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CHARACTERIZATION OF THE LGFSTF WIND TUNNEL IN PREPARATION FOR THE DOE/EPA HAZARDOUS CHEMICAL EVAPORATION RATE EXPERIMENTS

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SUMMARY

The Environmental Protection Agency and the Department of Energy are conducting chemical evaporation rate experiments in the DOE's Liquefied Gaseous Fuels Spill Test Facility (LGFSTF) wind tunnel to determine the effect on evaporation rate of pool temperature and wind speed. Evaporation rates measured in these tests will be used to verify mathematical models used to define the source (gas) rate inputs to dispersion models.

In preparation for the experiments the LGFSTF tunnel has been modified to provide for the simulation of an atmospheric boundary layer flow on the tunnel floor. This report describes work performed by the DOE Modeling Support Center at the University of Arkansas to define (characterize) the turbulence properties in the boundary layer of the (modified) wind tunnel test section.

Hot wire anemometry measurements were made to characterize the boundary layer flow over the evaporation test pan. Mean velocity and turbulence statistics were measured along a vertical line (extending from 0.5 cm to 60 cm above the tunnel floor) located on the tunnel centerline immediately upwind of the evaporation pan.

The x-direction mean velocity data were analyzed to estimate the applicable values of the surface roughness and friction velocity for four tunnel (variable frequency controller) speed settings: 15 Hz, 30 Hz, 45 Hz, and 60 Hz.

The following values for z_R and u_* are recommended.

$z_R = 4.8 \times 10^{-4}$ m

For 15 Hz fan speed, $u_* = 0.0835$ m/s

For 30 Hz fan speed, $u_* = 0.171$ m/s

For 45 Hz fan speed, $u_* = 0.263$ m/s

For 60 Hz fan speed, $u_* = 0.370$ m/s

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INTRODUCTION

The Environmental Protection Agency and the Department of Energy are conducting at the DOE's Liquefied Gaseous Fuels Spill Test Facility (LGFSTF) a cooperative research program to study the consequences of accidental releases of hazardous chemicals. The research program, designed to address requirements of the Clean Air Act, is currently divided into two parts:

> Baseline dispersion experiments. Carbon dioxide is used as a surrogate (denser-than-air) gas to study atmospheric dispersion. Controlled-rate releases of carbon dioxide from ground level low-momentum sources (to simulate evaporation from liquid pools) with dispersion over smooth, flat terrain are being performed to provide data sets for mathematical model verification. The baseline experiments will also provide a basis for comparison with experiments planned to determine the effects on dispersion of flow obstacles (such as buildings) and nonuniform terrain. Experiments are being conducted in neutral as well as stable meteorological conditions (stable conditions normally constitute the greatest hazard to the public).

> Chemical evaporation rate experiments. Wind tunnel (controlled) experiments will determine the effect on evaporation rate of pool temperature and wind speed for hazardous chemicals. Evaporation rates measured in these tests will be used to verify mathematical models used to define the source (gas) rate inputs to dispersion models. Initial experiments are planned to study evaporation of ammonia and chlorine. Experiments will be conducted in the LGFSTF wind tunnel.

The chemical evaporation rate experiments are being performed in the LGFSTF wind tunnel in order to provide for accurate specification and control of the wind conditions. The LGFSTF wind tunnel was constructed by an industry consortium in the late 1980's to study water curtain mitigation of hazardous chemical releases. The tunnel was designed to provide a uniform flow (over the tunnel cross-section).

In preparation for the proposed chemical evaporation rate experiments the LGFSTF tunnel has been modified to provide for the simulation of an atmospheric boundary layer flow on the tunnel floor. The boundary layer generation facilities were installed in the tunnel in early 1995 by the Western Research Institute. The DOE Modeling Support Center (MSC) at the University of Arkansas performed measurements in late February, 1995, to define (characterize) the turbulence properties in the boundary layer of the (modified) wind tunnel test section. This report describes the work performed and the results obtained by the MSC.

MODIFICATIONS TO THE LGFSTF TUNNEL FOR THE CHEMICAL EVAPORATION RATE EXPERIMENTS

The purpose of this section is to briefly describe the LGFSTF tunnel and the modifications performed by Western Research Institute to provide a simulated atmospheric boundary layer flow in the tunnel test section. Figure 1 is a photograph of the LGFSTF tunnel taken at the time of the (characterization) measurement program in late February 1995. The central section of the tunnel is 96 feet long, 8 feet wide, and 16 feet tall. Wind is pulled through the tunnel by an 84-inch axial fan (located at the left end of the tunnel in Figure 1) which provides for wind speeds to about 6.5 m/s. The tunnel inlet (right end of tunnel in Figure 1) is fitted with an inlet contraction (approximately 3.6:1) designed to reduce turbulence in the inlet flow. (The reflecting surface in Figure 1 is water; the lake bed was covered with water to a depth of 2-3 inches following rains in January-February.)

Figure 2 shows elevation and plan views of the tunnel along with details of the section of the tunnel which has been modified for the chemical evaporation experiments. The description is limited to those features which are important to the description of the simulated atmospheric boundary layer (designed specifically for the evaporation experiments) and to the the description of the measurements reported here.

The experiments are designed to provide measurements of the evaporation rates of chlorine and ammonia into a (simulated) atmospheric boundary layer flow. The primary variables to be considered are liquid (pool) temperature (which will be controlled at a desired setting) and the wind speed. The evaporation rate will be determined by measuring the rate of liquid weight loss from an evaporation pan. The evaporation rate measurement pan is positioned on the tunnel centerline so that the surface of the liquid in the pan is flush with the wind tunnel floor (Figure 3, looking upwind). Measurements of the evaporation rate will be made from the pan on the tunnel centerline. Two additional pans (downwind and to either side of the test pan) are used as intermediate fluid reservoirs to facilitate liquid level control in the test pan.

A (simulated) atmospheric boundary layer is generated with "Irwin spire" turbulence generators followed by a surface roughness section which extends to the (evaporation pan) measurement test section. The spire turbulence generators (fabricated by WRI) were constructed of 1/2" plywood. Eight spires are positioned across the tunnel (separation distance = 1 foot) approximately 4 feet downwind of a 3/8" cell size honeycomb flow straightener (Figure 4, looking upwind). Each spire comprises a triangular shape 22 3/8" tall with a base dimension of 2 7/8". The triangular spire is placed perpendicular to the wind. A 1/2" thick, right triangular stiffener with a 6" base (dimension) and 19 1/8" height is attached to the downwind side of the spire to provide for rigid attachment to the tunnel floor. The wind tunnel floor immediately downwind of the spires, extending approximately 12 feet downwind to the evaporation pan, is covered with rectangular shape roughness elements

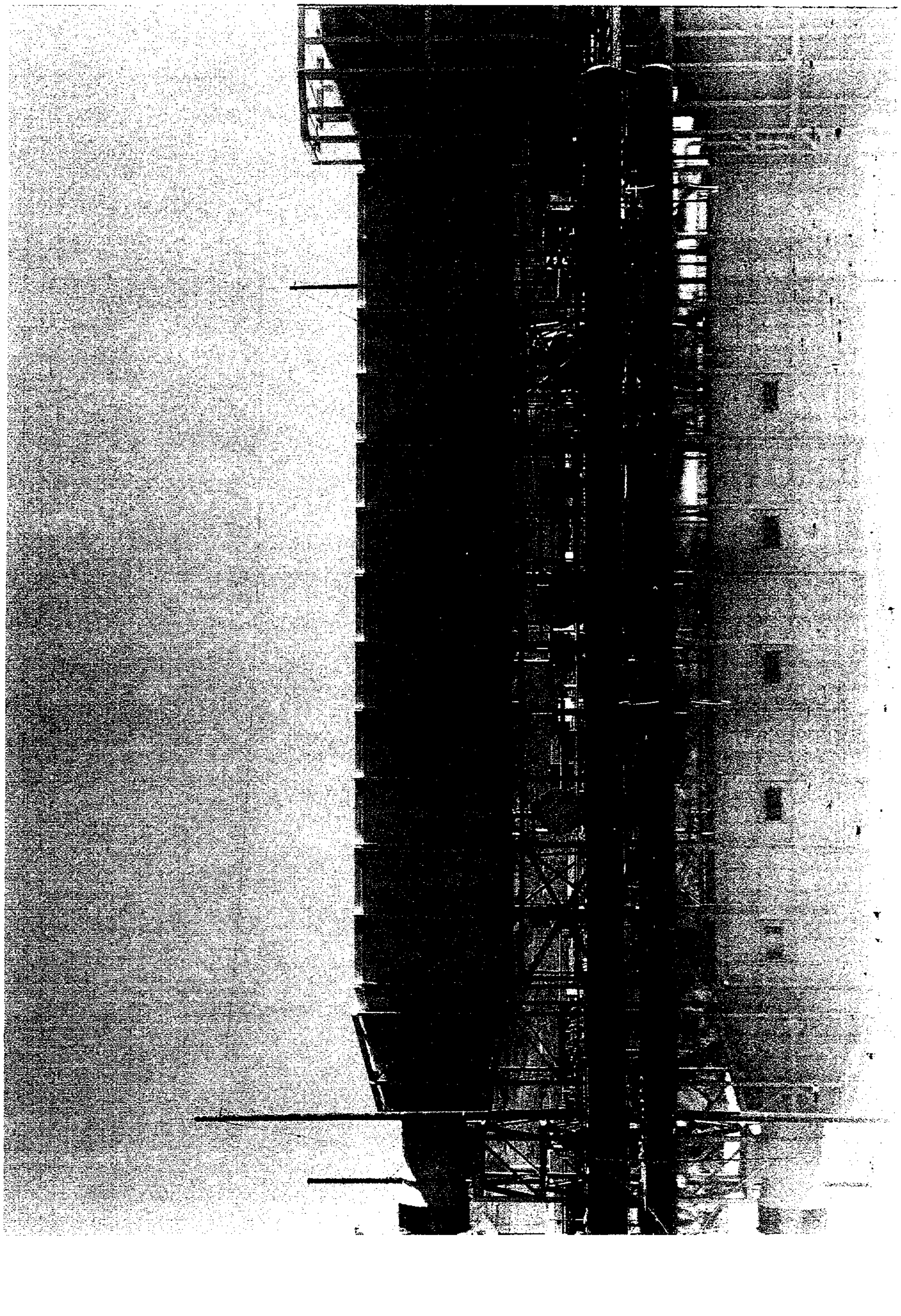

Figure 1. LGFSTF wind tunnel (February 1995)

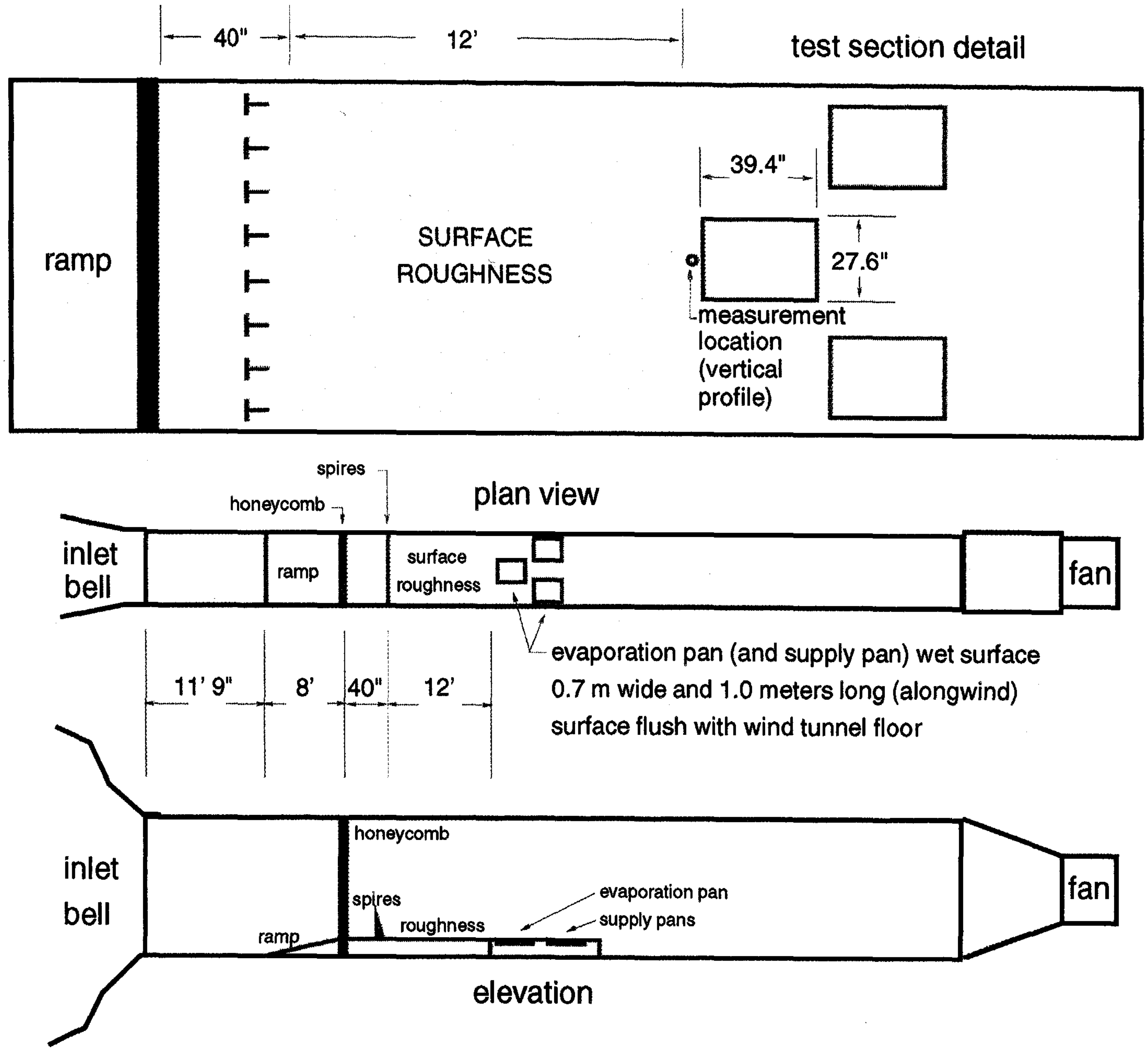

Figure 2. Tunnel modifications for chemical evaporation experiments

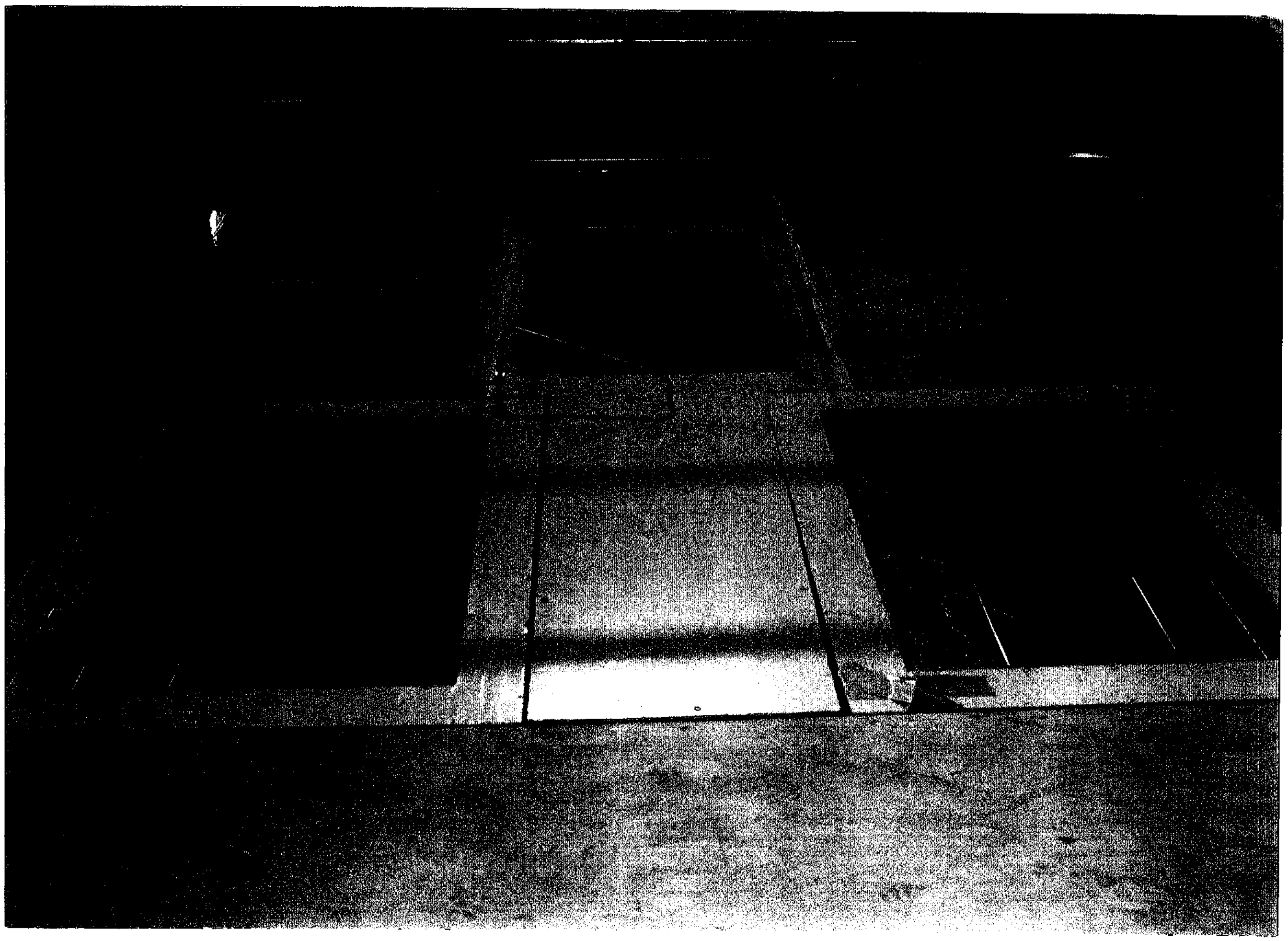

Figure 3. Chemical evaporation rate pan layout (looking upwind)

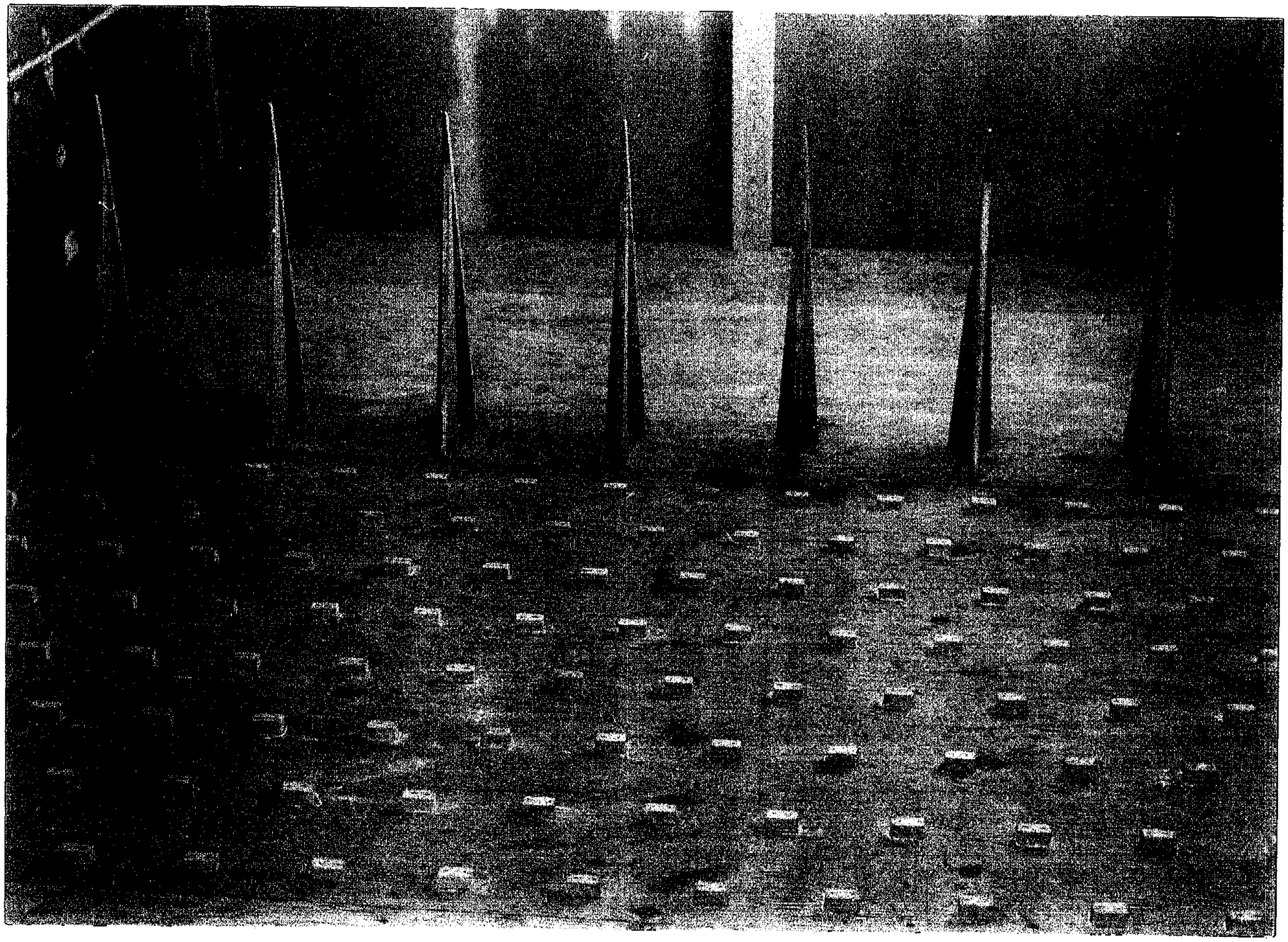

Figure 4. Boundary layer generation spires (looking upwind)

(Figure 5, looking downwind). The individual roughness element dimensions are 3/4" x 3/4" by 1.5", and the elements are laid out in a staggered array (6" centers) with the long dimension of the elements horizontal and perpendicular to the wind direction.

MEASUREMENTS PERFORMED TO CHARACTERIZE THE SIMULATED ATMOSPHERIC BOUNDARY LAYER

Wind Tunnel Fan Calibration

The LGFSTF tunnel was originally designed to provide for only two or three different operating speeds, and speed selection was accomplished by changing the motor/fan-shaft (belt-driven) pulley ratio. In 1994, the LGFSTF wind tunnel fan was fitted with a variable frequency controller (VFC) to allow for variable speed selection. Since no calibration of the VFC had been done, the MSC performed in late 1994 a calibration of the tunnel centerline wind speed vs. VFC setting (0 to 60 Hz) in preparation for the wind tunnel characterization reported here. The wind speed vs. VFC setting calibration was performed in the empty tunnel (neither the boundary layer generation equipment nor the honeycomb flow straightener was installed). The wind velocity was measured on the tunnel centerline approximately 20 feet from the downwind end of the rectangular (8 feet by 16 feet) test section.

The wind (mean) velocity was measured with a TSI Model 8450 air velocity transducer powered with a TSI Model 8910 display/power supply. The display/power supply provides 12 volt power to the transducer, accepts a 0-5 volt signal from the transducer, and displays an output that is linearly proportional to the signal. The transducer was calibrated by TSI using standards traceable to the National Institute of Standards and Technology, and the velocity measurements are considered to be accurate to within 1.5% of reading. The wind tunnel centerline velocity was measured at 5 Hz (VFC setting) increments from 5 Hz to 60 Hz. Wind speed and direction were monitored from the LGFSTF Meteorological Tower (located approximately 100 meters southwest of the tunnel) during the calibration.

Figure 6 illustrates the resulting calibration. Figure 6 shows three (repeat) measurements of the (mean) velocity at each VFC setting along with the straight line curve through the mean of the repeat measurements at each VFC setting. Figure 6 also indicates three (repeat) readings, at 30 and 60 Hz VFC settings, obtained when the air velocity sensor was positioned about 18" from the side wall of the wind tunnel (at ~8 feet height) approximately 5 feet downwind of the centerline position, as well as the mean value of the repeat readings. Last, per request by the LGFSTF facility manager, Figure 6 indicates the tunnel volumetric flow rate in CFM (ft^3/min), estimated as centerline velocity times tunnel cross sectional area times 0.9, as a function of VFC setting. The calibration curve of centerline wind speed vs. VFC setting is linear,

Figure 5. Roughness extending to evaporation pan (looking downwind)

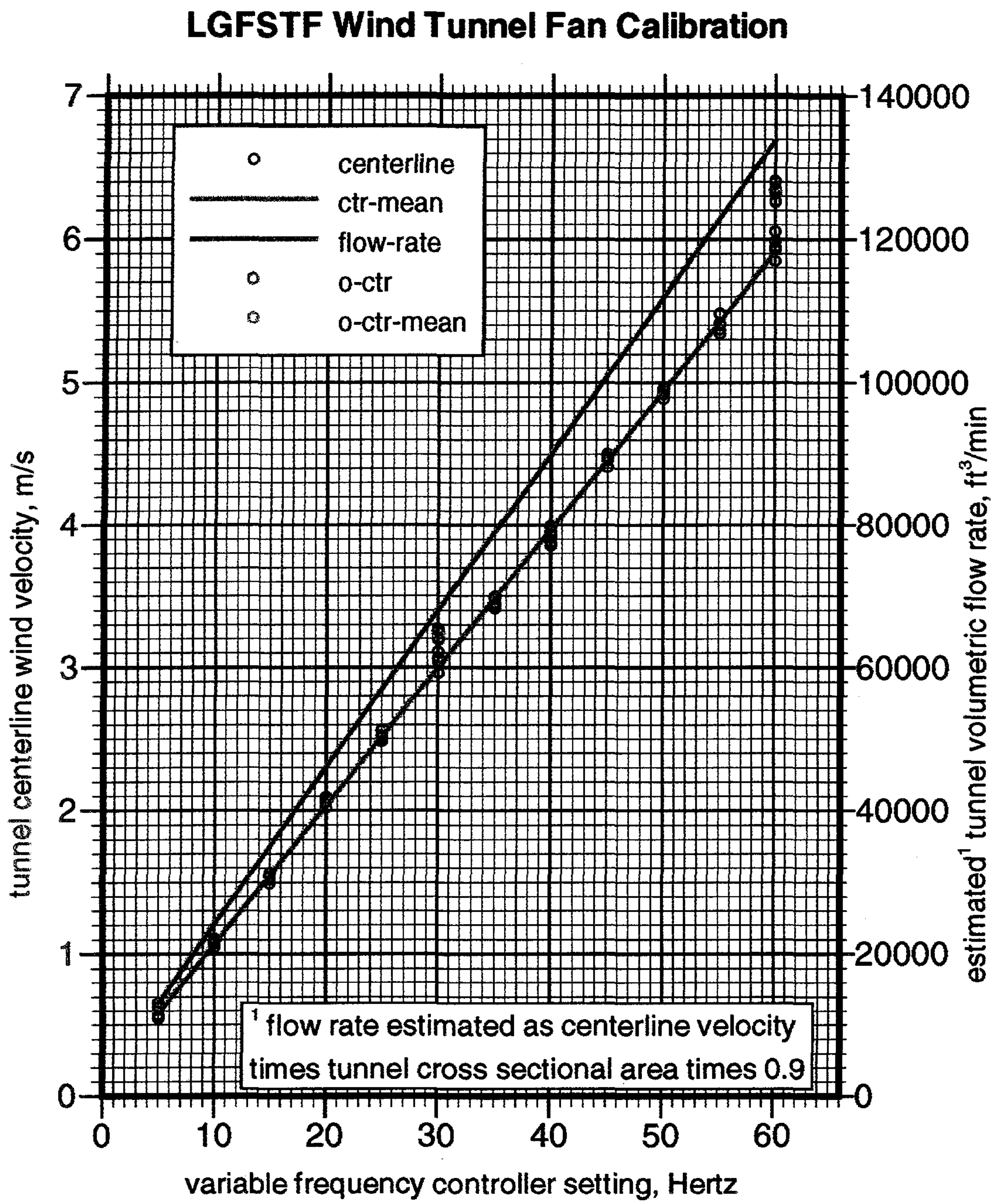

Figure 6. LGFSTF wind tunnel fan speed calibration

and it appears to have been influenced minimally by the exterior wind speed and direction variability experienced during the calibration period (Figure 7).

Wind Tunnel Boundary Layer Characterization

Measurements were made to characterize the boundary layer flow over the evaporation test pan. The mean velocity and turbulence statistics were measured along a vertical line (extending from 0.5 cm to 60 cm above the tunnel floor) located on the centerline, approximately 2 inches upwind of the upwind edge of the liquid (Figure 8). Measurements were made at elevations 0.5 cm, 1.5 cm, 2.7 cm, 4.2 cm, 5.9 cm, 8.0 cm, 10.5 cm, 13.5 cm, 17.1 cm, 21.4 cm, 26.6 cm, 32.8 cm, 40.3 cm, 49.2 cm, and 60.0 cm, for each of four VFC settings; 15 Hz, 30 Hz, 45 Hz, and 60 Hz. Two measurements (at different times) were made at each position.

The measurements were made with a TSI Model 1500 Series FLOWPOINT thermal anemometer-based system. The FLOWPOINT unit is a two-channel constant temperature anemometer with built-in signal conditioning and with a thermocouple circuit for measuring fluid temperature and correcting for variations therein (Figure 9). For this application, the two channels were connected to a TSI 1248-10 sub-miniature X-film sensor, and the X-film sensor was oriented to measure the x-direction (alongwind) and y-direction (vertical) components of the velocity. The X-film sensor was mounted on a TSI Model 1191 1-axis traverse system which interfaced with the FLOWPOINT software to provide for (remote) computer positioning of the X-film in the wind tunnel (see Figures 5 and 8). Figure 10 shows the X-film sensor positioned for the measurement at 0.5 cm height (Note that the first two measurements in the vertical profile, at 0.5 cm and 1.5 cm, are below the height of the roughness elements). The measurement system (except for the traverse-mounted-sensor) was located on the wind tunnel (outside) catwalk under a temporary shelter fabricated with plywood (Figure 11).

The X-film anemometer sensor was calibrated each day immediately before the measurement period (errors due to sensor drift should be negligible). The sensor was calibrated by placement on the centerline of a laminar-tube-flow. A 1/2" Plexiglass tube (approximately 60" length) was used to provide the laminar calibration flow. Bottled (breathing) air, controlled and measured with an MKS mass flow control system, was directed through the tube to achieve (centerline) air velocities spanning the calibration range of interest.

Measurements in the boundary layer were made with different sampling periods and at different sampling rates as follows:

15 Hz fan speed - 100 Hz for 102 seconds
30 Hz fan speed - 200 Hz for 51 seconds
45 Hz fan speed - 200 Hz for 51 seconds
60 Hz fan speed - 200 Hz for 51 seconds

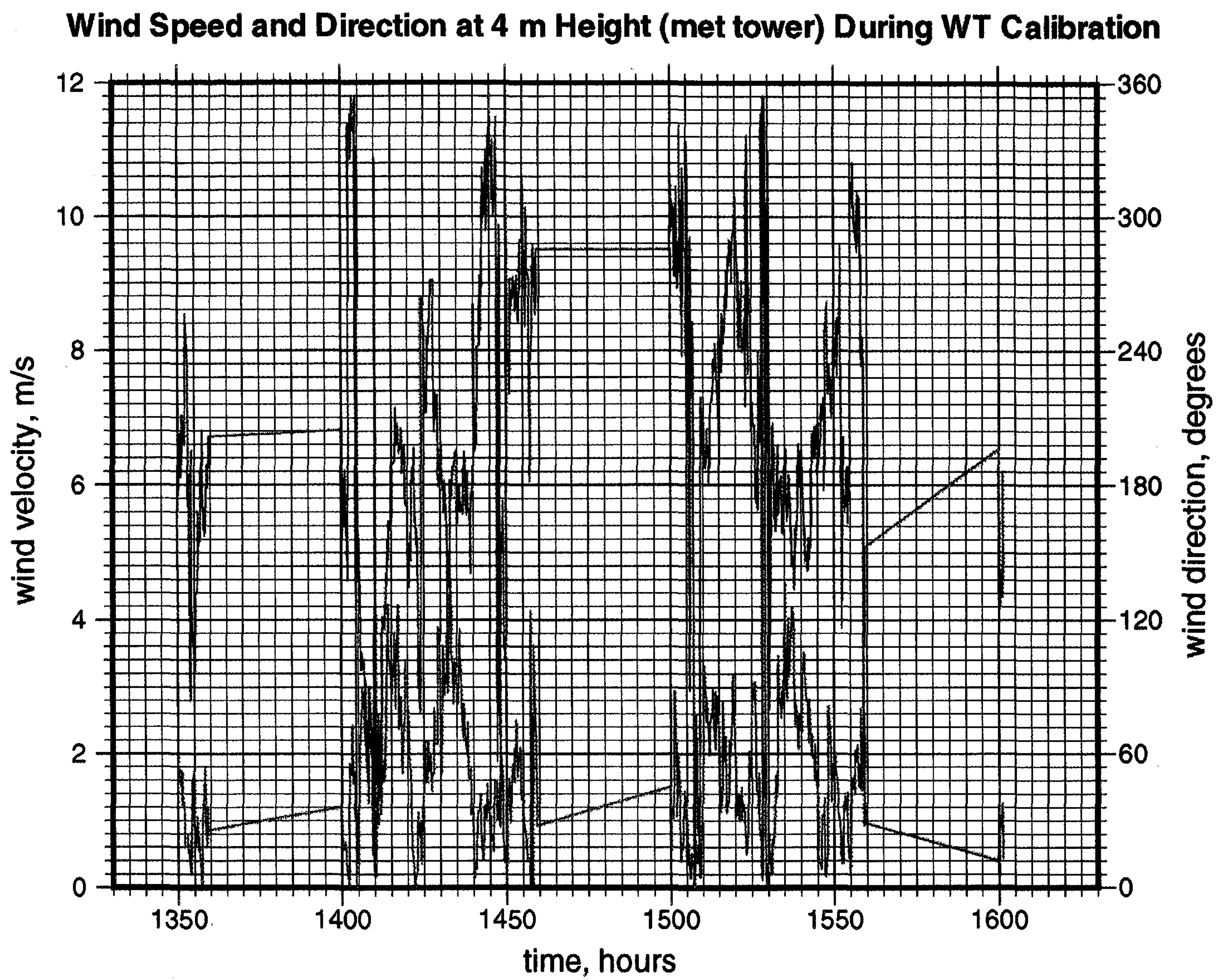

Figure 7. Wind speed and direction during fan speed calibration

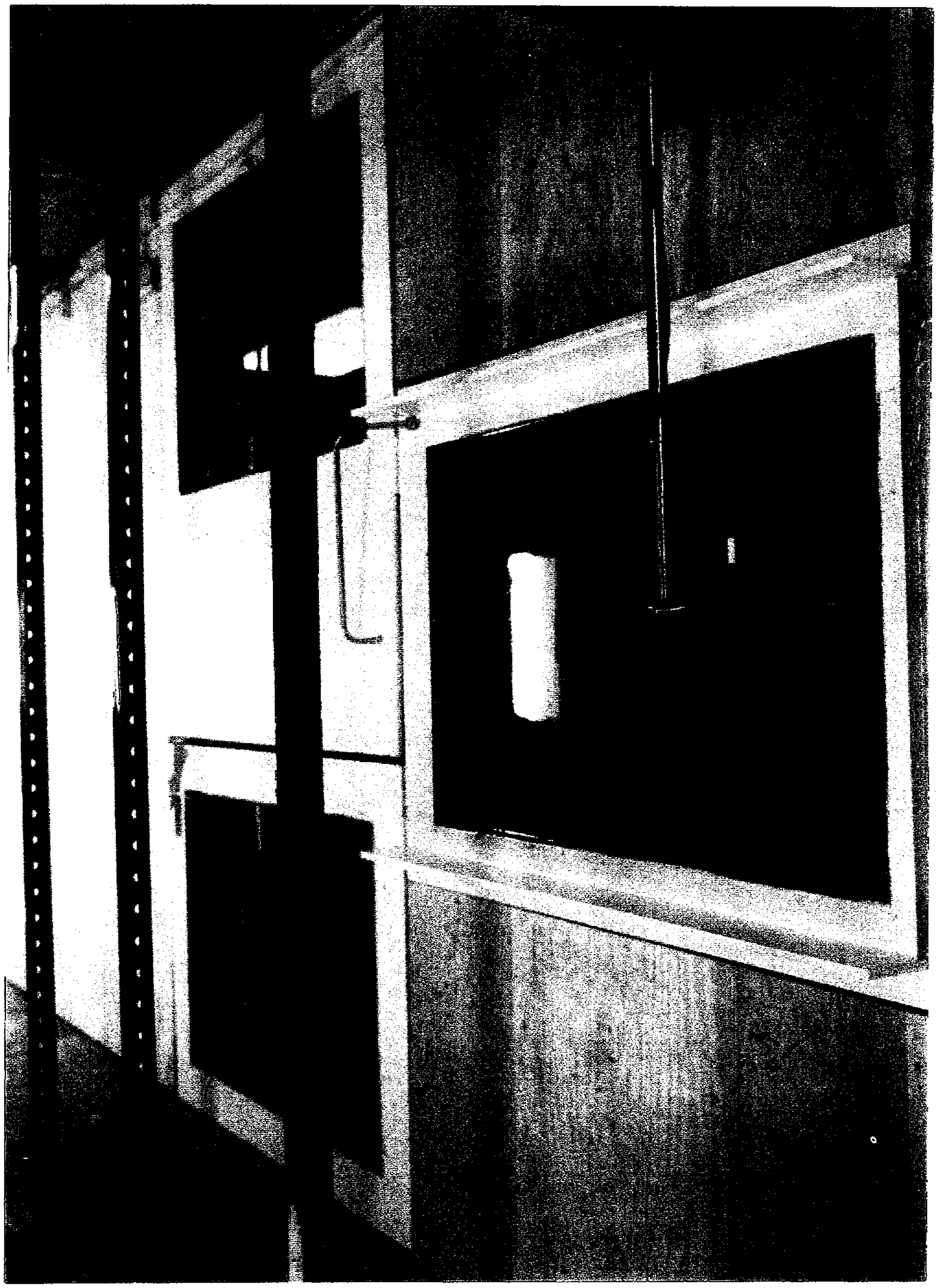

Figure 8. Traverse mounted anemometer probe (looking downwind)

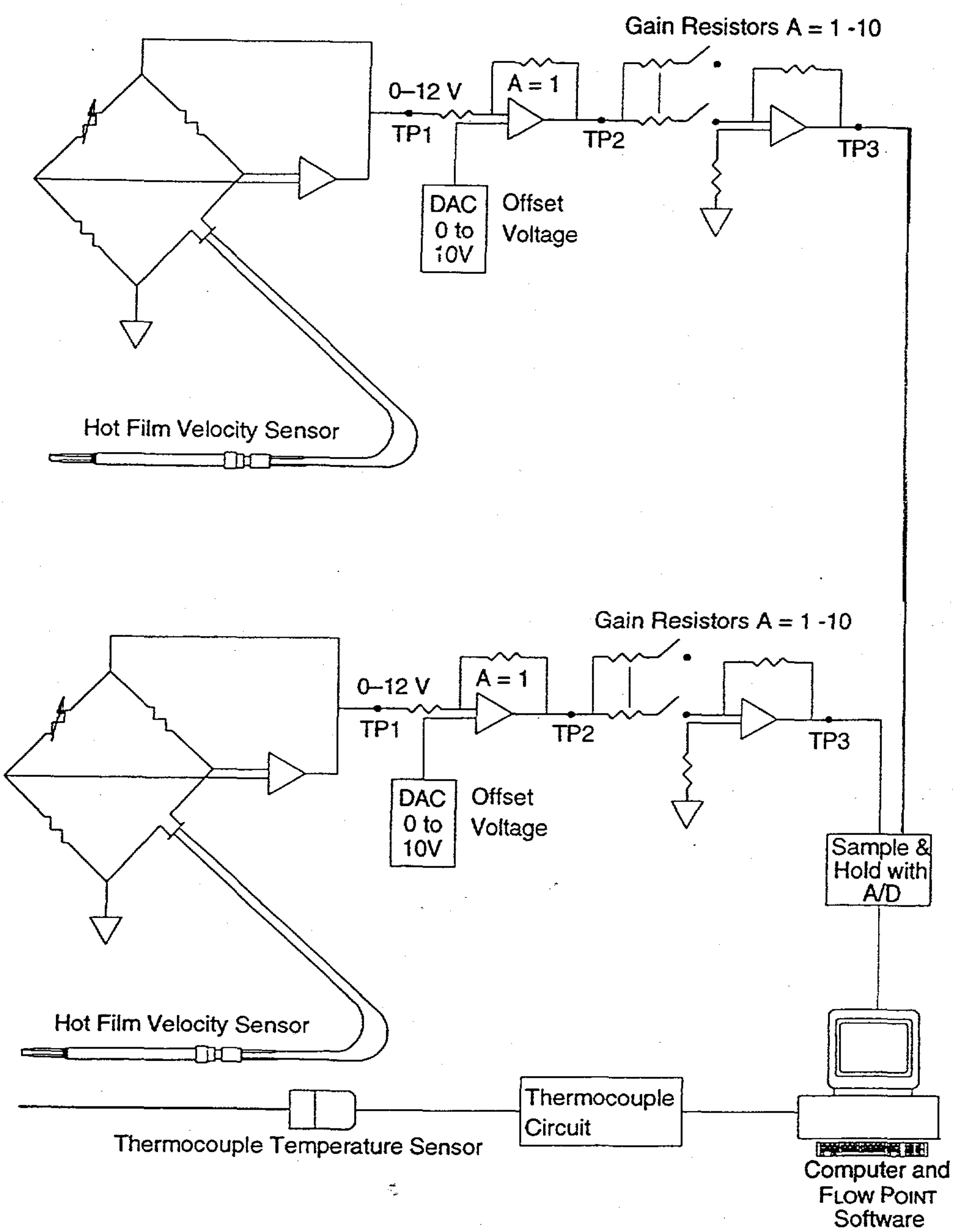

Figure 9. Functional overview of hot wire anemometer system

Figure 10. Anemometer probe positioned for measurement

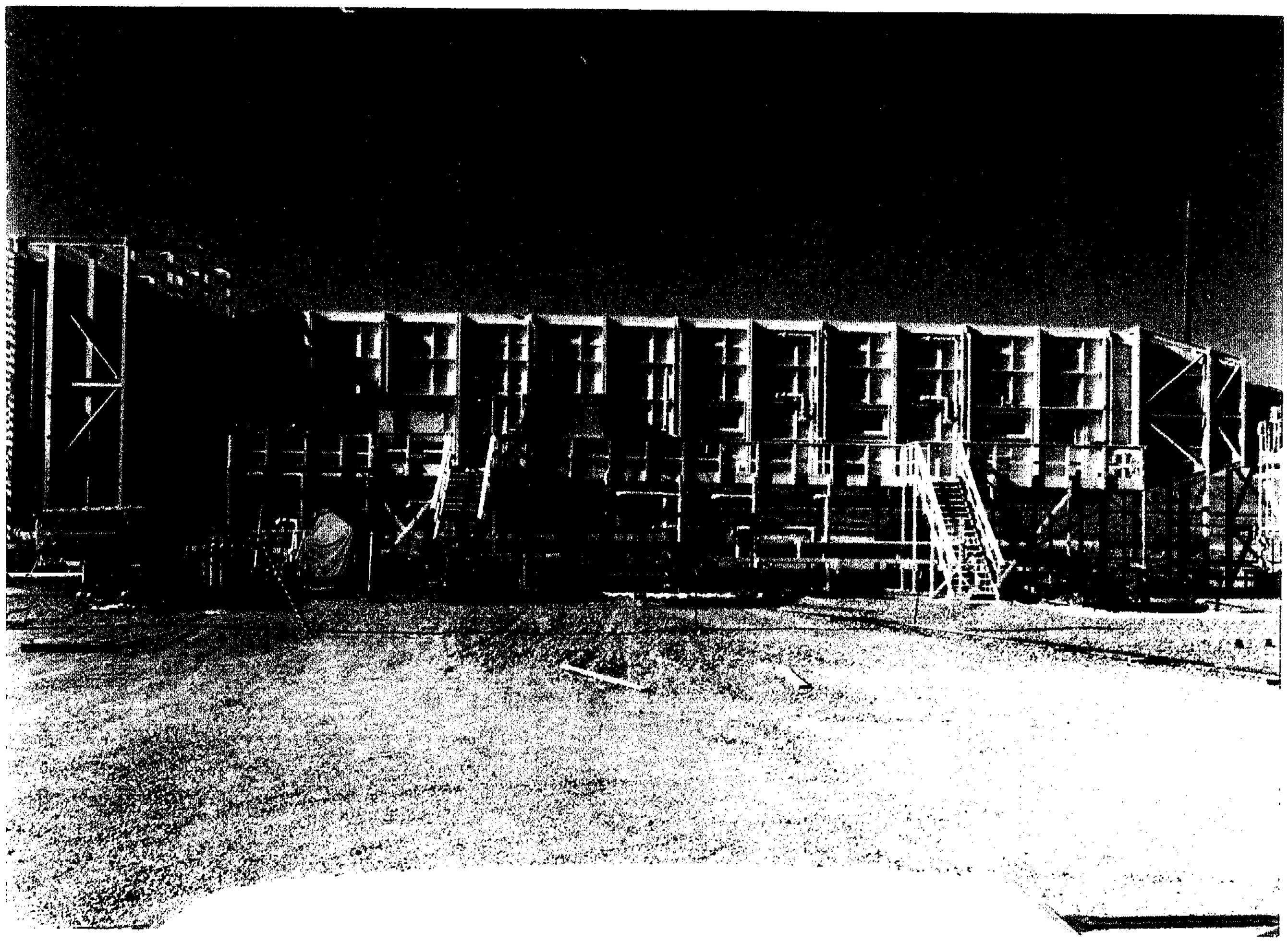

Figure 11. Temporary shelter for anemometer system on tunnel catwalk

For each of the measurements, the first four moments about the mean of each vector component; M_1, M_2, M_3, and M_4, are defined as

$$M_k(x_i, 0) = \frac{1}{n} \sum_{i=1}^{n} x^k$$

where x_i is the i^{th} data point in the sequence of length n.

For each of the velocity components, the following statistical parameters (constructed from its moments) are computed:

1. velocity mean: $U = M_1$
2. standard deviation: $\tau = (M_2 - M_1^2)^{1/2}$
3. turbulence intensity: $T = (\tau/M_1)\text{x}100$
4. skewness coefficient: $\delta_1 = (M_3 - 3M_2M_1 + 2M_1^3)/\tau^3$
5. flatness coefficient: $\delta_2 = (M_4 - 4M_3M_1 + 6M_2M_1^2 - 3M_1^4)/\tau^4$

By combining the statistics for the two velocity components, the following values are calculated for the X-film probe, where the x component is designated with the subscript u and the y component is designated with the subscript v:

1. resultant velocity: $V = (U_u^2 + U_v^2)^{1/2}$
2. direction angle: $\theta_u = \cos^{-1}(U_u/V)$
3. shear stress (covariance): $cov(u,v) = 1/n\ (cp(u,v) - nU_uU_v)$
4. correlation coefficient: $r(u,v) = cov(u,v)/(\tau_u\tau_v)$

where $cp(u,v) = \sum_{i=1}^{n} u_i v_i$

The velocity statistics for the data sets selected for analysis (several of the first data sets measured were trials to optimize the sampling period and frequency; they were not used) are included as Appendix A. The primary statistics of interest are presented graphically in Figure 12 as follows:

U_u	mean velocity (x-component)
τ_u	standard deviation (x-component)
T_u	turbulence intensity (x-component)
δ_{1u}	skewness coefficient (x-component)
δ_{2u}	flatness coefficient (x-component)
θ_u	direction angle (from x-direction)
cov(u,v)	covariance, or shear stress
r(u,v)	correlation coefficient
U_v	mean velocity (y-component)
τ_v	standard deviation (y-component)
δ_{1v}	skewness coefficient (y-component)
δ_{2v}	flatness coefficient (y-component)
	air temperature

Figure 12 (as well as Appendix 1) includes all data taken for characterization of the wind tunnel boundary layer at the four wind speeds 15 Hz, 30 Hz, 45 Hz, and 60 Hz.

The exterior wind speed and direction were monitored during the (characterization) measurement period. However, the wind was essentially calm during the entire period, and the wind speed and direction are not presented here.

CONCLUSIONS

Quality checks of the data indicated no serious errors or omissions.

The mean velocity vertical profiles (reflecting 50 and 100 second averaging times) were smooth, indicating a stable boundary layer flow at the evaporation measurement pan location.

The turbulence intensities (horizontal and vertical components) were typical of wind tunnel rough-surface boundary layers. It appears that the turbulence intensities above the boundary layer are higher than are typically observed in an environmental wind tunnel (> 5% in the LGFSTF tunnel compared to less than 1% in the MSC and EPA wind tunnels). This is probably due to the absence (in the LGFSTF tunnel) of turbulence damping screens.

Skewness and flatness coefficients were representative of near-Gaussian probability density distributions.

Direction angles (relative to the x-direction) were all less than two degrees.

The measured values of shear stress were somewhat smaller than the shear stress calculated by log-law fitting of the vertical mean velocity profiles. Because of possible limitations on resolution (by the 12 bit

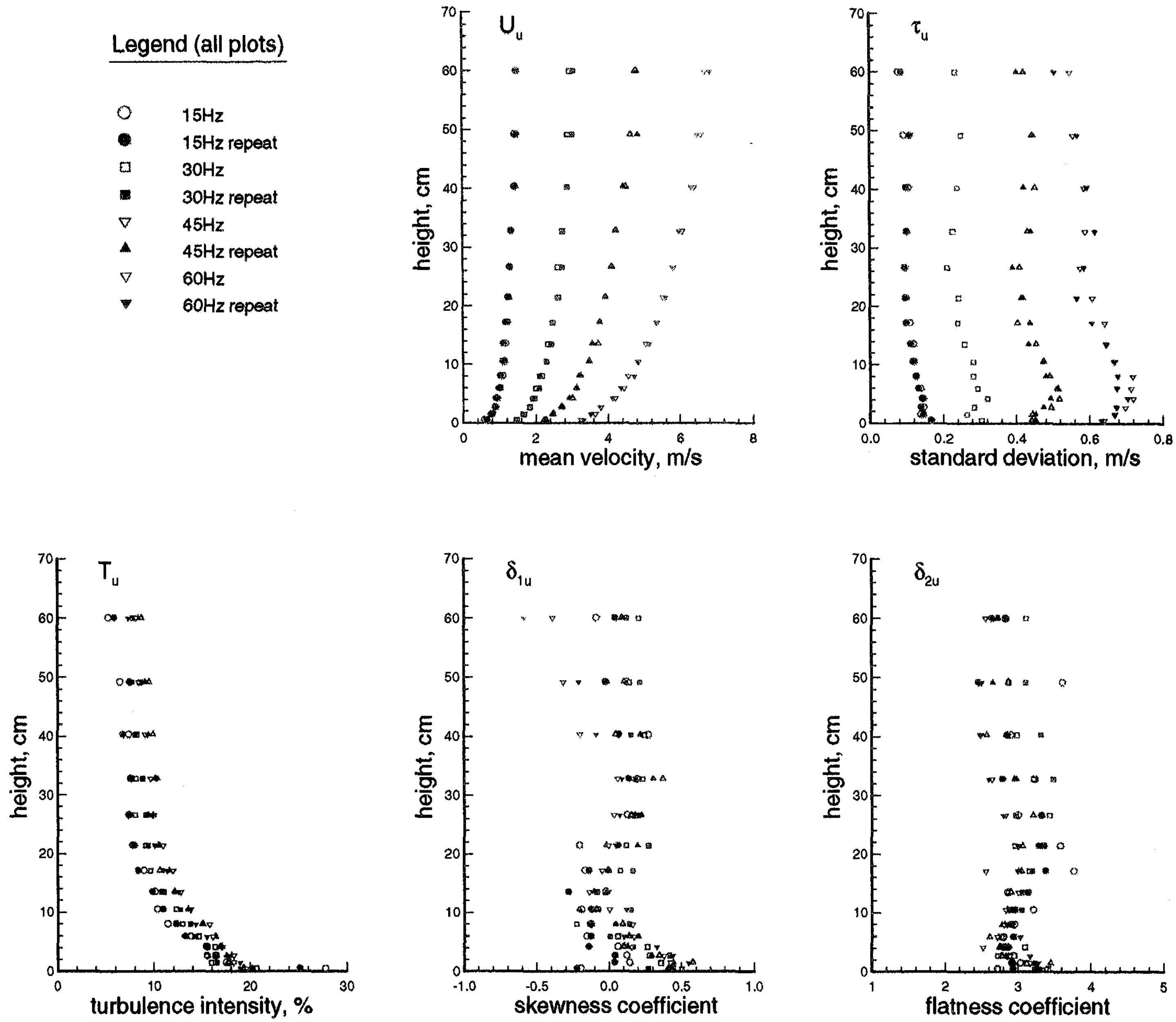

Figure 12. Presentation of turbulence statistics for boundary layer

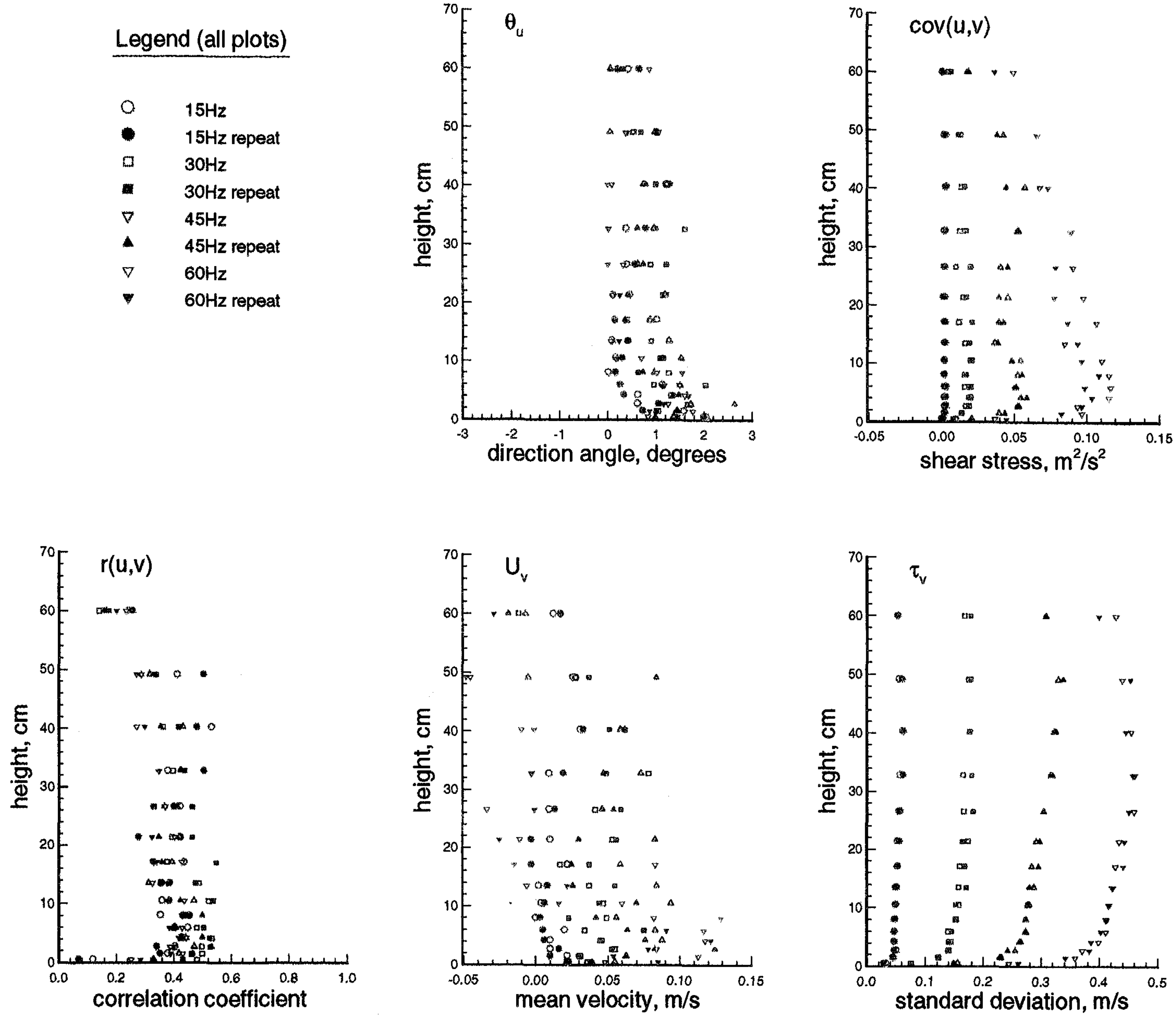

Figure 12. Presentation of turbulence statistics for boundary layer (continued)

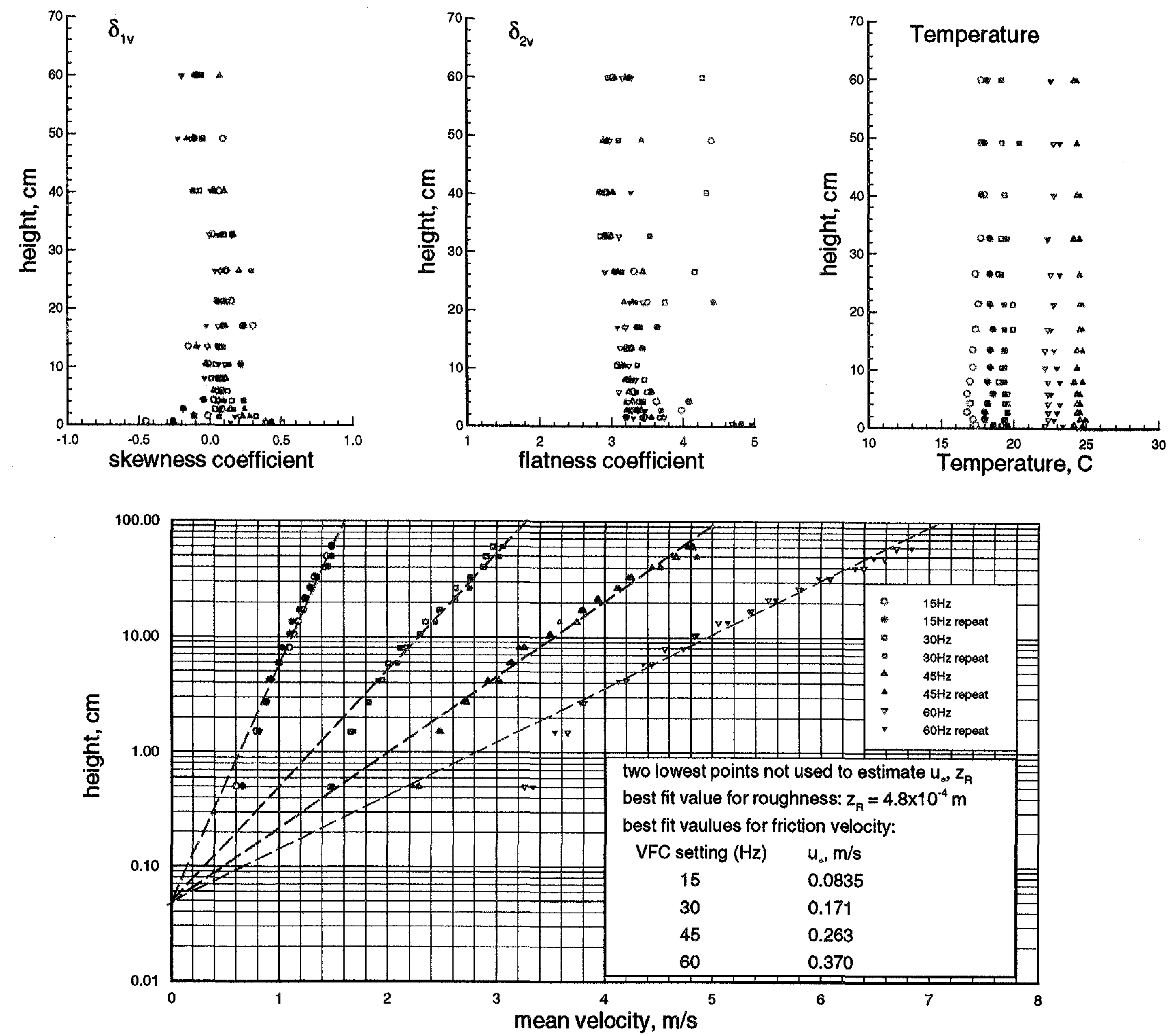

Figure 12. Presentation of turbulence statistics for boundary layer (continued)

digital data acquisition system) of the velocity fluctuations, the log-law fit values are recommended.

The x-direction mean velocity data were analyzed to estimate the applicable values of the surface roughness and friction velocity for each of the four tunnel speeds. The lowest two data points, at 0.5 cm and 1.5 cm elevation, were not used in the analysis because they are below the height of the roughness elements (1.9 cm). All of the remaining data, including two measurements at each measurement location, were then used to estimate the z_R and u_* for each of the four tunnel speeds, with the following results.

Fan Speed	u* (m/s)	zR (m)	95% confidence interval for zR (upper)	(lower)
15 Hz	0.0835	4.81×10^{-4}	3.1×10^{-4}	6.5×10^{-4}
30 Hz	0.163	3.65×10^{-4}	2.5×10^{-4}	4.8×10^{-4}
45 Hz	0.277	6.51×10^{-4}	4.3×10^{-4}	8.8×10^{-4}
60 Hz	0.390	6.55×10^{-4}	4.8×10^{-4}	8.3×10^{-4}

Since there was no definite trend in the values of surface roughness values indicated (as a function of the wind speed), $z_R = 4.8 \times 10^{-4}$ m was selected (representing the entire data set within the 95% confidence interval) and the values of friction velocity were redetermined, with the following (recommended) results.

$z_R = 4.8 \times 10^{-4}$ m

For 15 Hz fan speed, $u_* = 0.0835$ m/s

For 30 Hz fan speed, $u_* = 0.171$ m/s

For 45 Hz fan speed, $u_* = 0.263$ m/s

For 60 Hz fan speed, $u_* = 0.370$ m/s

Appendix

Summary of Boundary Layer Characterization Data

LGFSTF tunnel vertical profile data, length mm, velocity m/s

15 Hz

x	y	z	U_u	τ_u	T_u	δ_{1u}	δ_{2u}	θ_u	cov	r	U_v	τ_v	T_v	δ_{1v}	δ_{2v}	Temperature
0.000	0.500	0.000	0.606	0.168	27.823	-0.192	2.723	2.058	0.001	0.120	0.022	0.033	150.872	-0.447	9.093	17.400
0.000	1.500	0.000	0.792	0.139	17.538	0.143	3.043	1.590	0.002	0.379	0.022	0.045	205.248	-0.013	3.462	17.200
0.000	2.700	0.000	0.885	0.146	16.443	0.124	2.949	0.621	0.003	0.404	0.010	0.050	517.119	0.087	3.988	16.800
0.000	4.200	0.000	0.929	0.144	15.493	0.062	2.824	0.630	0.002	0.428	0.010	0.047	456.388	0.030	3.636	17.000
0.000	5.900	0.000	1.010	0.139	13.803	-0.154	2.802	1.146	0.003	0.449	0.020	0.047	230.736	0.085	3.315	16.800
0.000	8.000	0.000	1.101	0.126	11.412	-0.126	2.957	0.023	0.002	0.354	0.000	0.048	10555.	0.099	5.117	17.000
0.000	10.500	0.000	1.142	0.118	10.361	-0.188	3.214	0.182	0.002	0.360	0.004	0.049	1362.7	-0.009	3.094	17.200
0.000	13.500	0.000	1.183	0.120	10.151	-0.023	2.870	0.092	0.002	0.357	0.002	0.051	2653.6	-0.147	3.221	17.200
0.000	17.100	0.000	1.232	0.111	8.972	-0.165	3.774	1.028	0.002	0.437	0.022	0.053	241.325	0.306	6.559	17.400
0.000	21.400	0.000	1.246	0.098	7.835	-0.202	3.591	0.465	0.002	0.424	0.010	0.053	523.718	0.157	3.505	17.600
0.000	26.600	0.000	1.297	0.096	7.410	0.126	3.010	0.408	0.002	0.422	0.009	0.055	594.507	0.120	3.330	17.400
0.000	32.800	0.000	1.338	0.102	7.606	0.198	3.237	0.399	0.002	0.380	0.009	0.057	609.383	0.025	2.993	17.800
0.000	40.300	0.000	1.433	0.107	7.437	0.276	2.913	1.231	0.003	0.533	0.031	0.062	201.890	0.067	2.941	18.000
0.000	49.200	0.000	1.449	0.095	6.524	0.130	3.621	1.034	0.002	0.414	0.026	0.056	214.765	0.096	4.412	17.800
0.000	60.000	0.000	1.494	0.080	5.340	-0.085	2.838	0.452	0.001	0.244	0.012	0.053	447.432	-0.090	3.031	17.800
0.000	60.000	0.000	1.492	0.088	5.916	0.043	2.648	0.670	0.001	0.257	0.017	0.053	306.054	-0.098	3.272	18.200
0.000	49.200	0.000	1.494	0.112	7.496	-0.026	2.467	1.064	0.003	0.506	0.028	0.061	221.549	-0.102	2.956	18.000
0.000	40.300	0.000	1.460	0.100	6.845	0.071	2.866	1.296	0.003	0.481	0.033	0.063	191.253	0.030	2.847	17.800
0.000	32.800	0.000	1.358	0.103	7.597	0.139	2.793	0.796	0.003	0.505	0.019	0.062	329.990	0.164	2.931	18.400
0.000	26.600	0.000	1.306	0.097	7.446	0.173	3.320	0.581	0.002	0.400	0.013	0.057	430.708	0.118	3.059	18.400
0.000	21.400	0.000	1.259	0.100	7.967	0.063	3.363	0.118	0.001	0.279	-0.003	0.056	2181.7	0.053	4.437	18.400
0.000	17.100	0.000	1.193	0.100	8.366	-0.136	3.381	0.148	0.002	0.330	-0.003	0.052	1667.4	0.242	3.649	18.600
0.000	13.500	0.000	1.126	0.111	9.852	-0.282	3.144	0.427	0.002	0.387	0.008	0.049	583.471	0.061	3.289	18.400
0.000	10.500	0.000	1.105	0.121	10.939	-0.123	2.961	0.311	0.002	0.385	0.006	0.050	835.089	0.219	5.643	18.400
0.000	8.000	0.000	1.038	0.127	12.279	-0.131	2.920	0.172	0.002	0.455	0.003	0.047	1493.2	0.058	3.274	18.200
0.000	5.900	0.000	0.998	0.132	13.192	-0.126	2.940	0.263	0.002	0.401	0.005	0.047	1017.0	0.057	3.554	18.600
0.000	4.200	0.000	0.914	0.142	15.551	-0.138	2.875	0.348	0.003	0.426	0.006	0.047	837.540	-0.043	4.092	18.200
0.000	2.700	0.000	0.885	0.138	15.557	0.041	2.863	1.061	0.002	0.341	0.016	0.047	289.022	-0.184	3.365	18.000
0.000	1.500	0.000	0.819	0.146	17.858	0.038	2.915	0.724	0.002	0.353	0.010	0.046	440.431	-0.109	3.210	18.000
0.000	0.500	0.000	0.665	0.168	25.189	-0.223	2.940	2.003	0.000	0.069	0.023	0.029	125.689	-0.256	5.571	18.600

30 Hz

x	y	z	U_u	τ_u	T_u	δ_{1u}	δ_{2u}	θ_u	cov	r	U_v	τ_v	T_v	δ_{1v}	δ_{2v}	Temperature
0.000	0.500	0.000	1.479	0.306	20.679	0.443	3.416	1.395	0.010	0.482	0.036	0.076	211.953	0.511	5.156	19.200
0.000	1.500	0.000	1.666	0.266	15.987	0.358	3.129	1.060	0.014	0.499	0.031	0.123	397.916	0.325	3.679	19.400
0.000	2.700	0.000	1.832	0.284	15.491	0.284	2.735	1.725	0.017	0.498	0.055	0.141	254.981	0.037	3.272	19.600
0.000	4.200	0.000	1.955	0.320	16.356	0.268	3.102	1.327	0.020	0.534	0.045	0.144	317.776	0.155	3.386	19.600
0.000	5.900	0.000	2.012	0.294	14.638	0.059	2.779	0.960	0.016	0.481	0.034	0.139	412.864	0.126	3.503	19.600
0.000	8.000	0.000	2.180	0.282	12.913	-0.226	2.903	1.280	0.016	0.435	0.049	0.153	312.955	0.011	3.463	19.000
0.000	10.500	0.000	2.303	0.283	12.304	-0.076	2.893	1.166	0.021	0.523	0.047	0.158	336.072	0.042	3.079	19.200
0.000	13.500	0.000	2.354	0.259	11.002	-0.086	2.870	0.895	0.016	0.489	0.037	0.158	429.215	0.082	3.214	19.400
0.000	17.100	0.000	2.484	0.240	9.658	0.079	3.160	0.400	0.012	0.378	0.017	0.160	923.779	0.094	3.385	20.000
0.000	21.400	0.000	2.625	0.241	9.174	0.122	2.971	1.158	0.015	0.395	0.053	0.174	328.171	0.095	3.755	20.000
0.000	26.600	0.000	2.627	0.211	8.047	0.199	3.435	0.893	0.010	0.330	0.041	0.166	404.669	0.120	4.174	19.000
0.000	32.800	0.000	2.768	0.226	8.159	0.236	3.219	1.616	0.013	0.398	0.078	0.165	211.578	0.103	2.860	19.200
0.000	40.300	0.000	2.887	0.239	8.279	0.250	2.996	1.238	0.014	0.363	0.062	0.176	282.230	-0.070	2.918	19.400
0.000	49.200	0.000	2.908	0.250	8.613	0.143	2.879	0.549	0.013	0.340	0.028	0.175	627.325	-0.049	2.957	19.200
0.000	60.000	0.000	2.968	0.233	7.839	0.207	3.116	0.227	0.005	0.142	-0.012	0.168	1430.8	-0.070	4.288	19.200

LGFSTF tunnel vertical profile data, length mm, velocity m/s (cont.)

x	y	z	U_u	τ_u	T_u	δ_{1u}	δ_{2u}	θ_u	cov	r	U_v	τ_v	T_v	δ_{1v}	δ_{2v}	Temperature
30 Hz																
0.000	60.000	0.000	3.062	0.244	7.956	0.124	2.837	0.320	0.007	0.173	0.017	0.178	1040.6	-0.057	2.964	19.200
0.000	49.200	0.000	3.032	0.235	7.742	0.217	3.113	0.698	0.012	0.334	0.037	0.179	484.708	-0.047	3.113	20.400
0.000	40.300	0.000	2.887	0.234	8.107	0.155	3.318	1.004	0.016	0.418	0.051	0.177	349.268	-0.115	4.340	19.400
0.000	32.800	0.000	2.764	0.245	8.861	0.185	3.490	1.014	0.017	0.438	0.049	0.180	367.305	0.087	3.549	19.600
0.000	26.600	0.000	2.758	0.253	9.173	0.210	2.973	1.231	0.020	0.465	0.059	0.182	307.619	0.294	3.160	19.200
0.000	21.400	0.000	2.621	0.247	9.433	0.275	3.288	1.224	0.017	0.466	0.056	0.165	295.508	0.114	3.347	19.400
0.000	17.100	0.000	2.477	0.269	10.874	0.166	3.199	0.862	0.021	0.550	0.037	0.168	450.975	0.227	3.408	19.400
0.000	13.500	0.000	2.444	0.265	10.849	-0.080	3.059	1.281	0.019	0.477	0.055	0.171	312.583	0.097	3.444	19.400
0.000	10.500	0.000	2.304	0.292	12.684	0.152	3.054	1.095	0.020	0.538	0.044	0.153	348.085	0.136	3.369	19.400
0.000	8.000	0.000	2.118	0.291	13.754	0.141	2.894	0.632	0.017	0.454	0.023	0.152	649.772	0.102	3.332	19.400
0.000	5.900	0.000	2.095	0.299	14.271	0.005	2.742	2.046	0.020	0.505	0.075	0.146	195.011	0.038	3.353	19.400
0.000	4.200	0.000	1.919	0.298	15.531	0.169	2.838	1.360	0.019	0.526	0.046	0.141	309.119	0.239	3.453	19.400
0.000	2.700	0.000	1.828	0.300	16.442	0.420	2.884	1.670	0.019	0.528	0.053	0.139	260.497	0.164	3.697	19.600
0.000	1.500	0.000	1.692	0.280	16.544	0.429	3.229	1.017	0.014	0.463	0.030	0.122	406.741	0.065	3.432	19.400
0.000	0.500	0.000	1.491	0.289	19.371	0.274	3.290	1.463	0.008	0.433	0.038	0.077	202.942	0.434	4.817	19.600
45 Hz																
0.000	0.500	0.000	2.288	0.443	19.376	0.433	3.278	1.382	0.021	0.331	0.055	0.157	284.140	0.393	5.129	24.200
0.000	1.500	0.000	2.492	0.444	17.804	0.581	3.454	1.445	0.040	0.419	0.063	0.230	365.565	0.230	3.732	24.600
0.000	2.700	0.000	2.731	0.495	18.132	0.349	2.790	1.738	0.053	0.473	0.083	0.256	308.574	0.145	3.424	24.400
0.000	4.200	0.000	3.024	0.518	17.114	0.104	2.753	1.663	0.055	0.444	0.088	0.264	301.145	0.063	3.303	24.400
0.000	5.900	0.000	3.143	0.515	16.385	0.140	2.613	1.519	0.052	0.405	0.083	0.274	328.215	0.063	3.251	24.400
0.000	8.000	0.000	3.261	0.492	15.086	0.093	2.822	0.983	0.053	0.433	0.056	0.274	488.927	0.115	3.221	24.200
0.000	10.500	0.000	3.498	0.475	13.566	-0.086	2.860	1.546	0.055	0.472	0.094	0.277	293.882	-0.026	3.158	24.400
0.000	13.500	0.000	3.748	0.455	12.153	-0.015	2.913	1.286	0.037	0.314	0.084	0.283	342.149	-0.091	3.296	24.400
0.000	17.100	0.000	3.804	0.405	10.649	-0.006	3.055	0.889	0.040	0.396	0.059	0.284	481.499	0.097	3.196	24.600
0.000	21.400	0.000	3.946	0.415	10.505	-0.016	3.074	1.204	0.046	0.423	0.083	0.292	352.386	0.113	3.192	24.600
0.000	26.600	0.000	4.121	0.410	9.948	0.157	3.212	0.639	0.041	0.368	0.046	0.304	662.698	0.210	3.450	24.600
0.000	32.800	0.000	4.252	0.433	10.188	0.374	2.959	0.978	0.053	0.424	0.073	0.317	436.114	0.174	3.009	24.200
0.000	40.300	0.000	4.523	0.452	10.000	0.049	2.582	0.754	0.058	0.435	0.059	0.323	543.312	0.105	3.033	24.400
0.000	49.200	0.000	4.670	0.447	9.564	0.108	2.879	0.066	0.043	0.319	-0.005	0.330	6149.1	-0.112	2.900	24.400
0.000	60.000	0.000	4.821	0.422	8.745	0.093	2.723	0.082	0.019	0.168	-0.007	0.308	4465.2	0.074	3.208	24.200
0.000	60.000	0.000	4.782	0.403	8.429	0.097	2.745	0.231	0.018	0.160	-0.019	0.309	1601.8	-0.064	3.065	24.400
0.000	49.200	0.000	4.862	0.444	9.134	-0.010	2.662	0.987	0.039	0.289	0.084	0.338	403.162	-0.161	3.436	24.400
0.000	40.300	0.000	4.447	0.422	9.478	0.223	2.850	0.795	0.045	0.356	0.062	0.326	527.717	0.030	3.035	24.600
0.000	32.800	0.000	4.226	0.441	10.435	0.309	2.987	0.638	0.054	0.428	0.047	0.320	680.527	0.177	2.914	24.600
0.000	26.600	0.000	4.139	0.391	9.448	0.228	3.337	0.749	0.046	0.413	0.054	0.305	563.926	0.081	3.105	24.600
0.000	21.400	0.000	3.932	0.419	10.656	0.203	3.288	0.435	0.040	0.350	0.030	0.298	1000.2	0.058	3.310	24.800
0.000	17.100	0.000	3.782	0.439	11.606	0.002	3.018	0.378	0.043	0.360	0.025	0.296	1185.2	0.116	3.353	24.800
0.000	13.500	0.000	3.588	0.434	12.096	-0.104	3.146	0.416	0.039	0.357	0.026	0.280	1076.1	-0.008	3.433	24.800
0.000	10.500	0.000	3.499	0.473	13.533	-0.206	2.922	1.154	0.049	0.423	0.070	0.280	397.913	-0.023	3.192	24.400
0.000	8.000	0.000	3.209	0.481	15.000	0.045	2.787	0.742	0.056	0.500	0.042	0.274	658.404	0.077	3.197	24.800
0.000	5.900	0.000	3.124	0.511	16.351	0.204	2.737	1.167	0.051	0.410	0.064	0.273	428.734	0.027	3.569	24.600
0.000	4.200	0.000	2.925	0.494	16.876	0.133	2.775	1.492	0.059	0.500	0.076	0.266	348.538	0.097	3.211	24.600
0.000	2.700	0.000	2.697	0.474	17.574	0.295	2.857	2.657	0.054	0.533	0.125	0.243	194.567	0.246	3.216	24.600
0.000	1.500	0.000	2.471	0.453	18.318	0.446	2.951	1.460	0.044	0.467	0.063	0.232	367.729	0.283	3.567	25.000
0.000	0.500	0.000	2.235	0.453	20.273	0.409	3.248	0.995	0.021	0.330	0.039	0.150	386.531	0.434	4.719	24.800

LGFSTF tunnel vertical profile data, length mm, velocity m/s (cont.)

x	y	z	U_u	τ_u	T_u	δ_{1u}	δ_{2u}	θ_u	cov	r	U_v	τ_v	T_v	δ_{1v}	δ_{2v}	Temperature
<u>60 Hz</u>																
0.000	0.500	0.000	3.261	0.641	19.655	0.505	3.393	0.841	0.037	0.253	0.048	0.245	511.118	0.395	4.693	22.200
0.000	1.500	0.000	3.656	0.670	18.315	0.426	3.170	1.778	0.097	0.432	0.113	0.359	316.615	0.211	3.742	22.400
0.000	2.700	0.000	3.806	0.698	18.325	0.381	2.899	1.267	0.094	0.389	0.084	0.371	440.465	0.069	3.295	22.400
0.000	4.200	0.000	4.201	0.720	17.145	0.159	2.529	1.612	0.116	0.445	0.118	0.399	337.412	0.059	3.242	22.400
0.000	5.900	0.000	4.439	0.714	16.093	0.173	2.719	1.506	0.117	0.430	0.117	0.412	352.607	0.050	3.108	22.400
0.000	8.000	0.000	4.562	0.719	15.765	0.164	2.812	1.031	0.116	0.433	0.082	0.412	501.215	0.080	3.344	22.400
0.000	10.500	0.000	4.839	0.668	13.802	0.004	2.837	0.707	0.111	0.438	0.060	0.417	699.212	0.108	3.254	22.200
0.000	13.500	0.000	5.064	0.647	12.770	-0.134	3.012	0.067	0.085	0.327	-0.006	0.423	7152.8	-0.017	3.131	22.200
0.000	17.100	0.000	5.367	0.643	11.979	-0.047	2.565	0.886	0.107	0.430	0.083	0.428	515.587	0.061	3.210	22.400
0.000	21.400	0.000	5.524	0.608	11.006	0.000	3.010	0.112	0.098	0.404	-0.011	0.434	4023.8	0.128	3.450	22.800
0.000	26.600	0.000	5.802	0.575	9.909	0.034	2.832	0.336	0.091	0.370	-0.034	0.459	1349.1	0.076	2.924	22.600
0.000	32.800	0.000	6.088	0.590	9.689	0.061	2.652	0.028	0.089	0.349	-0.003	0.460	15661.	0.002	3.121	22.400
0.000	40.300	0.000	6.402	0.586	9.149	-0.198	2.497	0.092	0.068	0.272	-0.010	0.454	4435.5	-0.089	2.939	22.800
0.000	49.200	0.000	6.591	0.557	8.453	-0.315	2.504	0.392	0.066	0.289	-0.045	0.439	975.405	-0.129	2.988	22.800
0.000	60.000	0.000	6.704	0.548	8.180	-0.387	2.564	0.881	0.050	0.236	-0.103	0.428	414.616	-0.192	3.168	22.600
0.000	60.000	0.000	6.843	0.505	7.382	-0.587	2.847	0.239	0.037	0.202	-0.029	0.399	1397.5	-0.191	3.299	22.600
0.000	49.200	0.000	6.495	0.569	8.757	-0.208	2.499	0.427	0.066	0.272	-0.048	0.453	936.880	-0.222	2.917	23.200
0.000	40.300	0.000	6.322	0.594	9.401	-0.086	2.503	0.006	0.074	0.300	-0.001	0.445	66360.	0.007	3.285	22.800
0.000	32.800	0.000	5.989	0.617	10.304	0.090	2.606	0.028	0.090	0.347	-0.003	0.457	15706.	0.063	2.911	22.400
0.000	26.600	0.000	5.831	0.586	10.047	0.074	2.805	0.013	0.079	0.327	-0.001	0.450	33906.	0.040	2.928	23.200
0.000	21.400	0.000	5.590	0.566	10.131	0.049	3.024	0.261	0.078	0.326	-0.025	0.443	1740.3	0.067	3.267	22.800
0.000	17.100	0.000	5.345	0.608	11.379	-0.006	3.006	0.161	0.087	0.342	-0.015	0.441	2946.0	-0.024	3.093	22.600
0.000	13.500	0.000	5.148	0.646	12.546	-0.003	3.055	0.240	0.094	0.378	0.022	0.424	1961.1	-0.081	3.206	22.800
0.000	10.500	0.000	4.859	0.670	13.781	0.121	2.881	0.186	0.097	0.380	0.016	0.418	2655.1	0.063	3.165	23.000
0.000	8.000	0.000	4.733	0.678	14.320	-0.115	2.851	1.556	0.109	0.429	0.129	0.414	321.734	-0.038	3.311	23.200
0.000	5.900	0.000	4.359	0.675	15.478	0.102	3.034	1.193	0.099	0.386	0.091	0.403	443.337	0.076	3.351	22.600
0.000	4.200	0.000	4.129	0.705	17.065	0.331	2.874	1.688	0.104	0.418	0.122	0.386	317.405	0.106	3.425	23.200
0.000	2.700	0.000	3.781	0.674	17.811	0.443	3.170	1.176	0.097	0.400	0.078	0.383	494.004	0.070	3.477	23.000
0.000	1.500	0.000	3.538	0.671	18.974	0.552	3.281	0.871	0.083	0.390	0.054	0.342	635.349	0.178	3.315	22.800
0.000	0.500	0.000	3.337	0.635	19.018	0.429	3.315	1.456	0.045	0.285	0.085	0.261	307.913	0.148	4.961	23.400