



Experimental measurement of biofilm in a heat exchanger
by Douglas Wayne Heal

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering
Montana State University
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Abstract:

The purpose of this research, the experimental measurement of a biofilm in a heat exchanger, was to determine the relationship between the biofilm thickness and certain flow parameters. Four test runs were conducted using four different test sections to determine the effect a biofilm produces on the friction factor, the wall shear stress, and the pressure fluctuations in a heat exchanger. The change in the friction factor and the growth of the biofilm approximated the theoretical work, with slight discrepancies in the induction time and maximum values at the conclusion of each test run. The results of the wall shear stress were promising, with the maximum wall shear stress similar for all four test runs in all four flow loops. The pressure fluctuations proved inconclusive in the research, with a random variation of frequencies occurring throughout the investigation. The results of the detachment phase showed a linear relationship between the test parameters and the fluid velocity for the range tested.

EXPERIMENTAL MEASUREMENT OF BIOFILM

IN A HEAT EXCHANGER

by

Douglas Wayne Heal

**A thesis submitted in partial fulfillment
of the requirements for the degree**

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in

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APPROVAL

of a thesis submitted by

Douglas Wayne Heal

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

June 28, 89
Date

Harry W. Towns
Chairperson, Graduate Committee

Approved for the Major Department

6-29-89
Date

Amelia K. Hill
Head, Major Department

Approved for the College of Graduate Studies

July 5, 1989
Date

Henry L. Parsons
Graduate Dean

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NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
A	Area
A_c	Cross-Sectional Area
C	Circumference
c_f	Coefficient of Friction
D	Diameter
DMS	Data Monitoring Software
DO	Dissolved Oxygen
e	Average Depth of Roughness
e/D	Relative Roughness
F	Degrees Fahrenheit
f	Friction Factor
$f_{10,000}$	Friction Factor for a Reynolds number of 10,000
ft	Feet
FFT	Fast Fourier Transform
g	Acceleration Due to Gravity
gm	Gram
GPM	Gallons per Minute
h_f	Head Loss Due to Friction
hr	Hour
Hz	Cycles per Second

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
in	Inches
k	Average Depth of Roughness
Khz	Kilocycles per second
L	Length
Lbf	Pounds-Force
m	Meter
mm	Millimeters
MHz	Megacycles per Second
min	Minute
MSU	Montana State University
$\dot{m}$	Mass Flow Rate
P	Pressure
PPM	Parts per Million
PSI	Pounds-Force per Square Inch
P_{dyn}	Dynamic Pressure
r	Radius
Re	Reynolds number
s	Seconds
T	Temperature
t	Time

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
TFM	Turbine Flowmeter
$u()$	Uncertainty
v	Velocity
$v.$	Versus (in comparison to)
z	Elevation
μ	Absolute Viscosity
γ	Specific Weight
π	3.14
σ	Standard Deviation
τ_o	Wall Shear Stress
$\tau_{10,000}$	Wall Shear Stress for a Reynolds number of 10,000
ν	Kinematic Viscosity
$d()$	Differential Quantity
ρ	Mass Density

ABSTRACT

The purpose of this research, the experimental measurement of a biofilm in a heat exchanger, was to determine the relationship between the biofilm thickness and certain flow parameters. Four test runs were conducted using four different test sections to determine the effect a biofilm produces on the friction factor, the wall shear stress, and the pressure fluctuations in a heat exchanger. The change in the friction factor and the growth of the biofilm approximated the theoretical work, with slight discrepancies in the induction time and maximum values at the conclusion of each test run. The results of the wall shear stress were promising, with the maximum wall shear stress similar for all four test runs in all four flow loops. The pressure fluctuations proved inconclusive in the research, with a random variation of frequencies occurring throughout the investigation. The results of the detachment phase showed a linear relationship between the test parameters and the fluid velocity for the range tested.

CHAPTER 1

INTRODUCTION

One of the major problems facing industry today is the effect of fouling upon heat exchangers. Fouling refers to the formation of an unwanted substance on the surface of a heat exchanger. This formation, or film, can greatly reduce the overall efficiency of the heat exchanger by lowering the heat transfer rate and increasing the pressure drop within the heat exchanger. As the film continues to enlarge, it will continue to lower the efficiency and may eventually restrict the flow of fluid in the heat exchanger completely. The annual cost from this lowered efficiency due to fouling has been estimated by Marner and Suiter [1] to be four to seven billion dollars per year for the United States industrial sector alone.

There are several types of fouling which may affect a heat exchanger. Precipitation fouling occurs when soluble salts which are suspended in the heat exchanger fluid precipitate onto the heat exchanger surface. Particle fouling occurs when suspended particles accumulate on the inside of the heat exchanger. Chemical reaction fouling is caused by the attachment of the products of a chemical reaction onto the heat exchanger surface. Corrosion fouling is caused by the deposition of corrosion products onto the heat exchanger surface. Finally there is biological fouling, or biofouling, which results from the attachment and growth of microorganisms on the heat exchanger surface.

According to Strauss and Puckorius [2] the two recognized forms of industrial biofouling are microbiological fouling of heat exchangers and macrobiological fouling of intake and discharge canals. The former is caused by both plant and animal organisms such as algae and bacteria. The latter stems primarily from invertebrate life such as mussels or clams. This research was concerned exclusively with the investigation of the first, microbiological fouling.

Currently no satisfactory method exists to control the effect of the fouling in heat exchangers. One method is simply to wait until the heat exchanger performance has been substantially reduced, which is indicated by a decrease in the temperature rise across the heat exchanger surface or by reduced condenser vacuum, and then to stop the process and physically remove the deposits. These indicators are very poor in reflecting the fouling occurring within the heat exchanger and irreparable damage may have already occurred before the indicators show that a problem exists. A second method is to add to the heat exchanger fluid chemicals which inhibit any type of potential growth. Periodic chlorination of the water is a common example of this method. Unfortunately, government regulations have severely limited the level of chlorine in heat exchanger fluid discharges, which in turn makes this procedure illegal in many areas. Velocity excursions may be used to remove some of the fouling, but this method does not remove the fouling from the heat exchanger completely and the deposition from fouling quickly returns, causing the efficiency of the heat exchanger to be reduced again. Mechanical cleaning may be used, but the cost of this type of removal is high. Recently a thermal

backwash technique has been experimented with at power plants on the West and East coasts. Thermal backwash, however, must be done frequently enough to kill marine organisms in the juvenile stage. This technique's success depends on the organisms' acclimatization temperatures and thus has met with little success when implemented.

The above control strategies have three major weaknesses according to Turakhia [3]:

1. Process instrumentation is not accurate enough to adequately sense fouling. It may give erroneous information as to the presence of fouling, and by the time that a deposit has been sensed, it may be too late to control it by methods other than stopping the process and physically cleaning the heat exchanger.

2. Indirect methods of determining the cause of the deposit may suggest a variety of potential factors. Often an effective treatment program can only be determined by trial and error.

3. Diagnosis of the problem and prescription of the treatment program require a knowledge of not only fouling in general, but also the past history of the particular treatment. Such knowledge must be developed over time for each application because of the complex interactions which may contribute to fouling.

The problem of determining the type of fouling occurring within the heat exchanger also poses a dilemma. It may be evident that the heat exchanger has a film buildup, but identification of the film may be difficult if not impossible.

The biofilm composition may be determined visually, but it is then again necessary to shut the heat exchange process down, since shutting down is costly, this method is not appealing. This leaves examination of the heat transfer fluid and past consideration of the heat exchanger as the predominant methods for biofilm identification. These methods are inexact and unreliable in most applications.

The current research investigated the possibility of deriving a relationship between the biofilm thickness and various flow parameters such as the friction factor and the wall shear stress. This correlation would then be used to create a fouling "monitor" which would be capable of taking continuous data on the biofilm. The monitor would then use the information to create a base of information to help in determining the biofilm thickness and type. Corrective measures could then be implemented by the individual to remove the biofilm while the heat exchanger is still in operation.

CHAPTER 2

REVIEW OF PREVIOUS FINDINGS

Summary of Previous Findings

Although there has been a great deal of investigation into the effects of surface roughness on fluid flow, most previous work was based upon the assumption of a uniform surface roughness and a constant inside pipe diameter. Unfortunately, a biofilm is constantly changing its physical characteristics as it matures and grows.

Some of the earliest work in fluid dynamics was done by Sir Issac Newton who theorized that for straight and parallel motion of a fluid, the tangential stress, τ , between the two adjacent layers was proportional to the velocity gradient, ∂u , in a direction perpendicular to the layers, ∂y . This gives the relationship:

$$\tau = \mu \frac{\partial u}{\partial y} \quad (1)$$

The coefficient of proportionality μ is now known as the absolute viscosity of the fluid.

In 1840, G. H. L. Hagen [4] and J. L. M. Poiseuille [5] studied laminar flow in circular pipes. Hagen experimented with the flow of water through small brass tubes. His results showed that loss of head for a given length of pipe

was directly proportional to the rate of flow and inversely proportional to the diameter of the tube to the fourth power. Poiseuille also arrived at the same conclusion working with small capillary tubes. This relationship between the pressure loss and flow parameters was termed the Hagen-Poiseuille relationship and is defined by the equation:

$$p_1 - p_2 = 8\mu l \frac{Q}{\pi R^4} \quad (2)$$

In 1883, Osborne Reynolds [6] investigated the characteristics of laminar and turbulent flow. Reynolds performed a series of experiments in which dye was injected into water flowing through a glass pipe. Reynolds' experiments and his analytical work showed that the nature of pipe flow depends on a dimensionless parameter which he called the Reynolds number. This parameter was determined by the relationship:

$$Re = \frac{\rho u_m D}{\mu} \quad (3)$$

where ρ is the mass density of the fluid, u_m is the mean velocity of the fluid, D is the hydraulic diameter, and μ is the absolute viscosity of the fluid. With his experimental and analytical work he showed that the Reynolds number was characteristic to both laminar and turbulent flow. From his work, he concluded that the transition between laminar and turbulent flow occurred at a Reynolds number of 2000. If special precautions were taken not to disturb the fluid, Reynolds found that this transition period was delayed to Reynolds numbers as high as 3000.

In 1933, J. Nikuradse [7] investigated the relationship between surface

roughness and the pressure loss in pipes. In his research, Nikuradse obtained and classified sand grains of various sizes. He then glued these sand grains to the inside of various pipes to produce a desired roughness and the pressure drop was then determined for different values of Reynolds numbers. In his experiments observations were made on the loss of head (pressure drop), velocity distribution in the test pipe, discharge quantity and the temperature of the water. From this information, Nikuradse was able to determine a relationship between the Reynolds number and the friction factor of the pipe. This relationship had three distinct regions. The first region consisted entirely of laminar flow within the pipe and extended from Reynolds numbers from 0 to 2,000. In this region, the friction factor was related to the Reynolds number by the relationship:

$$f = 64 / Re \quad (4)$$

This first region was predicted analytically by Hagen and Poiseuille and was characterized by the linear relationship between the friction factor and the Reynolds number. The second region was termed the transition region and extended from Reynolds numbers of 2,000 to 100,000. The smoother the pipe used for experimentation, the higher the transition Reynolds number. For extremely rough pipes transition occurred at a Reynolds number of 4,000. For extremely smooth pipes, this region would last to Reynolds numbers nearing 100,000. The friction factor in the latter region was related to the Reynolds number by the relationship:

$$f = \frac{0.316}{(Re)^{.25}} \quad (5)$$

The final region was classified as the fully rough region and started with Reynolds numbers ranging from 4,000 to 100,000, depending upon the roughness of the pipe. In this region the friction factor was independent of the Reynolds number and was determined using the relationship:

$$f = \frac{1}{(1.74 + 2 \cdot (\log r/k))^2} \quad (6)$$

This last region was characterized by the dependence of the friction factor upon the r/k ratio instead of the Reynolds number. This r/k ratio is the inverse of the relative roughness k/r which was used in early experiments. Recently more literature has assigned the relative roughness as e/D . Each notation is found in literature.

The findings of Nikuradse help in the development of semi-empirical theories of fluid friction factors. In 1935, L. Prandtl developed the following formula for the friction factor in turbulent flow in smooth pipes:

$$\frac{1}{\sqrt{f}} = 2.0 \log(Re \sqrt{f}) - 0.8 \quad (7)$$

At about the same time, T. von Karmen developed the following relation for friction factor for completely turbulent flow:

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{e/D}{3.7} \right) \quad (8)$$

Both of these relationships are limited in their application to Nikuradse's work to the completely laminar or completely turbulent region.

In 1939, C. F. Colebrook [8] developed a formula that combined the laminar and turbulent limits and also covered the transition region. This relationship stated:

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{e/D}{3.7} + \frac{2.51}{Re\sqrt{f}} \right) \quad (9)$$

Colebrook's equation allowed a single relationship to relate the entire range for the friction factor. The drawback to the equation was that the friction factor was implicit with respect to f .

Shortly after Nikuradse and Colebrook published their works, Lewis Moody [9] realized the importance of these findings. In his paper, he plotted the experimental results of Nikuradse and Colebrook. This plot has since been termed the Moody Diagram. The diagram plotted the relationship between the Reynolds number, the friction factor, and the relative roughness of a pipe. If any two of these pieces of information were known, the third could be determined by using the diagram. Since data already existed on the relative roughness of most industrial piping, it was relatively easy to calculate the friction factor that would exist within a pipe for a certain Reynolds number. The Darcy-Weisbach equation:

$$gh_f = f \frac{L v^2}{d 2} \quad (10)$$

where f is the friction factor, v the fluid velocity, L the length of the pipe, d the diameter of the pipe, and g the acceleration due to gravity, may then be used to solve for the resulting head loss in the pipe. The Moody diagram greatly simplified pipe flow calculations and is still in wide use today.

In recent years, many researchers, such as Characklis [10,11,12], Turakhia [3], and Trulear [10] have realized the importance for investigation into the effects of biofouling on fluid dynamics. Many researchers have helped to define the basic processes involved in biofouling. For example, Trulear and Characklis [10], in their work 'Dynamics of Biofilm Processes', helped to define the basic processes occurring in biofouling. Their research found that the processes which contribute to the overall biofilm accumulation are:

1. Organic adsorption.
2. Transport of microbial particles to the surface.
3. Microorganism attachment to the surface.
4. Growth of attached microorganisms.
5. Reentrainment of biofilm by fluid shear.

Strauss and Puckorius [2] recently investigated the different types of fouling occurring in industrial heat exchangers. Their research helped to classify the different types of fouling depositions which may possibly occur within industrial heat exchangers. They investigated three major types of depositions which were precipitation fouling, biological fouling, and corrosion fouling. This work helped to give the reader a better understanding of the processes involved in these types of fouling and possible methods to remove the fouling.

In 1987, Carl Hoerger [13,14] began the study of heat transfer modeling for the control of fouling in heat exchangers. The theoretical work of Hoerger attempted to simulate biofilm parameters, such as growth rates and fouling factors, within a heat exchanger. These analytical simulations were then used to predict actual conditions within a heat exchanger.

Implications for this Investigation

The findings of the previous investigators were used to determine the basic variables for this experiment. The implications from the previous work are summarized as follows:

1. The major form of fouling currently affecting industrial heat exchangers was biological fouling. Due to that fact, this was the form of fouling that was investigated in this research.

2. The major factor affecting the fluid in the heat exchanger was the surface of the biofilm. Therefore, only the thickness of the biofilm and the surface conditions were investigated in this research. The biofilm characteristics were assumed constant throughout its thickness.

3. Since the important surface characteristics were those of the biofilm, the material of the pipe was unimportant. For this reason, glass tubing was used throughout the experimentation. This was done for ease in the observation and measurement of the biofilm thickness.

4. Since isolation of a single type of film is possible only if the entire system can be sterilized, the biofilm was seeded from microorganisms within the air and in the Bozeman water system. Currently methods such as autoclaving are available for sterilization of some test apparatus, but unfortunately this process is limited to dimensions significantly smaller than the test apparatus used for this experimentation. The water was exposed to air throughout the experimentation to allow any microorganisms present in the air to enter the flow loop. The flow loop was supplied with tap water to allow it to be seeded

with any microorganisms present in the Bozeman water system.

5. The only factor allowed to change the fluid temperature was a change in the temperature of the surrounding room air.

6. The oxygen level would be held constant throughout the investigation. Since the oxygen saturation point is dependent upon temperature, this point would fluctuate slightly as the temperature of the test fluid varied.

7. The nutrient level would be held constant for all of the four test runs in the investigation.

8. For ease in data reduction, the elevation of the entire test section remained the same throughout the investigation.

9. The biofilm thickness was neglected in determining the diameter of the glass in the test section. For all calculations, the diameter of the pipes was assumed constant throughout the research. For data reduction, the biofilm thickness would change the pipe diameter roughly 1 percent at the maximum biofilm thickness.

10. To determine a dimensional correlation, the diameter of the test sections would vary from that of an actual heat exchanger, roughly 7/8 inch diameter, to a diameter of 1/4 inch. This gives a variance in the cross-sectional area of ten, with the maximum area 0.615 square inches and the minimum area 0.0594 square inches.

CHAPTER 3

OUTLINE OF INVESTIGATION

Objectives

The objectives of the experimental research for predictive modeling of a biofilm had two major areas of concern. The first was to investigate the relationship between the friction factor and the biofilm thickness, and the second was to investigate the effect of the biofilm thickness on the heat transfer coefficient. It was felt that by combining these two pieces of information, a predictive model of the biofouling could be determined while the heat exchanger was still in operation. The research for this thesis was concerned primarily with the change in the friction factor as the biofilm grew.

Scope of the Investigation

During the initial design of the experiment, it was determined that the experimental variables to be investigated should be applicable to the conditions affecting heat exchangers. Therefore, the investigation varied the velocity of the fluid to the point of detachment of the biofilm from the surface of the pipe. Investigation beyond this point was considered unnecessary.

Four separate flow loops were used to determine the relationship between the pipe diameter and the flow parameters. The addition of more than one pipe diameter allowed investigation into the possibility of non-dimensionalizing the final results.

The biofilm thickness in the test section was allowed to vary from an initial condition of no biofilm to a final state of a fully matured biofilm within the test section.

Facilities and Equipment

All of the experiments and test runs performed were conducted at Montana State University in Ryon Laboratory, Room 21, Laboratory Station 1. The laboratory design consisted of four individual flow loops. All of the flow loops were identical except for the diameter of the pipe used in the entrance length and test section. Figure 1 gives a schematic drawing of one of the flow loops used in the experimentation.

All four flow loops were supplied by a thirty-gallon tank of fluid located on the floor of Ryon Laboratory. The lower tank was placed near the entrance to the test section for ease in operation. The lower tank was lined with plastic to stop corrosion by the biofilm. A pump located on the side of the tank was then used to supply fluid to a suspended tank, which was elevated to a height of approximately thirty feet. This upper tank rested upon a platform which was suspended on top of a support tower located in the laboratory. The

water level in this upper tank was held constant by placing an overflow pipe on the side of the tank. The overflow from this upper tank was then returned to the lower tank to recycle again.

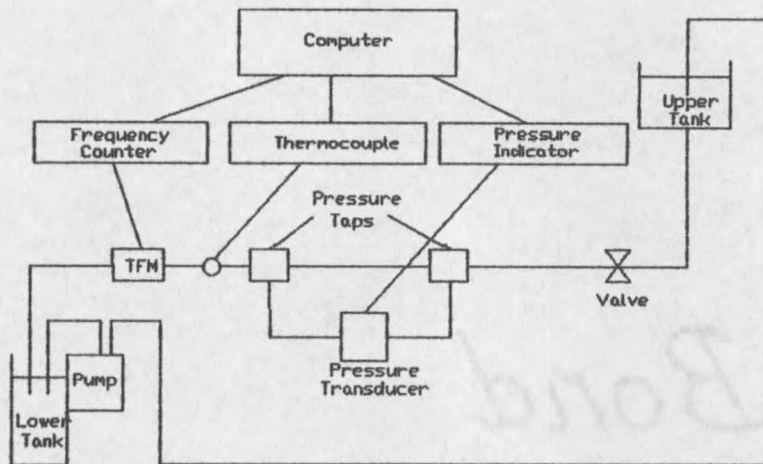


Figure 1. Diagram of Flow Loop and Instrumentation.

Hoses were attached to the bottom of the suspended tank to allow the water in the tank to gravity feed. By placing the tank at an elevation of thirty feet, a wide range of velocities could be measured. The supply hoses consisted of roughly thirty-five feet of 5/8 inch diameter garden hose. This eliminated any possibility of picking up vibrations which may have been caused by the building itself.

Once the hoses reached the support table, they were connected to gate

valves. These valves allowed control of the velocity of the fluid through the hoses. Locating these valves at the beginning of the support table was to reduce the difficulty in operation and access.

After passing the valves, the water entered a bubble trap. Removing the air bubbles from within fluid helped to give a more uniform growth pattern to the biofilm in the test section. The bubble trap consisted of an enlarged pipe tee with a valve located at the top to allow the trapped air to be removed.

After passing the bubble trap, the water was allowed to enter a section of pipe of the same diameter as the test section. This produced an entrance length which allowed the water to reach steady state conditions by the time it reached the test section. The entrance lengths and the length to diameter ratios (L/d) for the flow loops are listed in Table 1.

Table 1. Entrance Length Specifications

Loop Number	Entrance Length (inches)	Entrance Length Pipe Diameters
1	40.3	75.8
2	44.6	111.5
3	45.6	149.0
4	47.4	169.3

The minimum L/D ratio used was 75. According to Incropera and Dewitt [15], the minimum ratio necessary for fully developed conditions is between 10 and 60. Therefore, for all four flow loops fully developed conditions were assumed.

After leaving the entrance length, the test fluid passed through a plastic pressure tap. This pressure tap consisted of five inches of two-inch diameter polycarbonate plastic. Figure 2 gives a drawing of the pressure tap used in the research. The entire length of the plastic tap was bored to the inside diameter of the test pipe, and the first inch and last inch were bored so a brass sleeve could fit into the pressure tap. The sleeves were then sealed to the plastic pressure tap. This design of the pressure taps allowed the glass piping to be placed within the tap while maintaining a constant inside pipe diameter. The brass sleeve allowed the glass test section to be sealed to the plastic pressure tap. This was done by placing plastic tubing over the sleeve and glass test section and clamping. The sleeve was necessary since the plastic tap could not be clamped.

This pressure tap design allowed an average pressure reading to be taken as the fluid entered the test section. The pressure tap took readings from the top, bottom, and from both sides of the pipe and then averaged these readings. This averaged pressure reading was then transmitted to a pressure transducer. The pressure transducer was placed in parallel with the test section by connecting the pressure taps to the transducer with plastic tubing. Plastic tubing was used so that any air not removed by the bubble traps could be detected visually and removed. The pressure transducer was placed on the support table

by the test section and between the pressure taps. These pressure transducers were then attached to pressure indicators. The pressure transducer, pressure indicator, and connectors were calibrated as one unit and kept together throughout the experiment. Appendix B gives the results of the initial and final calibrations, with the resulting accuracies and resolutions.

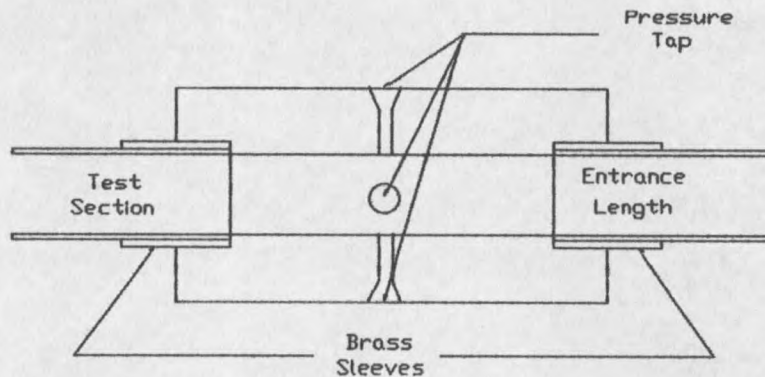


Figure 2. Diagram of Pressure Tap.

After passing the pressure taps, the water entered the glass test section. The test section was designed to be rotated to allow observations to be made on any side of the piping without changing any of the flow characteristics. The lengths and diameters of the test section are listed in Table 2. At the end of the test section the glass piping entered another pressure tap as described above. This allowed the pressure drop across the section to be calculated.

Table 2. Test Section Specifications

Loop Number	Test Length (inches)	Inside Diameter (inches)	Outside Diameter (inches)
1	35.6	0.532	0.625
2	36.0	0.400	0.475
3	36.0	0.306	0.392
4	36.0	0.280	0.352

Once the water passed the second pressure tap, it entered a six inch length of piping with the same diameter as the test section. The fluid then entered a turbine flow meter. The turbine flowmeter was connected to a frequency counter located on the equipment table. The calibrated turbine flowmeter readings from the frequency counter were used to calculate the velocity of the fluid passing through the test section. Appendix A gives the calibration statistics and the accuracy and resolution of the frequency counter and turbine flowmeters. Immediately after the turbine flowmeter, a T-type thermocouple was installed within the fluid flow. The thermocouple was connected to the computer to allow a constant recording of the temperature of the fluid exiting the test section. This recording could be taken at any time or averaged over a given time period. Tests of the temperature variation along the entire length of the flow loop showed identical temperature readings through all points of the flow loop. Therefore, the temperature probe was placed at the end of the test

section for ease of installation and maintenance. After passing the thermocouple, the fluid entered drain hoses which returned the water to the tank located on the floor.

The valves, entrance lengths, test sections, turbine flowmeters, and thermocouples of all four flow loops were held rigid by mounting the flow loop to a support stand. The support stand was elevated from the table to allow a microscope to be placed underneath the glass test section so that biofilm thickness measurements could be taken with greater ease. The piping was placed in circular plastic rings which were clamped to the support structure. This design lowered the possibility of breaking the glass tubing by reducing the radial movement of the test apparatus. A twenty-four inch viewing section was cut into the support structure underneath the test section to facilitate placing a microscope under the test section.

Test Matrix

Due to the length of time necessary for a single test run, it was decided during the initial stages of the research that only two major areas of concern were to be investigated. The first area was the characteristics of the initial growth of the biofilm in the test section, the second was the study of the characteristics of the biofilm in the test section during detachment from the pipe wall. It was felt that these two areas would give a much better understanding of biofouling processes occurring in heat exchangers. The test matrix used for the research was split into two areas of investigation. The first test

matrix was called the growth phase, and the second test matrix was termed the detachment phase. Throughout the thesis, the results for both phase will be listed. The test matrix for both phases follows.

For Growth Phase

1. Pressure measurements were taken to determine the pressure drop across the test section. From this information, the friction factor caused by the biofilm in the glass piping could be calculated.
2. Velocity measurements would be taken to determine the wall shear stress on the biofilm in the test section. The velocity would be held constant at 1.00, 1.25, 1.50, and 1.75 ft/sec for test runs one through four respectively. The corresponding Reynolds numbers varied from 2,800 to 17,000.
3. The temperature in the test section would be measured to determine the properties of the fluid.
4. The biofilm thickness in the test section would be measured to determine any correlation between the measured variables and the biofilm thickness.
5. Four individual flow loops would be used to determine the effects of the variation of pipe diameter on the results.
6. The oxygen level would be held constant throughout the experimentation. This level would be measured once every twenty-four hours during the test runs.

7. The nutrient level would be held constant throughout the experimentation. It would be determined at the beginning of each of the four test runs for comparison.
8. All data would be recorded at maximum intervals of twelve hours. The time between test points would be reduced as the growth of the biofilm increased.

For Detachment Phase

The second stage of the investigation was the detachment phase. The test matrix for the detachment phase was as follows:

1. The velocity would be varied from the growth velocity to 3 ft/sec.
2. All other pertinent information would be recorded as in the growth phase.

CHAPTER 4

PRESSURE MEASUREMENTS

Experimental Apparatus and Procedures

Pressure readings were taken in all four flow loops using 1.0 psi full scale pressure transducers. Table 14 in Appendix B gives the resolution and accuracy of the pressure transducers used in the experimentation. These measurements were taken for the purpose of determining the friction factor for the biofilm in the test section.

Friction Factor for Growth Phase

Figures 3 through 6 plot the relationship between the friction factor and test time during the growth phase for flow loops one through four respectively. To make an accurate comparison between data points, it was necessary to plot the friction factor at similar Reynolds numbers. To accomplish this, the relative roughness, e/D , was calculated for the data point. This relative roughness was used to determine the friction factor at a Reynolds number of 10,000. The value of 10,000 for the Reynolds number was chosen arbitrarily. Appendix C gives a description of the exact method used to accomplish this.

As can be seen from the results, the friction factor maintains a constant

value of roughly 0.033 between thirty-six and fifty-seven hours for test velocities of 1.0, 1.25, and 1.50 ft/sec. For a test velocity of 1.75 ft/sec, the friction factor did not change throughout the test run.

After the initiation stage, the friction factor increased linearly in relation to time for approximately one hundred and ninety hours for a test velocity of 1.0 ft/sec, to one hundred hours for a test velocity of 1.50 ft/sec.

Following the growth stage, the increase in the friction factor declined. Data was taken approximately eighteen hours into this plateau stage before the test run was ended. The maximum friction factor ranged from approximately 0.1 for a test velocity of 1.0 ft/sec, to 0.048 for a test velocity of 1.50 ft/sec.

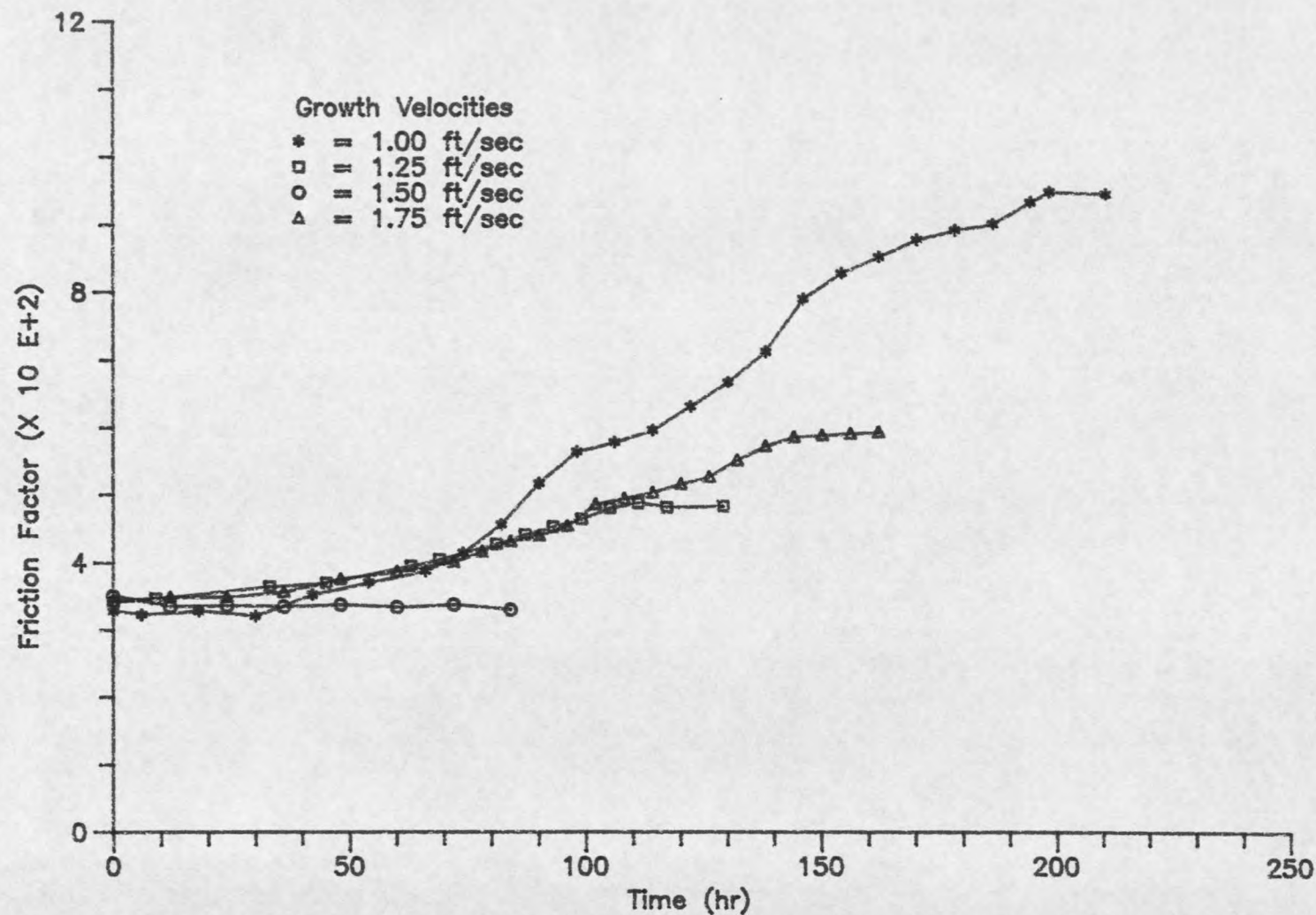


Figure 3. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches

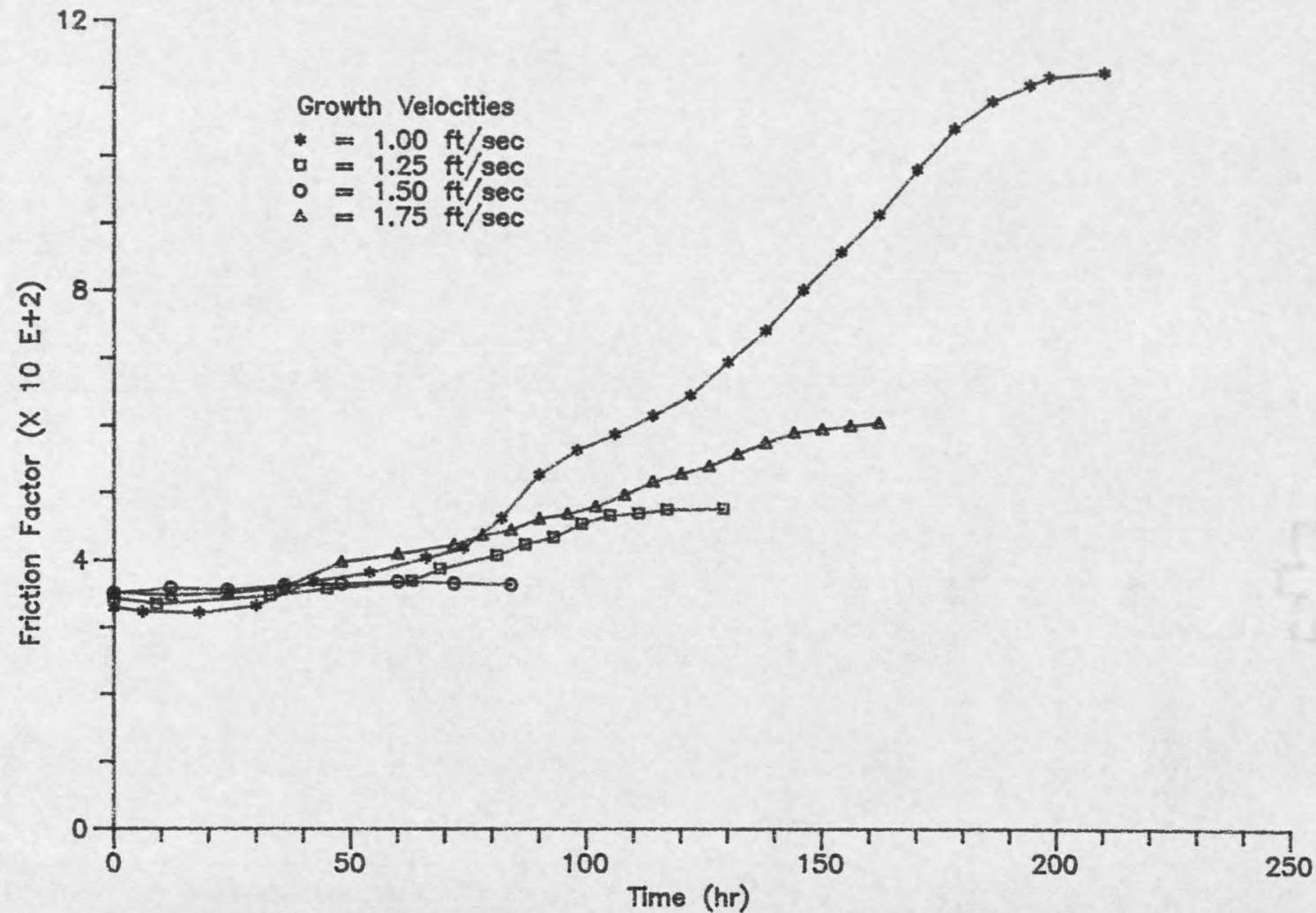


Figure 4. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches

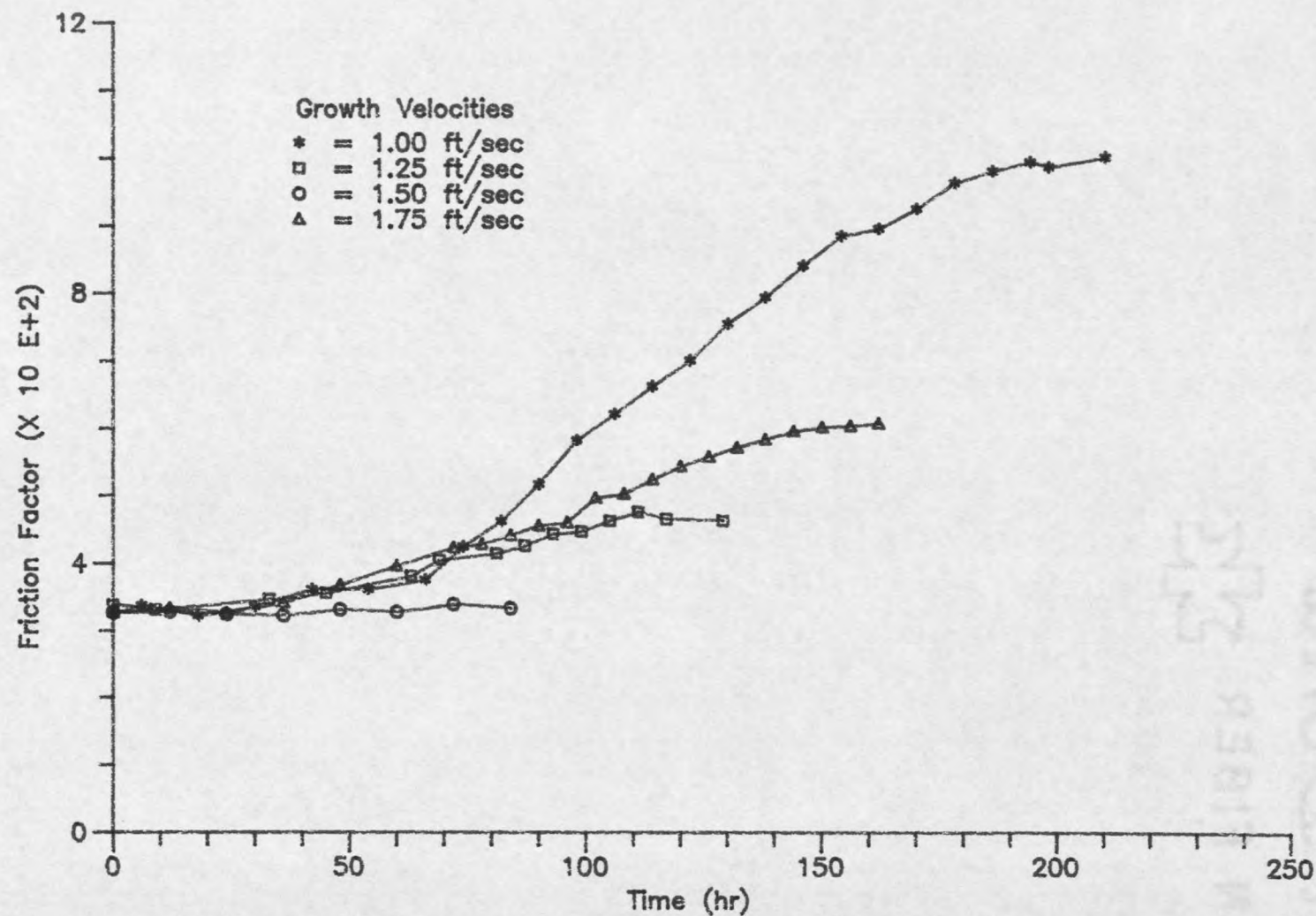


Figure 5. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter Of 0.370 Inches

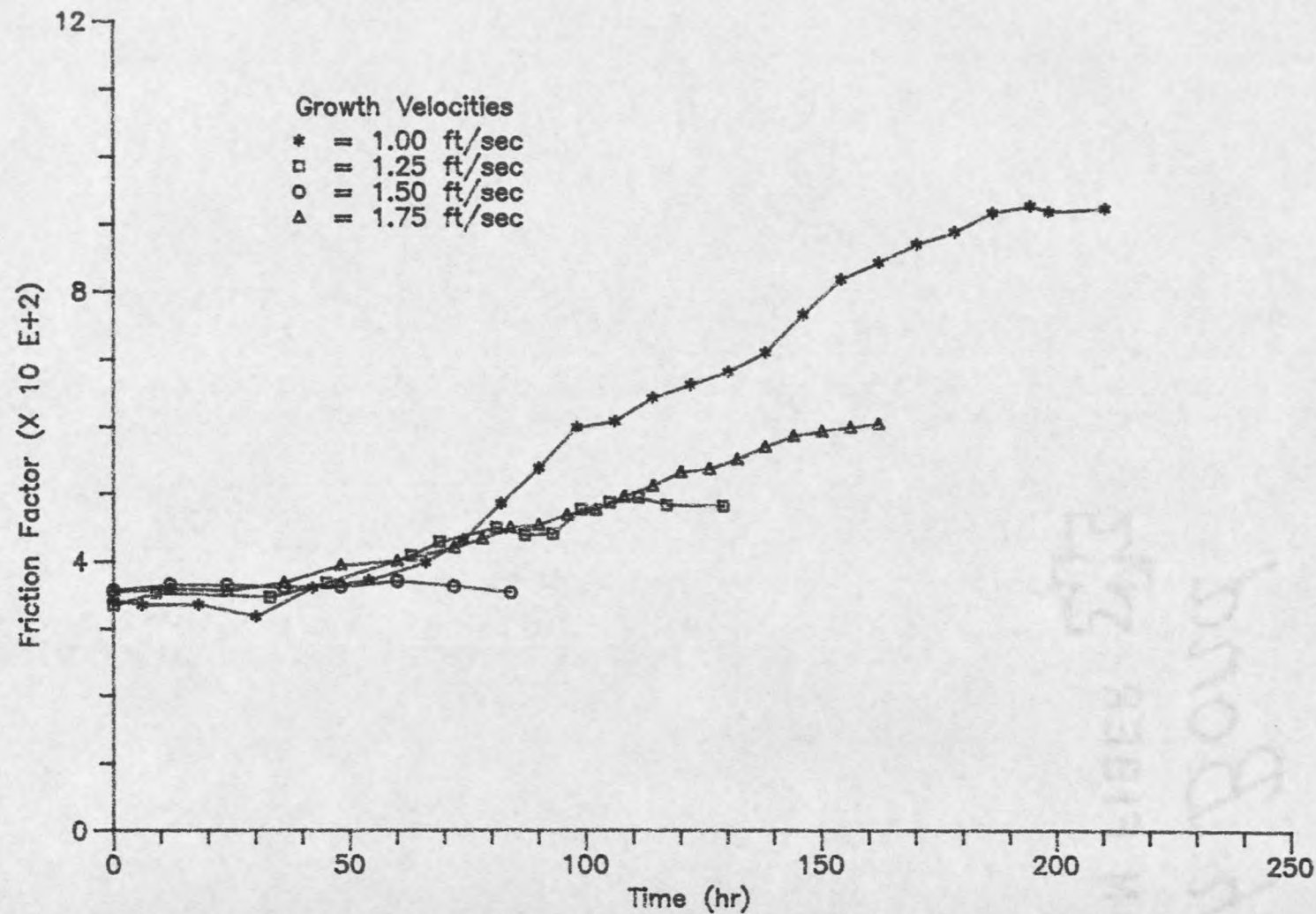


Figure 6. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches

Friction Factor for Detachment Phase

Figures 7 through 10 plot the relationship between the friction factor and the fluid velocity for the detachment phase. As in the growth phase, the friction factor was plotted with respect to a Reynolds number of 10,000. The friction factor exhibited two tendencies in the research. In the test runs with slower velocities, 1.00 and 1.25 ft/sec, the friction factor decreased linearly with respect to the fluid velocity, with two distinct regions occurring. The first region is marked by a large coefficient of friction for the test section, which decreases slightly with an increase in velocity. The second region is marked by a drastically reduced coefficient of friction within the test section, approaching clean pipe conditions. As the velocity is increased in the test section, the friction factor continues to approach ideal conditions. The two regions are separated by a detachment region. At this point a critical wall shear stress has been reached causing a large portion of the biofilm to detach from the surface, thereby significantly lowering the friction factor. The second tendency observed occurred in the higher velocity test runs, 1.50 and 1.75 ft/sec. In these test runs, the friction factor decreased linearly throughout the entire range of velocities and paralleled the slower velocities after the detachment of the biofilm.

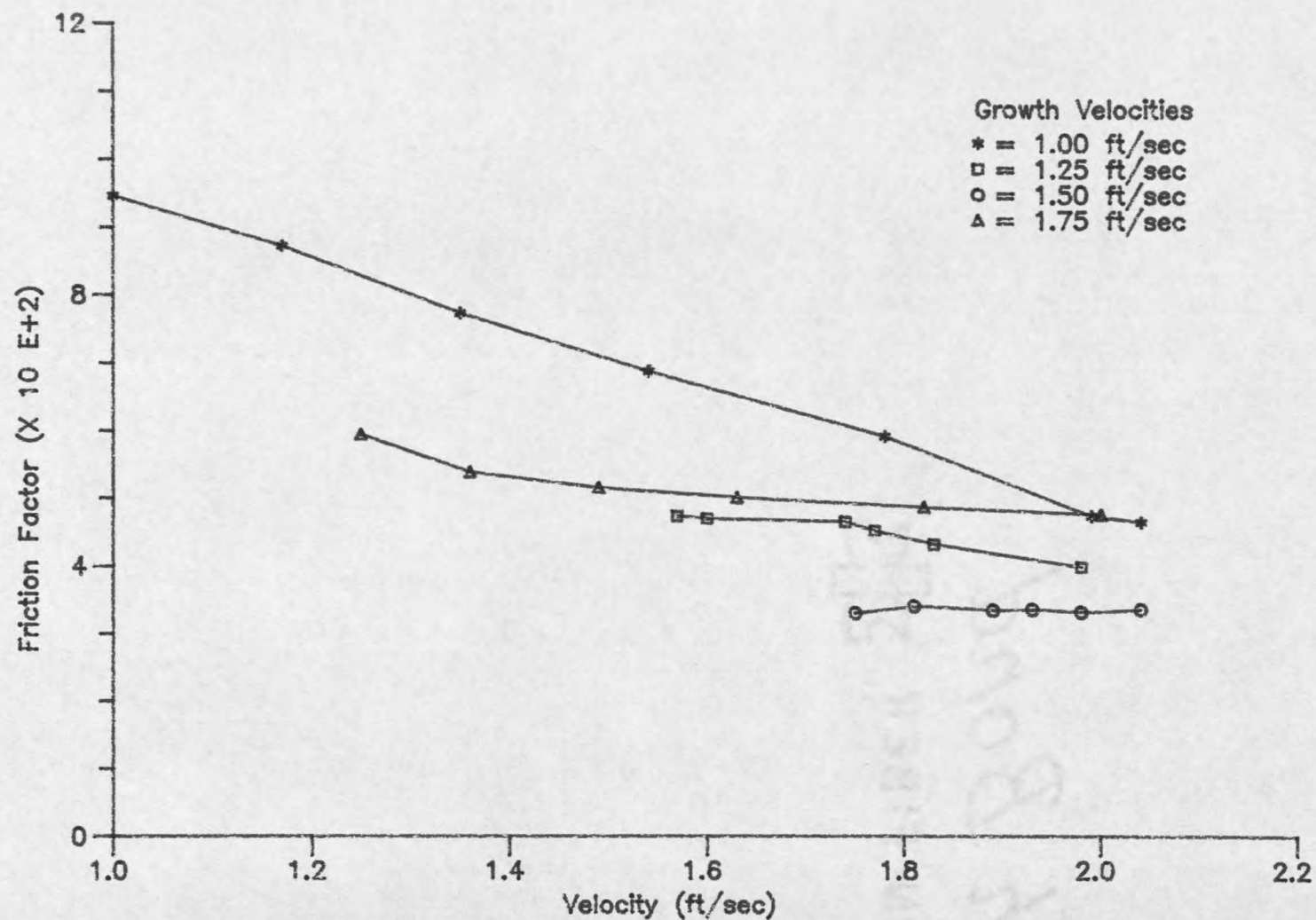


Figure 7. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches

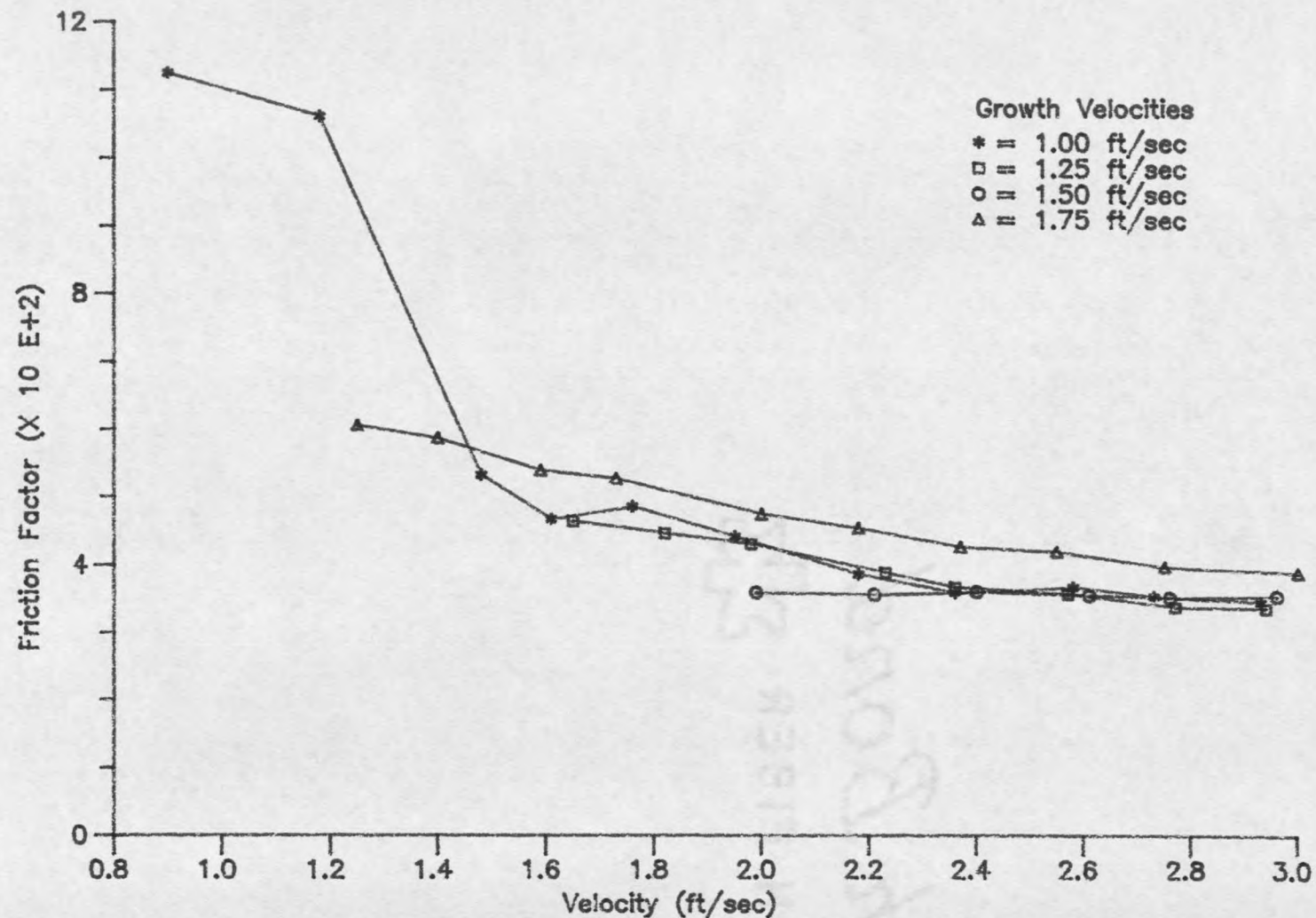


Figure 8. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches

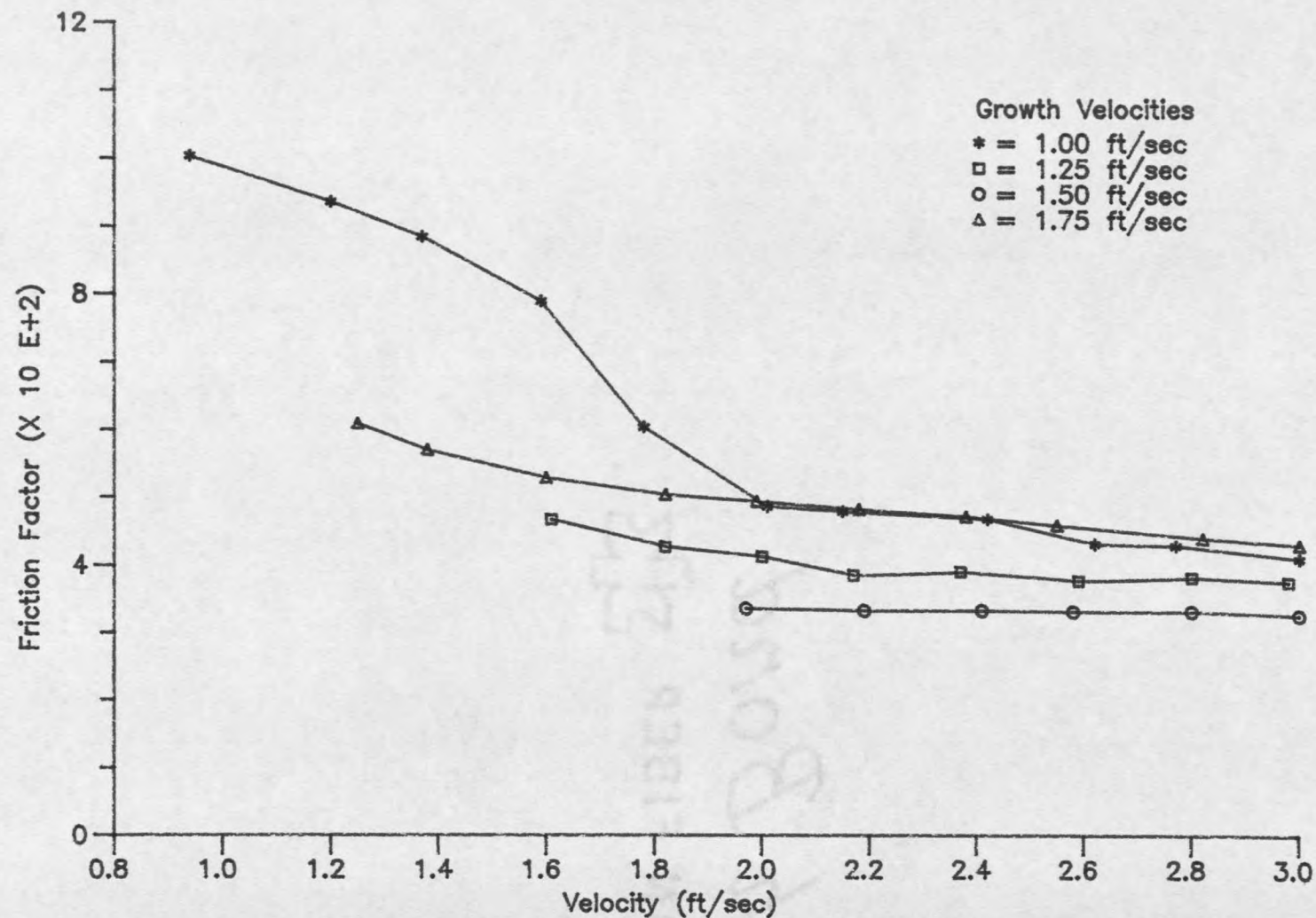


Figure 9. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches

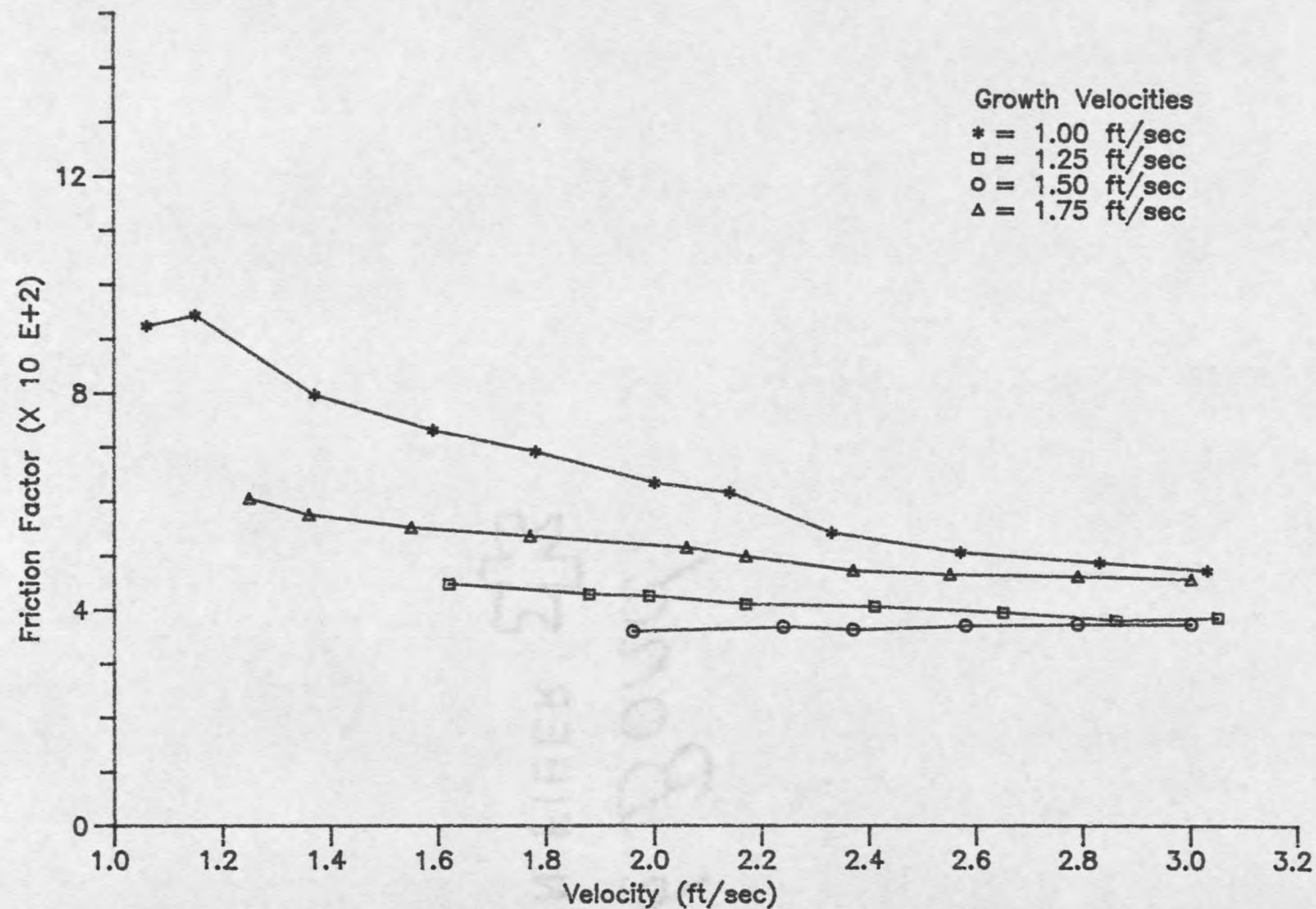


Figure 10. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe diameter of 0.275 Inches

CHAPTER 5

WALL SHEAR STRESS MEASUREMENTS

Experimental Apparatus and Procedures

The wall shear stress was determined during both phases of the experimentation. Readings were taken during the growth phase at the same time that visual observations were made on the biofilm. The wall shear stress was calculated at the initial clean pipe conditions, and results were calculated as the biofilm grew and matured within the test section. The data reduction program used to calculate the wall shear stress is listed in Appendix C.

Wall Shear Stress Results for Growth Phase

The relationship between the wall shear stress and the growth time for the individual flow loops are shown in Figures 11 through 14. To make an accurate comparison between the data points, it was necessary to determine the wall shear stress at a fixed Reynolds number. To accomplish this, the relative roughness, e/D , was determined at the data point. The relative roughness was used to determine the friction factor at a Reynolds number of 10,000. The velocity of the fluid was then calculated for a Reynolds number of 10,000 and

the wall shear stress determined.

As can be seen from the results, the wall shear stress exhibited three distinct regions. The first region was evident by a constant value for the wall shear stress. This value ranged from 0.008 lbf/ft² for a test velocity of 1.0 ft/sec to 0.024 lbf/ft² for a test velocity of 1.75 ft/sec. This period lasted between thirty-six and fifty-seven hours. After this time, the wall shear stress increased linearly to a value between 0.024 and 0.026 lbf/ft². This limit on the biofilm shear stress was representative of all four test runs and all four test loops.

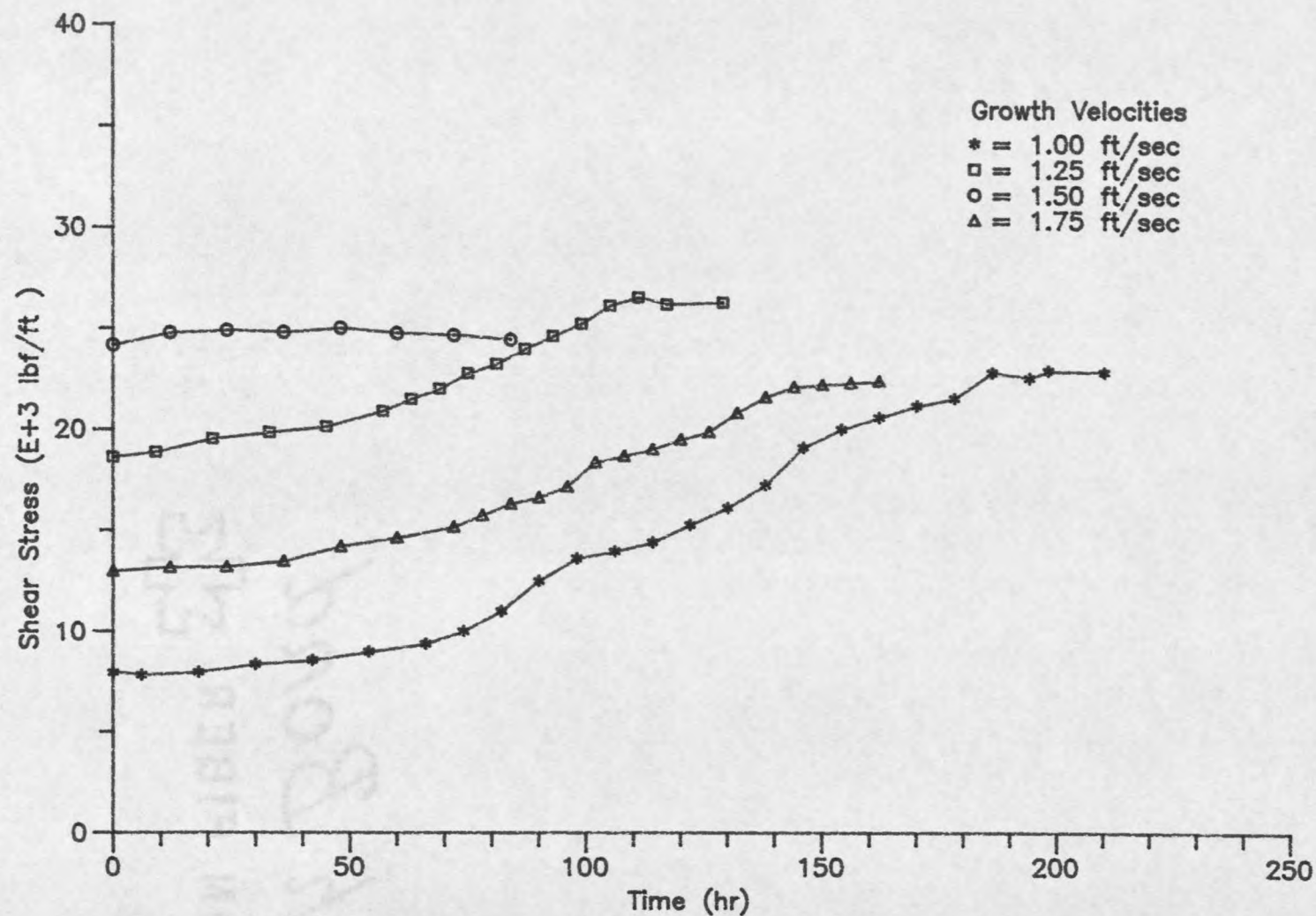


Figure 11. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches

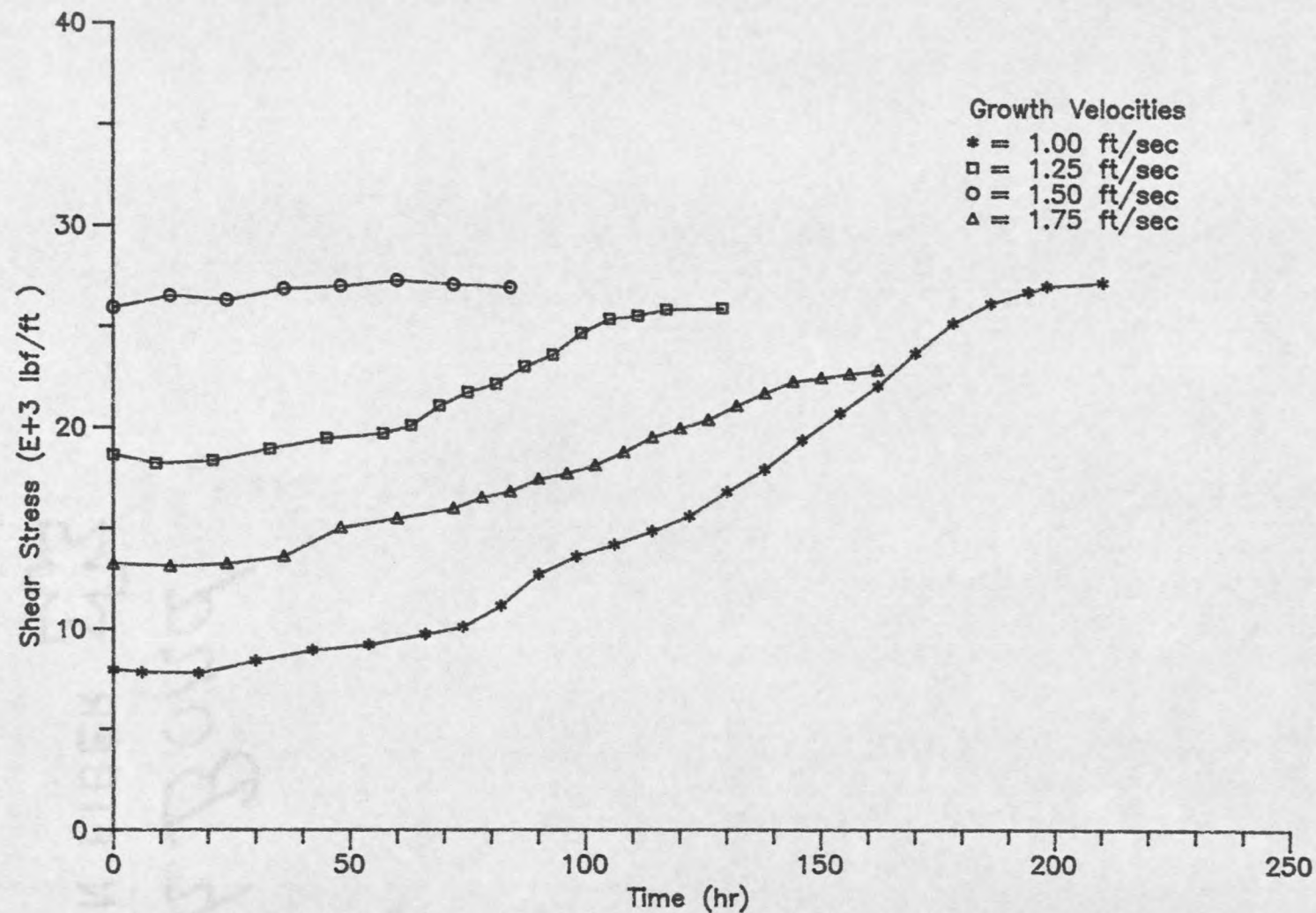


Figure 12. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches

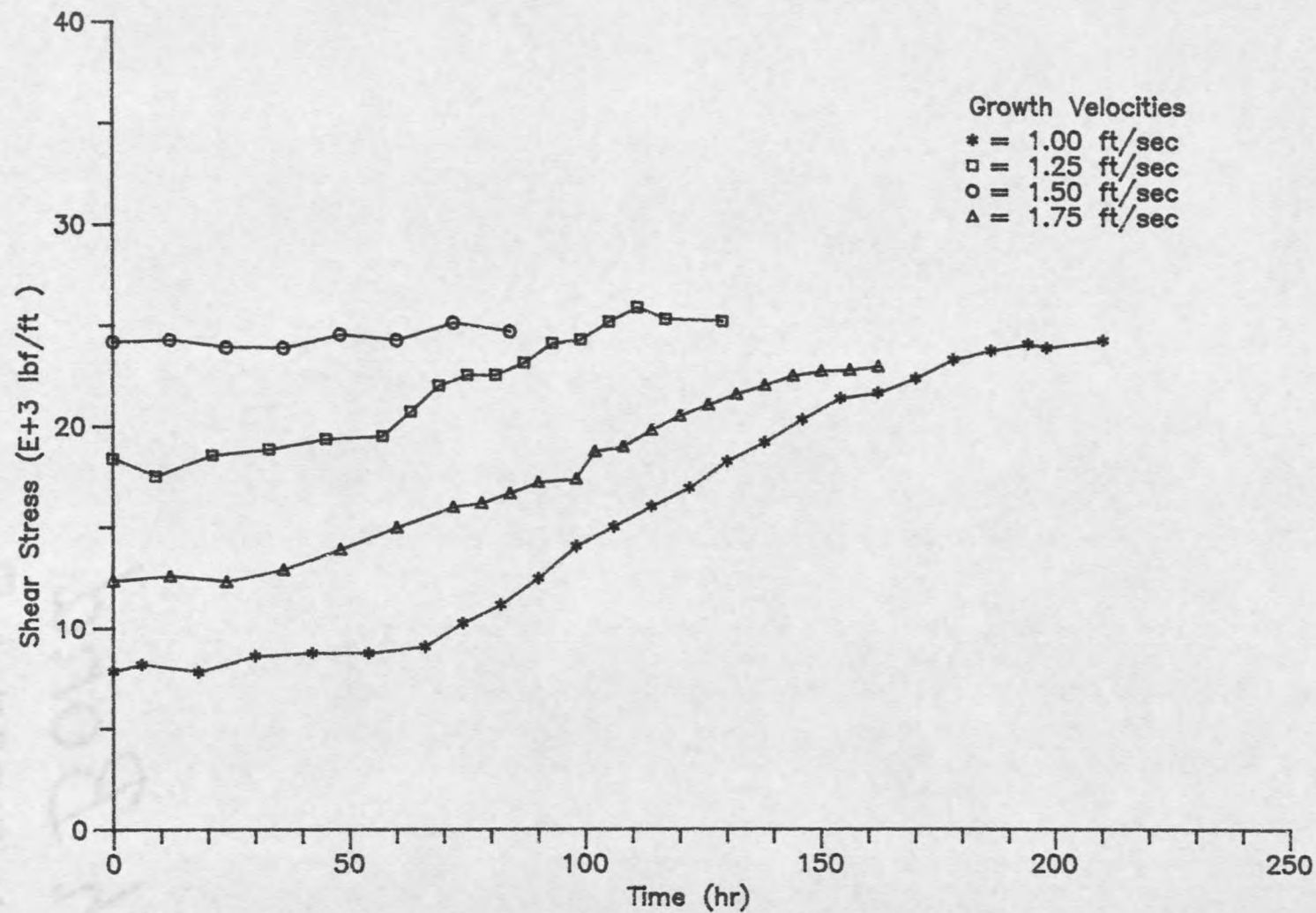


Figure 13. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter Of 0.370 Inches

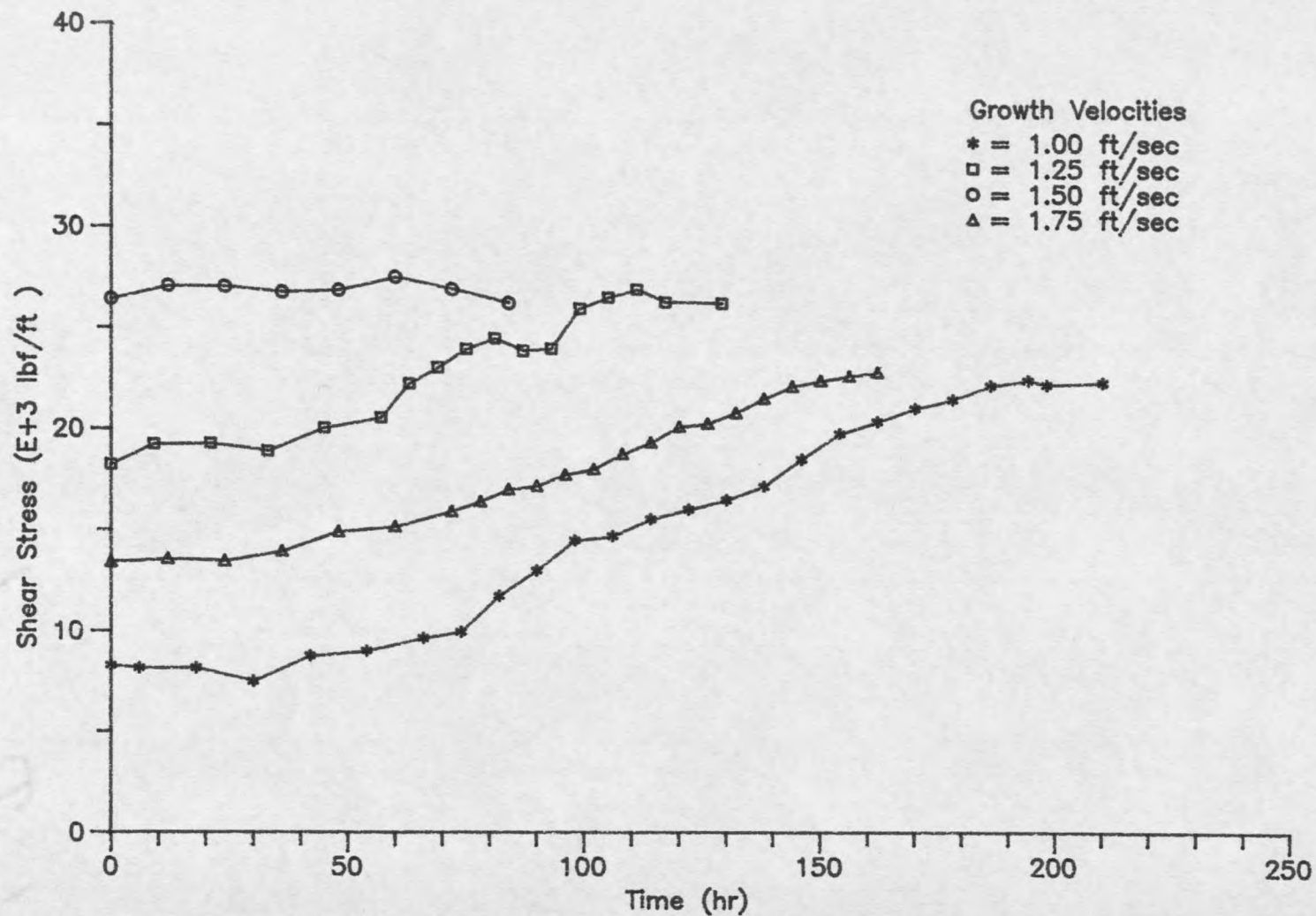


Figure 14. Wall shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches

Wall Shear Stress Result for Detachment Phase

The values for the wall shear stress on the biofilm in the test section during the detachment phase are plotted in Figures 15 through 18. The value of the wall shear stress was determined at a Reynolds number of 10,000 using the method described in the growth phase. As can be seen from the figures, the shear stress increases linearly as the velocity is increased, with all four test runs exhibiting similar tendencies. The wall shear stress increased from a value of 0.025 lbf/ft² to values of approximately 0.80 lbf/ft².

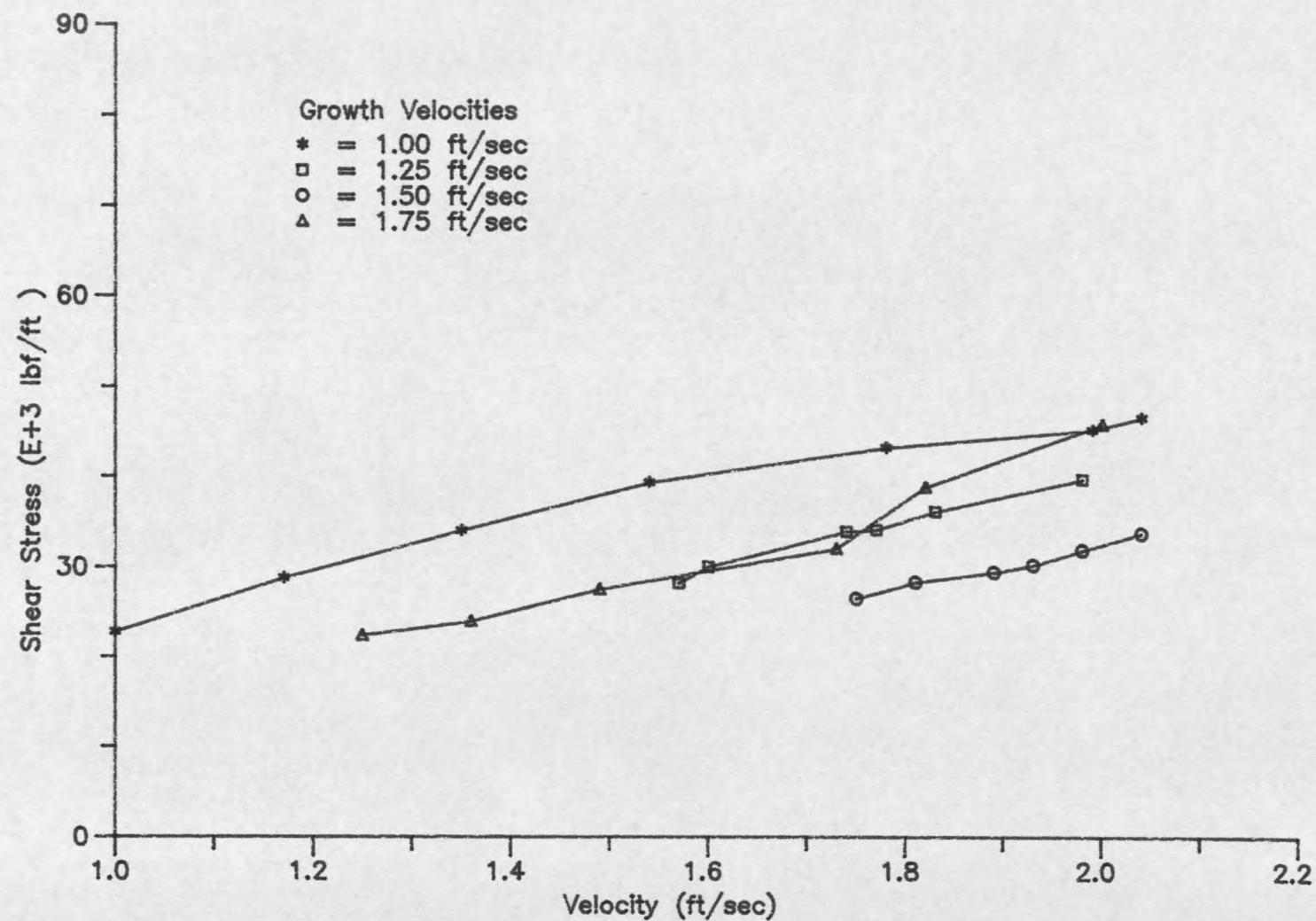


Figure 15. Wall Shear Stress v. Velocity for Detachment Phase For a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches

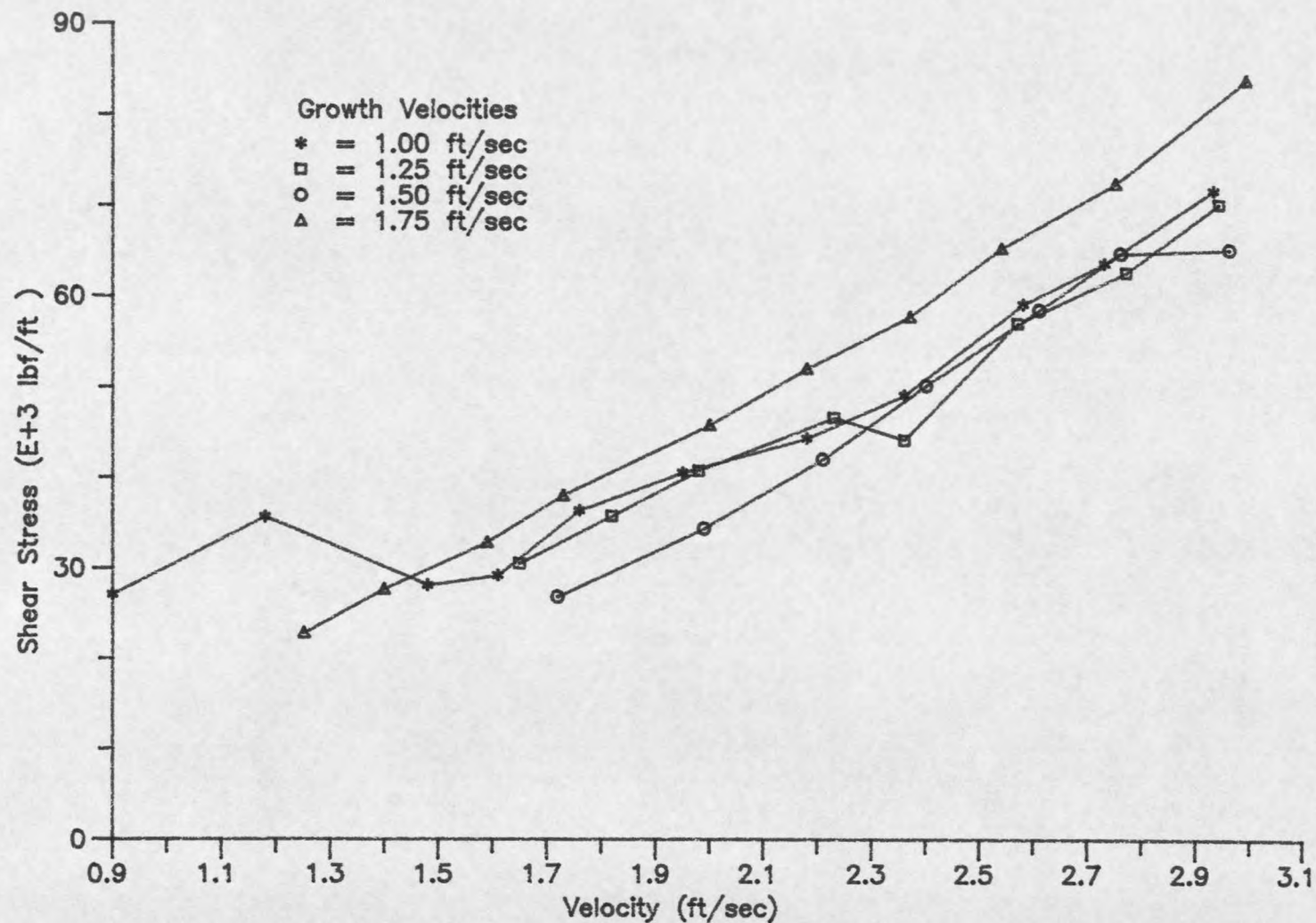


Figure 16. Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches

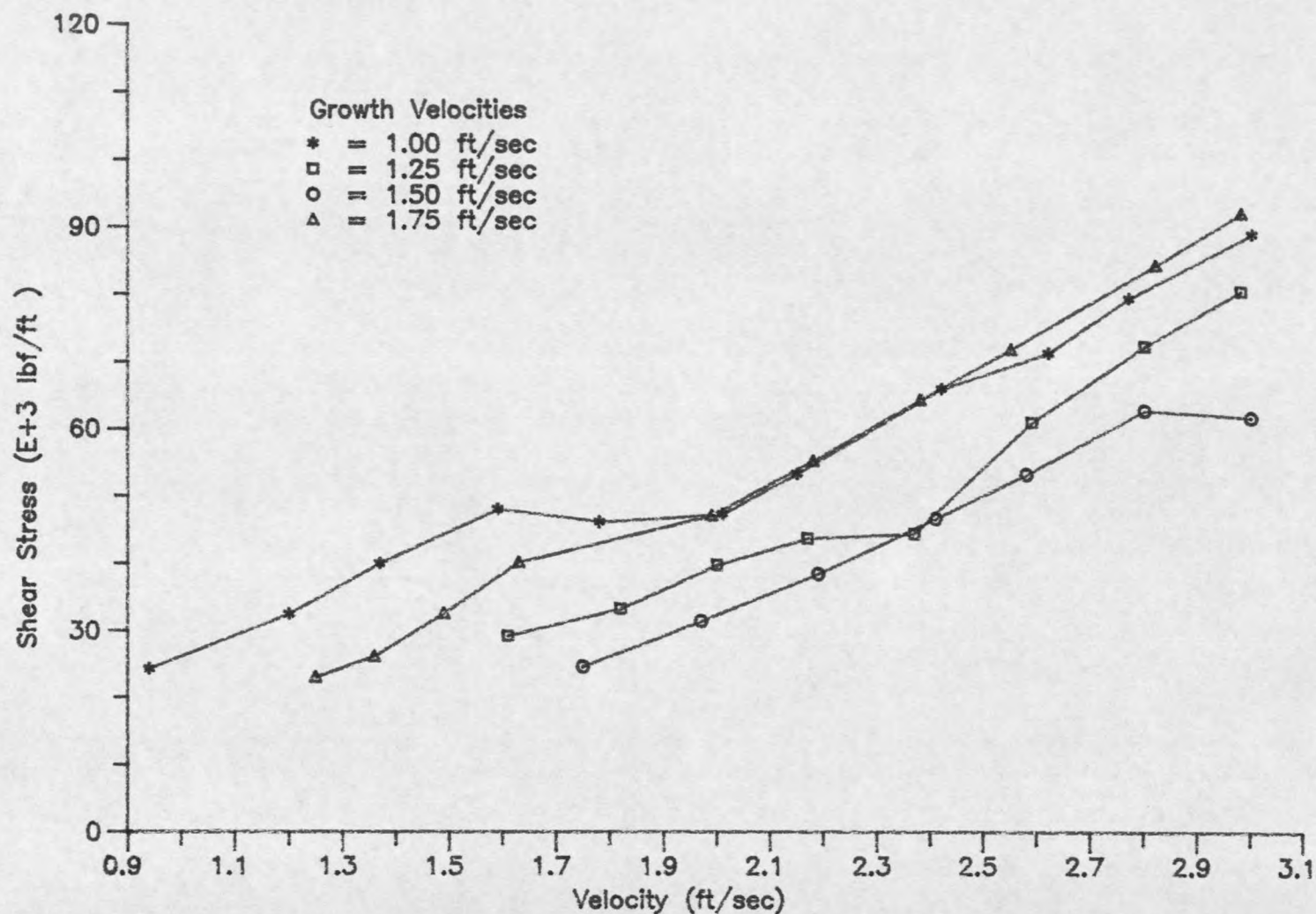


Figure 17. Wall shear Stress v. velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches

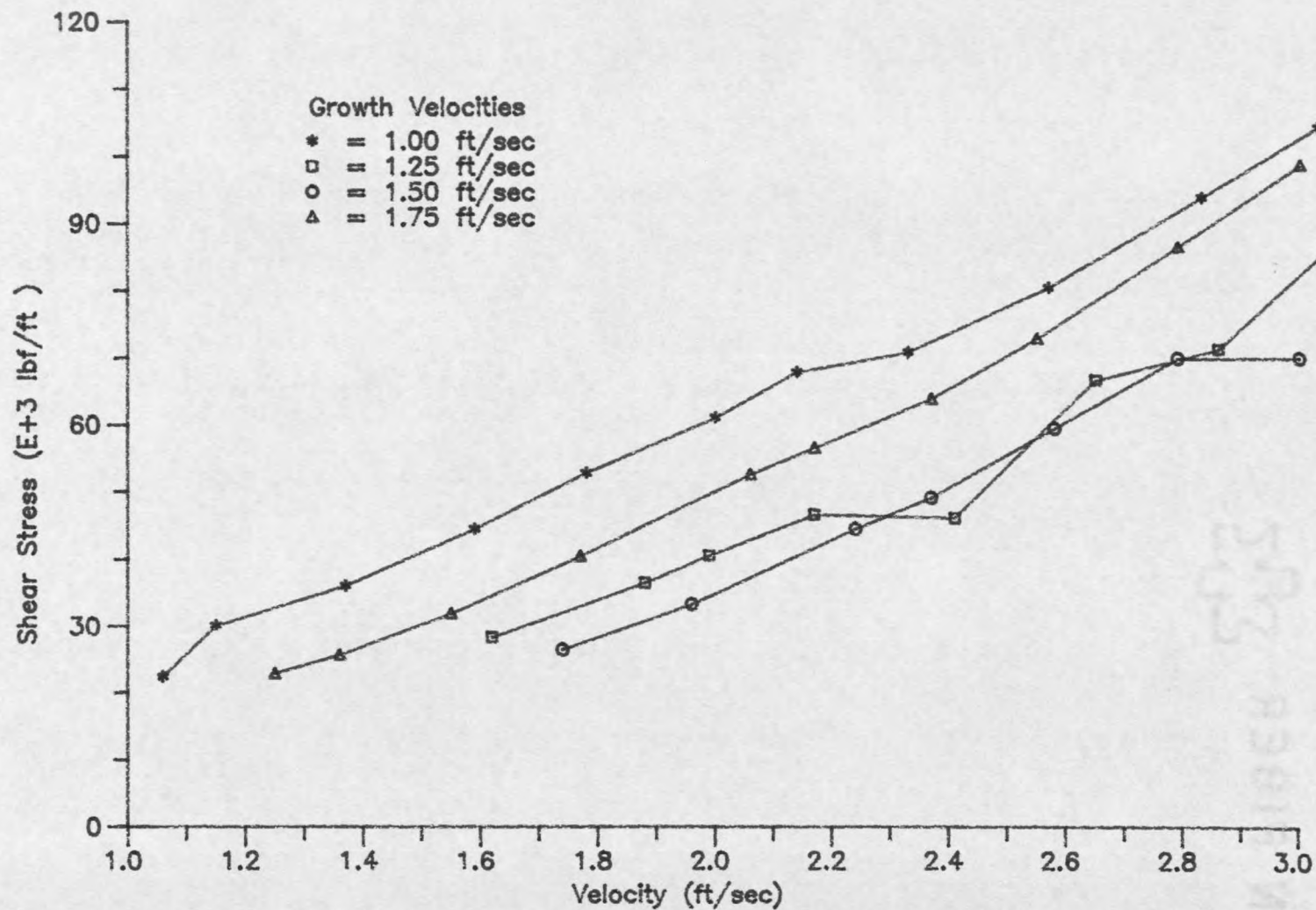


Figure 18. Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches

CHAPTER 6

BIOFILM MEASUREMENTS

Experimental Apparatus and Procedures

Examination of the biofilm in the test section was accomplished using a Bausch and Lomb optical microscope which allowed measurements of the biofilm thickness to be made to the nearest micrometer. The biofilm thickness was measured using the principle of optical microscopy, as outlined by Bakke and Olsson [16]. This method involved focusing a microscope first on the biofilm-fluid interface and then on biofilm-substratum surface, and measuring the difference between the two points. The actual distance is related to the measured distance by the relationship:

$$L_f = k_f y_f \quad (11)$$

Where y_f is the distance measured by the microscope and k_f is a proportionality constant given by the relationship:

$$k_f = \frac{n_f}{n_m} \quad (12)$$

Where n_f is the refractive index of the biofilm and n_m is the refractive index of the medium interfacing the film at its top surface, which is the surface of the glass for this experimentation. Since the refractive index of glass is between 1.5 and 1.55 [17] and the refractive index of the biofilm is 1.5 [16], the

proportionality constant was approximated as one and the distance measured by the microscope was the actual thickness of the biofilm.

Measurements on the biofilm thickness were taken at twelve locations in the test section. The biofilm measurement were taken at two inch intervals starting at the beginning of the second pressure tap. These twelve readings were taken to reduce the influence of local thickness fluctuations.

Biofilm Thickness for Growth Phase

Biofilm thickness measurements were taken for the growth period starting at the initial input of the test fluid into the flow loop. To eliminate the effects of residue biofilm left from previous experimental runs, the drain hoses, upper and lower tanks and test section for all four flow loops were cleaned with a bristle brush to remove any biofilm not removed by the velocity excursions. This process was done before each of the four test runs used in the research. This process allowed all four test runs to start from a clean pipe situation. Figures 19 through 22 show the biofilm thickness v. time for the growth stage of the biofilm for flow loops one through four respectively. As can be seen from the figures, all growths rates follow a similar pattern throughout the entire growth cycle. The growth cycles for all cases consist of three stages. The first stage is termed the induction phase. At this stage the glass pipe is clean, and the biofilm must build a base upon the pipe from which to grow. This stage is marked by a lack of any significant growth in the pipe and lasts between thirty-six and fifty-seven hours.

The second stage is the growth stage. At this stage, the biofilm has successfully attached itself to the pipe wall. This stage is marked by a linear rate of growth for the biofilm. This linear region lasts between one hundred and ninety hours for a test velocity of 1.00 ft/sec, to one hundred hours for a test velocity of 1.50 ft/sec.

After the growth stage, the increase in the biofilm thickness decreased significantly, with a maximum thickness of 360 micrometers for a test velocity of 1.00 ft/sec to no biofilm growth for a test velocity of 1.75 ft/sec.

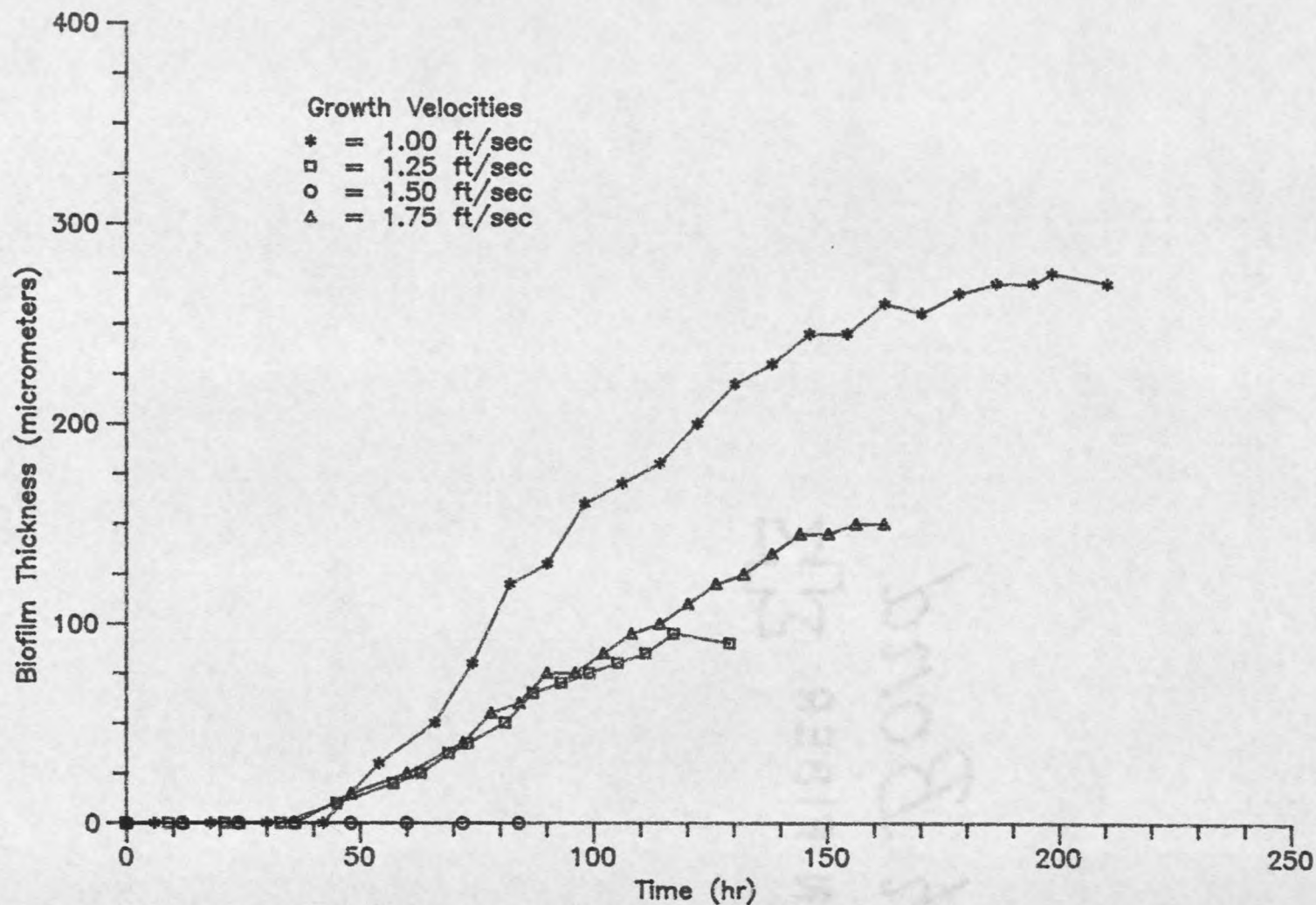


Figure 19. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter Of 0.885 Inches

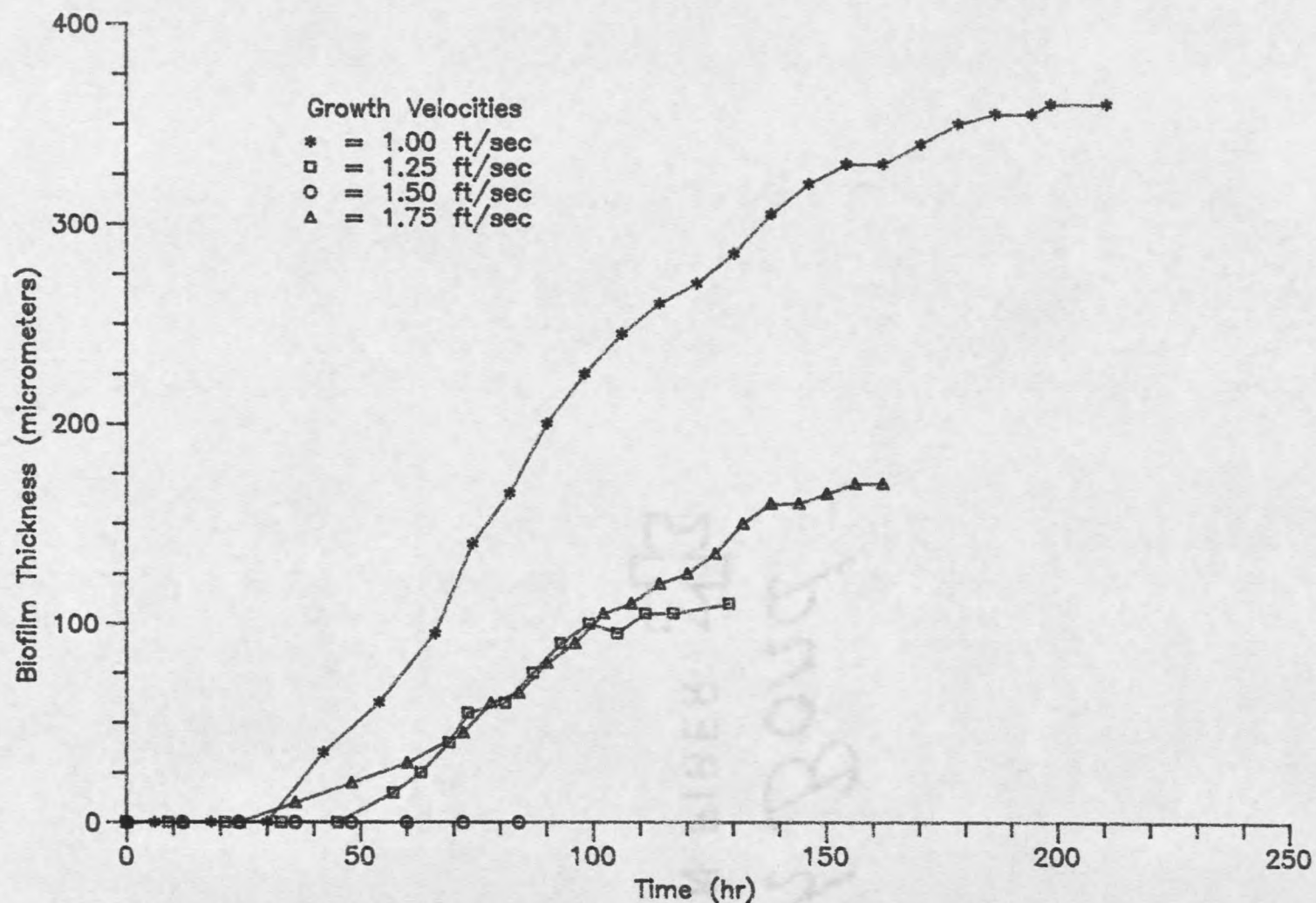


Figure 20. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter of 0.625 Inches

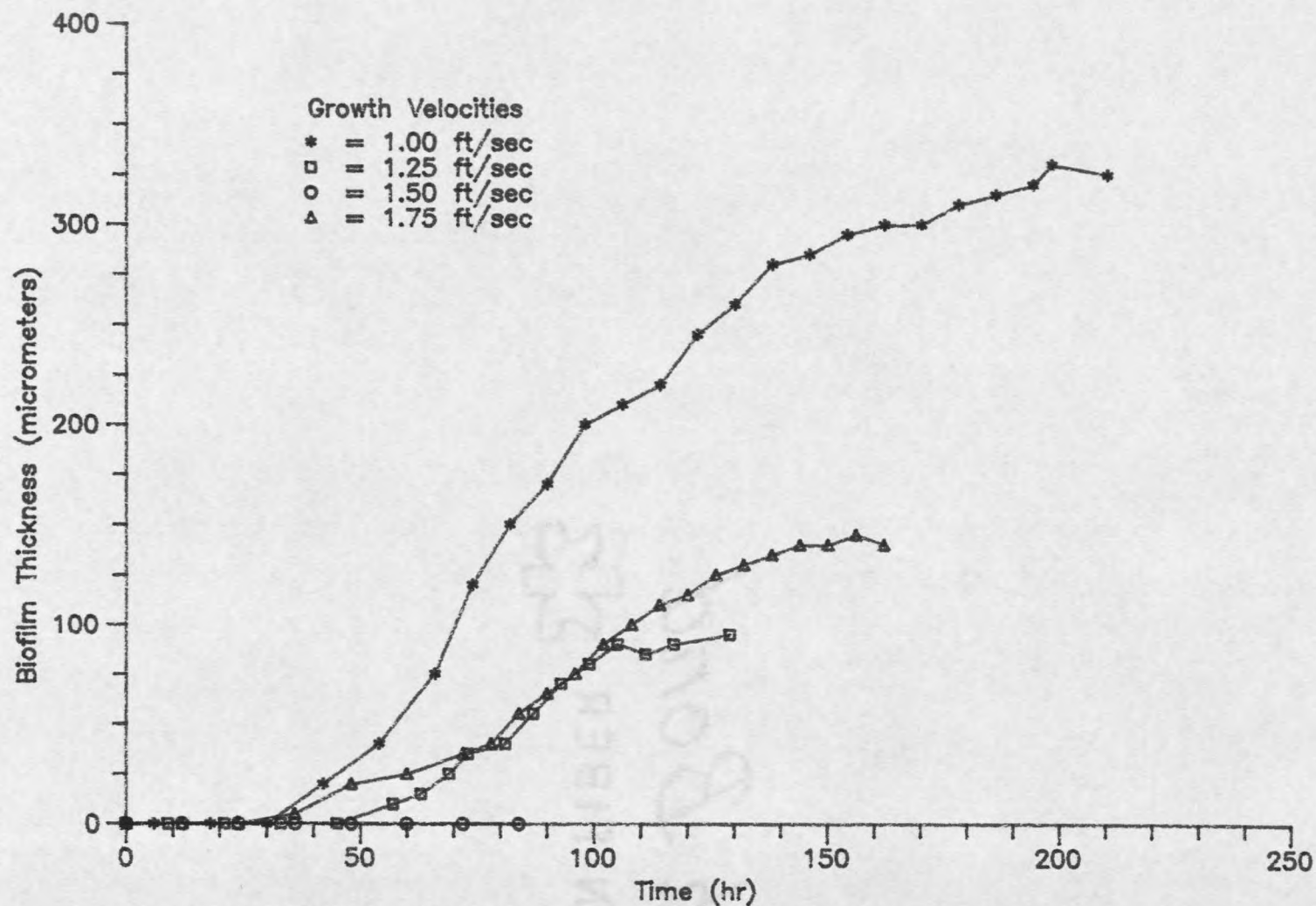


Figure 21. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter of 0.370 Inches

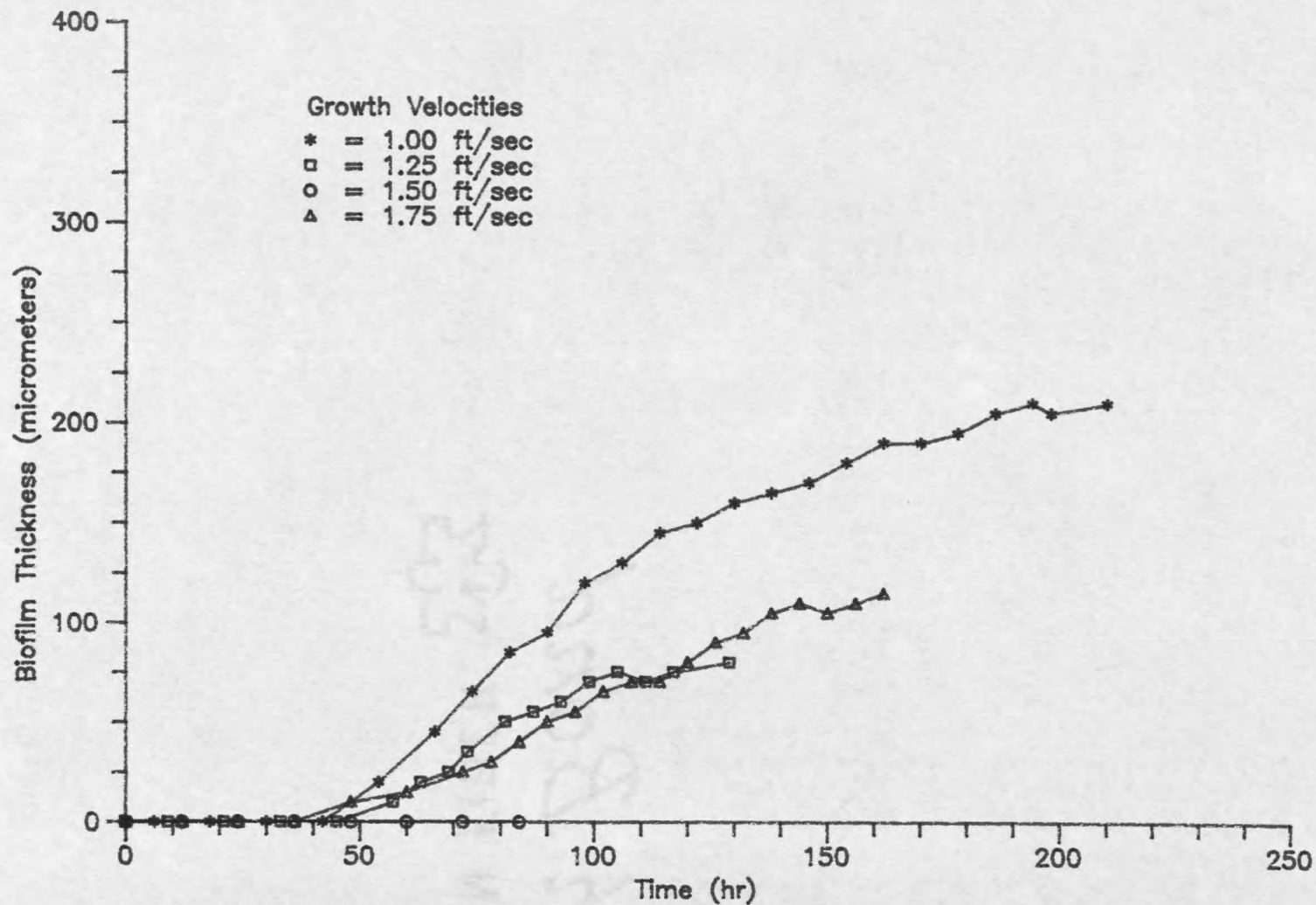


Figure 22. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter of 0.275 Inches

Biofilm Thickness for Detachment Phase

A plot of the biofilm thickness v. the fluid velocity is plotted in Figures 23 through 26. For smaller biofilm growths, those occurring for 1.50 and 1.75 ft/sec, the biofilm detaches linearly with respect to the fluid velocity. For the larger biofilm growths, the biofilm exhibits two regions of detachment. The first region is characterized by a linear decrease in the biofilm thickness as the velocity is increased. At a critical velocity, a vast majority of the biofilm is detached from the surface of the test section. Past this point, the biofilm again decreases linearly with an increase in fluid velocity.

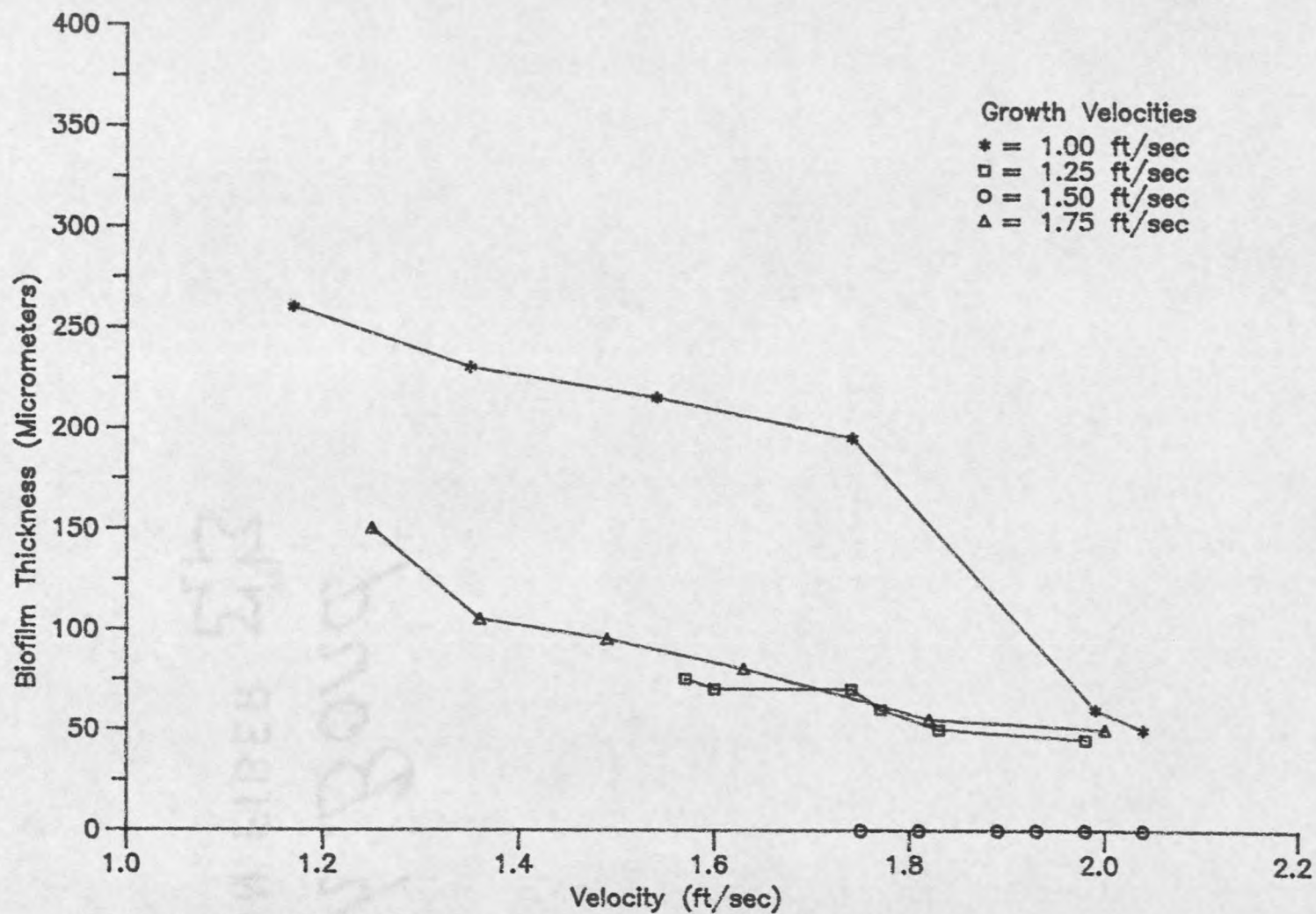


Figure 23. Biofilm Thickness v. Velocity for Detachment Phase with a Pipe Diameter of 0.885 Inches

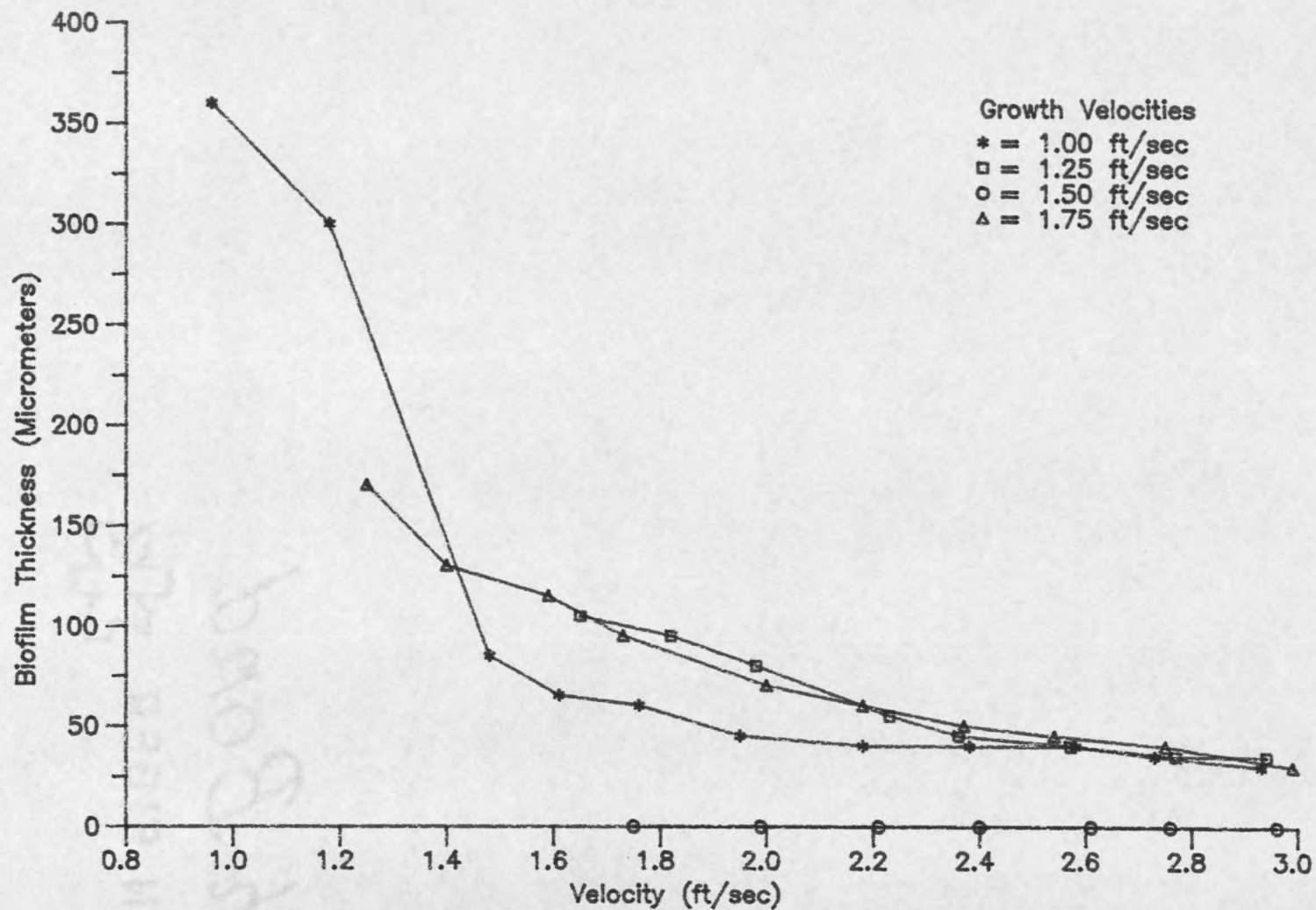


Figure 24. Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.625 Inches

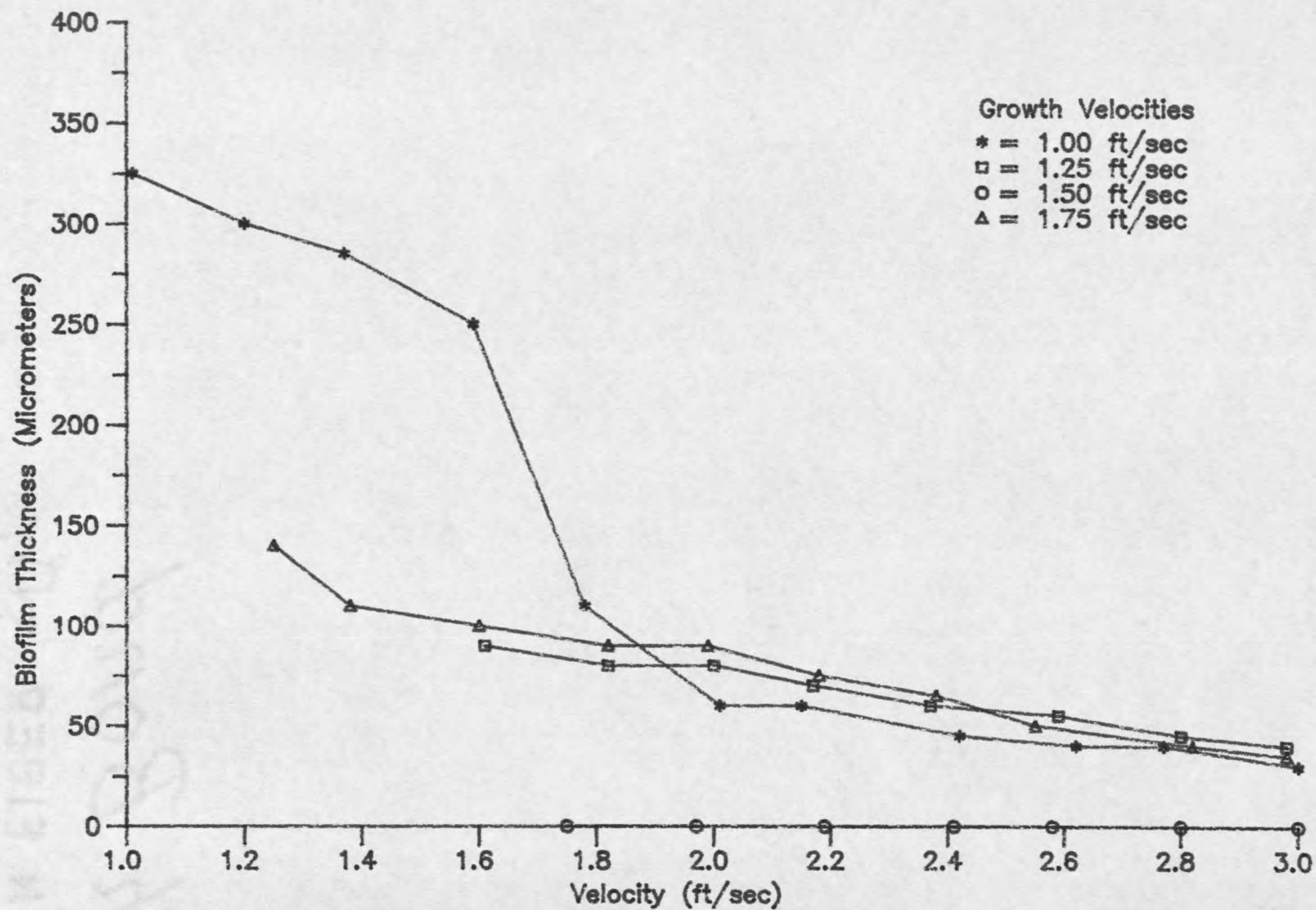


Figure 25. Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.370 Inches

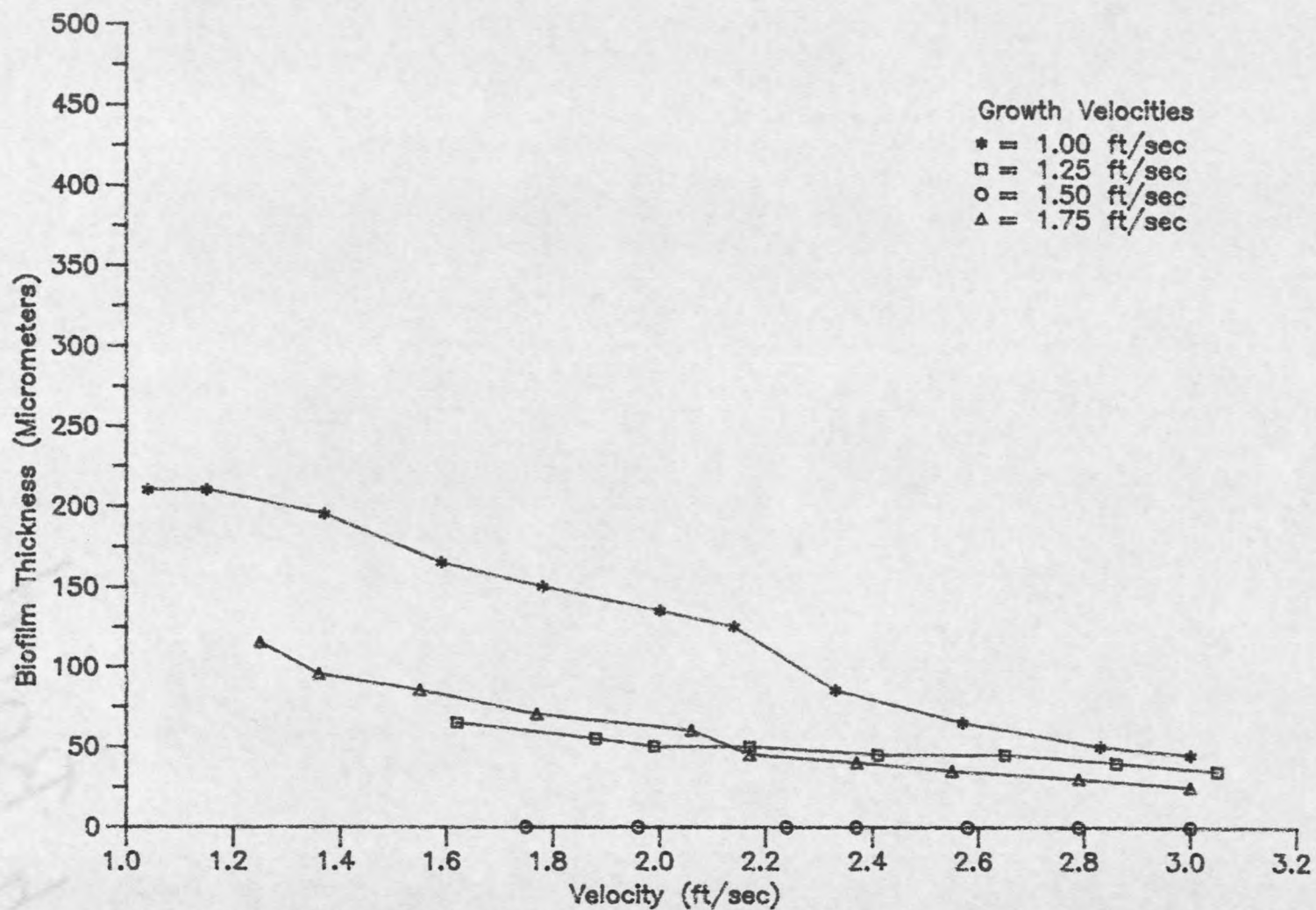


Figure 26. Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter Of 0.275 Inches

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Summary of Results for Growth Phase

The results of the investigation of the growth phase support several conclusions. Specific findings of the investigation are summarized in the following statements.

1. The friction factor had three distinct regions which appeared in all four test runs. The first region was characterized by a constant value in the friction factor and lasted approximately thirty to forty hours. Following this region, the friction factor increased linearly with respect to time. This second region lasted approximately one hundred and fifty hours. For the slower test velocities this time was slightly greater, and for the faster velocities, slightly less. The third region was characterized by a stable value for the friction value, with small increases occurring occasionally.
3. The wall shear stress on the biofilm in the test section exhibited similar tendencies to the friction factor. Three distinct regions occurred in the experimentation. The first region was marked by a stable value for the wall shear stress and lasted thirty to forty hours. Following this region the wall shear stress increased linearly with respect to time. This linearly

region continued until a wall shear stress of 0.024 to 0.026 lbf/ft² was reached. At this value, the wall shear stress stabilized for the remainder of the test run.

3. The growth of the biofilm also exhibited three distinct regions. During the first period, there was no apparent biofilm growth in the test section. This period lasted approximately thirty to forty hours. After this time, the biofilm increased linearly with respect to time for approximately one hundred and fifty hours. As in the results for the friction factor, this time was slightly greater for the slower test velocities, and slightly less for the slower velocities. The third region was evident by a stabilization in the biofilm thickness, with small changes in thickness over time.

Summary of Results for Detachment Phase

The results of the investigation of the detachment phase support several conclusions. Specific findings of the investigation are summarized in the following statements.

1. For growth velocities of 1.25, 1.50 and 1.75 ft/sec, the friction factor decreased linearly with an increase in fluid velocity. The values for all three test runs were similar, with a starting value for the friction factor of approximately 0.055 and concluding at a value of 0.36. For a growth velocity of 1.00 ft/sec, the friction factor exhibited two regions. From 1.00 ft/sec to 1.40 ft/sec the friction factor decreased linearly from a value of approximately 0.105 to a value of 0.085. Between 1.40 and 1.60

ft/sec, the friction factor was reduced from a value of 0.085 to a value of roughly 0.058. Beyond velocities of 1.6 ft/sec, the friction factor again decreased linearly, with similar results to the other three test runs.

2. For all cases investigated, the wall shear stress increased linearly with an increase in fluid velocity. In all test runs, the wall shear stress increased from a value of approximately 0.025 lbf/ft² to a value of 0.080 lbf/ft².
3. For growth velocities of 1.25, 1.50 and 1.75 ft/sec, the biofilm thickness decreased linearly with an increase in fluid velocity. For these three test runs, the biofilm thickness started at an initial value of approximately 120 microns, and decreased to a value of roughly 35 microns. For a growth velocity of 1.00 ft/sec, the biofilm thickness started at an initial value of approximately 300 microns and decreased linearly to a value of 275 microns at 1.40 ft/sec. Between 1.40 and 1.60 ft/sec, the biofilm thickness decreased from 275 microns to roughly 100 microns. Beyond this point the biofilm thickness again decreased linearly with respect to fluid velocity, and was similar to the results for the other test velocities investigated.

Recommendations for Further Investigation

Temperature variations were a slight problem in the investigation. The only factor affecting the fluid temperature was the temperature of the room. Unfortunately, due to the large size of the room and the abundance of windows

facing the sun, the room temperature was highly susceptible to environmental conditions. I would recommend that in further study, a room with the means to stabilize temperature be used.

Since garden hose was used to supply the test section with fluid, it was difficult to determine if the frequent bristle scrubbing fully removed the biofilm growths in this section. For future work, I would recommend using a clear plastic tubing so any biofilm growths could be seen more easily.

At the time of this research, efficient methods of in situ biofilm thickness measurement were unknown. This variable contained the greatest degree of inaccuracy. I would recommend in further study that more accurate methods be investigated to determine the biofilm thickness.

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REFERENCES CITED

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APPENDICES

APPENDIX A

TURBINE FLOWMETER CALIBRATION

TURBINE FLOW METER CALIBRATION

The turbine flowmeters used throughout the experimentation were calibrated at the beginning of the investigation and again at the conclusion of the experimentation. Tables 3 through 6 give the data used in plotting the initial calibration for the turbine flowmeters. The turbine flowmeters used in the research allowed two possible ranges to be used. The first range was between 0.1 to 1 GPM and was used entirely for flow loops three and four. The second range was 0.8 to 8 GPM and was used for flow loops one and two. To calibrate the flowmeters, eight test runs were taken at different velocities and the output to the frequency counter noted. The frequency counter used in the calibration of the turbine flowmeter was set at a gate time of ten seconds. Fluid was then passed through the flowmeter for sixty seconds and six readings were recorded. The gallons of fluid per minute of the fluid passing through the flowmeter was then determined and the average frequency counter reading was then compared with the GPM to determine the relationship between these two pieces of information. This relationship was then used in the data reduction program listed in Appendix C. The resolution of the frequency counter used in all calibrations was ± 0.05 and Table 8 gives the accuracy of the equations used.

**Table 3. Turbine Flowmeter One Calibration Statistics
For 0.8-8 GPM Range**

	run 1	run 2	run 3	run 4	run 5	run 6	run 7	run 8
reading 1	9.3	18.3	29.0	40.0	50.7	59.5	67.4	76.6
reading 2	8.8	18.2	29.1	40.1	50.8	59.5	67.4	76.5
reading 3	8.6	17.3	29.1	40.0	50.8	59.5	67.4	76.4
reading 4	8.6	16.9	29.0	39.9	50.8	59.4	67.5	76.5
reading 5	8.3	16.8	28.8	39.7	50.8	59.4	67.6	76.5
reading 6	8.3	16.7	28.8	39.6	50.8	59.4	67.6	76.8
average	8.65	17.37	28.97	39.88	50.78	59.45	67.48	76.55
GPM	0.99	1.83	2.82	3.75	4.65	5.22	5.88	6.51

The initial calibration of turbine flowmeter number one for the 0.8 to 8 GPM range was:

$$GPM = 0.41945 + 0.08096 * (\text{Frequency Reading}) \quad (13)$$

with a standard error of estimation of 0.09652 and an R Squared value of 0.9979.

Final calibration of the turbine flowmeter gave the relationship:

$$GPM = 0.49734 + 0.08054 * (\text{Frequency Reading}) \quad (14)$$

with a standard error of estimation of 0.078960 and an R squared value of 0.9990.

**Table 4. Turbine Flowmeter Two Calibration Statistics
For 0.8-8 GPM Range**

	run 1	run 2	run 3	run 4	run 5	run 6	run 7	run 8
reading 1	9.3	18.6	28.9	36.9	46.2	58.0	66.6	74.9
reading 2	9.3	18.7	28.8	36.8	46.4	58.0	66.4	74.8
reading 3	9.3	18.7	28.9	37.0	46.5	57.9	66.7	74.7
reading 4	9.3	18.7	29.0	37.1	46.4	56.4	67.1	74.9
reading 5	9.3	18.7	28.9	36.9	46.4	56.5	67.2	74.8
reading 6	9.3	18.7	29.0	36.8	46.5	56.4	67.5	74.8
average	9.3	18.68	28.92	36.92	46.40	57.20	66.92	74.82
GPM	1.02	1.80	2.85	3.51	4.32	5.16	5.94	6.47

The initial calibration of turbine flowmeter number two for the 0.1 to 1 GPM range was:

$$GPM = 0.31258 + 0.084354 * (\text{Frequency Reading}) \quad (15)$$

with a standard error of estimation of 0.08887 and an R Squared value of 0.9982.

Final calibration of the turbine flowmeter gave the relationship:

$$GPM = 0.27405 + 0.082040 * (\text{Frequency Reading}) \quad (16)$$

with a standard error of estimation of 0.03666 and an R squared value of 0.9996.

**Table 5. Turbine Flowmeter Three Calibration Statistics
For 0.1 to 1 GPM Range**

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Reading 1	10.5	18.4	24.5	37.0	47.6	56.9	63.0	72.4
Reading 2	10.3	18.1	25.1	36.9	47.3	56.9	63.0	72.5
Reading 3	10.2	18.2	24.9	36.7	47.3	56.6	62.8	72.4
Reading 4	10.1	18.0	24.7	36.6	47.4	56.7	62.4	72.4
Reading 5	10.2	17.8	24.6	36.4	47.3	56.4	62.3	72.2
Reading 6	10.2	17.6	24.5	36.2	47.1	56.0	62.2	72.1
Average	10.25	18.02	24.72	36.63	47.33	56.58	62.62	72.33
GPM	0.21	0.31	0.42	0.60	0.75	0.87	0.96	1.11

The initial calibration of turbine flowmeter number three for the 0.1 to 1 GPM range was:

$$GPM = 0.05917 + 0.014463 * (\text{Frequency Reading}) \quad (17)$$

with a standard error of estimation of 0.008196 and an R Squared value of 0.9994.

Final calibration of the turbine flowmeter gave the relationship:

$$GPM = 0.07129 + 0.014400 * (\text{Frequency Reading}) \quad (18)$$

with a standard error of estimation of 0.01017 and an R squared value of 0.9992.

**Table 6. Turbine Flowmeter Four Calibration Statistics
For 0.1 to 1 GPM Range**

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Reading 1	7.1	18.8	26.9	37.1	46.0	54.2	64.9	73.6
Reading 2	7.0	18.5	26.8	37.0	46.0	54.3	64.6	73.6
Reading 3	6.9	18.5	26.5	36.9	45.8	54.3	64.7	73.7
Reading 4	5.6	18.5	26.2	37.0	45.7	54.5	64.6	73.5
Reading 5	6.4	18.5	26.1	36.9	45.6	54.3	64.3	73.5
Reading 6	5.3	18.4	26.0	36.7	45.4	54.1	64.1	73.4
Average	6.38	18.53	26.42	36.93	45.75	54.28	64.53	73.55
GPM	0.18	0.35	0.48	0.63	0.75	0.93	1.05	1.17

The initial calibration of turbine flowmeter number four for the 0.1 to 1 GPM range was:

$$GPM = 0.08408 + 0.01493 * (\text{Frequency Reading}) \quad (19)$$

with a standard error of estimation of 0.01701 and an R Squared value of 0.9979.

Final calibration of the turbine flowmeter gave the relationship:

$$GPM = 0.07259 + 0.014862 * (\text{Frequency Reading}) \quad (20)$$

with a standard error of estimation of 0.01307 and an R squared value of 0.9987.

The resolution of the data points for the turbine flowmeters was determined using the equation:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \quad (21)$$

Where σ is the standard deviation of the data, x_i is the value of the data point, $\bar{x}$ is the value of the data point predicted by the equation and n is the number of data points. The total uncertainty of the pressure transducer is then determined by the relationship:

$$u_{tfm} = \sqrt{(u_{f.c.})^2 + (u_{data})^2} \quad (22)$$

where u_{tfm} is the uncertainty in the final output, u_{data} is the uncertainty in the test data and $u_{f.c.}$ is the uncertainty in the frequency counter. The error calculated is the maximum error possible in the experimentation, and not a root mean square error.

Table 7. Resolution of Frequency Counters

Equipment.	Initial Resolution (GPM)	Final Resolution GPM
Frequency Counter One (0.8-8)	± 0.00405	± 0.00403
Frequency Counter Two (0.8-8)	± 0.00422	± 0.00410
Frequency Counter Three (0.1-1)	± 0.00072	± 0.00072
Frequency Counter Four (0.1-1)	± 0.00075	±0.00074

Table 8. Resolution and Accuracy of Turbine Flowmeters

	Initial Resolution	Final Resolution	Initial Accuracy	Final Accuracy
TFM One (0.8-8)	± 0.0966	± 0.0791	$\pm 5.06 \%$	$\pm 4.14 \%$
TFM Two (0.8-8)	± 0.0889	± 0.0369	$\pm 6.95 \%$	$\pm 2.88 \%$
TFM Three (0.1-1)	± 0.0082	± 0.0102	$\pm 2.48 \%$	$\pm 3.09 \%$
TFM Four (0.1-1)	± 0.0170	± 0.0131	$\pm 9.44 \%$	$\pm 7.28 \%$

APPENDIX B

PRESSURE TRANSDUCERS CALIBRATION

PRESSURE TRANSDUCER CALIBRATION

The pressure transducers used in the experiment were calibrated at two different times. The first calibration was done during the initial design and building of the test apparatus. The final calibration was concluded after the last experimental run was completed. Tables 9 through 12 give the initial readings used in calibration of the pressure transducers. The resolution of the data points for the pressure transducers was determined using the equation:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \quad (23)$$

Where σ is the standard deviation of the data, x_i is the value of the data point, $\bar{x}$ is the value of the data point predicted by the equation and n is the number of data point. The uncertainty of the data is then taken to be the 90% level, or 1.6449σ . The total uncertainty of the pressure transducer is then determined by the relationship:

$$u_{p.t.} = \sqrt{(u_w)^2 + (u_{data})^2 + (u_{p.i.})^2} \quad (24)$$

where $u_{p.t.}$ is the uncertainty in the final output, u_w is the uncertainty in the column of water, u_{data} is the uncertainty in the data and $u_{p.i.}$ is the uncertainty in the pressure indicator. The error calculated is the worst possible error, and not the root mean square.

Table 9. Pressure Transducer One Calibration Statistics

Indicator Reading	Elevation Difference (inches)	Ratio Reading/PSI	Pressure Difference PSI
0.0	0.0	-----	0.0000
12.7	2.5	140.64	0.0903
23.0	4.5	141.45	0.1626
48.8	9.625	140.35	0.3477
57.1	11.25	140.50	0.4064
81.8	16.125	140.41	0.5826
94.0	18.625	139.69	0.6729

This information was entered into a curvefit program to determine the equation of the data. The program determined that this data followed a linear relationship with a standard error of estimation of 0.001227, and a R squared value of 0.9999. Therefore, the equation for pressure transducer one was calculated to be:

$$P(\text{lb f/inch}^2) = -.001559 + .007157 * (\text{Indicator Reading}) \quad (25)$$

The equation determined by the curvefit program for the final calibration of pressure transducer one gave the following relationship:

$$P(\text{lb f/inch}^2) = -0.00073461 + 0.007225 * (\text{Indicator Reading}) \quad (26)$$

with a standard error of estimation of 0.001145 and an R squared value of 0.9999.

Table 10. Pressure Transducer Two Calibration Statistics

Indicator Reading	Elevation Difference (inches)	Ratio Reading/PSI	Pressure Difference PSI
16.7	2.1	217.17	0.0769
36.1	4.5	222.02	0.1626
56.7	7.04	222.96	0.2543
81.2	10.1	223.45	0.3634
107.4	13.3	223.33	0.4809
141.9	17.6	222.87	0.6367
0.0	0.0	-----	0.0000

This information was entered into the curvefit program and the equation best represented by this data was a linear equation. The equation had a standard error of estimation of 0.0008929 and a R squared value of 0.9999. The equation determined by the program was:

$$P(\text{lb f/inch}^2) = 0.0012725 + 0.0044708 * (\text{Indicator Reading}) \quad (27)$$

The equation determined by the curvefit program for the final calibration for pressure transducer two gave the relationship:

$$P(\text{lb f/inch}^2) = 0.0028943 + 0.0044059 * (\text{Indicator Reading}) \quad (28)$$

with a standard error of estimation of 0.001339 and an R squared value of 0.9999.

Table 11. Pressure Transducer Three Calibration Statistics

Indicator Reading	Elevation Difference (inches)	Ratio Reading/Inches	Pressure Difference PSI
14.3	3.2	124.13	0.1152
23.2	5.1	125.27	0.1852
32.2	7.1	126.26	0.2551
47.2	10.4	125.93	0.3748
59.2	12.9	126.66	0.4674
75.0	16.3	127.30	0.5893
00.0	00.0	-----	0.0000

This information was entered into the curvefit program and the equation best represented by the data was a linear equation. The equation had a standard error of estimation of 0.001435 and a R squared value of 0.9999. The equation determined by the program was:

$$P(\text{lb f/inch}^2) = 0.003091 + 0.0089447 * (\text{Indicator Reading}) \quad (29)$$

The equation determined by the curvefit program for the final calibration of pressure transducer number three was:

$$P(\text{lb f/inch}^2) = -0.00057 + 0.009151 * (\text{Indicator Reading}) \quad (30)$$

with a standard error of estimation of 0.001732 and an R squared value of 0.9997.

Table 12. Pressure Transducer Four Calibration Statistics

Indicator Reading	Elevation Difference (inches)	Ratio Reading/PSI	Pressure Difference
11.8	2.5	130.67	0.0903
22.3	4.7	131.71	0.1693
29.0	6.1	131.04	0.2213
43.2	9.1	131.95	0.3274
54.8	11.5	131.89	0.4967
65.9	13.8	132.68	0.4967
00.0	00.0	-----	0.0000

This information was entered into a curvefit program and the equation best represented by this information was a linear equation. The equation had a standard error of estimation of 0.0008718 and a R squared value of 0.9999. The equation determined by the program was:

$$P(\text{lbf/inch}^2) = 0.002118 + 0.007523 * (\text{Indicator Reading}) \quad (31)$$

The equation determined by the curvefit program for the final calibration of pressure transducer four was:

$$P(\text{lbf/inch}^2) = -0.001276 + 0.007477 * (\text{Indicator Reading}) \quad (32)$$

with a standard error of estimation of 0.001105 and an R squared value of 0.9999.

Table 13. Resolution of Pressure Calibration Equipment

Equipment	Initial Resolution (PSI)	Final Resolution (PSI)
Water Column	± 0.00113	± 0.00113
Pressure Transducer 1	± 0.00101	± 0.00115
Pressure Transducer 2	± 0.00073	± 0.00134
Pressure Transducer 3	± 0.00108	± 0.00173
Pressure Transducer 4	± 0.00059	± 0.00110
Pressure Indicator 1	± 0.00036	± 0.00036
Pressure Indicator 2	± 0.00025	± 0.00022
Pressure Indicator 3	± 0.00045	± 0.00046
Pressure Indicator 4	± 0.00038	± 0.00037

Table 14. Resolution and Accuracy of Pressure Transducers

	Pressure Readout One	Pressure Readout Two	Pressure Readout Three	Pressure Readout Four
Initial Resolution (PSI)	± 0.00156	± 0.00137	± 0.00163	± 0.00133
Final Resolution (PSI)	± 0.00165	± 0.00177	$\pm .00212$	± 0.00162
Initial Accuracy (%)	± 14.7	± 8.8	± 3.9	± 2.91
Final Accuracy (%)	± 15.6	± 10.4	± 5.5	± 3.8

APPENDIX C

DATA REDUCTION PROGRAM

DATA REDUCTION PROGRAM

The data reduction program was used to determine several parameters related to the basic measurements. The program called information from a data file named bio.dat which contained the time the data was taken, the temperature of the fluid, the pressure drop across the test section, the biofilm thickness, the oxygen content of the fluid and the frequency counter reading for all four flow loops. The program first calculated the kinematic viscosity using the relationship:

$$\nu = (A + B*T + C*T^2 + D*T^3) * 10^{-5} \frac{ft}{s^2} \quad (33)$$

Where T is the fluid temperature and the variables A, B, C, and D are:

$$A = 3.11187E-00$$

$$B = -4.78969E-02$$

$$C = 3.21462E-04$$

$$D = -7.99526E-07$$

This relationship was determined using a curvefit program and accurately represented the values of the kinematic viscosity for temperatures between 0°F and 140°F.

The loss of head pressure was then determined using Bernoulli's equation:

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2} + gz_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2} + gz_2 + h_f \quad (34)$$

Where the specific weight, γ was derived from the relationship:

$$\gamma = \rho g \quad (35)$$

where g is the acceleration due to gravity. Since the elevation and velocity remained constant throughout the experimentation, Bernoulli's equation reduced to:

$$h_f = \frac{p_1 - p_2}{\gamma} \quad (36)$$

The friction factor was then determined using the relationship:

$$f = h_f * 2 \frac{d}{L} * \rho v^2 \quad (37)$$

The friction factor was then used to determine the coefficient of friction using the relationship:

$$c_f = \frac{f}{4} \quad (38)$$

The wall shear stress was then solved for using the relationship:

$$\tau_o = \frac{c_f \rho v^2}{2} \quad (39)$$

The Reynolds number and relative roughness were found using the equations:

$$Re = \frac{vD}{\nu} \quad (40)$$

and

$$\frac{e}{D} = 3.7 e^{(-1/2\sqrt{f})} - \frac{9.287}{Re\sqrt{f}} \quad (41)$$

The dynamic pressure was then found using the relationship:

$$P_{dyn} = \frac{\rho v^2}{2g} \quad (42)$$

To help in comparison of data, the friction factor and wall shear stress were then determined for a Reynolds number of 10,000 using the relationships:

$$f_{10,000} = \frac{0.25}{\left(\log\left(\frac{e/d}{3.7} + \frac{2.51}{Re_{10,000}\sqrt{f_{10,000}}}\right)\right)^2} \quad (43)$$

$$\tau_{10,000} = \frac{f_{10,000} \rho v^2}{8g} \quad (44)$$

The solutions to this information was stored in a data file or sent to a printer for later reference. A listing of the program follows.

Figure 27. Data Reduction Program Used to Determine Flow Parameters.

```

1 C *****
2 C
3 C DOUGLAS W. HEAL
4 C FEBRUARY 4, 1989
5 C
6 C THIS IS THE PROGRAM USED TO DETERMINE THE WALL
7 C SHEAR STRESS ON THE BIOFILM IN THE TEST SECTION.
8 C THE PROGRAM READS THE PRESSURE DROP, THE FREQUENCY
9 C COUNTER READING, THE TEMPERATURE, AND THE TIME THE
10 C DATA WAS TAKEN FROM A DATA FILE CALLED BIO.DAT.
11 C THE PROGRAM THEN USES THIS INFORMATION TO CALCULATE
12 C THE DESIRED RESULTS.
13 C *****
14 C
15 C ***** NOMENCLATURE USED *****
16 C
17 C DP = PRESSURE DROP
18 C D = DIAMETER OF PIPE
19 C L = LENGTH OF TEST SECTION
20 C RHO = MASS DENSITY OF FLUID
21 C F = FRICTION FACTOR
22 C CF = COEFFICIENT OF FRICTION
23 C V = FLUID VELOCITY
24 C T = FLUID TEMPERATURE
25 C KV = KINEMATIC VISCOSITY
26 C TAU = WALL SHEAR STRESS
27 C RE = REYNOLDS NUMBER
28 C E = RELATIVE ROUGHNESS
29 C MON = MONTH
30 C DAY = DAY
31 C H = HOUR
32 C N = COUNTER
33 C FC = FREQUENCY COUNTER RESULT
34 C GPM = GALLONS PER MINUTE
35 C GAM = SPECIFIC WEIGHT OF FLUID
36 C HF = HEAD LOSS DUE TO FRICTION
37 C G = ACCELERATION FROM GRAVITY
38 C O = OXYGEN CONTENT OF WATER
39 C DYN = DYNAMIC PRESSURE
40 C FNEW = CORRECTED FRICTION FACTOR
41 C VNEW = CORRECTED VELOCITY
42 C TNEW = CORRECTED WALL SHEAR STRESS
43 C
44 C *****

```

Figure 27--Continued

```

45 C
46     DOUBLE PRECISION DP(4),D(4),L(4),RHO,F(4),CF(4),FC(4)
47     DOUBLE PRECISION V(4),S(4),T(4),KV(4),TAU(4),RE(4),E(4)
48     DOUBLE PRECISION GPM(4),GAM,HF(4),G,BT(4),O,DYN(4),FNEW(4)
49     DOUBLE PRECISION VNEW(4),TNEW(4)
50     INTEGER MON,DAY,H
51 C
52 C     FIRST, INITIALIZE ALL VARIABLES TO BE USED IN CALCULATING
53 C     THE RESULTS. THESE ARE THE SAME VALUES LISTED IN THE TEST
54 C     SECTION SPECIFICATIONS.
55 C
56     D(1) = 0.04366
57     D(2) = 0.03167
58     D(3) = 0.02533
59     D(4) = 0.02175
60     L(1) = 2.75
61     L(2) = 2.75
62     L(3) = 2.75
63     L(4) = 2.75
64     G     = 32.159
65     RHO   = 62.1
66     GAM   = RHO * G
67 C
68 C     NOW, OPEN THE DATA FILE TO BE USED.
69 C
70     OPEN(UNIT=1,FILE='BIO.DAT',STATUS = 'OLD')
71     READ(1,*) H,MON,DAY,T(1),T(2),T(3),T(4),
72     &DP(1),DP(2),DP(3),DP(4),FC(1),FC(2),FC(3),FC(4),
73     &BT(1),BT(2),BT(3),BT(4),O
74 C
75 C
76 C     NOW, DETERMINE THE KINEMATIC VISCOSITY FOR THE KNOWN
77 C     TEMPERATURE.
78 C
79     DO 30, N = 1, 4 1
80     KV(N) = (3.111874 -.047896*T(N) + .00032146*(T(N)**2) .1
81     & -.00000079952*(T(N)**3))*0.00001 1
82 30 CONTINUE
83 C
84 C     NOW, CALCULATE THE GALLONS PER MINUTE OF FLUID PASSING
85 C     THROUGH THE TURBINE FLOWMETER.
86 C
87     GPM(1) = 0.058167 + ( 0.024196 * FC(1))
88     GPM(2) = 0.055474 + ( 0.013650 * FC(2))

```

Figure 27--Continued

```

89      GPM(3) = 0.075626 + ( 0.014003 * FC(3))
90      GPM(4) = 0.067479 + ( 0.013770 * FC(4))
91 C
92 C      NOW, CALCULATE THE VELOCITY OF THE FLUID IN THE TEST SECTIONS.
93 C
94      V(1) = ((GPM(1)/60)*0.13368)/(3.14*((D(1)/2)**2))
95      V(2) = ((GPM(2)/60)*0.13368)/(3.14*((D(2)/2)**2))
96      V(3) = ((GPM(3)/60)*0.13368)/(3.14*((D(3)/2)**2))
97      V(4) = ((GPM(4)/60)*0.13368)/(3.14*((D(4)/2)**2))
98 C
99 C      NOW, CALCULATE THE PRESSURE DROP IN PSI.
100 C
101      DP(1) = (-0.001559 + 0.007157*DP(1)) * 144
102      DP(2) = ( 0.000213 + 0.004441*DP(2)) * 144
103      DP(3) = (-0.009023 + 0.009337*DP(3)) * 144
104      DP(4) = ( 0.002118 + 0.007523*DP(4)) * 144
105 C
106 C      NOW, ENTER A DO-LOOP TO DETERMINE THE RESULTS.
107 C
108      DO 1, N = 1,4 1
109          HF(N) = DP(N)/RHO 1
110          F(N) = (HF(N)*D(N)**2*G)/(L(N)*(V(N)**2)) 1
111          CF(N) = F(N)/4 1
112          TAU(N) = (CF(N)*RHO*(V(N)**2))/(2*G)
113          RE(N) = V(N)*D(N)/KV(N) 1
114          E(N) = 3.7*((10**(-0.5/(F(N)**0.5)))) 1
115      &          -(2.51/(RE(N)*(F(N)**0.5)))) 1
116          DYN(N) = (RHO*(V(N)**2))/(2*G) 1
117      1 CONTINUE
118
119 C      NOW, DETERMINE THE FRICTION FACTOR FOR A REYNOLDS NUMBER
120 C      OF 10,000 121 C
121 C      DO 70, N = 1,4 1
122          FNEW(N) = F(N) 1
123          DO 80, I= 1,4 2
124              FNEW(N) = 0.25/((ALOG10((E(N)/3.7)+(2.51/(10000* 2
125                  &          (FNEW(N)**0.5))))))**2) 2
126          80 CONTINUE 1
127      70 CONTINUE
128 C
129 C      NOW, CALCULATE THE CORRECTED WALL SHEAR STRESS FOR A REYNOLDS
130 C      NUMBER OF 10,000
131 C
132 C

```

Figure 27--Continued

```

133      DO 110, N = 1, 4 1
134          VNEW(N) = 10000*KV(N)/D(N) 1
135          TNEW(N) = (FNEW(N)*RHO*(VNEW(N)**2)/(8*G)) 1
136 110 CONTINUE
137 C      NOW, PRINT THE RESULTS
138 C
139 C
140      WRITE(*,2) H
141      2  FORMAT(' ', 'THE DATA WAS TAKEN AT ', I2, ':00')
142      WRITE(*,20) MON, DAY
143      20  FORMAT(' ', 'ON ', I2, '-', I2, '-89')
144      WRITE(*,*)
145      WRITE(*,9) GAM
146      WRITE(*,*)
147      WRITE(*,60) O
148      60  FORMAT(' ', 'THE OXYGEN CONTENT WAS', F7.2, ' PPM')
149      9   FORMAT(' ', 'THE SPECIFIC WEIGHT OF THE FLUID WAS', F7.1,
150      &' LBM/FT^S^2')
151      WRITE(*,*)
152      WRITE(*,*) 'FLOW    FRICTION    COEFF.    SHEAR    REYNOLDS'
153      WRITE(*,*) 'LOOP    FACTOR    OF    STRESS    NUMBER'
154      WRITE(*,*) '          FRICTION    LBF/FT^2 '
155      WRITE(*,*) '-----'
156      DO 5, N=1,4 1
157          WRITE(*,6) N, F(N), CF(N), TAU(N), RE(N) 1
158      6   FORMAT(' ', I1, ' ', F7.4, ' ', F8.5, ' ', F7.4, ' ', F10.1) 1
159      5   CONTINUE
160      WRITE(*,*)
161      WRITE(*,*) 'FLOW    RELATIVE    VELOCITY    GPM'
162      WRITE(*,*) 'LOOP    ROUGHNESS    FT/S'
163      WRITE(*,*) '-----'
164      DO 7, N=1,4 1
165          WRITE(*,8) N, E(N), V(N), GPM(N) 1
166      8   FORMAT(' ', ' ', I1, ' ', F8.5, ' ', F7.2, ' ', F6.4) 1
167      7   CONTINUE
168      WRITE(*,*)
169      WRITE(*,*)
170      WRITE(*,*) 'FLOW    HEAD LOSS    PRESSURE    BIOFILM'
171      WRITE(*,*) 'LOOP    FROM FRICTION    DROP    THICKNESS'
172      WRITE(*,*) '          FT          LBF/FT^2    METERS'
173      WRITE(*,*) '-----'
174      DO 10, N = 1, 4 1
175          WRITE(*,11) N, HF(N), DP(N), BT(N) 1
176      11  FORMAT(' ', ' ', I1, ' ', F7.5, ' ', F7.2, ' ', F9.6) 1

```

Figure 27--Continued

```

177      10 CONTINUE
178      WRITE(*,*)
179      WRITE(*,*)
180      WRITE(*,*) 'FLOW    TEMPERATURE    DYNAMIC    KINEMATIC '
181      WRITE(*,*) 'LOOP    DEGREES F    PRESSURE    VISCOSITY '
182      WRITE(*,*) '                                LBF/FT^2    FT/S^2 '
183      WRITE(*,*) '-----'
184      DO 50, N = 1, 4 1
185          WRITE(*,40) N, T(N),DYN(N),KV(N) 1
186      40      FORMAT(' ', ' ', I1, ' ', F4.1,5X,F7.3, 1
187              &4X,F10.8) 1
188      50 CONTINUE
189      WRITE(*,*)
190      WRITE(*,*)
191      WRITE(*,*) '    FLOW          CORRECTED    CORRECTED'
192      WRITE(*,*) '    LOOP          FRICTION    SHEAR'
193      WRITE(*,*) '                                FACTOR    STRESS'
194      WRITE(*,*) '-----'
195      DO 90, N =1,4 1
196          WRITE(*,100) N,FNEW(N),TNEW(N) 1
197      100      FORMAT(' ', ' ', I1,10X,F7.5,5X,F8.6) 1
198      90 CONTINUE
199 C
200 C      NOW, CLOSE THE DATA FILE
201 C
202 C      CLOSE (1)
203 C
204 C      END

```

APPENDIX D

OXYGEN LEVEL MEASUREMENTS

OXYGEN LEVEL MEASUREMENTS

Oxygen Level Measurements

The level of oxygen in the fluid was determined using a Dissolved Oxygen Meter, or DO meter. This instrument was capable of determining the percentage of dissolved oxygen in a sample of the test fluid. The DO Meter was used to take readings once a day throughout the test runs. The readings were taken by placing the DO Meter tip in the lower tank at the exit of the flow loop drain hoses. The meter was placed in this position for approximately five minutes to allow the meter to stabilize its reading. The oxygen content was then read from the meter in parts per million of dissolved oxygen per sample of test fluid.

Oxygen Level Results

The results of the DO meter for oxygen are shown in Figure 28. As can be seen, the oxygen level varies with the temperature of the fluid throughout the experiment. The DO meter determined that the water remained near the saturation point of oxygen throughout the entire investigation. This was caused by the design of the test apparatus. The fluid dropped approximately thirty feet in circulating through the flow loop. This continually reintroduced water into the test fluid throughout the experimentation.

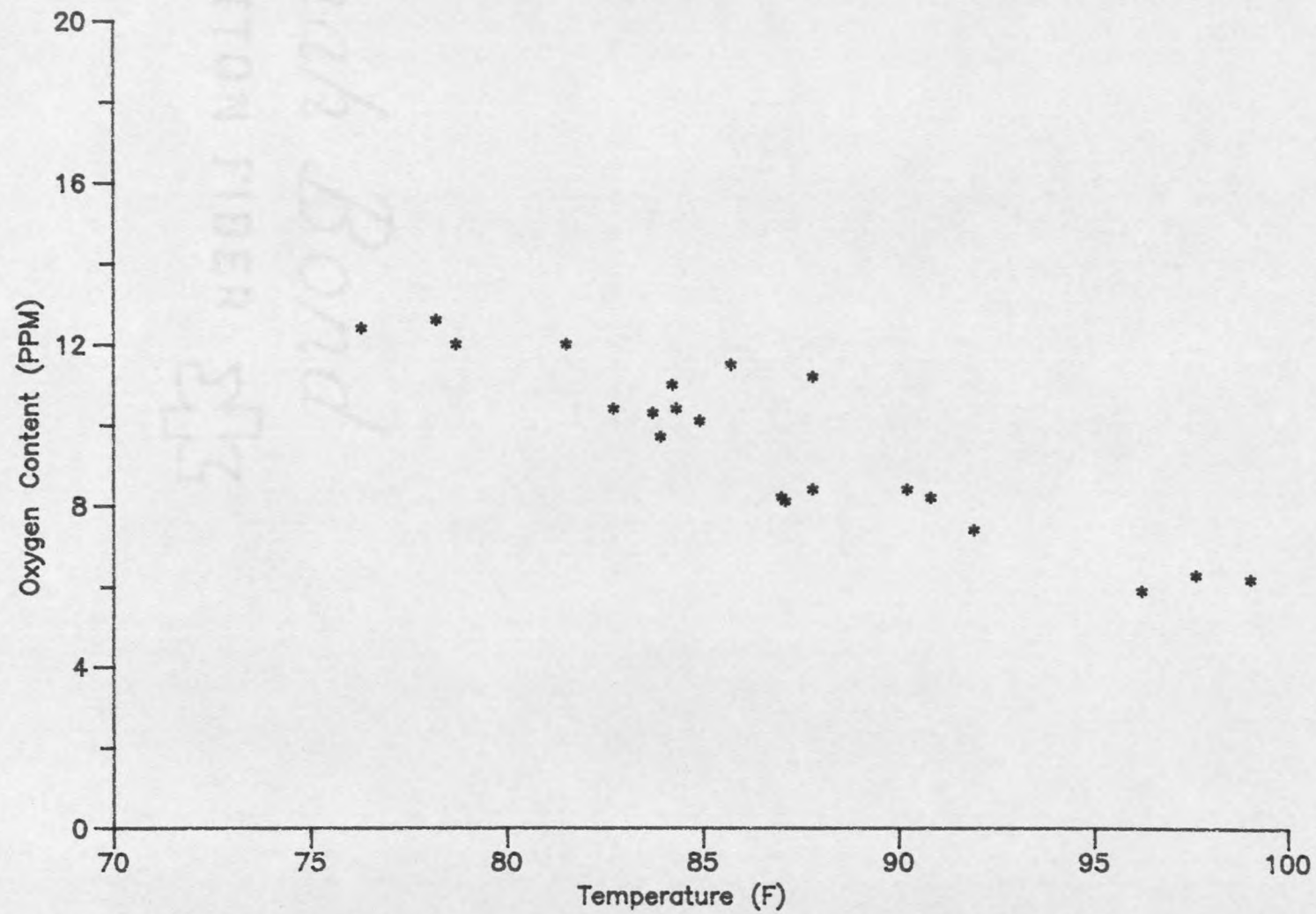


Figure 28. Oxygen Level in Test Fluid

APPENDIX E

FLUID NUTRIENT MEASUREMENT

FLUID NUTRIENT MEASUREMENT

Nutrient Measurements

At the beginning of each test run, nutrients were added to the test fluid to increase the growth rate of the biofilm in the test section. This consisted of mixing 11.35 gm of glucose, $C_6H_{12}O_6$, 1.42 gm of potassium nitrate, KNO_3 , and a trace of yeast extract into the fluid in the lower tank. This combination of glucose, potassium nitrate and yeast extract provided a carbon to nitrogen ratio in the tank of 8, with a carbon content at 40 parts per million and a nitrogen content at 5 parts per million, which was ideal for microbial growth. Yeast extract added the trace elements to speed the growth process. The trace element and carbon to nitrogen ratio were maintained throughout the experiment by adding 3.78 gm of glucose, 0.47 gm of potassium nitrate and a trace of yeast extract to the fluid in the tank once a day.

Nutrient measurements were taken at the beginning of each of the four test runs. This measurement consisted of taking a sample of the fluid leaving the test section of flow loop number one and storing it in a glass container. The glass container was then frozen to stop biological processes within the container. At the end of the test runs, all of the frozen glass containers were taken to the Industrial and Process Analysis Laboratory on the second floor of Cobleigh Hall to be analyzed for organic carbon. To determine the carbon

content, ultraviolet light was passed through the test sample and the amount of absorbed light recorded. Since carbon absorbs ultraviolet, the amount of carbon in a test sample could then be determined.

Nutrient Results

Table 15 shows the organic carbon content of the fluid for test runs number one through four. As can be seen from the figure, the carbon content varied slightly throughout the experiment, with a maximum of 145 ppm and a minimum of 212 ppm. This variation is relatively insignificant, with similar growth rates occurring for carbon contents between 20 ppm and 10,000 ppm.

Table 15. Nutrient Content of Test Fluid.

	Carbon Content One (PPM)
Test Run One	145
Test Run Two	183
Test Run Three	212
Test Run Four	165

APPENDIX F

TEMPERATURE VARIATION MEASUREMENTS

TEMPERATURE VARIATION MEASUREMENTS

Temperature Measurements

Throughout the investigation, the major factors affecting the fluid temperature were the pump located in the lower tank and the surrounding room temperature. Any fluctuation in the room temperature resulted in a corresponding fluctuation in the fluid temperature. The lower pump influenced the fluid temperature by heating the fluid during circulation.

Temperature Results

Figures 29 through 32 show the temperature of the test fluid and room temperature in flow loop number one for test runs one through four respectively. Only the temperature in flow loop one was plotted because the temperatures in all four flow loops remained within $1^{\circ}F$ of each other. As can be seen from the figures, the fluid temperature varied throughout the investigation with a maximum variation of twenty degrees F for test run one over a nine day period, with a maximum temperature of $98^{\circ}F$ and a minimum temperature of $72^{\circ}F$.

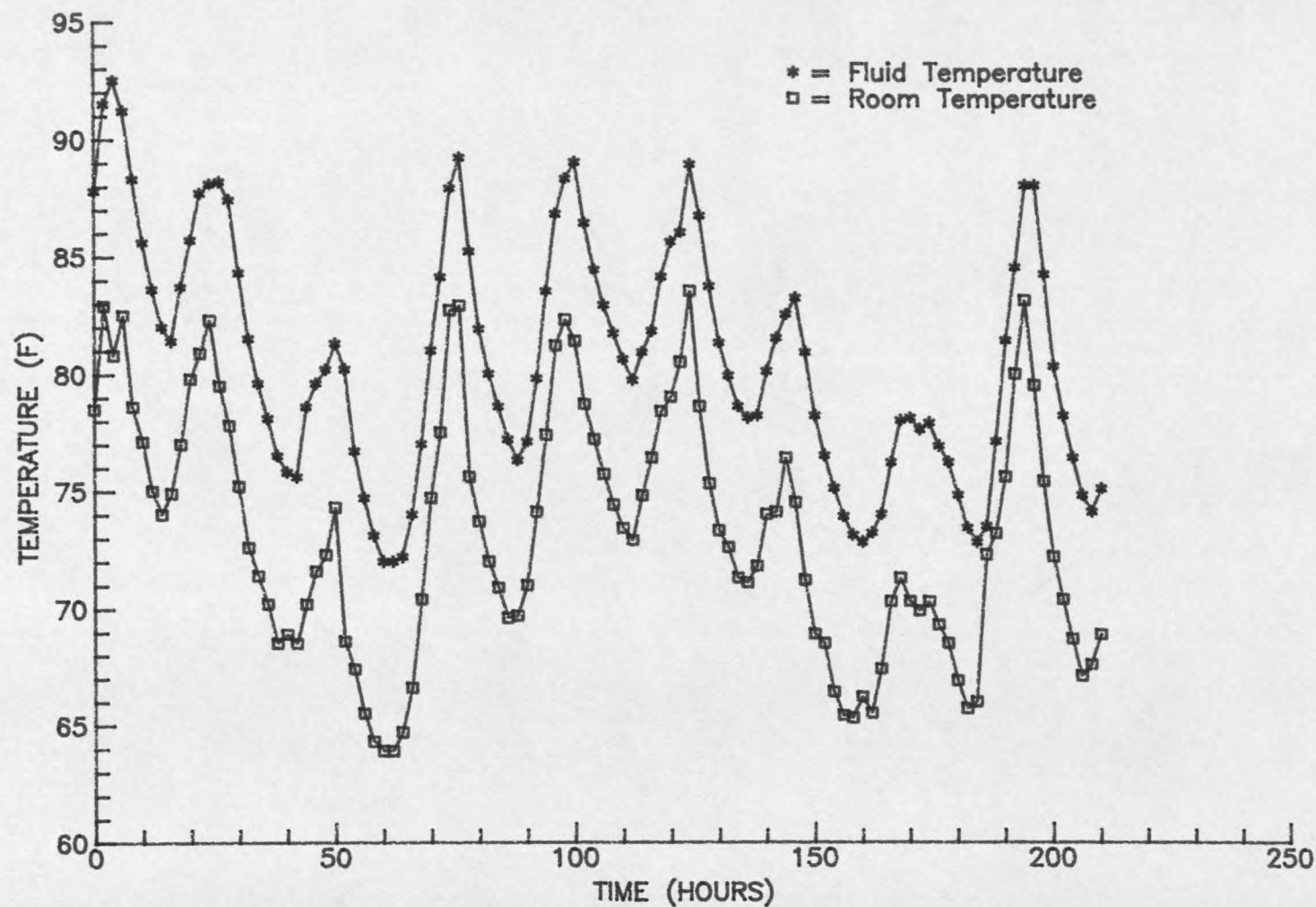


Figure 29. Variation in Fluid and Room Temperature v. Time for a Fluid Velocity of 1 ft/sec

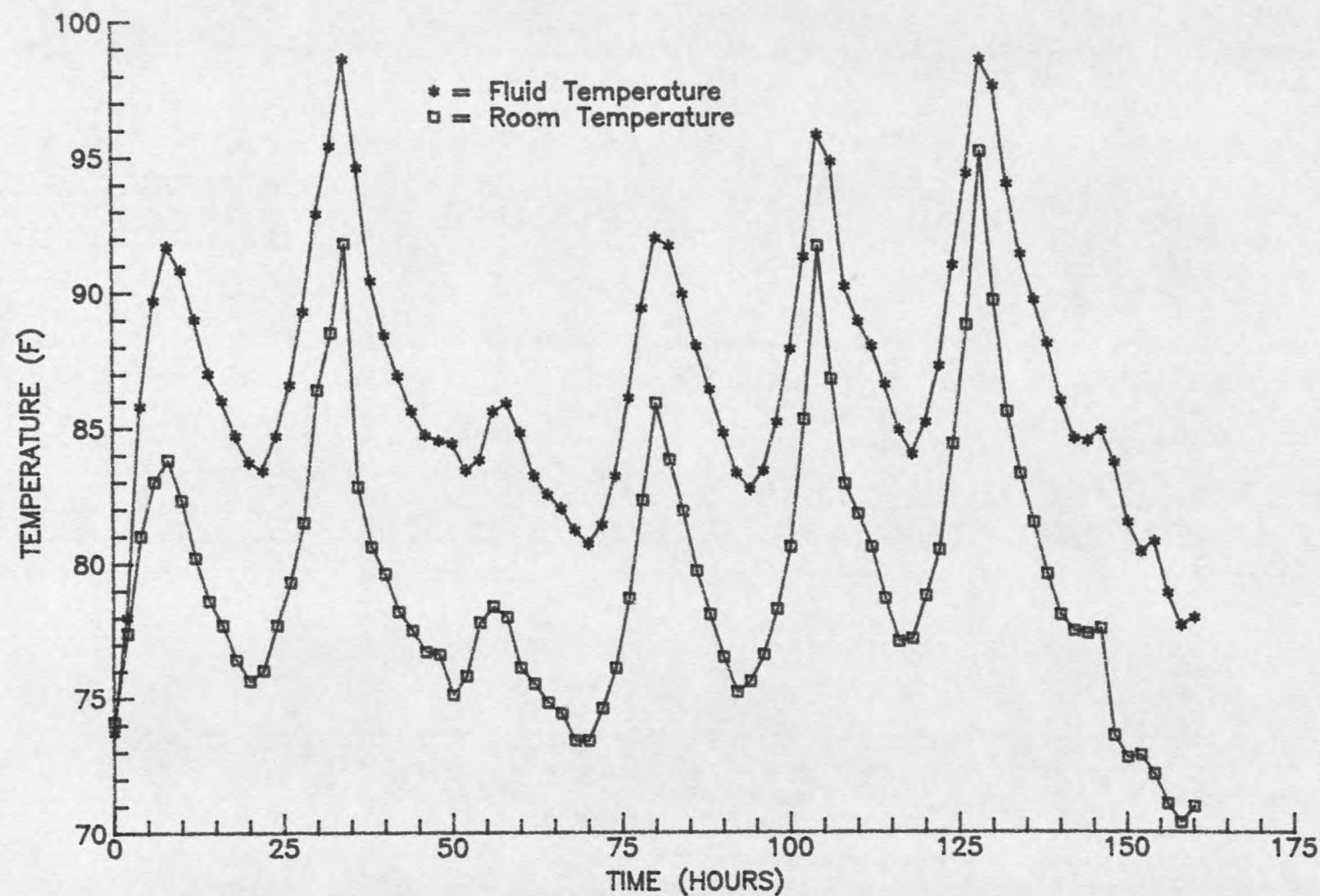


Figure 30. Variation in Fluid and Room Temperature v. Time for a Fluid velocity of 1.25 ft/sec

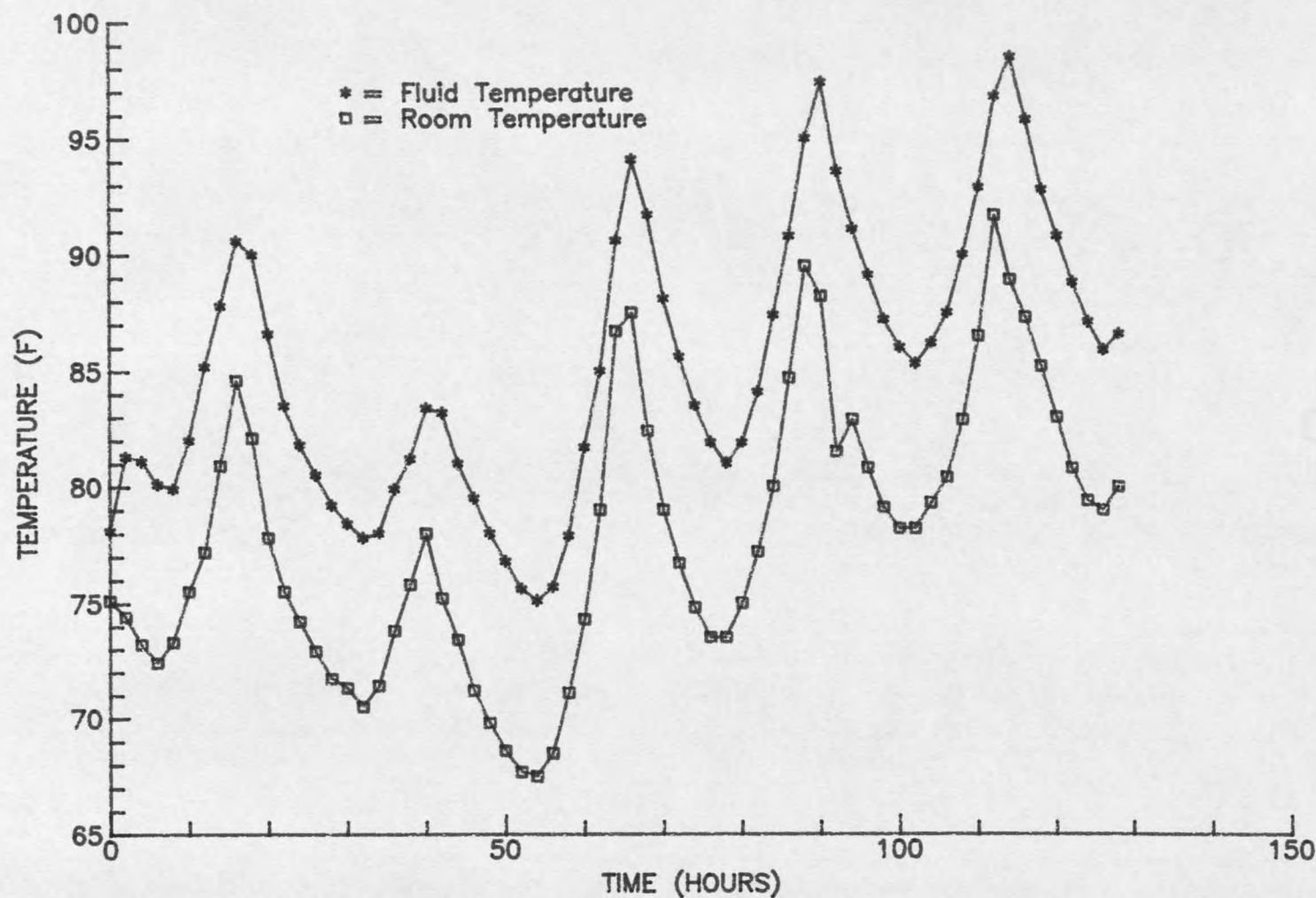


Figure 31. Variation in Fluid and Room Temperature
v. Time for a Fluid Velocity of 1.50 ft/sec

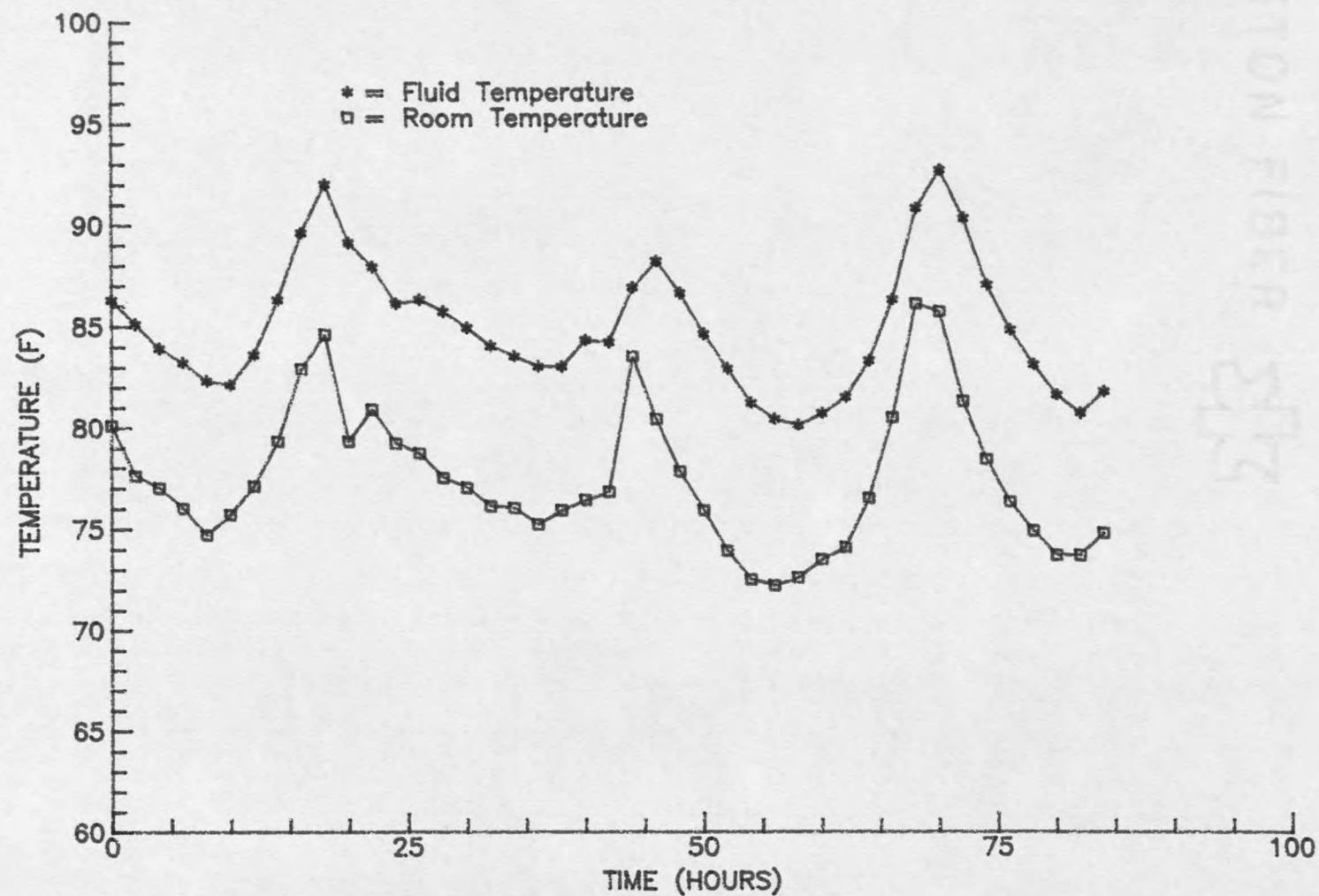


Figure 32. Variation in Fluid and Room Temperature
v. Time for a Fluid Velocity of 1.75 ft/sec

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