PROGRESS REPORT

CALIBRATION OF THE BOUNDARY LAYER WIND TUNNEL

ENERGY EFFICENT INDUSTRIALIZED HOUSING
RESEARCH PROGRAM

CENTER FOR HOUSING INNOVATION
UNIVERSITY OF OREGON

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EXECUTIVE SUMMARY

Since 1989 the U. S. Department of Energy has sponsored a research program organized to improve energy efficiency in industrialized housing. Two research centers share responsibility for the Energy Efficient Industrialized Housing (EEIH) program: the Center for Housing Innovation at the University of Oregon and the Florida Solar Energy Center, a research institute of the University of Central Florida. Additional funding for the program is provided by non-DOE participants from private industry, state governments and utilities. The program is guided by a steering committee composed of industry and government representatives.

Industrialization of U.S. housing production varies from mobile home builders who ship furnished houses *to* the site, to production builders who assemble factory produced components *on* the site. Such housing can be divided into four major categories: HUD code (mobile) homes, modular houses, panelized houses, and production built houses. There are many hybrids of these categories.

The goal of the Energy Efficient Industrialized Housing research project is to develop techniques to produce marketable industrialized housing that is 25% more energy efficient than required by today's most stringent U.S. residential codes, yet less costly than present homes.

One aspect of the EEIH project is testing the energy performance of houses at several stages from design through occupancy. The activity described here comprises part of Task 2.6, "Tests of Construction Methods, Products, and Materials," a process which involves both field and laboratory studies. Toward this end the project will use the low speed boundary layer wind tunnel to study building ventilation and microclimates.

This report describes progress toward the calibration of this instrument. First is a description of the tunnel itself -- a duct roughly 60 feet long, coupled to a variable speed fan, and shaped to provide a smooth air flow with minimum background turbulence. During calibration this level of turbulence was examined using the tunnel's three-part set of instruments: anemometry sensors (TSI Model 1066) and electronics, data acquisition system (IDAC-1000 plus custom communication program), and controlling Macintosh computer.

Initial tests revealed two irregularities: a long (90 second) period air speed variation, and probe oscillations traced to fan vibration. This latter problem was effectively solved by decoupling the fan from the duct; the former, however, awaits further study with flow visualization techniques.

Finding a polynomial fit to the the TSI probe calibration data established that a third- rather than fourth-order solution is adequate for the present speed range, though extending the tunnel's operating speed range may require editing the programs to include the higher order.

Initial speed measurements in the plane of the test section throat provided data weakened by two factors: possible inadvertent blocking of the air flow by test personnel involved in moving the data probe, and decay of agreement between the control and data sensors to 97% or less. In the absence of other probe calibration facilities, an attempt was made to employ the tunnel itself to recalibrate the sensors. Limited air speed range of the tunnel impeded this effort, but the low range was successfully extended. To date no attempt has been made to extend the upper speed range.

Setup and calibration activites typefy the puzzles involved in the reconfiguration of a unique, complex and sensitive test instrument. They also indicate that its overall performance -- particularly the background turbulence level of the "clean" air flow -- is within acceptable limits. Completion of the calibration studies will permit work with the tunnel to proceed to generation and manipulation of boundary layers, and the instrument's incorporation into the EEIH energy testing program.

1.0 INTRODUCTION

The United States housing industry is undergoing a metamorphosis from hand built to factory built products. Virtually all new housing incorporates manufactured components; indeed, an increasing percentage is totally assembled in a factory. Industrial processes offer the promise of houses with higher energy efficiencies, higher quality, and lower cost. To ensure that this promise can be met, the U.S. housing industry must begin to develop and use new technologies, new design strategies, and new industrial processes. Yet the fragmentation of the industry makes research by individual companies prohibitively expensive and retards innovation.

The goal of the Energy Efficient Industrialized Housing project is to develop techniques to produce marketable industrialized housing that is 25% more energy efficient than required by today's most stringent U.S. residential codes, yet less costly than present homes.

The multiyear project is conducted by a team from the Center for Housing Innovation of the University of Oregon, the Florida Solar Energy Center and the Department of Industrial Engineering at the University of Florida. The project is co-funded by industry. Leading members of the housing industry serve on a project steering committee as well as several task technical committees.

The EEIH project focuses on the fact that the major impediment to improved energy efficiency in U.S. housing lies not in the components of the product -- insulation, heat pumps, improved windows, etc. -- but in the design, construction and evaluation processes. These processes are optimized and integrated in these research tasks:

1. Design Process
    - Develop house designs for energy efficiency and manufacturability
    - Develop energy software which is an integral part of the design, sales and production software house designers use
    - Develop a dimensional coordinating hierarchy which will allow design and engineering of custom homes at production home prices
2. Manufacturing Process
    - Develop a manufacturing process simulation and data base to introduce manufacturing innovations to the housing industry
    - Develop guidelines for concurrent engineering and design of energy efficient houses

3. Evaluation Process
    - Develop effective quality control methods (e.g., using infrared cameras and blower doors) to find and rectify energy leaks in homes during the construction and acceptance process
    - Test the energy efficiency of components and subassemblies to ensure industry and consumer acceptance through field and laboratory (wind tunnel and artifical sky) facilities

Results of these research tasks are taken to the marketplace through construction of prototypes, trade press articles, technical papers, and public presentations.

One aspect of the EEIH project is testing the energy performance of houses at several stages from design through occupancy. The activity described here comprises part of Task 2.6, "Energy Testing of Houses," an process which involves both field and laboratory studies. Toward this end the project will use the low speed boundary layer wind tunnel to study building ventilation and microclimates. This report describes progress toward the calibration of this instrument. Included are descriptions of the equipment involved, as well as notes on preliminary testing and calibrations. While instrumentation and testing are emphasized, estimates of what accuracy a user can expect are also reported.

2.0 DESCRIPTION OF THE BOUNDARY LAYER WIND TUNNEL

A boundary layer wind tunnel is a test device in which air flow is manipulated to create an air motion profile which imitates, in a scaled fashion, the wind near the earth's surface. The device is used to model air flow in and around structures.

The tunnel boundary layer, usually starting at a very low velocity at the surface and increasing with elevation according to some characteristic pattern, is created by inserting "roughening elements" such as small blocks or bricks in the path of the air flow ahead of the model. To set up different boundary layers in a reliable and repeatable way the model area of the tunnel must first exhibit smooth and consistent velocities when the air flow is free of roughening elements. This consistency requires an aerodynamically "clean" air entry and smooth, straight walls in the tunnel throat. Tests must ensure that the air flow in the model area is consistent and smooth (no buffeting or speed variations, and no waves).

In addition, since model velocities are typically needed, data taken are normalized to a "free-air" (control) value from a sensor mounted in an unobstructed position just ahead of the model area. For the resulting ratios to be meaningful the control and data sensors must be calibrated so that they track together (report the same air speed when presented with identical flows). For model studies tracking is more important than absolute accuracy -- the ability to report exact velocities -- since test results must be scaled by some "world" factor in order to have meaning for a specific situation. To ensure that the data fit these criteria, additional testing and calibrations need to be done on the sensors and electronics.

2.1 PHYSICAL STRUCTURE

The wind tunnel consists of four basic parts: inlet, throat, model area, and fan system. In addition, there is an implied fifth part, the air return, which in this case is the room housing the tunnel (Figure 2.1-1).

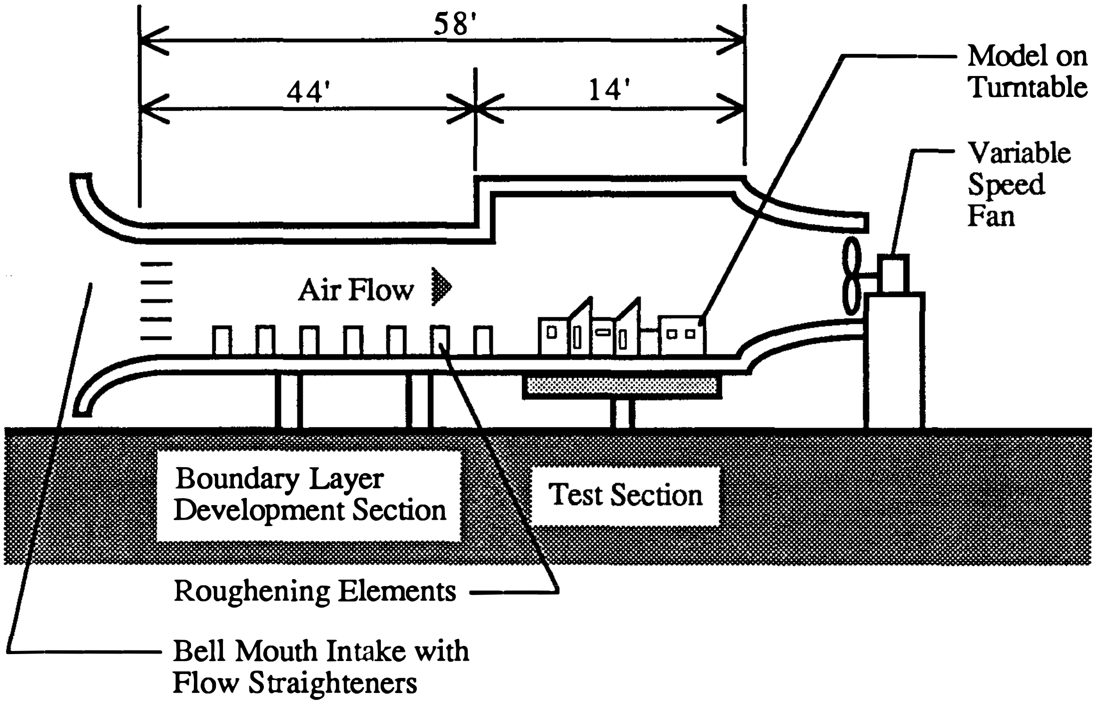


Figure 2.1-1
Schematic Diagram of EEIH Wind Tunnel

The inlet is a specially constructed fiberglass "mouth" roughly two feet long, in the direction of air motion, flared in the front in order to minimize distortion of the air volume as it enters the tunnel. To further limit random air motion, a hexagonal, open-celled aluminum honeycomb fills the open area of the inlet, covering the entry to the tunnel. The honeycomb, approximately 4 inches deep with a cell size of about 3/8 inch, serves as a short period oscillation filter, reducing air motion not along the throat axis (z direction) of the tunnel.

After air passes through the honeycomb it enters the throat. This is the largest section of the structure: 30 feet 6 inches long, 7 feet wide and 6 feet high. Here the x and y components of mean air velocities are removed. By the time the air reaches the end of the throat the air mass is moving uniformly in the z direction. The air mass is not "monodirectional," however, due to short period oscillations (turbulence).

2.2 INSTRUMENTATION

Tunnel instrumentation is separated into three parts: anemometry sensors and electronics, data acquisition system (DAS), and controlling computer. Anemometers are the active part of the system, sensing the air motion. They are placed in the path of the air flow and send signals to the anemometry electronics, which convert those signals into voltages which relate in a predictable way to the air speed. The DAS receives the voltage signals and converts them into digital signals for the computer. The DAS also communicates with the computer, acting on requests for information. In the EEIH tunnel the computer asks the DAS for data from a sensor; the DAS "reads" the information from one of its ports, which is connected to the anemometer electronics, and reports that value to the computer. Besides controlling the DAS, the computer uses a program to convert the digital signals from the DAS into air speed and reports the results to the user. Figure 2.2-1 schematically displays the path of signals through the various electronic components.

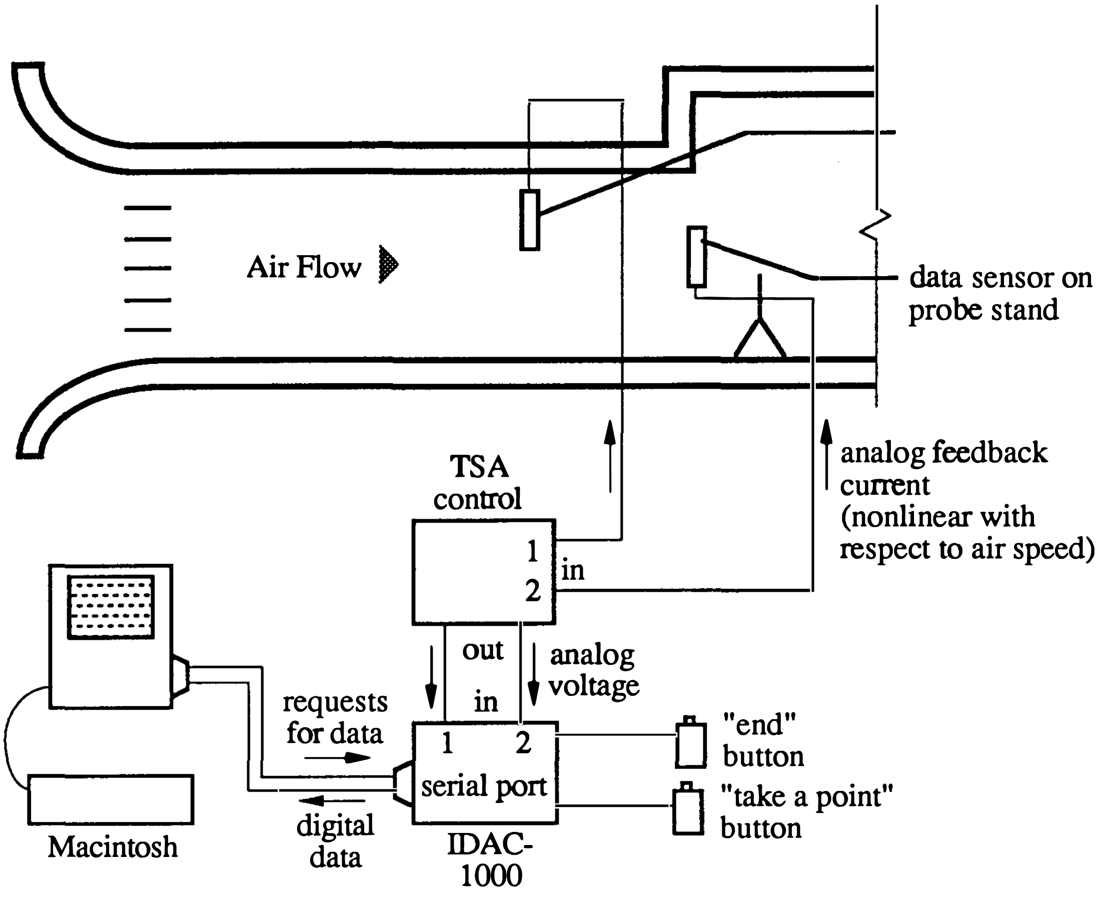


Figure 2.2-1
Schematic Diagram of Electronics in EEIH Wind Tunnel

2.3 BACKGROUND

2.3.1 Acquisition and construction

The tunnel was originally designed and built by Dr. Ed Arens for Environmental Impact Planning Corporation of Berkeley, CA and acquired under a grant from that firm in 1988. The tunnel was disassembled and shipped to the University of Oregon, where during the following year it was reassembled with needed repairs and improvements. Several areas on the tunnel walls were filled and smoothed, and the whole tunnel painted, inside and out. Also, to aid in a possible future relocation, the entire structure was mounted on wheels. The University Physical Plant was employed to wire the lights and fan motor.

Before testing began a rubber "skirt" was installed around the base of the model area, which had a four inch gap created by installation of the wheels. This gap caused a large air leak in the otherwise airtight tunnel. Six inch sanitary moulding was subsequently nailed to the base of the tunnel structure, extending to the floor, and sealed throughout with silicone sealant. The seal formed by the broad base of the moulding and the concrete floor was imperfect but satisfactory.

2.3.2 Instrumenting the tunnel

Data acquisition system

No intrumentation was acquired with the tunnel. In order to maintain continuity with instrumentation used in the EEIH artificial sky, which acquires data with an IDAC-1000 DAS connected to a Macintosh computer, this equipment was considered for use with the wind tunnel. The sky instrument was able to use a program, MaControl, supplied by IDAC to handle communication between DAS and Macintosh. MaControl wrote data files in spreadsheet format, then performed basic spreadsheet manipulations on the files. All data were collected before any calculations were performed. By contrast, calculations on tunnel data needed to be done "on the fly" since much more preliminary data would be collected than spreadsheets can store. Since there are small turbulences in the tunnel, it was also necessary to collect data from all sensors simultaneously. (See Section 3.0 for a description on data collection and conversion methods.)

MaControl was inadequate for this task, so it was necessary to write a communications program to perform the necessary collection and calculations. The IDAC programming interface proved easy to work with, so a "C" program was written which would do the job. The IDAC/MacIntosh system would be used for data acquisition and display.

Anemometry equipment

Choosing anemometry equipment was more difficult. Besides being the most expensive part of the electronics, this would be the most sensitive to planned uses for the tunnel. In addition, most anemometers are extremely fragile, so a balance had to be found between anticipated use and probable care. Ongoing maintenance costs could be high if the more sensitive and fragile sensors were chosen.

A major supplier of anemometry equipment was queried: TSI Inc, St. Paul MN. For low speed applications TSI offers a wide variety of sensors and considerable system flexibility. An additional reason for considering TSI was compatibility with equipment used by UC Berkeley wind tunnel researchers, which would allow EEIH to draw on that group's considerable experience in this area.

Useful advice and assistance came from Fred Bowman, the technician in the Berkeley group; a graduate student, David Ernest, who is the major user of their tunnel and quite knowledgeable about programming considerations; and Dr. Ed Arens, the designer of both tunnels. After the Berkley group installed their anemometers, TSI had developed a new anemometry system, the 8400 series, which reported voltages directly proportional to wind speed. TSI sent EEIH a self-contained version (Velociscale, model 8352) for evaluation.

The standard, old style sensors require a fourth-order polynomial to convert voltage output to wind speed; however, the new sensors simplified calculations. The drawbacks to this system were slow response time (approximately one second) and limited sensor variety (only two probe types: 8460, windowless, and 8470, omnidirectional).

Tests of the evaluation model (the first examination of wind patterns in the EEIH tunnel) showed the need for the flexibility of the old system, which is still in use at Berkeley. Consequently a simple, two probe system was selected which would supply present EEIH needs.

The same base electronics were employed as those used at Berkeley: Model 1051-6 six slot rack and power supply, and two 1053B "utility anemometers." The utility anemometers are the feedback electronics connected to the probes, which supply constant current to each probe (to keep the probe at a constant temperature) and report a voltage proportional to that current. The 1051-6 could hold up to four 1053B's, leaving room for expansion. Model 1066 'ruggedized' sensors were selected, the sturdiest probes TSI makes. They are nondirectional in the plane perpendicular to the probe axis and have a time constant of 0.1 second.

3.0 TESTING AND CALIBRATION PROCESS

3.0.1 Rationalizations

It was important to acquire data as rapidly as possible in order calculate a reasonable mean value for air speed using an averaging process to smooth out short term fluctuations due to turbulence, and to arrive at a reasonable mean value for air speed. In some studies standard deviations are also needed as a measure of turbulence, so this process had to be done with care. After some testing it was determined that the frequency of the turbulence was on the order of one to two seconds, so a data collection period of 30 seconds was enough to collect several cycles. Averaging over this collection time would result in accurate averages and meaningful standard deviations for the final speed values.

3.0.2 Variations and oscillations

Working with the evaluation probe revealed two possible problems: a relatively long period air speed variation, and probe oscillations caused by vibrations in the floor of the tunnel. Both of these problems added to data uncertainty. Before beginning tests it was necessary to locate the sources of these problems if possible and evaluate their effect on data, then remove any sources which caused problems with data accuracy.

The source of the vibration was traced to the fan system. There were two obvious transmission paths by which vibrations could reach the tunnel: directly through the metal fan housing, which was bolted to the wooden tunnel with two all-thread bolts, or indirectly through the concrete floor. Investigation revealed that both paths had been changed during the tunnel relocation. When the tunnel was in Berkeley it was bolted to a concrete floor through rubber and cork vibration pads, so no direct connection was made between fan assembly and tunnel. Since the whole apparatus was now on wheels, bolts had been added to hold the fan to the tunnel. The bolts were removed, the two elements separated by a fraction of an inch and the wheels chocked. A test showed a marked improvement in tunnel vibration and probe oscillation. Since both the tunnel and fan assembly were on rubber wheels, at least partially decoupling each from the floor (and removing the possibility of using shock mounts), there was no apparent way of improving on that result. The situation was acceptable, although not perfect.

Oscillations were a harder problem. There appeared to be a long (90 second) period speed oscillation, varying the air speed amplitude by 2 to 3 percent, and a second, 4 percent variation, with a 20 second period. While variations this slow would have little effect on normalized data (assuming the "simultaneous" data collection and averaging process worked), they presented a source of uncertainty and would be troublesome if there were ever a need to compare absolute speeds over two time periods.

One possible source was fan motor speed variation. A stroboscope was focused on the fan shaft while it was rotating at near maximum speed. No regular frequencies were found, although smaller, irregularly spaced variations of about one per cent were observed. A second possiblility for oscillations was pressure waves set up in the tunnel throat by the air entering in an unstable fashion. These waves were thought to be less likely to cause long period oscillations, since the time for air to travel the length of the throat at test speeds (about 1100 feet per minute) was two seconds, not close to either oscillation period. No visualization equipment was then available so this problem, considered unimportant for the present tests, was shelved for the time being.

3.1 METHODS

3.1.1 Programming

The acquisition process, controlled by the Macintosh program "IDAC," is done in two steps. First 100 voltage samples per channel are taken as rapidly as possible, about ten per second, one sample at a time per channel, on command from the control program. These preliminary data values are stored in two arrays in the computer. Next the data are converted into velocity by applying a 4th order polynomial to each data value. If V is the data voltage from the anemometer electronics; A, B, C, D, and E are calibration constants which are unique to each sensor and S is the resultant air speed, then:

$$S = A + VxB + V^2xC + V^3xD + v^4xE$$

All velocity values for one channel are then averaged together and a mean and standard deviation are calculated for that channel. Both channels are processed in this manner. Then data air speed, calculated using data from the channel connected to the sensor used for data collection, is divided by control air speed. The resulting ratio is reported along with both mean velocities and their standard deviations.

A "free-running" mode was added to the program to facilitate testing short period oscillations in the air flow. Called "test" in the menu, this mode simply takes data as rapidly as possible, about 10 samples per second, and reports the corresponding air speed for each sample to the user. No averaging is done. Using this mode, the user can observe speed fluctuations directly.

Later in the test phase, a second program was written which compared the air speed as reported by the control sensor to the voltage of the other. It was hoped that with this program the tunnel could be used as a probe calibration facility, using data collected at several air speeds to construct new polynomial curves. This project is still at the "hope" stage.

A note here about the polynomial fit used in the collection programs. To determine the constants in the equation a multivariate regression utility was used, one of several in a package called "Unixstat" developed for Unix systems. Regression techniques rely on source data (the volts versus velocity data in the wind tunnel case) leading to a unique polynomial solution. One enters "degree" of the polnomial to which the data is to be fitted and the utility program attemts to find the equation of the best curve through those data. The literature on the type of sensor employed in the EEIH tunnel indicates a fourth order polynomial, one whose highest power is four. When a fit between the TSI calibration data and a fourth order polynomial was tried, it was discovered that the constant for the highest order would not fit (the solution contained a singular matrix), indicating that the fourth order was unnecessary. A third order solution was rewarded with a very good fit to the data.

Study led to the discovery that the TSI calibration data represented a small segment of the fourth order curve, and was not enough to define the fourth order poynomial. The calibration had been focused on this part of the curve since that was the area of interest. Therefore in the EEIH programs third order polynomials are used in place of the more general fourth order ones suggested in the literature. These curves and calculations are presented in the Appendix. If a broader air speed range is needed the programs may need to be edited to include the higher order.

3.1.2 Plan of attack

The process described provided the equipment needed to determine the flow and speed pattern in the test area: the air flow was stable enough to support basic tests, and the new control and data sensors tracked well (reported identical speeds when placed in identical flows).

First it was necessary to validate the new equipment by running side-by-side tests of the sensors. This test would reveal any calibration problems, and suggest what could be expected from the tunnel in terms of speeds and turbulences. It would also permit familiarization with the new equipment, and allow it to "burn-in."

When the calibrations were satisfactory and the equipment familiar, the first real calibration could begin. This process would involve defining a three dimensional grid in the model space and taking data at each grid node. A grid spacing of six inches in the plane perpendicular to air flow and 12 inches between planes was selected. Data from the nodes on this grid would develop a velocity profile for the model space.

Since this process would be lengthy (close to a day required to run one complete calibration), as a first step the throat plane alone was measured, in order to check methods. After the process was sampled a full calibration of five planes would be performed, starting at the throat and moving into the model area.

A complete picture of the air flow in the test area would permit adjustments to the inlet and throat to correct aberrations if necessary. Remedies could involve placing deflectors outside the inlet, vanes or other straightening devices at the inlet, and/or smoothing or roughening the walls of the throat.

With a smooth air flow established, the process of creating a specified boundary layer could begin. This is usually done by placing roughening elements in the throat. Roughening elements are flow obstructors which can be anything from bricks and wooden blocks to specially constructed geometric shapes. The shapes are placed so that they restrict the flow in specific ways to obtain the desired effect.

3.2 INITIAL TESTS

3.2.1 Tracking

The side-by-side tests were performed first. The control sensor was installed in the ceiling of the throat, immediately upstream of the model area and extending into the air flow about 6 inches. The data sensor was placed about one inch to the side of the control sensor, attached to a probe stand improvised from a microphone boom-stand. Due to restricted headroom, the data sensor was inverted with respect to the control sensor. The fan was started and data collection begun with the averaging program (IDAC).

Results were mixed. The sensors tracked well, but the standard deviations were somewhat larger than expected, and there were still evidently some long-term, apparently random, speed variations. At low air speeds the relative amplitude of random variations increased, as did standard deviation, but tracking was satisfactory. At higher speeds, approaching maximum, tracking and standard deviation improved (maximum standard deviations of about 4%), but long-term variations increased.

The long-term variations had to reflect true variations in air speed (a long-term problem), but of greater concern were what appeared to be large standard deviations. These could be due to problems in the electronics and/or collection problems, or they could be due to turbulence. Discussion with Fred Bowman at Berkeley indicated that 3 to 4 percent turbulence in an open tunnel was normal. Apparently the tunnel was behaving satisfactorily.

3.2.2 First throat-plane calibration

The first throat-plane calibration was run in early June,1990, using the IDAC program and probe stand. Colored stick-on dots were attached to the walls and floor of the throat plane to aid in sensor positioning. Since the probe stand had height adjustments which could be reliably tightened, the probe could be adjusted once for each height and the stand moved across the throat to take points at that height. This process speeded the collection somewhat; however, one calibration run still required over an hour.

Worth noting are two problems with these methods. To speed the process the probe was moved in a "snake" fashion up the plane, rather than begining each new height on the same side of the tunnel. The resulting data organization will cause problems when the data are read by a computer to create contour plots, since contours are normally made from arrays of numbers which are organized by rows and columns.

A second possible problem (also due to haste) was partial blocking of air flow by the technician's body near the throat during data collection. This error was noted early in the process and collection timing revised so that he was out of the flow during collection. An obstruction of that size in the area of the throat could cause additional turbulence and an increase in air speed near the sensors due to the decrease in effective throat aperture.

From the raw data it was immediately apparent that in positions where the data and control sensors were close together -- where the ratio of the two outputs should be unity (100%) -- the ratio was no closer than 97%. Some quick tests confirmed this finding, showing that the calibration of one or both sensors had changed: they no longer tracked. Recalibration was needed before more tunnel tests could be performed, and data from this run were in question.

3.2.3 In-tunnel probe calibration attempts

Since no probe calibration facilities were available it was decided to use the tunnel to calibrate one probe against the other. If successful this procedure would permit bringing air speed measurements from the two probes together but would not enable absolute (air speed) calibrations since there was no absolute standard against which to compare. The control sensor would serve as the standard for calibrating the data sensor.

Several possible problems presented themselves. First, normal turbulence in tunnel air flow is considerably larger than one would wish for a calibration device. With no control over flow quality at this point, it was hoped that the averaging process would effectively reduce this problem and that the reported value would reflect the true air speed.

A much more serious problem was the narrow speed regime in which the EEIH tunnel operated. In order to to obtain data over a broad enough speed range to allow generation of a fourth (or even third) order polynonal, very low velocity data (less than 1 fpm) were needed as well as relatively high velocity data (to 30 fpm). The low speed problem was solved by placing a burlap "filter" against the wire safety screen at the rear of the model area, effectively slowing the air flow.

Taking data with and without the screen expanded the range considerably, but extended high speeds were also needed. These could be attained only by increasing the flow (faster fan or higher pitched blades) or reducing the tunnel aperture. This problem remains to be addressed in future work.

4.0 CONCLUSION

Setup and calibration activites for the EEIH boundary layer wind tunnel typefy the puzzles involved in the reconfiguration of a unique, complex and sensitive test instrument. They also indicate that its overall performance -- particularly the background turbulence level of the "clean" air flow -- is within acceptable limits. Completion of the calibration studies will permit work with the tunnel to proceed to generation and manipulation of boundary layers, and the instrument's incorporation into the EEIH energy testing program.

5.0 APPENDIX -- CALIBRATION CURVES AND CALCULATIONS

Calibration curves for the two probes, #3038 and #3039, follow the calculations. If V is the data voltage from the anemometer electronics; A, B, C, D, and E are calibration constants which are unique to each sensor and S is the resultant air speed, then

$$S = A + VxB + V^2xC + V^3xD + v^4xE$$

Probe # 3038

Analysis for 14 points of 4 variables:

Variable	S	V	V^2	V^3
Min	0.0000	4.4710	19.9898	89.3746
Max	35.0000	9.5820	91.8147	879.7690
Sum	147.9000	101.5550	763.4588	5919.5036
Mean	10.5643	7.2539	54.5328	422.8217
SD	10.2291	1.4354	20.5656	229.6893

Correlation matrix:

S	1.000			
V	0.9174	1.000		
V^2	0.9545	0.9939	1.000	
V^3	0.9790	0.9781	0.9950	1.000
	S	V	V^2	V^3

Regression equation for S:

$$S = (-40.3803) + (22.14)\ V + (-4.202)V^2 + (0.2827)V^3$$

Significance test for prediction of S:

Mult-R	R-squared	F(3,11)	Prob (F)
0.9997	0.9994	5995.9677	0.0000

Significance test(s) for predictor(s) of S:

Predictor	beta	b	Rsq	t(10)	F(1,10)	p
V	3.1067	22.1389	0.9998	6.3896	40.8271	0.0001
V^2	-8.4489	-4.2024	0.9999	8.3160	69.1556	0.0000
V^3	6.3473	0.2827	0.9998	11.8010	139.2631	0.0000

0	4.471	19.9898	89.3746	399.594
1	5.47	29.9209	163.667	895.26
2	5.967	35.6051	212.456	1267.72
3	6.323	39.9803	252.796	1598.43
3.9	6.584	43.3491	285.41	1879.14
5	6.859	47.0459	322.688	2213.31
6.5	7.141	50.9939	364.147	2600.38
8	7.379	54.4496	401.784	2964.76
10	7.678	58.9517	452.631	3475.3
12.5	7.989	63.8241	509.891	4073.52
16	8.346	69.6557	581.347	4851.92
20	8.706	75.7944	659.866	5744.8
25	9.06	82.0836	743.677	6737.72
35	9.582	91.8147	879.769	8429.94

Probe # 3039

Analysis for 15 points of 4 variables:

Variable	S	V	V^2	V^3
Min	0.0000	4.4810	20.0794	89.9756
Max	35.0000	9.5520	91.2407	871.5310
Sum	182.9000	110.5740	846.4677	6694.3626
Mean	12.1933	7.3716	56.4312	446.2908
SD	11.7033	1.4967	21.8201	247.7804

Correlation matrix:

S	1.000			
V	0.9272	1.000		
V^2	0.9613	0.9942	1.000	
V^3	0.9830	0.9794	0.9954	1.000
	S	V	V^2	V^3

Regression equation for S:

$$S = (-36.8368) + (20.43)\,V + (-3.949)V^2 + (0.2717)V^3$$

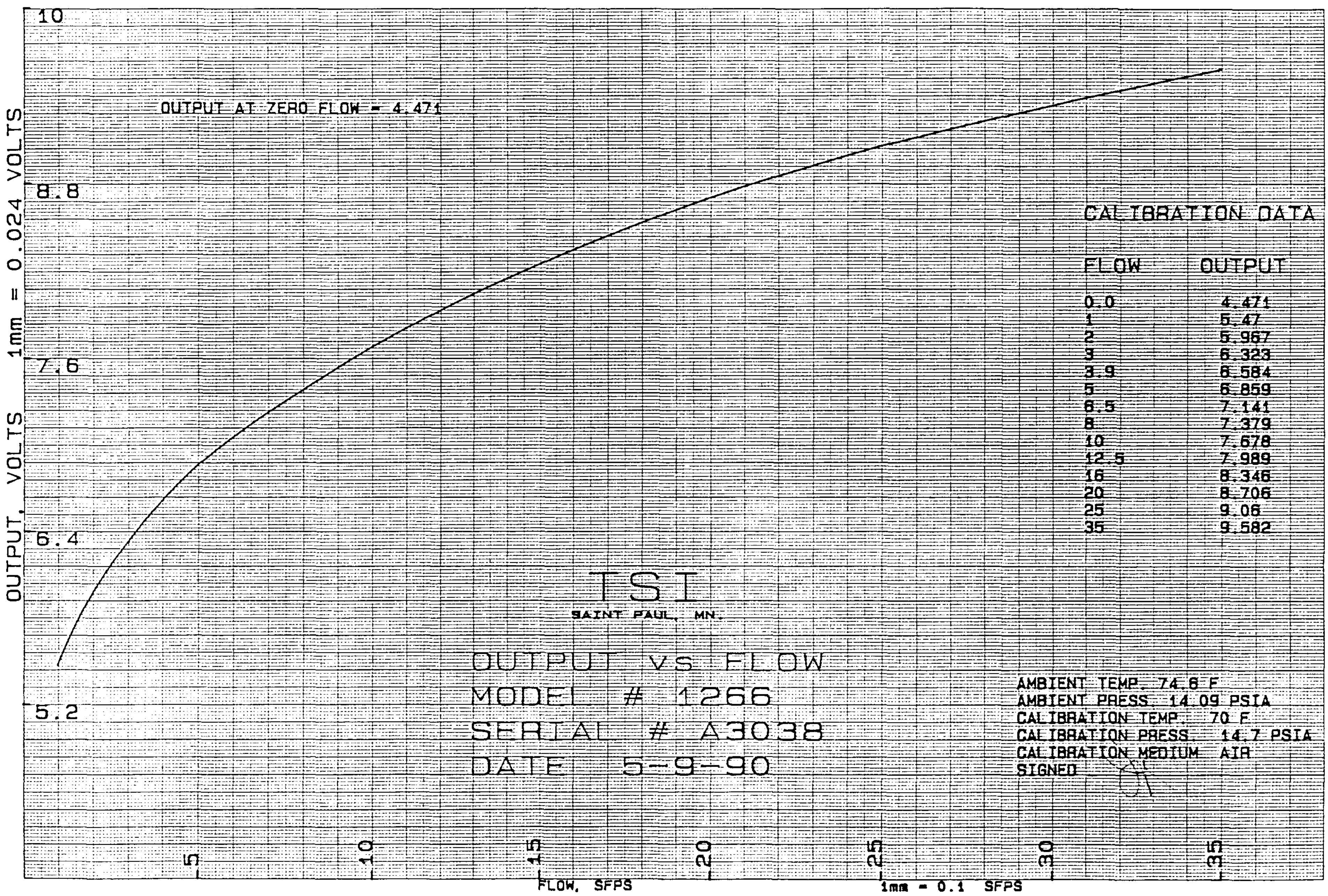
Significance test for prediction of S:

Mult-R	R-squared	F(3,11)	Prob (F)
1.0000	1.0000	9999.0000	0.0000

Significance test(s) for predictor(s) of S:

Predictor	beta	b	Rsq	t(11)	F(1,11)	p
V	2.6128	20.4312	0.9998	99.9950	9999.0000	0.0000
V^2	-7.3628	-3.9491	1.0000	99.9950	9999.0000	0.0000
V^3	5.7531	0.2717	0.9998	99.9950	9999.0000	0.0000

0	4.481	20.0794	89.9756	403.181
1	5.466	29.8772	163.309	892.644
2	5.945	35.343	210.114	1249.13
3	6.289	39.5515	248.74	1564.32
3.9	6.54	42.7716	279.726	1829.41
5	6.802	46.2672	314.71	2140.65
6.5	7.089	50.2539	356.25	2525.46
8	7.335	53.8022	394.639	2894.68
10	7.629	58.2016	444.02	3387.43
12.5	7.939	63.0277	500.377	3972.49
16	8.295	68.807	570.754	4734.41
20	8.648	74.7879	646.766	5593.23
25	9.012	81.2161	731.92	6596.06
35	9.552	91.2407	871.531	8324.87
35	9.552	91.2407	871.531	8324.87



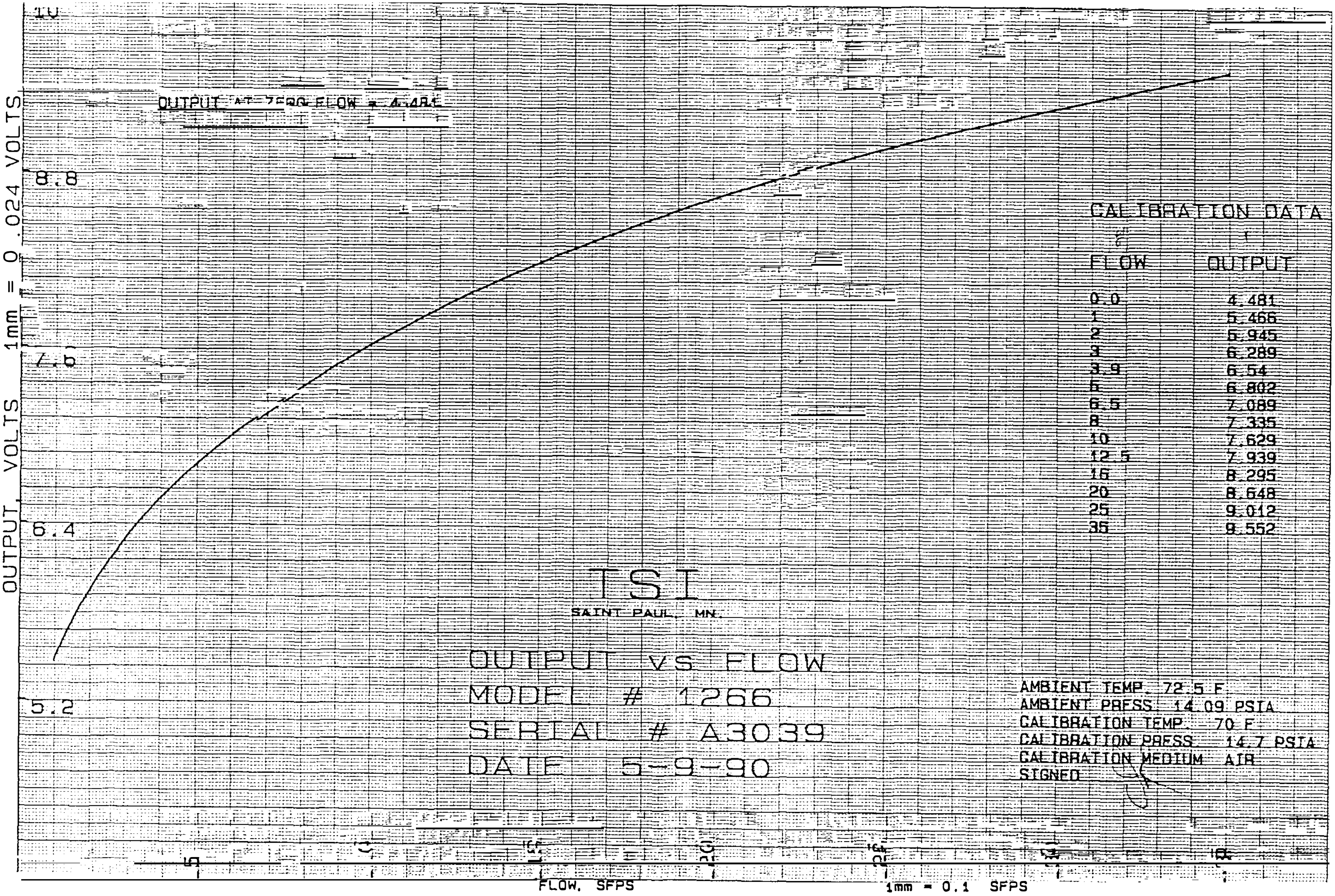
TSI
SAINT PAUL, MN.

OUTPUT vs FLOW
MODEL # 1266
SERIAL # A3038
DATE 5-9-90

CALIBRATION DATA

FLOW	OUTPUT
0.0	4.471
1	5.47
2	5.967
3	6.323
3.9	6.584
5	6.859
6.5	7.141
8	7.379
10	7.678
12.5	7.989
16	8.346
20	8.706
25	9.06
35	9.582

AMBIENT TEMP. 74.6 F
AMBIENT PRESS. 14.09 PSIA
CALIBRATION TEMP. 70 F
CALIBRATION PRESS. 14.7 PSIA
CALIBRATION MEDIUM AIR
SIGNED



CALIBRATION DATA

FLOW	OUTPUT
0.0	4.481
1	5.466
2	5.945
3	6.289
3.9	6.54
5	6.802
6.5	7.089
8	7.335
10	7.629
12.5	7.939
16	8.295
20	8.648
25	9.012
35	9.552

TSI
SAINT PAUL, MN.

OUTPUT vs FLOW
MODEL # 1266
SERIAL # A3039
DATE 5-9-90

AMBIENT TEMP. 72.5 F
AMBIENT PRESS. 14.09 PSIA
CALIBRATION TEMP. 70 F
CALIBRATION PRESS. 14.7 PSIA
CALIBRATION MEDIUM AIR
SIGNED