% to reflect this field calibration. Wind speed data collected at J08 in 1988 were from the Maximum cup, so no correction was necessary.

The other problem with J08 was in orientation of the vane. It was discovered that the north point on the wind vane was oriented towards 22.5° east of true north. With this orientation all wind direction data would be recorded 22.5° too low. (For example, a north wind at 360° would read 337.5°). It was evident from the base plate and guy wires that the mast had not turned, but had been installed incorrectly. Therefore, 22.5° have been added to J08 wind direction data collected in 1987. The position of the mast was corrected prior to the 1988 testing and the R. M. Young sensor was still used to measure wind direction.

These problems were not evident at the other R. M. Young sensor installed at site S13 on the Souza Ranch.

2.4 Test Configurations and Chronology

There were seven different test configurations. Six of these involved active testing and one was passive. The test configurations are described below with the help of Figure 2-4. Figure 2-4 does not include the buffer turbines, which surround the test arrays.

The Direct Wake Effect Test was the most basic test plan to determine the wake effects of a single row of turbines on a downwind test row. The term "test" turbines means those turbines whose energy production data are analyzed. These turbines are usually in the downwind row of the test array. In this test, the turbines in the middle row marked with "*" (see the upper left portion of Figure 2-4) are turned on and off simultaneously and the downwind row marked with "?" remains on line. Energy production from the test turbines marked with "?" is analyzed. The production data are sorted into two time groups -- upwind "*" row on and upwind "*" row off. In one test, data from a third row that was about 18 D downwind of the "*" row were analyzed to determine persistence of the wakes.

Two 10-min data samples were taken back-to-back in one mode, followed by a 10-min transition period. During the transition period, the upwind row "*" was turned on or off. Then two more 10-min samples were collected in the alternate mode. This process was repeated for 6 to 12 h.

The Sixteen-Diameter Test was designed to determine the persistence of wake deficits at greater distances. (See the upper right portion of Figure 2-4.)

```
                    Wind Direction ---->>

Upwind   Middle   Downwind          Upwind   Middle Downwind
  .        *         ?                *        .       ?
  .        *         ?                *        .       ?
  .        *         ?                *        .       ?
  .        *         ?                *        .       ?
  .        *         ?                *        .       ?
   Direct Wake Effect                       16 RD Test

 *        *         ?                        *
 *        *         ?                        ?
 *        *         ?                        *
 *        *         ?                        ?
 *        *         ?                        *
     Blockbuster                      Lateral Induction

          *         ?                *        *       ?
          *         ?                *        *       ?
          *         ?                *        *       ?
          *         ?                *        *       ?
          *         ?                *        *       ?
 Multiple Row (1 row on)            Multiple Row (2 rows on)

          .         ?                         .       ?
          .         ?                         .       ?
          .         ?                         .       ?
          .         ?                         *2      ?
         *1         ?                         .       ?
 Meandering (Hour 1)                Meandering (Hour 2)
```

Key

? = Downwind test turbines whose energy output is analyzed. These remain on-line for entire test.
* = Turbines which are switched on/off during test.
. = Turbines which are off for entire test.

Figure 2-4. Generic Test Array Configurations

The test is a variation of the direct wake test except the spacing between rows is double. In this test, the middle row is switched off for the entire test. The downwind row "?" remains on throughout the test and is the test row. The upwind row "*" is switched on and off. Production data from the test row "?" is sorted into two groups -- "*" row on (wakes) and "*" row off. Deficits from these tests were compared to direct wake effect deficits to determine how far the deficits persist.

The Blockbuster Test was a variation of the direct wake test except that two rows of turbines are turned on and off simultaneously instead of one. This test can be thought of as an array wake effect test. (See the second from the top left portion of Figure 2-4.) Thus both upwind rows marked "*" are turned on and off, and energy production data from the test row "?", which remains on line, are analyzed. The production data is sorted into two time groups -- upwind rows "*" on, and rows "*" off. In one test, data from the row downwind of the test row "?" were analyzed to determine the persistence of the wakes.

The Multiple Row Wake Effect Test is the most elaborate test plan and it produces the most data. (See the third from the top portion of Figure 2-4.) This test is designed to measure the incremental wake deficits of one, two, or three rows of upwind turbines. Row "?" is the test row and remains on line. Upwind rows "*" are off line and two 10-min data samples are collected. Then one upwind row "*" is switched on line and two 10-min samples are taken. Finally, the second upwind row "*" is switched on line and two 10-min samples are collected. The production data from the test row "?" is sorted into three groups -- upwind rows "*" off line (no wakes), one upwind row "*" on line, and two upwind rows "*" on line. The data from the middle row are analyzed as well. When this row is on line, its production data are sorted into two groups -- upwind row "*" on and upwind row "*" off. Thus the middle row data are the same as a direct wake effect case.

The Lateral Induction Test was designed to measure the effects (enhancement) that might occur at an individual turbine as adjacent turbines are switched on and off. The theory is that the wind, to some extent, will follow the path of least resistance, which is between turbines. A venturi effect could be occurring as a result. As the gaps between turbines within a row are closed, production could be enhanced. This could occur because the wind blowing around the rotor disk of one turbine would be forced through the adjacent turbine's rotor. This is generally referred to as the "windwall" effect by the developers. In this scenario, only one row is used. (See the right, second from the top portion of Figure 2-4.) Turbines "*" are switched on and off. The energy production at "?" turbines is compared between the two periods. If there are lateral induction effects, "?" turbine output will increase during the periods when "*" are on line. In this study, energy production was analyzed at the next downwind row as well, to determine the wake effects downwind of one-half row of turbines.

The Meandering Wake Test was designed to measure the effects of a single turbine on a downwind row of turbines. In this test, row "?" turbines remain on line and "*1" is switched on. One hour later, "*1" is turned off and "*2" is switched on. In Figure 2-4, only "*1" and "*2" are illustrated at the bottom of the figure. In another hour, "*2" is switched off and "*3" is switched on. This continues until "*5" is reached. The data are analyzed from the test row "?" by sorting it into 1-h periods. The wake deficit should

progress up the test "?" row in hourly steps, if the wind direction remains constant. The individual 10-min records were also examined. The mean wind direction for each period was used to determine wake trajectory. Energy production from the turbines in the expected wake path was compared to the other turbines in the test row, to see if production dropped. The analysis is more qualitative than quantitative.

The Northwest or Parallel Case is a passive test. During the winter and spring seasons, north-northwest winds, which are parallel to the rows, occur intermittently. The 10-min data from two entire six-month periods were analyzed. Data were screened by wind direction; only records with this type of flow were analyzed. In this scenario (not illustrated), the northernmost turbine in each row is the upwind reference turbine. Energy production from the remaining turbines in each row is compared to the reference turbine in each row. In this scenario, turbines are spaced at 1.9 D.

Additional analysis was done by screening further. Data were screened for wind directions that were nearly parallel, i.e., 22½° (1 compass-point) off axis. The production data were analyzed in the same manner as above, except the winds were nearly parallel instead of parallel. Screening data by wind speed and time of day was also done. In all these cases, energy ratios between the upwind turbine and the downwind turbines in each row were calculated. On flat terrain, with no wake deficits, one would expect energy ratios of unity. If the energy ratios are less than unity, then there is an energy deficit. Unfortunately, the terrain is not flat, which complicates matters. The measured energy ratios are a result of terrain and wake influences.

Table 2-4 lists the dates, locations, test duration and the section in this report of all the active tests described above.

2.5 Free-Flow Variability Results

The free-flow data were collected to determine terrain effects on wind speeds on the Jess and Souza Ranches. The term free flow is used because all turbines were shut down for these tests, ensuring no local wake effects. The data and analyses are contained in the report Free-Flow Variability on the Jess and Souza Ranches, Altamont Pass (see Bibliography). Some brief excerpts from that report are contained in this section.

The results of the free-flow report are useful for interpreting the wake deficit results. The subsequent speed and energy ratio maps are of particular interest. Because the terrain is complex on these ranches, there are variations in the ambient flow at the test turbines. Turbines at the best exposed sites had higher speed and energy ratios than other turbines in a given test row. In Section 3.0, it will be shown that there was a strong inverse relationship between wind speed and energy deficits. Because of the variation in exposure in the test rows and the inverse relationship, there were large variations in the deficits within the test rows. The best exposed sites in each row typically had the highest energy output (highest winds) and the smallest deficits. Sites with poor exposure had lower output and higher deficits. No attempt has been made to normalize the individual turbine deficits for terrain (speed-up) effects. This would be a difficult process, with no prescribed methodology or purpose. The wake test results present the individual deficits, as well as the row average.

Table 2-4. Test Dates and Locations

Test Type	Date	Array	Report Section	Test Duration
Direct Wake	Aug. 7, 1987	Souza-C	3.1.1	8 hours
	Sep. 25, 1987	Jess-A	3.1.2	10 hours
	Oct. 1-2, 1987	Souza-C	3.1.3	11 hours
	July 18, 1988	Jess-C	3.1.7	4 hours
	July 20, 1988	Jess-C	3.1.5	10 hours
	July 21, 1988	Jess-C	3.1.6	6 hours
Sixteen RD	June 14-15, 1988	Jess-C	3.2.1	10 hours
	June 16, 1988	Jess-C	3.2.2	8 hours
Blockbuster	Sep. 25, 1987	Jess-C	3.3.1	10 hours
	Oct. 7, 1987	Souza-C	3.3.2	10½ hours
Multiple Row	Sep. 4, 1987	Jess-C	3.4.1	8 hours
	Sep 10, 1987	Jess-A	3.4.2	10 hours
	Oct. 9, 1987	Souza-C	3.4.3	12 hours
Lateral Induction	Sep. 10, 1987	Jess-C	3.5	4 hours
Meandering Wake	Aug. 12, 1987	Souza-C	3.6.1	5 hours
	Aug. 13, 1987	Jess-A	3.6.2	5 hours

free-flow data collection took place on the Souza Ranch from September 10, 1987 through September 14, 1987. The duration of the data collection phase was 94 h. Data collection on the Jess Ranch took place in two periods: October 1 through October 3, 1987, and October 7 through October 10, 1987. The duration of the Jess data collection phase was 102 h. Although data collection took place in October on the Jess Ranch, the meteorological conditions were typical of summer.

2.5.1 Souza Ranch Correlations

The first step in the free-flow data analysis was the correlation of all hourly wind speed data to the reference towers. Correlation is defined as the degree of relationship between variables. The correlation coefficient is a dimensionless number that varies from -1 to +1. A positive correlation means that variable y tends to increase as variable x increases. A negative or inverse correlation means that variable y tends to decrease as variable x increases. The correlation coefficient should not be confused with a ratio. Two variables or sites could have a high degree of correlation, close to 1.0,

but have a ratio very different from unity. Figure 2-5 is a plot of all the linear correlation coefficients (r) to reference site S13. The figure shows that the turbines in the test array were all highly correlated to site S13. The correlation coefficients ranged from 0.94 to 0.99. Turbines at the north end of each row had the highest correlations. The correlation data are important because they show how representative the reference anemometer data are to the study arrays.

2.5.2 Jess Ranch Correlations

Figure 2-6 is a plot of the correlation coefficients to site J08 for the Jess Ranch test arrays. Note that only the end turbines in each row are labeled on this figure and on Figures 2-9 and 2-10. All turbines are labeled on Figure 2-1. Figure 2-6 shows that the correlations on Jess decreased at sites immediately downwind of the 678-ft hill near the Jess-A array. The turbines in the Jess-C array were highly correlated to J08 with a range of 0.98 to 1.0. The turbines in the Jess-A array had correlation coefficients that were fair to good. The range was from 0.76 to 0.96. The last two rows of this array, where most of the wake analysis was done, had higher correlations than the first two rows. The coefficients in the back two rows ranged from 0.84 to 0.96.

2.5.3 Souza Ranch Ratios

Figure 2-7 is a plot of the speed ratios to S13 for the free-flow data period. The wind speeds were quite uniform. Almost all the site ratios were within a range of 90%-110% of S13. There is a high wind area at turbines F2-F6. Speed ratios decrease at successive downwind rows. It is especially important to note the ratios at E10, E12, and E14, where almost all the Souza wake data were collected. Note the low ratio at turbine E14. This turbine usually had the highest wake deficit in this row. Deficits at turbine E10 were usually much lower.

Figure 2-8 is a plot of the theoretical energy ratios to S13. The pattern is the same as Figure 2-7. No vertical shear adjustments were made to correct the 35-ft data to hub-height (72 ft). Site S13 vertical shear exponent (alpha) was about one-half the "normal" value of 0.14 (for flat terrain) and S27 shear was about zero. At sites that are not on the tops of well-exposed ridges, shear values may be close to 0.14. This is probably true at many of the "E" sites, which are on terrain that slopes gently down behind a ridge. Therefore, the energy ratios on Figure 2-8 may be artificially low at these sites. However, trying to estimate wind shear at individual sites is difficult. The resulting errors could be larger than if the data are simply presented as is.

2.5.4 Jess Ranch Ratios

Figure 2-9 is a plot of the speed ratios to J08 for the free-flow data period. Note that all ratios are less than 100%. This is due to site J08's excellent exposure. J08 is situated on a bluff that juts into the large canyon that Interstate 580 runs through. J08 is exposed to this channel, which is oriented parallel to the west-southwest flow. Ratios within rows in the Jess-C array are highest at the north end and lowest in the south end. Much of the wake data were collected at turbines M4 through M8 in this

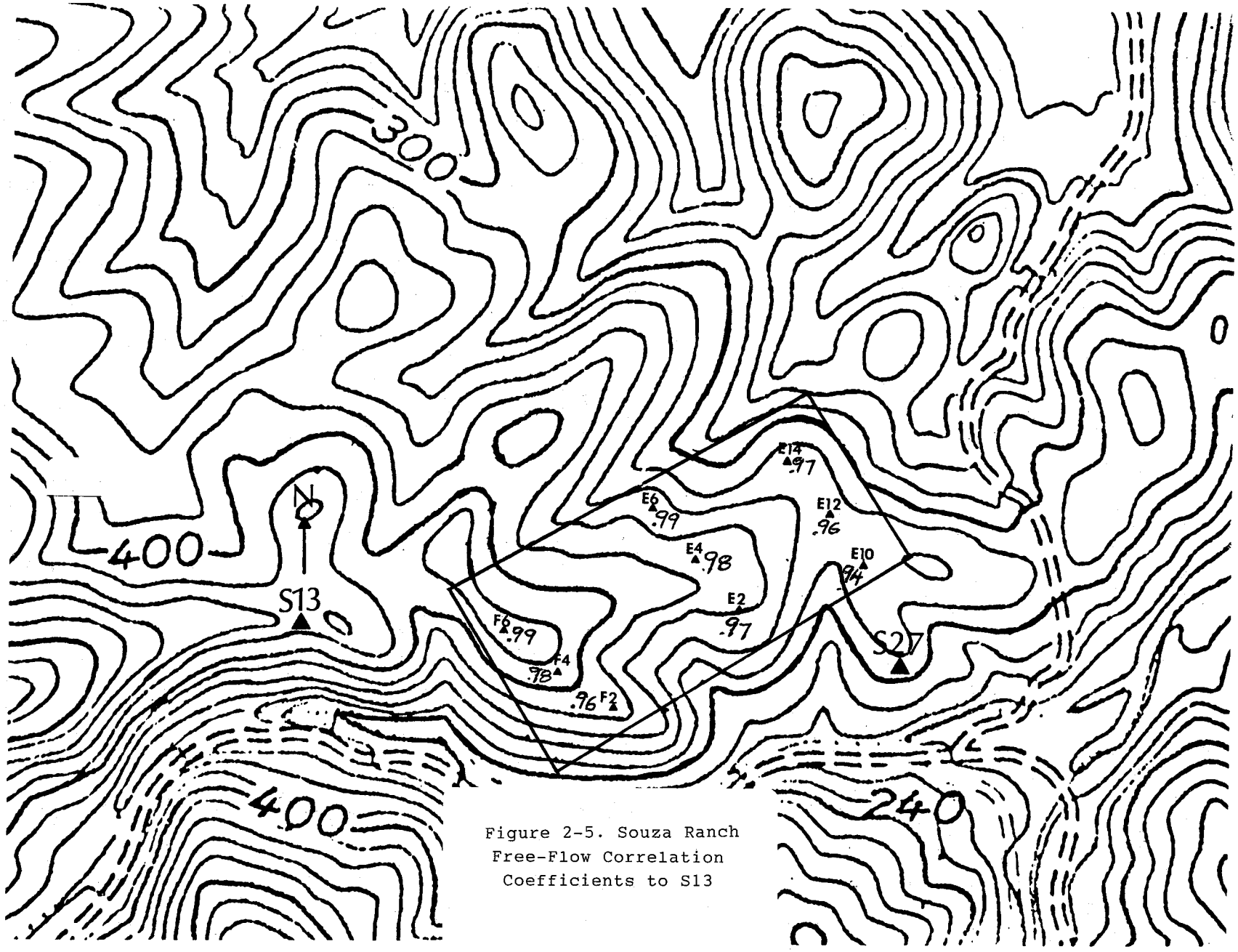

Figure 2-5. Souza Ranch Free-Flow Correlation Coefficients to S13

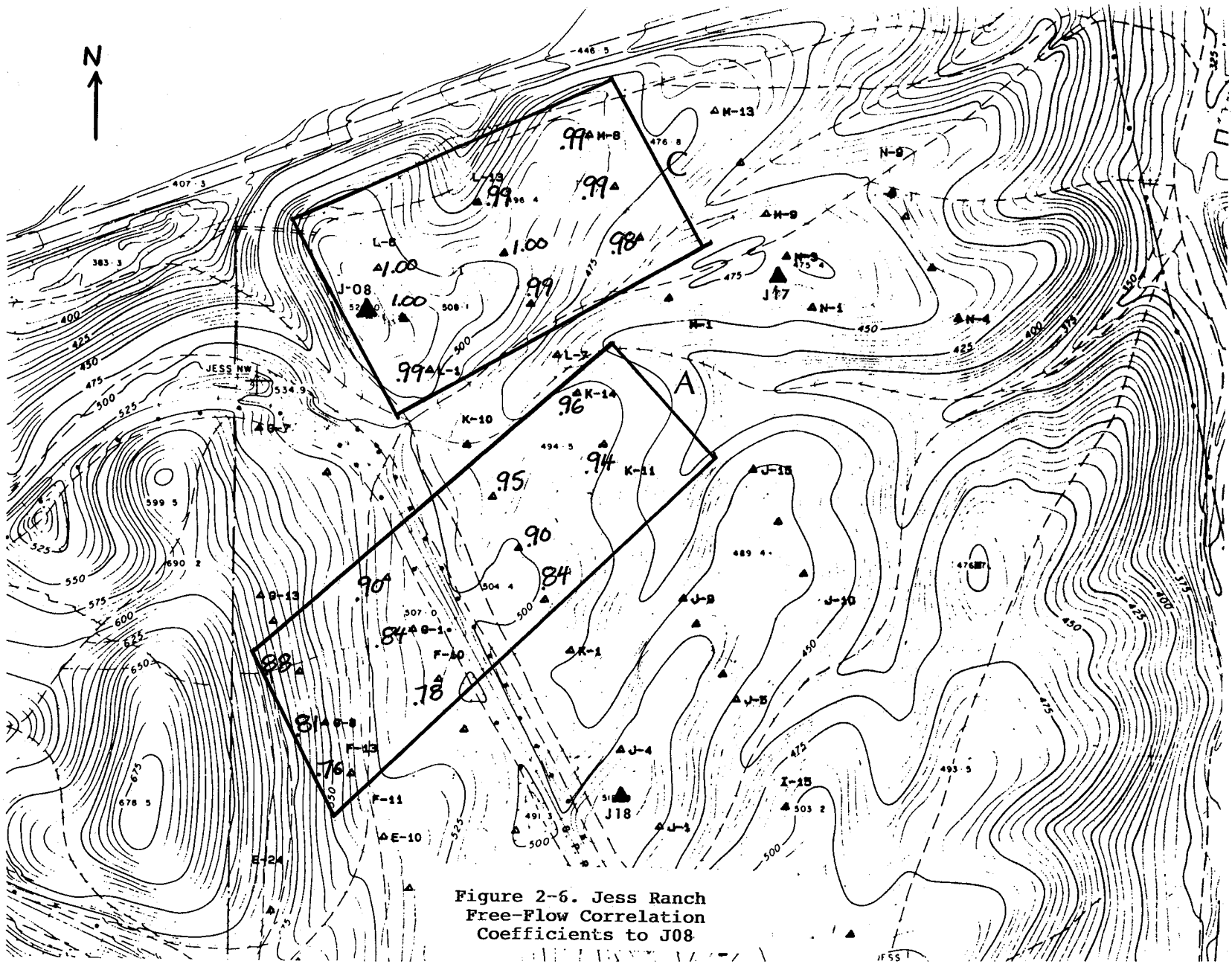

Figure 2-6. Jess Ranch Free-Flow Correlation Coefficients to J08

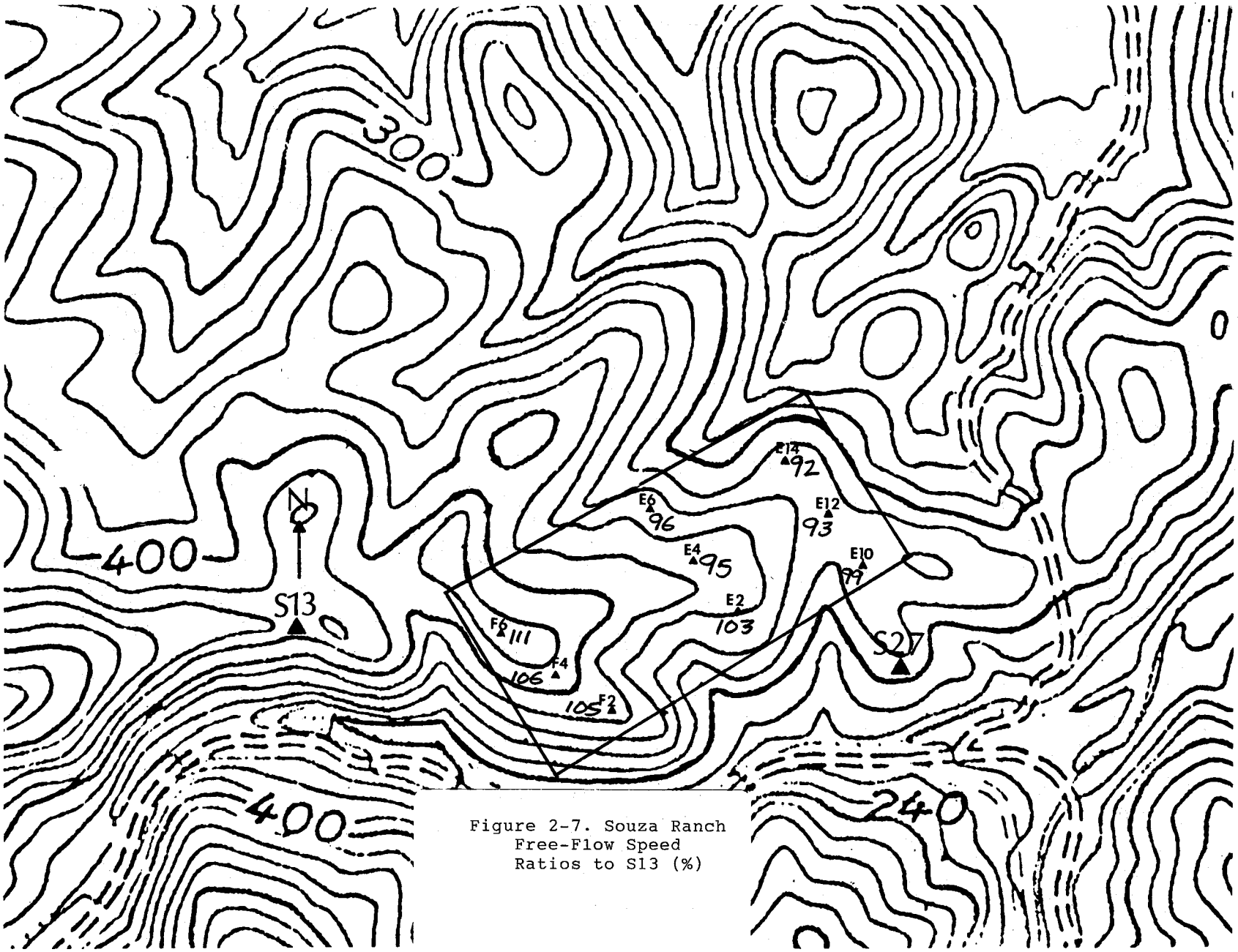

Figure 2-7. Souza Ranch
Free-Flow Speed
Ratios to S13 (%)

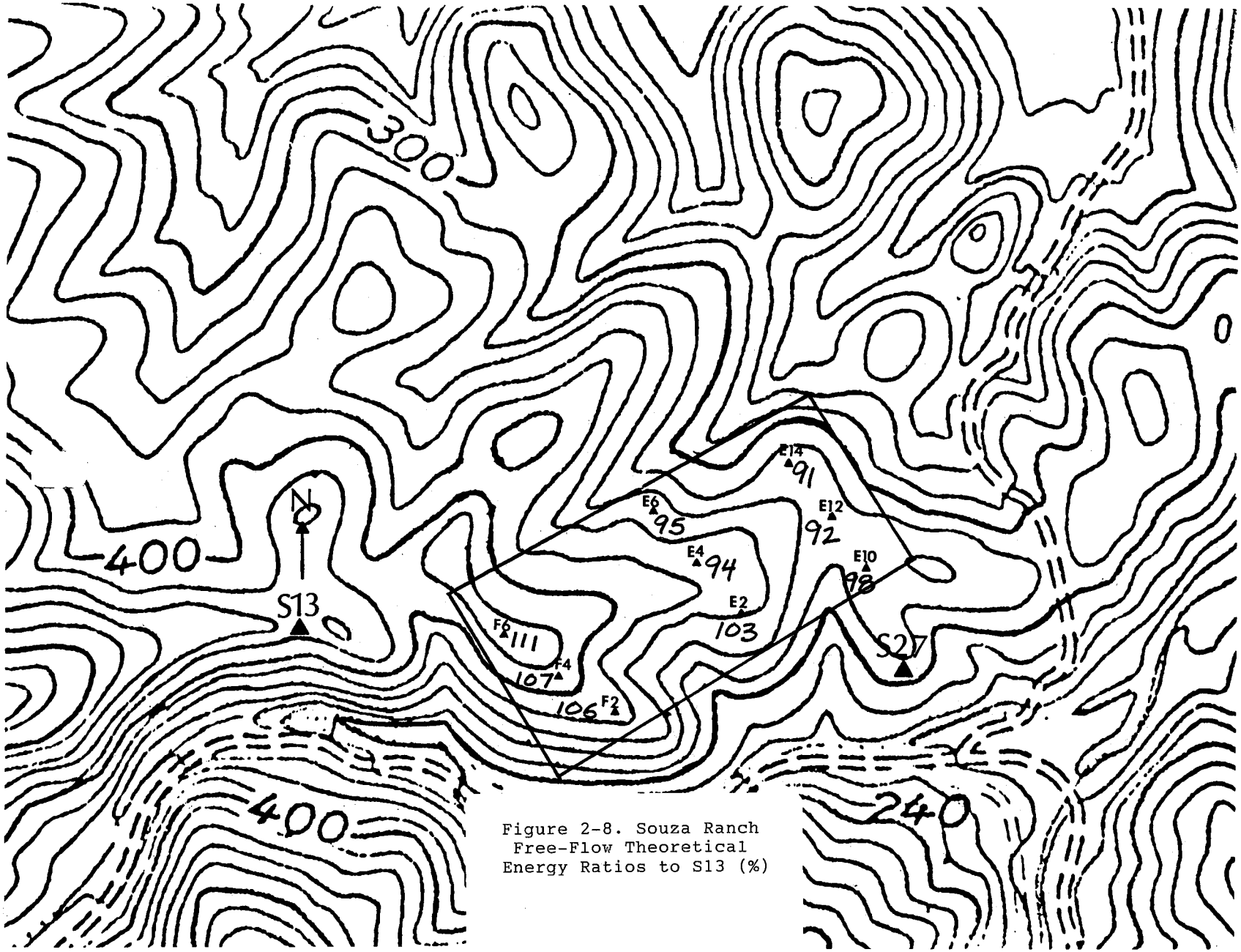

Figure 2-8. Souza Ranch Free-Flow Theoretical Energy Ratios to S13 (%)

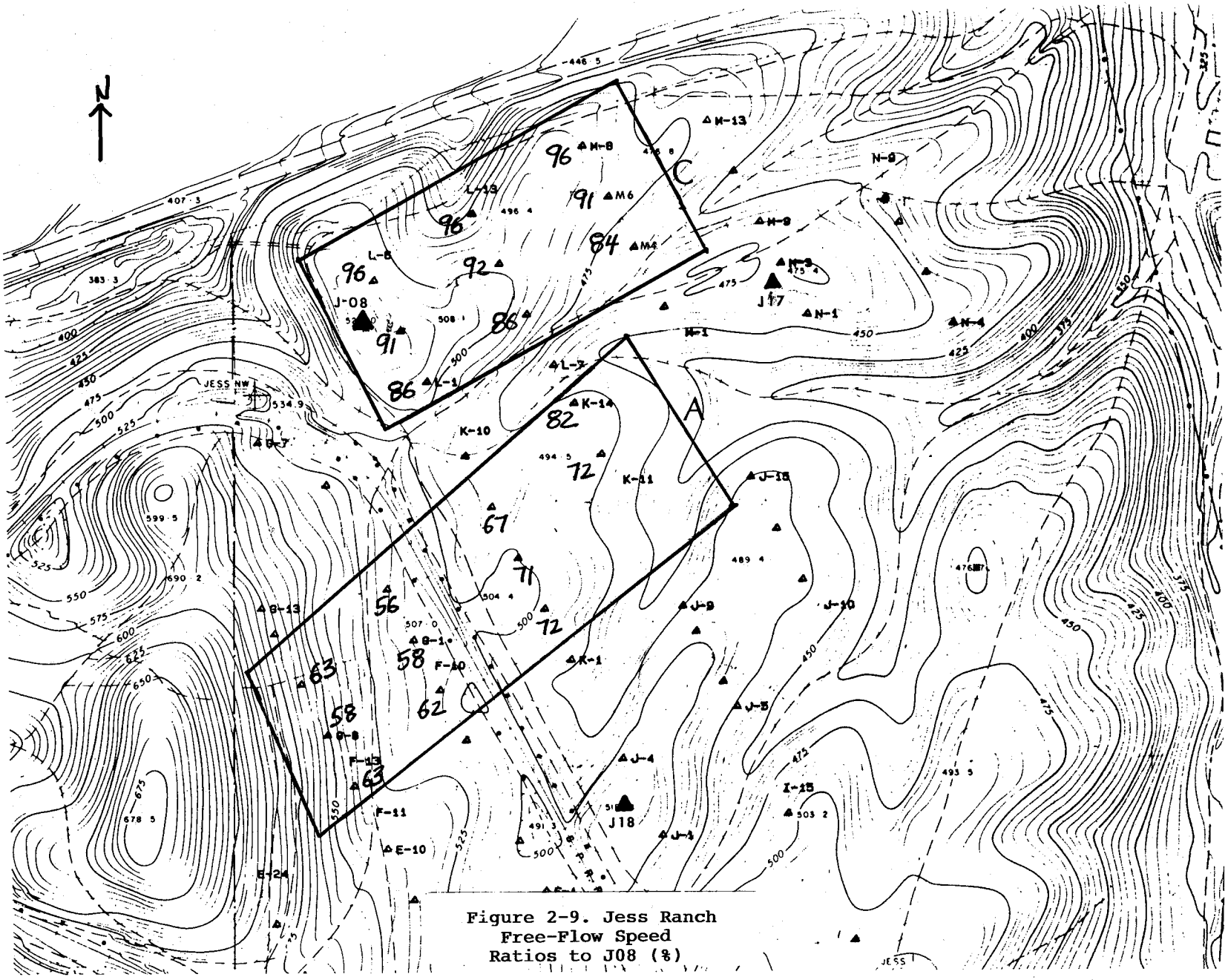

Figure 2-9. Jess Ranch
Free-Flow Speed
Ratios to J08 (%)

array. Turbine M8 at the north end of the row is on the highest terrain and had the highest ratios. This turbine almost always had the lowest deficits within the row. Turbine M4, at the other end, is on lower terrain, had lower speed and energy ratios and usually had the highest deficits.

It is interesting to note that the range of ratios on Jess is considerably larger than on Souza. The Jess test arrays are larger than Souza, but because of the flatter terrain, more homogeneity was expected on Jess. Note that ratios in Jess-A are considerably lower than in Jess-C. This is probably caused by shadowing of the Jess-A group by the 678-ft hill immediately upwind.

Figure 2-10 is a plot of the theoretical energy ratios to J08. Note that all sites except J08 have been normalized to hub-height (72 ft) using a vertical wind shear exponent of 0.10. Sites J17 and J18 had shear exponents of about 0.10. These sites have exposure that is representative of many of the sites on Jess. They are in fairly flat areas and not on highly exposed knolls like J08. Use of an alpha of 0.10 is a good compromise. Some sites like turbines L3 and L5 near J08 probably have less positive shear because of their similar exposure to J08. Thus their theoretical energy production may be biased positively. Other sites downwind of a hill, such as G1, G3, and G8, probably have higher shear than 0.10. Thus, they may be negatively biased. As mentioned earlier, estimating individual sites' vertical shear is difficult and so the reader is cautioned that individual energy ratios on Figure 2-10 could be in error by as much as 10%. Figure 2-10 shows a similar pattern to Figure 2-9 except that there is a wider range of ratios.

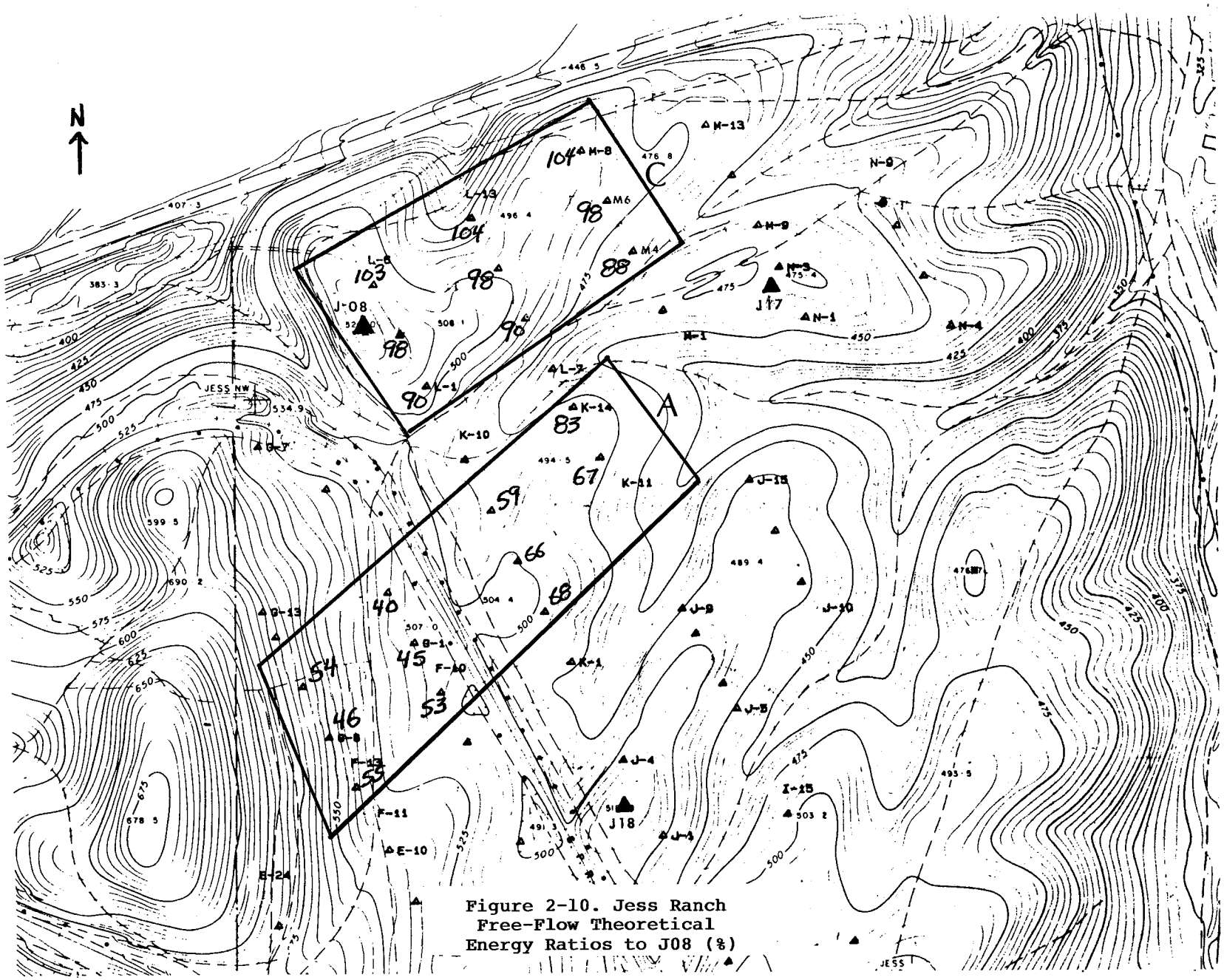

Figure 2-10. Jess Ranch
Free-Flow Theoretical
Energy Ratios to J08 (%)

SECTION 3.0 DATA ANALYSIS

3.1 Direct Wake Effect Test

The Direct Wake Effect case was the most basic of the tests for determining row-to-row wake deficits. In this test case, an upwind row was switched on and off, and the downwind row remained on. The rows are separated by about 8-1/2 D. The downwind row is the test row, and the energy production data from this row were sorted into two classes: samples with the upwind row on and samples with the upwind row off. For additional discussion of test methodology, see Section 2.4. Six direct wake effect tests were conducted. Test #4 was aborted after 4 h because of high winds. Test #6 ended prematurely because of low winds. The tests took place on:

1. Souza-C group, August 7, 1987, 15:50-24:00 PDT (8 h)
2. Jess-A group, September 25, 1987, 09:00-19:00 PDT (10 h)
3. Souza-C group, October 1-2, 1987, 14:30-01:30 PDT (11 h)
4. Jess-C group, July 18, 1988, 18:00-22:10 PDT (4 h)
5. Jess-C group, July 20, 1988, 12:10-22:20 PDT (10 h)
6. Jess-C group, July 21, 1988, 17:10-23:20 PDT (6 h)

In the first test, two rows of buffer turbines, upwind and crosswind of the test array, were turned off for the duration of the test. After several tests were conducted, a review meeting took place in Livermore with the project technical monitor from PNL, the project manager from AEC, and the author. At this meeting, it was decided that using crosswind buffer turbines should be discontinued, as it appeared that they might be providing "wind corridors" down the sides of the test array that could artificially reduce wake deficits at the end turbines in a given row. In the last four tests, the crosswind buffer turbines were cycled on and off with the other upwind turbines in their row. This later proved to be helpful in interpreting the data from the Jess-A group.

3.1.1 Test 1 Analysis, Souza-C, August 7, 1987

Table 3-1.a is the data listing for the August 7, 1987 test on Souza-C. A complete description of the format of the data can be found on page 11. Spacing between the two rows used in this array is only 6.8 D. Wind direction data were unavailable for this analysis; however, the winds were generally from the southwest, based on visual observation. Mean wind speed was about 22 mph at the reference anemometer S13 and about 20 mph at site S27. Ten-min wind speeds remained below 30 mph for the entire test.

The mean wind speeds at both reference anemometers were slightly higher during the period with upwind turbines on. This introduces a slight bias to the data. In this analysis, and in a few others as well, the following methodology was used to try to reduce or eliminate this type of bias. Because the data records are sorted by increasing wind speed, omission of one data record at the beginning or end of the data set reduces the wind speed difference between periods. In this particular analysis, the last record (highest wind speed) was eliminated from the second test period. An additional set of means

Table 3-1.a Souza-C Direct Wake Test Analysis 1

FOR WINDFARM: SOUZA RANCH WINDFARM
Ten Minute Data Report Date: 08/07/87

Time Of Day	ROWS ON UPWIND	S13 wspeed	S27 wspeed	E11 energy	E12 energy	E13 energy	E14 energy	SUM OF E11-E14
16:30	0	15.4	13.9	1.7	1.6	1.5	1.1	5.8
16:20	0	15.7	14.4	2.0	1.9	2.3	1.8	7.9
17:20	0	17.4	16.1	3.3	3.4	3.6	2.8	13.2
17:30	0	17.3	17.0	4.3	4.4	4.5	3.6	16.7
18:10	0	21.1	18.2	5.3	5.5	5.7	5.0	21.5
18:20	0	20.9	18.9	5.1	5.4	5.9	5.2	21.6
19:20	0	22.4	20.9	7.4	7.8	8.4	7.9	31.5
23:20	0	26.6	21.8	5.2	5.3	4.7	4.6	19.8
22:20	0	27.1	21.9	5.5	5.3	5.6	5.5	21.9
22:10	0	26.1	22.0	5.3	4.9	5.3	5.6	21.2
23:10	0	23.6	22.4	6.6	7.0	6.9	5.7	26.2
19:10	0	21.9	22.6	7.7	8.1	8.3	7.4	31.5
20:10	0	20.2	22.8	7.9	8.5	9.1	8.5	33.9
20:20	0	22.0	23.1	8.4	8.9	9.2	8.7	35.1
21:10	0	23.1	25.1	8.4	8.8	8.9	8.2	34.3
21:20	0	23.6	25.1	8.5	8.9	9.2	8.6	35.2
Mean (all)		21.5	20.4	5.8	6.0	6.2	5.6	23.6
16:50	1	15.6	13.9	1.5	1.4	1.6	1.4	5.9
15:50	1	15.3	14.4	1.3	1.3	1.5	1.3	5.3
16:00	1	14.9	14.5	1.5	1.5	1.7	1.4	6.1
17:50	1	17.0	17.2	3.6	3.9	4.0	3.1	14.7
17:00	1	17.2	17.4	2.1	2.4	2.7	1.9	9.1
18:40	1	20.7	19.8	3.9	4.1	4.7	4.1	16.8
21:40	1	28.8	21.5	7.6	8.2	8.2	8.0	32.0
23:40	1	26.3	21.8	6.0	6.1	5.8	4.1	22.0
18:50	1	19.5	21.9	5.5	5.4	4.8	4.6	20.4
23:50	1	26.4	22.3	5.8	5.8	4.9	3.4	19.8
21:50	1	28.1	22.3	6.7	6.0	6.1	5.7	24.5
22:40	1	24.8	22.4	6.6	6.9	6.3	4.5	24.2
19:40	1	22.3	23.0	7.3	7.9	8.6	7.3	31.0
22:50	1	26.6	23.1	8.2	8.5	7.8	6.9	31.4
19:50	1	21.1	24.0	7.2	7.4	7.9	7.3	29.7
20:40	1	22.8	24.9	8.1	8.3	8.9	8.4	33.7
20:50	1	23.8	25.6	8.2	8.4	9.4	8.2	34.2
Mean (all)		21.8	20.6	5.3	5.5	5.6	4.8	21.2
mean (-last)		21.7	20.3	5.2	5.3	5.3	4.6	20.4
Ratio (on/off %)		101.4	101.0	92.5	92.0	90.2	85.0	90.0
Ratio (norm)		100.9	99.4	89.4	89.1	86.3	81.2	86.6

was then calculated for this normalized data set (see line marked "mean [-last]"), and a second set of ratios was calculated between the two test periods (see line marked "Ratio [Norm]"). The second set of ratios shows that the mean wind speeds at the two upwind anemometers have smaller differences between periods. Thus, there is probably a reduction in the bias.

The energy ratios calculated between these two periods show the energy deficit during the period when the upwind turbines were on line. In the first set of ratios calculated with the entire data set, the four test turbines had an energy ratio of 90%, i.e., there was a 10% energy deficit in spite of an increase of 1% or more in wind speed. Using the second set of ratios with roughly the same wind speed in both test periods, the energy ratio was 86.6%. This is equivalent to an energy deficit of 13.4%. There is a pattern to the energy deficits within the test row, with the smallest deficits (about 11%) at turbines E11 and E12. The deficits increase along the row to 18.8% at turbine E14. There are two possible explanations for this pattern -- the wind direction or the terrain. (The wind direction data are not available). It is interesting to note that (1) the elevation decreases slightly along the row, approaching E14; (2) E14 is the lowest producer in the row; and (3) speed ratios from the free-flow data study showed a progressive decrease in E14. Thus, the slight decrease in elevation within this row contributes to a natural decrease in available energy and an increase in the wake deficit. Wind speed data from the turbine anemometers were not available for this test.

The statistical significance using the "Student's" t distribution test for both the row deficit of 13.4% and the turbine E14 deficit of 18.8% was 0.80. This indicates that there is a 20% possibility that these results could have occurred by chance.

3.1.2 Test 2 Analysis, Jess-A, September 25, 1987

Table 3-1.b is the data listing for the September 25, 1987 test on Jess-A. Spacing between the two test rows used in this array is 9.5 D. Turbines F9, F10, G1, G2, and G3 were the upwind turbines that were switched on and off. Winds were from the west-southwest at about 20 mph, and the two test periods had only a 0.1 mph difference (0.4%) at the upwind reference anemometer J08. Wind speeds measured at the 35-ft level at turbines K3, K5, and K7 were considerably lower, with a range from about 13 mph to 15 mph. However, this is within the range of expected wind speeds at these turbines based on the free-flow speed ratios of about 0.70, as shown on Figure 2-9. It should be noted that there were three 10-min data records from turbine K7 that were questionable. One problem arose in the 09:50 record when the turbine faulted and was reset. It was off line for about 2 min out of the 10-min data period. An adjustment was made to this record based on the mean ratio of production to turbine K6. At 1800, the CTM failed and was replaced about a 30 min later. There were two missing 10-min records (18:10 and 18:20), and the energy at K7 was estimated again, based on the mean energy ratio to K6.

Table 3-1.b shows the ratios of energy between the two periods. Turbine K2 was included in the analysis even though it was not a part of the Jess-A array. As in the first test, there was a significant drop in energy when the upwind turbines were switched on line. The mean energy ratio was 89.5%, which is equivalent to a 10.5% energy deficit. A number of samples had wind directions with a westerly component that was too high for good alignment.

Table 3-1.b Jess-A Direct Wake Test Analysis

JESS RANCH 09/25/87

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	K02 energy	K03 energy	K04 energy	K05 energy	K06 energy	K07 energy	sum of K02-K07	35-ft anemometers K03 wspeed	K05 wspeed	K07 wspeed
16:10	0	16.5	245	1.8	1.6	1.2	1.5	1.7	1.4	9.2	12.2	12.8	12
15:10	0	17.1	255	1.2	1.4	1.3	1.4	1.3	1.2	7.8	11.7	12.3	11.5
13:10	0	17.3	260	1.3	1.5	1.6	1.7	1.6	1.4	9.1	12.4	13.2	11.9
13:20	0	17.3	252	1.7	1.6	1.9	2.1	1.8	1.4	10.5	13.4	13.8	12.1
16:20	0	17.5	248	1.3	1.4	1.3	1.6	1.6	1.3	8.5	11.8	13	11.6
15:20	0	17.6	253	1.3	1.4	1.4	1.7	1.5	1.2	8.5	12.1	12.8	12.2
12:20	0	18.6	252	1.4	1.5	1.7	2.1	1.8	1.6	10.1	12.6	14.6	12.9
14:20	0	18.9	246	2.2	2.4	2.5	2.3	2.4	2.1	13.9	13.8	14.2	13.8
11:20	0	18.9	250	1.7	1.6	1.6	1.8	1.7	1.5	9.9	12.4	13.6	13
11:10	0	19.1	248	0.7	1.3	1.2	1.5	1.4	1.4	7.5	11.6	12.7	12.2
12:10	0	19.2	245	1.6	1.8	1.5	1.7	1.7	1.5	9.8	12.7	13.2	12.1
14:10	0	19.2	260	1.9	2.3	2.6	2.8	2.6	1.9	14.1	13.8	15.2	13.9
18:20	0	19.9	245	2.8	2.8	2.9	3.3	3.2	e2.9	17.9	14.4	15.1	e14.1
17:20	0	20.7	253	1.5	1.5	1.7	2.7	3	3.3	13.7	11.9	15.7	14.9
18:10	0	20.7	250	2.6	3.3	3.1	2.2	2.8	e2.6	16.6	15.1	13.9	e13.0
17:10	0	21.1	262	2	2.1	2.6	3.3	3.1	2.7	15.8	13.8	15.9	14.6
10:20	0	22.7	250	3.7	4	3	3	3.5	3.7	20.9	16.3	15.4	16.3
10:10	0	24.1	253	4	4.1	3.8	3.5	3.4	3.9	22.7	16	15.6	16.7
09:10	0	24.3	243	4	3.3	3	3.9	3.2	2.3	19.7	15.6	16.3	14.1
09:20	0	24.8	245	2.8	2.9	3.4	3.5	3	2.8	18.4	15.2	15.9	15.6
Mean:		19.8	251	2.1	2.2	2.2	2.4	2.3	2.1	13.2	13.4	14.3	13.4
Mean for WD comp		20.3	250	2.2	2.3	2.3	2.5	2.5	2.2	14.0	13.7	14.5	13.7
15:40	1	17.1	239	1.2	1.5	1.5	1.6	1.5	1.3	8.6	12.3	12.7	11.4
17:50	1	21.7	239	2.6	3	2.6	2.3	2.6	2.6	15.7	15.1	14.4	14.3
15:50	1	17.1	241	1.5	1.5	1	1.4	1.5	1.5	8.4	12.1	12.6	12.5
16:40	1	19.6	243	2.1	2	1.8	2	2.1	2.2	12.2	13.2	13.5	14.2
18:40	1	20.5	245	2.1	2.7	2.6	1.6	1.8	1.7	12.5	14.1	12.8	13.2
18:50	1	21.5	245	3	3.1	2.6	2.3	2.8	2.1	15.9	14.7	14.4	13.7
09:40	1	24.4	248	2.9	3.1	2.8	2.3	3.1	3.3	17.5	15.1	14.6	15
17:40	1	20.8	249	1.7	1.5	1.3	1.5	2	2.4	10.4	12.4	12.7	14.7
09:50	1	26.1	249	2.4	2.3	2.1	2	2.5	e2.4	13.7	14.2	13.9	e13.7
13:50	1	18.9	250	1.7	1.8	1.5	1.7	1.6	1.4	9.7	12.6	13	12.2
11:40	1	18.5	252	1.3	1.6	1.5	1.4	1.4	1.3	8.5	12.5	12.6	12.6
16:50	1	20.8	252	2	1.9	2.3	3.3	3.2	3	15.7	13.4	15.8	15.2
12:50	1	17.1	253	1.3	1.7	1.7	1.4	1.4	1.4	8.9	12.5	12.6	12
11:50	1	19.3	253	1.3	1.2	1.3	1.5	1.6	1.5	8.4	11.8	12.8	12.9
14:50	1	18.1	255	1.6	1.5	1.2	1.6	1.7	1.5	9.1	12.1	13.3	13
10:50	1	20.4	255	1.9	2.4	2.3	2.1	2.2	2.1	13	13.8	13.6	13.9
10:40	1	21.3	255	2.1	2.2	2.3	2.3	3.1	3.3	15.3	13.7	14.2	15.2
14:40	1	17.4	256	1.5	1.5	1.5	1.6	1.7	1.5	9.3	11.9	13.1	12.4
13:40	1	18.5	256	1.6	2.3	2.6	2.6	2.1	1.9	13.1	13.7	14.6	13.2
12:40	1	17.9	257	1.3	1.6	2.1	2.2	2.1	1.7	11	12.9	14.4	13
Mean:		19.8	249	1.9	2.0	1.9	1.9	2.1	2.0	11.8	13.2	13.6	13.4
* WD<255		20.2	247	1.9	2.1	1.9	1.9	2.1	2.0	11.9	13.3	13.5	13.4
Ratio on/off(%)		100.4		89.4	92.2	89.1	81.3	90.7	95.2	89.5	98.3	95.2	99.9
* WD<255		99.9		88.5	89.3	82.4	74.3	84.7	89.6	84.6	97.1	92.7	97.7
* Turbine Anemometer Speed:				N/A	97.1	N/A	92.7	N/A	97.7				

e=estimate

Table 3-1.b Jess-A Direct Wake Test Analysis

FOR WINDFARM: JESS RANCH WINDFARM (18 RD Analysis)
REPORT 09/25/87
Ten Minute Data Report

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	K11 energy	K12 energy	K12 wspeed
16:10	1	16.5	245	1.4	1.5	11.9
15:10	1	17.1	255	1.1	1.5	11.8
13:10	1	17.3	260	1.4	1.5	12
13:20	1	17.3	252	1.5	1.8	12.9
16:20	1	17.5	248	1.3	1.5	12.2
15:20	1	17.6	253	1.3	1.8	12.9
12:20	1	18.6	252	1.6	1.8	13
14:20	1	18.9	246	1.9	2.3	14.2
11:20	1	18.9	250	1.5	1.7	13.1
11:10	1	19.1	248	1.4	1.8	12.6
12:10	1	19.2	245	1.4	1.4	12.2
14:10	1	19.2	260	2.4	2.8	14.4
19:20	1	19.4	246	1.4	1.6	12.4
18:20	1	19.9	245	2.7	4.5	16.4
18:10	1	20.7	250	2.1	3	14.9
17:20	1	20.7	253	2.3	2.8	14.6
19:10	1	21.0	263	1.5	2	13.2
17:10	1	21.1	262	2.2	2.9	14.8
10:20	1	22.7	250	3.3	3.7	15.9
10:10	1	24.1	253	3	4.4	16.7
09:10	1	24.3	243	2.3	2.4	14.4
09:20	1	24.8	245	2.3	2.9	15.6
Mean		19.8	251	1.9	2.3	13.7
Mean for WD comp		20.2	251	2.0	2.5	14.0
15:40	2	17.1	239	1.2	1.5	11.8
17:50	2	21.7	239	2.2	2.8	14.6
15:50	2	17.1	241	1.4	1.6	12.7
16:40	2	19.6	243	1.8	2.2	13.7
18:40	2	20.5	245	1.5	2.1	14
18:50	2	21.5	245	2.1	2.6	14.4
09:40	2	24.4	248	2.1	3.3	15.2
17:40	2	20.8	249	2	2.6	14.9
09:50	2	26.1	249	2.4	4	16.6
13:50	2	18.9	250	1.5	1.6	12.6
11:40	2	18.5	252	1.2	1.3	12.3
16:50	2	20.8	252	2.7	3.1	14.8
12:50	2	17.1	253	1.3	1.5	12.4
11:50	2	19.3	253	1.6	1.8	13.2
14:50	2	18.1	255	1.5	2	13.6
10:50	2	20.4	255	2	2.4	14.3
10:40	2	21.3	255	2.8	3.7	15.6
14:40	2	17.4	256	1.7	1.9	12.9
13:40	2	18.5	256	1.8	2.1	13.2
12:40	2	17.9	257	1.7	2.2	13.5
Mean		19.8	249	1.8	2.3	13.8
"WD<255		20.2	247	1.8	2.3	13.8
Ratio on/off (%)		100.2		97.2	98.7	100.6
" WD<255		100.4		90.3	91.6	98.6

page 2 of 2

The expected wake trajectory associated with this direction would be south of the test row. When the samples with wind directions above 255° were deleted, the mean energy ratio dropped to 84.6%, which is equivalent to a 15.4% energy deficit. The deficit at turbine K7 at the northern end of the test row doubled when the wind direction data were screened. The largest energy deficit was near the center of the test row. The range of energy ratios was from 74.3% to 89.6%, which is equivalent to energy deficits of 25.7% to 10.4%. Wind speed data were analyzed from turbines K3, K5, and K7. The table shows that the speed ratios ranged from 92.7% at K5 to 97.7% at K7. These are equivalent to speed deficits of 7.3% and 2.3%, respectively. The speed deficits were quite small compared to the energy deficits. This is probably because the anemometers are below the wake centerline.

The statistical significance of the row energy deficit of 15.4% was 0.90. The energy deficit of 25.7% at turbine K5 was statistically significant at the 0.99 level. The speed deficit at K5 of 7.3% was also significant at the 0.99 level.

The second page of Table 3-1.b is an analysis of the row downwind of the principal test row discussed above. This row is 18 D downwind of the turbines that were switched on and off and 8 D downwind of the principal test row. This analysis illustrates the persistence of the wake deficit. Although there are four turbines in this test row, the apparent wake trajectory was to the south of turbines K13 and K14. These turbines had negligible wake deficits. The table lists the data from turbines K11 and K12. As in page one of this table, means were calculated for the entire data set and for samples with wind direction less than 255°. The ratios for the entire data set show negligible deficits. However, when the data were screened by direction, the energy ratios at K11 and K12 were 90.3% and 91.6%, respectively. These are equivalent to 9.7% and 8.4% energy deficits. Wind speed data from turbine K12 were also analyzed but the deficit was negligible.

The energy deficits are quite large considering the 18-D distance. Turbines K11 and K12 are roughly downwind of K6 and K7. K6 and K7 had energy deficits of about 13%, and K11 and K12 deficits were 9%. Thus the deficit in this 18-D row was about 70% of the deficit in the 9.5-D row.

Figure 3-1.a is a topographic map of the Jess-A array and has the individual turbine energy deficits plotted as bars at each turbine. The length of the bar is proportional to the deficit and the bar is plotted parallel to the mean wind direction. The figure shows which turbines were switched on and off, and the individual turbine deficits are listed at the bottom of the figure.

3.1.3 Test 3 Analysis, Souza-C, October 1-2, 1987

Table 3-1.c is the data listing for the October 1-2, 1987 test on Souza-C. Recall that spacing between rows is only 6.8 D. Mean winds were from the south-southwest at about 22 mph. The energy ratios between periods show a decrease in energy when the upwind row was on line, but the energy deficit was lower than in the first test on Souza. The energy ratio at turbines E12 through E14 was 92.4%, which is equivalent to a 7.6% energy deficit. As in the previous test on Jess, there were some records that had to be screened because of wind direction alignment problems. Because of the southerly wind direction component, turbine E11 was at the edge of the expected wake and was

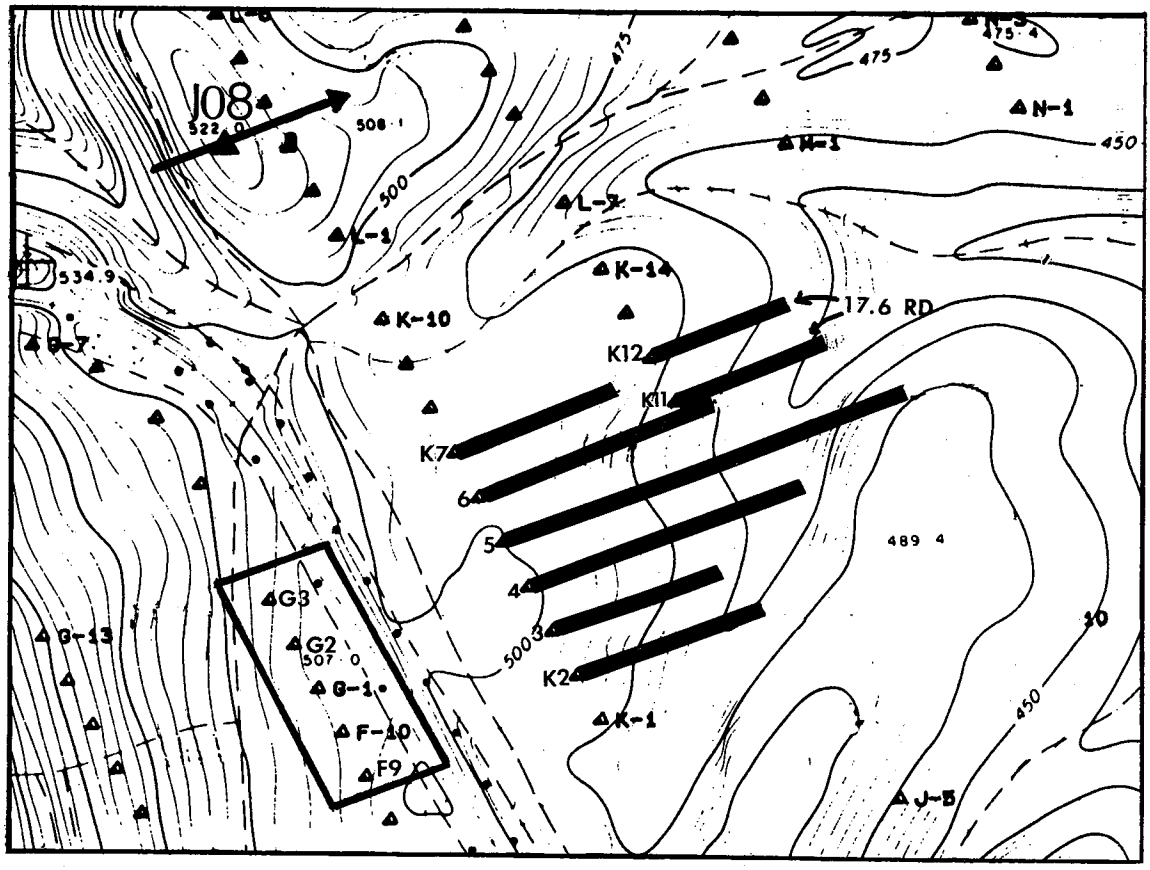

Figure 3-1.a. Jess-A Direct Wake Effect Test Individual Turbine Deficits

Sept 25, 1987 test conditions at reference anemometer, J-08: mean speed = 20.2 mph, mean direction = 250 degrees.

KEY

▲▲▲ = turbines switched on and off

▬ = % wake energy deficit, 1" = 10%

Deficits

9.5 RD		17.6 RD	
K2	11.5%	K11	9.7%
K3	10.7%	K12	8.4%
K4	17.6%	Mean	9.1%
K5	25.7%		
K6	15.3%		
K7	10.4%		
Mean	15.4%		

Table 3-1.c Souza-C Direct Wake Test Analysis 2

Ten Minute Data Report
FOR WINDFARM: SOUZA RANCH WINDFARM
REPORT 10/01/87-10/02/87
Ten Minute Data Report

Time Of Day	rows on upwind	S13 wspeed	S13 w.dir.	S27 wspeed	E11 energy	E12 energy	E13 energy	E14 energy	sum of E12-E14	Anemometers E12 wspeed	Anemometers E14 wspeed
18:40	0	10.7	205	15.9	4.9	5.3	5.6	5.1	16.0	19.1	19.6
19:50	0	14.9	211	16.6	4.3	4.1	3.8	3.2	11.1	17.3	16.7
18:50	0	16.4	160	17.2	5.9	6.1	6.4	6.0	18.5	20.7	21.1
17:50	0	17.4	222	19.9	6.3	5.8	5.7	5.1	16.6	19.7	19.1
19:40	0	18.8	194	19.0	5.5	5.1	5.0	4.1	14.2	18.6	18.1
14:50	0	19.1	222	21.3	4.3	4.5	5.3	5.3	15.1	17.4	19.7
16:50	0	19.6	217	19.0	6.5	5.2	4.7	4.1	14.0	18.8	18.3
15:50	0	19.6	233	19.2	4.1	3.2	3.5	3.4	10.1	15.1	16.9
15:40	0	19.8	219	20.2	4.0	4.1	4.4	4.0	12.5	16.7	17.5
20:50	0	20.6	219	25.1	6.5	7.0	7.3	6.7	21.0	21.2	22.9
20:40	0	20.6	228	22.4	5.3	5.3	5.5	4.6	15.4	18.1	18.8
16:40	0	20.7	217	19.5	6.5	5.3	4.1	3.6	13.0	19.2	17.3
14:40	0	20.9	228	20.9	4.8	5.0	5.4	4.8	15.2	18.1	18.7
17:40	0	22.2	225	21.7	8.4	8.4	8.2	7.7	24.3	24.5	24.3
01:50	0	22.7	211	31.3	9.5	9.2	8.1	6.3	23.6	30.2	22.7
22:40	0	23.1	197	26.0	9.3	9.5	9.6	8.8	27.9	31.3	28.4
22:50	0	23.2	191	26.0	9.6	9.8	10.0	9.7	29.5	33.8	31.6
01:40	0	24.9	211	31.7	9.5	9.0	8.2	7.2	24.4	29.8	24.0
21:50	0	25.4	200	28.1	8.6	8.6	8.7	8.3	25.6	26.4	25.9
21:40	0	26.7	186	26.4	8.7	9.0	8.9	8.2	26.1	28.2	25.8
23:50	0	27.7	194	31.1	9.7	9.7	9.8	9.2	28.7	32.9	29.6
23:40	0	29.1	188	31.1	9.7	9.8	9.9	9.4	29.1	33.5	30.6
00:40	0	29.2	208	31.6	9.7	9.8	9.6	8.9	28.3	34.6	29.8
00:50	0	29.6	208	31.5	9.7	9.8	9.7	8.5	28.0	33.8	27.6
Mean(all data)		21.8	208	23.9	7.1	7.0	7.0	6.3	20.3	24.1	22.7
Mean for WD comp		20.0	211	22.2	6.5	6.3	6.3	5.7	18.3	21.9	21.1

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Table 3-1.c Souza-C Direct Wake Test Analysis 2

10/01/87-10/02/87

Time Of Day	rows on upwind	S13 wspeed	S13 w.dir.	S27 wspeed	E11 energy	E12 energy	E13 energy	E14 energy	sum of E12-E14	Anemometers E12 wspeed	Anemometers E14 wspeed
00:10	1	27.4	177	30.6	9.7	9.9	9.7	9.1	28.7	34.5	30.1
22:20	1	24.5	180	25.5	9.3	9.6	9.4	8.8	27.8	31.4	28.6
23:20	1	27.2	180	29.9	9.7	9.7	9.9	9.5	29.1	33.4	30.8
23:10	1	26.5	186	27.4	9.4	9.4	9.5	8.7	27.6	31.1	28.1
22:10	1	25.6	197	25.2	9.0	9.3	9.2	8.0	26.5	29.2	26.6
00:20	1	29.3	200	29.4	9.6	9.7	9.6	8.8	28.1	33.1	28.9
18:20	1	15.9	203	18.1	5.2	5.3	5.2	3.5	14.0	19.5	18.0
19:10	1	22.4	203	22.6	7.0	5.9	5.6	3.9	15.4	20.9	18.5
19:20	1	21.9	203	22.4	5.9	5.2	4.4	4.1	13.7	19.1	18.9
17:10	1	20.7	208	22.6	7.2	5.5	5.1	4.9	15.5	20.7	20.4
01:20	1	26.5	208	30.2	9.6	9.5	9.2	8.5	27.2	32.6	26.6
17:20	1	21.4	211	23.2	5.8	5.1	4.8	5.1	15.0	19.9	20.7
01:10	1	24.1	214	30.2	9.6	9.6	9.7	8.9	28.2	33.4	27.9
18:10	1	14.2	217	18.4	6.4	5.9	4.8	3.7	14.4	20.8	18.2
21:20	1	18.6	217	26.2	7.4	6.8	6.9	6.8	20.5	22.9	23.6
20:20	1	19.6	217	23.4	5.2	5.5	5.5	5.1	16.1	20.1	19.6
16:20	1	18.1	217	18.3	4.6	3.3	3.2	2.9	9.4	16.4	16.7
21:10	1	22.2	219	26.0	5.4	5.4	5.3	4.4	15.1	19.5	19.2
20:10	1	17.1	222	20.5	3.6	3.5	4.1	3.7	11.3	16.6	16.9
16:10	1	18.8	231	20.0	4.8	3.7	3.6	3.4	10.7	17.1	17.3
15:10	1	21.4	233	19.4	3.5	3.6	3.9	3.0	10.5	16.9	16.9
15:20	1	18.8	239	18.3	2.5	2.8	3.2	2.8	8.8	15.7	16.1
Mean(all data)		21.9	208	24.0	6.8	6.6	6.4	5.8	18.8	23.9	22.2
Mean WD>200		20.1	216	22.5	5.9	5.4	5.3	4.7	15.4	20.8	19.7
Energy ratios, turbines on/off (%)											
all data		100.6		100.5	95.8	93.3	92.4	91.5	92.4	98.9	97.8
WD>200 deg		100.4		101.5	89.9	85.3	84.0	82.1	83.9	94.8	93.3
Turbine anemometer data:											
Speed ratios (all data):					N/A	98.9	N/A	97.8			
" " WD>200 deg					N/A	94.8	N/A	93.3			
Available power ratios (W/sq.m)						97.6		95.3			
" " " WD>200 deg						84.8		79.5			

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not included in the row mean calculations. When the records with wind directions below 200° were deleted, the mean energy ratio at E12 - E14 dropped to 83.9%, which is equivalent to a 16.1% energy deficit. As in the other Souza test, the deficits became progressively larger towards E14. This is probably due to a combination of the wind direction during the test and terrain effects. Wind speed data from E12 and E14 were analyzed. The speed ratios were 94.8% and 93.3%, respectively, which are equivalent to speed deficits of 5.2% and 6.7%. Power density (W/m^2) was calculated from these turbine anemometers. The power density deficits were 15.2% and 20.5%, which are very close to the energy deficits at these turbines.

Statistical significance using the "Student's" t test was calculated for the energy deficits with wind direction screening. The significance level was 0.90 for the row average and for turbine E14, which had the largest deficit. The significance level for the turbine E14 speed deficit was also 0.90.

3.1.4 Souza-C Combined File

Two of the tests discussed above were conducted on the same set of turbines, Souza-C. Data from the two tests were combined into one file for further analysis. The records discussed above with wind directions below 200° were not included in this file. Table 3-1.d lists these data with the addition of column 4, which shows the wind power density at S13 in W/m^2 (not corrected for ambient air density). Means were calculated for the entire combined data set as well as low, middle, and high wind speed subsets. There are four sets of ratios as well.

A comparison of the ratios shows that the low and middle speed classes (approximately 17.5 mph and 21.5 mph means) had almost the same energy deficits, about 15%. By contrast, the high speed class (26.5 mph) had lower deficits, about 11%. Recall that the Nordtank power curve is less steep in this region, and the Cp is decreasing, so smaller deficits would be expected.

Statistical significance of the deficits for the row average was 0.95. Turbine E14, which had the largest deficit, had a significance level of 0.975.

Figure 3-1.b is a topographic map of the Souza study array. The wake deficits measured (in percent) during these two tests are plotted as bars at the individual turbines, parallel to the mean wind direction. The length of each bar is proportional to the deficit; 1 in. equals a 10% deficit.

3.1.5 Test 5 Analysis, Jess-C, July 20, 1988

Table 3-1.e is the data listing for the July 20, 1988 test on Jess-C. (Test 4 was conducted two days earlier at the same array, but was aborted because of high winds. The results of that test are discussed in Section 3.1.7).

Spacing between rows in this test array was 7.8 D. Turbines L7 through L13 were switched on and off during the test. The turbines in the next upwind row, L1 through L6, remained off line for the entire test. Winds were from the west to west-southwest and the mean speed was 26.6 mph at J08, and 22 mph to 25 mph at turbines M4 through M8. These speeds are higher than the three tests discussed previously. There was a 0.3 mph difference in mean speeds at the upwind anemometer, between the two test periods, so a second set of means

Table 3-1.d Combined File, Souza-C Direct Wake Test Analysis

FOR WINDFARM: SOUZA RANCH WINDFARM

Time Of Day	ROWS ON UPWIND	S13 wspeed	S13 W/sq M	E11 energy	E12 energy	E13 energy	E14 energy	SUM OF E11-E14
18:40	0	10.7	67.0	4.9	5.3	5.6	5.1	20.9
19:50	0	14.9	180.9	4.3	4.1	3.8	3.2	15.4
16:30	0	15.4	199.8	1.7	1.6	1.5	1.1	5.82
16:20	0	15.7	211.7	2.0	1.9	2.3	1.8	7.91
18:50	0	16.4	241.3	5.9	6.1	6.4	6.0	24.4
17:30	0	17.3	283.2	4.3	4.4	4.5	3.6	16.68
17:20	0	17.4	288.2	3.3	3.4	3.6	2.8	13.16
17:50	0	17.4	288.2	6.3	5.8	5.7	5.1	22.9
19:40	0	18.8	363.5	5.5	5.1	5.0	4.1	19.7
14:50	0	19.1	381.1	4.3	4.5	5.3	5.3	19.4
16:50	0	19.6	411.9	6.5	5.2	4.7	4.1	20.5
15:50	0	19.6	411.9	4.1	3.2	3.5	3.4	14.2
15:40	0	19.8	424.6	4.0	4.1	4.4	4.0	16.5
20:10	0	20.2	450.9	7.9	8.5	9.1	8.5	33.93
20:40	0	20.6	478.2	5.3	5.3	5.5	4.6	20.7
20:50	0	20.6	478.2	6.5	7.0	7.3	6.7	27.5
16:40	0	20.7	485.2	6.5	5.3	4.1	3.6	19.5
14:40	0	20.9	499.4	4.8	5.0	5.4	4.8	20
18:20	0	20.9	499.4	5.1	5.4	5.9	5.2	21.63
18:10	0	21.1	513.8	5.3	5.5	5.7	5.0	21.49
19:10	0	21.9	574.5	7.7	8.1	8.3	7.4	31.49
20:20	0	22	582.4	8.4	8.9	9.2	8.7	35.11
17:40	0	22.2	598.5	8.4	8.4	8.2	7.7	32.7
19:20	0	22.4	614.8	7.4	7.8	8.4	7.9	31.46
01:50	0	22.7	639.8	9.5	9.2	8.1	6.3	33.1
22:40	0	23.1	674.3	9.3	9.5	9.6	8.8	37.2
21:10	0	23.1	674.3	8.4	8.8	8.9	8.2	34.34
22:50	0	23.2	683.0	9.6	9.8	10.0	9.7	39.1
21:20	0	23.6	719.0	8.5	8.9	9.2	8.6	35.2
23:10	0	23.6	719.0	6.6	7.0	6.9	5.7	26.22
01:40	0	24.9	844.5	9.5	9.0	8.2	7.2	33.9
21:50	0	25.4	896.4	8.6	8.6	8.7	8.3	34.2
22:10	0	26.1	972.5	5.3	4.9	5.3	5.6	21.15
23:20	0	26.6	1029.5	5.2	5.3	4.7	4.6	19.78
21:40	0	26.7	1041.2	8.7	9.0	8.9	8.2	34.8
22:20	0	27.1	1088.7	5.5	5.3	5.6	5.5	21.9
23:50	0	27.7	1162.6	9.7	9.7	9.8	9.2	38.4
23:40	0	29.1	1347.9	9.7	9.8	9.9	9.4	38.8
00:40	0	29.2	1361.9	9.7	9.8	9.6	8.9	38
00:50	0	29.6	1418.6	9.7	9.8	9.7	8.5	37.7
Means:	(all)	21.7	620.0	6.6	6.6	6.7	6.1	25.9
	norm	21.1	558.7	6.3	6.3	6.4	5.8	24.9
	low	17.5	312.1	4.7	4.6	4.7	4.2	18.1
	middle	21.7	563.1	7.3	7.5	7.6	6.9	29.3
	high	26.4	1021.9	8.2	8.2	8.2	7.7	32.2

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Table 3-1.d Combined File, Souza-C Direct Wake Test Analysis

Time	rows	mph	W/sq m	E11	E12	E13	E14	E11-E14
18:10	1	14.2	156.6	6.4	5.9	4.8	3.7	20.8
16:00	1	14.9	180.9	1.5	1.5	1.7	1.4	6.08
15:50	1	15.3	195.9	1.3	1.3	1.5	1.3	5.32
16:50	1	15.6	207.7	1.5	1.4	1.6	1.4	5.92
18:20	1	15.9	219.9	5.2	5.3	5.2	3.5	19.2
17:50	1	17	268.7	3.6	3.9	4.0	3.1	14.66
20:10	1	17.1	273.5	3.6	3.5	4.1	3.7	14.9
17:00	1	17.2	278.3	2.1	2.4	2.7	1.9	9.12
16:20	1	18.1	324.4	4.6	3.3	3.2	2.9	14
21:20	1	18.6	352.0	7.4	6.8	6.9	6.8	27.9
16:10	1	18.8	363.5	4.8	3.7	3.6	3.4	15.5
15:20	1	18.8	363.5	2.5	2.8	3.2	2.8	11.3
18:50	1	19.5	405.6	5.5	5.4	4.8	4.6	20.36
20:20	1	19.6	411.9	5.2	5.5	5.5	5.1	21.3
17:10	1	20.7	485.2	7.2	5.5	5.1	4.9	22.7
18:40	1	20.7	485.2	3.9	4.1	4.7	4.1	16.75
19:50	1	21.1	513.8	7.2	7.4	7.9	7.3	29.73
17:20	1	21.4	536.1	5.8	5.1	4.8	5.1	20.8
15:10	1	21.4	536.1	3.5	3.6	3.9	3.0	14
19:20	1	21.9	574.5	5.9	5.2	4.4	4.1	19.6
21:10	1	22.2	598.5	5.4	5.4	5.3	4.4	20.5
19:40	1	22.3	606.6	7.3	7.9	8.6	7.3	31.03
19:10	1	22.4	614.8	7.0	5.9	5.6	3.9	22.4
20:40	1	22.8	648.3	8.1	8.3	8.9	8.4	33.72
20:50	1	23.8	737.4	8.2	8.4	9.4	8.2	34.19
01:10	1	24.1	765.7	9.6	9.6	9.7	8.9	37.8
22:40	1	24.8	834.3	6.6	6.9	6.3	4.5	24.23
23:40	1	26.3	995.1	6.0	6.1	5.8	4.1	22.01
23:50	1	26.4	1006.5	5.8	5.8	4.9	3.4	19.8
01:20	1	26.5	1017.9	9.6	9.5	9.2	8.5	36.8
22:50	1	26.6	1029.5	8.2	8.5	7.8	6.9	31.4
21:50	1	28.1	1213.7	6.7	6.0	6.1	5.7	24.45
21:40	1	28.8	1306.7	7.6	8.2	8.2	8.0	31.98
Means:	(all*)	21.0	560.9	5.6	5.5	5.4	4.7	21.2
	low	17.6	310.8	4.1	3.9	3.9	3.4	15.4
	middle	21.7	565.7	6.4	6.2	6.3	5.7	24.6
	high	26.5	1021.2	7.5	7.6	7.2	6.2	28.6
ratio on/off (%)								
	all	96.8	90.5	84.8	82.6	81.6	78.1	81.9
	norm	99.7	100.4	88.2	86.0	84.8	81.2	85.1
	low	100.6	99.6	88.3	85.6	83.0	81.6	84.7
	middle	100.0	100.5	87.3	83.0	83.6	82.5	84.1
	high	100.3	99.9	91.8	92.1	88.3	81.6	88.6

* Note: Wind directions less than 200 degrees eliminated.

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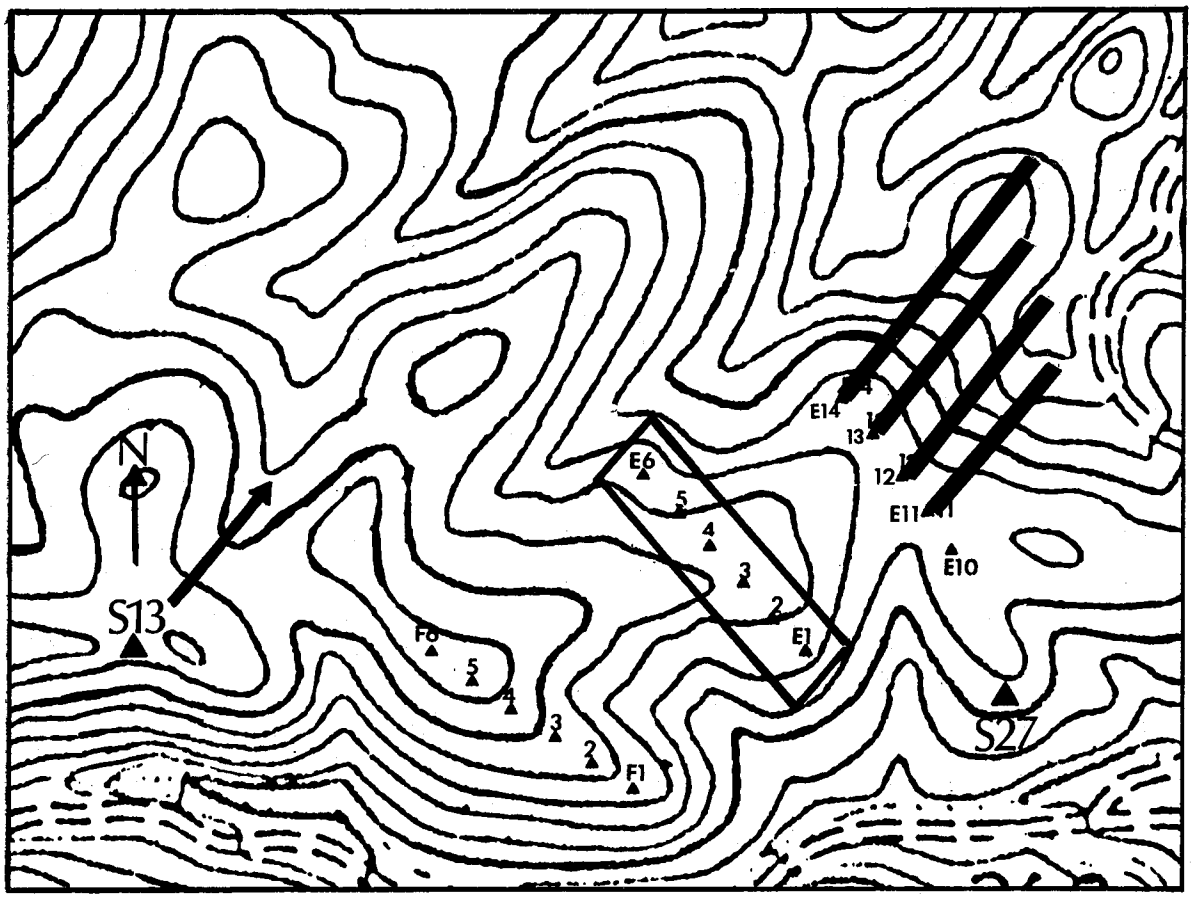

Figure 3-1.b. Souza-C Direct Wake Effect Tests Individual Turbine Deficits

Aug 7, Oct 1-2, 1987 test conditions at reference anemometer, S-13: mean speed = 21.1 mph, mean direction = 220 degrees.

KEY

▲ ▲ ▲ = turbines switched on and off
= % wake energy deficit, 1" = 10%

Deficits

E11	11.8%
E12	14.0%
E13	15.2%
E14	18.8%
Mean	14.9%

Table 3-1.e Jess-C Direct Wake Test Analysis 1

FOR WINDFARM: JESS RANCH WINDFARM

Ten Minute Data Report Date: 07/20/88

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M03-M07	35-ft Anemometers M04 wspeed	M06 wspeed	M08 wspeed
13:20	0	21.4	256	5.5	5.4	5.6	5.8	6.1	6.3	28.4	19.6	20	21.1
19:20	0	21.9	255	3.9	4.5	4.9	5.2	5.6	6.2	24.1	18.1	18.7	20.8
13:10	0	22	257	5.7	5.5	5.9	6.1	6.4	6.6	29.6	18.8	20.2	21.4
19:10	0	22.1	252	4.6	4.5	4.6	4.7	5.4	6.3	23.8	17.9	18.6	20.6
12:20	0	24.2	259	6	6.1	6.6	7	7.4	7.4	33.1	20.2	22.4	23.9
14:10	0	24.2	263	6.2	6.1	6.5	6.8	6.9	6.9	32.5	20.4	22	22.1
21:20	0	24.4	257	5.9	5.8	6	6.2	6.5	6.7	30.4	19.1	20.2	21.6
15:10	0	24.6	257	6.8	6.6	6.6	6.7	6.9	7.2	33.6	20.6	21.3	22.9
15:20	0	24.6	266	6.2	6.2	6.5	6.4	6.4	6.7	31.7	20.2	21.4	22.3
14:20	0	25.2	260	6.7	6.7	7	7.4	7.3	7.5	35.1	21.1	23.2	23.7
12:10	0	25.6	246	6.6	6.9	7.3	7.4	7.7	7.9	35.9	22.1	23.2	24.7
21:10	0	26	245	6.5	6.5	7.1	7.3	7.1	6.7	34.5	21.1	22.2	22.1
16:20	0	26.5	263	7.1	7.1	7.6	7.8	8	8.3	37.6	22.6	24.1	25.3
22:10	0	26.9	256	6.1	6.3	6.8	7.1	7.2	7.2	33.5	19.8	22.1	21.9
18:20	0	27.7	255	8	7.7	8.2	8.5	8.6	8.7	41	24.3	26.7	27.4
22:20	0	27.9	252	6.4	6.2	6.2	6.4	6.7	6.4	31.9	19.2	21.1	20.7
16:10	0	28.2	266	7.7	7.7	8.2	8.3	8.5	8.8	40.4	23.8	25.1	26.6
20:10	0	28.7	249	8	7.8	8.2	8.7	9.4	9.5	42.1	23.6	26.7	28.5
18:10	0	29.1	240	8.3	8.2	8.5	8.9	9.1	9.4	43	25.6	27.7	29.9
20:20	0	30.3	255	8.5	8.3	8.6	8.7	8.8	9.2	42.9	24.9	26.6	28.1
17:10	0	33.4	263	9.3	8.8	9.6	9.6	9.7	9.8	47	27.6	30.1	30.4
17:20	0	34.5	260	9.4	9	9.8	9.6	9.7	10.1	47.5	29.4	30.1	31.7
Mean:		26.3	256	6.8	6.7	7.1	7.3	7.5	7.7	35.4	21.8	23.4	24.4
Normalized:		26.6	256	6.9	6.8	7.2	7.4	7.6	7.8	35.8	21.9	23.5	24.6
12:40	1	21.4	264	3.8	4.1	4.2	4.5	4.9	5.8	21.5	18	18.8	20.4
12:50	1	21.4	266	4	4.1	4.3	4.9	5.3	6.3	22.6	17.7	19.2	21.1
19:50	1	23.8	256	4.7	5.7	6.2	6.8	7.3	8.1	30.7	20.4	23.7	25.8
19:40	1	24.2	262	5.4	5.4	5.6	5.5	6	6.9	27.9	20.2	20.6	23.1
14:50	1	24.4	250	5.5	5.9	5.7	5.9	6	6.8	29	20.9	21.4	22.6
14:40	1	24.6	262	5.8	5.6	5.6	6.1	6.5	7.4	29.6	20.7	21.8	23.5
13:50	1	24.9	256	6	6.1	6.1	6.2	6.5	7	30.9	21.3	22.1	23.1
13:40	1	25.3	270	5.8	5.9	5.9	6.1	6.5	7.3	30.2	20.7	22.1	22.9
18:40	1	25.5	256	5.9	6.2	6.2	6.5	7.2	7.8	32	21.4	22.9	25.1
21:40	1	26.1	257	5.6	5.9	5.9	6.2	6.3	6.5	29.9	20.7	22.8	22.4
18:50	1	26.5	259	6	6.6	6.6	6.8	7	7.4	33	22.5	23.8	24.7
15:50	1	26.6	267	6.2	6.2	6.5	6.8	7.2	8	32.9	21.5	23.1	24.9
15:40	1	27.2	264	6.4	6.4	6.7	6.8	7.2	8.1	33.5	21.9	23.4	25.1
20:50	1	27.4	262	6.9	7.4	7.3	7.1	7.5	8.7	36.2	22.9	23.4	26.1
21:50	1	28.1	250	6.1	6.4	6.6	7	7	7.2	33.1	21.8	23.8	22.7
20:40	1	28.8	253	7.3	7.2	7	7	7.7	8.9	36.2	22.9	24.2	27.2
17:50	1	29.2	262	7.7	7.8	8.1	8.3	8.7	9.1	40.6	24.9	26.8	28.6
17:40	1	30.8	256	7.9	8.1	8.5	8.6	8.9	9.5	42	26.2	28.1	29.7
16:40	1	31.6	256	8.2	8.4	8.7	8.8	9	9.8	43.1	26.3	28.1	30.8
16:50	1	34.2	262	9	8.8	9.2	9.1	9.2	9.6	45.3	28.9	28.7	29.6
Mean:		26.6	259	6.2	6.4	6.5	6.8	7.1	7.8	33.0	22.1	23.4	25.0
Ratios (on/off %)													
All data		101.0		91.4	95.3	92.1	92.5	94.4	101.2	93.2	101.2	100.4	102.2
Normalized		100.1		90.6	94.5	91.2	91.6	93.5	100.3	92.3	100.8	99.7	101.5

was calculated for the first test period. The second set of means is marked "normalized." The difference in mean speeds at J08, and presumably any bias, has been reduced.

The energy ratios between these two periods are listed on the bottom of the page. The normalized ratios for the turbines ranged from 90.6% at M03 to 100.3% at M08. These ratios are equivalent to an energy deficit of 9.4% at M03, and an energy increase of 0.3% at M08. Because of the alignment of the array and the mean wind direction of 259 with turbines on, turbine M08 was not in the expected wake trajectory. The mean row deficit, excluding M08, was 7.7%. These energy deficits are considerably lower than the previous test results, but the speeds in this test were quite a bit higher.

Wind speeds at the 35-ft turbine anemometers are listed in the three right-hand columns of Table 3-1.e. The ratios at the bottom of the table show that there were no speed deficits at these sensors. These sensors are 11 ft below the bottom of the rotor and presumably well below the wake centerline.

The statistical significance of the energy deficits of 7.7% for the row and 9.4% for M03 were 0.90 and 0.95, respectively.

3.1.6 Test 6 Analysis, Jess-C, July 21, 1988

Table 3-1.f is the data listing for the July 21, 1988 test on Jess-C. This test ended prematurely after 5 h because the winds dropped below cut-in speed at about 23:30. The table shows that the mean wind direction at J08 was 260, almost westerly, with a mean speed of 26.1 mph. The mean speeds at the test turbines ranged from 21 mph to 24 mph. The test turbine configuration was identical to the previous test.

The table shows that there was a substantial difference in mean speeds at the upwind reference anemometer between the two test periods; 26.2 mph versus 24.4 mph. A second set of means was calculated that had a mean speed of 26.1 mph at J08. This "normalized" mean eliminated the first three records of the second data set.

The energy ratios at the bottom of the table for the normalized period ranged from 82.8% at M05 to 99.8% at M08. These are equivalent to energy deficits of 17.2% at M05 and 0.2% at M08. Because of the wind direction and array alignment, turbine M08 was out of the expected wake trajectory. The row mean deficit, which excluded M08, was 13.9%.

The 35-ft wind speed data showed deficits of 3.4% at M04, 2.6% at M05, and 0.6% at M08.

These test results were quite different from the previous test at this array. The energy deficits were almost twice as high, even though the mean speed at J08 was only 0.5 mph less than the first test. Considering the similarities in mean speeds at the upwind reference, the results were expected to be more consistent. However, the second test was much shorter, with only half the number of data points, and the normalizing process eliminated three more data points. These two tests will undergo additional analysis in the next section.

Table 3-1.f Jess-C Direct Wake Test Analysis 2

FOR WINDFARM: JESS RANCH WINDFARM
Ten Minute Data Report Date: 07/21/88

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M03-M07	35-ft Anemometers M04 wspeed	M06 wspeed	M08 wspeed
18:40	0	21.4	266	4.3	4.4	4.8	5.3	6	6.5	24.8	16.6	18.6	20.9
17:40	0	21.8	274	4.4	4.5	4.9	5.1	5.2	4.7	24.1	16.9	17.9	17.6
17:50	0	22.3	267	5	4.8	4.8	5.4	5.9	6.2	25.9	17.6	19	20.3
21:50	0	25	260	7.1	6.9	7.2	7.3	7.4	7.4	35.9	20.8	21.9	22.5
18:50	0	25.1	264	6.1	5.8	6.5	6.9	7.4	8.1	32.7	18.9	21.9	24.2
22:50	0	25.2	263	6.4	6.5	6.4	6.5	6.6	7.3	32.4	20.1	20.6	22.2
22:40	0	26.1	252	6.8	6.6	6.3	6.3	6.5	6.8	32.5	20.4	20	20.8
20:50	0	28.4	260	8.1	8.2	8.5	8.8	8.9	8.9	42.5	24.5	26.2	26.5
19:40	0	29.3	257	8.6	8.7	9.4	9.4	9.9	10	46	25.9	28.7	30.7
19:50	0	29.4	256	8.7	8.7	9.3	9.5	9.9	10.1	46.1	26.1	28.1	30.9
21:40	0	29.8	252	8.5	8.2	7.5	6.8	6.7	7.6	37.7	24.6	21.8	23.1
20:40	0	31.1	257	9	8.6	8.9	9	8.7	8.8	44.2	26	27.1	26
Mean:		26.2	261	6.9	6.8	7.0	7.2	7.4	7.7	35.4	21.5	22.7	23.8
18:20	1	16.6	257	1.5	1.9	2	2	2.5	3	9.9	13.9	14.9	16
23:20	1	17.8	256	1.8	2.3	2.5	2.9	3.6	5	13.1	13.8	15.8	17.7
23:10	1	20.7	259	3.2	3.9	4.1	4.8	5.4	7.4	21.4	17.7	19.7	21.7
18:10	1	20.7	259	3.4	3.6	3.8	4.3	4.6	6	19.7	16.8	18.8	19.2
17:20	1	21.7	269	2.6	2.5	3.5	4.2	5.3	6.1	18.1	15.9	17.8	19.8
17:10	1	22.4	267	3.3	3.1	3.4	3.9	4.7	5.9	18.4	16.1	17.1	19.6
22:10	1	24.4	253	5.3	5.8	5.3	5.3	5.2	6.5	26.9	19.7	20.2	20.8
21:10	1	25.5	259	6.3	6.6	6.6	7.1	7.8	8.7	34.4	21.4	23.5	25.7
21:20	1	26.2	259	6	6.1	5.7	6.1	6.9	8	30.8	20.3	22.2	24.1
19:10	1	26.9	259	6.3	6.7	7	7.2	7.6	8.6	34.8	22.6	23.8	25.5
22:20	1	27.3	256	6.8	6.4	5.4	5.6	5.9	6.5	30.1	21.6	21	21.3
19:20	1	29.7	260	7.6	8.4	8.8	9.2	9.5	9.7	43.5	25.6	28.5	30.1
20:10	1	30.5	256	7.7	7.7	7.1	7.8	8.3	9.4	38.6	23.5	25.1	26.9
20:20	1	31.3	255	8.3	8.2	7.5	7.6	8.3	9.1	39.9	25.2	24.7	27.2
Mean (all)		24.4	259	5.0	5.2	5.2	5.6	6.1	7.1	27.1	19.6	20.9	22.5
Normalized:		26.1	259	5.8	5.9	5.8	6.2	6.7	7.7	30.5	20.8	22.1	23.7
Ratios (on/off %)													
All data		93.0		72.4	76.6	73.7	77.5	82.3	92.7	76.6	90.9	92.4	94.7
Normalized		99.3		83.6	86.7	82.8	86.3	90.7	99.8	86.1	96.6	97.4	99.4

The statistical significance of the row energy deficit and individual turbine deficit at M05 was 0.90 and 0.95, respectively.

3.1.7 Jess-C Combined File

The data from all three tests conducted in this array were combined and are listed in Table 3-1.g. Data from the aborted test conducted on July 18, 1988 were also included. The July 18 data are listed in Table 3-1.h. This test was aborted after 4 h because of high winds. Energy deficits for this brief test ranged from 0% to 3%.

Table 3-1.g, the combined file, shows that wind speeds ranged from 16.6 mph to 37.6 mph at J08 with a mean speed of 27.8 mph. The mean wind direction was west-southwesterly to west.

There were no wind speed deficits at the 35-ft turbine anemometers, so these data are not included in this table. The data have been stratified by J08 wind speed into three subsets; winds above 30 mph, winds below 30 mph, and a low wind speed set. This low speed data set has the same mean speed as the 16-D tests that were conducted at this array and discussed in Section 3.2. There is also a subset stratified by wind direction, which excludes the records with wind directions greater than 265.

Energy ratios were calculated for these data sets. The first ratio is for the entire data set, which had a mean speed of 27.8 mph. In this set and in all the subsets, M08 had negligible deficits and was not included in the row means. The row energy deficit for this data set was 7.9%, and M03 had the highest deficit, 10.1%. The second set of ratios is for the wind directions less than 265. The deficits increased by about 1.5% at all turbines. This increase was a result of better alignment with the test array and not of a wind speed change. The next two ratios are for winds below and above 30 mph. The mean speeds for these two data sets were 24.8 mph and 33.1 mph. The energy deficits for these two sets were 10.6% and 3.8%, respectively. The last set of ratios is for low winds and consists of the lower one-third of the observations. This subset had a mean speed of 22.7 mph and a mean deficit of 12.7%. The last three sets of ratios illustrate the inverse relationship between wind speed and energy deficits.

The low speed subset (last set) is especially useful because it can be compared to results of the 16-D tests in Section 3.2. Data from this low-speed subset have been plotted on Figure 3-1.c. This is a topographic map with bars plotted, showing the magnitude of the individual turbine deficits. It is similar to Figures 3-1.a and 3-1.b.

3.1.8 Summary

Six direct wake effect tests were conducted on the Jess and Souza Ranches. Spacing between test rows varied from 6.8 D at Souza-C to 9.5 D at Jess-A. Row deficits varied from 3.8% in 33.0-mph winds to 16.1% in 20.1-mph winds. Individual turbine deficits ranged from 0.0% to 25.7%. Analysis of the individual tests showed that wind speed, thrust coefficient (Ct), and system coefficient of power (Cp) were variables that were highly correlated to the magnitude of the deficits. Wind direction is important too, because there were little or no wake deficits at turbines outside the expected wake trajectory.

Table 3-1.g Combined File, Jess-C Direct Wake Test Analysis

FOR WINDFARM: JESS RANCH WINDFARM
DATE: 07/18/88 thru 07/21/88
Ten Minute Data Report

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M03-M07
18:40	0	21.4	260	4.3	4.4	4.8	5.3	6.0	6.5	24.8
13:20	0	21.4	252	5.5	5.4	5.6	5.8	6.1	6.3	28.4
17:40	0	21.8	252	4.4	4.5	4.9	5.1	5.2	4.7	24.1
19:20	0	21.9	262	3.9	4.5	4.9	5.2	5.6	6.2	24.1
13:10	0	22.0	256	5.7	5.5	5.9	6.1	6.4	6.6	29.6
19:10	0	22.1	243	4.6	4.5	4.6	4.7	5.4	6.3	23.8
17:50	0	22.3	255	5.0	4.8	4.8	5.4	5.9	6.2	25.9
14:10	0	24.2	249	6.2	6.1	6.5	6.8	6.9	6.9	32.5
12:20	0	24.2	246	6.0	6.1	6.6	7.0	7.4	7.4	33.1
21:20	0	24.4	243	5.9	5.8	6.0	6.2	6.5	6.7	30.4
15:20	0	24.6	243	6.2	6.2	6.5	6.4	6.4	6.7	31.7
15:10	0	24.6	253	6.8	6.6	6.6	6.7	6.9	7.2	33.6
21:50	0	25.0	253	7.1	6.9	7.2	7.3	7.4	7.4	35.9
18:50	0	25.1	248	6.1	5.8	6.5	6.9	7.4	8.1	32.7
14:20	0	25.2	257	6.7	6.7	7.0	7.4	7.3	7.5	35.1
22:50	0	25.2	250	6.4	6.5	6.4	6.5	6.6	7.3	32.4
12:10	0	25.6	250	6.6	6.9	7.3	7.4	7.7	7.9	35.9
21:10	0	26.0	248	6.5	6.5	7.1	7.3	7.1	6.7	34.5
22:40	0	26.1	242	6.8	6.6	6.3	6.3	6.5	6.8	32.5
16:20	0	26.5	256	7.1	7.1	7.6	7.8	8.0	8.3	37.6
22:10	0	26.9	255	6.1	6.3	6.8	7.1	7.2	7.2	33.5
18:10	0	26.9	257	7.6	7.5	8.3	8.6	8.4	8.7	40.4
18:00	0	27.1	252	7.7	7.5	7.9	7.7	7.8	8.0	38.6
18:20	0	27.7	259	8.0	7.7	8.2	8.5	8.6	8.7	41.0
22:20	0	27.9	263	6.4	6.2	6.2	6.4	6.7	6.4	31.9
16:10	0	28.2	257	7.7	7.7	8.2	8.3	8.5	8.8	40.4
20:50	0	28.4	257	8.1	8.2	8.5	8.8	8.9	8.9	42.5
20:10	0	28.7	266	8.0	7.8	8.2	8.7	9.4	9.5	42.1
18:10	0	29.1	260	8.3	8.2	8.5	8.9	9.1	9.4	43.0
19:40	0	29.3	246	8.6	8.7	9.4	9.4	9.9	10.0	46.0
19:50	0	29.4	245	8.7	8.7	9.3	9.5	9.9	10.1	46.1
21:40	0	29.8	263	8.5	8.2	7.5	6.8	6.7	7.6	37.7
20:10	0	30.2	256	8.6	8.3	8.5	8.3	8.5	8.7	42.2
20:20	0	30.3	255	8.5	8.3	8.6	8.7	8.8	9.2	42.9
18:20	0	30.8	252	8.7	8.6	9.2	9.0	9.3	9.3	44.8
20:40	0	31.1	266	9.0	8.6	8.9	9.0	8.7	8.8	44.2
19:20	0	31.7	249	9.0	8.7	9.0	9.0	9.4	9.8	45.1
20:20	0	31.9	240	8.9	8.5	9.0	9.2	9.3	9.0	44.9
17:10	0	33.4	255	9.3	8.8	9.6	9.6	9.7	9.8	47.0
19:10	0	33.9	263	9.2	8.9	9.4	9.6	9.6	10.1	46.7
17:20	0	34.5	260	9.4	9.0	9.8	9.6	9.7	10.1	47.5
22:20	0	35.4	264	9.5	8.9	9.0	9.5	9.5	9.5	46.4
21:10	0	35.6	266	9.3	9.0	10.1	9.9	10.2	10.4	48.5
21:20	0	35.7	256	9.5	9.3	10.2	9.9	10.2	10.5	49.1
22:10	0	37.4	262	9.6	9.1	9.5	9.7	9.7	9.9	47.6
Means:		27.8	254	7.3	7.2	7.6	7.7	7.9	8.1	37.7
Winds<30 mph		24.8	252	6.2	6.2	6.5	6.7	6.9	7.1	32.5
Winds>30 mph		33.2	257	9.1	8.8	9.3	9.3	9.4	9.6	45.9
Low Winds		22.8	251	5.2	5.3	5.6	5.8	6.2	6.4	28.0

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Table 3-1.g Combined File, Jess-C Direct Wake Test Analysis

Time	rows on	J08 ws	J08 wd	M03	M04	M05	M06	M07	M08	M03-M07
18:20	1	16.6	250	1.5	1.9	2.0	2.0	2.5	3.0	9.9
23:20	1	17.8	262	1.8	2.3	2.5	2.9	3.6	5.0	13.1
18:10	1	20.7	256	3.4	3.6	3.8	4.3	4.6	6.0	19.7
23:10	1	20.7	270	3.2	3.9	4.1	4.8	5.4	7.4	21.4
12:40	1	21.4	256	3.8	4.1	4.2	4.5	4.9	5.8	21.5
12:50	1	21.4	257	4.0	4.1	4.3	4.9	5.3	6.3	22.6
17:20	1	21.7	259	2.6	2.5	3.5	4.2	5.3	6.1	18.1
17:10	1	22.4	267	3.3	3.1	3.4	3.9	4.7	5.9	18.4
19:50	1	23.8	264	4.7	5.7	6.2	6.8	7.3	8.1	30.7
19:40	1	24.2	262	5.4	5.4	5.6	5.5	6.0	6.9	27.9
22:10	1	24.4	250	5.3	5.8	5.3	5.3	5.2	6.5	26.9
14:50	1	24.4	253	5.5	5.9	5.7	5.9	6.0	6.8	29.0
14:40	1	24.6	262	5.8	5.6	5.6	6.1	6.5	7.4	29.6
13:50	1	24.9	256	6.0	6.1	6.1	6.2	6.5	7.0	30.9
13:40	1	25.3	256	5.8	5.9	5.9	6.1	6.5	7.3	30.2
21:10	1	25.5	262	6.3	6.6	6.6	7.1	7.8	8.7	34.4
18:40	1	25.5	266	5.9	6.2	6.2	6.5	7.2	7.8	32.0
21:40	1	26.1	274	5.6	5.9	5.9	6.2	6.3	6.5	29.9
21:20	1	26.2	267	6.0	6.1	5.7	6.1	6.9	8.0	30.8
18:50	1	26.5	260	6.0	6.6	6.6	6.8	7.0	7.4	33.0
15:50	1	26.6	264	6.2	6.2	6.5	6.8	7.2	8.0	32.9
19:10	1	26.9	263	6.3	6.7	7.0	7.2	7.6	8.6	34.8
15:40	1	27.2	252	6.4	6.4	6.7	6.8	7.2	8.1	33.5
22:20	1	27.3	260	6.8	6.4	5.4	5.6	5.9	6.5	30.1
20:50	1	27.4	257	6.9	7.4	7.3	7.1	7.5	8.7	36.2
21:50	1	28.1	256	6.1	6.4	6.6	7.0	7.0	7.2	33.1
20:40	1	28.8	252	7.3	7.2	7.0	7.0	7.7	8.9	36.2
17:50	1	29.2	257	7.7	7.8	8.1	8.3	8.7	9.1	40.6
18:40	1	29.5	257	7.7	7.6	8.0	8.4	8.6	9.1	40.3
19:20	1	29.7	256	7.6	8.4	8.8	9.2	9.5	9.7	43.5
19:40	1	30.3	259	8.2	8.0	8.3	8.4	8.8	9.0	41.7
20:10	1	30.5	259	7.7	7.7	7.1	7.8	8.3	9.4	38.6
19:50	1	30.6	269	8.1	7.6	7.9	8.4	8.7	8.4	40.7
17:40	1	30.8	267	7.9	8.1	8.5	8.6	8.9	9.5	42.0
20:20	1	31.3	253	8.3	8.2	7.5	7.6	8.3	9.1	39.9
16:40	1	31.6	259	8.2	8.4	8.7	8.8	9.0	9.8	43.1
18:50	1	32.6	259	8.4	8.5	9.2	9.4	9.5	9.7	45.0
16:50	1	34.2	259	9.0	8.8	9.2	9.1	9.2	9.6	45.3
20:40	1	34.4	256	9.4	8.8	9.2	9.6	9.7	9.8	46.7
21:50	1	35.3	260	9.0	8.9	9.7	9.8	10.1	10.4	47.5
20:50	1	35.4	256	9.2	8.9	9.5	9.8	10.0	10.3	47.4
21:40	1	37.6	255	9.6	9.3	10.3	10.0	10.3	10.5	49.5
Means:										
All data		27.8	260	6.6	6.7	6.9	7.1	7.5	8.2	34.8
Winds<30 mph		24.8	259	5.4	5.6	5.7	6.0	6.4	7.3	29.0
Winds>30 mph		33.1	259	8.6	8.5	8.8	9.0	9.3	9.7	44.2
Low winds		22.7	259	4.4	4.6	4.8	5.1	5.6	6.6	24.5
Ratios (on/off %)										
All data:		100.0		89.9	93.0	90.5	92.2	94.7	100.6	92.1
WD<265 deg		100.0		88.2	91.4	89.5	90.8	93.3	99.7	90.7
Winds<30 mph		100.2		86.5	90.7	87.6	89.3	92.7	101.8	89.4
Winds>30 mph		99.7		94.5	96.6	94.7	96.6	98.3	100.6	96.2
Low Winds		99.6		83.3	88.1	85.8	88.0	91.0	102.8	87.3

page 2 of 2

Table 3-1.h Jess-C Direct Wake Test Analysis (Aborted Test)

FOR WINDFARM: JESS RANCH WINDFARM
DATE: 07/18/88
Ten Minute Data Report

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M03-M07	M04 wspeed	M06 wspeed	M08 wspeed
18:10	0	26.9	260	7.6	7.5	8.3	8.6	8.4	8.7	40.4	23.6	25.9	26.8
18:00	0	27.1	252	7.7	7.5	7.9	7.7	7.8	8	38.6	23.2	24	25.2
20:10	0	30.2	252	8.6	8.3	8.5	8.3	8.5	8.7	42.2	25.6	24.9	26.3
18:20	0	30.8	262	8.7	8.6	9.2	9	9.3	9.3	44.8	27.2	27.6	28.8
19:20	0	31.7	256	9	8.7	9	9	9.4	9.8	45.1	28.1	27.9	32.4
20:20	0	31.9	243	8.9	8.5	9	9.2	9.3	9	44.9	26.7	28.1	27.6
19:10	0	33.9	255	9.2	8.9	9.4	9.6	9.6	10.1	46.7	29.1	29.7	33.3
22:20	0	35.4	249	9.5	8.9	9	9.5	9.5	9.5	46.4	29.4	30.2	31
21:10	0	35.6	246	9.3	9	10.1	9.9	10.2	10.4	48.5	29.6	32.6	35.2
21:20	0	35.7	243	9.5	9.3	10.2	9.9	10.2	10.5	49.1	31.1	32.5	35.6
22:10	0	37.4	243	9.6	9.1	9.5	9.7	9.7	9.9	47.6	30.6	31.4	32.4
Mean:		32.4	251	8.9	8.6	9.1	9.1	9.3	9.4	44.9	27.7	28.6	30.4
18:40	1	29.5	253	7.7	7.6	8	8.4	8.6	9.1	40.3	25.2	27.4	29.9
19:40	1	30.3	253	8.2	8	8.3	8.4	8.8	9	41.7	26.6	26.3	27.7
19:50	1	30.6	248	8.1	7.6	7.9	8.4	8.7	8.4	40.7	24.9	26.9	25.8
18:50	1	32.6	257	8.4	8.5	9.2	9.4	9.5	9.7	45	28.5	30.8	32.7
20:40	1	34.4	250	9.4	8.8	9.2	9.6	9.7	9.8	46.7	29.2	30.8	31.9
21:50	1	35.3	250	9	8.9	9.7	9.8	10.1	10.4	47.5	30.6	32.2	34.9
20:50	1	35.4	248	9.2	8.9	9.5	9.8	10	10.3	47.4	29.5	31.9	34.1
21:40	1	37.6	242	9.6	9.3	10.3	10	10.3	10.5	49.5	32	34.1	37.4
Mean (all)		33.2	250	8.7	8.5	9.0	9.2	9.5	9.7	44.9	28.3	30.1	31.8
Normalized:		32.6	251	8.6	8.3	8.8	9.1	9.3	9.5	44.2	27.8	29.5	31.0
Ratios (on/off %)													
All data		102.5		98.1	98.6	99.0	101.1	102.1	102.2	99.8	102.4	105.0	104.5
Normalized		100.5		96.6	97.2	97.0	99.9	100.9	100.9	98.3	100.5	103.0	101.9

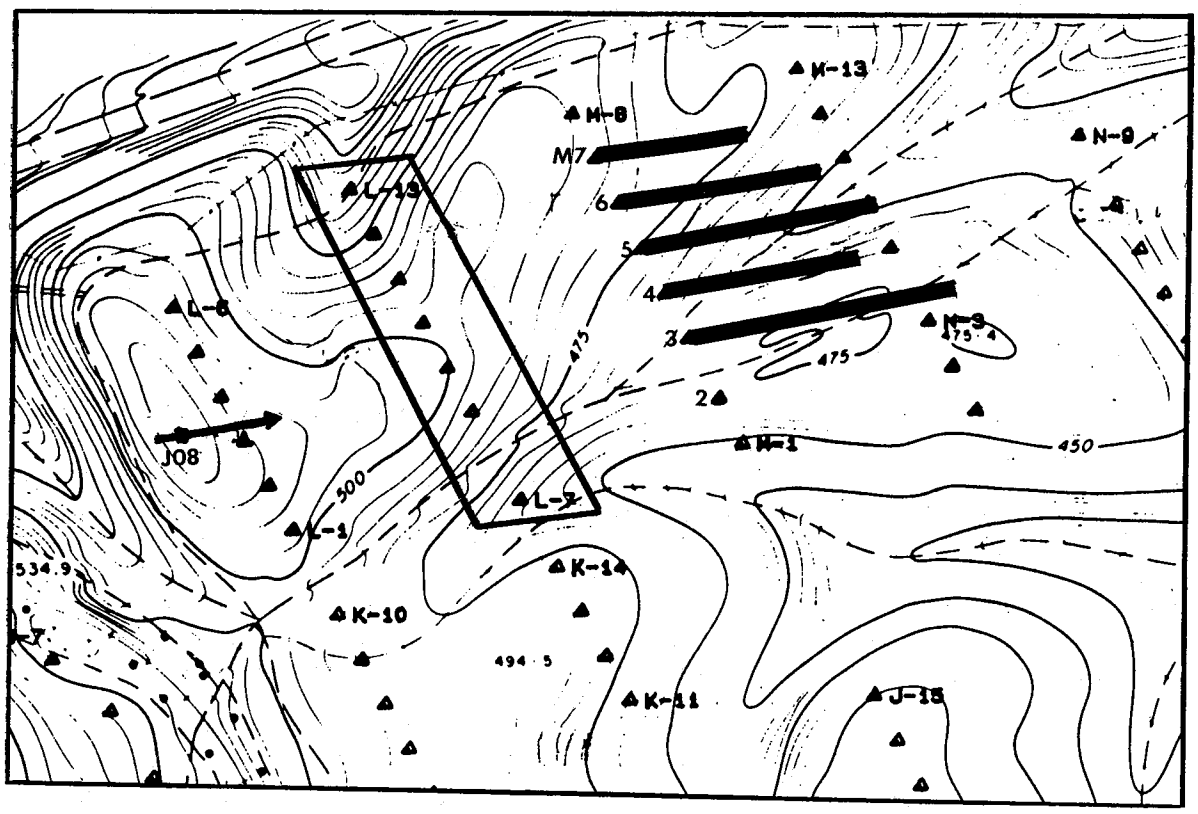

Figure 3-1.c. Jess-C Direct Wake Effect Tests Individual Turbine Deficits (Low-speed Sub-set)

July 18-21, 1988 test conditions at reference anemometer, J-08: mean speed = 22.7 mph, mean direction = 259 degrees.

KEY

▲ ▲ ▲ = turbines switched on and off

▬ = % wake energy deficit, 1" = 10%

Deficits

M3	16.7%
M4	11.9%
M5	14.2%
M6	12.0%
M7	9.0%
M3-M7	12.7%

To illustrate the relationship between speed and energy deficits, the mean row deficits and maximum individual turbine deficits from each test have been plotted as a function of wind speed. The deficits from the stratified subsets of the combined files have also been plotted. Figure 3-1.d shows the relationship between wind speed and wake deficits. The x-axis is wind speed. The wind speed at the reference anemometer was used in most cases, except when the turbine anemometers showed that there was a large difference between the reference and the turbines, notably at Jess-A. In this case, the 35-ft turbine anemometers' speeds were used, adjusted to hub-height using a vertical shear exponent, alpha, of 0.14. Although the free-flow data showed that alphas were slightly lower than this, long-term measurements with wakes present show that 0.14 is an appropriate number.

The mean row deficits are plotted as squares and the maximum individual deficits as diamonds. Two lines of best fit have been analyzed by hand on the figure. The best-fit lines show the inverse relationship between wind speed and energy deficits. The correlation coefficient between these two variables was quite good at -0.92. Thus, 85% of the variability in the energy deficits was explained by wind speed variation. The best-fit line for the maximum individual turbine is slightly steeper, but the correlation coefficient is also -0.92. The mean row deficit line intercepts zero at about 35 mph. Figure 2-3, the Nordtank power curve, shows that the turbine reaches its rated output of 65 kW near this speed. Regression analysis shows that the slope of this best-fit line is -0.8. The inverse relationship between speed and deficit is very similar to findings by Simon (1986) and D. L. Elliott et al. (1988). There is some scatter about the best-fit lines, which could be caused by different spacing between rows, different terrain, and varying levels of atmospheric stability and turbulence.

The inverse relationship was responsible for much of the variation in individual turbine deficits within the test rows. Turbines at lower elevation sites often had lower energy output (lower winds) and higher energy deficits. No attempt has been made to try to normalize these terrain effects on wake deficits. There is no prescribed methodology for this exercise, or any purpose.

Recall from the discussion of the Nordtank turbine, in Section 2.2.3, that wind speed and Ct had a near-perfect inverse correlation. Because of this near-perfect correlation, these two variables are suitable surrogates for each other. The inverse correlation between wake deficits and wind speed discussed above was essentially the same in magnitude as the correlation between energy deficits and Ct. However, this correlation was positive at 0.91. The best correlation, 0.94, was obtained between energy deficits and Cp. The three parameters; wind speed, Cp, and Ct, are interrelated. The wake deficits were a function of a combination of wind speed and turbine performance.

Figures 3.1.e and 3.1.f show the relationship between the mean row energy deficits and Cp and Ct. The mean row deficits are plotted as squares and the best-fit lines have also been plotted. The correlation coefficients (r) are plotted in the lower left corner.

Statistical significance of the mean row energy deficits was 0.90 in four of the tests and 0.80 in one. Statistical significance of the maximum individual turbine deficits ranged from 0.80 to 0.99 and was about 0.05 higher than the mean row deficits.

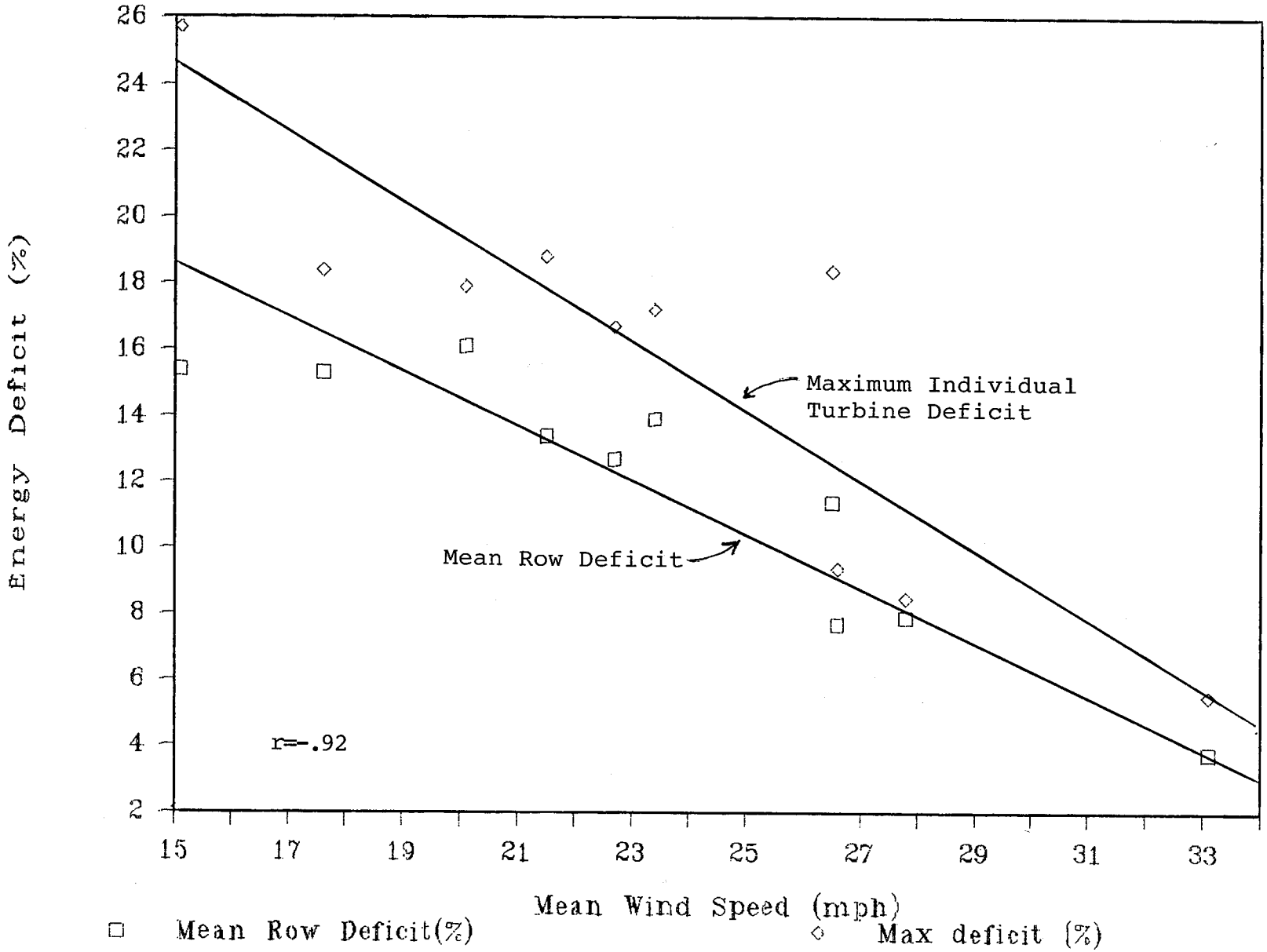

Figure 3-1.d. Wake Deficits (%) vs. Mean Wind Speed

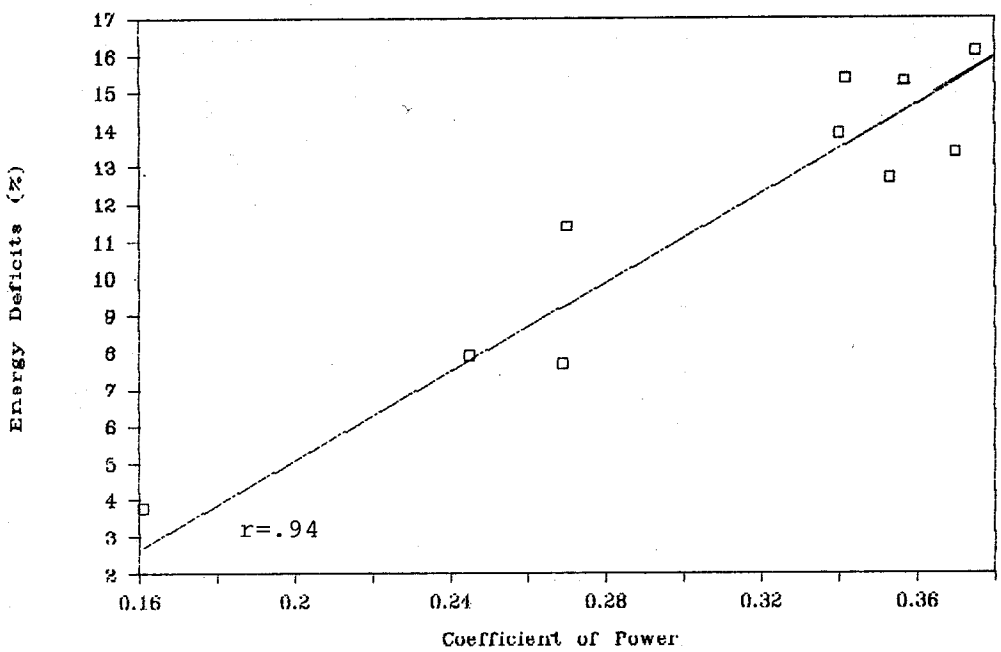

Figure 3-1.e. Wake Deficits (%) vs. Coefficient of Power

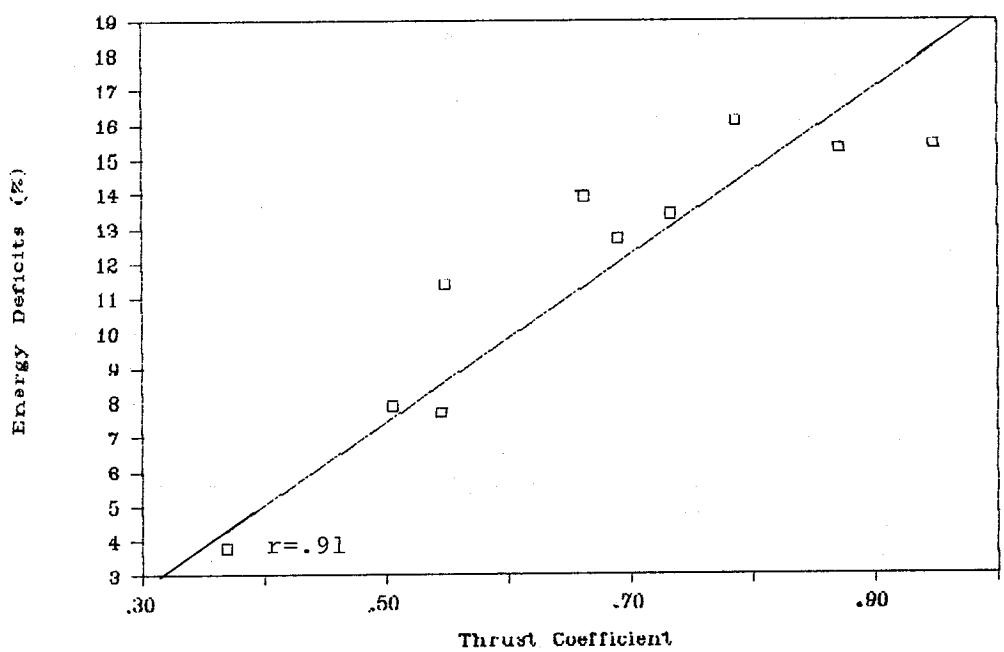

Figure 3-1.f. Wake Deficits (%) vs. Thrust Coefficient

Wind speed deficits were analyzed in these tests as well. The turbine anemometers were at 35-ft agl, which is about half of hub-height. The speed deficits ranged from 0 to 7.3%, which is considerably lower than the energy deficits. The speed deficits were relatively low because the sensors were probably below the wake centerline.

3.2 Sixteen-Diameter Test

The Sixteen-Diameter Test is a variation of the Direct Wake Effect Test. The only difference is the spacing between rows, which is roughly double in these tests. The purpose of this test was to see if wake effects were present at this distance. Many developers had assumed that wake deficits would be negligible at 10 D, which is the spacing of many commercial windfarm arrays. In this test, the middle row in the array was switched off for the duration of the test and the next row, which is 16 D upwind of the test row, was switched on and off. The downwind row was the test row, and energy production data were analyzed in the same fashion as in the direct wake test. For additional discussion of test methodology, see Section 2.4. Two sixteen-diameter tests were conducted on the Jess-C array. Turbines L1 through L6 were turned on and off, and data from M1 through M8 were analyzed. The wind direction in the second test was about 10° more westerly than normal, so the wake trajectory was a bit more westerly than the array axis. Therefore, energy data were analyzed from turbines M1 and M2, even though they were not part of the Jess-C array. Turbine M2 was operating, but the CTM was not communicating, so the data were not available. The tests were conducted on:

1) June 14, 1988, 17:40 - June 15, 1988 03:20 (10 h)
2) June 16, 1988, 12:30 - 20:20 (8 h)

In addition to these two tests, there was one aborted test that lasted 2 h. This test was aborted because of high winds. The data from this test are included in the analysis in Section 3.2.3.

3.2.1 Test 1 Analysis, Jess-C, June 14-15, 1988

Table 3-2.a is the data listing for the June 14-15 test. See page 11 for a complete description of the data format. Wind speeds at the upwind reference, J08, averaged 22 mph with a mean direction of 256°. Wind speeds at the test turbines were 1 to 2 mph lower. Because wind speeds at J08 were a little lower in the first block of data, a "normalized" data set was used to reduce this possible bias between test periods.

The energy ratios between periods, at the bottom of the page, reveal the energy deficits. Using the normalized period, the table shows that the deficits decreased uniformly and ranged from almost 17% at turbine M3 to zero at M8. With a mean wind direction of 256°, one would not expect the wake to impinge on M8. The mean energy deficit at turbines M1 through M6 was 12.9%. This is quite remarkable, since this deficit at 16 D is nearly identical to those measured in the direct wake tests, in which the distance between rows was only 8 D. One would not expect wakes to be this persistent at such great distances. There are two possible explanations for these results. First, the data were collected mostly at night, presumably under stable atmospheric conditions. Wakes are expected to be more persistent under stable conditions

Table 3-2.a Sixteen Rotor Diameter Wake Test 1

FOR WINDFARM: JESS RANCH WINDFARM
REPORT 06/14/88
Ten Minute Data Report 06/15/88

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M01 energy	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M01-M06	M04 wspeed	M06 wspeed	M08 wspeed
17:50	0	17.4	252	2.1	2.9	3.5	4.2	4.7	5	5.1	17.4	15.8	17.4	18.5
21:50	0	17.7	257	2.1	3	4.3	5.5	6	6.8	6.8	20.9	16.5	18.6	21.4
18:40	0	18.7	257	1.5	3.3	4.3	5	5.4	5.7	5.8	19.5	16.8	18.4	19.6
21:40	0	19.5	260	1.5	3.3	4.3	5.1	5.7	6.3	6.3	19.9	16.3	18	20.1
18:50	0	19.6	255	1.6	3.7	4.4	5.1	5.6	5.6	5.8	20.4	16.9	18.5	19.6
17:40	0	19.7	246	2.1	4.1	4.2	4.1	4.6	4.8	5.3	19.1	16.9	17.6	19
22:50	0	21.4	255	3.9	5.4	5.8	6	6.5	6.8	6.9	27.6	18.9	20.5	22.3
00:50	0	21.6	257	4.8	6	6.5	7	7.1	7.4	7.3	31.4	20.6	21.9	23.8
00:40	0	21.8	259	4.9	6.1	6.6	7.1	7.2	7.6	7.5	31.9	20.6	22.5	24.2
01:50	0	21.9	252	4.7	5.7	6.2	6.7	7.2	7.8	8	30.5	19.3	21.4	23.8
01:40	0	22	259	4.2	6	6.6	7	7.1	7.6	7.7	30.9	20.4	21.4	23.6
19:40	0	22.1	249	1.3	4.2	5	5.4	5.8	5.4	5	21.7	17.7	18.6	17.8
20:40	0	22.3	252	2.9	4.8	4.9	5.5	6.4	7.1	7.2	24.5	17.6	19.9	21.7
19:50	0	22.3	249	1.1	4	5.2	5.7	6	5.8	4.9	22	18.4	19.2	17.4
22:40	0	22.4	260	4	6	6.2	6.7	7	7.1	7.2	29.9	19.1	20.7	22.3
23:40	0	23.3	260	5.6	6.4	6.9	7.4	7.3	7.7	7.6	33.6	20.2	21.6	23.2
02:50	0	23.5	260	4.8	6.5	7.4	8.1	8.1	8.3	8.2	34.9	21.1	22.7	24.4
20:50	0	23.5	255	3.2	5.6	6.4	6.9	6.8	6.8	6.4	28.9	19.5	19.9	20.1
02:40	0	24.2	262	5.1	7	7.5	8.1	8.3	8.6	8.4	36	21.9	24.1	25.1
23:50	0	24.9	257	5.8	7.1	7.5	8	7.9	8.2	8	36.3	21.6	22.9	24.2
Mean:		21.5	256	3.4	5.1	5.7	6.2	6.5	6.8	6.8	26.9	18.8	20.3	21.6
Norm:		22.3	255	3.8	5.5	6.1	6.6	6.8	7.0	7.0	28.7	19.4	20.8	22.0
18:10	1	18.3	253	1.5	2.3	2.5	3.1	3.5	4.7	5	12.9	15.2	16.2	18.8
21:20	1	18.9	259	2	2.2	3	4	5	6.1	6.3	16.2	14.9	17.5	19.7
18:20	1	19.1	256	1.6	2.5	3.2	3.9	4.4	4.9	5.2	15.6	17	17.9	19.2
01:20	1	20.4	256	2.9	3.8	4.2	4.4	5	5.5	6.2	20.3	17.2	18.3	21.4
23:10	1	20.7	259	2.9	3.9	4.5	4.9	5.2	6.3	6.4	21.4	18.1	18.9	21.4
21:10	1	20.8	253	1.8	3.4	4.8	5.4	5.7	6.7	6.6	21.1	18.2	18.8	20.9
01:10	1	21.3	257	3.7	4.9	5.2	5.6	6.2	6.2	6.6	25.6	19	20.2	22.1
22:10	1	21.4	262	3	4.5	5	5.3	5.6	6.5	6.5	23.4	18.3	19.1	20.7
00:20	1	21.6	256	3.9	5	5.7	6.1	6.6	7.2	7.4	27.3	20	21.1	24.1
02:20	1	22.1	256	3.6	5.2	5.9	6.6	7.3	8.2	8.4	28.6	19.5	21.7	24.3
20:10	1	22.4	253	1.9	3.9	4	4.4	4.6	5.4	5.8	18.8	17.1	17.6	18.9
00:10	1	22.4	257	3.9	5.4	6.3	6.7	7	7.8	7.8	29.3	20.8	22	24.8
23:20	1	22.7	259	4	5.1	5.7	6	6.3	7.3	7.3	27.1	19.3	20.5	23.1
22:20	1	22.7	262	3.6	5.2	5.4	5.6	6	6.9	7	25.8	18.9	19.8	21.9
02:10	1	23.1	260	4.8	6	6.9	7.8	8.2	9.2	9.1	33.7	21.3	23.5	25.9
20:20	1	23.4	253	3.4	4.7	5.4	6.1	6.8	6.9	6.9	26.4	18.8	20.7	21.6
19:10	1	23.4	245	1.8	4.2	4.8	5	5.2	5.2	5.6	21	18.2	18.5	19.2
19:20	1	24.7	245	1.8	4.3	5.1	5.4	5.6	5.7	6.2	22.2	18.7	18.9	20.4
03:10	1	27.3	260	6.4	7.6	8.1	9.1	9.1	9.9	9.9	40.3	23.4	25.1	27.5
03:20	1	28.8	262	6.9	8.3	8.7	9.7	9.7	10.5	10.5	43.3	24.9	27.1	29.6
Mean:		22.3	256	3.3	4.6	5.2	5.8	6.2	6.9	7.0	25.0	18.9	20.2	22.3
Ratios (on/off)														
All data(%)		103.7		97.3	91.4	91.8	92.4	94.1	100.5	103.9	93.1	100.7	99.4	103.1
Normalized(%)		100.0		87.2	83.4	85.8	87.9	90.4	97.4	101.0	87.1	97.5	96.8	101.1

because there is less mixing. A second reason could be the low subsidence inversion. The depth of the marine layer or flux layer in this part of the Altamont is estimated to have been very shallow on this date, on the order of 200 ft thick. This is not an unusual event in the Altamont Pass, although this layer is normally several hundred feet thicker. Typically there is very little wind energy above the top of the inversion in the Altamont. If the flux layer were this shallow, one would expect wake deficits to be very persistent because there is only a small reservoir of momentum aloft to restore the lost energy. If the persistence of these deficits is a function of the shallow inversion peculiar to the Altamont Pass, these results may have limited application outside this area.

Wind speed data from the 35-ft anemometers at M4, M6, and M8 were analyzed. Turbine M8 had no deficit (actually a 1% increase in speed), and M4 and M6 had speed deficits of 2.5% and 3.2%, respectively. Power density deficits (W/m^2) were also calculated from the anemometer data. The deficits were 4.7% and 6.5% at M4 and M6. These speed and power density deficits are quite small compared to the energy deficits, and this may be due to the fact that the anemometers are not at hub-height and could be well below the wake centerline.

Although the middle (8 D) row turbines were shut off during this test, wind speed data were available and analyzed at turbines L8, L10, and L12. This permits a comparison of speed and power density deficits at 8 D versus 16 D. The speed deficits at L8 and L10 were 3.0% and 2.9%, respectively, and L12 had no deficit. These speed deficits are very similar to those at M4, M6, and M8. The power density deficits at L8 and L10 were 5.2% and 6.0%, respectively. These are within 0.5% of the deficits at turbines M4 and M6. Thus we see that there were practically no differences in the speed and power density deficits between 8 D and 16 D (at 35 ft agl).

The statistical significance of the row energy deficit of 12.9% was 0.95. The energy deficit of 16.6% at turbine M3 was significant at the 0.975 level.

3.2.2 Test 2 Analysis, Jess-C, June 16, 1988

Table 3-2.b is the data listing for the June 16 test. Wind speeds were nearly identical to the first test; however, the mean wind direction was about 5° more westerly. Data in the second block (upwind turbines on line) were sorted by J08 wind direction. A second set of means that excluded the westerly (last 2) records was calculated. In winds with a direction of 270°, the expected wake trajectory would miss all turbines except M1 through M3.

There are two sets of energy ratios at the bottom of the page: one for all data and one with the directional screening. The analysis will focus on the latter. The energy ratios ranged from 83.9% at M1 to 103.1% at M8. Turbines M6 through M8 had no deficits at all, which is not surprising based on the wind direction. Turbine M1 had the largest deficit, 16.1%, and deficits decreased steadily down the row to M6. The mean deficit at turbines M1 through M4 was 10.6%, which is lower than in the first test. Much of this difference is attributable to the wind direction, as the maximum individual turbine deficit was about the same in both tests: 16.1% versus 16.6%.

The wind speed deficit was 3% at turbine M4 and there was no speed deficit at M6 and M8. This is quite similar to the first test.

Table 3-2.b Sixteen Rotor Diameter Wake Test 2

FOR WINDFARM: JESS RANCH WINDFARM
REPORT 06/16/88
Ten Minute Data Report

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	M01 energy	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	sum of M01-M04	M04 wspeed	M06 wspeed	M08 wspeed
14:50	0	17	280	2.2	2.3	2.2	2.6	2.6	3.1	3.3	6.7	13.8	14.6	15.9
14:40	0	17.4	269	2.5	2.9	2.7	3.1	3.2	3.6	3.6	8.1	14.7	15.2	16.6
12:40	0	17.4	256	1.7	2.6	2.7	2.9	2.7	2.9	2.9	7	14.4	14.7	15.1
12:50	0	17.6	273	1.9	2.6	2.9	2.9	3.1	3.1	2.8	7.4	14.8	14.9	15
13:50	0	17.6	253	1.9	2.4	2.7	3.3	3.7	3.9	3.9	7	14.7	16.1	16.7
13:40	0	17.9	255	3.1	3.1	3.4	3.8	4.1	4.4	4.3	9.6	15.7	16.6	17.4
18:40	0	22.7	260	4.3	5.1	5.2	5.9	6.4	6.9	7.2	14.6	18.1	20.1	21.1
15:40	0	24.3	263	5.9	6.2	6.4	6.6	7	7.3	7.3	18.5	20.2	21.7	22.7
15:50	0	24.4	248	5.6	6.4	6.5	6.7	6.8	7.1	7.2	18.5	20.6	21.6	22.1
17:40	0	25.4	267	5.9	6.8	6.7	7	7.4	7.7	8	19.4	20.6	22.3	23.7
16:50	0	26.1	253	6.3	7.2	7.2	7.4	7.6	7:7	7.5	20.7	21.6	22.8	22.9
16:40	0	26.4	257	6.8	7.5	7.8	8.5	8.5	8.6	8.5	22.1	22.6	23.9	24.8
17:50	0	26.9	238	6.4	7.3	7.2	7.6	7.6	7.7	7.9	20.9	21.3	22.9	23.2
18:50	0	27.7	266	6.1	7.6	7.9	8.7	9.1	9.2	8.7	21.6	23.2	25.4	24.4
19:40	0	30.4	250	7	8.5	8.3	8.6	8.6	9	9	23.8	24.1	24.4	25.6
19:50	0	31.8	239	6.9	9	9.3	10.2	10.2	10.3	10.1	25.2	27.5	29.1	28.9
Mean:		23.2	258	4.7	5.5	5.6	6.0	6.2	6.4	6.4	15.7	19.2	20.4	21.0
15:10	1	16.9	250	1.8	1.9	2.2	2.8	3	3.1	3.2	5.9	14.2	15	15.8
20:10	1	28.5	256	3.3	6.5	7.3	8.1	9.1	10	10.4	17.1	22.3	26.8	29.6
13:20	1	18.1	257	2	2.7	2.9	2.9	3.3	3.6	3.8	7.6	14.7	15.8	17.1
14:10	1	18.8	259	2.8	3.2	3.5	3.7	4.1	4.5	4.9	9.5	15.7	16.4	18.5
16:20	1	26.5	259	6.2	7	7.1	7.5	8	8.1	8.2	20.3	21.6	23.4	25
19:20	1	31.8	260	7.5	8.8	8.7	8.9	9.3	9.4	9.3	25	25.2	26.4	26.6
15:20	1	20.2	262	2.3	3.3	3.7	3.8	3.7	4	4.6	9.3	16.3	16.6	18.1
18:20	1	24.5	262	4.6	5.5	5.6	6.4	7.4	7.5	7.8	15.7	18.8	21.4	22.5
13:10	1	18.2	263	2.2	2.6	2.6	3	3.6	3.8	3.8	7.4	14.6	15.9	16.4
14:20	1	18.2	263	2.2	3	3	3.2	3.4	3.5	3.6	8.2	15.3	16.1	16.6
17:20	1	25.8	263	6	6.7	6.8	7.6	7.8	7.8	7.9	19.5	20.9	23.1	23.3
18:10	1	23.3	264	3.9	4.4	4.9	5.9	6.5	6.6	6.9	13.2	18.2	20.3	21.1
20:20	1	29.7	264	4.6	7	7.8	8.7	9.1	9.5	9.8	19.4	23	26.1	28.3
17:10	1	24.7	266	5.3	6.4	6.6	7.2	7.5	7.8	8	18.3	20.5	22.4	23.9
19:10	1	30.4	269	7	7.7	7.9	8.1	8.6	9.1	9.4	22.6	23.2	25.2	26.8
16:10	1	25.7	271	6.1	6.8	6.9	7.3	7.8	8.1	8.3	19.8	21.3	23.2	24.2
Mean:		23.8	262	4.2	5.2	5.5	5.9	6.4	6.7	6.9	14.9	19.1	20.9	22.1
WD<269 deg		23.2	261	3.9	4.9	5.2	5.7	6.1	6.4	6.6	14.0	18.7	20.4	21.6
Ratios (on/off)														
all data(%)		102.8		91.0	95.4	98.2	99.3	103.7	103.8	107.5	95.1	99.3	102.4	105.3
Dir. screen(%)		100.2		83.9	90.1	93.2	95.1	99.4	99.5	103.1	89.4	97.0	100.1	103.0

The results of this test confirm that the wake energy deficits do persist well beyond 10 D. The second test took place in afternoon and early evening hours. Therefore, the subsidence inversion was probably weakened and considerably higher for part of this test because of daytime surface heating. Thus, the deficits measured in the first test were not an anomaly merely associated with stable nighttime conditions and an extremely shallow subsidence inversion.

The statistical significance of the mean deficit of 10.6% was 0.75. This indicates that there is a 25% possibility that these results could have occurred by chance. The 16.1% deficit at turbine M1 had a significance level of 0.80, which is slightly better.

3.2.3 Combined File Analysis

Data from the two tests discussed above and the aborted test were combined into a single file for further analysis. Table 3-2.c contains these data. The data were screened by J08 wind direction and speed. There are four sets of means and ratios. The first set analyzes all available data, while the second through fourth sets analyze records with wind directions less than 260°. The second set is all records with wind directions below 260°, and the third and fourth sets are low and high wind-speed subsets. Turbine M8 was not analyzed, as it was shown in the previous discussions to be out of the expected wake trajectory.

The ratios show that the mean deficit for turbines M1 through M5 was 11.1% using all data (first set of ratios) and 12.1% using only the records screened by wind direction (second set). These deficits are plotted on Figure 3-2.a. The deficits decrease uniformly across the row from M1 to M7. Using the second set of ratios, M1 had a deficit of 14.2% and M7 had a deficit of about 3.5%. The speed deficits at 35 ft agl at M4 and M6 were about 2%.

The third and fourth sets of ratios show the inverse relationship between wind speed and energy deficits. The low speed data set (third) had mean speeds at J08 of 19.5 mph and about 16 mph to 18 mph at M4 and M6. The mean energy deficit at M1 through M5 was 18.5%, and M3 had the highest deficit, about 21%. The speed deficits were about 4% and 5% at M4 and M6. The high speed data set (fourth) had mean speeds at J08 of 26.4 mph and 22 mph to 23 mph at M4 and M6. The mean energy deficit dropped dramatically to 10.1% (versus 18.5%). Turbine M1 had the worst deficit, about 16%. There were practically no speed deficits at M4 and M6. Thus we see that with a 7-mph increase in speed at J08, the mean energy deficit dropped by 8.4%. This is a larger drop in energy for a given change in wind speed than in the direct wake tests. Recall that the slope of the best fit line for those tests was about -0.8. This implies that a 7-mph change in wind speed would yield about a 5% change in the deficits. Thus, it appears that the 16 D energy deficits are even more sensitive to changes in speed than the 8 D deficits. Regression analysis (not plotted) of these two variables from this limited data set shows that the slope of the best fit line is about -1.5, much steeper than the direct wake tests. The zero intercept is much lower than the direct wake test: 31 mph versus 35 mph. This suggests that negligible deficits would be expected at 16 D above 31 mph.

Table 3-2.c Sixteen Rotor Diameter Wake Test, Combined File

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM

June 14-18, 1988

rows on upwind	J08 wspeed	J08 w.dir.	M01 energy	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	sum of M01-M05	35-ft turbine Anemometers M04 wspeed	M06 wspeed
0	17.4	246	2.1	2.9	3.5	4.2	4.7	5.0	12.7	15.8	17.4
0	17.4	256	1.7	2.6	2.7	2.9	2.7	2.9	9.9	14.4	14.7
0	17.6	253	1.9	2.4	2.7	3.3	3.7	3.9	10.3	14.7	16.1
0	17.7	249	2.1	3.0	4.3	5.5	6.0	6.8	14.9	16.5	18.6
0	17.9	255	3.1	3.1	3.4	3.8	4.1	4.4	13.4	15.7	16.6
0	18.7	252	1.5	3.3	4.3	5.0	5.4	5.7	14.1	16.8	18.4
0	19.5	252	1.5	3.3	4.3	5.1	5.7	6.3	14.2	16.3	18.0
0	19.6	252	1.6	3.7	4.4	5.1	5.6	5.6	14.8	16.9	18.5
0	19.7	253	2.1	4.1	4.2	4.1	4.6	4.8	14.5	16.9	17.6
0	21.4	253	3.9	5.4	5.8	6.0	6.5	6.8	21.1	18.9	20.5
0	21.6	255	4.8	6.0	6.5	7.0	7.1	7.4	24.3	20.6	21.9
0	21.8	255	4.9	6.1	6.6	7.1	7.2	7.6	24.7	20.6	22.5
0	21.9	255	4.7	5.7	6.2	6.7	7.2	7.8	23.3	19.3	21.4
0	22.0	255	4.2	6.0	6.6	7.0	7.1	7.6	23.8	20.4	21.4
0	22.1	256	1.3	4.2	5.0	5.4	5.8	5.4	15.9	17.7	18.6
0	22.3	257	1.1	4.0	5.2	5.7	6.0	5.8	16.0	18.4	19.2
0	22.3	257	2.9	4.8	4.9	5.5	6.4	7.1	18.1	17.6	19.9
0	23.5	257	3.2	5.6	6.4	6.9	6.8	6.8	22.1	19.5	19.9
0	24.4	248	5.6	6.4	6.5	6.7	6.8	7.1	25.2	20.6	21.6
0	24.9	257	5.8	7.1	7.5	8.0	7.9	8.2	28.4	21.6	22.9
0	26.1	253	6.3	7.2	7.2	7.4	7.6	7.7	28.1	21.6	22.8
0	26.4	257	6.8	7.5	7.8	8.5	8.5	8.6	30.6	22.6	23.9
0	26.9	238	6.4	7.3	7.2	7.6	7.6	7.7	28.5	21.3	22.9
0	30.4	250	7.0	8.5	8.3	8.6	8.6	9.0	32.4	24.1	24.4
0	31.7	246	7.8	8.9	9.1	9.7	9.6	10.0	35.5	27.6	28.4
0	31.8	239	6.9	9.0	9.3	10.2	10.2	10.3	35.4	27.5	29.1
0	32.1	250	7.7	9.3	9.2	9.5	9.6	10.1	35.7	27.9	28.2
0	28.6	259	6.6	7.9	8.2	8.7	8.8	8.9	31.4	24.5	25.1
0	27.6	260	6.6	7.9	8.2	8.8	9.0	9.4	31.5	23.8	25.6
0	22.4	260	4.0	6.0	6.2	6.7	7.0	7.1	22.9	19.1	20.7
0	22.7	260	4.3	5.1	5.2	5.9	6.4	6.9	20.5	18.1	20.1
0	23.3	260	5.6	6.4	6.9	7.4	7.3	7.7	26.3	20.2	21.6
0	23.5	260	4.8	6.5	7.4	8.1	8.1	8.3	26.8	21.1	22.7
0	24.2	262	5.1	7.0	7.5	8.1	8.3	8.6	27.7	21.9	24.1
0	24.3	263	5.9	6.2	6.4	6.6	7.0	7.3	25.1	20.2	21.7
0	27.7	266	6.1	7.6	7.9	8.7	9.1	9.2	30.3	23.2	25.4
0	25.4	267	5.9	6.8	6.7	7.0	7.4	7.7	26.4	20.6	22.3
0	17.4	269	2.5	2.9	2.7	3.1	3.2	3.6	11.2	14.7	15.2
Means:											
All data	23.5	255	4.4	5.8	6.2	6.7	7.0	7.2	23.2	20.1	21.5
WD<260	22.9	252	4.0	5.5	5.9	6.4	6.6	6.9	21.8	19.7	20.9
" , low	19.6	253	2.9	4.1	4.7	5.2	5.5	5.9	16.9	17.4	18.8
" ,high	26.5	251	5.3	6.9	7.2	7.7	7.8	8.0	27.1	22.2	23.2

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Table 3-2.c Sixteen Rotor Diameter Wake Test, Combined File

rows on upwind	J08 wspeed	J08 w.dir.	M01 energy	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	sum of M01-M05	M04 wspeed	M06 wspeed
1	30.6	243	7.7	8.8	8.5	9.0	9.0	9.3	34.0	26.3	27.0
1	16.9	250	1.8	1.9	2.2	2.8	3.0	3.1	8.7	14.2	15.0
1	18.1	257	2.0	2.7	2.9	2.9	3.3	3.6	10.5	14.7	15.8
1	18.3	250	1.5	2.3	2.5	3.1	3.5	4.7	9.4	15.2	16.2
1	18.8	259	2.8	3.2	3.5	3.7	4.1	4.5	13.2	15.7	16.4
1	18.9	253	2.0	2.2	3.0	4.0	5.0	6.1	11.2	14.9	17.5
1	19.1	253	1.6	2.5	3.2	3.9	4.4	4.9	11.2	17.0	17.9
1	20.4	253	2.9	3.8	4.2	4.4	5.0	5.5	15.3	17.2	18.3
1	20.7	256	2.9	3.9	4.5	4.9	5.2	6.3	16.2	18.1	18.9
1	20.8	256	1.8	3.4	4.8	5.4	5.7	6.7	15.4	18.2	18.8
1	21.3	256	3.7	4.9	5.2	5.6	6.2	6.2	19.4	19.0	20.2
1	21.6	256	3.9	5.0	5.7	6.1	6.6	7.2	20.7	20.0	21.1
1	22.1	256	3.6	5.2	5.9	6.6	7.3	8.2	21.3	19.5	21.7
1	22.4	257	1.9	3.9	4.0	4.4	4.6	5.4	14.2	17.1	17.6
1	22.4	257	3.9	5.4	6.3	6.7	7.0	7.8	22.3	20.8	22.0
1	22.7	257	4.0	5.1	5.7	6.0	6.3	7.3	20.8	19.3	20.5
1	23.4	259	3.4	4.7	5.4	6.1	6.8	6.9	19.6	18.8	20.7
1	23.4	259	1.8	4.2	4.8	5.0	5.2	5.2	15.8	18.2	18.5
1	24.7	259	1.8	4.3	5.1	5.4	5.6	5.7	16.6	18.7	18.9
1	26.5	259	6.2	7.0	7.1	7.5	8.0	8.1	27.8	21.6	23.4
1	28.5	256	3.3	6.5	7.3	8.1	9.1	10.0	25.2	22.3	26.8
1	32.7	253	7.4	8.8	8.9	9.6	9.5	9.7	34.7	27.7	28.1
1	33.2	253	7.7	9.3	9.5	10.2	10.5	10.8	36.7	29.4	32.1
1	23.1	260	4.8	6.0	6.9	7.8	8.2	9.2	25.5	21.3	23.5
1	27.3	260	6.4	7.6	8.1	9.1	9.1	9.9	31.2	23.4	25.1
1	31.8	260	7.5	8.8	8.7	8.9	9.3	9.4	33.9	25.2	26.4
1	20.2	262	2.3	3.3	3.7	3.8	3.7	4.0	13.1	16.3	16.6
1	21.4	262	3.0	4.5	5.0	5.3	5.6	6.5	17.8	18.3	19.1
1	22.7	262	3.6	5.2	5.4	5.6	6.0	6.9	19.8	18.9	19.8
1	24.5	262	4.6	5.5	5.6	6.4	7.4	7.5	22.1	18.8	21.4
1	28.8	262	6.9	8.3	8.7	9.7	9.7	10.5	33.6	24.9	27.1
1	32.7	262	8.1	9.4	9.3	9.9	10.0	10.2	36.7	27.7	29.7
1	18.2	263	2.2	2.6	2.6	3.0	3.6	3.8	10.4	14.6	15.9
1	18.2	263	2.2	3.0	3.0	3.2	3.4	3.5	11.4	15.3	16.1
1	25.8	263	6.0	6.7	6.8	7.6	7.8	7.8	27.1	20.9	23.1
1	23.3	264	3.9	4.4	4.9	5.9	6.5	6.6	19.1	18.2	20.3
1	29.7	264	4.6	7.0	7.8	8.7	9.1	9.5	28.1	23.0	26.1
1	24.7	266	5.3	6.4	6.6	7.2	7.5	7.8	25.5	20.5	22.4
Means:											
All data	23.5	258	3.9	5.1	5.5	6.1	6.5	6.9	20.6	19.6	21.1
WD<260	22.9	255	3.5	4.7	5.2	5.7	6.1	6.7	19.1	19.3	20.6
" ,low	19.5	255	2.4	3.3	3.8	4.3	4.7	5.3	13.7	16.7	17.8
" ,high	26.4	256	4.5	6.2	6.6	7.1	7.4	7.8	24.3	21.8	23.2
Ratios (on/off %)											
all data	100.1		87.5	87.9	89.2	90.3	92.8	96.1	88.9	97.4	98.0
WD<260	100.0		85.8	86.8	88.7	89.4	92.4	96.5	87.9	98.0	98.3
" ,low	99.7		85.4	79.1	81.0	81.8	85.3	90.6	81.5	96.2	94.7
" ,high	99.5		84.3	89.5	91.7	92.5	95.1	98.1	89.9	98.6	100.1

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3.2.4 Summary

Two sixteen-diameter tests were conducted at the Jess-C array. A third test was aborted after 2 h, but the data were included in the analysis. The results of the two tests were quite similar. In the first test, the mean energy deficit was 12.9% and the maximum individual turbine deficit was 16.6%. In the second test, with slightly higher wind speeds, the mean energy deficit was 10.6%, and the maximum individual deficit was 16.1%. Speed deficit data were available from the 35-ft anemometers on turbines at 8 D and 16 D. There were practically no differences between the 8 D and 16 D speed deficits. The speed deficits at 16 D ranged from 2.5% to 3.2%. At 8 D, the deficits were 2.9% to 3.0%. Power density deficits were calculated from the 35-ft wind speed data and these also showed the similarity between the 8 D and 16 D sites. At 16 D, the power density deficits were 4.7% to 6.5%, and at 8 D they were 5.2% to 6.0%.

The sixteen-diameter tests resulted in an average energy deficit, when screened by direction, of 12.1% at the affected turbines. This is quite remarkable, considering the distance between rows, and that these deficits are just as high as those measured in rows separated by only 8 D. In fact they are almost identical to the deficits measured in the 8 D tests that took place in this same array. Recall that in the combined file in Section 3.1.7, in the subset with the mean speed of 22.7 mph, the energy deficit was 12.7%.

Regression analysis of wind speed versus energy deficit data showed an inverse relationship. The slope of the best-fit line was much steeper in the 16 D tests than in the 8 D tests. This implies that a given increase in wind speed produced a larger decrease in the deficit. The zero intercept was about 31 mph, i.e., negligible deficits are expected above this speed at 16 D.

Figure 3-2.a is a topographic map of the Jess-C turbines with the individual turbine deficits plotted on it. The length of the bars is proportional to the deficit and the bars are plotted parallel to the mean wind direction. The figure uses only the data records with wind direction less than 260°. It is interesting to compare it to Figure 3-1.c in Section 3.1.7. Figure 3-2.a shows the results of the 16 D tests. Figure 3-1.c shows the results of the 8 D tests conducted on the same turbines. The two figures illustrate the remarkable similarity of the test results, in spite of the different test conditions (upwind spacing).

Figure 3-2.a helps to illustrate how terrain effects can enhance wake deficits. The turbines at the southern end of the row, M1 and M3, are at lower elevations than the northern end. These turbines had lower energy output (lower winds) during the test and during the free-flow study as well. Because of the inverse relationship between wind speed and wake deficits, these lower energy (and elevation) sites experienced higher deficits.

3.3 Blockbuster Test

The Blockbuster Test is similar to the Direct Wake Effect Test with one change. Instead of switching a single row of upwind turbines on and off, two rows of upwind turbines are switched on and off simultaneously. The downwind (third) row is the test row where all analysis is performed. Additional discussion on the test methodology can be found in Section 2.4.

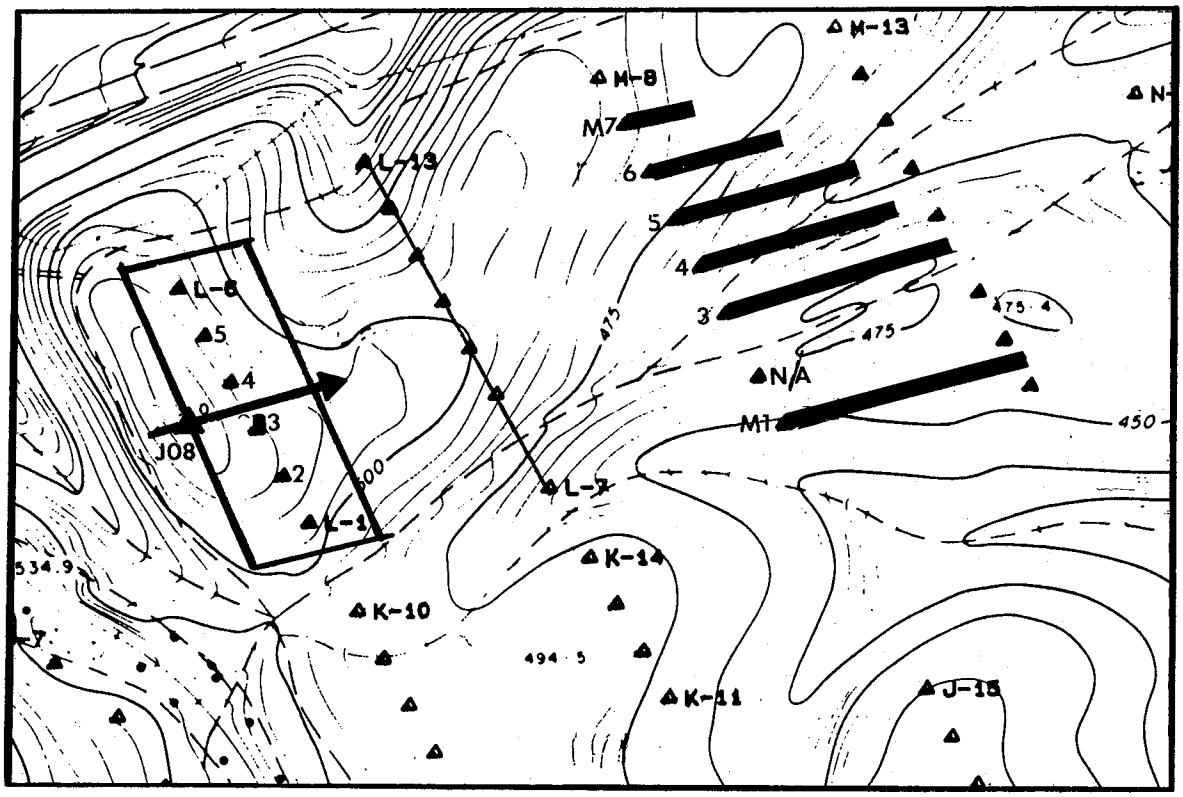

Figure 3-2.a. Jess-C 16 RD Wake Tests Individual Turbine Deficits

June 14-16, 1988 test conditions at reference anemometer, J-08: mean speed = 22.9 mph, mean direction = 255 degrees.

KEY

= turbines switched on and off
= turbines in middle row, off for entire test
= % wake energy deficit, 1" = 10%

Deficits (samples with wind direction <260 degrees)

M1	14.2%
M2	N/A = not available
M3	13.2%
M4	11.3%
M5	10.6%
M6	7.6%
M7	3.5%
M1-M5	12.1%

Two blockbuster tests were conducted and neither used buffer turbines.

1. Jess-C group, September 25, 1987, 09:00-19:00 PDT (10 hours).
2. Souza-C group, October 7, 1987, 13:30-24:00 PDT (10-1/2 hours).

3.3.1 Test 1 Analysis, Jess-C, September 25, 1987

Table 3-3.a is the data listing for the Blockbuster Test that took place on Jess-C on September 25, 1987. A complete description of the data format can be found on page 11. The spacing between all three test rows is about 8 D. The table shows that the mean speed at J08 was about 20 mph from the west-southwesterly. Mean speeds at the turbine anemometers were quite low, ranging from 15 mph to 18 mph. The mean speeds at the J08 anemometer for the two test periods were almost identical, indicating little possible bias.

The energy ratios between the two test periods reveal the magnitude of the energy deficits. The mean ratio of the six test turbines was 75.4%, which is equivalent to an energy deficit of 24.6%. The pattern within the row was quite clear; energy ratios were lowest at M3, 66.0%; and highest at M8, 90.3%. The terrain, which slopes gently down from the higher ground at M8 to M2, was probably a factor in this pattern. The free-flow study results showed a steady decrease in wind speeds from M8 to M2. This pattern was also seen in this test. Because of the inverse relationship between wind speed and deficits discussed in the previous sections, the lower energy sites (lower winds) experienced higher deficits. A second factor probably contributing to the loss pattern is the good exposure of M8 to the free-stream flow. Turbine M8 is on the edge of the array and has good exposure to the large channel that Interstate 580 passes through. On the other hand, turbine M3 is embedded in the array and is not exposed to this channel.

The statistical significance of the row deficit was 0.99. For turbine M3, which had the largest deficit, the significance was 0.995.

Although not shown on the table, the data were stratified by wind speed. A second set of means and ratios was calculated for the windier half of the observations. This stratified data set had a mean wind speed at J08 of 21.7 mph, about 2 mph higher than the overall mean. Deficits at all turbines decreased by about 3% and the row deficit was 22.0%, versus 24.6% for the overall data set.

Some additional analyses were performed on this test data set because the deficits were so large. Figure 3-3.a is a plot of J08 wind speed versus turbine energy. The data is from Table 3-3.a. There are two plots. The upper plot is J08 wind versus turbine M03 energy. Turbine M03 had the largest deficits. The plot shows two symbols, one for non-wake data and one for the periods in which the two upwind rows were on. The figure shows that for a given wind speed, there is a one to two kWh difference in 10-min energy production between wake and nonwake situations. The lines connecting the symbols are roughly parallel, indicating fairly uniform absolute deficits over the range of wind speeds. However, because the absolute deficit remains fairly constant in winds above 21 mph, at about 1.75 kWh, it decreases on a percentage basis.

Table 3-3.a Jess-C Blockbuster Test Analysis

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM
Ten Minute Data Report Date: 09/25/87

Time Of Day	ROWS ON UPWIND	J08 wspeed	J08 w.dir.	M03 energy	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	SUM OF M03-M08
16:10	0	16.5	245	2.3	2.6	2.8	3.2	3.5	3.5	17.9
15:10	0	17.1	255	2.3	2.4	2.5	2.7	2.8	2.8	15.5
13:10	0	17.3	260	2.6	2.4	2.5	2.7	2.7	2.7	15.6
13:20	0	17.3	252	2.3	2.3	2.4	2.7	2.8	2.9	15.4
16:20	0	17.5	248	2.7	2.6	2.7	3.1	3.5	3.5	18.1
15:20	0	17.6	253	2.3	2.6	2.8	3.3	3.5	3.3	17.8
12:20	0	18.6	252	3	3.2	3.3	3.5	3.9	4	20.9
14:20	0	18.9	246	3.5	3.6	3.5	3.8	3.8	3.9	22.1
11:20	0	18.9	250	3.3	3.5	3.9	4.1	4.1	4.3	23.2
11:10	0	19.1	248	3.3	3.4	3.7	4.1	4.4	4.4	23.3
12:10	0	19.2	245	3.2	3.5	3.3	3.6	3.7	3.4	20.7
14:10	0	19.2	260	2.9	3.3	3.6	4.2	4.4	4.5	22.9
18:20	0	19.9	245	3.9	4.2	4.1	4.5	4.9	5.3	26.9
17:20	0	20.7	253	4.4	4.4	4.5	4.6	4.5	5	27.4
18:10	0	20.7	250	4.5	4.6	4.7	5	5.2	5.6	29.6
17:10	0	21.1	262	4.7	4.7	4.7	4.8	5	5.3	29.2
10:20	0	22.7	250	5.7	6	6.1	6.6	6.8	6.8	38
10:10	0	24.1	253	5.9	6.3	6.3	7	7.3	7.2	40
09:10	0	24.3	243	6.1	6.9	6.9	6.8	6.9	7.2	40.8
09:20	0	24.8	245	6.4	6.8	6.6	7.1	7.2	7.4	41.5
Mean:		19.8	251	3.8	4.0	4.0	4.4	4.5	4.7	25.3
12:50	2	17.1	253	1.5	1.6	1.6	1.8	2	2.3	10.8
15:40	2	17.1	239	1.6	1.6	1.7	1.9	2.5	3	12.3
15:50	2	17.1	241	1.5	1.5	1.7	2.1	2.5	2.6	11.9
14:40	2	17.4	256	1.6	1.6	1.9	2.4	2.6	3	13.1
12:40	2	17.9	257	1.7	1.7	1.9	2.3	3.2	3.6	14.4
14:50	2	18.1	255	1.7	1.9	2.4	2.5	3.1	3.5	15.1
13:40	2	18.5	256	1.7	1.8	2.1	2.3	2.8	3	13.7
11:40	2	18.5	252	1.7	1.8	1.9	2.3	3.3	3.7	14.7
13:50	2	18.9	250	1.8	1.7	2	2.2	2.9	3.1	13.7
11:50	2	19.3	253	1.9	2.1	2.2	2.4	3.1	3.4	15.1
16:40	2	19.6	243	2.3	2.5	2.8	3.1	3.6	4.3	18.6
10:50	2	20.4	255	2.9	2.9	3.2	3.7	4.4	4.8	21.9
18:40	2	20.5	245	2.6	3.1	3.3	3.5	4.4	4.4	21.3
17:40	2	20.8	249	2.7	3.1	3.3	3.7	4.4	4.9	22.1
16:50	2	20.8	252	3	3	3.1	3.3	4.1	4	20.5
10:40	2	21.3	255	3.2	3.8	3.9	4.2	5.1	6.2	26.4
18:50	2	21.5	245	3.3	3.5	3.4	4	4.9	5.5	24.6
17:50	2	21.7	239	3.2	3.3	3.6	3.9	4.6	5.5	24.1
09:40	2	24.4	248	4.5	4.8	4.8	5.1	5.6	6.2	31
09:50	2	26.1	249	5.3	5.6	6	6.4	6.6	7	36.9
Mean:		19.8	249	2.5	2.6	2.8	3.2	3.8	4.2	19.1
Ratio on/off (%)		100.4		66.0	66.7	70.2	72.2	83.3	90.3	75.4
" Turbine Anemometers Speed:				N/A	94.4	N/A	94.7	N/A	99.4	
" Turbine Anemometers Power:					84.1		84.4		97.5	

page 1 of 3

Table 3-3.a Jess-C Blockbuster Test Analysis

Time Of Day	ROWS ON UPWIND	Turbine Anemometer Wind Speed Analysis M04 wspeed	M04 W/Sq. m	M06 wspeed	M06 W/sq. m	M08 wspeed	M08 W/sq. m	Ratios to J-08 50-ft M04 (%)	M06 (%)	M08 (%)
16:10	0	14.5	166.8	15.8	215.8	16.6	250.2	87.8	95.6	100.5
15:10	0	14.3	160.0	15	184.6	15.1	188.3	83.6	87.7	88.3
13:10	0	14.2	156.6	14.7	173.8	15.3	195.9	82.1	85.0	88.4
13:20	0	14.1	153.3	14.5	166.8	15.3	195.9	81.5	83.8	88.4
16:20	0	14.6	170.2	15.4	199.8	16.1	228.3	83.4	88.0	92.0
15:20	0	14.3	160.0	15.6	207.7	16.1	228.3	81.3	88.7	91.5
12:20	0	15.2	192.1	16.2	232.6	17	268.7	81.9	87.3	91.6
14:20	0	15.9	219.9	16.5	245.7	17.1	273.5	84.3	87.5	90.7
11:20	0	16.1	228.3	16.9	264.0	17.4	288.2	85.4	89.6	92.3
11:10	0	16.1	228.3	17.1	273.5	17.5	293.2	84.5	89.8	91.9
12:10	0	15.7	211.7	16.1	228.3	16	224.1	81.6	83.7	83.1
14:10	0	15.4	199.8	16.8	259.4	17.6	298.2	80.0	87.3	91.4
18:20	0	16.7	254.8	17.7	303.3	19.1	381.1	83.8	88.8	95.9
17:20	0	16.9	264.0	17.4	288.2	18.5	346.3	81.6	84.0	89.4
18:10	0	17.6	298.2	18.6	352.0	19.9	431.1	85.0	89.8	96.1
17:10	0	17.4	288.2	17.9	313.7	19.1	381.1	82.5	84.9	90.6
10:20	0	19.2	387.2	20.8	492.2	21.7	558.9	84.4	91.4	95.4
10:10	0	19.9	431.1	21.8	566.7	22.5	623.1	82.6	90.4	93.3
09:10	0	21.6	551.2	21.5	543.6	23	665.5	88.9	88.5	94.7
09:20	0	20.8	492.2	22.2	598.5	23.1	674.3	83.9	89.6	93.2
Mean:		16.5	260.7	17.4	305.5	18.2	349.7	83.5	88.1	91.9
12:50	2	13.2	125.8	13.8	143.8	14.6	170.2	77.2	80.7	85.3
15:40	2	13.1	123.0	14.1	153.3	16	224.1	76.6	82.4	93.5
15:50	2	13.4	131.6	14.3	160.0	15.6	207.7	78.3	83.6	91.2
14:40	2	13.8	143.8	15	184.6	16.1	228.3	79.3	86.2	92.5
12:40	2	13.8	143.8	15	184.6	16.7	254.8	77.2	83.9	93.4
14:50	2	14.5	166.8	15.2	192.1	16.7	254.8	80.2	84.1	92.4
13:40	2	14	150.1	14.9	180.9	16.1	228.3	75.8	80.7	87.2
11:40	2	14.1	153.3	15	184.6	16.7	254.8	76.3	81.2	90.4
13:50	2	14.1	153.3	14.7	173.8	16.4	241.3	74.8	78.0	87.0
11:50	2	14.7	173.8	15.4	199.8	16.5	245.7	76.0	79.6	85.3
16:40	2	15.4	199.8	16.4	241.3	18.1	324.4	78.4	83.5	92.2
10:50	2	16.3	236.9	17.6	298.2	18.9	369.3	79.9	86.2	92.6
18:40	2	16.7	254.8	17.1	273.5	18.4	340.8	81.4	83.4	89.7
17:40	2	16.7	254.8	17.8	308.5	19.4	399.4	80.3	85.6	93.3
16:50	2	16.2	232.6	17.1	273.5	18.2	329.8	77.9	82.2	87.5
10:40	2	17.7	303.3	18.4	340.8	20.9	499.4	83.2	86.4	98.2
18:50	2	17.2	278.3	18.4	340.8	20.8	492.2	80.1	85.7	96.8
17:50	2	17.1	273.5	18.2	329.8	19.9	431.1	78.9	84.0	91.8
09:40	2	19.4	399.4	20.1	444.2	22.8	648.3	79.5	82.4	93.5
09:50	2	20.7	485.2	21.6	551.2	23.1	674.3	79.2	82.6	88.3
Mean:		15.6	219.2	16.5	258.0	18.1	340.9	78.5	83.1	91.1
Ratio %		94.4	84.1	94.7	84.4	99.4	97.5	94.0	94.4	99.1

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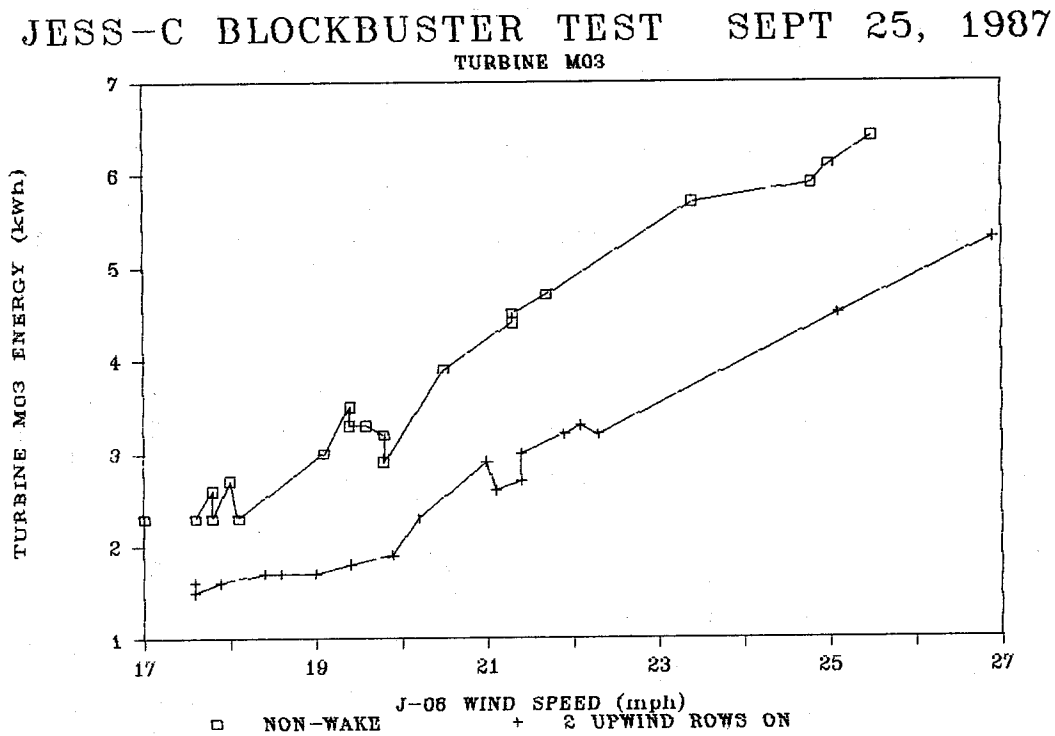
Table 3-3.a Jess-C Blockbuster Test Analysis

Row Downwind of Test Row; (16 RD Downwind)

Time Of Day	ROWS ON UPWIND	M09 energy	M10 energy	M11 energy	M12 energy	M13 energy	SUM OF M09-M13
16:10	1	2	1.9	2	2	2.7	10.6
15:10	1	2	1.7	1.7	1.7	2	9.1
13:10	1	1.9	1.7	1.8	1.7	1.8	8.9
13:20	1	1.9	1.6	1.5	1.5	2.6	9.1
16:20	1	2	1.8	1.9	2.2	2.8	10.7
15:20	1	1.8	1.8	1.9	1.9	2.2	9.6
12:20	1	2.3	2.1	2.1	2.2	2.7	11.4
14:20	1	2.8	2.6	2.6	2.5	3	13.5
11:20	1	2.6	2.7	2.7	2.6	0	10.6
11:10	1	2.6	2.5	2.8	2.8	1.9	12.6
12:10	1	2.7	2.3	2.2	2.1	2.5	11.8
14:10	1	2.7	2.4	2.7	3.1	4	14.9
18:20	1	3.4	3	3.2	3.4	3.8	16.8
17:20	1	3.4	3.2	3.3	3.1	4.5	17.5
18:10	1	3.8	3.6	3.6	3.6	4.3	18.9
17:10	1	3.6	3.6	3.4	3.5	4.9	19
10:20	1	5	4.8	5.7	5.5	6	27
10:10	1	5	5.1	5.7	5.9	6.4	28.1
09:10	1	5.6	5.7	6	5.5	6.1	28.9
09:20	1	5.7	5.7	5.8	5.7	6.1	29
Mean:		3.1	3.0	3.1	3.1	3.5	15.9
12:50	3	1.5	1.5	1.5	1.4	1.7	7.6
15:40	3	1.6	1.5	1.6	1.7	2.5	8.9
15:50	3	1.5	1.6	1.5	1.8	2.2	8.6
14:40	3	1.8	1.6	1.7	1.8	2.4	9.3
12:40	3	1.6	1.5	1.6	2	2.7	9.4
14:50	3	2.3	2.1	1.9	2.3	3.3	11.9
13:40	3	1.7	1.5	1.7	2	2.3	9.2
11:40	3	1.8	1.5	1.8	2.2	0.5	7.8
13:50	3	1.6	1.5	1.8	2.1	2.8	9.8
11:50	3	2.1	1.8	1.9	1.9	2.7	10.4
16:40	3	2.5	2.1	2.6	2.6	4	13.8
10:50	3	2.9	2.5	3.2	3.6	4	16.2
18:40	3	2.7	2.7	2.9	3.3	3.7	15.3
17:40	3	2.7	2.6	3.2	3.5	4.1	16.1
16:50	3	3.1	2.6	2.7	2.9	3.4	14.7
10:40	3	3	3.1	3.5	4.2	5.6	19.4
18:50	3	3.1	2.8	3.2	3.8	4.8	17.7
17:50	3	3.2	2.8	3.1	3.5	5	17.6
09:40	3	4.4	4.2	4.5	4.2	5	22.3
09:50	3	5.3	5.4	5.7	5.7	6.7	28.8
Mean:		2.5	2.3	2.6	2.8	3.5	13.7
Ratio on/off (%)		80.3	78.4	82.4	90.4	98.7	86.4

page 3 of 3



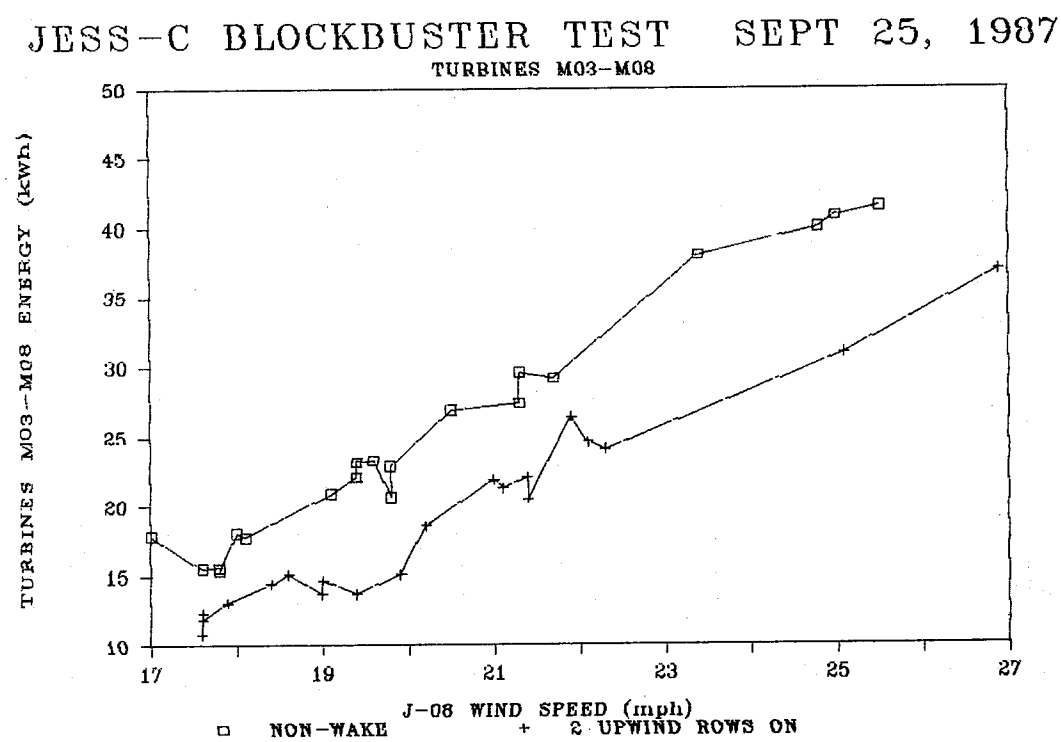


Figure 3-3.a. Jess-C Blockbuster Test Analysis

The lower half of the figure is a plot of J08 wind speed versus energy production for the entire turbine string of M03 through M08. The data is similar to the upper half of the figure except that the lines diverge slightly, indicating slight increases in the absolute deficits at higher winds. Thus the deficit is fairly constant on a percentage basis.

The second analysis is on page 2 of Table 3-3.a. This is the wind speed data from turbine anemometers M04, M06, and M08. Wind power density, in W/m^2 was calculated for each 10-min wind speed record. Speed ratios to J08 were also calculated. The upper half of the page is for nonwake periods, and the lower half is for wake periods. At the bottom of the page, ratios were calculated between the two period means as in all the other tables. The table shows that the wind speed deficits were very small compared to the energy deficits. For example, turbine M04 had an energy deficit of 33.3% and a speed deficit of only 5.6%. Power density deficits were between the speed and energy deficits. For example, the M04 power density deficit was 15.9%. The large difference between the energy deficits and the speed and power density deficits could come from two sources. First, the anemometer is at 35 ft agl and the turbine hub-height is 72 ft agl. The wake may not have spread vertically and could be worse at hub-height than at 35 ft. Second, wake turbulence from the upstream turbines could have different effects on a turbine and cup anemometer. Turbulence could have a negative effect on power output but could cause overspeeding of the cup, a positive effect.

The third analysis is the calculation of speed ratios to J08. It is interesting to compare these to the free-flow speed ratios. The free-flow ratios were 84%, 91%, and 96% at turbines M04, M06, and M08, respectively. During this test, the ratios were 84%, 88%, and 92% during the nonwake period and 79%, 83%, and 91% during the wake period.

The last analysis is on page three of Table 3-3.a. In this table, the energy production from the next row downwind was examined. Although they are not in the Jess-C array, turbines M09 through M13 were analyzed in the same fashion as M03 through M08. Bear in mind that these turbines are about 16 D and 24 D downwind of the two turbine rows that were switched on and off, and 8 D downwind of the principal test row. Therefore, this analysis studies the incremental wake effects of going from one row on-line that is 8 D upwind, to three rows on-line that are 8, 16 and 24 D upwind. The energy deficits are still quite large in this row, and the pattern within the row is the same. The northern turbine closest to Interstate 580, M13, has almost no deficit. At the other end of the string, turbine M09 has a deficit of 19.7%. The mean deficit in this row was 13.6%, which is about 55% of the deficit of the M03-M08 row. Together, these two test rows experienced a mean energy deficit of 19.1%.

Figure 3-3.b is a plot of the individual turbine wake deficits measured at the two rows on the Jess Ranch. This figure is similar to Figure 3-1.a except that the scale of the wake bar is different.

3.3.2 Test 2 Analysis, Souza-C, October 7, 1987

Table 3-3.b lists the data for the test that took place on Souza-C on October 7, 1987. The table shows that the mean speeds at the upwind anemometer were about 28 mph from the southwest. More than half the 10-min

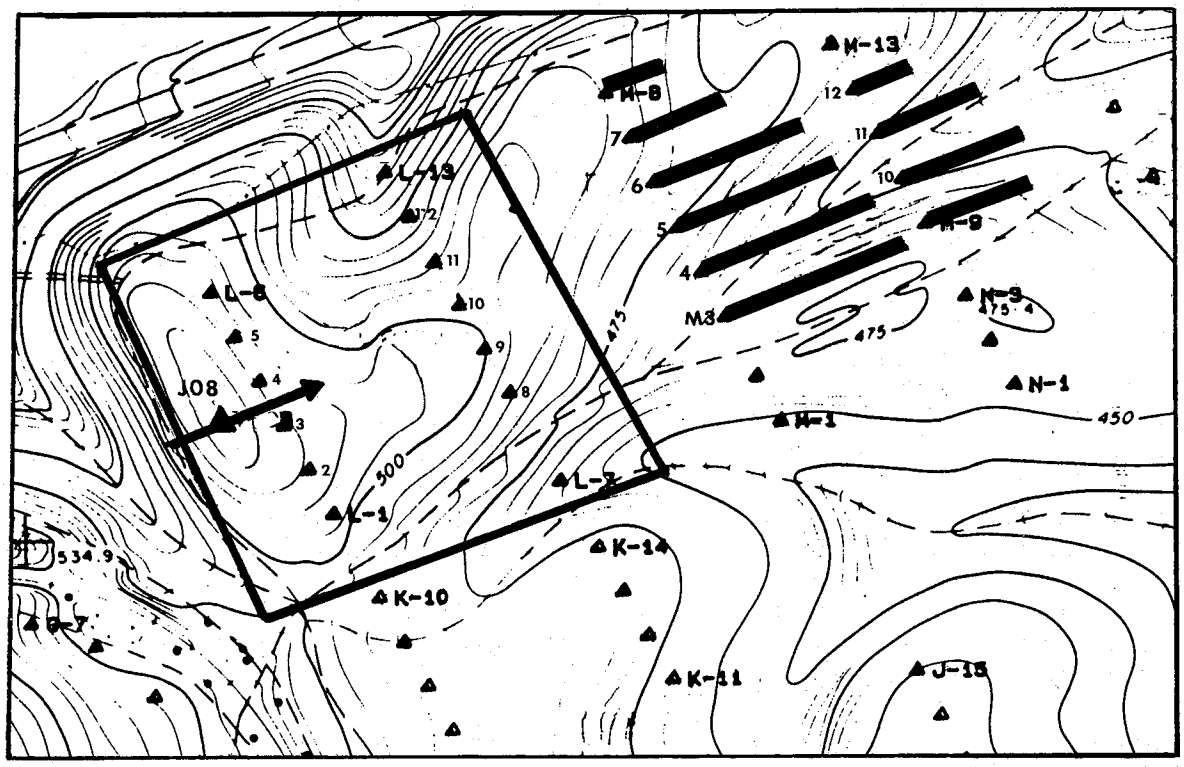


Figure 3-3.b. Jess-C Blockbuster Test Individual Turbine Deficits

Sept 25, 1987 test conditions at reference anemometer, J-08: mean speed = 19.8 mph, mean direction = 250 degrees.

KEY

▲ ▲ ▲ = turbines switched on and off
▬ = % wake energy deficit, 1" = 30%

Deficits

8+16 RD		16+24 RD (downwind of rows switched on/off)	
M3	34.0%	M9	19.7%
M4	33.3%	M10	21.6%
M5	29.8%	M11	17.6%
M6	27.8%	M12	9.6%
M7	16.7%	M13	1.3%
M8	9.7%	Mean	13.6%
Mean	24.6%		

Table 3-3.b Souza-C Blockbuster Test Analysis

FOR WINDFARM: SOUZA RANCH WINDFARM 10/07/87

Time Of Day	rows on upwind	S13 wspeed	S13 w.dir.	S27 wspeed	E10 energy	E11 energy	E12 energy	E13 energy	E14 energy	sum of E10-E14	Turbine Anemometers E10 wspeed	E12 wspeed	E14 wspeed
15:50	0	19.4	224	19.9	6	4.5	4.9	5.1	5.1	25.6	20.6	19.1	19.3
13:40	0	19.9	212	21.1	6.5	5.6	6.4	6.6	6	31.1	21.6	20.4	20.5
16:40	0	20.1	235	21.8	6.4	5.1	5.5	5.5	4.7	27.2	20.9	18.8	18.5
17:40	0	20.6	232	17.6	4.8	4.5	4.6	4.6	4.2	22.7	18.6	17.1	17.1
15:40	0	21.2	229	20.6	5.4	3.9	4.3	5	4.6	23.2	20	18.2	19.2
16:50	0	21.6	241	21.3	5.5	4.8	5	4.9	4.1	24.3	20	18.2	17.2
14:50	0	21.8	232	21.1	6.3	5	4.7	4.9	4.5	25.4	21.3	17.7	18.1
14:40	0	22.1	238	19.1	5.4	4.9	5.5	6.2	5.6	27.6	20	18.8	19.4
17:50	0	22.6	243	18.1	5.4	5.1	5.6	5.8	4.9	26.8	19.4	18.2	18.2
13:50	0	23.6	229	18.5	6.5	5.8	6.4	6.7	6.4	31.8	21.1	19.9	20.8
18:40	0	28.6	229	21.8	8.8	8.1	8.9	9.2	8.9	43.9	26.2	25.7	27.2
18:50	0	30.7	235	22.7	8.5	7.7	8.7	9	8.6	42.5	25.4	25.1	26.3
19:40	0	31.8	229	32.1	10.5	9.2	9.7	9.8	9.1	48.3	34.7	30.2	28.9
19:50	0	33.3	226	34	10.5	9.2	9.6	9.7	9.2	48.2	35	30	28.6
22:50	0	33.6	215	37.6	10.8	9.6	10.1	10.5	10.4	51.4	40.6	37.9	36.2
22:40	0	33.8	221	37.4	10.7	9.6	10	10.3	10	50.6	39.5	35.2	32.3
21:50	0	33.8	221	31.7	10.7	9.5	10	10.4	10.2	50.8	37	35.1	34
21:40	0	33.8	218	33.3	10.7	9.5	10.1	10.3	9.9	50.5	36.6	35.2	32.6
23:40	0	34.3	221	36.5	10.8	9.6	10.2	10.4	10.2	51.2	39.4	36.7	34.8
20:40	0	34.9	224	35.7	10.5	9.3	9.8	10.1	9.9	49.6	35.7	31.1	31.9
23:50	0	34.9	229	37.2	10.8	9.6	10.2	10.4	10.2	51.2	39.2	36.9	34.6
20:50	0	35.2	229	35.3	10.6	9.4	9.8	9.9	9.6	49.3	37.7	32.4	30.4
Mean:		27.8	228	27.0	8.3	7.3	7.7	8.0	7.6	38.8	28.7	26.3	25.7
17:20	2	18.8	238	17.3	3.6	2.9	2.9	3.3	3	15.7	16.6	15	15.4
16:10	2	17.6	229	19	5.3	3.6	3.7	3.5	2.9	19	19.4	16.9	16.4
17:10	2	20.2	243	19.1	5	4.5	4.7	4.8	4.4	23.4	19.1	18.1	17.9
14:10	2	22.4	232	19.2	5.4	4.5	4.8	5	4.4	24.1	20.3	18.7	18.2
16:20	2	18.9	241	19.7	5.8	4.3	4.4	4.6	4	23.1	20.4	18.4	18
15:10	2	23.4	238	20.2	6.4	5.8	5.9	6.2	5.9	30.2	22.1	21	20.7
18:20	2	24.8	235	20.4	6.9	5.8	6.4	6.9	6.5	32.5	22.7	22.2	22
14:20	2	20.5	221	20.8	6.2	5.1	5.4	5	4.7	26.4	21.1	19.6	19.1
15:20	2	23	235	20.8	5.4	4.6	4.8	5	4.9	24.7	20.3	18.9	18.7
18:10	2	24	229	21.9	6.2	5.1	5.7	6.1	5.8	28.9	21.3	20.8	20.7
19:10	2	34	229	27.7	7.8	6.6	7.7	8	8	38.1	24.3	24.2	25.7
19:20	2	33	238	29.1	8.7	7	7.2	7.5	7.8	38.2	26.6	23.8	25.3
20:10	2	32.5	229	34	10.7	9.3	9.6	9.6	9.3	48.5	37.2	30.7	29.5
22:10	2	34.4	229	35.1	10.6	9.3	9.9	9.9	9.6	49.3	36.7	33.2	30.7
00:20	2	31.1	224	35.2	10.6	9.1	9.5	9.5	9.4	48.1	35.4	30.6	30.1
22:20	2	34.2	229	35.5	10.7	9.3	9.6	9.6	9.5	48.7	37.5	31.9	30.9
20:20	2	34.3	226	35.6	10.5	9.1	9.7	9.8	9.3	48.4	35.6	31.7	29.9
00:10	2	31.3	229	35.7	10.7	9.5	9.8	9.8	9.4	49.2	38.2	32.6	30.3
23:20	2	34.9	218	35.7	10.8	9.6	10.3	10.5	10.3	51.5	39.6	36.4	34.7
21:10	2	35.2	229	36.7	10.6	9.3	9.8	9.9	9.6	49.2	36.3	32.2	30.8
21:20	2	35.8	229	36.7	10.6	9.2	9.6	9.8	9.4	48.6	35.7	30.9	30.5
23:10	2	36.1	221	37.2	10.8	9.5	10.1	10.4	10.2	51	38.9	34.5	34.4
Mean:		28.2	230	27.8	8.2	7.0	7.3	7.5	7.2	37.1	28.4	25.6	25.0
Norm.S13 Mean:		27.8	231	27.4	8.0	6.8	7.2	7.3	7.1	36.5	27.9	25.1	24.5
Ratio on/off(%)		101.4		103.1	98.5	95.9	95.0	94.0	95.2	95.7	99.2	97.3	97.1
Norm. ratio:		100.1		101.4	96.9	94.3	93.3	92.2	93.3	94.0	97.4	95.7	95.4
Norm. speed ratio (%)					97.4	N/A	95.7	N/A	95.4				

records had wind speeds above 30 mph. Recall that the Nordtank power curve becomes less steep at this speed and that smaller deficits are expected in these high speeds. The 16 D data analysis also suggested that in winds above 31 mph, negligible deficits could be expected from the more distant row. This mean speed is considerably higher than the test conducted on Jess and discussed previously. It should be noted that turbine F4 in the first row of turbines, and one of the 12 to be switched on and off, was not operational during this test.

Because the mean speeds for the two test periods at the upwind reference anemometer had a half-mph difference, a second set of means was calculated to eliminate this possible source of bias. The second set of ratios between periods uses these means (see line "Norm. ratio:"). The energy deficits were much smaller during this test than during the test conducted on Jess. The mean energy ratio of the five test turbines was 94.0%, which is equivalent to a 6.0% energy deficit. The pattern within the row was the same as it was during the Direct Wake Tests with the smallest deficits at E10 and increasing to E13 and E14. Wind speed data from turbines E10, E12, and E14 showed speed deficits of 2.6% to 4.6%. These speed deficits are consistent with the 6.0% energy deficit as one can square the speed deficit for a crude approximation of the energy deficit.

Statistical significance of the mean row deficit was only 0.70. This is not a very high confidence level. At turbine E13, which had the greatest deficit, the significance level was 0.80.

The likely explanation for these relatively low energy deficits is the higher winds. Recall that on the Jess Ranch test, the mean wind speed was ~20 mph at J08 and 15 to 18 mph at the turbine anemometers, versus ~28 mph during this test on Souza. Although not shown on Table 3-3.b, the data were divided into subsets, and a low wind speed subset was calculated based on the records with wind speeds below 30 mph. The mean speeds for the two test subperiods were about 23 mph at S13 and 22 mph at the turbine anemometers. The mean energy ratio for the five test turbines was 88.0%, which is equivalent to an energy deficit of 12.0%. This is exactly twice as high as the 6.0% deficit measured in the higher wind speeds. Recall that in the 16 D tests, it appeared that the wake energy deficits were more sensitive to changes in speed than in the 8 D tests, and that negligible deficits were expected above 31 mph. The Blockbuster Test employs both the 8 D and 16 D rows simultaneously. Thus the deficits may also have a higher sensitivity to wind speed than the direct wake tests.

3.3.3 Summary

Two Blockbuster Tests were conducted: one at Jess-C and one at Souza-C. The wake deficits measured during the two tests were quite different. In the first test, mean speeds were quite low -- about 20 mph at J08 and 15 mph to 18 mph at the test turbines. The energy deficits were enormous -- about 25% for the row average. The maximum individual deficit was 34%. In the second test, wind speeds were much higher, about 28 mph at S13 and 25 mph to 28 mph at the turbine anemometers. The energy deficits were much lower than the first test -- 6% for the row average. The maximum individual deficit was about 8%. The large difference in mean speeds, approximately 10 mph, is believed to be the principal reason for the large difference in the deficits

-- 25% versus 6%. The inverse relationship between speed and energy deficits, seen in the direct wake and sixteen-diameter tests, was evident here as well. This inverse relationship was also responsible for the variation in individual turbine deficits within the test rows. Turbines at lower elevation sites, with lower energy output (lower winds) experienced higher energy deficits. No attempt has been made to try to normalize these terrain effects on wake deficits.

3.4 Multiple Row Wake Effect Test

The Multiple Row Wake Effect Test was designed to measure the incremental effects of several rows of turbines. Energy production in the downwind row is compared for periods when 0, 1, 2, or 3 upwind rows are on line. In addition to the analysis of the downwind row, the data from the middle row(s) are analyzed as well. In a three row test group, data collected in the middle row are analyzed exactly the same as in the Direct Wake Test. In the middle row analysis, the data collected while it is on line are sorted into two time groups, when the front row was on line or off. Additional discussion on test methodology can be found in Section 2.4. Three Multiple Row Wake Tests were conducted on:

1. Jess-C (3 rows), September 4, 1987, 13:30-21:10 PDT (8 h)
2. Jess-A (4 rows), September 10, 1987, 13:50-24:00 PDT (10 h)
3. Souza-C (3 rows), October 9, 1987, 10:30-23:10 PDT (12 h)

Buffer turbines were used in the first two tests but not in the third.

3.4.1 Test 1 Analysis, Jess-C, September 4, 1987

Tables 3-4.a and 3-4.b are the data listings for the back and middle rows for the September 4 test on Jess-C. A complete description of the data format can be found on page 11. Table 3-4.a shows that the mean wind speed at the upwind reference tower was about 30 mph from the west-southwest. The Nordtank power curve begins to flatten out at this speed. Mean speeds at the turbine anemometers ranged from 24 mph to 28 mph. The three period means show that there was about a 1% difference in mean speeds between the periods, which introduces a slight bias. To reduce this bias, a second set of means was calculated for the third data period: two upwind rows on. The table shows that the mean speed for this "normalized" period was 29.7 mph, which is the same as the first period. Thus, the bias is reduced.

At the bottom of Table 3-4.a there are several sets of energy and speed ratios, one showing the effects of one row, and the other two showing the effects of two rows. One set of ratios uses all the data, and the last set of ratios uses the "normalized" data set. The mean ratio, which excludes M8, shows a 5.4% drop in energy for the period when one row was turned on and only an additional 1.7% decrease during the period when the second row was turned on ("normalized" data set). However, inspection of the individual turbines reveals that a pattern seen earlier was present. Turbine M8, at the northern edge of the array, had little or no deficits in either period. At the other end of the row, at turbines M4 and M5, there were 5% to 7% deficits when the first row was on and an additional 2% to 4% deficit when the second upwind row was turned on. Some of the probable reasons for this pattern (i.e., terrain

Table 3-4.a Jess-C Multiple row wake test analysis

FOR WINDFARM: JESS RANCH WINDFARM

Ten Minute Data Report Date: 09/04/87

Time Of Day	ROWS ON UPWIND	J08 wspeed	J08 w.dir.	M04 energy	M05 energy	M06 energy	M07 energy	M08 energy	SUM OF M04-M07	Anemometer data: M04 wspeed	M06 wspeed	M08 wspeed
13:40	0	23.3	250	5.9	6	6.4	6.5	6.5	24.8	19.4	20.4	21.1
15:00	0	25.9	241	6.7	7.3	7.8	8	8.2	29.8	20.8	23.5	24.9
15:10	0	27.9	242	7.8	7.9	8.2	8.1	8.3	32	22.8	24.2	25.5
16:40	0	29.7	224	8.1	8.6	9	8.9	9	34.6	24.2	26.3	27.8
16:30	0	31.4	241	8.6	9.2	9.5	9.5	9.7	36.8	26	27.9	29.8
18:00	0	31.4	249	8.7	9.3	9.7	9.9	10.3	37.6	26.4	29.4	31.7
18:10	0	31.5	238	8.8	9.3	9.6	9.6	9.6	37.3	26.5	28.8	29.7
19:40	0	32.4	253	9	9.4	9.8	9.7	10.1	37.9	26.4	28.4	31.1
19:30	0	33.5	253	9.1	9.5	9.6	9.3	9.8	37.5	27.1	28.2	29.8
Mean:		29.7	243	8.1	8.5	8.8	8.8	9.1	34.3	24.4	26.3	27.9
Low speed:		26.7	239	7.1	7.5	7.9	7.9	8.0	30.3	21.8	23.6	24.8
14:10	1	23.2	235	5.6	5.7	6	6.5	7	23.8	20	21.3	22.3
14:00	1	24.1	243	5.4	5.4	6	6.6	7.1	23.4	19.7	20.7	22.4
15:40	1	27.7	243	7.1	7.2	7.5	7.9	8.3	29.7	22.9	23.7	25.4
15:30	1	27.8	232	6.9	7	7.4	7.7	8	29	22.4	23.9	24.8
20:20	1	29.9	250	8.6	8.9	9	9.3	9.7	35.8	26.5	26.8	29.1
17:00	1	31.8	236	8.5	8.9	9.1	9.2	9.7	35.7	26.8	28.5	29.7
17:10	1	31.9	238	8.4	8.6	8.8	8.9	9.2	34.7	26.8	27.6	27.7
20:30	1	32	250	8.9	9.4	9.9	10	10.5	38.2	27.9	30.6	32.9
18:40	1	32.9	253	8.6	8.8	9.2	9.5	10.2	36.1	26.7	29.3	31.6
18:30	1	33.2	245	8.8	9.3	9.8	9.7	10.1	37.6	27.5	31.2	31.1
Mean:		29.5	243	7.7	7.9	8.3	8.5	9.0	32.4	24.7	26.4	27.7
Low speed:		26.5	241	6.7	6.8	7.2	7.6	8.0	28.3	22.3	23.3	24.8
14:30	2	25	236	5.8	6.2	6.7	6.8	7.4	25.5	20.7	22.2	23.2
14:40	2	25.4	235	5.8	6	6.7	7.3	7.7	25.8	20.4	22.4	24
16:00	2	29.1	228	7.4	7.5	7.9	8.2	8.9	31	24.2	25.7	27.1
16:10	2	29.6	239	7	7.4	8.3	8.6	9	31.3	23.2	26.2	27.2
21:00	2	30.1	248	8.1	8.6	9.5	9.7	10.4	35.9	25.3	29.3	32.8
17:40	2	31.8	236	7.8	8.2	8.8	9.1	9.8	33.9	25	27.6	30.1
17:30	2	32	229	7.6	7.8	8.5	9	9.4	32.9	24.7	26.8	28.5
19:10	2	32.1	246	7.9	8	8.1	8.5	9.5	32.5	25.7	25.4	28.6
20:50	2	32.4	257	8.9	9.2	9.6	9.8	10.4	37.5	27.9	29.7	32.2
19:00	2	32.9	243	8.3	8.3	8.7	9	9.7	34.3	26.3	26.8	29.4
Mean:		30.0	240	7.5	7.7	8.3	8.6	9.2	32.1	24.3	26.2	28.3
Norm. mean:		29.7	239	7.4	7.7	8.2	8.6	9.2	31.8	24.1	26.1	28.2
Low speed:		26.5	233	6.3	6.6	7.1	7.4	8.0	27.4	21.8	23.4	24.8

All speeds:		Energy Ratios (%):						Speed ratios(%):		
1 row on/0 on	99.3	95.1	93.2	93.5	96.6	99.2	94.6	101.3	100.1	99.2
2 rows/0 rows	101.3	92.4	90.8	93.6	97.4	101.8	93.6	99.8	99.5	101.3
Norm. 2/0 on	100.2	91.2	90.1	93.1	96.9	101.2	92.9	98.9	99.2	100.9
Low speeds only:										
1 row on/0 on	99.4	94.3	91.8	91.5	96.5	100.3	93.5	102.3	98.6	99.9
2 rows on/0 on	99.3	88.9	88.1	90.4	94.4	100.0	90.5	99.8	99.3	99.8
2 rows on/1 on	99.8	94.2	96.0	98.9	97.8	99.8	96.8	97.6	100.7	99.9

Table 3-4.b Jess-C Middle Row Analysis, Multiple Row Test

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM
Ten Minute Data Report Date: 09/04/87

Time Of Day	ROWS ON UPWIND	J08 wspeed	J08 w.dir.	L08 energy	L09 energy	L10 energy	L11 energy	sum of L08-L11	L08 wspeed	L10 wspeed	L12* wspeed
14:10	0	23.2	235	6.3	6.9	7.5	7.3	28	20.5	21.6	22.7
14:00	0	24.1	243	6.5	7.1	7.4	7.1	28.1	20.6	21.8	22.6
15:40	0	27.7	243	7.9	8.6	9.1	8.8	34.4	24.1	24.8	25.8
15:30	0	27.8	232	8	e 8.7	9.1	8.7	34.5	24.2	24.9	25.2
20:20	0	29.9	250	8.9	9.7	10.7	10	39.3	26.8	28.4	29
17:00	0	31.8	236	9.1	e 9.9	10.9	10.3	40.2	27.3	29.9	30.6
17:10	0	31.9	238	9	9.9	10.6	10.2	39.7	27	29.4	29.1
20:30	0	32	250	9.4	10.3	11.2	10.8	41.7	27.9	30.4	32.6
18:40	0	32.9	253	9.7	10.1	10.6	10.3	40.7	29	28.9	31.6
18:30	0	33.2	245	9.6	e 10.4	11.2	11	42.2	28.5	31	33.1
Mean:		29.5	243	8.4	9.2	9.8	9.5	36.9	25.6	27.1	28.2
Norm. Mean		30.1	243	8.7	9.4	10.1	9.7	37.9	26.2	27.7	28.8
14:30	1	25	236	6.3	6.7	7.5	7.7	28.2	21.6	23.1	23.9
14:40	1	25.4	235	6.3	6.9	7.6	7.9	28.7	21.9	23.2	24.2
16:00	1	29.1	228	7.7	8.6	9.4	9.2	34.9	24.4	27.1	27.5
16:10	1	29.6	239	7.8	8.3	8.9	9.3	34.3	24.7	25.8	28.2
21:00	1	30.1	248	8.9	9.2	10	10.1	38.2	27.4	28.1	31.6
17:40	1	31.8	236	8.6	9.2	10	9.9	37.7	27	28.8	29.7
17:30	1	32	229	8.2	9	9.7	9.7	36.6	26.3	27.6	29.9
19:10	1	32.1	246	8.3	9.1	9.4	8.9	35.7	27.4	26.7	28.4
20:50	1	32.4	257	9.2	10	10.8	10.2	40.2	28.8	30.1	31.6
19:00	1	32.9	243	8.8	9.6	10	9.4	37.8	28.1	27.7	29.5
Mean:		30.0	240	8.0	8.7	9.3	9.2	35.2	25.8	26.8	28.5
Ratios (%):											
all data:		102.0		94.9	94.5	94.9	97.7	95.5	100.7	98.9	100.8
Normalized		99.7		92.3	92.0	92.5	95.3	93.0	98.5	96.7	98.6
" speed ratio:				98.5	N/A	96.7	N/A				

* Note: L12 speeds valid, although turbine not operational
e = estimate, L9 off-line for portion of 10-minute period

effects and wake trajectory) have been discussed in previous sections. In addition, there may have been problems with turbine L12 (see last paragraph on this page), which is upwind of M8.

Analysis of the turbine anemometer data shows negligible speed deficits at all three turbines.

Statistical significance levels for this test were 0.80 for one row on versus none on, and 0.75 for two rows on versus none. Turbine M5, with the highest energy deficit, had higher significance levels for the two rows on versus none: 0.90.

Some additional analysis was done to examine the wake deficits at lower wind speeds. Recall that the 16 D test data in Section 3.2 suggested that the wake deficit from the more distant (16 D) row was more sensitive to changes in speed than the closer (8 D) row. The analysis also showed that negligible deficits were expected above 31 mph from the distant row. Therefore only samples with mean speeds below 30 mph at J08 were used. The mean speed at J08 for these lower speed subsets was about 26 mph. Ratios were calculated for the three low speed data sets, and the results are different from those discussed in the paragraph above. With one upwind row on, the mean ratio at turbines M4 through M7 was 93.5%, which is equivalent to a deficit of 6.5%. When the second upwind row was switched on, the mean energy ratio was 90.5%, which is equivalent to an energy deficit of 9.5%. Thus the incremental energy deficit for the second upwind row is 3%, which is almost a 50% incremental increase above the single row deficit. This is a much larger incremental increase than is seen in the entire data set with the higher wind speeds. A third line of low speed ratios ("2 on/1 on") displays these incremental energy ratios. The pattern within the row is consistent with other test results. The largest deficits were at M4, and the lowest deficits were at M8. The results of this lower wind speed analysis are in agreement with the 16 D test data. Specifically, the analysis shows that the incremental wake deficit from the more distant (16 D) row is much more pronounced in winds below 30 mph.

The individual turbine deficits are plotted in Figure 3-4.a. The deficits are plotted parallel to the wind direction at each turbine. The deficits from the first row are plotted as solid black bars. The deficits from the second row are plotted as open rectangles extending from the bars. There are two separate maps. The upper map shows the deficits for the entire data set. The lower map shows the deficits for the lower speed subset, which used the samples with wind speeds below 30 mph. The figure shows the increase in deficits in the lower speed subset, and shows that the increase is more substantial in the two-row deficit. The figure shows that turbine M5, which had the largest deficits, is downwind of the center of the two upwind rows.

Table 3-4.b is the analysis of the middle row and is the same as a direct wake test analysis. The data from turbine L12 were rejected from the data set because the energy values looked very low, around 1 kWh per 10-min period. It is not clear if turbine production was actually that low or if there was a problem with communication. In addition, there were three data periods when turbine L9 faulted and was manually restarted 2 to 4 min into the data period. The data for these three periods were adjusted based on the energy ratio to turbine L8. The energy ratio to L8 was calculated using the other valid data samples in the same test scenario.

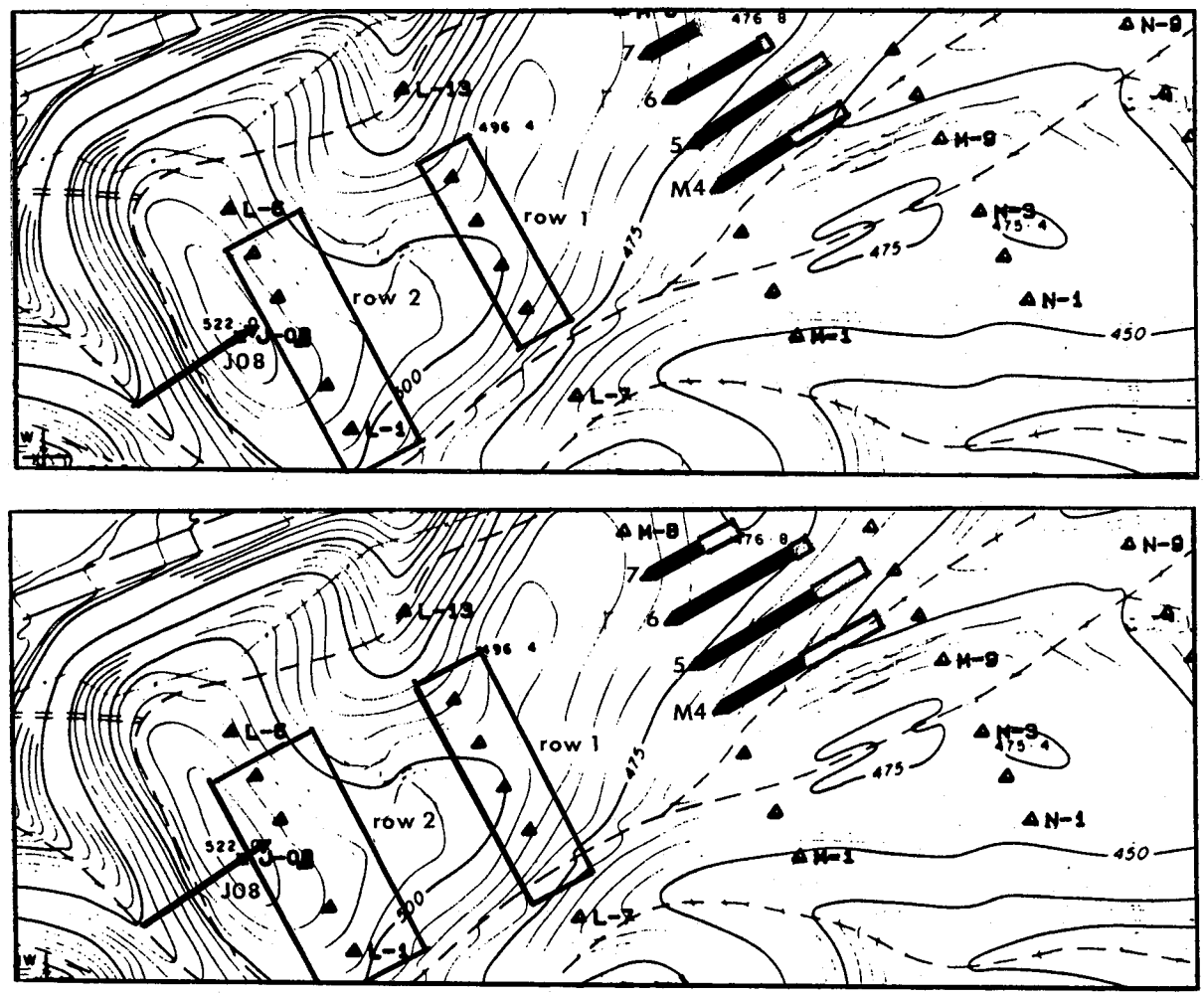


Figure 3-4.a. Jess-C Multiple Row Wake Test Individual Turbine Deficits

Sep 4, 1987 test conditions at reference anemometer;
J-08: mean speed = 29.7 mph, mean direction = 237 degrees,
J-08: mean speed = 26.5 mph, (low speed dataset)

KEY

= turbine rows switched on and off
= % wake energy deficit, 1 row on, 1" = 10%
= % wake energy deficit, 2 rows on, 1" = 10%

Deficits (all speeds) Upper Picture			Deficits (low speeds) Lower Picture	
Turbine	1 row on	2 rows on	1 row on	2 rows on
M4	4.9%	8.8%	5.7%	11.1%
M5	6.8%	9.9%	8.2%	11.9%
M6	6.5%	6.9%	8.5%	9.6%
M7	3.4%	3.1%	3.5%	5.6%
Mean	5.4%	7.1%	6.5%	9.5%

Table 3-4.b shows that there was a 1/2 mph difference between periods. A second set of means was calculated for the first period to reduce the wind speed bias. The second mean is on the line entitled "Norm. mean" and has a mean speed within 0.1 mph of the other test period. There are two sets of ratios at the bottom of the table, one using all available data and the other entitled "normalized," which uses the second set of means. The "normalized" energy ratio between the two periods was 93.0%, which is equivalent to a 7.0% energy deficit. The deficit was fairly uniform at turbines L8 through L10, about 7.5%, and a bit lower at L11, about 5%. Statistical significance for the row mean and for L9 were 0.90.

Speed deficits at the two test turbines were only 1.5% and 3.3%. The speed and energy deficits were consistent at turbine L10 (3.3% and 7.5%, respectively). One would expect the energy deficit to be close to the square of the speed deficit, based on the slope of the Nordtank power curve. At turbine L8 the energy deficit was considerably larger than the speed deficit (7.7% versus 1.5%). There is no apparent reason for this inconsistency, but it could be related to vertical shear or terrain.

3.4.2 Test 2 Analysis, Jess-A, September 10, 1987

The Multiple Row Wake Test that took place on September 10 at the Jess-A array was the most elaborate test undertaken during this study. This test involved four rows of turbines, so the analysis is done on three separate rows. Tables 3-4.c, 3-4.d, and 3-4.e list the 10-min data for this test.

Table 3-4.c is the analysis for the back (downwind) row of the group. The table shows that the winds at the J08 anemometer were about 29 mph from the west-southwest. Wind speeds at turbine K3, not shown on the table, were about 7 mph lower than at J08 throughout the test. There are four periods to compare in this analysis: no upwind rows on versus 1 row on, 2 rows on, and 3 rows on. The table shows that the mean speed at J08 for the no-rows-on period was 27.2 mph versus 28.5 to 29.1 mph for the other three periods. To reduce this bias, the 14:20 observation in the first period was eliminated, and the mean speed for this normalized data set was 28.7 mph. At the bottom of the table, three sets of ratios are calculated for the entire data set and for the "normalized" data set described above. The analysis will focus on the latter because the wind speed bias is much lower.

The ratios between periods show some curious results. The energy ratio for the period when the first row of upwind turbines was switched on was 83.3% for the four-turbine mean. This is equivalent to a 16.7% energy deficit. The deficit was worse at the southern end of the row, at K11, than at K14. The ratio at K11 was 74.2% and the ratios increased steadily to 90.7% at K14. The probable explanation for the lower deficit at K14, based on the wind direction data from J08, is that K14 was not in the wake trajectory.

As successive rows of upwind turbines were switched on line, the ratios increased instead of decreasing. This increase occurred at all four turbines and in both periods. The mean ratio for the four turbines, which was 83.3% with one row on, increased to 86.7% with two upwind rows on and 94.3% with three rows on. These ratios are equivalent to energy deficits of 16.7% for one row, 13.3% for two rows, and 5.7% for three upwind rows on. There was no change in mean wind direction at J08 to help explain these energy increases.

Table 3-4.c Jess-A Multiple Row Wake Test

FOR WINDFARM: JESS RANCH WINDFARM

Ten Minute Data Report 09/10/87

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	K11 energy	K12 energy	K13 energy	K14 energy	sum of K11-K14
14:20	0	22.3	250	4.5	4.8	4.8	4.3	18.4
14:10	0	22.7	243	4.8	5.6	5.6	5	21
16:20	0	22.9	248	3.6	4.3	4.9	4.3	17.1
16:10	0	22.9	259	4.9	5.4	5	4.4	19.7
12:10	0	25.1	245	5.8	6.9	6.6	6.1	25.4
12:00	0	26.3	248	5.7	6.8	7	6.8	26.3
18:10	0	27.6	249	7.4	8.2	8	7.2	30.8
18:20	0	28.7	252	7.6	8	7.8	7.7	31.1
20:10	0	30.0	249	9.5	9.5	8.6	8.6	36.2
20:20	0	30.8	252	8.8	9.6	9.6	9.3	37.3
22:20	0	33.4	253	9.6	9.9	10	9.8	39.3
22:10	0	33.6	248	10.1	9.3	9.5	9.4	38.3
	mean:	27.2	249	6.9	7.4	7.3	6.9	28.4
last 9	obs.	28.7	250	7.7	8.2	8.0	7.7	31.6
14:40	1	21.8	259	4.2	5.1	5.6	5.3	20.2
14:50	1	23.1	255	3.2	4.5	4.7	4.4	16.8
16:50	1	24.4	252	3.5	4.2	4.4	4.2	16.3
16:40	1	25.1	252	2.9	3.9	4.3	4	15.1
12:40	1	26.0	245	4.9	6	6.9	6.8	24.6
12:30	1	28.1	238	4.8	6.3	6.7	6.1	23.9
18:40	1	28.8	250	6.4	8.1	8.6	8.7	31.8
18:50	1	29.1	248	6.6	7.4	7.8	7.7	29.5
22:40	1	33.2	252	8.4	8.9	9.4	9.3	36
20:50	1	35.9	249	8.6	7.4	8	8.7	32.7
22:50	1	36.2	246	8.7	9.1	9.4	9.3	36.5
20:40	1	37.2	239	6.5	7.8	8.8	9.3	32.4
	mean:	29.1	249	5.7	6.6	7.1	7.0	26.3
15:20	2	23.7	262	4.3	5.5	5.4	5.1	20.3
15:10	2	24.4	255	4	5	4.9	4.5	18.4
17:10	2	25.7	256	3.4	4.5	5.3	5.1	18.3
13:10	2	26.4	243	4.4	5.4	5.7	5.3	20.8
13:00	2	27.0	250	4.5	6.2	7.1	6.5	24.3
17:20	2	27.1	252	5	6.8	7.3	6.7	25.8
19:10	2	28.4	246	5.9	8.1	8.4	8.3	30.7
19:20	2	29.7	246	7	8.4	8.9	8.7	33
23:20	2	31.2	252	10.5	9.6	8.8	8.5	37.4
21:20	2	32.9	248	8.1	9.1	9.5	9.4	36.1
23:10	2	33.6	245	7.9	7.7	7.9	8.1	31.6
21:10	2	34.2	249	7.5	7.9	8.4	8.4	32.2
	mean:	28.7	250	6.0	7.0	7.3	7.1	27.4

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Table 3-4.c Jess-A Multiple Row Wake Test

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	K11 energy	K12 energy	K13 energy	K14 energy	sum of K11-K14
13:50	3	24.0	259	4.3	5.6	5.9	5.6	21.4
15:50	3	24.0	260	4.9	5.9	5.8	5.4	22
17:40	3	24.3	246	4.8	6.1	6.4	6	23.3
15:40	3	24.5	252	5	5.8	5.8	5.1	21.7
13:40	3	24.7	259	3.5	4.4	4.7	4.4	17
17:50	3	26.3	253	5.2	7	7.5	7.2	26.9
19:40	3	29.5	245	7.7	8.1	8.6	8.9	33.3
19:50	3	30.9	242	8	8.5	8.2	8.3	33
23:50	3	31.0	245	11	10.7	10.3	9.4	41.4
23:40	3	31.6	243	10.7	10.5	9.8	9.6	40.6
21:50	3	35.1	249	8.6	10	10.1	9.6	38.3
21:40	3	36.1	252	8.6	10.1	10.1	9.8	38.6
	mean:	28.5	250	6.9	7.7	7.8	7.4	29.8

Scenario:	Ratios for entire dataset:					
1 row on/0 on(%)	106.8	83.5	89.1	96.8	101.1	92.6
2 rows on/0 on(%)	105.5	88.1	95.4	100.2	102.1	96.5
3 row on/0 on(%)	104.7	100.0	105.0	106.6	107.7	104.9

Scenario:	Ratios to period normalized for wind speed:					
1 row on/0 on(%)	101.2	74.2	80.2	88.0	90.7	83.3
2 rows on/0 on%	99.9	78.4	85.8	91.1	91.6	86.7
3 rows on/ 0 on%	99.2	88.9	94.5	96.9	96.6	94.3

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Table 3-4.d Jess-A Multiple Row Wake Test, Second Row Analysis

FOR WINDFARM: JESS RANCH WINDFARM

Ten Minute Data Report 09/10/87

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	K03 energy	K04 energy	K05 energy	K06 energy	K07 energy	sum of K03-K07
14:40	0	21.8	259	4.6	4.3	4.6	4.6	4.3	22.4
14:50	0	23.1	255	3.3	2.8	3.2	3.6	3.8	16.7
16:50	0	24.4	252	4.8	4.3	4.2	4.3	4.0	21.6
16:40	0	25.1	252	3.3	2.8	3.1	3.2	4.0	16.4
12:40	0	26.0	245	5.4	5.4	5.5	5.2	5.4	26.9
12:30	0	28.1	238	4.9	4.8	5.5	3.8	3.9	22.9
18:40	0	28.8	250	7.5	7.3	7.0	6.5	6.8	35.1
18:50	0	29.1	248	7.6	7.5	7.5	6.5	6.2	35.3
22:40	0	33.2	252	9.4	9.0	9.2	8.5	7.7	43.8
20:50	0	35.9	249	10.5	9.7	9.2	8.4	6.7	44.5
22:50	0	36.2	246	9.9	9.1	9.3	8.8	7.7	44.8
20:40	0	37.2	239	9.8	8.2	7.7	7.1	6.6	39.4
	mean:	29.1	249	6.8	6.3	6.3	5.9	5.6	30.8
15:20	1	23.7	262	2.6	3.2	4.6	5.2	5.0	20.6
15:10	1	24.4	255	3.8	3.7	4.5	4.5	4.5	21.0
17:10	1	25.7	256	4.4	3.9	3.5	3.7	4.3	19.8
13:10	1	26.4	243	3.2	3.9	4.9	5.1	5.0	22.1
13:00	1	27.0	250	4.6	4.4	5.4	5.5	5.7	25.6
17:20	1	27.1	252	3.5	3.3	3.6	5.3	6.1	21.8
19:10	1	28.4	246	7.3	7.3	6.1	5.9	6.8	33.4
19:20	1	29.7	246	7.6	7.5	7.2	6.9	7.1	36.3
23:20	1	31.2	252	10.4	9.9	9.9	9.8	9.4	49.4
21:20	1	32.9	248	8.4	8.8	8.7	8.0	7.7	41.6
23:10	1	33.6	245	10.3	9.5	9.2	8.2	7.8	45.0
21:10	1	34.2	249	10.3	9.2	8.5	7.6	7.6	43.2
	mean:	28.7	250	6.4	6.2	6.3	6.3	6.4	31.7
13:50	2	24.0	259	3.6	4.0	5.1	5.0	4.5	22.2
15:50	2	24.0	260	3.3	4.0	5.4	5.4	5.0	23.1
17:40	2	24.3	246	5.5	5.3	5.1	5.4	5.4	26.7
15:40	2	24.5	252	3.3	3.8	5.1	5.8	5.3	23.3
13:40	2	24.7	259	3.1	3.8	4.3	4.4	3.9	19.5
17:50	2	26.3	253	5.7	5.6	5.8	5.5	5.9	28.5
19:40	2	29.5	245	7.5	7.8	8.0	7.8	7.0	38.1
19:50	2	30.9	242	8.3	8.0	7.9	8.0	7.9	40.1
23:50	2	31.0	245	10.3	9.9	10.1	9.9	10.1	50.3
23:40	2	31.6	243	10.1	9.7	9.9	9.7	9.7	49.1
21:50	2	35.1	249	9.0	8.7	7.9	7.9	8.8	42.3
21:40	2	36.1	252	8.5	8.6	7.9	7.8	8.7	41.5
	mean:	28.5	250	6.5	6.6	6.9	6.9	6.9	33.7
	ratios:								
1 row on/0 rows		98.7		94.3	99.2	100.1	107.4	114.8	102.7
2 rows/ 0 rows %		98.0		96.5	105.3	108.6	117.2	122.5	109.4

Table 3-4.e Jess-A Multiple Row Wake Test Analysis (Row 3)

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM

Ten Minute Data Report 09/10/87

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	F09 energy	F10 energy	G01 energy	G03 energy	sum of F09-F10
15:20	0	23.7	262	2.9	2.8	2.5	3.4	5.7
15:10	0	24.4	255	4.3	3.7	3.1	3.6	8.0
17:10	0	25.7	256	4.8	4.5	4.0	2.8	9.3
13:10	0	26.4	243	4.7	3.5	2.9	4.5	8.2
13:00	0	27.0	250	4.4	4.1	4.3	4.6	8.5
17:20	0	27.1	252	3.4	3.4	3.0	3.0	6.8
19:10	0	28.4	246	6.4	6.9	7.0	5.8	13.3
19:20	0	29.7	246	8.2	7.0	7.1	7.2	15.2
23:20	0	31.2	252	11.7	11.3	11.0	10.9	23.0
21:20	0	32.9	248	10.5	8.2	8.0	9.2	18.7
23:10	0	33.6	245	11.6	11.2	10.7	9.6	22.8
21:10	0	34.2	249	11.9	11.3	9.8	7.9	23.2
	mean:	28.7	250	7.1	6.5	6.1	6.0	13.6
15:50	1	24.0	260	2.7	3.1	2.6	3.8	5.8
13:50	1	24.0	259	2.3	2.9	2.9	3.8	5.2
17:40	1	24.3	246	4.3	4.6	4.9	4.7	8.9
15:40	1	24.5	252	2.8	3.2	2.4	3.9	6.0
13:40	1	24.7	259	3.0	2.5	2.8	3.3	5.5
17:50	1	26.3	253	4.4	4.6	4.8	5.3	9.0
19:40	1	29.5	245	8.5	6.8	7.1	8.1	15.3
19:50	1	30.9	242	8.8	7.9	7.7	8.1	16.7
23:50	1	31.0	245	10.6	10.8	11.0	10.9	21.4
23:40	1	31.6	243	10.3	10.3	10.5	10.5	20.6
21:50	1	35.1	249	8.1	8.0	8.9	8.0	16.1
21:40	1	36.1	252	8.7	7.9	8.5	7.9	16.6
	mean:	28.5	250	6.2	6.1	6.2	6.5	12.3
ratio (1/0 %)		99.3		87.9	93.2	101.0	108.0	90.4

The Jess-A study array is aligned for winds from a direction of about 230°. However, the winds at J08 were more westerly, from 250°. Apparently the wake deficits passed to the south of the array. Evidence for this is that the turbines at the south end of each string experienced more wake deficits than those at the north end. In addition, many of the 10-min mean wind speeds were above 30 mph. The 16 D test data suggested that wake deficits from the more distant upwind rows would be negligible in winds of this magnitude. Thus there were problems with both the wind direction and speed that masked the deficits from the more distant rows.

Statistical analysis of these deficits shows decreasing levels of significance as more rows are switched on. With one row on, the significance level of the energy deficit was 0.95, but this decreased to 0.90 for two rows on, and to 0.70 for three upwind rows on.

Table 3-4.d is the analysis of the second row (from the back). There are two upwind rows and the data is sorted into three groups, no upwind rows on, one row on and two rows on. The curious pattern seen in the back row was evident here as well. The mean energy in this row increased as one, and then two upwind rows were switched on line. Only the southern end of the row, at turbine K3, showed an energy decrease, and the other four turbines all showed energy increases. Perhaps decreases would have been measured at turbines K1 and K2, but these buffer turbines were switched off for the entire test. The deficit at turbine K3 was only significant at the 0.60 level.

Table 3-4.e is the analysis of the next upwind row, and it is essentially the same as a direct wake test. Turbines F9 and F10 at the south end of the row showed a decrease in energy when the upwind row was switched on. However, turbines G1 and G3 showed energy increases. (Turbine G2 was faulted for most of the test, so the data is not included in the analysis). The deficit at turbine F9 had a significance level of only 0.70.

Thus, we see that in all three test rows, the southern ends of the rows had some energy decreases while the northern ends of the rows had increases. Based on the wind direction data at J08, and the observed pattern of energy decreases in each row, the test array was poorly aligned with the wake trajectory during this test.

3.4.3 Test 3 Analysis, Souza-C, October 9, 1987

Tables 3-4.f and 3-4.g are the data listings for the October 9 test on Souza. Because of the way the upwind rows were cycled on and off, there are only half as many observations in the mode with no upwind rows on. It does not appear to have affected the data, although the smaller sample size affects the statistical significance calculation. The results from this test are somewhat similar to those from the September 4 test. Table 3-4.f shows that the winds at S13 were about 23 mph from the southwest. The table also shows that winds at S27 were about 21 mph. In this test, energy production at the test turbines was found to be better correlated to S27 speeds than to S13 speeds, so S27 was used as the reference anemometer. As in several previous tests, there was a difference in mean speeds between test periods, so a second set of means was calculated for the second and third periods. The "normalized" data sets have mean speeds of 20.6 mph and 20.8 mph, which are very close to those of the first period. Two sets of ratios were calculated: one

Table 3-4.f Souza-C Multiple Row Wake Test Analysis

Ten Minute Data Report
FOR WINDFARM: SOUZA RANCH WINDFARM

10/09/87

Time Of Day	rows on upwind	S13 wspeed	S13 w.dir.	S27 wspeed	E10 energy	E11 energy	E12 energy	E13 energy	E14 energy	sum of E10-E14	Turbine Anemometers E10 wspeed	E12 wspeed	E14 wspeed
17:40	0	23	245	16.8	5.9	5.1	4.8	4.5	3.6	23.9	19.6	16.7	16.3
17:50	0	22.9	245	18.1	6.3	5.4	5.8	5.5	4.5	27.5	19.9	18.2	17.4
22:30	0	25.5	232	19.7	6.7	5.9	6.5	7.1	7.2	33.4	21.4	20.9	22.6
20:00	0	26.4	235	20.1	7.1	6.6	7.2	7.4	6.7	35	22.2	21.1	21.5
15:30	0	21.3	217	20.3	6.4	5.8	6.2	6.4	6.4	31.2	21.1	19.6	20.8
20:10	0	26.9	235	20.6	7.9	7	7.3	7.3	6.7	36.2	23.3	21.7	21.4
15:20	0	22	231	21.3	7.4	6.5	6.6	6.7	6.1	33.3	22.7	20.7	20.6
22:20	0	26.1	218	21.6	7	6	5.7	5.9	6	30.6	22.4	19.9	20.4
10:40	0	24.7	233	21.6	7.7	6.8	7.1	7.4	7	36	23.4	21.6	22
13:10	0	22.4	214	22.1	6.9	5.1	6.2	6.6	6	30.8	22.6	20.7	20.3
10:50	0	24.7	233	23.2	8.5	7.6	8	7.7	7.1	38.9	25	23.9	22.7
13:00	0	22.3	219	23.4	7.9	6.5	6.8	6.7	5.6	33.5	23.9	21.2	20.1
Mean:		24.0	230	20.7	7.1	6.2	6.5	6.6	6.1	32.5	22.3	20.5	20.5
18:10	1	21.7	231	14.9	2.9	2.3	2.2	2.6	2.2	12.2	15.6	14.4	14.7
17:10	1	20.4	242	16.5	4.8	4	3.8	3.8	3.2	19.6	18.8	16.7	16.3
16:00	1	18.8	245	16.9	3.7	3.3	3.1	3.4	2.7	16.2	17	15	15
18:20	1	21.8	239	18.1	4.5	2.8	2.5	2.2	1.6	13.6	18.4	14.7	13.5
17:20	1	23.2	239	18.4	4.6	3.6	3.4	3.1	2.1	16.8	18.8	16.3	15.1
20:30	1	26.5	229	19.5	7.4	6.4	6.5	7	6.8	34.1	23.2	21.4	22.4
19:40	1	26.3	231	19.7	6.7	6	6	6.4	6.2	31.3	22.4	20.7	21.4
15:50	1	20.2	248	19.7	5.2	4.2	4.3	4.4	3.6	21.7	19.6	17.4	16.3
14:50	1	21.8	231	19.9	6.2	4.8	5	5.5	4.8	26.3	21.2	19	18.9
20:40	1	26.1	232	19.9	6.3	5.8	5.9	6.5	6.3	30.8	21.9	20.6	21.4
19:30	1	27	242	19.9	6.7	6.2	6.2	6.8	5.6	31.5	22.2	20.6	20.1
12:30	1	22.7	233	20.2	6.8	5.5	5.8	e 5.8	5.2	29.1	22.4	20.2	19.6
13:30	1	21.2	214	20.7	6.4	e 4.5	4.7	4.8	4.4	24.8	21.2	18.7	18.5
12:40	1	21.2	231	20.7	6.5	5.3	5.1	5.5	5.2	27.6	22.4	20.2	19.8
15:00	1	21.6	231	20.7	6	4.9	4.7	4.8	4.5	24.9	21.3	18.9	18.2
13:40	1	20.1	236	21.4	6.6	e 5.2	5.4	5.7	4.9	27.8	21.7	19.7	19.1
22:00	1	21.8	221	21.8	9.1	7.6	7.7	7.1	6.2	37.7	26.7	24.6	22.1
22:50	1	27	221	22.5	7.5	5.8	5.6	5.8	5.8	30.5	22.8	20.6	21.1
23:00	1	26.1	229	23.3	7	5.2	5.2	5.5	5.6	28.5	22.1	19.6	20.3
11:20	1	25.3	211	24.1	9	7.4	7.6	7.5	7	38.5	26.6	23.9	23.4
11:10	1	23.5	211	24.3	8.8	7.4	7.4	7.2	7	37.8	26.1	23.8	23.3
21:50	1	23.6	218	25.2	9	7.2	7.4	7	6.6	37.2	26	24.3	22.6
Mean:		23.1	230	20.4	6.4	5.2	5.3	5.4	4.9	27.2	21.7	19.6	19.2
Norm. Mean:		23.2	230	20.6	6.6	5.4	5.4	5.5	5.0	27.9	22.0	19.9	19.4

Note: e = estimate due to turbine not operating full 10-minutes

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Table 3-4.f Souza-C Multiple Row Wake Test Analysis

Time Of Day	rows on upwind	S13 wspeed	S13 w.dir.	S27 wspeed	E10 energy	E11 energy	E12 energy	E13 energy	E14 energy	sum of E10-E14	E10 wspeed	E12 wspeed	E14 wspeed
16:20	2	20.7	217	14.4	2.3	1.7	1.7	1.9	1.7	9.3	15.3	13.2	14.1
16:30	2	21.1	233	15.9	3.7	2.9	3	3.3	3.1	16	17.4	15.9	15.9
14:20	2	20.1	219	17.7	4.3	3.5	3.7	3.9	3.5	18.9	18.4	16.6	16.8
16:40	2	22.1	245	18.6	4.6	3.5	3.2	3.2	2.5	17	18.8	16.4	15.1
14:00	2	21.3	231	18.9	5.3	e 4.3	4.5	4.9	4.5	23.5	19.8	18.4	18.5
16:50	2	21	245	18.9	3.7	2.6	2.7	2.8	1.9	13.7	16.7	14.6	13.7
14:30	2	22.5	233	20	5.9	4.5	4.5	4.7	3.8	23.4	20.7	18.1	17.6
14:10	2	20.5	236	20	5.6	3.8	3.8	4.1	3.9	21.2	20.2	17.1	17.2
23:20	2	23.4	224	20.9	7.8	5.9	5.8	5.8	5.7	31	23.2	20.5	20.6
18:40	2	24.4	236	21.3	6.1	5.2	4.6	4.6	4	24.5	21.3	18.2	17.9
19:10	2	26.8	235	21.5	7	6.4	6.5	6.2	5.7	31.8	23.1	20.9	20.7
21:10	2	24.3	224	21.9	6.2	4.7	5.4	6.2	5.9	28.4	21.3	20.5	20.9
23:30	2	24	224	22.4	8.2	6.2	6.4	7	6.3	34.1	24.6	21.9	22.2
19:00	2	25.7	236	22.4	7.3	6.7	7.1	7	6.8	34.9	23.6	22.7	21.8
12:10	2	23	228	22.5	6.7	4.9	4.9	5.3	4.9	26.7	22.1	19.4	19.4
18:50	2	25.4	236	22.6	7.3	6.8	6.8	6.7	6	33.6	24.1	22	21.5
21:00	2	24.5	232	22.7	6.8	5.2	5.8	6.2	5.8	29.8	21.8	20.5	20.6
12:00	2	23	217	23	8.1	6.2	6.3	6	5.6	32.2	24.1	21.6	20.6
11:50	2	22.6	236	23.4	8.1	6.3	6.4	6.4	5.9	33.1	24.6	21.4	21.3
11:40	2	24.7	219	23.8	8.3	6.3	6.8	6.7	6.3	34.4	24.9	22.1	21.6
23:50	2	23.8	224	23.9	8	5.8	6	6	5.7	31.5	23.9	21.3	21.1
23:40	2	22.6	229	24.2	7.6	5.6	6.3	6.9	6.6	33	23.2	21.4	22.2
21:30	2	24	229	25.2	8.3	6	5.8	5.2	4.5	29.8	24.7	20.9	19.3
21:20	2	24.1	226	25.4	8.6	6.3	6.2	5.5	4.7	31.3	25.6	21.5	19.6
Mean:		23.2	230	21.3	6.5	5.1	5.2	5.3	4.8	26.8	21.8	19.5	19.2
Norm. Mean:		23.1	230	20.8	6.3	4.9	5.0	5.2	4.7	26.1	21.4	19.2	19.0
Ratios, using all available data:													
1 row on/none on		96.1		98.3	90.2	84.7	80.6	81.5	80.4	83.6	97.5	95.6	93.8
2 rows on/none		96.4		102.8	90.9	81.6	79.4	79.9	79.1	82.4	97.8	94.9	93.5
Normalized ratios:													
1 row on/none on		96.4		99.5	92.5	87.0	82.8	83.5	82.5	85.8	98.9	96.8	94.8
2 rows on/none		96.1		100.3	87.5	79.5	77.4	78.6	78.0	80.4	96.1	93.6	92.7
2 rows on/1 on		99.7		100.8	94.6	91.4	93.5	94.0	94.5	93.6	97.2	96.7	97.7
Turbine anemometer data:													
Speed ratios (normalized period)													
1 row on/none on					98.9	N/A	96.8	N/A	94.8				
2 rows on/none					96.1		93.6		92.7				
Power ratios (anem. data, norm. period)													
1 row on/none on					99.4	N/A	93.9	N/A	88.4				
2 rows on/none					91.8		84.8		82				

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Table 3-4.g Souza-C Multiple Row Wake Test - Middle Row Analysis

10/09/87

Time Of Day	rows on upwind	S13 wspeed	S13B w.dir.	S27 wspeed	E01 energy	E02 energy	E03 energy	E04 energy	E05 energy	E06 energy	sum of E01-E05
18:10	0	21.7	231	14.9	3.6	4.1	4.2	4.2	3.8	3	19.9
17:10	0	20.4	242	16.5	5.8	5.9	5.7	5.4	4.7	4.4	27.5
16:00	0	18.8	245	16.9	4.8	5	4.7	4.4	3.5	2.8	22.4
18:20	0	21.8	239	18.1	4.6	4.1	3.8	3.4	2.7	2.4	18.6
17:20	0	23.2	239	18.4	5.3	5.2	5	4.6	3.8	3.7	23.9
20:30	0	26.5	229	19.5	7.4	7.9	8.1	8	7.2	7.2	38.6
19:40	0	26.3	231	19.7	7.3	7.7	7.7	7.7	7.1	7.1	37.5
15:50	0	20.2	248	19.7	3.9	4.1	3.8	3.3	2.5	2.5	17.6
14:50	0	21.8	231	19.9	6.3	6.7	6.7	6.5	5.7	5.4	31.9
20:40	0	26.1	232	19.9	6.8	7.4	7.7	7.7	7	7.2	36.6
19:30	0	27	242	19.9	7.5	7.9	7.8	e 7.3	6.5	6.4	37
12:30	0	22.7	233	20.2	6.8	7.3	7.4	6.9	6.1	5.8	34.5
13:30	0	21.2	214	20.7	5.8	6.3	6.4	6	5.7	5.5	30.2
15:00	0	21.6	231	20.7	6.3	6.3	6.5	6.3	5.5	5.5	30.9
12:40	0	21.2	231	20.7	6.4	6.8	7	6.9	6.3	6	33.4
13:40	0	20.1	236	21.4	6.3	6.8	7	6.5	6.2	5.9	32.8
22:00	0	21.8	221	21.8	8.3	8.4	8.2	7.4	6.3	2.2	38.6
22:50	0	27	221	22.5	6.8	6.8	7.1	7.3	7	6.9	35
23:00	0	26.1	229	23.3	6	6.4	6.9	7	6.9	7	33.2
11:20	0	25.3	211	24.1	8.1	8.5	8.8	8.1	7.5	8	41
11:10	0	23.5	211	24.3	7.9	8.1	8.5	8.3	7.2	7.7	40
21:50	0	23.6	218	25.2	8.2	8.4	8.2	7.8	7	6.8	39.6
means:		23.1	230	20.4	6.4	6.6	6.7	6.4	5.7	5.4	31.9
16:20	1	20.7	217	14.4	2.1	3	3.7	3.3	2.9	2.9	15
16:30	1	21.1	233	15.9	3.6	4.6	4.7	4.3	4.1	4	21.3
14:20	1	20.1	219	17.7	4.7	5.3	5.3	5	4.6	4.6	24.9
16:40	1	22.1	245	18.6	4.8	5.1	4.9	4	3.8	3.6	22.6
14:00	1	21.3	231	18.9	5.3	6	6.5	6	5.6	5.8	29.4
16:50	1	21	245	18.9	4.4	4.8	4.3	4	3.4	3	20.9
14:30	1	22.5	233	20	5.8	6.3	6.3	5.6	4.9	4.6	28.9
14:10	1	20.5	236	20	4.9	5.2	5.3	5.3	5	5.1	25.7
23:20	1	23.4	224	20.9	7.1	7.1	7.2	7	6.6	6.9	35
18:40	1	24.4	236	21.3	6.4	6.7	6	5.5	5.1	5.5	29.7
19:10	1	26.8	235	21.5	7.7	8.2	7.6	7	6.5	6.7	37
21:10	1	24.3	224	21.9	5.3	6.5	7.4	7.1	6.6	7.1	32.9
23:30	1	24	224	22.4	7.3	7.8	8.3	7.8	6.8	7	38
19:00	1	25.7	236	22.4	7.5	8.4	8.4	7.9	7.1	7.5	39.3
12:10	1	23	228	22.5	6.2	6.6	6.8	6.4	5.9	5.9	31.9
18:50	1	25.4	236	22.6	7.8	8.5	8	7.6	6.9	7.2	38.8
21:00	1	24.5	232	22.7	5.9	6.8	7.5	7.1	6.5	6.9	33.8
12:00	1	23	217	23	7.2	7.5	7.7	7.2	6.4	6.8	36
11:50	1	22.6	236	23.4	7	7.6	7.4	7.5	6.4	6.8	35.9
11:40	1	24.7	219	23.8	7.3	8	7.9	7.9	7.3	7.7	38.4
23:50	1	23.8	224	23.9	7.1	7.3	7.6	7.2	7	7.5	36.2
23:40	1	22.6	229	24.2	7	7.8	8.4	8.1	7.5	8	38.8
21:30	1	24	229	25.2	6.7	6.6	6.4	6	5.4	5.7	31.1
21:20	1	24.1	226	25.4	6.9	6.9	6.3	6.2	5.1	5.2	31.4
means:		23.2	230	21.3	6.1	6.6	6.7	6.3	5.7	5.9	31.4
Norm:		23.0	231	20.3	5.8	6.4	6.4	6.0	5.5	5.6	30.1
Norm. ratios(%)		99.6		99.7	90.7	95.7	96.2	93.7	95.6	103.5	94.4
ratio on/off(%)		100.3		104.6	95.5	99.5	99.6	98.2	99.8	109.0	98.5

for the entire data set and one for the adjusted data set. The analysis will focus on the latter because the bias in wind speeds at S27 is smaller.

The mean energy ratio of the five turbines, E10 - E14, shows that a large drop occurred when the first set of upwind turbines was switched on. Table 3-4.f shows that the ratio was 85.8%, which is equivalent to an energy deficit of 14.2%. The lowest ratios, or highest deficits, were at E12 through E14, and the smallest deficits were at E10 and E11. This pattern was probably due to a combination of terrain effects and wake trajectory. It is likely that turbine E10 was at the wake boundary because this array is aligned with 240° and the wind direction was 230°.

When the second set of upwind turbines was switched on, there was an additional 5.4% deficit, which is 38% of the initial 14.2% drop. Turbine E11 experienced the largest incremental deficit -- 7.5%. The other turbines in this row had deficits of about 5%.

Wind speed data from three turbine anemometers installed at 35 ft agl were analyzed and wind power density (W/m^2) was calculated for the individual 10-min wind speeds. The wind power density deficits were not as large as the energy deficits at two of the three turbines, E10 and E12. However, at E14 the power density deficits were almost as large as the energy deficits.

Statistical significance of the energy deficits for one and two rows on was 0.95 and 0.99, respectively. However, the statistical significance for the incremental deficit of two rows on versus one row on was only 0.75. The level of significance for turbine E11 was a bit higher at 0.80 for the incremental wake.

The individual turbine deficits are plotted in Figure 3-4.b. This is a topographic map with the deficits plotted at each turbine, parallel to the wind direction. The deficits from the first row of turbines are plotted as solid black bars. The deficits from the second row are plotted as open rectangles extending from the solid bars.

Table 3-4.g is the middle row analysis and is basically the same as a direct wake test. It should be noted that turbine F4, in the middle of the upwind row, was nonoperational throughout this test. This gap in the upwind row could have affected the wake deficits in this test row. Spacing between these rows is 10.2 D. S27 was also used as the reference anemometer in this test. Because there was a 0.9 mph difference between periods, a second set of means was calculated for the second period. Table 3-4.g shows that the mean speeds were within 0.1 mph for the normalized period, indicating little bias. The energy ratio between the two periods shows that the mean deficit at turbines E1 through E5 was 5.6%. The largest deficit was at turbine E1 -- 9.3%. Turbine E6 actually had a 3.5% increase in energy when the upwind row was turned on. It would appear that the increased distance between rows, as well as the nonoperational status of turbine F4 in the middle of the upwind row, reduced the deficits at this row. Because of the small magnitude of the energy deficits, the speed deficits were not calculated in this case. The statistical significance of the individual deficit at turbine E1 was 0.90 and 0.80 for the mean row deficit.

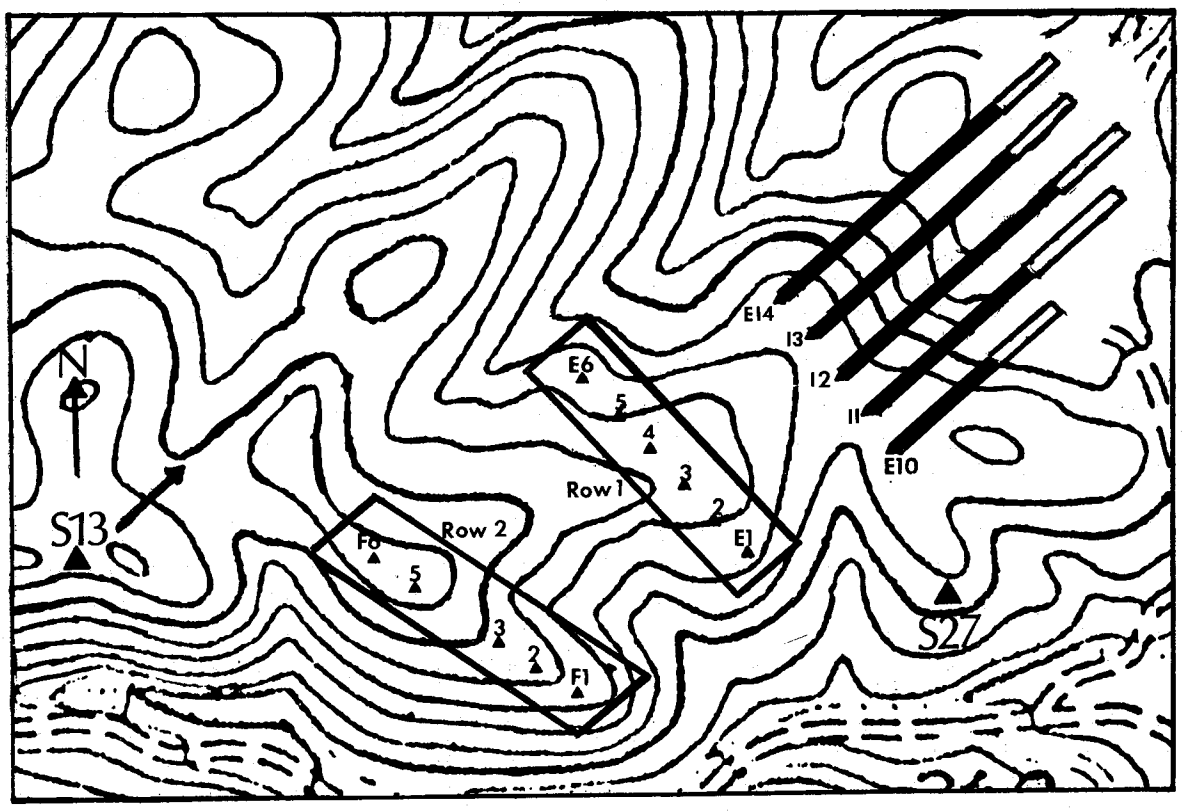

Figure 3-4.b. Souza-C Multiple Row Wake Test Individual Turbine Deficits

Oct 9, 1987 test conditions at reference anemometers;
S-13: mean speed = 23.2 mph, mean direction = 230 degrees,
S-27: mean speed = 20.6 mph.

KEY

▲▲▲▲ = turbine rows switched on and off
= % wake energy deficit, 1 row on, 1" = 10%
= % wake energy deficit, 2 rows on, 1" = 10%

Deficits

Turbine	1 row on	2 rows on
E10	7.5%	12.5%
E11	13.0%	20.5%
E12	17.2%	22.6%
E13	16.5%	21.4%
E14	17.5%	22.0%
Mean	14.2%	19.6%

3.4.4 Summary

The results of the three Multiple Row Wake Tests are consistent with the previous findings. There was a significant energy deficit when the first upwind row was switched on. In Test 1, there was a 4.5% energy deficit. In Test 2 there was almost a 17% deficit, and in Test 3, the deficit was about 14%. The smaller deficit in Test 1 may have been due to the higher winds, which were about 30 mph. In Test 2 and 3, the winds were lower than in Test 1.

Thus, we see that in all three tests, there was a significant energy deficit when one row of upwind turbines was switched on. The magnitude of the deficit was consistent with the direct wake test results. When the second row of upwind turbines was switched on, there was an additional deficit. In Test 1, there was an incremental deficit of about 1% at the test turbines. Recall that the winds at J08 were close to 30 mph. When the analysis was restricted to winds below 30 mph, the incremental deficit was 3%. This 3% deficit was close to 50% of the single row deficit of 6.5%. In Test 2, there was no incremental deficit, but the wind direction during this test was 20° off axis of the test array. The wake deficits apparently missed the test turbines. In addition, many of the 10-min mean speeds were above 30 mph, which is apparently too high to measure the more distant row wake deficits. In Test 3, the incremental energy deficit from the second row was 5.4%. This deficit is close to 40% of the single row deficit of 14.2%. In this test, the distance to the second upwind row is 250% of the distance to the first upwind row -- 17 D, versus 6.8 D. In addition, turbine F4, in the middle of the second upwind row, was not operational. Thus, we see that in the two tests that had proper wind directions for the study groups, the incremental deficits were 50% and 40% of the first row deficit. The 40% deficit might have been closer to 50% if the second upwind row were fully operational and the upwind spacing to this row were 200% instead of 250%.

These results are consistent with the blockbuster and the 16 D tests conducted at Jess-C. The 16 D test data suggested that wake deficits from the more distant rows would be negligible above 31 mph. In these three Multiple Row Tests, the incremental deficit was negligible in the higher winds, but quite apparent in the tests with lower winds. The Jess blockbuster (2 row) deficits were much higher than any of the single row (direct wake) deficits, and that test was conducted in fairly low winds (17-18 mph).

To illustrate the inverse relationship between wind speed and wake deficits, the mean two-row deficits have been plotted as a function of wind speed. Figure 3-4.c is a plot of the two-row deficits, and uses data from the Multiple Row Wake Tests and the blockbuster tests. The regression lines have been plotted for the two-row data (heavier line), and for comparison purposes, from the one-row data (direct wake tests). The regression analysis shows that the slope of the two-row deficit line is roughly twice as steep as that of the one-row line. Thus, a given change in wind speed would produce twice as large a change in wake deficits. The correlation coefficient between the energy deficits and wind speed was excellent at -0.96. Although not plotted, the correlation coefficient between the energy deficits and two turbine performance parameters were also calculated. The correlation was 0.97 to the thrust coefficient and 0.93 to the coefficient of power.

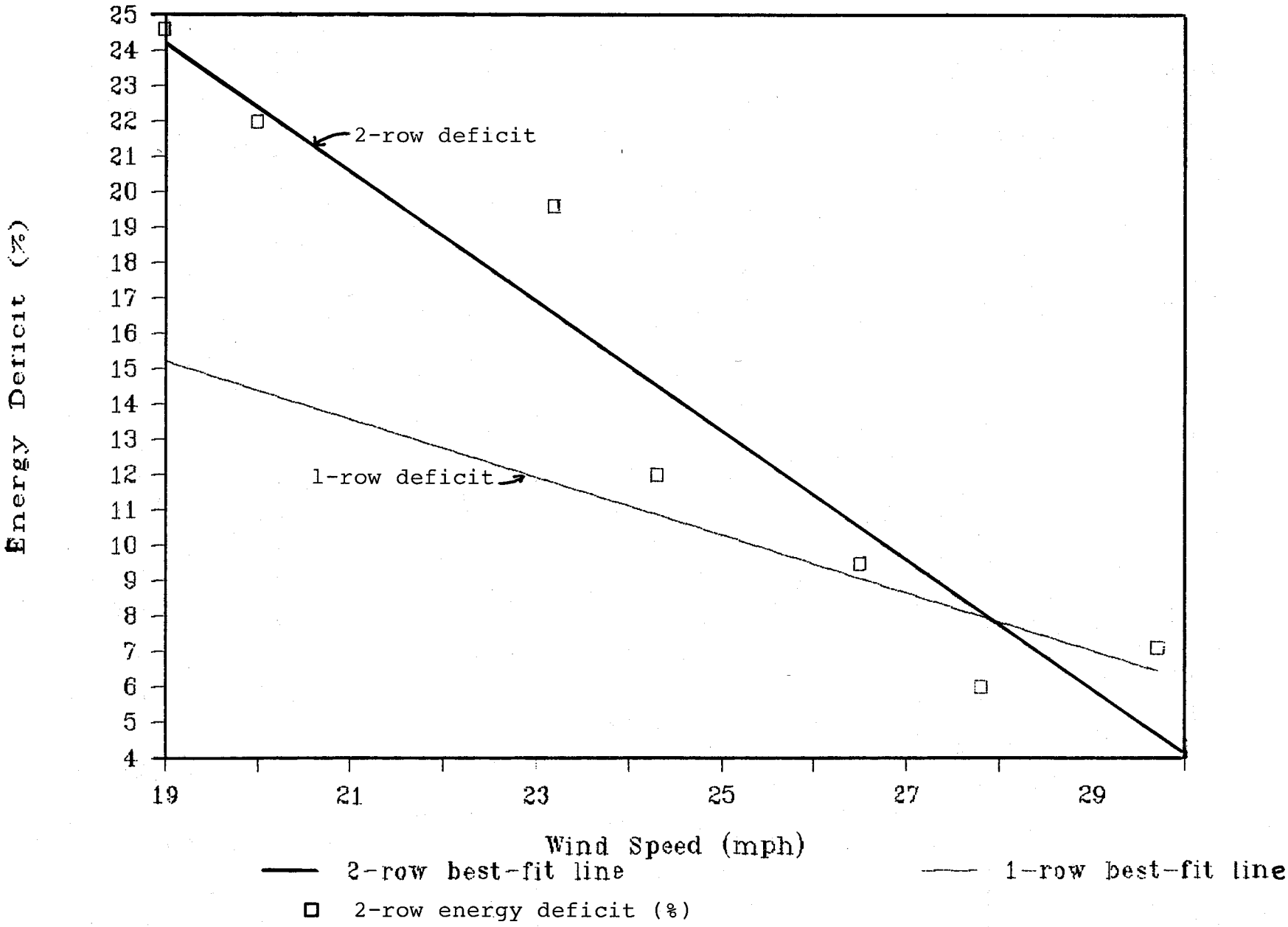

Figure 3-4.c. 2-Row Wake Deficits (%) vs. Wind speed (mph)

A curious phenomenon seen in a few instances was an energy increase at one end of a row and an energy deficit at the other end. The magnitude of the energy increases was larger than the deficits (see Tables 3.4.d and 3.4.e). The area where these increases occurred was outside the expected wake trajectory, so one might expect little change in energy at these sites. A possible explanation for the energy increase is the "windwall" effect. Perhaps when an entire row of turbines is switched on, there is divergence around the row. This could cause an energy increase at the sites that are not directly downwind of the row that was switched on line.

3.5 Lateral Induction Test, Jess-C, September 10, 1987

The Lateral Induction Test was designed to measure the effects on an individual turbine when the turbines immediately adjacent to it are switched on and off. The test plan was to turn on and off every other turbine in a given row. The other turbines (test turbines) in the row remain on throughout the test. The energy production from the test turbines was sorted into two periods -- when the adjacent turbines were on, and when they were off. If lateral induction effects were present, the test turbines' performance should increase when all the turbines are switched on.

The Lateral Induction Test was conducted on September 10, 1987, from 14:40 PDT to 18:40 PDT on the Jess-C group turbines (see Figure 2-1). Turbines L1 through L5 were used in the test -- L1, L3, and L5 were turned on and off every 20 min, and L2 and L4, which are embedded in this group, were the test turbines. Turbine L6 was left on during the test, but the data were not analyzed because L6 is at the end of the row.

The data records and analysis for this test can be found in Table 3-5.a. The table shows that the winds were from the west-southwest and the mean speeds for the two test periods were 25.0 mph and 24.9 mph, almost exactly equal. The ratios of energy (calculated by dividing the period with adjacent turbines on by the period with them off) were 97.2% at turbine L2, 99.8% at L4, and 98.5% for the average of the two. Thus, there was almost no difference between the two periods and no statistically significant lateral induction effects were measured in this test. Perhaps closer crosswind spacing is needed to see these effects.

Although the test was not designed for the following purpose, the energy production at the next row downwind was also examined. In essence, this is an analysis of the wake effects of turning on/off a half-row of turbines, or changing the lateral spacing of the upwind row from 3.8 to 1.9 D. Because this was designed as a lateral induction test, there were no 10-min transition periods between test configuration changes as there would have been for other kinds of tests. These periods allow wakes to reach or leave the downwind test rows, and data during these periods are not included in the test analysis. However, in wind speeds of 25 mph, with the spacing on the Jess Ranch, the wakes would only take 11 s to reach the next row. Thus, the lack of transition periods should have negligible effects on the data analysis.

Table 3-5.b lists the data for turbines L8 through L13. (Turbine L12 was not communicating properly during this test, and the data are not included here). In this analysis, the energy ratios between the two periods show that

Table 3-5.a Lateral Induction Test

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM
REPORT 09/10/87

Time Of Day	turbines on:	J08 wspeed	J08 w.dir.	L02 energy	L04 energy	Sum of L2+L4
16:30	3	22.6	246	6.4	6.4	12.8
16:20	3	22.9	248	6.7	6.4	13.1
15:00	3	23.5	235	6.9	6.9	13.8
17:00	3	23.6	248	7.3	7	14.3
15:50	3	24.0	260	7	7	14
17:40	3	24.3	246	7.4	7.1	14.5
15:10	3	24.4	255	6.8	7.5	14.3
15:40	3	24.5	252	7.3	7.4	14.7
17:10	3	25.7	256	7.5	7.7	15.2
17:50	3	26.3	253	8	8	16
18:20	3	28.7	252	9	9.1	18.1
18:30	3	29.4	246	9.7	9.3	19
Mean:		25.0	250	7.5	7.5	15.0
14:40	6	21.8	259	6.1	5.9	12
16:10	6	22.9	259	6.3	6.7	13
14:50	6	23.1	255	6.4	6.7	13.1
16:00	6	23.2	252	6.9	6.5	13.4
15:20	6	23.7	262	7	6.8	13.8
15:30	6	24.1	253	7.2	7.3	14.5
16:50	6	24.4	252	6.9	7.3	14.2
16:40	6	25.1	252	7.2	7.7	14.9
17:20	6	27.1	252	8.2	8.2	16.4
17:30	6	27.3	252	8.3	8.4	16.7
18:10	6	27.6	249	8.4	8.8	17.2
18:00	6	28.6	250	8.6	9.3	17.9
Mean:		24.9	254	7.3	7.5	14.8
Ratio on/off (%)		99.7		97.2	99.8	98.5
Inverse ratio		100.3		102.9	100.2	101.5

Table 3-5.b Effect of 1/2 row of turbines
(changing lateral spacing at upwind row from 3.8 to 1.9 RD)

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM
REPORT 09/10/87

Time Of Day	rows on upwind	J08 wspeed	J08 w.dir.	L08 energy	L09 energy	L10 energy	L11 energy	L13 energy	sum of L08-L11
16:30	0.5	22.6	246	5.7	5.5	6.4	6	6.2	23.6
16:20	0.5	22.9	248	5.8	5.5	6.4	5.9	6	23.6
15:00	0.5	23.5	235	6.1	6.2	7	6.9	6.5	26.2
17:00	0.5	23.6	248	6.1	6.4	7.1	6.8	6.7	26.4
15:50	0.5	24.0	260	6.2	6.9	7.4	7	6.7	27.5
17:40	0.5	24.3	246	6.3	6.7	7.3	7.5	7.5	27.8
15:10	0.5	24.4	255	6.2	6.5	7.6	7.7	6.8	28
15:40	0.5	24.5	252	6.7	6.9	7.6	7.6	6.8	28.8
17:10	0.5	25.7	256	6.9	7.1	8.1	7.6	6.7	29.7
17:50	0.5	26.3	253	6.9	8.2	7.5	7.5	6.8	30.1
18:20	0.5	28.7	252	8.2	9.2	9.2	9	7.9	35.6
18:30	0.5	29.4	246	8.7	9.6	9.6	10.1	8.4	38
Mean:		25.0	250	6.7	7.1	7.6	7.5	6.9	28.8
14:40	1	21.8	259	4.8	5	5.2	5.5	6.1	20.5
16:10	1	22.9	259	5.2	5.6	6	6	6.2	22.8
14:50	1	23.1	255	5.3	5.6	5.8	5.8	5.9	22.5
16:00	1	23.2	252	5.2	5.6	6	6.2	6.4	23
15:20	1	23.7	262	5.5	6.1	6.2	6	6.3	23.8
15:30	1	24.1	253	5.8	6.3	6.6	6.5	6.4	25.2
16:50	1	24.4	252	5.4	6	6.5	6.7	6.7	24.6
16:40	1	25.1	252	6.3	6.4	7.5	6.8	6.2	27
17:20	1	27.1	252	7.2	7.5	7.9	7.6	7.2	30.2
17:30	1	27.3	252	7.2	7.8	8.2	7.9	7.5	31.1
18:10	1	27.6	249	7.5	8.2	9	8.8	8.1	33.5
18:00	1	28.6	250	7.6	8.3	9.3	9.4	8	34.6
Mean:		24.9	254	6.1	6.5	7.0	6.9	6.8	26.6
Ratio on/off (%)		99.7		91.5	92.6	92.3	92.9	97.6	92.3

significant changes occurred. The average energy ratio between the two periods for turbines L8 through L11 was 92.3%. Thus, there was a 7.7% energy deficit when the half-row of upwind turbines was switched on. This is entirely consistent with the deficits measured in the direct wake tests. A clear pattern was evident within the row. The biggest change occurred at turbine L8 -- the ratio was 91.5%, which is equivalent to an 8.5% energy deficit. There were slight decreases as one progressed across the row to turbine L11, which had a ratio of 92.9% or an energy deficit of 7.1%. Turbine L13, at the end of the row, had the highest ratio or least deficit, 2.4%. Turbine L13 was at the edge of the entire array and may have been getting more energy from the (freestream) side of the array, whereas turbine L8 was deep in the array and received none of this freestream energy. In addition, turbine L13 was downwind of turbine L6, which was always on during this test.

Using the "Student's" t distribution to test for statistical significance yielded a confidence level of 0.80 for this row's energy deficit of 7.7%.

3.5.1 Summary

The Lateral Induction Test took place on the Jess-C array. The test was designed to measure any enhancement that might occur at a turbine when turbines adjacent to it are switched on. The enhancement would occur if wind turbines create a venturi effect between their rotors. This effect could be created when wind accelerates around the rotor disk, rather than passing through it. No enhancement was measured in the test, possibly because of the spacing between turbines. The crosswind spacing was 1.9 D, which might have been too wide to see this effect. It might have been possible to see this effect with an anemometer placed between adjacent turbines, but that was beyond the scope of this test.

Wake deficits at the row downwind of the test row were examined. In this situation, the deficit is due to the effect of turning on every other turbine in the upwind row, thus reducing the crosswind spacing from 3.8 to 1.9 D. The energy deficit was 7.7%, in winds of about 25 mph at J08. This result is consistent with the energy deficits measured in the direct wake tests.

3.6 Meandering Wake Test

The Meandering Wake Test plan analysis was inherently more qualitative than quantitative. The test started with one turbine on at one end of the upwind row. Each hour the position of the on-line turbine moved to the next turbine. Thus, the position of the on-line turbine progressed from one end of the upwind row to the other. An additional hour of data was collected with no turbines on line in the upwind row to aid in the analysis. The analysis would determine if the wake deficit tracked through the downwind row as the position of the upwind on-line turbine changed. The individual 10-min records were also analyzed. Using the mean wind direction, one can predict where the wake trajectory should be. Downwind turbines in the expected trajectory were scrutinized to see if their energy production dropped. Because of the qualitative nature of these tests, turbine anemometer data were not analyzed. Additional discussion of the test methodology can be found in Section 2.4.

Two Meandering Wake Tests were conducted and both tests used buffer turbines, upwind and crosswind of the array. The tests occurred on:

1. Souza-C group, August 12, 1987, 14:50-19:50 PDT (5 h)
2. Jess-A group, August 13, 1987, 13:00-17:50 PDT (5 h)

3.6.1 Test 1 Analysis, Souza-C, August 12, 1987

Table 3-6.a lists the data for the August 12 test on Souza. At the bottom of the table, the overall mean statistics have been calculated for the upwind anemometer and the four test turbines. The mean wind speed at S13 was ~21 mph and ranged from about 16 mph to 28 mph, from the west. The data are listed in sequential order and grouped in "hourly" blocks. Each block of data is for one configuration at the upwind row. The column marked "config." shows which upwind turbine was on line for each data block. The mean statistics are calculated for each block or period, and the energy ratio is calculated between each period mean and the overall mean.

The energy ratios in each hourly block have been analyzed. The lowest individual ratio in each block could reveal which turbine is being affected by the wake. In the first and second time block, turbine E12 has the lowest ratio and presumably is being affected by wakes. In the third time block, the lowest ratio has moved to turbine E13. This move is in the same direction as the change in upwind turbine status. In the fourth time block, the lowest ratio has moved to E14. Again, the move is in the same direction as the change in upwind status. Thus, we see to some extent that as the upwind on-line turbine progresses through the row, the apparent wake also moves through the downwind row.

The right column on the table shows where the expected wake trajectory should be, based on the 10-min wind direction. The double asterisk indicates a period when the energy production at the expected wake turbine is low and apparently affected by the wake. The 10-min energy output is considered "low" at the expected wake site by comparison with the other turbines in the row. The pattern of energy production is compared to the pattern on the bottom line of the table which is marked "overall." If there is a negative discrepancy from the overall pattern, it indicates the existence of the expected wake. This analysis is somewhat subjective and the presence of the wake has not been analyzed statistically to determine levels of significance.

The right column of Table 3-6.a shows that the expected wake should have been at turbine E10 most of the time. This was due to the unusual frequency of west winds during this test. Unfortunately, turbine E10 was a buffer turbine and was off line for the entire test, so energy data are not available. There were 11 records when E11 was the expected wake location, and on only two of these there appeared to be a wake. These results are disappointing, and there are a few explanations for these results. First, the location of the wake is difficult to determine accurately. This test might be better suited for a flat terrain site with uniform wind characteristics in the test row. Second, if the wind direction at the test turbines is slightly different from the reference anemometer, then the expected trajectory will be incorrect. Wind direction data were not available at the test turbines. And, third, the expected wake turbine, E10, was not on line during this test.

Table 3-6.a Souza-C Meandering Wake Test Analysis

Ten Minute Data Report
FOR WINDFARM: SOUZA RANCH WINDFARM
Date: 08/12/87

Time Of Day	S13 wspeed	S13 direc	E11 energy	E12 energy	E13 energy	E14 energy	Config.	Expected Wake Location
14:50	16.6	239	3.3	3.1	3.1	2.3	E2 on	E11
15:00	16.4	250	3.5	2.8	3.0	3.0		E10
15:10	17.4	256	2.4	2.0	2.6	2.4		E10
15:20	15.5	248	3.1	3.1	2.9	2.5		E10
15:30	16.9	239	3.4	3.1	4.1	3.9		E11
Mean	16.6	246	3.1	2.8	3.1	2.8		E10
% of overall mean:			65.9	59.4	65.0	68.7		
15:50	16.3	270	3.0	3.0	3.0	2.5	E3 on	E10
16:00	16.7	248	3.5	3.2	3.5	3.2		E11
16:10	16.9	273	3.8	3.5	2.9	2.7		E10
16:20	18	273	4.9	4.2	4.6	4.0		E10
16:30	17.9	270	4.4	3.7	4.5	3.8		E10
Mean	17.2	267	3.9	3.5	3.7	3.2		E10
% of overall mean:			82.2	74.2	76.6	78.9		
17:00	16.6	273	3.7	3.5	3.4	3.1	E4 on	E10
17:10	18.5	262	2.4	2.5	2.9	2.4		**E11**
17:20	18.8	273	2.6	2.5	2.9	2.6		E10
17:30	20.1	270	4.5	4.3	3.9	3.2		E10
17:40	22.7	264	5.7	5.8	5.3	5.2		E11
17:50	21.3	273	5.3	5.0	4.3	4.2		E10
Mean	19.7	269	4.0	3.9	3.8	3.5		E10
% of overall mean:			84.6	82.9	78.4	84.0		
18:00	19.9	276	4.3	4.4	4.1	2.9	E5 on	E10
18:10	20.8	270	4.5	4.6	4.0	2.7		E11
18:20	21.8	270	5.5	5.7	5.6	4.2		E11
18:30	22.1	270	5.9	6.2	6.4	4.7		E11
18:40	22.4	267	5.9	5.8	5.6	3.8		E11
18:50	24.9	267	6.0	6.2	6.4	4.9		**E11**
Mean	22.0	270	5.4	5.5	5.4	3.9		E11
% of overall mean:			112.2	115.5	110.8	94.1		
19:00	24.2	256	6.4	6.6	6.7	5.8	None on	None
19:10	27.1	273	7.4	7.7	7.8	7.3		
19:20	26.1	262	7.3	7.7	7.9	6.8		
19:30	25.2	262	6.7	7.2	7.5	6.5		
19:40	28.7	264	7.1	7.8	8.2	7.2		
19:50	28.1	264	7.0	7.7	8.1	7.2		
Mean	26.6	263	7.0	7.5	7.7	6.8		
Overall	20.6	264	4.8	4.7	4.8	4.1		

** Indicates apparent wake is at expected location.

Based on the analysis of the 10-min records, it is not clear whether the progression of the apparent wake through the row in the hourly block analysis is caused by a wake effect.

3.6.2 Test 2 Analysis, Jess-A, August 13, 1987

Table 3-6.b lists the data for the August 13 test on Jess-A. The format is the same as in Table 3-6.a. With the exception of the first hourly block, the winds were quite high during this test, ranging between 35 mph and 41 mph at J08. Using the first analysis approach, analyzing the data in hourly blocks, turbine K3 has the lowest ratio when turbine F10 is on. In subsequent hourly blocks, it is difficult to track the "wake." In the next block, turbine K6 has the lowest ratio, and this is followed by K7 in the next period. These changes are in the same directional sense as the changes in the upwind row. However, the ratios at the "affected" turbines are only ~2% lower than the adjacent turbines. In the last time period, the lowest ratio moves back to turbine K4, which is not in the same progression as the upwind row status. It is probable that the high winds masked the wake effect in this test case.

Analysis of the individual 10-min data shows that there were only two records when an expected wake location could be predicted. The wind speeds were too high after the 14:30 record to expect to see a wake deficit. Of these two records, one had an apparent wake at the expected location. If the winds had been lower, the results from this test might have been more encouraging.

3.6.3 Summary

Two meandering wake tests were conducted, and in both cases the results were inconclusive. In one test, the winds were too high to see a wake deficit. In the other test, the expected wake impinged on a buffer turbine that was not on line. This type of test does not necessarily lend itself to rigorous statistical analysis. To be certain about the expected wake trajectory, this test is better suited for a test array on flat terrain with several wind direction sensors throughout the array.

3.7 Northwest or Parallel Case

Data have been analyzed from five rows of Nordtank 65/13 kW turbines on the Souza Ranch and three on the Jess Ranch to calculate wake energy deficits associated with "northwest" or winds parallel to rows. The rows are oriented along an axis from approximately north-northwest to south-southeast as shown in Figures 2-1 and 3-7. Spacing within rows is 1.9 D, and there are four to eight turbines in each of the rows examined.

The data periods analyzed were from November 1986 through April 1987 and from November 1987 through April 1988. Fewer northwest winds occur in the central Altamont, where the Jess Ranch is located, than in northern Altamont, where the Souza Ranch is located. This difference may be due in part to wake effects. In northwest winds, the Jess Ranch is downwind of many miles of turbines, whereas the Souza Ranch is upwind of these turbines. Based on research by this author, Nierenberg (1987), not related to this study, there is evidence that wake energy deficits from large arrays of turbines persist for several miles in the Altamont Pass. The wake energy deficit from a 50 MW wind turbine array was measured as far downwind as three miles (250 D). The energy deficit at this distance was approximately 10%.

Table 3-6.b Jess-A Meandering Wake Test Analysis

Ten Minute Data Report
FOR WINDFARM: JESS RANCH WINDFARM
REPORT 08/13/87

Time Of Day	J08 wspeed	J08 w.dir.	K03 energy	K04 energy	K05 energy	K06 energy	K07 energy	Config.	Expected Wake Location
13:00	14.4	248	1.0	0.7	0.9	0.7	0.6	None on	None
13:10	17.6	248	1.1	1.3	1.4	1.4	1.2		
13:20	16.4	248	2.5	2.7	2.8	2.3	2.2		
13:30	18.3	225	0.3	0.7	0.9	1.2	1.2		
Mean:	16.7	242	1.2	1.4	1.5	1.4	1.3		
14:20	31.9	225	7.2	8.0	9.0	8.9	8.6	F10 on	K4+K5
14:30	30.3	225	5.8	5.7	5.5	5.6	6.0		**K4+K5*
14:40	36.2	225	7.4	6.8	6.4	6.4	7.1		too windy
14:50	40.8	225	8.3	8.5	9.1	9.8	9.8		" "
Mean:	34.8	225	7.2	7.3	7.5	7.7	7.9		" "
% of overall mean:			90.9	92.8	95.2	96.3	98.0		" "
15:00	38.5	248	9.3	9.2	9.3	9.2	9.4	G1 on	" "
15:10	40	225	10.3	10.0	9.4	9.5	9.7		" "
15:20	39.1	225	8.9	9.4	9.6	9.9	9.6		" "
15:30	37.6	225	8.8	8.6	8.6	8.2	8.0		" "
15:40	34.6	225	6.8	6.8	6.7	6.5	6.9		" "
15:50	38.8	225	9.1	9.1	8.7	8.7	9.0		" "
Mean:	38.1	229	8.9	8.9	8.7	8.7	8.8		" "
% of overall mean:			112.3	113.3	110.7	108.7	109.1		
16:00	39.1	248	9.9	9.6	9.3	9.6	9.5	G2 on	" "
16:10	42.4	248	10.0	9.8	9.9	9.9	9.8		" "
16:20	41.6	248	10.4	10.4	10.2	10.3	10.0		" "
16:30	41.2	248	10.3	10.1	9.9	9.7	9.7		" "
16:40	41.8	248	10.6	10.6	10.3	10.3	10.4		" "
16:50	40.2	225	9.3	10.0	10.4	10.5	10.4		" "
Mean:	41.1	244	10.1	10.1	10.0	10.1	10.0		" "
% of overall mean:			127.8	129.1	127.0	126.0	124.0		
17:00	41.3	248	8.9	8.6	9.1	9.5	9.7	G3 on	" "
17:10	40	225	9.4	8.9	9.2	9.7	9.7		" "
17:20	37.9	225	9.1	8.4	9.0	9.4	9.7		" "
17:30	40.9	248	10.4	9.6	9.4	10.0	10.2		" "
17:40	40.9	248	10.2	9.9	10.1	10.2	10.5		" "
17:50	38.4	248	9.9	9.7	9.7	9.9	10.0		" "
Mean:	39.9	240	9.7	9.2	9.4	9.8	10.0		" "
% of overall mean:			122.3	117.6	119.5	122.7	124.0		
Overall:	35.4	236	7.9	7.8	7.9	8.0	8.0		

** Indicates apparent wake is at expected location.

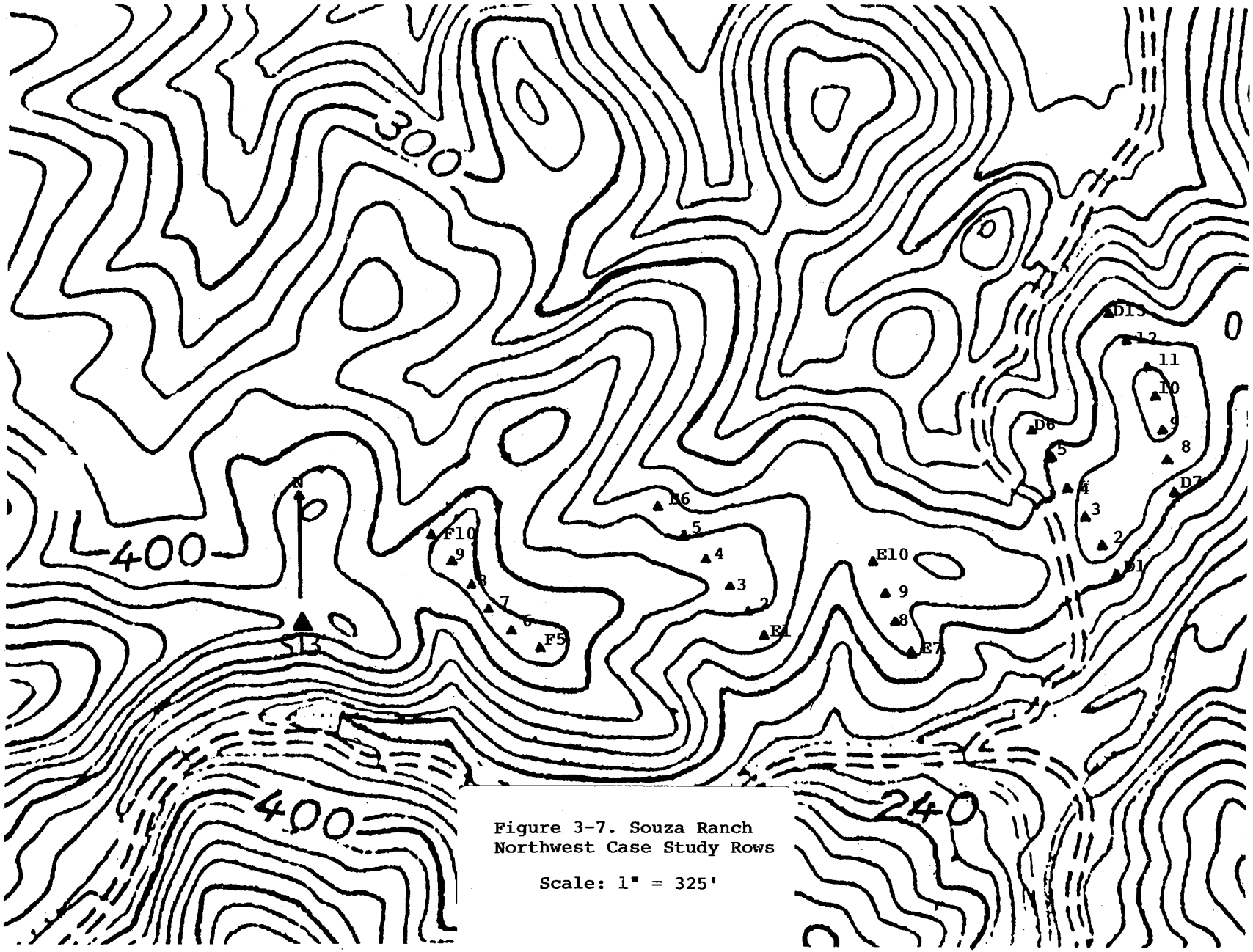

Figure 3-7. Souza Ranch
Northwest Case Study Rows

Scale: 1" = 325'

In the winter period of 1986-87, there were too few power-producing northwest winds on the Jess ranch to warrant analysis. However, there were stronger and more frequent northwest winds in winter 1987-88 on both ranches. Therefore, only one winter was analyzed on Jess and two winters on Souza. The winter/spring season is when most of the north-northwesterly power-producing winds occur. The data analyzed were 10-min mean energy output at the turbines, and mean wind speed and direction at the reference tower.

For each winter season (November through April), the 30 days with the highest occurrence of northwest power-producing winds were analyzed. In the winter of 1986-87, there were about 160 hours of northwest power-producing winds on the days analyzed, and in the winter of 1987-88, there were 430 hours on the Souza Ranch. During the 1987-88 winter, there were about 190 hours on the Jess Ranch. The dates selected for this analysis were chosen at the end of the winter season. The parallel case studies were not attended tests like the previous wake cases. No personnel were present to verify conditions visually, such as alignment of rows with actual wind directions.

After the analysis days were selected, turbine availability was determined. If a turbine was available less than about 70%, it was not included in the analysis. In a few cases, several turbines within a row did not meet this criteria, so the entire row was excluded from the analysis.

Figure 3-7 shows that the turbine rows on Souza are on complex terrain. Within most rows, the highest terrain is found in the middle of the row with elevation dropping off at either end. The rows on Souza are not all parallel to one another. In order to ensure that the wind direction band was parallel to each row, slightly different bands were analyzed for each row. Figure 2-1 shows that the terrain on Jess is also moderately complex. The L7-L13 row, like Souza, has the highest terrain in the middle of the row. The next row, M1-M7, slopes steadily downward from the upwind turbine (M7). The last row, N1-M13, has the lowest terrain in the middle of the row. In northwest winds in the Altamont Pass, elevation generally enhances wind speed. Thus, there could be terrain speed-up effects on the order of 5% in the data analyzed. These effects, which have not been quantified, may either enhance or suppress in-line wake deficits. A speed-up effect of 5% is roughly equivalent to an energy increase of 10%; therefore, this could be considered the noise level of this analysis.

The 10-min energy production data from the second through nth turbine in each row, were correlated to the upwind (northernmost) turbine in each row. Correlation coefficients and energy ratios were calculated. If the upwind turbine in a given row was available less than the row average, typically 85%, it was not used, because the reference turbine should have high availability.

3.7.1 1986-87 Souza Ranch Data

Table 3-7.a summarizes the data analyzed on a row-by-row basis for the first period, 1986-87. The table lists the turbine row, stratification class, sample size and mean energy ratio of the downwind turbines to the upwind turbines. Data were stratified by wind direction into three 22½° bins, one bin parallel to the row and one bin on either side of this direction band. Twenty-two-and-a-half-degree bins are equivalent to one 16-point compass sector. During the 1986-87 winter, the central monitoring computer archived

the wind direction data to the nearest 22½°. This was changed in summer 1987 so that the wind direction data were stored to the nearest tenth of a degree.

Table 3-7.a shows that three rows were analyzed in 1986-87. The two D rows were excluded because of availability problems. Almost all ratios are less than unity, with the exception of the E7-E10 row. (This portion of the E row was analyzed because there is a kink in the row at E10, and turbines E11-E14 are on a slightly different axis.) Note that the lowest ratios do not always occur in the parallel wind direction band. In two of the three rows, the ratios are lower (and deficits are higher) in the +22½° band. These results could have been caused by an alignment error in the wind vane. If there was an alignment error, there is no way to determine this at this date, as the sensor was replaced in summer 1987. Subsequent analysis of the 1987-88 data (see next section), suggests that there could have been an alignment problem with the wind vane, as the 1987-88 data showed maximum deficits in the parallel direction band. The poor resolution (22½°) of the 1986-87 wind direction data may also introduce some error. In addition, because there was only one wind direction vane on each ranch, one cannot state with certainty how representative the reference site direction is of each individual row. The assumption has been made that these data are representative, but local terrain effects can cause wind direction shifts at these sites. These tests were unattended, so there is no way to verify that these direction data are representative.

Table 3-7.a Northwest or Parallel Case Summary: November 1986 - April 1987, Souza Ranch

Upwind Turbine	Downwind Turbines	Stratification1 Wind Direction	Sample2 Size	Mean Energy Ratio (%) to Upwind Turbine
E6	E1-E5	Parallel	65	67.9%
" " "		-22½°	89	80.6
" " "		+22½°	400	97.4
E10	E7-E9	Parallel	400	91.1
" " "		-22½°	65	144.3
" " "		+22½°	519	42.2
F10	F5-F9	Parallel	65	77.4
" " "		-22½°	89	94.8
" " "		+22½°	400	34.7

NOTES:

1. -22½° indicates direction band with more westerly component, +22½° is more northerly as measured at S13 tower. Note that S13 is only 2 D downwind of operating turbines in northwest winds and therefore is in the "near wake" of turbines G5 or G6.

2. Sample size in 10-minute means.

Weighted mean energy ratios have been calculated for these three rows (weighted by sample size). Table 3-7.b lists these weighted mean energy ratios and the energy deficit, defined as 100% minus the energy ratio in percent.

Table 3-7.b shows that the weighted mean energy deficit, assuming negligible terrain effects, is 30.4%. The table also shows that the deficit is higher, 43.4%, for the +22½° band. There is no deficit for the -22½° band, again suggesting a possible wind vane alignment problem.

The raw data sheets summarized by Tables 3-7.a and 3-7.b are contained in Appendix A. There is a table for each line of data in Table 3-7.a. Each table lists the following information:

1) Screening parameters such as speed, direction, or time of day
2) Turbines analyzed
3) Correlation coefficient to upwind turbine
4) 10-min mean energy output at each turbine
5) Energy ratio to upwind turbine
6) Sample size
7) Turbine availability (listed on the first table of each set only).

The tables contained in Appendix A are sorted by:

1) Year (ascending order)
2) Ranch (Souza followed by Jess)
3) Turbine strings (alphabetical order)
4) Stratification type
   a) wind direction (3 tables)
   b) wind speed (3 tables)
   c) time-of-day (2 tables)

Table 3-7.b Weighted Mean Energy Ratios for 1986-87 Souza Ranch Northwest Case Data

Wind Direction Band	Energy Ratio (%)	Deficit (%)
Parallel	86.6%	13.4%
-22½°	102.8	<< 2.8>>
+22½°	56.6	43.4
Mean	69.6	30.4

For each row of turbines analyzed, there are a minimum of three tables -- the parallel wind direction followed by the -22½° bin and then the +22½° bin. A number of turbine rows had additional analyses done on the parallel wind direction bin. The sequence of these tables is low, moderate, and high wind-speed class. These tables are followed by two more, sorted by time into daylight and nighttime hours. The appendix contains a total of 72 tables. Tables 3-7.1a through 3-7.1r contain the 1986-87 Souza Ranch data. Tables 3-7.2a through 3-7.2nn contain the 1987-88 Souza Ranch data. Tables 3-7.3a through 3-7.3n contain the 1987-88 Jess Ranch data.

The "reference" turbine is the upwind turbine and the "referred" turbines are the downwind turbines. Note that the listings of the referred turbines are in numerical order, which is the opposite order of their placement within the row. These tables contain a great deal of information useful for detailed analysis. For example, if a turbine had a low availability, the turbine immediately downwind usually had a higher energy output and energy ratio. There was no universal pattern within rows. It is not possible to say that the nth turbine in each row had the lowest energy output. The 1986-87 tables contain some additional analysis of the E-rows, including stratification by wind speed and time of day. These will be discussed at length in the 1987-88 analysis.

3.7.2 1987-88 Souza Ranch Data

The 1987-88 winter season had a higher frequency of occurrence of northwest winds than the 1986-87 winter season. Five rows of turbines were analyzed on the Souza Ranch, and Table 3-7.c summarizes the results.

Table 3-7.c shows that the weighted mean energy ratio for the parallel direction is 57.9%, or the energy deficit is 42.1%. The two neighboring direction bands have higher energy ratios, i.e., lower deficits. This is a more reasonable result than obtained in the 1986-87 analysis in the previous section. One would expect the deficits to be highest when the wind direction is parallel to the row. The deficits are higher in this season than in the first season analyzed.

Because the sample sizes were larger in the 1987-88 season, some additional analysis was done. The data from these rows were stratified by wind speed and time of day. Table 3-7.d summarizes these data.

Table 3-7.d shows that stratification by time of day has slightly more impact than stratifying by speed. The daytime ratios at all rows have higher energy ratios (lower deficits) than all hours. The opposite is true for night -- the ratios are lower; i.e., deficits are higher. On the average, the deficits are 19% higher at night versus day. There are two probable explanations. One could be atmospheric stability. There is generally more instability in the daytime, which promotes more vertical mixing of horizontal momentum and quicker diffusion of the wake. The other explanation is speed. In most of the daytime samples, the upwind turbine had a higher mean energy output, i.e., higher mean speed, than the nighttime means. The higher daytime speeds would yield lower deficits.

Table 3-7.c Northwest or Parallel Case Summary: November 1987 - April 1988, Souza Ranch

-------Row--------- Upwind Turbine	Downwind Turbines	Stratification Wind Direction	Sample Size	Mean Energy Ratio (%) To Upwind Turbine
D6	D1-D4	Parallel	1614	47.1%
"	" "	-22½°	685	36.7
"	" "	+22½°	398	69.7
D13	D7-D11	Parallel	1406	50.6
"	" "	-22½°	158	77.5
"	" "	+22½°	990	72.2
E6	E1-E5	Parallel	896	81.6
"	" "	-22½°	82	69.4
"	" "	+22½°	1426	101.6
E10	E7-E9	Parallel	898	45.2
"	" "	-22½°	1510	68.5
"	" "	+22½°	205	53.8
F9	F5-F8	Parallel	1310	71.7
"	" "	-22½°	227	91.9
"	" "	+22½°	467	86.2
Weighted Means:		Parallel		57.9%
-22½°		62.9		
+22½°		84.7		

The stratification by speed shows that there are higher deficits in lower winds. On the average, the ratios increase (deficits decrease) by 9% in winds above 25 mph versus the all-winds case. The deficits increase by 5% in winds below 25 mph. This is the expected result based on the inverse relationship between speed and wake deficits, which was discussed in earlier sections.

3.7.3 1987-88 Jess Ranch Data

Data from three rows on the Jess Ranch were analyzed from the winter of 1987-88. Table 3-7.e summarizes these data.

The table shows that the mean energy ratio for parallel winds is 56.9%, or the energy deficit is 43.1%. The deficits for the two neighboring directions are 6% to 9% lower. The M8 row data were stratified by wind speed and time of day. This row was analyzed because it had the highest overall availability. Table 3-7.f summarizes the data.

The table shows similar results to the Souza data contained in Table 3-7.d. Deficits are lower in the daytime than at nighttime. The deficits decrease in higher winds and increase in lower winds.

Table 3-7.d Stratification by Wind Speed and Time of Day

Upwind Turbine	Wind Direction	Other Stratification	Sample Size	Mean Energy Ratio (%)
D6	Parallel	All data	1614	47.1%
"	" "	Daytime	496	59.8
"	" "	Nightime	696	38.4
"	" "	Winds above 25 mph	525	50.8
"	" "	Winds below 25 mph	1095	42.8
D13	Parallel	All data	1406	50.6%
"	" "	Daytime	215	62.3
"	" "	Nightime	803	47.3
"	" "	Winds above 25 mph	228	67.2
"	" "	Winds below 25 mph	1181	45.2
E6	Parallel	All data	896	81.6%
"	" "	Daytime	94	93.7
"	" "	Nightime	576	80.2
"	" "	Winds above 25 mph	75	94.7
"	" "	Winds below 25 mph	823	77.7
E10	Parallel	All data	898	45.2%
"	" "	Daytime	556	48.4
"	" "	Nightime	187	37.2
"	" "	Winds above 25 mph	422	51.0
"	" "	Winds below 25 mph	479	35.1
F9	Parallel	All data	1310	71.7%
"	" "	Daytime	293	94.0
"	" "	Nightime	652	62.2
"	" "	Winds above 25 mph	292	75.8
"	" "	Winds below 25 mph	1021	68.0
Mean	Parallel	All data		59.2%
"	" "	Daytime		71.6
"	" "	Nightime		53.1
"	" "	Winds above 25 mph		67.9
"	" "	Winds below 25 mph		53.8

3.7.4 Summary

Three sets of data have been analyzed -- two seasons on Souza and one on Jess. The results obtained on Souza in 1986-87 raised some doubts about wind vane orientation, so this summary will focus on the 1987-88 data. It is important to note two points. First, the analysis is of energy production data that were collected during routine operations, not in a controlled test environment. There are factors other than wakes that can affect the energy ratios, notably terrain speed-up effects. It was suggested that this effect could be on the order of ±10%. No attempt has been made to account for or normalize these effects. Second, turbine availability was not 100%. There is

Table 3-7.e Northwest or Parallel Case Summary: November 1987 - April 1988, Jess Ranch

-------Row--------- Upwind Turbine	Downwind Turbines	Mean Energy Wind Direction	Sample Size	Ratio (%) To Upwind Turbine
L13	L7-L12	Parallel	538	71.2
"	" "	-22½°	466	88.8
"	" "	+22½°	120	74.1
M8	M1-M7	Parallel	499	47.3
"	" "	-22½°	402	53.1
"	" "	+22½°	98	52.7
M13	M9-M11, N1-N3	Parallel	540	51.6
"	" " "	-22½°	481	52.7
"	" " "	+22½°	120	59.7
Weighted Means:		Parallel		56.9
-22½°		65.6		
+22½°		62.8		

Table 3-7.f Stratification of Jess M8 Row by Wind Speed and Time of Day

Stratification	Sample Size	Mean Energy Ratio(%)	Deficit(%)
All data	499	47.3%	52.7%
Daytime	235	53.4	46.6
Nightime	147	40.6	59.4
Winds above 25 mph	118	63.9	36.1
Winds below 25 mph	405	40.7	59.3

an inverse relationship between availability and the wake deficits. If a turbine is not operating in the middle of a row, the turbine immediately downwind of it often has increased energy output resulting in a lower deficit. Turbine availability, on the days analyzed with northwest winds, was about 84%. It is not known if the relationship between availability and deficits is linear, but if it is, we could expect a 16% increase in overall deficits. With these two caveats in mind, the data from the tables above can be summarized. Table 3-7.g summarizes the 1987-88 data from both ranches, stratified by wind direction bins.

The table shows that the weighted mean energy deficit is 42.3% for winds blowing parallel to the row axis. It is not known why the two off-axis bins

Table 3-7.g Weighted Mean Energy Deficits, Souza and Jess Ranches

Stratification	Souza 1987-88	Jess 1987-88	Weighted Mean Deficit
Parallel	42.1%	43.1%	42.3%
-22½°	37.1%	34.4%	36.5%
+22½°	15.3%	37.2%	19.9%
Sample size	12,272	3,264	

have different energy deficits. The Jess Ranch deficits are more symmetric about the parallel bin than the Souza deficits. If the two off-axis deficits are combined, the mean off-axis energy deficit is 28.2%. This is exactly two-thirds of the mean parallel deficit of 42.3%.

If these deficits are normalized by 116% as a rough accounting for the effects of availability, the resulting mean deficits are:

parallel to axis = 49.1%

22½° off-axis = 32.7%

Because the noise level of this exercise introduced by terrain speed-up effects is approximately ±10%, the above deficits should be rounded off to:

parallel to axis = 1/2 or 50%

22½° off-axis = 1/3 or 33%

These calculations are based on the assumption that the net terrain effect is negligible.

SECTION 4.0 CONCLUSIONS

A variety of tests were conducted on three Nordtank 65-kW wind turbine arrays in the Altamont Pass. Spacing within the arrays was 1.9 D in the lateral direction by about 8 D in the downwind direction. Approximately 125 h of data were collected and analyzed. Most of the test scenarios were designed to measure the effects or deficits of one row of turbines on another. In a few tests, the incremental effects of up to three rows were measured.

In the basic scenario, the Direct Wake Effect, six tests were conducted. The mean row energy deficit was 12.3% at approximately 8 D. Higher deficits were measured in lower wind speeds and deficits of about 4% were measured in winds above 30 mph. Figure 4-1 is a plot of the mean row and maximum individual turbine deficits versus wind speed for each test. The figure includes data from the direct wake tests, the 16 D tests, and the portions of the multiple row tests that are applicable (one row on). Mean row deficits are plotted as squares, and the maximum individual turbine deficits from each test are plotted as plus signs. The regression lines have been plotted for the mean row and individual deficits. The lines show the inverse relationship between wind speed and energy deficits. The correlation coefficient between wind speed and mean row deficits is -0.92. Thus, wind speed variation alone explains 85% of the variation in the deficits. The remaining 15% of the variation in the deficits may be due to factors such as turbulence intensity, spacing between rows, stability, terrain, and diurnal effects. On Figure 4-1, the mean row deficit line crosses the zero line at about 37 mph; i.e., there are negligible deficits above this speed. The Nordtank turbine reaches rated output at this speed. The slope of this line is -0.82. Mean row deficits range from 19% at 15 mph down to 0% at 37 mph. The regression line for the maximum individual turbine deficit is steeper than the mean row deficit. The slope of this line is -1.15 and the correlation coefficient between wind speed and turbine deficits is also -0.92.

The mean row deficits have also been correlated to the thrust coefficient (Ct) and the system coefficient of power (Cp). Recall that Ct and wind speed have a near-perfect inverse correlation for the Nordtank turbine. The correlation between energy deficits and wind speed is essentially the same in magnitude as the correlation between energy deficits and Ct. Only the sign is changed, as the correlation coefficients are -0.92 and +0.91, respectively. The best correlation was between the energy deficits and Cp: 0.94. These three parameters -- wind speed, Cp, and Ct -- are not independent variables. They are interrelated, and the wake deficits are a function of a combination of wind speed and turbine performance.

Figures 4-2 and 4-3 are plots of the mean row energy deficits versus Cp and Ct. The figures show the regression lines as well as the data points. The correlation coefficients are plotted in the lower left-hand corner of the figures.

There was considerable variation in energy deficits within the test row in each test. The driving factors believed to cause the variability within rows were (1) expected wake trajectory based on wind direction and (2) terrain speed-up effects. Turbines at the end of rows were often at the edge of the expected wake, based on measured wind direction, and these turbines usually had small or negligible deficits, and on a few occasions energy enhancement.

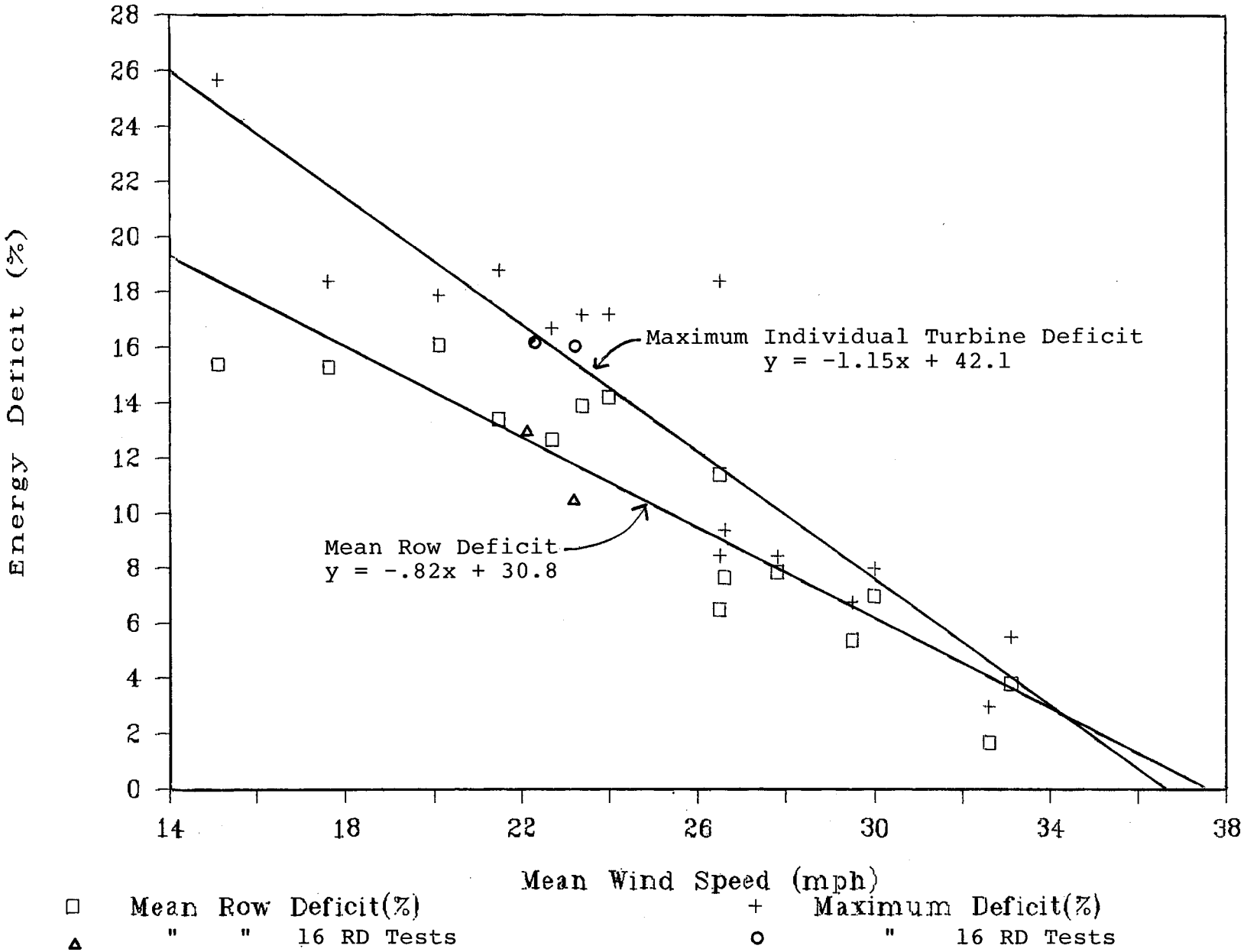

Figure 4-1. Wake Deficits (%) vs. Mean Wind Speed

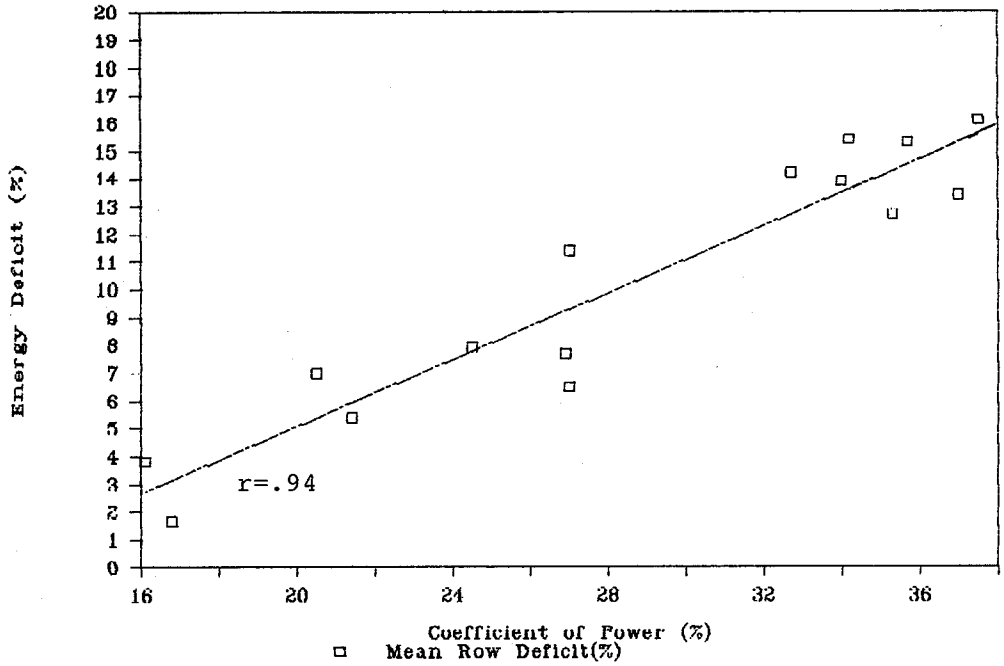

Figure 4-2. Wake Deficits (%) vs. Coefficient of Power (%)

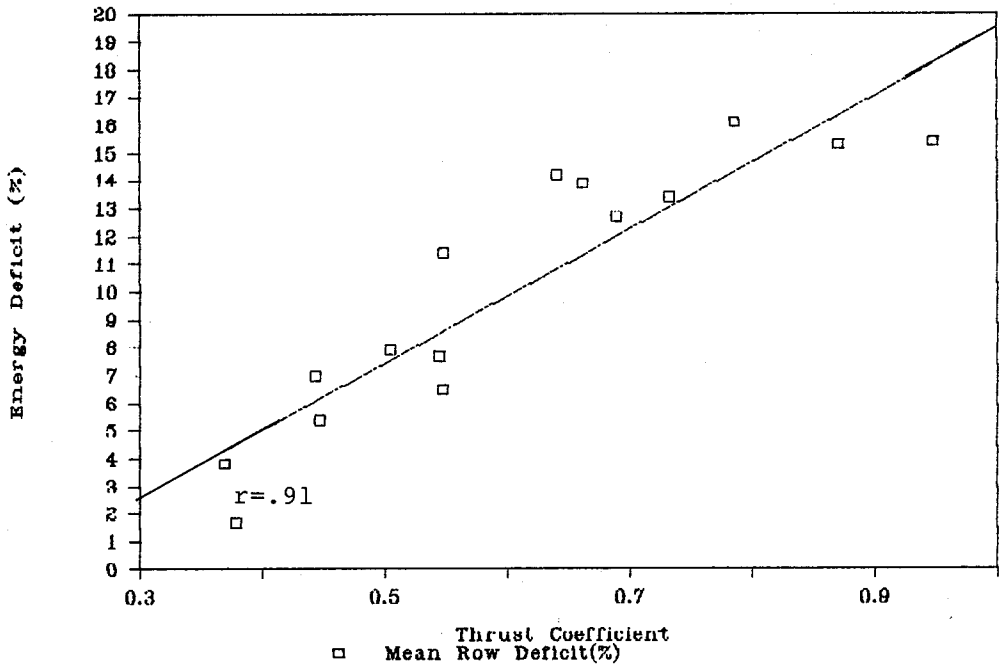

Figure 4-3. Wake Deficits (%) vs. Thrust Coefficient

Terrain enhances or diminishes ambient flow conditions. Turbines at lower elevation sites within a row had lower energy production and higher energy deficits. Thus terrain effects can significantly compound or decrease wake deficits, because of the inverse relationship between wind speed and wake deficits. This is an important finding for siting wind turbines because a terrain-related low wind resource site is likely to experience more deficits than high wind sites. No attempt was made to try to normalize the terrain effects on wake deficits.

Two tests were conducted to measure the effects of a single row of turbines with an upwind spacing of 16 D (double the normal spacing in these arrays). The mean row energy deficit was 12.1%, about the same as in the 8 D tests. This is rather remarkable, as one would have expected lower deficits at greater distances. The stable flow conditions and generally shallow flux layer that characterize the Altamont Pass winds may be responsible for these persistent deficits. The shallow flux layer is typically only about 500 ± 300 ft thick in the Altamont. The top of this layer is marked by the top of the West Coast subsidence inversion. There is usually little wind energy above the top of this inversion. The deficits from these 16 D tests are also plotted on Figure 4-1. The figure shows that these data points lie near the regression line of the 8 D tests. Regression analysis of the 16 D deficits suggests that these deficits are more sensitive to changes in speed than the 8 D deficits. The slope of the 16 D regression line (not plotted) is considerably steeper than the 8 D slope. The analysis also suggests that deficits would be negligible in winds speeds above 31 mph.

Two array wake effect tests were conducted to determine the effects of two rows of turbines on a downwind row. In the first test, with relatively low wind speeds, the mean energy deficit was 25%, which is considerably higher than the single row tests. However, the results from the second test were quite different. The wind speeds were about 10 mph higher during this test, and the mean energy deficit was only 6%. The inverse relationship between wind speed and energy deficits was more pronounced in this type of test. Linear regression showed that the slope of the regression line was twice as steep for the two-row tests as for the one-row tests. Thus a given change in wind speed produced twice as large a change in energy deficits in the two-row tests.

Three multiple-row tests were conducted to determine the incremental energy deficits of one versus two and one versus three rows of upwind turbines. The wake effects of the first row were similar to other single row tests. The incremental wake energy deficits of the additional rows were on the order of 50% of the single row deficit in winds below 30 mph. In winds above 30 mph, the incremental wake deficit from the additional rows was negligible. These results are consistent with the findings of the 16 D tests; in winds above 31 mph, the deficits were not discernible.

One test was conducted to measure lateral induction or the "windwall" effect. No discernable effect was measured, possibly because the spacing between turbines was too wide.

Wind speed data were available from every other turbine in the test rows. The wind speed data were collected at 35 ft agl, which is almost exactly half of turbine hub-height of 72 ft. In the tests described above, the speed deficits

were typically 1% to 5%. Power density (W/m^2) deficits were calculated from the wind speed data. These were usually smaller than the energy deficits. The speed and power density deficits are thought to be smaller than the energy deficits because the sensor height was 35 ft. It is possible that the wake deficit had not spread much in the vertical and so the anemometer was below the wake. Ideally, wind speed deficits should be measured at hub-height or over the entire rotor disk.

Energy production data collected during periods when the winds blew parallel to the turbine row axis were analyzed. In this situation, spacing between turbines was 1.9 D. Two entire winters, the season when these conditions are most likely to occur, were analyzed. Energy production from turbines in each row was compared to that of the lead (upwind) turbine in each row. The energy ratios ranged from about 40% to 70%, with an overall average of about 50%. From this, we can conclude that the energy deficit was also about 50% for parallel winds. For winds blowing 22½° off axis, the mean deficit was 33%. The data were also stratified by wind speed and time of day. The deficits decreased as wind speeds increased. The deficits were higher at night, presumably because of a combination of higher atmospheric stability and lower winds.

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APPENDIX A

NORTHWEST OR PARALLEL CASE DATA ANALYSES

The tables listed in this appendix contain the following information:

1) Screening parameters such as speed, direction, or time of day
2) Turbines analyzed
3) Correlation coefficient to upwind turbine
4) 10-min mean energy output at each turbine
5) Energy ratio to upwind turbine
6) Sample size
7) Turbine availability (listed on the first table of each set only)

The tables are sorted by:

1) Year (ascending order)
2) Ranch (Souza followed by Jess)
3) Turbine strings (alphabetical order)
4) Stratification type
    a) wind direction (3 tables)
    b) wind speed (3 tables)
    c) time of day (2 tables)

Tables 3-7.1a through 3-7.1r contain the 1986-87 Souza Ranch data. Tables 3-7.2a through 3-7.2nn contain the 1987-88 Souza Ranch data. Tables 3-7.3a through 3-7.3n contain the 1987-88 Jess Ranch data.

Table 3-7.1a Souza E6 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
E06	1.00	1.5	1.000	65	86.9
Referred:					
E01	0.96	1.1	0.699		94.0
E02	0.83	1.1	0.725		94.2
E03	0.69	0.7	0.449		71.0
E04	0.86	1.0	0.665		82.4
E05	0.84	1.3	0.858		93.1
REFERRED AVERAGE	0.84	1.0	0.679		86.9

Table 3-7.1b Souza E6 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	275	297	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	0.9	1.000	89
Referred:				
E01	0.78	0.7	0.788	
E02	0.86	0.8	0.920	
E03	0.60	0.6	0.652	
E04	0.67	0.7	0.866	
E05	0.85	0.9	1.076	
REFERRED AVERAGE	0.73	0.7	0.806	

Table 3-7.1c Souza E6 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	319	341	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	1.6	1.000	400
Referred:				
E01	0.71	0.9	0.567	
E02	0.73	2.3	1.477	
E03	0.56	1.4	0.873	
E04	0.67	1.5	0.979	
E05	0.47	1.3	0.834	
REFERRED AVERAGE	0.67	1.5	0.974	

Table 3-7.1d Souza E6 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	1.5	1.000	65
Referred:				
E01	0.96	1.1	0.699	
E02	0.83	1.1	0.725	
E03	0.69	0.7	0.449	
E04	0.86	1.0	0.665	
E05	0.84	1.3	0.858	
REFERRED AVERAGE	0.84	1.0	0.634	

Table 3-7.1e Souza E6 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	1.5	1.000	29
Referred:				
E01	0.93	1.0	0.678	
E02	0.78	1.1	0.708	
E03	0.32	0.8	0.493	
E04	0.86	0.8	0.529	
E05	0.94	1.0	0.665	
REFERRED AVERAGE	0.72	0.9	0.602	

Table 3-7.1f Souza E6 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	0.4	1.000	16
Referred:				
E01	0.76	0.3	0.592	
E02	0.48	0.5	1.194	
E03	0.23	0.2	0.550	
E04	-0.19	0.5	1.265	
E05	0.02	1.0	2.223	
REFERRED AVERAGE	0.32	0.4	0.900	

Table 3-7.1g Souza E10 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
E10	1.00	1.2	1.000	400	90.0
Referred:					
E07	0.59	1.4	1.183		92.2
E08	0.46	1.0	0.799		79.7
E09	0.50	0.9	0.751		94.3
REFERRED AVERAGE	0.52	1.1	0.911		88.7

Table 3-7.1h Souza E10 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	305	327	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	0.7	1.000	65
Referred:				
E07	0.72	1.1	1.506	
E08	0.72	0.9	1.232	
E09	0.83	1.2	1.592	
REFERRED AVERAGE	0.76	1.1	1.443	

Table 3-7.1i Souza E10 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	349	11	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	2.8	1.000	519
Referred:				
E07	0.86	1.5	0.518	
E08	0.77	0.9	0.320	
E09	0.87	1.2	0.429	
REFERRED AVERAGE	0.83	1.2	0.422	

Table 3-7.1j Souza E10 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	1.1	1.000	389
Referred:				
E07	0.54	1.4	1.288	
E08	0.42	0.9	0.866	
E09	0.40	0.9	0.810	
REFERRED AVERAGE	0.45	1.1	0.988	

Table 3-7.1k Souza E10 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	15	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	2.5	1.000	159
Referred:				
E07	0.45	2.0	0.807	
E08	0.29	1.4	0.560	
E09	0.47	1.1	0.465	
REFERRED AVERAGE	0.40	1.5	0.611	

Table 3-7.1l Souza E10 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	4.1	1.000	54
Referred:				
E07	0.48	2.5	0.609	
E08	0.33	1.8	0.434	
E09	0.64	1.5	0.367	
REFERRED AVERAGE	0.48	1.9	0.470	

Table 3-7.1m Souza E10 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	1.3	1.000	97.
Referred:				
E07	0.66	1.4	1.103	
E08	0.59	1.0	0.804	
E09	0.60	1.1	0.904	
REFERRED AVERAGE	0.62	1.2	0.937	

Table 3-7.1n Souza E10 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	1.3	1.000	225
Referred:				
E07	0.59	1.4	1.146	
E08	0.36	0.9	0.732	
E09	0.42	0.8	0.662	
REFERRED AVERAGE	0.46	1.0	0.847	

Table 3-7.1o Souza F10 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: F10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
F10	1.00	1.6	1.000	65	89.0
Referred:					
F05	0.69	1.7	1.052		93.5
F06	0.91	1.3	0.815		91.1
F07	0.89	1.7	1.067		94.0
F09	-0.06	0.3	0.161		76.9
REFERRED AVERAGE	0.61	1.3	0.774		88.9

Note: F08 was not included due to low availability.

Table 3-7.1p Souza F10 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	287	309	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F10	1.00	1.0	1.000	89
Referred:				
F05	0.41	1.2	1.255	
F06	0.57	0.9	0.874	
F07	0.56	1.0	0.998	
F09	0.43	0.7	0.666	
REFERRED AVERAGE	0.49	1.0	0.948	

Table 3-7.1q Souza F10 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 86-87 Correlation Variable: ENERGY

Reference Turbine: F10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	331	353	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F10	1.00	2.9	1.000	400
Referred:				
F05	0.64	1.1	0.381	
F06	0.65	1.0	0.333	
F07	0.86	1.4	0.473	
F09	0.40	0.6	0.201	
REFERRED AVERAGE	0.64	1.0	0.347	

Table 3-7.1r Souza F10 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F10	1.00	1.6	1.000	65
Referred:				
F05	0.69	1.7	1.052	
F06	0.91	1.3	0.815	
F07	0.89	1.7	1.067	
F09	-0.06	0.3	0.161	
REFERRED AVERAGE	0.61	1.3	0.774	

Table 3-7.2a Souza D6 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	315	337	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
D06	1.00	4.7	1.000	1614	91.8
Referred:					
D01	0.40	1.0	0.214		64.7
D02	0.88	2.6	0.557		87.3
D03	0.58	2.7	0.583		59.9
D04	0.63	2.5	0.530		62.2
REFERRED AVERAGE	0.62	2.2	0.471		68.5

Note: D05 was not included due to low availability.

Table 3-7.2b Souza D6 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	293	315	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	2.4	1.000	685
Referred:				
D01	0.44	0.4	0.154	
D02	0.81	1.1	0.472	
D03	0.60	1.3	0.514	
D04	0.49	0.8	0.329	
REFERRED AVERAGE	0.59	0.9	0.367	

Table 3-7.2c Souza D6 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	337	359	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	6.5	1.000	398
Referred:				
D01	0.58	3.6	0.554	
D02	0.92	5.0	0.769	
D03	0.68	5.3	0.811	
D04	0.59	4.3	0.655	
REFERRED AVERAGE	0.69	4.6	0.697	

Table 3-7.2d Souza D6 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	315	337	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	3.2	1.000	1095
Referred:				
D01	0.47	0.7	0.206	
D02	0.75	1.4	0.425	
D03	0.69	2.1	0.634	
D04	0.51	1.5	0.448	
REFERRED AVERAGE	0.61	1.4	0.428	

Table 3-7.2e Souza D6 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	315	337	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	6.4	1.000	991
Referred:				
D01	0.32	1.4	0.215	
D02	0.84	3.8	0.595	
D03	0.45	3.7	0.579	
D04	0.55	3.5	0.550	
REFERRED AVERAGE	0.54	3.1	0.485	

Table 3-7.2f Souza D6 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	25	65	mph
Screen by Direction:	YES	S13	315	337	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	7.7	1.000	525
Referred:				
D01	0.21	1.7	0.221	
D02	0.79	5.2	0.672	
D03	0.42	4.2	0.538	
D04	0.48	4.7	0.602	
REFERRED AVERAGE	0.48	4.0	0.508	

Table 3-7.2g Souza D6 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	315	337	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	5.5	1.000	496
Referred:				
D01	0.45	2.2	0.396	
D02	0.91	3.7	0.672	
D03	0.63	3.8	0.694	
D04	0.63	3.4	0.631	
REFERRED AVERAGE	0.66	3.3	0.598	

Table 3-7.2h Souza D6 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	315	337	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D06	1.00	4.1	1.000	696
Referred:				
D01	0.32	0.4	0.099	
D02	0.84	2.0	0.485	
D03	0.53	2.2	0.523	
D04	0.54	1.8	0.427	
REFERRED AVERAGE	0.56	1.6	0.384	

Table 3-7.2i Souza D13 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	304	326	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
D13	1.00	3.5	1.000	1406	83.9
Referred:					
D07	0.27	1.1	0.315		71.1
D08	0.49	0.6	0.185		69.1
D09	0.58	1.6	0.464		84.7
D10	0.69	2.3	0.661		71.7
D11	0.83	3.1	0.905		88.7
REFERRED AVERAGE	0.57	1.7	0.506		77.1

Note: D12 was not included due to low availability.

Table 3-7.2j Souza D13 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	282	304	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	2.4	1.000	158
Referred:				
D07	0.67	1.0	0.403	
D08	0.75	1.5	0.620	
D09	0.83	2.2	0.919	
D10	0.44	2.0	0.822	
D11	0.95	2.7	1.110	
REFERRED AVERAGE	0.73	1.9	0.775	

Table 3-7.2k Souza D13 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	326	348	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	5.2	1.000	990
Referred:				
D07	0.34	3.4	0.661	
D08	0.66	2.6	0.494	
D09	0.74	3.8	0.736	
D10	0.81	3.5	0.673	
D11	0.88	5.4	1.045	
REFERRED AVERAGE	0.69	3.7	0.722	

Table 3-7.21 Souza D13 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	304	326	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	3.1	1.000	1181
Referred:				
D07	0.46	0.6	0.178	
D08	0.45	0.5	0.173	
D09	0.48	1.3	0.411	
D10	0.55	2.0	0.647	
D11	0.79	2.6	0.852	
REFERRED AVERAGE	0.55	1.4	0.452	

Table 3-7.2m Souza D13 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	304	326	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	5.3	1.000	624
Referred:				
D07	-0.14	2.1	0.408	
D08	0.42	1.0	0.192	
D09	0.47	2.6	0.496	
D10	0.62	3.2	0.607	
D11	0.73	4.9	0.929	
REFERRED AVERAGE	0.42	2.8	0.526	

Table 3-7.2n Souza D13 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	25	65	mph
Screen by Direction:	YES	S13	304	326	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	5.3	1.000	228
Referred:				
D07	-0.30	3.9	0.734	
D08	0.49	1.2	0.223	
D09	0.63	3.3	0.629	
D10	0.82	3.7	0.700	
D11	0.85	5.6	1.073	
REFERRED AVERAGE	0.50	3.5	0.672	

Table 3-7.2o Souza D13 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: D13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	304	326	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	3.3	1.000	215
Referred:				
D07	0.54	1.9	0.564	
D08	0.56	0.8	0.242	
D09	0.73	2.0	0.621	
D10	0.85	2.1	0.646	
D11	0.86	3.4	1.043	
REFERRED AVERAGE	0.71	2.0	0.623	

Table 3-7.2p Souza D13 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	304	326	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
D13	1.00	3.4	1.000	803
Referred:				
D07	0.14	0.9	0.268	
D08	0.50	0.7	0.190	
D09	0.56	1.4	0.409	
D10	0.61	2.3	0.659	
D11	0.84	2.9	0.841	
REFERRED	0.53	1.6	0.473	

Table 3-7.2q Souza E6 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
E06	1.00	2.7	1.000	896	93.6
Referred:					
E01	0.94	2.4	0.916		93.7
E03	0.91	2.6	0.990		93.4
E04	0.95	2.3	0.873		92.6
E05	0.83	1.3	0.484		93.7
REFERRED AVERAGE	0.91	2.2	0.816		93.4

Note: E02 was not included due to low availability.

Table 3-7.2r Souza E6 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	275	297	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	3.0	1.000	82
Referred:				
E01	0.97	2.4	0.816	
E03	0.87	1.7	0.562	
E04	0.93	1.9	0.651	
E05	0.92	2.2	0.746	
REFERRED AVERAGE	0.92	2.1	0.694	

Table 3-7.2s Souza E6 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	319	341	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	5.1	1.000	1426
Referred:				
E01	0.93	5.2	1.019	
E03	0.87	5.6	1.110	
E04	0.93	5.4	1.071	
E05	0.90	4.4	0.864	
REFERRED AVERAGE	0.91	5.2	1.016	

Table 3-7.2t Souza E6 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	2.3	1.000	823
Referred:				
E01	0.92	2.0	0.900	
E03	0.88	2.2	0.972	
E04	0.95	1.9	0.842	
E05	0.79	0.9	0.395	
REFERRED AVERAGE	0.89	1.8	0.777	

Table 3-7.2u Souza E6 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	5.5	1.000	295
Referred:				
E01	0.86	4.9	0.899	
E03	0.82	5.2	0.945	
E04	0.89	4.9	0.901	
E05	0.85	2.9	0.535	
REFERRED AVERAGE	0.86	4.5	0.820	

Table 3-7.2v Souza E6 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	25	65	mph
Screen by Direction:	YES	S13	297	319	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	7.3	1.000	75
Referred:				
E01	0.55	7.1	0.968	
E03	0.65	7.7	1.053	
E04	0.65	7.2	0.977	
E05	0.67	5.8	0.788	
REFERRED AVERAGE	0.63	7.0	0.947	

Table 3-7.2w Souza E6 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E06

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	2.5	1.000	94
Referred:				
E01	0.97	2.5	1.019	
E03	0.94	2.7	1.116	
E04	0.95	2.3	0.953	
E05	0.90	1.6	0.661	
REFERRED AVERAGE	0.94	2.3	0.937	

Table 3-7.2x Souza E6 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	297	319	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E06	1.00	2.7	1.000	576
Referred:				
E01	0.94	2.5	0.906	
E03	0.90	2.6	0.968	
E04	0.95	2.3	0.865	
E05	0.82	1.3	0.471	
REFERRED AVERAGE	0.90	2.2	0.802	

Table 3-7.2y Souza E10 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
E10	1.00	6.3	1.000	898	85.0
Referred:					
E07	0.75	2.7	0.427		90.0
E08	0.61	2.5	0.400		93.0
E09	0.77	3.3	0.528		85.0
REFERRED AVERAGE	0.71	2.8	0.452		89.3

Table 3-7.2z Souza E10 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	305	327	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	2.2	1.000	1510
Referred:				
E07	0.64	1.9	0.834	
E08	0.53	1.5	0.686	
E09	0.69	1.2	0.536	
REFERRED AVERAGE	0.62	1.5	0.685	

Table 3-7.2aa Souza E10 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	349	11	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	6.7	1.000	205
Referred:				
E07	0.83	3.2	0.480	
E08	0.76	3.4	0.503	
E09	0.88	4.3	0.632	
REFERRED AVERAGE	0.82	3.6	0.538	

Table 3-7.2bb Souza E10 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	4.4	1.000	479
Referred:				
E07	0.82	1.6	0.362	
E08	0.72	1.4	0.327	
E09	0.77	1.6	0.363	
REFERRED AVERAGE	0.77	1.5	0.351	

Table 3-7.2cc Souza E10 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	7.8	1.000	637
Referred:				
E07	0.55	3.4	0.440	
E08	0.37	3.2	0.412	
E09	0.68	4.4	0.562	
REFERRED AVERAGE	0.53	3.7	0.471	

Table 3-7.2dd Souza E10 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	25	65	mph
Screen by Direction:	YES	S13	327	349	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	8.5	1.000	422
Referred:				
E07	0.40	4.0	0.465	
E08	0.22	3.8	0.443	
E09	0.59	5.3	0.624	
REFERRED AVERAGE	0.40	4.4	0.510	

Table 3-7.2ee Souza E10 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: E10

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	7.0	1.000	556
Referred:				
E07	0.72	3.0	0.432	
E08	0.61	3.0	0.426	
E09	0.76	4.2	0.594	
REFERRED AVERAGE	0.70	3.4	0.484	

Table 3-7.2ff Souza E10 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	327	349	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
E10	1.00	5.3	1.000	187
Referred:				
E07	0.81	2.2	0.413	
E08	0.67	1.7	0.320	
E09	0.80	2.0	0.383	
REFERRED AVERAGE	0.76	2.0	0.372	

Table 3-7.2gg Souza F9 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: F09

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
F09	1.00	2.8	1.000	1310	72.0
Referred:					
F05	0.30	1.8	0.642		69.2
F06	0.66	2.5	0.874		68.8
F07	0.53	2.4	0.835		73.5
F08	0.57	1.5	0.515		67.9
REFERRED AVERAGE	0.52	2.1	0.717		69.9

Note: F10 was not included due to low availability.

Table 3-7.2hh Souza F9 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	287	309	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	1.5	1.000	227
Referred:				
F05	0.63	1.5	1.036	
F06	0.77	1.1	0.756	
F07	0.72	1.6	1.074	
F08	0.71	1.2	0.810	
REFERRED AVERAGE	0.71	1.4	0.919	

Table 3-7.2ii Souza F9 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: F09

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	331	353	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	5.9	1.000	467
Referred:				
F05	0.61	4.5	0.768	
F06	0.72	5.7	0.972	
F07	0.76	5.3	0.901	
F08	0.71	4.7	0.809	
REFERRED AVERAGE	0.70	5.1	0.862	

Table 3-7.2jj Souza F9 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	25	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	2.0	1.000	1021
Referred:				
F05	0.38	1.4	0.739	
F06	0.52	1.5	0.747	
F07	0.33	1.7	0.874	
F08	0.38	0.7	0.359	
REFERRED AVERAGE	0.40	1.3	0.680	

Table 3-7.2kk Souza F9 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: F09

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	20	65	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	4.3	1.000	700
Referred:				
F05	-0.01	2.6	0.610	
F06	0.53	4.0	0.922	
F07	0.28	3.5	0.811	
F08	0.44	2.4	0.547	
REFERRED AVERAGE	0.31	3.1	0.722	

Table 3-7.2ll Souza F9 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	25	65	mph
Screen by Direction:	YES	S13	309	331	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	6.0	1.000	292
Referred:				
F05	-0.23	3.2	0.531	
F06	0.31	6.1	1.020	
F07	0.07	4.7	0.789	
F08	0.21	4.1	0.693	
REFERRED AVERAGE	0.09	4.5	0.758	

Table 3-7.2mm Souza F9 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: F09

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	309	331	hrs
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	3.2	1.000	293
Referred:				
F05	0.53	2.7	0.841	
F06	0.71	3.7	1.160	
F07	0.58	3.2	1.017	
F08	0.58	2.4	0.744	
REFERRED AVERAGE	0.60	3.0	0.940	

Table 3-7.2nn Souza F9 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	S13	9	65	mph
Screen by Direction:	YES	S13	309	331	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
F09	1.00	2.6	1.000	652
Referred:				
F05	0.10	1.5	0.583	
F06	0.68	1.9	0.717	
F07	0.54	2.0	0.769	
F08	0.58	1.1	0.420	
REFERRED AVERAGE	0.48	1.6	0.622	

Table 3-7.3a Jess L13 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: L13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
L13	1.00	3.4	1.000	538	94.8
Referred:					
L07	0.58	1.6	0.469	535	78.9
L08	0.94	2.9	0.867	535	95.9
L10	0.91	2.9	0.865	537	75.0
L11	0.80	2.1	0.610	537	75.0
L12	0.92	2.6	0.751	533	92.6
REFERRED AVERAGE	0.83	2.4	0.712		83.5

Note: L09 was not included due to low availability.

Table 3-7.3b Jess L13 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	300	322	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
L13	1.00	2.4	1.000	466
Referred:				
L07	0.44	1.4	0.574	459
L08	0.93	2.6	1.095	466
L10	0.81	2.6	1.054	464
L11	0.64	1.8	0.749	465
L12	0.91	2.4	1.015	453
REFERRED AVERAGE	0.75	2.2	0.898	

Table 3-7.3c Jess L13 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: L13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	344	6	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
L13	1.00	2.8	1.000	120
Referred:				
L07	0.76	1.7	0.594	120
L08	0.95	2.7	0.956	120
L10	0.89	2.3	0.814	120
L11	0.77	1.7	0.603	120
L12	0.93	2.1	0.738	119
REFERRED AVERAGE	0.86	2.1	0.741	

Table 3-7.3d Jess M08 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M08

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
M08	1.00	4.4	1.000	499	74.9
Referred:					
M01	0.83	1.6	0.361	499	91.7
M02	0.94	3.3	0.748	498	93.7
M03	0.87	2.2	0.492	499	95.6
M04	0.87	2.1	0.472	499	90.9
M05	0.55	1.2	0.282	499	74.2
M06	0.86	2.2	0.504	499	94.0
M07	0.78	2.0	0.452	499	80.3
REFERRED AVERAGE	0.81	2.1	0.473		88.6

Table 3-7.3e Jess M08 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	300	322	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	3.1	1.000	402
Referred:				
M01	0.89	1.4	0.460	
M02	0.96	2.7	0.855	
M03	0.92	1.8	0.583	
M04	0.85	1.6	0.500	
M05	0.58	1.0	0.310	
M06	0.91	2.1	0.662	
M07	0.57	1.1	0.344	
REFERRED AVERAGE	0.81	1.7	0.531	

Table 3-7.3f Jess M08 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M08

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	344	6	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	4.3	1.000	98
Referred:				
M01	0.86	1.7	0.388	
M02	0.96	3.4	0.788	
M03	0.91	2.4	0.549	
M04	0.93	2.3	0.541	
M05	0.66	1.5	0.355	
M06	0.90	2.5	0.572	
M07	0.80	2.2	0.499	
REFERRED AVERAGE	0.86	2.3	0.527	

Table 3-7.3g Jess M08 row, low winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	25	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	3.7	1.000	405
Referred:				
M01	0.80	1.1	0.297	
M02	0.92	2.6	0.684	
M03	0.83	1.6	0.427	
M04	0.84	1.6	0.420	
M05	0.36	0.8	0.211	
M06	0.82	1.7	0.448	
M07	0.72	1.4	0.364	
REFERRED AVERAGE	0.76	1.5	0.407	

Table 3-7.3h Jess M08 row, moderate winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M08

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	15	65	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	5.4	1.000	389
Referred:				
M01	0.79	2.0	0.366	
M02	0.90	4.1	0.760	
M03	0.84	2.7	0.494	
M04	0.83	2.6	0.482	
M05	0.49	1.5	0.282	
M06	0.82	2.7	0.507	
M07	0.76	2.5	0.456	
REFERRED AVERAGE	0.78	2.6	0.478	

Table 3-7.3i Jess M08 row, high winds

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	25	65	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	8.0	1.000	118
Referred:				
M01	0.86	4.3	0.541	
M02	0.93	7.3	0.902	
M03	0.91	5.4	0.676	
M04	0.89	5.2	0.646	
M05	-0.24	2.7	0.337	
M06	0.89	5.4	0.671	
M07	0.86	5.6	0.704	
REFERRED AVERAGE	0.73	5.1	0.639	

Table 3-7.3j Jess M08 row, daylight hours

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M08

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	322	344	deg.
Screen by Time:	YES	---	08:00	17:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	4.8	1.000	235
Referred:				
M01	0.87	2.0	0.422	235
M02	0.96	4.0	0.827	234
M03	0.91	2.7	0.570	235
M04	0.90	2.6	0.554	235
M05	0.51	1.4	0.294	235
M06	0.89	2.8	0.586	235
M07	0.74	2.3	0.486	235
REFERRED AVERAGE	0.83	2.5	0.534	

Table 3-7.3k Jess M08 row, nightime hours

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	322	344	deg.
Screen by Time:	YES	---	19:00	05:00	hrs

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M08	1.00	4.0	1.000	147
Referred:				
M01	0.79	1.2	0.297	
M02	0.92	2.7	0.659	
M03	0.85	1.7	0.409	
M04	0.90	1.5	0.383	
M05	0.62	1.1	0.273	
M06	0.86	1.7	0.419	
M07	0.84	1.6	0.401	
REFERRED	0.83	1.6	0.406	

Table 3-7.3l Jess M13 row, parallel winds

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	322	344	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size	Availability %
Reference:					
M13	1.00	4.7	1.000	540	94.3
Referred:					
M09	0.91	2.9	0.616	540	61.2
M11	0.64	1.4	0.292	539	67.1
M12	0.83	2.1	0.453	540	95.5
N01	0.88	2.4	0.504	539	93.2
N02	0.90	2.4	0.515	540	93.9
N03	0.93	3.4	0.714	540	93.7
REFERRED AVERAGE	0.85	2.4	0.516		84.1

Table 3-7.3m Jess M13 row, -22 degrees

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	300	322	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M13	1.00	3.0	1.000	481
Referred:				
M09	0.92	1.9	0.617	479
M11	0.59	0.8	0.264	481
M12	0.87	1.5	0.498	481
N01	0.90	1.5	0.506	480
N02	0.92	1.6	0.512	481
N03	0.94	2.3	0.765	481
REFERRED AVERAGE	0.86	1.6	0.527	

Table 3-7.3n Jess M13 row, +22 degrees

WINDFARM CORRELATION REPORT

REPORT INTERVAL: WINTER 87-88 Correlation Variable: ENERGY

Reference Turbine: M13

	Screen Enabled	Screening Turbine	Minimum (from)	Maximum (to)	Units
Screen by Speed:	YES	J08	9	65	mph
Screen by Direction:	YES	J08	344	6	deg.

Turbine	Correlation Coefficient	Mean	Ratio Of Means	Sample Size
Reference:				
M13	1.00	4.4	1.000	120
Referred:				
M09	0.94	3.1	0.695	120
M11	0.80	1.8	0.408	119
M12	0.84	2.1	0.487	120
N01	0.89	2.6	0.590	120
N02	0.92	2.6	0.599	120
N03	0.94	3.5	0.805	120
REFERRED AVERAGE	0.89	2.6	0.597	

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16. Abstract (Limit: 200 words)
This report is ninth in a series of documents presenting the findings of field tests under DOE's Cooperative Field Test Program (CFTP) with the wind industry. This report provides results of a project conducted by Altamont Energy Corp. (AEC) to measure wake deficits on the Jess and Sousa Ranches in Altamont Pass, CA. This research enhances and complements other DOE-funded projects to refine estimates of wind turbine array effects. This project will help explain turbine performance variability caused by wake effects.

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