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ANALYSIS OF PROCESSING FLUCTUATIONS DURING EXTRUSION OF POLYSTYRENE SHEET

DISSERTATION

Presented in Partial Fulfillment of the Requirements of
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

William M. Fugel, B.S., M.S.

* * * * * *

The Ohio State University
1977

Reading Committee:
Professor R. Emerson Lynn, Jr.
Professor Robert S. Brodkey
Professor John T. Heibel

Approved By

R. Emerson Lynn, Jr.
Adviser
Department of Chemical
Engineering

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VITA

February 7, 1951	Born - Norwalk, Ohio
1973	B.S.Ch.E., The Ohio State University, Columbus, Ohio
1973-1974	Academic Advisor, University College, The Ohio State University, Columbus, Ohio
1974-1975	B.F. Goodrich Fellowship, Department of Chemical Engineering, The Ohio State University, Columbus, Ohio
1975	M.Sc., The Ohio State University, Columbus, Ohio
1975-1976	Teaching Associate, Department of Chemical Engineering, The Ohio State University, Columbus, Ohio
1976-1977	B.F. Goodrich Fellowship, Department of Chemical Engineering, The Ohio State University, Columbus, Ohio

FIELDS OF STUDY

Major Field: Chemical Engineering

Studies in Polymer Processing, Professor R. Emerson Lynn, Jr.

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ABSTRACT

The effects of external disturbances on extruder stability in the production of polystyrene sheet were studied. Isolation of the extruder from these external disturbances would permit the study of extruder-induced instabilities.

Potential process disturbances associated with the post-extrusion operations were eliminated by the development of a computer-controlled, constant-tension take-up system. The position of a "dancer" roll was monitored by a linear displacement transducer which controlled the tension of the sheet in the take-up equipment. The tension was controlled through adjustments in the linear take-off rate of the sheet. The system demonstrated the control potential of the digital computer system.

A feed baffle system was developed to reduce extrusion rate fluctuations caused by changes in the height of feed material over the extruder throat. These head changes resulted in flow rate instability for the conventional gravity feed system. For polystyrene pellet feed, the feed baffle system reduced the flow rate fluctuations by 40 percent and significantly improved the extruder stability. The feed baffle system was used with polystyrene flake feed and it was observed that the extruder stability was greatly improved and the bridging was eliminated. From these

studies the feed baffle system has been demonstrated to be an inexpensive alternative to the starve-feed system often proposed as a solution to feeding problems.

INTRODUCTION

The growth of the Plastics Industry has resulted in increased interest in three major areas:

1. increased plastics production rates on existing equipment, due to increased demand,
2. improved plastics quality, either visual appearance or dimensional tolerance, due to increased plastic application, and
3. decreased scrap or "off-spec" production, due to increased raw material costs.

The realization of the first area often results in being unable to meet the requirements of the latter two.

The plasticating extruder is a widely used processing tool in the polymer industry. Over 50 percent of all polymeric materials pass through an extruder at least once during conversion from monomer to finished product. In attempting to solve the problems associated with the increased extrusion demands, industry has relied heavily upon screw design optimization. Thus, attention has been focused upon understanding the phenomena occurring during the melt processing operation.

In an era of computer control, an understanding of the processing phenomena could lead to better optimization of present systems or a more efficient control strategy. This understanding could also lead to alternate process designs or processing techniques, and new product applications.

The purpose of this work was to implement a study on the effects of extruder system variables upon fluctuations of melt temperature, pressure, and flow rate. The study was based upon data acquisition from a 2 1/2-inch, 24:1 length to diameter ratio (L/D) plasticating extruder producing polystyrene sheet. This study consisted of three phases.

Phase 1 - design of a computer-controlled, constant-tension take-up system to insure uniform take-up and non-interaction with extruder-induced system fluctuations,

Phase 2 - determination of an optimum screw design to reduce fluctuations as much as possible prior to further study of the system variables, and

Phase 3 - design of a feed system to determine the significance of feed-related fluctuation upon the overall system performance.

CHAPTER I

LITERATURE SURVEY

The plasticating extruder is the most widely used processing tool in converting polymer resins into finished products. The extruder consists of an Archimedian screw rotating in a heated barrel. The polymeric feed material in the form of pellets, beads, powder, or flakes is passed through the extruder, where it is melted, then forced through a forming die. Post extrusion steps include cooling of the molten polymer and subsequent processing or packaging.

A closer analysis of a single screw extruder operation indicates that the function of the screw can be divided into three stages. The first stage of the screw is known as the solid- or feed-conveying section. This section has a constant flight depth to carry the solid pellets down the barrel where they are subsequently melted. Analysis of the forces on the pellets indicates that the friction between the barrel and pellets force the material toward the discharge end of the extruder. The friction between the screw and pellets is much less, and the pellets experience a slight drag as they slide down the screw.

The second stage of the screw is known as the transition section. In this section, the flight depth uniformly changes from the deeper feed section depth to the shallower depth of the compression section. As the feed material is forced through this section, the increased compression, barrel heating, and heating due to the dissipation of shear energy continue the melting process. As the material melts, a pool of molten polymer begins to form behind the rotating screw flight. This region is thus characterized as a two-phase flow system.

The third stage of the screw is called the melt pumping, melting conveying, or metering section. This section has a constant, shallow flight depth, which compresses the feed material and completes the melting process. The molten polymer is usually pumped through a screen pack and breaker plate to aid in mixing of the molten stream. It is then forced through some type of forming die.

As previously mentioned, the growth of the Polymer Industry has resulted in increased production demand from existing equipment. However, increased production rates usually result in increased scrap or "off-spec" production. The study of "off-spec" production and processing fluctuations has grown with the industry, but solutions as to the causes of these fluctuations have been slow in emerging. Two major classifications of processing instability are generally recognized; extruder-induced and die-induced fluctuations. These will be briefly discussed below.

EXTRUDER-INDUCED FLUCTUATIONS

Extruder-induced fluctuations, also known as surging, have been studied by various researchers for the past 30 years. Although the exact cause has not been established, there is general agreement that the instability originates due to instability of the melt mechanisms, commonly referred to as melt bed "break-up." The first studies on melt mechanisms were conducted by Maddock (14) and Street (26). In their work, experimental techniques were developed which led to subsequent development of the first theoretical melt model proposed by Tadmor (27,28).

These studies on melt mechanism have indicated that an apparent, inherent instability exists within the solid bed. This instability results in a cyclical solid bed "break-up" which is dependent upon the feed material, pellet size, and screw geometry. Marshall, Klein, and Uhl (19) have observed this instability in both pressure and temperature recordings. With extruder-induced fluctuations, the quality of the extrudate depends primarily upon the extruder melting performance. Thus, instability of the melt mechanism which result in pressure or temperature fluctuations can be directly related to surging.

For a pseudoplastic polymer following the "power law" fluid model, the flow rate through a capillary is given by

$$Q = \frac{n\pi R^3}{3n+1}\left(\frac{R\Delta P}{2mL}\right)^{1/n} \qquad (1)$$

where: Q = flow rate
m,n = power law parameters
R = radius of flow
L = length of capillary
ΔP = pressure drop

From Equation (1) it can be seen that small changes in the pressure drop can result in large fluctuations in the flow rate. Kessler, Bonner, Squires, and Wolf (10) have shown that a pressure change of 3.7 percent will result in a flow rate change of 7.3 percent. In similar studies, Maddock (15) has shown that a 1 percent pressure fluctuation can result in a 3 percent flow rate fluctuation.

Maddock (16) has made similar comparisons for temperature fluctuations. Using the "power law" model, the apparent viscosity is given by:

$$\eta = \eta_o e^{a(T-T_o)} \gamma^{n-1} \qquad (2)$$

where: η = apparent viscosity
η_o = apparent viscosity at $T=T_o$ and $n=1$

γ = shear rate

a = temperature coefficient (a constant for constant shear rate)

If the flow rate is to remain constant as the temperature fluctuates, the pressure must also fluctuate. Thus, as the temperature changes, the viscosity will change, and the pressure must change such that ($\Delta P/m$), from the "power law" model, remains constant. Solving for this quantity gives:

$$\frac{\Delta P}{m} = \text{constant} = \frac{\Delta P}{\eta_o \exp(-a\Delta T)} \tag{3}$$

For polystyrene a one degree Celcius temperature fluctuation, will result in a 1.4 to 2.2 percentage change in pressure if the flow rate is to remain constant.

From these studies, surging can be related to pressure fluctuations, temperature fluctuations, or both. Pressure, temperature and flow rate recordings can be used to correlate the occurrence of surging with the extruder operation. Correlation of pressure and flow rate fluctuations usually indicates melt flow instability. The correlation of pressure and temperature fluctuations with surging usually indicates poor mixing in the extruder, as well as possible melt flow instability.

Kirby (11) has used the methods of process dynamics to relate stability to the melt column length, which is defined as the length of the screw filled with melt. From this work, operating conditions which tend to increase the melt column length are found to minimize surging. This is believed to be due to the dampening effect of the increased polymer reservoir. In a study of causes and cures for surging, Carley (3) proposed two cyclical mechanisms for surging. The first case is based upon a feed controlling mechanism, where small feed rate changes appear as large production rate changes. These cycles can be caused by over-loading the feed section of the screw which results in varied packing of the feed in the screw flights. These packing forces tend to fluctuate and cause subsequent feed rate fluctuation. The second case is based upon a melt controlling mechanism, where the feed rate is higher than the melting rate. Thus, pressure will build in the melt section until the frictional forces in the feed section are overcome, and the feed rate is reduced. At a reduced feed rate, the melting zone is increased, and the pressue subsequently begins to drop. As the pressure drops, the feed rate begins to increase and the cycle is repeated.

Wheeler (34) has proposed several classifications for surging dependent upon the frequency of the fluctuations. Class 1 of the surging phenomena are for surging frequencies approximately equal to the frequency of the screw revolution. These fluctuations are believed to be caused by the solid conveying or feed rate controlling mechanism.

Class 2 are flow rate fluctuations at intermediate frequencies of 1-15 cycles per minute. These fluctuations may be caused by the melt-mechanism controlling case. For this system, a longer melt column is found to decrease the magnitude of the fluctuation by the reservoir dampening effect. Class 3 corresponds to low frequency fluctuations on the order of 1 or 2 cycles per hour. These fluctuations are usually due to external systems such as die heating or take-up rate fluctuations. Class 4 are random flow rate fluctuations which may be due to external factors such as feed hopper fill height and poor feed section design.

Recently, Maddock (17) has studied the improved stability achieved by screw cooling. This effective channel depth reduction results in increased shear rate and improved mixing. However, lower flow rates are usually experienced and operation may become more sensitive and difficult to control. More work is needed in this area.

DIE-INDUCED FLUCTUATIONS

Die-induced fluctuations, also known as melt fracture, refer to the distortion of the extrudate surface. There is general agreement that this phenomenon is due to the viscoelastic nature of the polymeric material. However, there are many proposed mechanisms by which the fluctuations are initiated and propagated. Since the pioneering work by Spencer and Dillion (25), it has been established that melt fracture starts at some critical value of the throughput rate. This value is dependent upon the polymeric material, its additives, and the operating conditions of the system in which the material is being processed.

The work of Han (7) emphasizes the correlation of the rheological properties of the polymer materials, processing variables and die geometry with the occurrence of the unstable flow phenomena. The most popular mechanisms, as proposed by leading researchers (8,9,21,22,31,35) include:

(i) buckling of the extrudate,
(ii) slippage, stick/slip phenomena, of the melt at the die wall,
(iii) propagation and amplification of disturbances caused by secondary flow cells at the die entrance, and
(iv) critical recoverable shear criterion

However, at present there is no clear cut evidence to support one mechanism over the other.

Tordella (30) has done much work with regard to die geometry, namely die entry angle and L/D ratio for capillary dies. Die entry angle results indicate that improved quality can be obtained by proper entry design. This work would tend to eliminate secondary flow cells at the die entrance. But, the existence of melt fracture for even the best designed system indicates that there are a combination of factors affecting unstable production.

An interesting proposal by Han (7) suggests that there is a limit as to the amount of elastic energy the polymer material can contain. If this limit is exceeded, the material releases this energy in the form of surface distortion. This correlates with the observation of increased distortion at increased throughput rates. However, much more experimental work is needed to gain an insight as to the causes and cures for melt fracture.

FEED SYSTEMS

The importance of feed rate uniformity has been mentioned in the Extruder-Induced Fluctuations section. Changes in the feed rate, feed density, feed packing or even height of feed in the hopper have been found to cause considerable output rate fluctuations. Although little work on feed systems has been reported, Maddock (14) and Kruder and Nickols (13) have investigated the effect of starve feeding on extruder performance. During normal feed operations, the extruder feed system is flood fed; that is, the hopper is kept full of feed material which is gravity fed to the screw. Starve feeding refers to the process of directly metering the feed material to the screw at feed rates ranging from 35 percent to 100 percent of the flood feed rate.

Kruder and Kim (12) report no significant change in output rate for starve feed rates as low as 50 percent of the flood feed rate. Advantages of the starve fed system are reported to include better stability, greater extruder versatility and better control potential. However, excessive pressure build-up has been observed for some systems, and accurate metering systems are expensive and can produce control problems of their own. Additional study is needed to establish operating characteristics and limitations for these systems.

CHAPTER II

EQUIPMENT AND INSTRUMENTATION

EXTRUDER

The extruder used in this study is a 2 1/2-inch diameter, 24:1 L/D Spacemaker^R manufactured by NRM Corp. of Akron, Ohio. The system is shown schematically in Figure 1, and photographs of the system are presented in Figures 2 and 3. The extruder is a single-screw model. Several screws of different design were used in this study. The screw is driven by a 40 horsepower d.c. motor which is powered by a rectified-power, variable speed unit manufactured by Reliance Electric Company. This unit has also been equipped with a speed control to maintain the revolutions per minute (rpm) variance at a level of less than 0.5 percent.

The extruder barrel is a one-piece unit that has been lined with Xaloy^R and has a working pressure of 10,000 psi. The temperature along the barrel is controlled by four heater zones containing resistance heating elements and a manually operated cooling fan. Thermocouples buried one-half inch in the barrel are used to signal silicon-controlled rectifiers (SCR's) made by the Barber-Coleman

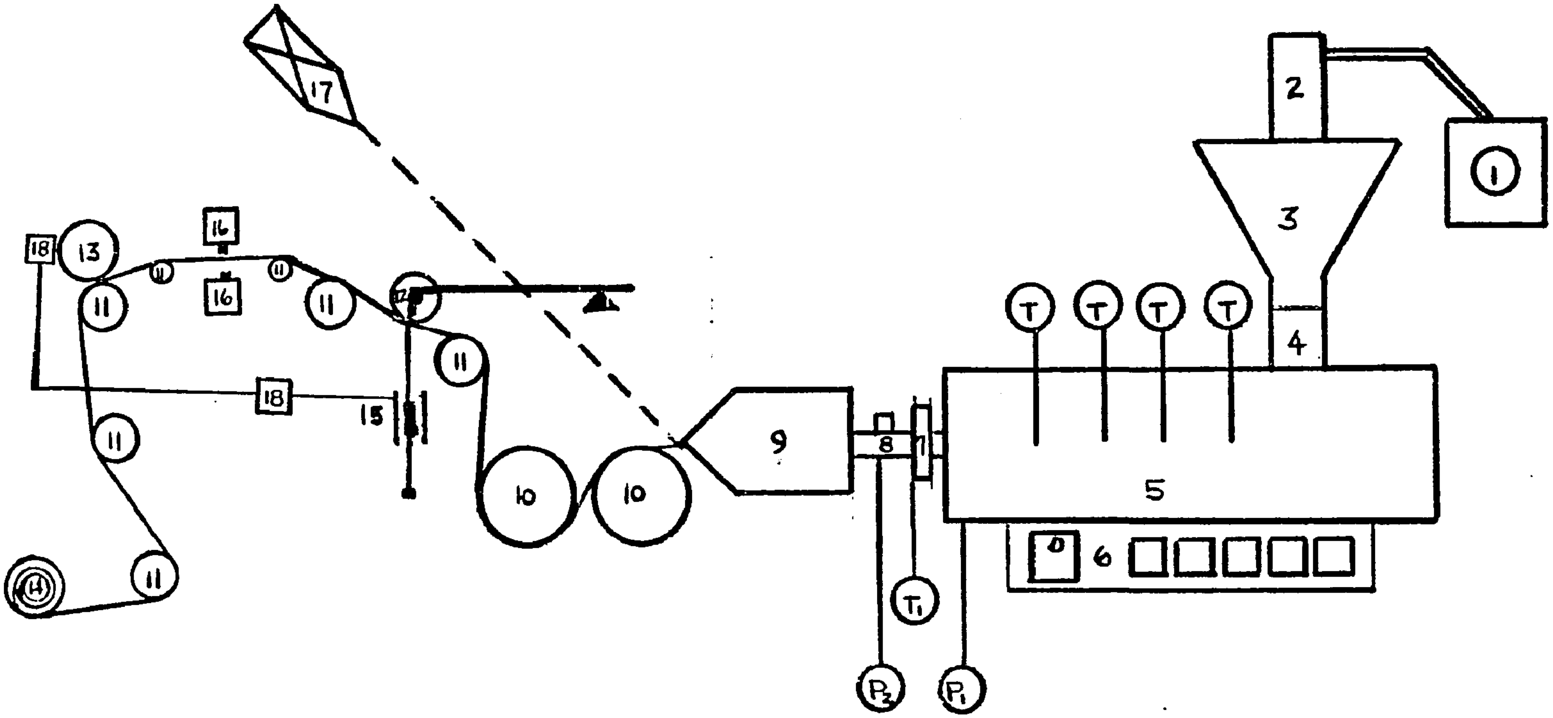


Figure 1.--Processing Equipment Schematic*

*Refer to Table 1 for equipment listing.

TABLE 1

PROCESSING EQUIPMENT LIST*

Item No.	Description	Item No.	Description
1.	Feed barrel station	14.	Wind-up roll
2.	Automatic feed loader	15.	Linear displacement transducer
3.	Feed hopper	16.	Beta Gauge
4.	Feed baffle system	17.	Infrared Pyrometer
5.	Extruder	18.	Nip roll drive electronics with PDP-15 Digital Computer Interface
6.	Extruder control panel	T	Thermocouple
7.	Transition adapter	T_1	Valve thermocouple
8.	Valve	P_1	Head pressure transducer
9.	Sheet die	P_2	Valve pressure transducer
10.	Cooling rolls		
11.	Idler rolls		
12.	Dancer		
13.	Nip roll		

*Refer to Figure 1.

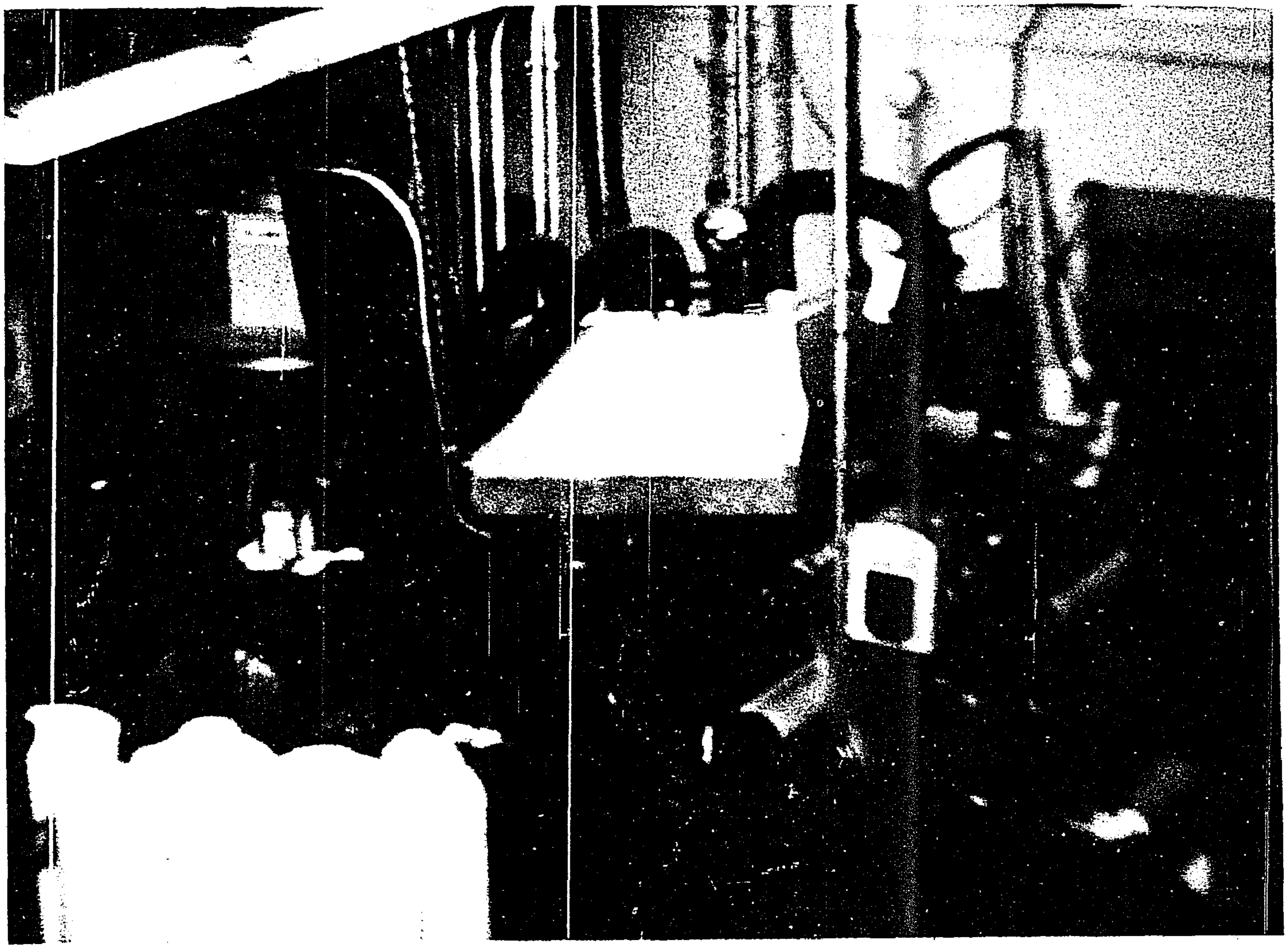


Figure 2.--Processing Equipment Photograph

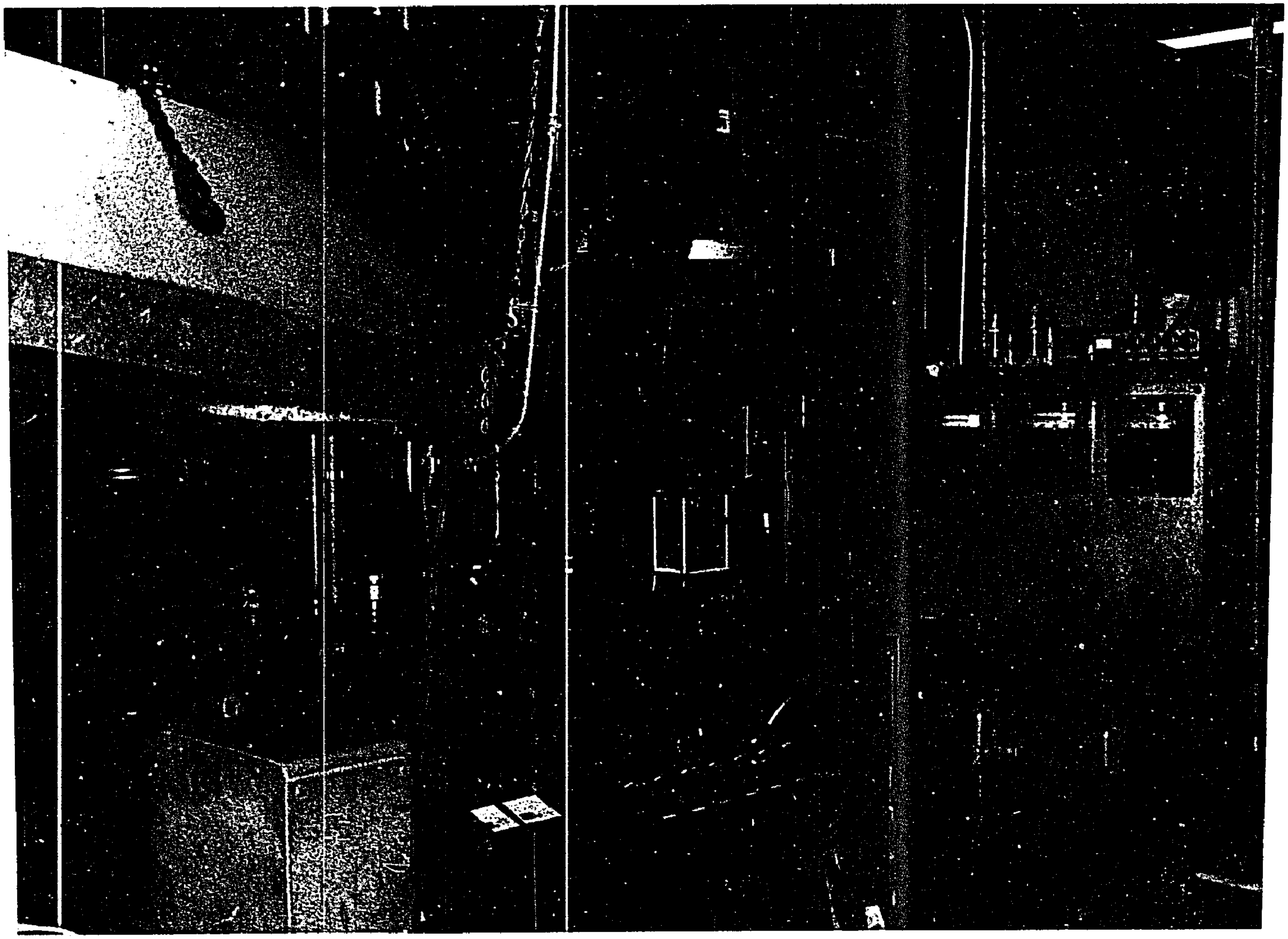


Figure 3.--Extruder and Feed System Photograph

Company. The SCR's are used to power the resistance heaters. Each heater zone has a limit switch which shuts-off all power to the heaters if any of the blocks reach 316°C. Power to the heaters remains off until the temperature in all zones drops below this limit.

The feed hopper is a five cubic feet-capacity spun aluminum hopper with a feed opening of 4 3/4 inches x 2 1/2 inches. The throat of the extruder is water-cooled to prevent premature melting of the feed and feed bridging in the hopper or throat section. The extruder was flood-fed during all runs. The hopper is equipped with a shut-off gate to allow the extruder to be emptied after each day's operation. The feed baffle used during a portion of this study and the feed loader will be discussed in separate sections.

The control panel for the system is mounted on the main extruder support frame. The panel has power switches and control and monitoring units. The screw speed is adjusted by a variable control knob. Rpm and current are displayed on meters. The heater zone units contain individual temperature monitoring and control units. Access to the electronics of the control units can only be attained after "locking-out" all power to the system. For a more detailed description of the extruder unit, the reader is referred to Reber (24) and Fontaine (5).

FEED-LOADER

A Conair Model 100-072 Flake Ratio Automatic Vacuum Hopper Loader was used to fill the feed hopper. The unit operates on a one-minute cycle. A vacuum system is used to lift the feed material from drums to the feed hopper. The loader operates on 115 volt a.c. power and has a one horsepower blower--protected by a cloth filter--which supplies the propelling air stream. The unit is designed to give a nearly continuous head of feed material. A limit switch located inside the hopper is used to prevent the system from operating when there is already sufficient feed in the hopper. The self-contained unit rests on top of the feed hopper.

PDP-15 DIGITAL COMPUTER

The tension-control, extruder monitor, data acquisition and data treatment routines were implemented by a PDP-15 Model 30/10 dual processor system manufactured by Digital Equipment Corp. This system is described in detail by Bartram (1).

TEMPERATURE AND PRESSURE SENSORS

Temperature measurements were made using iron-constantan, exposed junction thermocouples. These units were mounted in the four heater zones, flush along the barrel surface, and just prior to the valve. The wires from the thermocouple are taken to a reference oven to establish a base reading for all measurements. Twinax^R shielded, twisted pair wires are then used to connect the leads to the Analog to Digital Converter (ADC) units of the PDP-15 computer.

Pressure measurements were made using Dynisco mercury-filled pressure transducers. The transducers used had operating ranges of 0 to 500 through 0 to 10,000 psi. Each transducer had a power supply to convert pressure readings to milli-volt signals which are transferred to the computer by Twinax^R cables. Pressures were monitored between the extruder screw and screen pack and just after the valve.

Because of system noise, the signals from the thermocouples and transducers required amplification and filtering. A detailed description of the amplifiers and filters can be found in Bartram (1). A diagram of the monitoring positions for temperature and pressure are given in Figure 1.

INFRARED PYROMETER

A Mikron 66 Infrared Thermometer, also known as an I.R. Pyrometer was used to monitor melt temperature as the polymer flowed from the sheet die. The pyrometer is mounted on the Beta Gauge framework, and can traverse across the sheet with the Beta Gauge. The pyrometer is located 6 feet from the sheet, but focused to cover an area of approximately 0.2 square inches. The system operates by relating the electromagnetic energy emitted from the molten polymer to the temperature of the material. The major advantages are the ability to make accurate non-contact measurements and the system's fast response to temperature fluctuations. Waller (33) gives a detailed description of the unit, its calibration, operation and comparison to other systems.

BETA GAUGE

An Industrial Nucleonics O-2, S-11 Series 400 Accuray^{R} measuring system, also known as a Beta Gauge, was used to monitor sheet thickness. The radiation and detection unit are mounted on a traverse that has been attached to the take-up framework. The thickness of the polymer sheet is directly related to the amount of radiation absorbed. A detailed description of the system is given by Bartram (1) and Draudt (4).

POST-EXTRUDER PROCESSING

The molten polymer exits the extruder after passing through a four-part screen pack and standard breaker plate. Because a new valve and die were to be used, a transition adapter was constructed. This adapter had two purposes. First, the adapter served as a base onto which the valve and die system could be physically attached, and in turn attached to the face-plate of the extruder. Second, the adapter provided a conical transition zone to reduce the polymer flow area from the 2 1/2-inch extruder outlet to the 1 1/4-inch valve inlet. A schematic of the adapter is given in Figure 4.

The valve and sheet die used in this study were loaned by NRM Corp. The valve had been machined to form a tight seal with the die and provided for physical attachment to the extruder. The valve stem has a total travel of 1 1/2-inch from full-open to full-close. This corresponds to 8 turns of the valve stem. During this study the valve was operated at 4 turns of the valve stem, or 50 percent open. The valve is also tapped just prior to and after the valve stem with standard thermocouple or pressure transducer threads. During this study the temperature was monitored just prior to the valve and the pressure was monitored just after the valve.

A 42-inch Microchoke die was used to form the polymer sheet. This die was a variable choke to allow for flow adjustments. Temperature in the die was controlled by power supplied to five heater zones through the use of tubular resistance heaters. The center and two exterior zones were connected to the SCR controllers on the extruder console. The intermediate zones were connected to a 220-volt Variac^R which was operated so as to maintain the surrounding zone temperature at approximately 230°C.

This die was chosen because of its extended lips which allow closer operation to the cooling rolls. In previous studies, problems developed because of vapor condensation

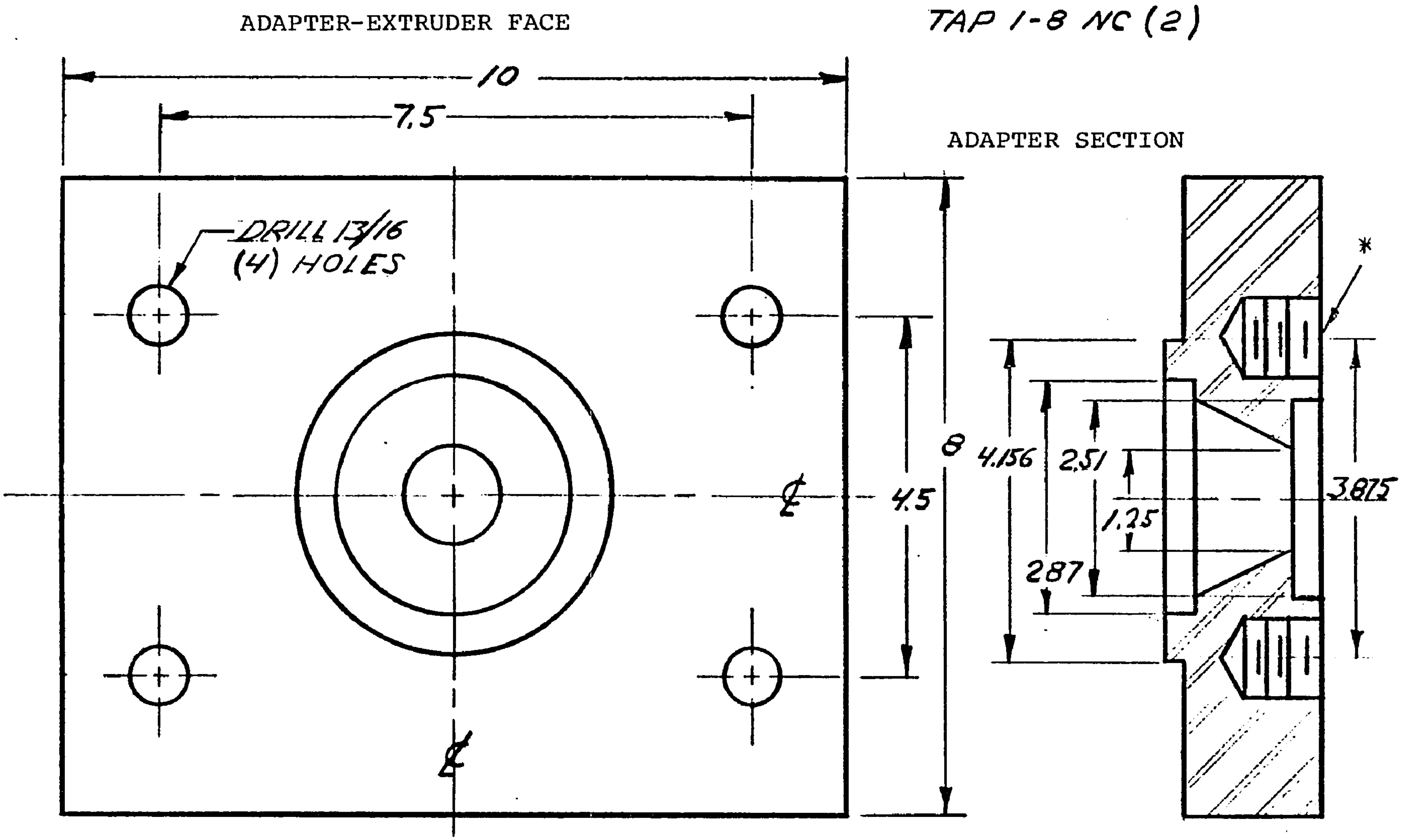


Figure 4.--Transition Adapter Schematic

between the sheet and the cooling rolls. By use of the die with extended lips, this condensation was significantly reduced. However, care was taken to insure the lower surface of the die was kept clean otherwise polymer material collected, degraded, and dropped onto the cooling roll. This material appeared as a grease or high viscosity oil and tended to produce surface irregularities. Another advantage of the extended lips was the reduction of necking of the sheet and the attendant fluctuation of the thickness.

Because the take-up equipment of the present system can only handle 30-inch sheet, the width of the die outlet was reduced. This was accomplished by using 5-inch modified deckels supplied by NRM Corp. The deckels were designed for 5-inch blockage, but a six-inch blockage plate was installed on each side to give a total flow width of 30-inches. Because of the nonuniformity of the edges of the sheet, selvage trimmers were constructed of razor blades, but the increased drag caused by these edgers made their use impractical. Therefore, the deckels were rearranged to allow for leakage flow outboard of the deckels. The system was operated in this manner and it was observed that as long as the sheet was less than 16-mils thick, the edge roughness presented no problem on the wind-up roll. A schematic and photograph of the post-extrusion equipment are presented in Figures 5 and 6, respectively.

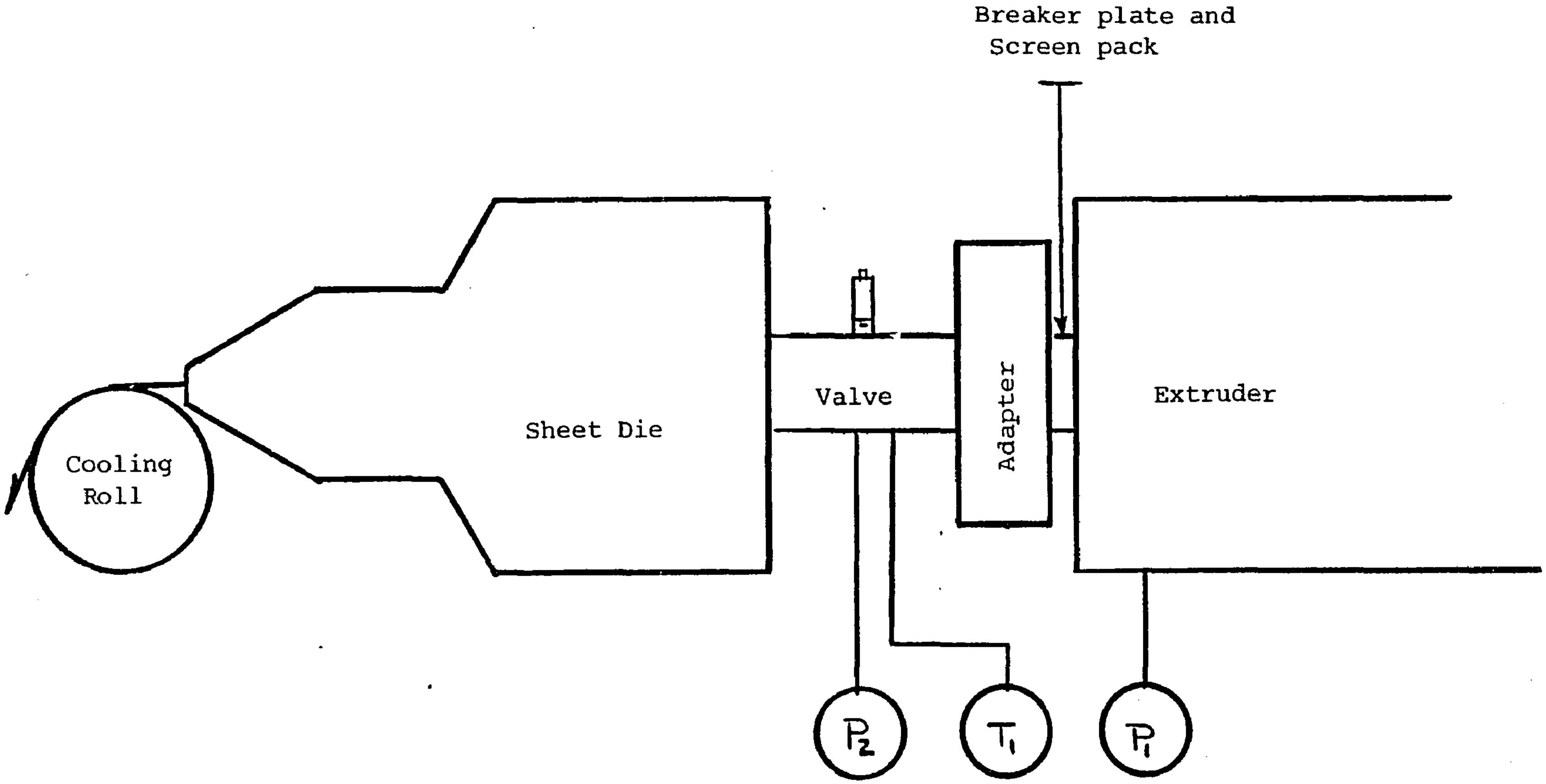


Figure 5.--Post Extrusion Equipment Schematic

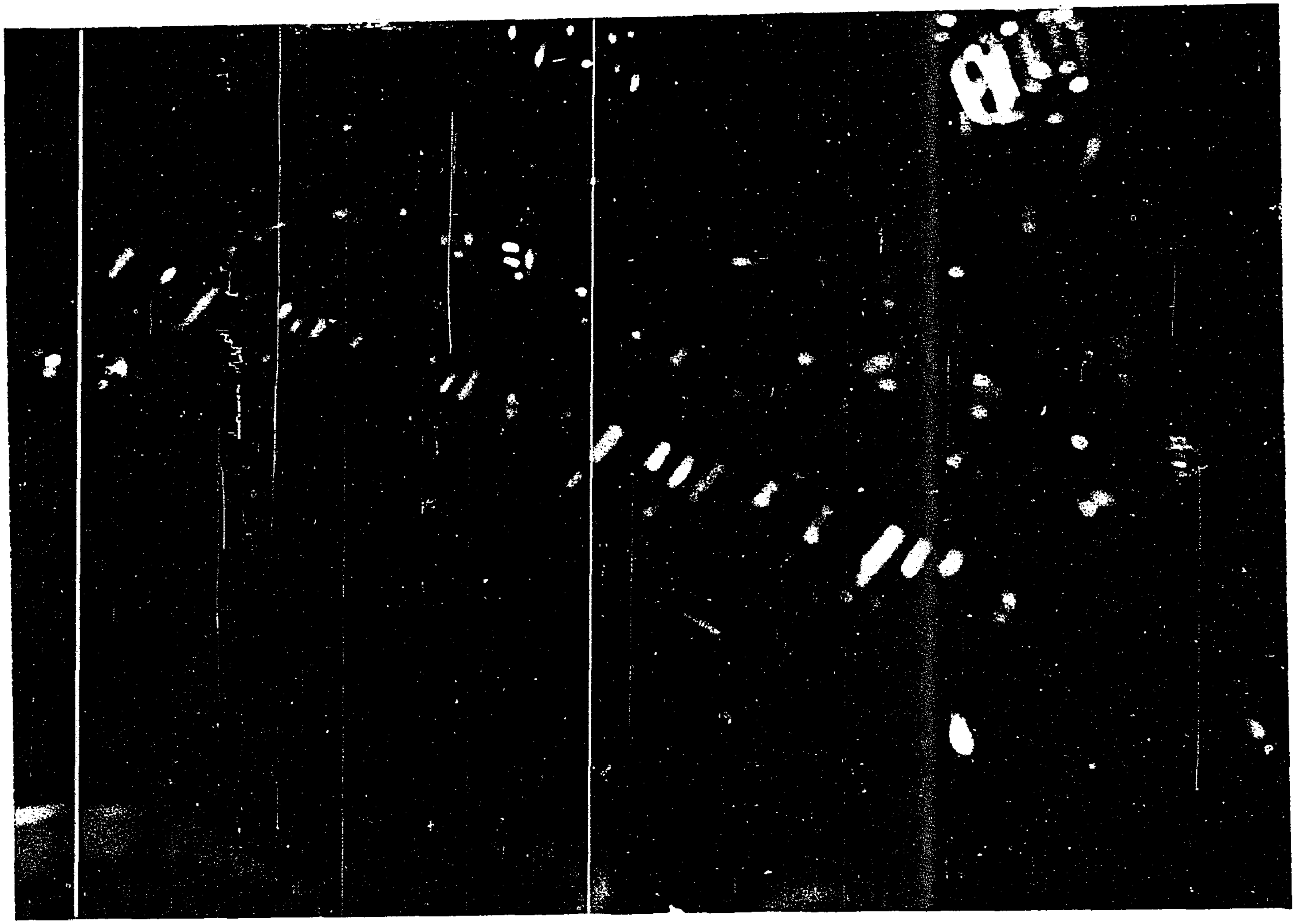


Figure 6.--Post Extrusion Equipment Photograph

TAKE-UP SYSTEM

The molten polymer sheet issuing from the die is cooled, solidified and wound on rolls using a converted Egan laminator. The basic system, as described by Fontaine (5) was further modified in order to implement computer control of the sheet tension. In previous work, the take-off tension was set by the torque transmitted through an electromagnetic clutch which drives the wind-up roll. However, as the size of the roll increased the torque changed, and the power to the electromagnetic clutch had to be changed. These tension fluctuations were transmitted to the sheet and appeared as thickness variations.

The molten polymer first passed over a set of water-cooled, variable speed cooling rolls. During this study, the rolls were operated at 140°F and a linear take-off rate of 16 feet per minute. These conditions were found to produce the best quality sheet.

The sheet then passed over two idler rolls between which a "floating dancer" roll rested upon the sheet. The purpose of the dancer was to monitor the tension of the sheet as evidence by the position at which the dancer operated. Thus, as the tension in the sheet was reduced, the dancer dropped to a lower position, and vice versa. In order to monitor the tension, the position of the dancer was monitored by a linear displacement transducer, LDT.

As the dancer moved, a bar was raised or lowered within an induction coil. The corresponding electrical change was transmitted to the LDT electronics which supplied a signal to the PDP-15 computer. By the use of a computer control package which is discussed in the Experimental Prodecure section, a control signal was sent to a variable speed 0 to 1750 rpm motor. The motor in turn drove a "nip roll" which set the linear take-off rate of the sheet. Thus, if the dancer dropped, the linear take-up rate was increased, keeping the tension constant.

In order to control the tension, a "dead band" had to be set such that the speed would only be changed when the dancer was outside this range. Experimentally the upper and lower dancer positions were established, then the dead band was varied to find the best control band. From these tests, the best response of the system was found to correspond to a dead band of 20 percent of the overall range.

The computer package is designed to implement a speed change only if the dancer is outside the dead band and only if the error, position minus dead band, is increasing. Thus, if the system is slowly responding to previous control and is returning to the dead band region, no further speed changes are needed. This method was found to significantly reduce overshoot and provide excellent system stability.

If a speed change is necessary, a digital signal is sent to a control box which either begins to increase or decrease the motor speed by means of a potentiometer. Once the system begins to respond, the speed is set, and the controller monitors for further speed alterations. The motor speed is transmitted through a 60 to 1 speed reducer to a rubber-coated, chain-driven nip roll located on the back side of the take-off frame.

Between the nip roll and fixed idler of the dancer system, the sheet passes between the Beta Gauge thickness sensors. After the nip roll, the sheet passes over two additional idlers, and is collected on the variable-torque, wind-up roll. In this study it was found that torque changes made on the wind-up roll were not transmitted through the dancer-controlled nip system. However, it was discovered that during the wind-up rolls change-over period, the decreased load on the drive system caused a significant cooling roll speed fluctuation. This in turn caused a major thickness fluctuation. Thus, wind-up roll changes should only be scheduled between experimental runs.

A schematic and photograph of the take-up system are presented in Figures 7 and 8, respectively.

FEED BAFFLE

In consideration of external factors which could cause extruder fluctuations, mention of possible feed fluctuations

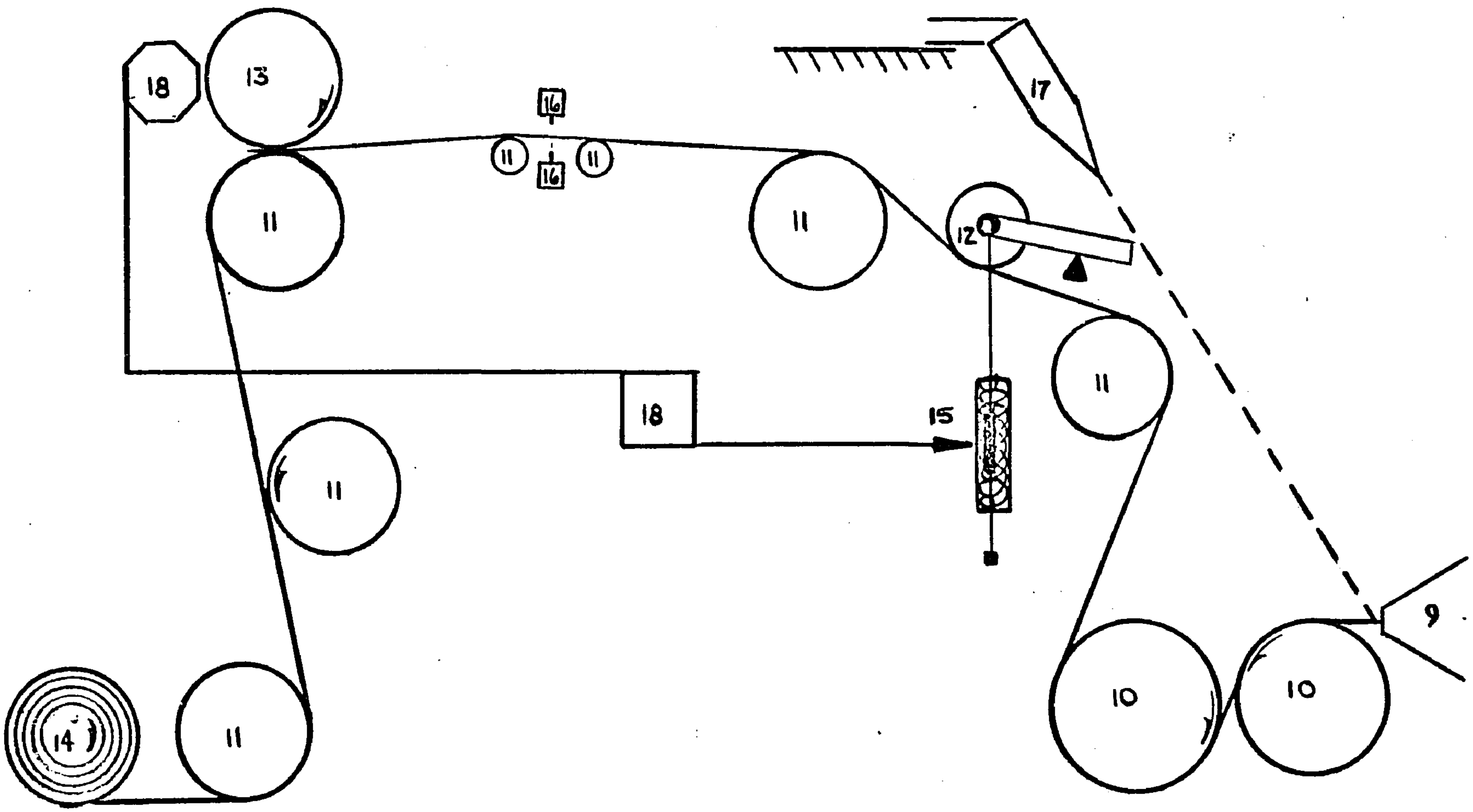


Figure 7.--Take-up Equipment Schematic*

*Refer to Table 1 for equipment listing.

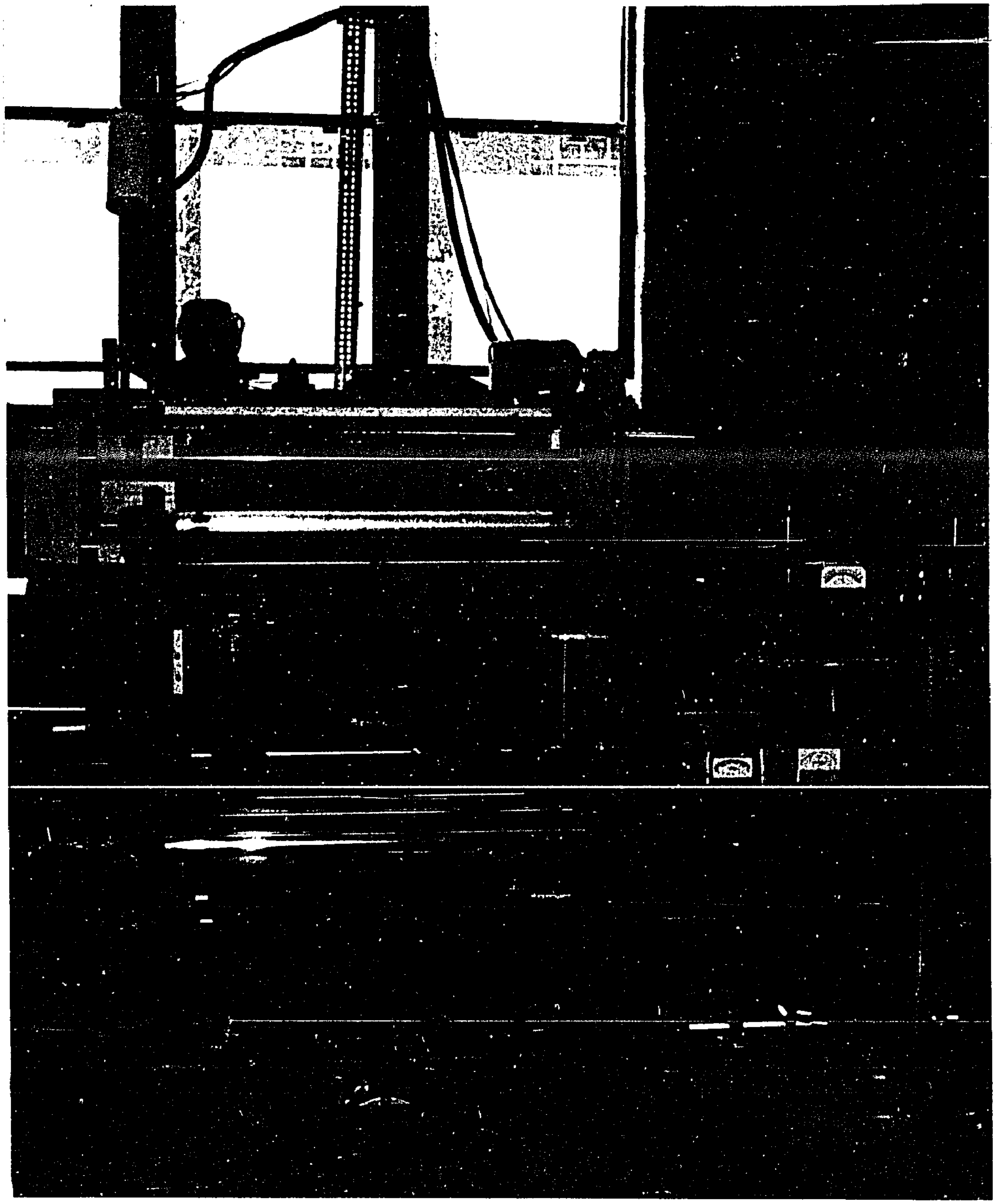


Figure 8.--Take-up Equipment Photograph

was made both by Wallace (32) and by McCormick (20). Although not considered a major problem in extrusion of polystyrene pellets, significant flow fluctuations have correlated to changes in height of feed for other polymer systems. It was determined experimentally that the feed normally had a two-foot head when the automatic loader was used, but the head changed as much as a six-inches during peak cycling.

In order to deal with this potential problem, a system for constant head control was desired. An interesting parallel was found in the process of reloading ammunition. In the reloading of spent shells (shotgun or rifle) a non-uniformity of the gun powder charge existed because of changes in the powder height of the filling apparatus. The solution was found by placement of baffles in the powder-feed system. These baffles were designed such that the charge to each shell is independent of the powder height. This principle was adapted to the extruder. An acrylic duct was first prepared such that pellet flow into the extruder throat could be observed. From this study, a preferential path corresponding to the throat opening was observed to extend vertically through the hopper. Therefore, a dual set of flow baffles were designed for the duct, refer to Figures 9 and 10.

The first baffle presents a flow barrier, interrupting the vertical flow path, and forcing the pellets to the

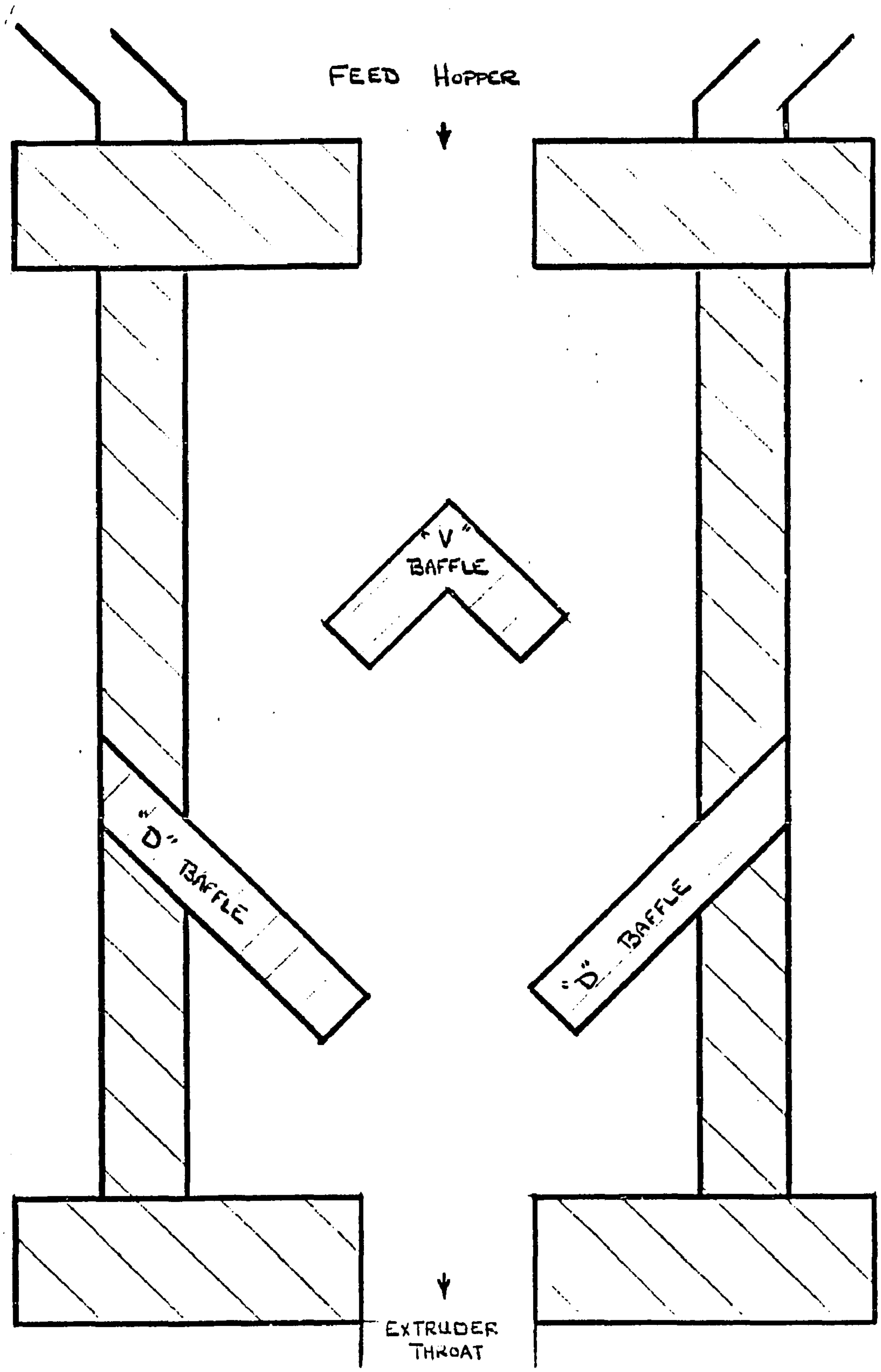


Figure 9.--Feed Baffle Schematic

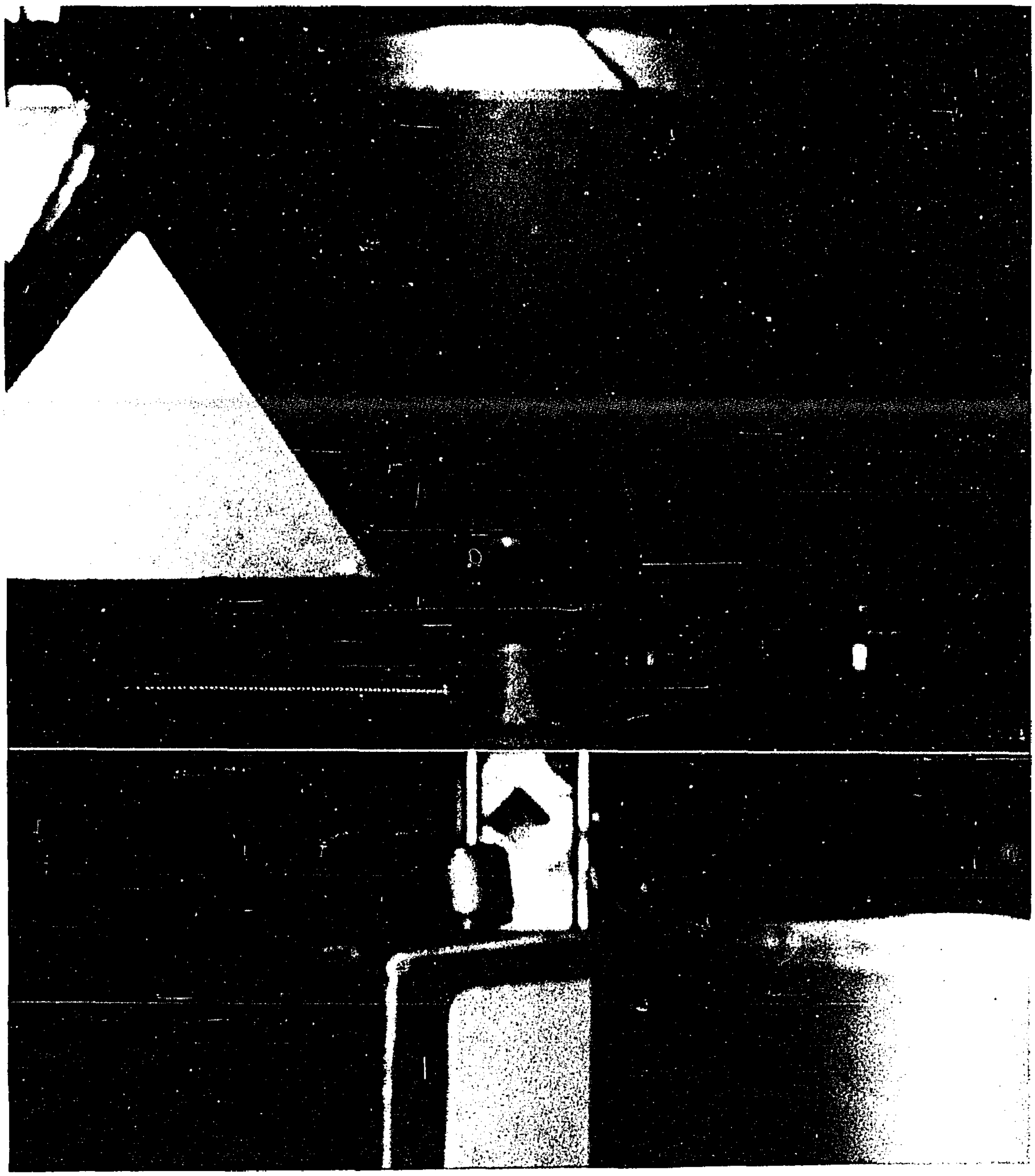


Figure 10.--Feed Baffle Photograph

walls of the duct. The second, lower-directional baffles redirect the pellet flow to the throat opening. These baffles were designed such that the total feed flow area of the system remains the same as when the baffles were not used.

The function of the baffles was to produce a constant head of approximately 12-inches above the extruder feed screw no matter what the height of feed material in the hopper. The vertical flow barrier of the first baffle also tends to interrupt any hydraulic effects associated with head changes experienced during automatic hopper filling.

As reported in the Literature Survey section on feed systems, major fluctuations in extrusion can be induced by packing force changes, feed rate changes, and feed head changes. An analysis of the baffle system using the force balance technique demonstrated the constant head developed by use of baffles in the feed system.

Figures 11 and 12 show the position of the flow path in the system with and without the feed baffles. Figure 13 gives an analysis of the forces acting on the vertical flow baffle. From this analysis, the resultant force, F_2, has been directed to the wall of the duct. The wall and directional baffles then redirect the flow stream through a 90° angle, toward the center of the feed stream. Figure 14 gives an analysis of the forces acting in this region and their resulting force, F_4. Figure 15 presents a final

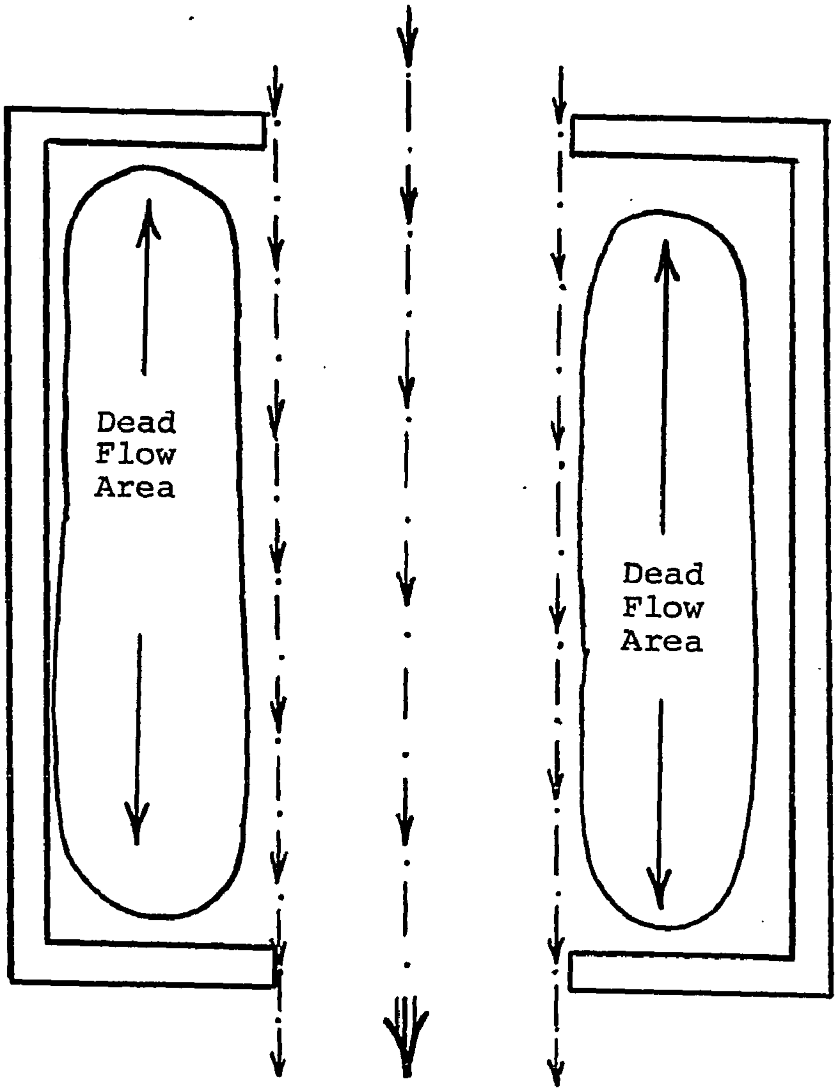


Figure 11.--Feed Flow Path for Conventional Gravity Fed System

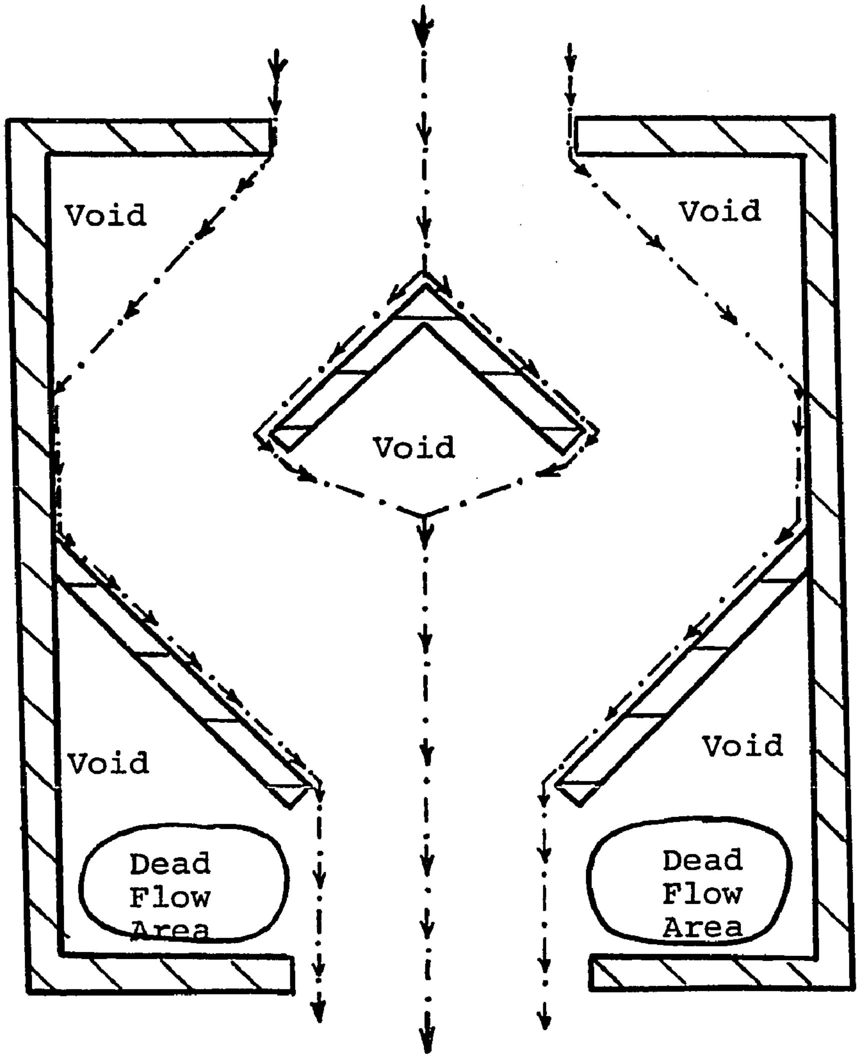
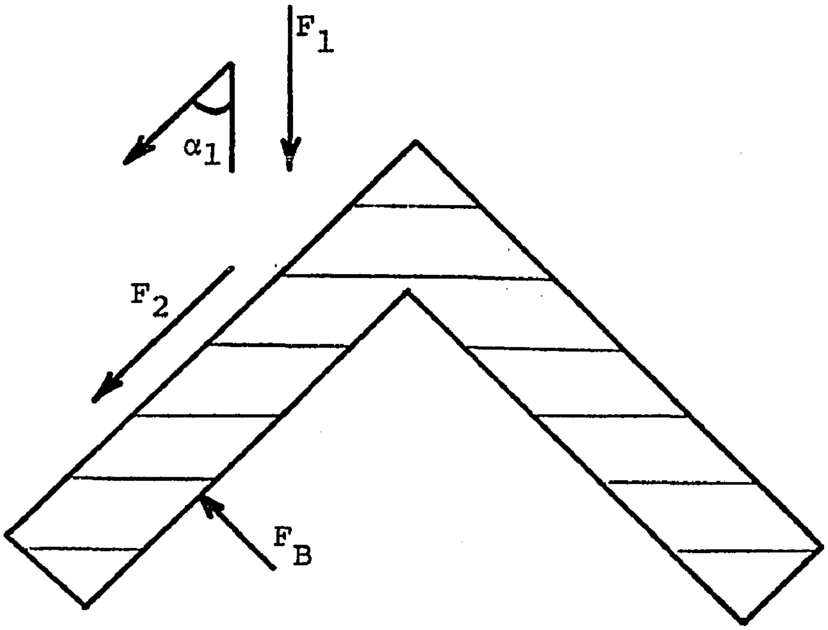


Figure 12.--Feed Flow Path for Feed Baffle System



$F_1 = F_{head-1} + F_{gravity}$

F_{head-1} = weight of feed over "V" baffle

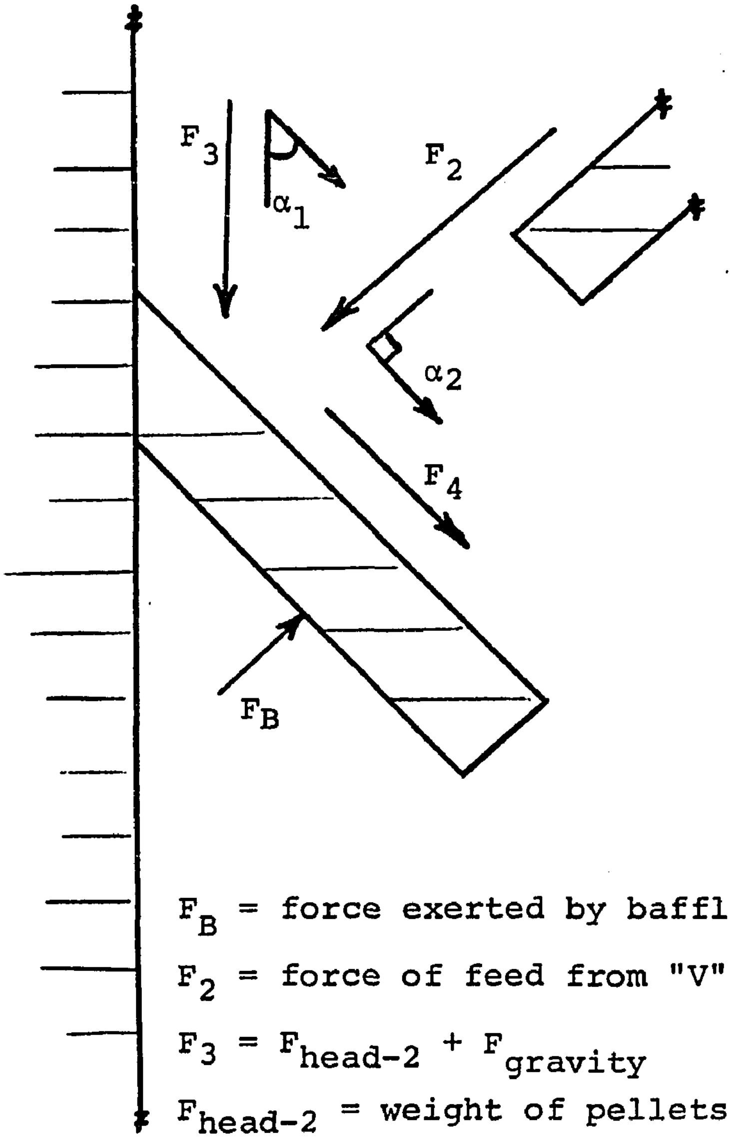
F_B = force exerted by baffle

F_2 = resultant force of feed

$= F_1 \cdot \cos \alpha_1$

$\alpha_1 = 45°$

Figure 13.--Flow ("V") Baffle Force Analysis



F_B = force exerted by baffle

F_2 = force of feed from "V" baffle

$F_3 = F_{head-2} + F_{gravity}$

F_{head-2} = weight of pellets over "D" baffle

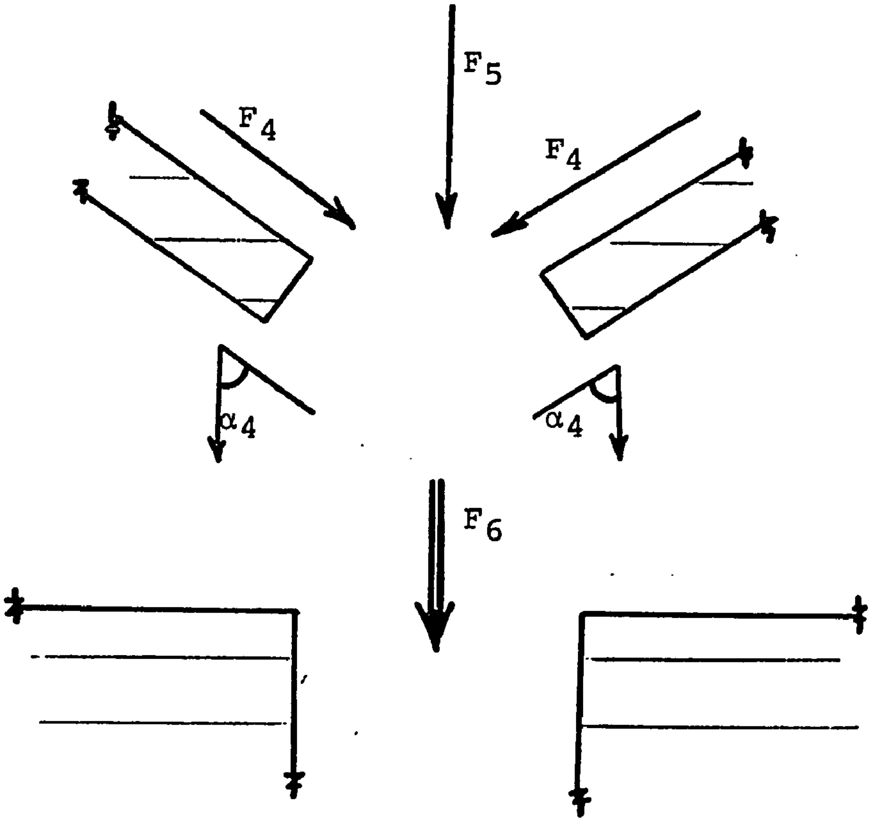
F_4 = resultant force of feed

$= F_2 \cdot \cos \alpha_2 + F_3 \cdot \cos \alpha_2$

$\alpha_2 = 90°$

$\alpha_3 = 45°$

Figure 14.--Directional ("D") Baffle Force Analysis



F_4 = resultant force from "D" baffle

$F_5 = F_{head-3} + F_{gravity}$

F_{head-3} = weight of feed over extruder throat

F_6 = resultant force over extruder throat

$= F_5 + 2 \cdot F_4 \cdot \cos \alpha_4$

Figure 15.--Extruder Throat Force Analysis for Feed Baffle System

analysis of the forces acting upon the system directly above the throat, with the resultant force, F_6, being the effective head on the system.

From this analysis, the effective head is found to remain constant as long as the duct is kept filled above the "V"-baffle. The design provided baffle overlap which prevents shortcutting and channeling. Typical particle flow paths are shown in Figure 12.

FEEDSCREW

In order to determine differences in feedscrew configuration for this system, a series of runs were made using three screw designs. These screws were manufactured by NRM Corp. The first screw tested was a single stage feedscrew, with a designed capacity of 2.2 pounds of feed per hour per revolution per minute. This screw had a flight depth of 0.375-inches in the feed section and 0.125-inches in the metering section.

The second feedscrew was a two-stage polystyrene screw with a design capacity of 2.5 pounds of feed per hour per revolution per minute. This screw had a flight depth of 0.36-inchees in the feed section and 0.134-inches in the metering section of the first stage, and 0.36-inches in the feed section and 0.183-inches in the metering section of the second stage.

The third feedscrew was also a two-stage screw with a design capacity of 1.7 pounds of feed per hour per revolution per minute. This screw had a flight depth of 0.37-inches in the feed section and 0.90-inches in the metering section of the first stage, and 0.25-inches in the feed section and 0.110-inches in the metering section of the second stage.

CHAPTER III

EXPERIMENTAL PROCEDURE AND COMPUTER PROGRAMMING

In operating an experimental system of the size and complexity of the extruder-sheet system, a rigid procedure for start-up, experimentation, and shut-down is required to insure reproducible data with minimal wasted effort and materials. This section discusses the three operational phases and computer programming necessary for acquisition of such data. Operating conditions for these studies are summarized in Table 2.

START-UP PROCEDURE

The start-up procedure actually begins the day before an experimentation run is to be made. All motor, controller, heater and computer lines and instrumentation are checked to insure proper functioning. The feed material is checked and operating conditions and scheduling are established.

Four hours prior to the scheduled operation, the heat-up procedure is started. Power is supplied to the four extruder heater zones and the five heater zones of the sheet die. The adapter and valve are wrapped with insulation to facilitate heat-up in this region. This insulation

TABLE 2

EXPERIMENTAL OPERATING CONDITIONS SUMMARY

Run No.	Screw No.	Nip Control	Auto-loader	Feed Baffle	Screw Rpm	Take-off Rate	Sheet Thickness (mils)
101	1	yes	yes	no	100	17.0	10
202	2	yes	yes	no	100	16.3	9
302	3	yes	yes	no	100	15.7	11
402	1	yes	yes	no	100	14.7	11
406	1	yes	no	yes	100	14.7	11
407	1	yes	no	no	100	14.7	11
504	1	yes	yes	yes	100	14.1	10

is removed once the system has attained operating temperature. The cooling water heater is turned on and circulation through the cooling rolls is begun using the appropriate circulation pump. A separate cooling water stream is started to the extruder throat to prevent premature feed melting.

The Beta Gauge, IR Pyrometer, and Linear Displacement Transducer electronics are turned on to allow for warm-up. The remaining equipment is turned-on to insure proper operation, then shut-down to await attainment of actual operating conditions. At this time, the tension control and data acquisition routines are loaded into the PDP-15, and the monitoring routine loaded and activated.

Two hours are usually required to bring the system up to operating temperatures. Once the system has attained these levels, the pressure transducers are installed, and the screw rotated one revolution by hand to insure that it is free to turn. Power is then supplied to the screw drive mechanism, the feed hopper is opened and the feed loader activated.

The screw is then operated at 10 rpm until the system is filled with polymer as evidenced by polymer issuing from the die slit. During this period and all subsequent screw speed changes, particular attention must be paid to the operating pressures. If the pressure increases rapidly, a flow blockage is probable, and the system should be shut-down until the situation can be corrected. As the polymer flows from the die, the take-up and tension control systems are activated and the screw speed increased to 30 rpm. At this speed, the polymer can be strung on the take-up framework, and wrapped on the wind-up roll.

The screw speed and take-off rate are slowly increased to the desired operating level. Approximately every 15 minutes the wind-up roll is filled, the roll is removed and a new wind-up roll placed on the take-up drive. The system is operated at the experimental conditions for at least one-hour prior to data acquisition in order to assure attainment of steady state.

EXPERIMENTATION

Three separate experimentation procedures were required during this study, corresponding to the three phrases previously mentioned. These procedures will be individually discussed below.

The tension control experimentation was designed to determine if implementation of a computer-control tension system was possible. The system was first set up for manual override of the control routine to allow operator interaction with the take-up. After the system was judged to be mechanically operative, the computer control package was added. The purpose of the experimentation was to determine the set of control variables which would produce the best quality sheet. The results of this study are presented in the Discussion section. It was found that by allowing a slight leak to flow from the outboard edge of the deckels the sheet and edge uniformity were increased. This change significantly improved the operation of the nip tension controller.

After the system was developed, a series of runs were made using the data from the screw and feed hopper study to determine the effectiveness of the tension-controller. For these runs the system was operated both with and without the nip system. The results of this study are discussed in the Results section.

During the feedscrew experimentation, the extruder was run at 100 rpm and two, twenty minute data acquisition runs were made using automatic dectape storage of the raw data. The programs used in these studies are discussed in detail in the Computer Programing section. After the second data run, the screw speed was changed to 80 rpm a one-hour transition period observed, and a second set of data acquisition runs were made at the new steady state conditions.

This procedure was repeated with each of the three screw designs discussed in the Equipment section. The data collected represented head and valve pressures, valve and sheet temperatures, dancer position and the sheet thickness. From these data, comparisons were made to determine which feedscrew design presented the best configuration for the feed-head study.

The feed-head experimentation was designed to study the effect of the feed baffle system discussed in the Equipment section. The extruder was operated at 100 rpm and four runs were made with the automatic feed loader operating. The first two runs used the standard feed system with the acrylic duct but without baffles. The second set of two runs used the baffle system.

The feed loader was then removed and the level of the hopper was controlled by manual addition of feed to the hopper. A second series of four runs was then made (two without baffles and two with baffles) in which a step change in feed hopper level was initiated two minutes after the start of the twenty minute data acquisition run. These level changes were made by maintaining the feed level at the base of the feed hopper, then adding three fifty pound bags of feed at the two minute mark of each run. This procedure required two operators, the first to maintain the feed level, and the second to handle data acquisition and system requirements.

A series of runs using flake feed was also planned but feed and sheet quality problems which are to be discussed later resulted in cancellation of this study.

SHUT-DOWN PROCEDURE

After termination of the experimentation, the screw speed is gradually reduced and the feed hopper closed. The system is allowed to pump itself empty at 10 rpm. Power is shut-off all equipment except the heater zones. This is to allow time to remove the pressure transducers, before the polymer can cool, contract and possibly damage the diaphrams. At this point the entire system is shut-down, and general clean-up of the area begun.

COMPUTER PROGRAMS

This study required the use of several computer routines to facilitate the acquisition and subsequent analysis of the experimental data. These program will be discussed individually below. A listing of the programs discussed in this section can be found in Appendix B.

XNIP-NIP ROLL-TENSION CONTROL

Because it was necessary to accurately control the sheet tension, a nip roll and floating dancer system were developed. As the tension in the sheet changes the dancer which is supported on the polymer sheet moves vertically between two fixed idler rolls. The position of the dancer is determined by the voltage from a Linear Displacement Transducer whose output is monitored by the PDP-15 computer system. The computer program, XNIP, was developed to relate this position to an experimental dead band for the sensor.

If the signal is outside the dead band, the system determines if the dancer is moving toward or away from the dead band area. If the dancer is moving toward the dead band, no control action is taken. If the dancer is moving away from the dead band or is stationary outside the dead band, the control package triggers an output signal to the speed control system. This system consists of a potentiometer which supplies the power to a variable speed motor which derives the nip roll used to change the take-off rate. In essence, the tension of the sheet is controlled by the linear take-off rate set by the nip roll controller. Thus, if a speed change is needed, the output signal activates a speed increase or decrease through a potentiometer change.

The range of the dead band and sampling frequency were determined experimentally and will be discussed in the Discussion of Results section. The routine operates for a 30 second period, then requests the execution of the system monitoring routine, XMONT. This program (which will be discussed next) is activated, performs its task, then requests the resumption of XNIP.

XMONT-SYSTEM MONITOR ROUTINE

In order to keep the operator informed as to operating conditions during start-up and experimentation runs, the systems monitoring routine, XMONT was developed. This routine monitors various system variables such as zone temperatures and system pressures, and outputs the readings to the videoscope. The program requires approximately 0.2 seconds execution time. Execution of the routine is requested within the tension control routine, XNIP, which is then requested after completion of execution.

XTRUD-DATA ACQUISITION ROUTINE

In order to obtain fast data with minimal computer tie-up the data acquisition routine, XTRUD, was developed to allow automatic data buffer filling and intermittent data output to a Dectape^R unit. The data is stored in integer form at a supposed rate of 10 points per second. However, it was discovered that because of a change in the computer's fast clock which schedules buffer filling the acquisition rate was only 9 points per second. Although this presents no problems with data acquisition, it can present a problem in subsequent frequency analysis routines.

The data channels collected by XTRUD include the head and valve pressures, the valve and molten sheet temperatures, the dancer's position, and the sheet thickness. At the collection frequency of this study, the magnetic tape storage unit can handle up to 30 minutes of data acquisition. Data acquisition and termination are singalled by a remote switch located near the extruder console. At termination, the computer prints the number of storage buffers output to the tape.

XPLOT-DATA ANALYSIS--PLOT ROUTINE

In order to get the data into usable form, a data analysis- plot routine, XPLOT, was developed. This routine reduces the raw integer data to 10 sample point averages for each channel collected, and stores these values in a direct access disk storage file. The routine also computes the maximum, minimum and average for each channel, as well as the standard deviation and variance. The program then allows creation of a new Dectape^{R} file for the reduced data and plotting of the data at various block-averaging frequencies.

BTA14-FREQUENCY ANALYSIS ROUTINE

In order to determine the frequency components of the raw data, a fast fourier and power spectral density function (PSDF) analysis were performed using the BTA14 task prepared by Bartram (1). This routine uses a modified power-of-two Cooley-Tukey algorithm, fast fourier analysis which is discussed in detail by Bartram (1).

CHAPTER IV

DATA INTERPRETATION AND DISCUSSION OF RESULTS

The complexity of the extruder system and its related processing equipment makes the analysis of extrusion data quite difficult. In attempting to determine the cause or causes of process fluctuations, every attempt must be made to isolate the extruder from external factors, such as take-up and feed disturbances. For this reason, this study has attempted to eliminate both pre- and post-extrusion variables from the analysis of extruder-induced fluctuation. The study has also been designed to insure operation at shear stress levels below the melt fracture critical point, and with an optimum screw configuration to reduce screw design considerations. The analysis portion of this study is presented in the sections which follow.

EXTRUDER- VS DIE-INDUCED INSTABILITY

The existence of process fluctuations was demonstrated in the previous work of this author (6); however, the interaction of external disturbances was suspected. In this study, a new die system was used to eliminate such processing problems as necking and vapor condensation on the cooling rolls. This new system was analyzed to determine the shear level experienced by the molten polymer.

As was previously discussed, die-induced instability has only been reported at shear stress levels above 10^5 N/m^2. Since the purpose of this study was to investigate extruder-induced instability, operation at shear stress levels below this limit was required. Using the data supplied by Dow Chemical Company for impact-modified polystyrene pellets and data developed by Reber (24) relating shear rate to shear stress, the shear stress was calculated. Details of these calculations are presented in Appendix A.

From this analysis, the shear stress at 100 rpm was found to be 6.7×10^4 N/m^2, while at 80 rpm, the shear stress was found to be 5.4×10^4 N/m^2. Thus, the shear stress level was below the melt fracture limit. If external disturbances can be eliminated, this would indicate that any process fluctuations are related to extruder-induced instability.

COMPUTER-CONTROLLED TAKE-UP SYSTEM

In the equipment section, the possibility of thickness fluctuations due to torque changes from the old take-up system was discussed. The design of the computer controlled nip system was also presented. Initially the mechanical components of the system were manually controlled to demonstrate that the system was operative.

From this testing, it was found that speed matching of the cooling roll take-off speed and the nip roll take-off speed were quite sensitive to system fluctuations. Thus, if the system was not monitored closely, a high nip speed resulted in a loading of the cooling rolls, and a slow nip speed resulted in sheet irregularities.

As long as the dancer freely floats upon the sheet, the tension of the sheet will remain essentially constant. This tension is related to the weight of the dancer and the lever arm through which this weight acts. If the dancer moves vertically up or down, the tension will change only slightly due to the difference in weight of the sheet strung between the fixed idlers. Since the position is to be kept within a certain dead band range, these tension changes are within the desired limits. If a new tension level is desired to give a different sheet thickness, the dancer support arms can be loaded with fixed weights. As long as the weights remain in position, the controller will maintain the new tension setting.

In developing the control package, two control characteristics had to be established. These were the system dead band and the sampling frequency. Since the linear displacement transducer (LDT) uses a six-inch induction coil, the total operating range of the dancer was set at two and one-half inches on either side of the LDT zero point. This setting insured accurate LDT readings over the entire dancer range. Around the set point or zero point, a dead band was desired such that operation in this region would not activate the speed controller.

It should be emphasized that the controller has been designed to maintain the set tension by means of take-up rate adjustments. If process fluctuations occur, the sheet thickness will change, thus changing the linear footage of sheet produced. This change is sensed by the dancer which signals the nip system to adjust the take-off rate accordingly and maintain the dancer within the desired operating range.

Since the setting for the dead band and sampling frequency are related to the effectiveness of control, several ranges of both variables were investigated. The goal of this study was to find the system which adequately controlled the dancer position without "over-controlling" the system. Although sophisticated control routines and stability analysis programs could have been incorporated, it was decided to test several control systems and base the final strategy upon the simplest control system which produced acceptable results.

The final control package used a dead band equivalent to 20 percent of the overall dancer operating range and a sampling frequency of 5 cycles per second. The system only activates a speed change if the dancer is moving away from the dead band or is stationary outside the dead band.

Once the system begins to respond to a speed change, no further control is initiated until the dancer position again is found to violate the previously mentioned constraints.

This system was found to be quite effective in maintaining the stability of the take-off system. Another particularly strong point was its effectiveness in maintaining smooth transition during start-up, shut-down or system alteration such as changes in the flow rate or take-off rate. These non-steady state transitions have in the past been quite troublesome, but presented no problems with the computer-controlled system. One precaution is necessary, the control package has been found to have the ability to maintain the dancer in an almost stationary position, but the control is only as good as the input signal from the LDT. Thus, system sensitivity is controlled more by the LDT signal and system noise limitations rather than control package limitations.

In order to evaluate the overall performance of the control system and verify that the control package does isolate the extruder from post-extrusion operations, a series of runs were made with and without the controller. Analysis of these data revealed that the controller eliminated the low frequency cycling associated with torque changes of the original system. A comparison of the thickness data indicated that the dancer does not introduce higher frequency fluctuation due to the speed changes of the nip system. From this analysis, the system was found to successfully isolate the extruder from post extrusion disturbances as desired.

FEEDSCREW CONFIGURATION

Much work has been done to attain the maximum quality throughput by optimum screw design. The purpose of this phase of the study was to determine which of the three available screws would give the best processing stability at the required operating conditions. This was done to reduce the effect of screw design on processing instability, and to further isolate extruder-induced fluctuations.

The first screw was a general purpose, single-stage feedscrew, while the latter two systems were two-stage feedscrews designed specifically for polystyrene feedstock. In this discussion, the single-stage feedscrew is referred to as Screw 1, and the experimental runs are labeled as RN100's. For example, Figure 16 presents head pressure data from experimental run RN101, that is Screw 1 and Run Number 01. The high throughput two-stage screw is referred to as Screw 2 and the experimental runs labeled RN200's. The low throughput two-stage screw is referred to as Screw 3 and the experimental runs labeled RN300's. Experimental runs were made at 80 and 100 revolutions per minute (rpm) for each of the screws. The experimental data were analyzed to determine the minimum, maximum, mean, standard deviation, and variance for each data set. Several block averaging techniques were then used to plot the data for comparison.

Since the rated capacity, experimental throughput, and operating pressure for each of the screws were different, a method to standardize the data analysis was desired. The basis for this study was to determine the magnitude of the processing instability. Therefore, each system parameter was analyzed using the percentage of fluctuation as given by the ratio of the standard deviation to the mean ($\sigma/\overline{x}$) for the data series of interest.

During the experimentation, the polymer throughput for each of the systems was found to be only 80 percent of the designed capacity. This was believed to be because of high heat generation in the extruder feed zone which would reduce the frictional coefficient between the barrel and pellets. The reduced force would lower the feed rate and therefore the output. Attempts to lower the first zone temperature by the use of the manual cooling fans were found to have little effect on the throughput. Since the flow reduction was found to be nearly equivalent for all screws, the systems were operated without the use of the cooling fans.

Comparison of the head pressure data revealed that the two-stage feedscrews had significantly less pressure fluctuation than the single-stage screw, refer to Table 3. The single-stage pressure fluctuations were greater than 0.4 percent, while the two-stage screws had fluctuations of 0.3 percent or less. This was expected because of the hydraulic-interruptive effect of the second stage feed section. For a single-stage screw, feed and transition region fluctuations are usually amplified in the compression or metering section and transmitted through the extruder. For a two-stage model, the fluctuations that develop during the melting process in the first stage are not transmitted to the second stage.

After reviewing the reduction of head pressure fluctuations associated with the two-stage models, similar reductions in the thickness fluctuations were expected. However, analysis of the Beta Gauge-thickness data indicated that the single-stage feedscrew was the most stable system, refer to Table 4. The single-stage system produced thickness fluctuations of 6.9 percent. While the two-stage systems produced fluctuations of more than 13 percent at 100 rpm. At 80 rpm the differencesin the comparative thickness fluctuations were reduced, but the single-stage system was still the most stable.

In order to understand this apparent discrepancy, analysis of the Infrared Pyrometer-melt temperature data was required. These data indicated that the melt temperature fluctuations were significantly less for the

TABLE 3

SCREW CONFIGURATION--HEAD PRESSURE SUMMARY

Rpm		100		80	
Screw No.	Run No.	Head Pressure (psi)	$\left(\frac{\sigma}{\bar{x}}\right)^{*} \times 10^{2}$	Head Pressure (psi)	$\left(\frac{\sigma}{x}\right)^{*} \times 10^{2}$
1	RN101	1850	0.42	1710	0.39
2	RN202	2400	0.30	2260	0.35
3	RN302	1575	0.23	1530	0.19

*Standard deviation/mean.

TABLE 4

SCREW CONFIGURATION--BETA GAUGE THICKNESS SUMMARY

Rpm		100		80	
Screw No.	Run No.	Thickness (mils)	$\left(\frac{\sigma}{\bar{x}}\right)^{*} \times 10^{2}$	Thickness (mils)	$\left(\frac{\sigma}{\bar{x}}\right)^{*} \times 10^{2}$
1	RN101	10	6.9	9	7.8
2	RN202	9	13.0	8	8.0
3	RN302	11	15.2	9	8.8

*Standard deviation/mean.

single-stage feedscrew. At 100 rpm, the temperature fluctuations for Screw 1 were 0.22 percent, while the fluctuations for Screw 2 and Screw 3 were 0.31 and 0.47 percent, respectively. Referring to the studies of Maddock (15,16), the effects of poor mixing are usually seen as melt temperature fluctuations and corresponding flow rate fluctuations.

The single-stage screw proved to be a better mixing system than the two-stage screws tested. The better mixing produced a more uniform flow and an apparent dampening effect on the head pressure fluctuations for the single-stage screw. This dampening was also evident in comparison to the valve pressure data, refer to Table 5. The fluctuations in the valve pressure versus the head pressure were reduced by a factor of 2.7 for the single-stage model, but were reduced by a factor of only 1.6 and 1.3 for the two-stage models. Thus, the better mixing, single-stage feedscrew produced a more stable system even in the presence of higher head pressure fluctuations. Plots of the head pressure and thickness data at 100 rpm for the three feedscrews are presented in Figures 16 through 21.

The purpose of this phase of the study was to determine the optimum feedscrew configuration. Therefore a decision had to be made regarding head pressure versus poor mixing effects on extruder performance as indicated by the sheet thickness. The single-stage feedscrew was

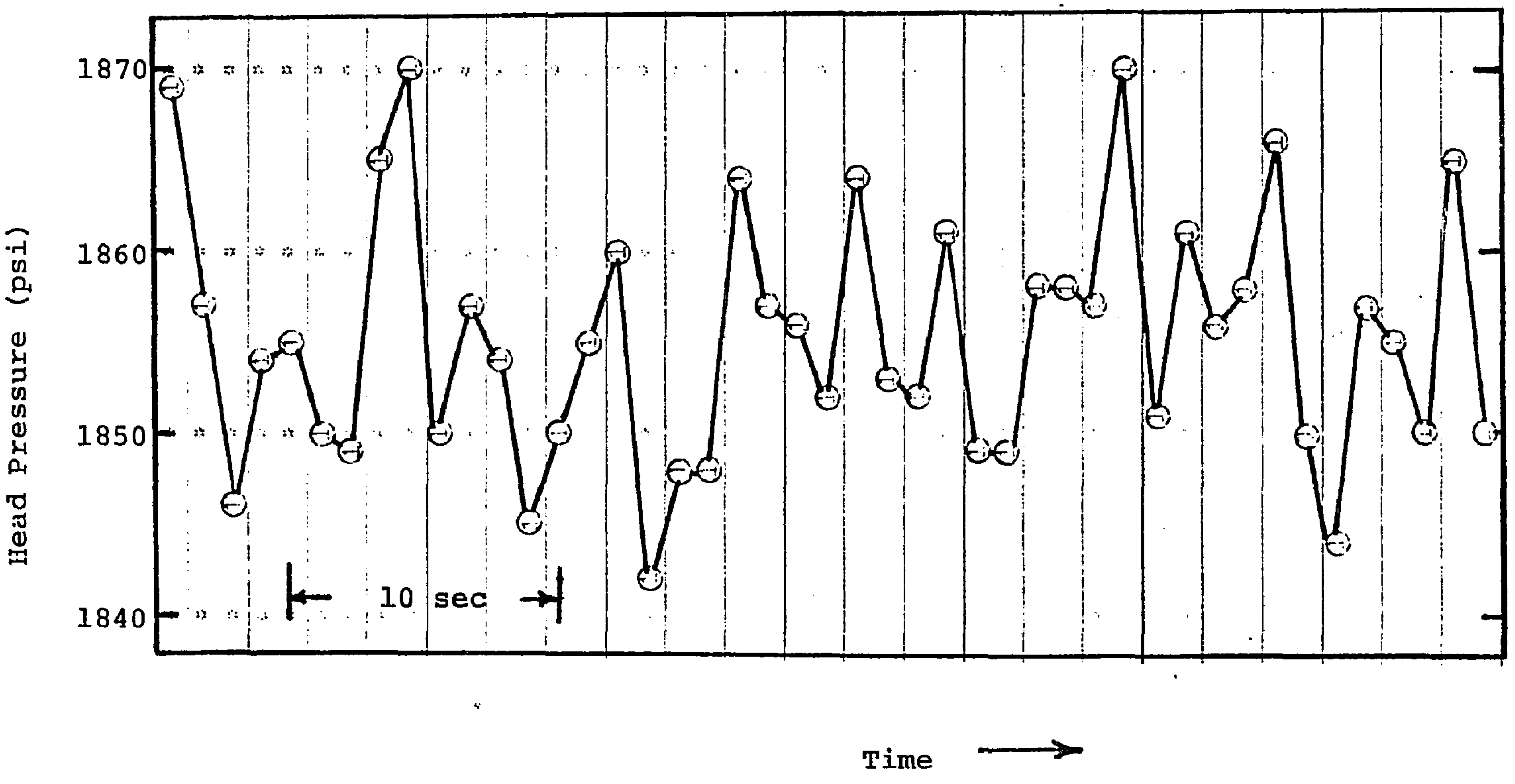


Figure 16.--RN101 Head Pressure Data

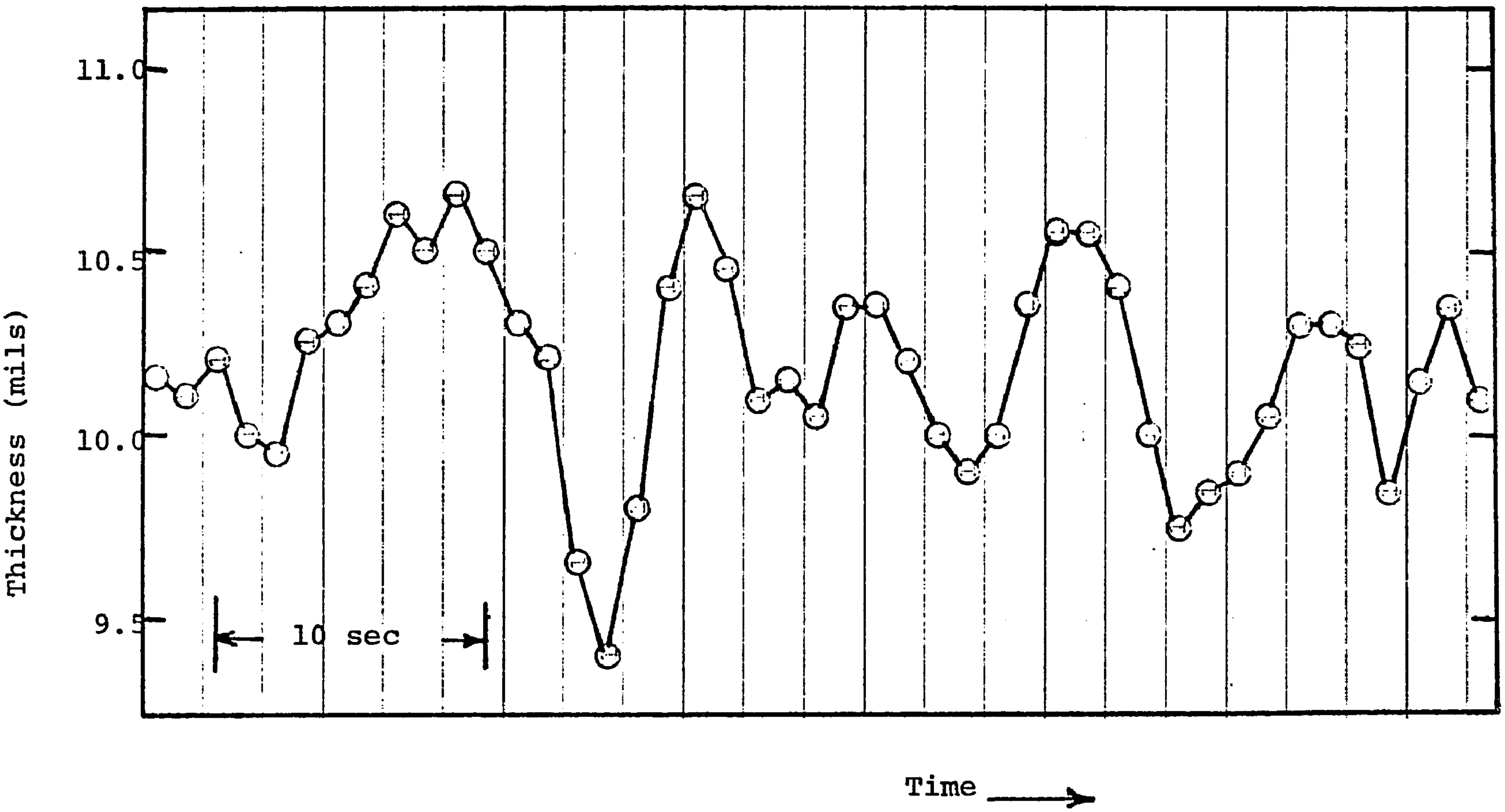


Figure 17.--RN101 Beta Gauge Thickness Data

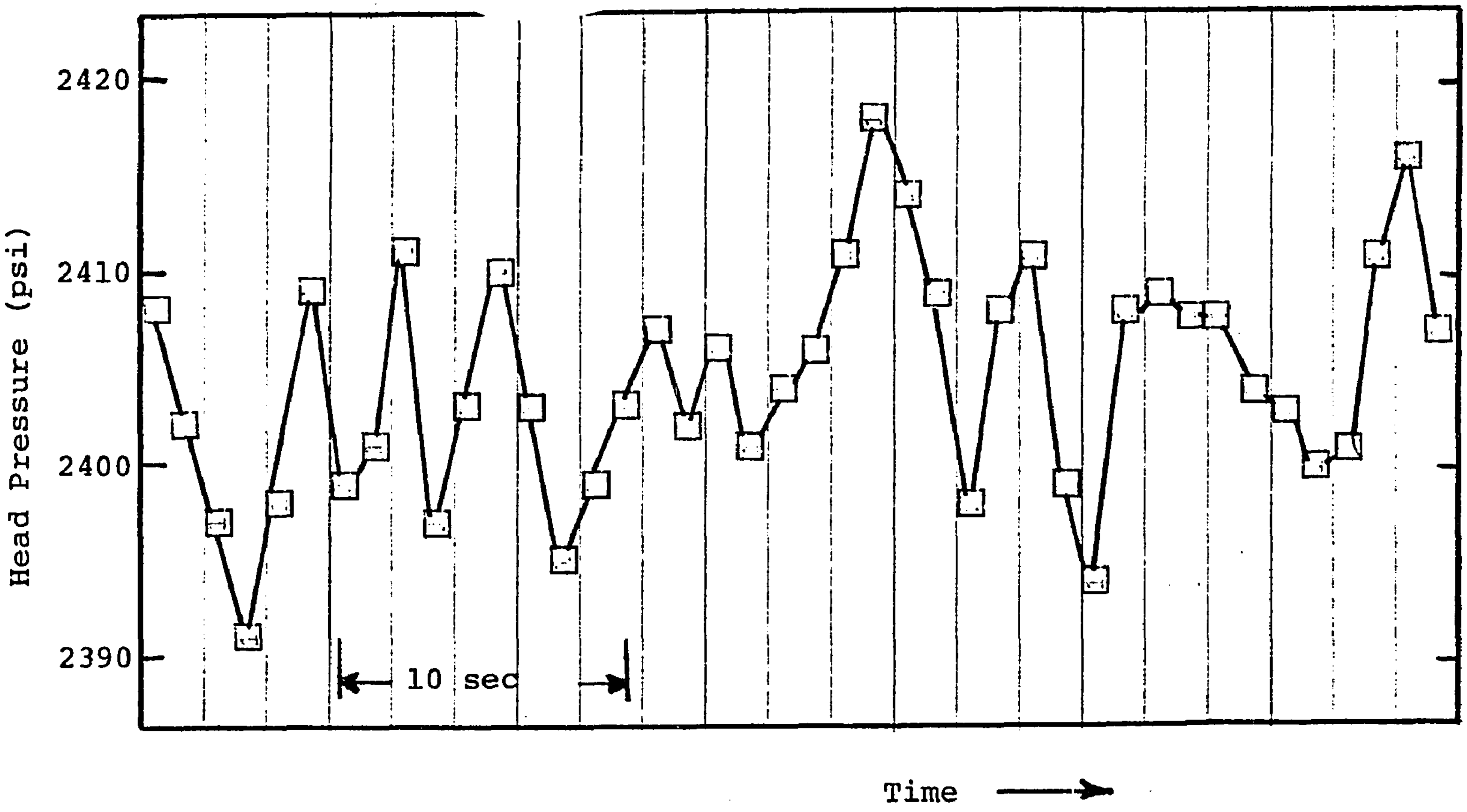


Figure 18.--RN202 Head Pressure Data

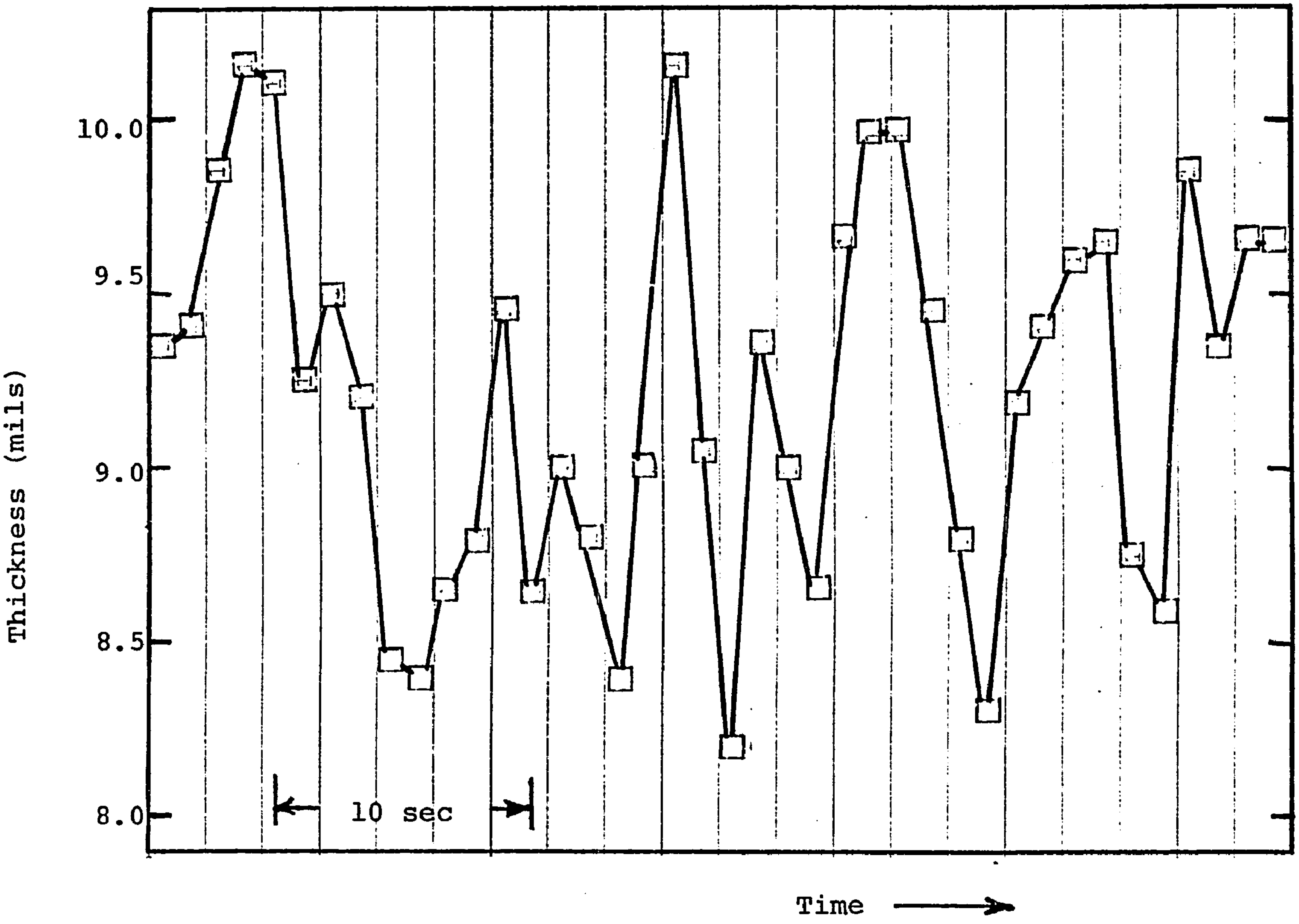


Figure 19.--RN202 Beta Gauge Thickness Data

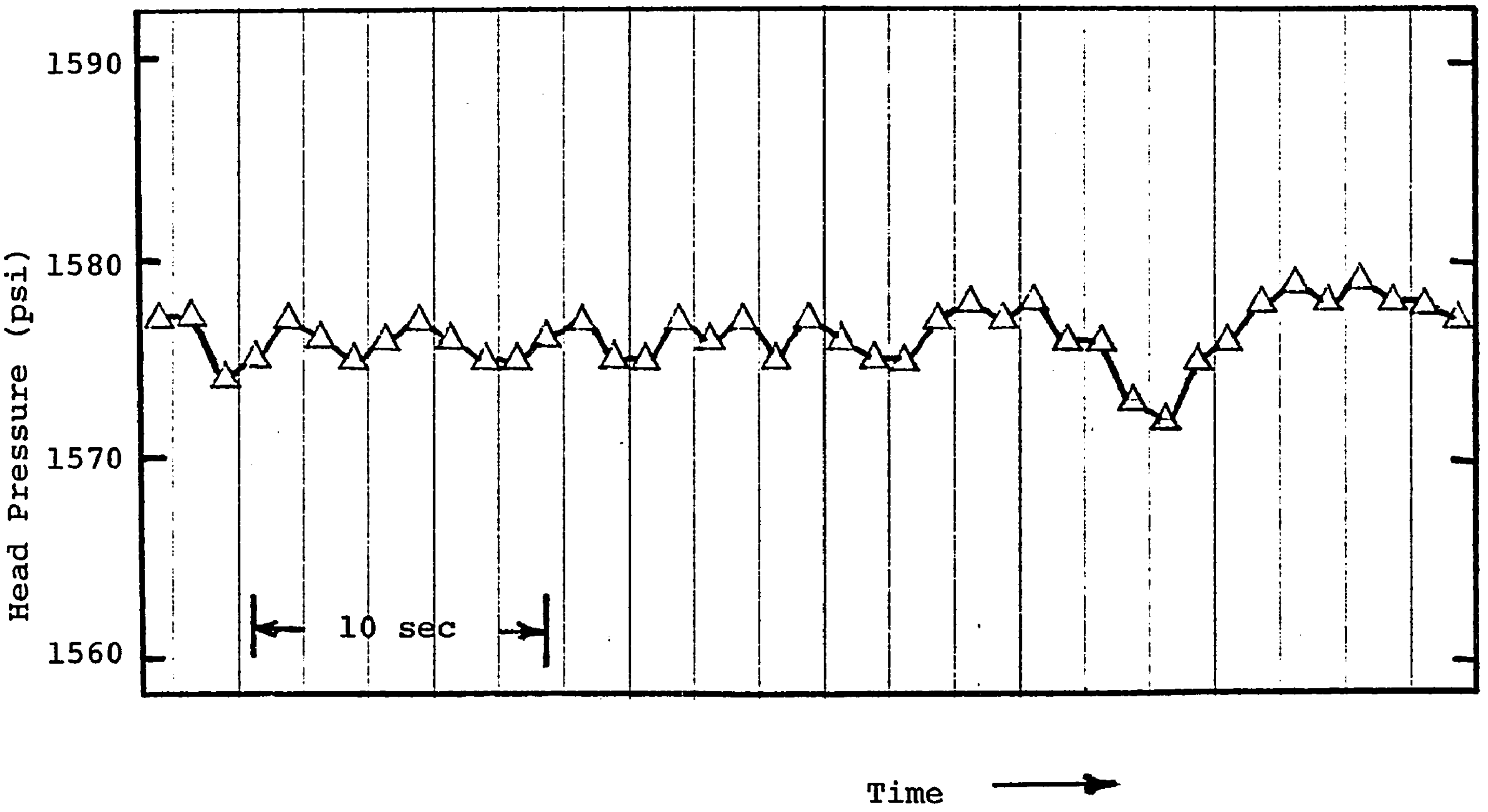


Figure 20.--RN302 Head Pressure Data

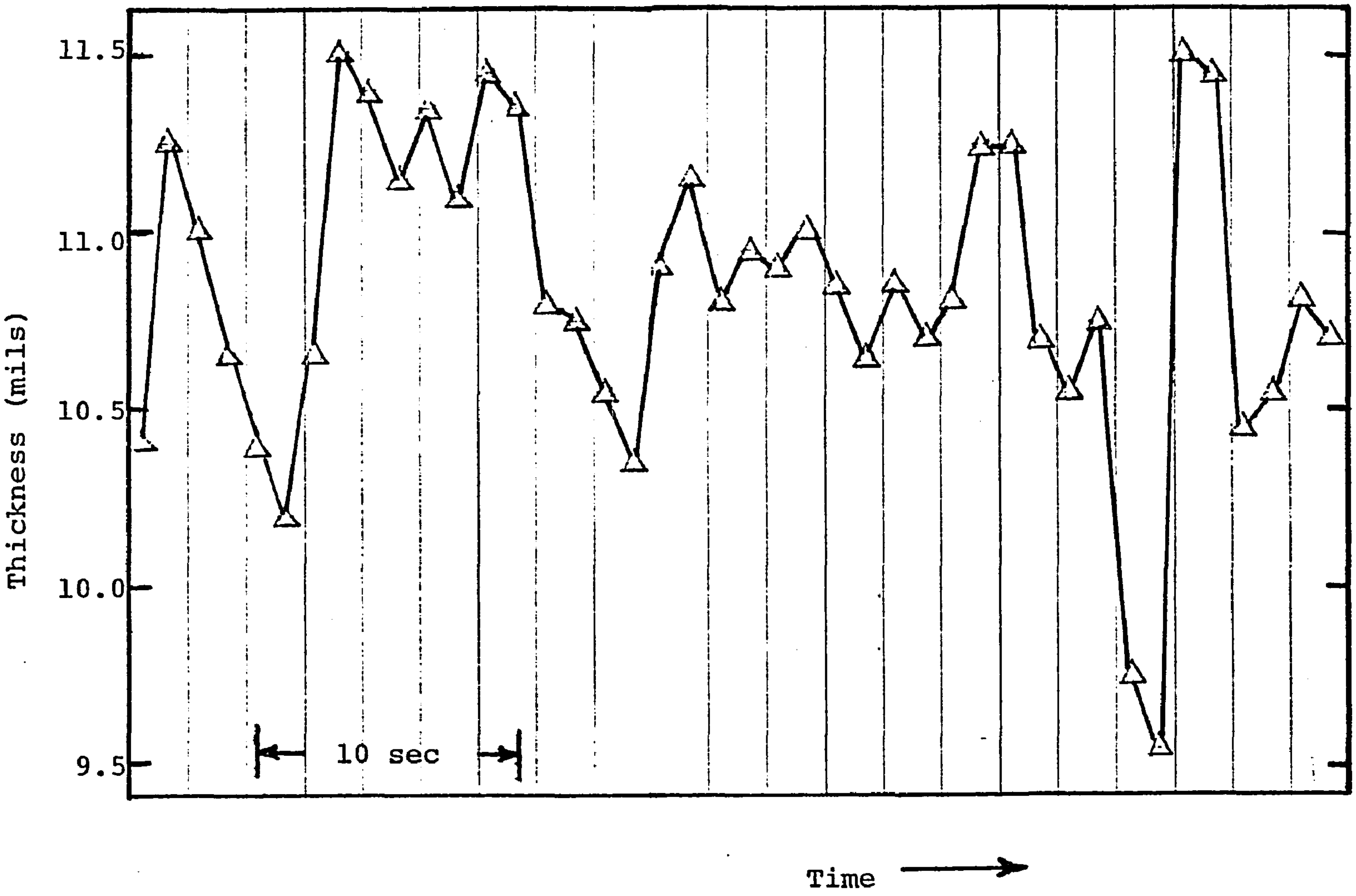


Figure 21.--RN302 Beta Gauge Thickness Data

selected for continued study for the following reasons.

1. Poor mixing tends to mask other system instability, therefore the single-screw model most effectively isolated the extruder system.
2. The single-stage model had higher head pressure fluctuations which are usually associated with feed related fluctuations. Since a feed system study was to be conducted, the higher feed sensitivity would be beneficial in feed related analysis.

TABLE 5

SCREW CONFIGURATION--MELT TEMPERATURE AND VALVE PRESSURE DATA AT 100 RPM

Screw No.	Run No.	Infrared Pyrometer Melt Temperature (°C)	Infrared Pyrometer Melt Temperature $(\sigma/\bar{x})^* \times 10^2$	Valve Pressure (psi)	Valve Pressure $(\sigma/\bar{x})^* \times 10^2$
1	RN101	232	0.22	1060	0.16
2	RN202	225	0.47	1420	0.18
3	RN303	230	0.31	1060	0.20

*Standard deviation/mean.

FEED BAFFLE SYSTEM

In order to eliminate potential feed related fluctuations originating in the feed hopper, a feed baffle sysetm was developed. The design is presented in Chapter 2, while the experimentation is outlined in Chapter 3. Analysis of the experimental data to determine the effect of the feed baffle system paralleled the screw configuration analysis. During subsequent reference to the feed baffle system, its use will be termed "baffled" operation, while the conventional gravity fed system will be termed "unbaffled" operation.

Experimental runs were conducted using the automatic feed loader. This system is designed to maintain a nearly constant feed height in the feed hopper. During preliminary experimentation the pellet height was found to vary as much as six-inches, 20 percent of the fill height, between cycles. A preferential flow channel extending above the extruder throat was also observed. Because of these potential packing fluctuations, a means of eliminating or at least reducing the effects was desired.

Data analysis of the unbaffled system indicated sheet thickness fluctuations of 7.6 percent, refer to Table 6. The effect of the feed baffle system was significant. The thickness fluctuations for the baffled system were 4.6 percent, which represented a 40 percent reduction in the fluctuations at the 100 rpm operating conditions. Plots of the thickness data for the unbaffled and baffled systems are presented in Figures 22 and 23, respectively. Figures 11 and 12 present the pellet flow paths for the systems. For the baffled system the effect of the vertical flow barrier and the overlap design of the directional baffles are evident. The entire flow channel for the conventional feed

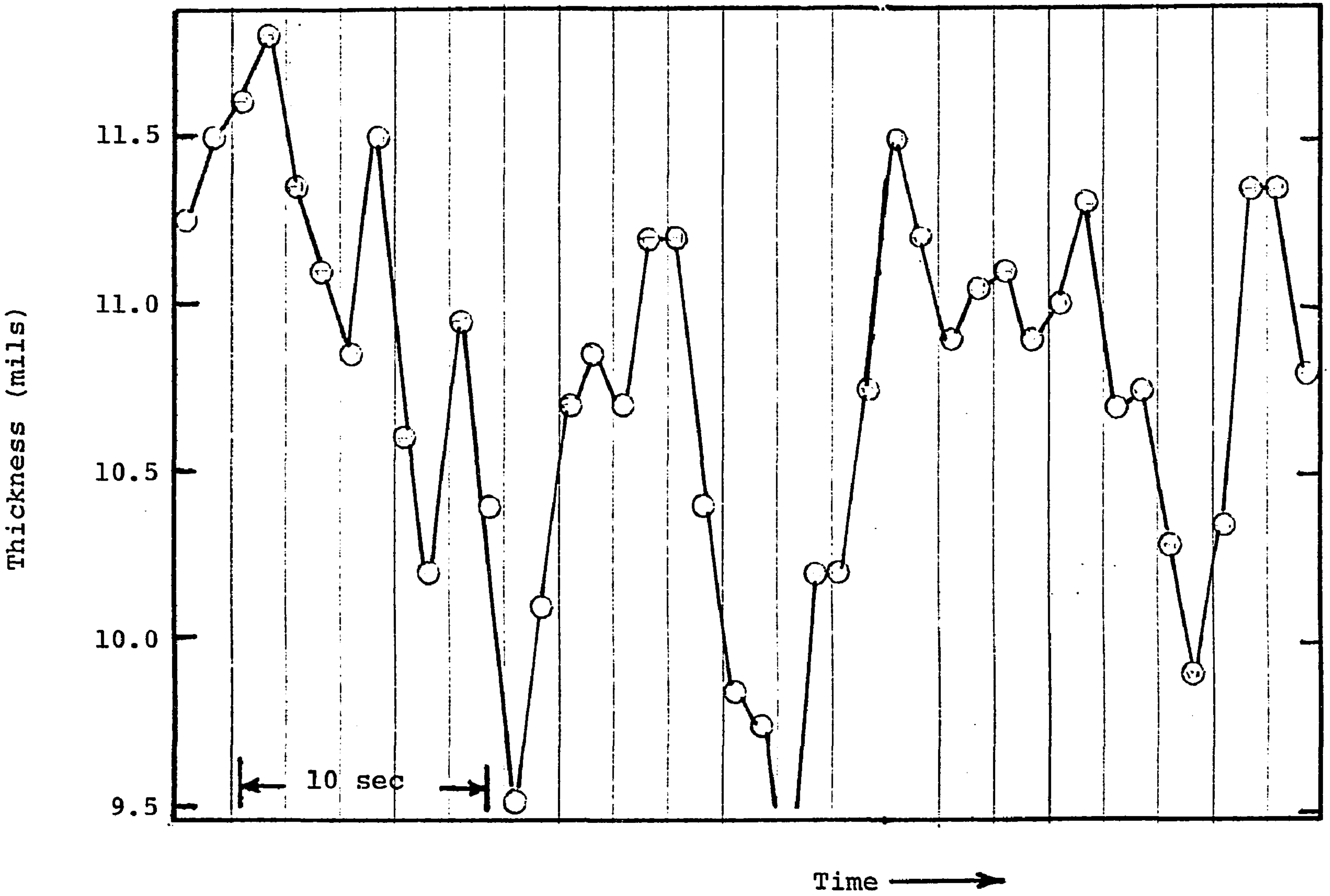


Figure 22.--RN402 Beta Gauge Thickness Data--Unbaffled System

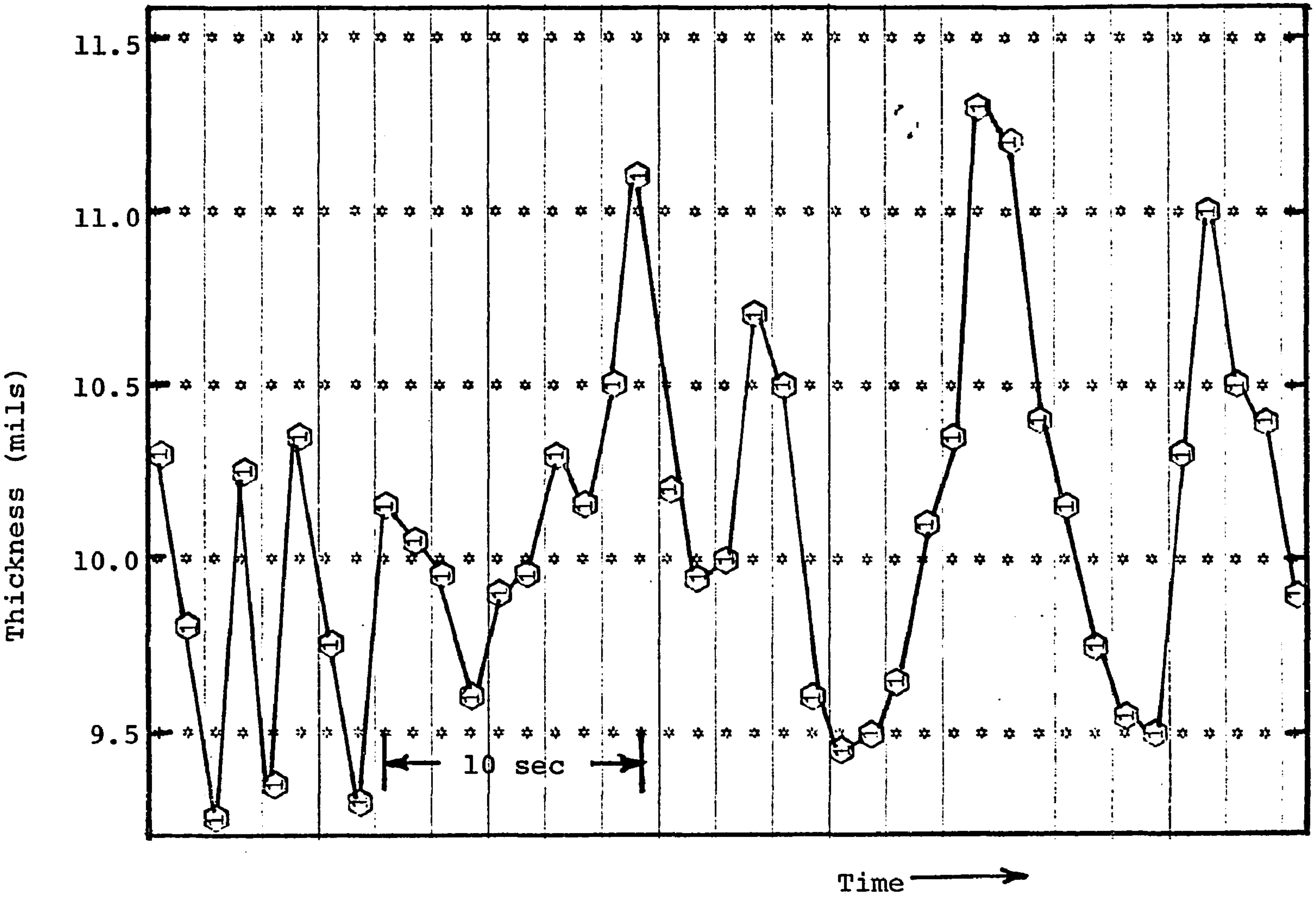


Figure 23.--RN504 Beta Gauge Thickness Data--Baffled System

system has been redirected through the baffle system as designed, and without reducing the production rate of the system.

TABLE 6

FEED BAFFLE STUDY BETA GAUGE THICKNESS SUMMARY

Run No.**	Auto Loader	Feed Baffle	Thickness	
			mils	$(\sigma/\bar{x})^{*} \times 10^2$
407	no	no	11	7.8
406	no	yes	11	5.9
402	yes	no	11	7.6
504	yes	yes	11	4.6

*Standard deviation/mean.

**Refer to Table 2 for experimental conditions.

In order to study the feed related fluctuations more easily, the auto loader was removed, and the feed height was manually controlled. This required the constant addition of feed, but permitted operation with a precisely controlled feed head. During the experimentation, the feed height was initially maintained twelve-inches above the extruder throat. At the two minute mark of the twenty minute data acquisition run, the feed height was increased to thirty-inches above the throat. This level was maintained for the duration of the experimental run. The step change increase in the feed height was used because of the ease of implementation and to evaluate the response of the system to the increase in the packing forces.

For the unbaffled system, the occurrence of the step change was directly evident in the data, refer to Figures 24 and 25. Increases in the head pressure and flow rate, as indicated by the sheet thickness fluctuations, were observed. After the onset of the step change, the head pressure and sheet thickness responses were slowly dampened in a cyclic manner. Approximately thirty minutes after the step change the parameters had returned to the steady state values that had been observed prior to the change. The response of these parameters substantiate the proposal by Wheeler (34) on low frequency fluctuations caused by external systems. The cyclic response to the feed height change also indicated the potential problem of process instability due to the cycling of the automatic feed loader.

Using the feed baffles, the step change fluctuations were significantly reduced, refer to Table 6 and to Figures 26 and 27. The sheet thickness fluctuations were reduced from 7.8 percent for the unbaffled system to 5.9 percent, a reduction of 25 percent. The effective reduction of the fluctuations for the baffle system was 65 percent when compared to the data obtained from the auto loader study. This indicated that the feed baffles do not totally eliminate the effects of head changes, but the improved operating stability was apparent.

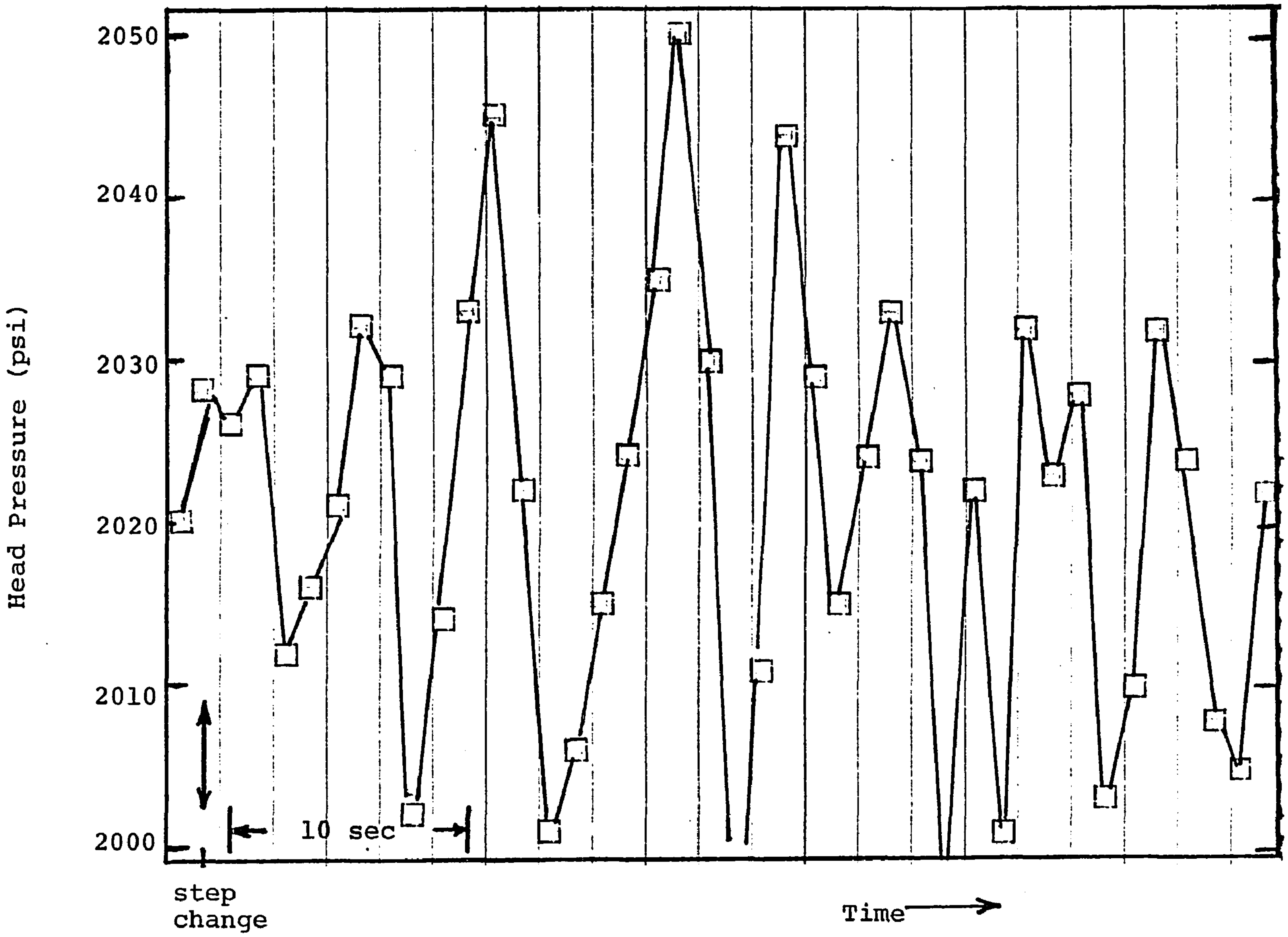


Figure 24.--RN407 Head Pressure Data--Unbaffled System

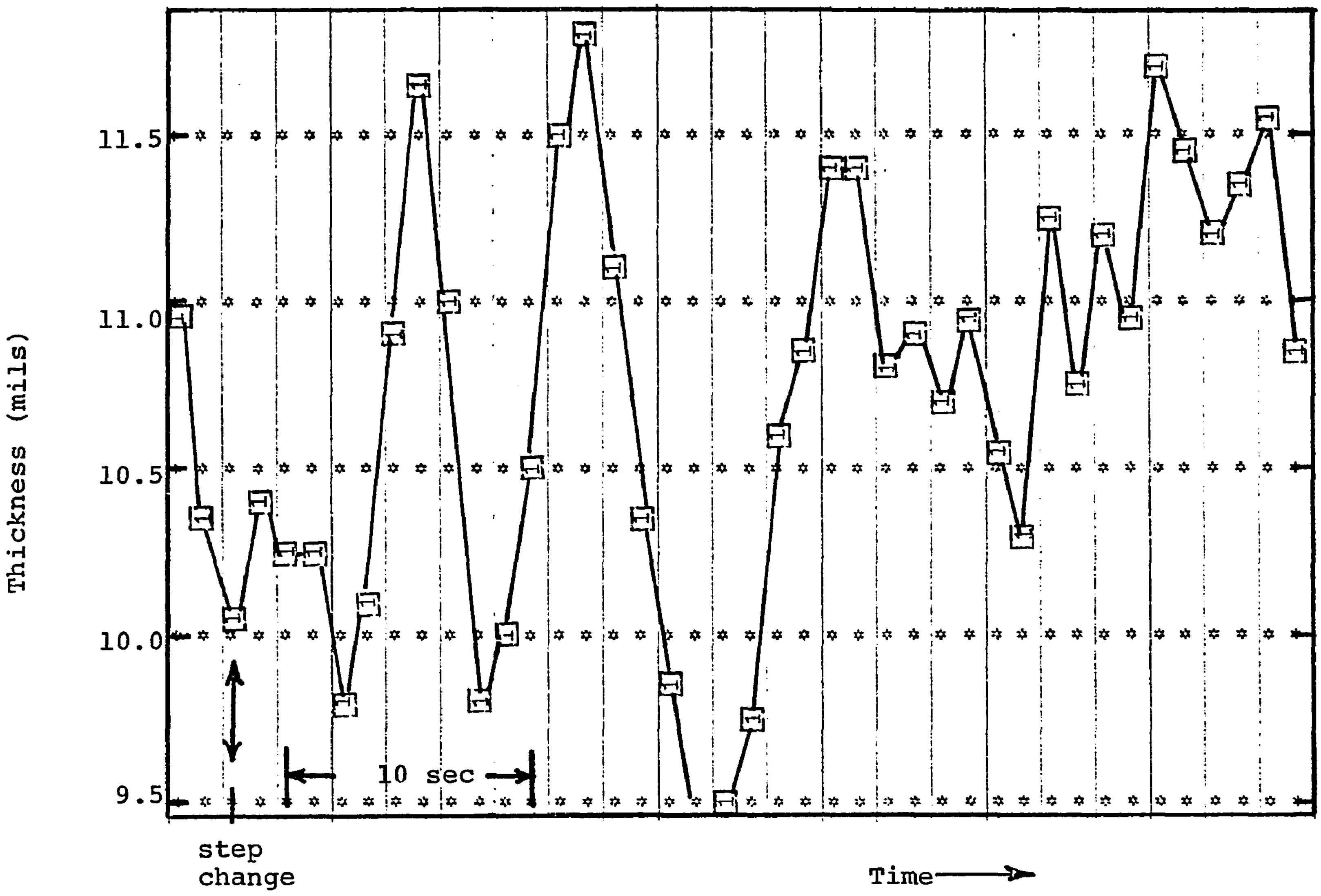


Figure 25.--RN407 Beta Gauge Thickness Data--Unbaffled System

These findings are significant in that polystyrene pellets are generally recognized as a good feed material. Thus if the feed baffles can improve extruder performance for this system, its effects should be even more significant for systems which present feed problems. In an attempt to evaluate these findings for other systems, a series of runs were proposed using polystyrene flake. The flake material was obtained from regrind of the polystyrene sheet produced during the initial phase of this study.

Polystyrene flake is a poor feed, and typically presents major problems for conventional gravity fed systems. During the initial portion of the flake study, the unbaffled gravity fed system was used to obtain data for subsequent systems comparison. However, major flow rate fluctuations were evident, the feed hopper and extruder throat continually bridged, and the sheet was unusable for data acquisition. After numerous attempts to stabilize the system, the data acquisition for the unbaffled system was terminated.

When the feed baffles were inserted into the feed duct, the effect was pronounced. The system stabilized with a reasonably steady flow rate and the elimination of bridging of the feed. The quality of the sheet improved, but the cooling water system to the take-up rolls malfunctioned with resultant sheet irregularities. The baffled system was operated for two hours to establish the effect on flow stability, then the experimentation was terminated.

Although numerical data to compare the flake systems were not obtained, the observed effects were evident.

1. The feed showed no signs of bridging in the baffled system. This was probably due to the reduction of the packing force in the region of the extruder throat by the baffles (refer to the force analysis, Chapter 2).
2. The flow rate at 100 rpm for the baffled flake system was less than that for pellets, but higher and much more stable than for the unbaffled flake system.
3. Polystyrene sheet can be produced from flake feed if a take-up system with more stable low speed operation and cooling control were available.

In summary, the overall effectiveness of the feed baffle system was significant. The system reduced process fluctuations by as much as 40 percent, and reduced feed instability by over 65 percent. The improved stability was also demonstrated with polystyrene flake feed although numerical analysis was not made. These studies demonstrate that the feed baffle system is an inexpensive alternative to the proposed starve-feed system when feed related problems are encountered.

MODIFIED SYSTEM OVERVIEW

An analysis of the total, modified system indicated that the extruder has been effectively isolated from external fluctuations, refer to Table 7. The thickness fluctuation were reduced by over 60 percent. The analysis also indicated that the system had improved operating stability. However, the existence of the reduced process fluctuations would indicate that extruder-induced instability is present.

In an attempt to determine the nature of the extruder-induced fluctuations, a frequency analysis routine was employed. This routine was a modified version of the Fast Fourier Analysis-Power Spectial Density Function program prepared by Bartram (1). The results of the analysis were inconclusive, with no predominant frequency component evident. At this time the analysis package is suspect. Additional study of subsequent extruder-induced fluctuation data is recommended.

TABLE 7

PERFORMANCE SUMMARY

System No.	System Description	Thickness Stability (Percent Fluctuation)	Fluctuation Reduction (Percent)
E-1	System prior to study	12.0	--
E-2	E-1 with modified take-up	7.8	35
E-3	E-2 with auto loader	7.6	37
E-4	E-3 with feed baffle system	4.6	62

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This study was designed to determine the ability to isolate an extruder from external disturbances. If this can be accomplished, the existence of extruder-induced instabilities can be more effectively studied and existing equipment can be modified to insure similar stability improvements. From this study, the following conclusions and recommendations can be made.

CONCLUSIONS

1. The extended-lip sheet die effectively reduced sheet necking and condensation on the cooling rolls, thus improving sheet quality.

2. The computer-controlled, constant tension take-up system effectively isolated post-extrusion disturbances The system also demonstrates the effectiveness of the PDP-15 digital computer system in control applications.

3. The screw design experimentation revealed that the single-stage feedscrew was more sensitive to feed related disturbances. The two-stage feedscrews that were tested significantly reduced pressure fluctuations, but demonstrated characteristics of poor mixing.

4. The feed baffles provided a constant-head feed system and significantly reduced process fluctuations due to feed changes and packing variations. The baffles eliminated feed bridging and provided a much more stable flow rate for flake feed. The baffle system provides an inexpensive alternative to starve-feeding for feed materials which present problems for conventional gravity fed systems.

5. The overall, modified system significantly reduced processing fluctuations. However, fluctuations believed to be associated with extruder-induced or melt-mechanism instability are still evident.

RECOMMENDATIONS

1. The potential of the feed baffle system should be further developed through study of additional feed materials.

2. The existence of extruder-induced instability should be further studied, but will require the use of pressure transducers in the barrel to monitor feed and melt characteristics.

3. Efforts should be made to incorporate an "inhouse" frequency analysis package on the PDP-15 system. The present system gave inconclusive results.

4. The collection system for sheet take-up should be driven by an independent unit to avoid the surges of the cooling rolls experienced during portions of this study.

APPENDICES

APPENDIX A

CRITICAL SHEAR STRESS CALCULATION

In order to evaluate extruder-induced instability, the system must be operated such that melt fracture is avoided. Because melt fracture only occurs above a critical shear stress of 10^5 Newtons per square meter, calculation of the operating shear stress for this study was required. To insure that the system operates below the critical shear stress for all experimental runs, the calculation was based on the operating conditions that would produce the highest shear stress.

The shear rate is given by

$$\gamma_{app} = \frac{6Q}{WH^2} \tag{1}$$

where: γ_{app} = shear rate
Q = volumetric flow rate
H,W = flow channel dimension

From the polystyrene data supplied by Dow Chemical Co., the density is given by

$$\rho = 66.906 + 0.3067 \times 10^{-3}\,(\Delta P) - 0.1522 \times 10^{-1}\,(T) + 0.148818 \times 10^{-6}\,(T)(\Delta P) \tag{2}$$

where: ρ = density of melt

T = temperature of melt

ΔP = pressure drop over system

From this equation the density was calculated to be 61.2 pounds per cubic foot. Therefore the volumetric flow rate was calculated to be 3.2 cubic feet per hour, and the shear rate was calculated to be 110 $\sec^{-1}$.

From the shear stress versus shear rate correlation given by Reber (24), the shear stress is 6.7×10^4 N/m^2 at 100 rpm, and 5.3×10^4 N/m^2 at 80 rpm. Therefore, even for the most critical operating conditions the shear stress remained below the critical level for melt fracture.

APPENDIX B

COMPUTER PROGRAMS

This section contains a listing of the computer programs used during the development of this study. The programs are listed as follows:

The programs used during this study have been saved on Dectape^R storage registers, and have been submitted to Dr. R. Emerson Lynn, Jr. For additional information on the programs, contact Dr. Lynn at the Department of Chemical Engineering, The Ohio State University, Columbus, Ohio 43210.

```
C       XNIP TSK: CONTROL ROUTINE TO MONITOR POSITION
C       OF TENSION DANCER AND IMPLEMENT COMPUTER
C       CONTROL OF TAKE-UP RATE.................
        DIMENSION IT(2)
        IT(1)=7
        IT(2)=1
        VMAX=0.1
        ERR=VMAX
        DO 510 J=1,200
        SUM=0.0
        DO 120 I=1,10
        CALL RTINX(-1,56,VLDT,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 105,105,110
 105    KEY8=105
        GO TO 850
 110    SUM=SUM+VLDT
 120    CONTINUE
        VLDT=SUM/10.0
        VOLT=ABS(VLDT)
        IF(VOLT-VMAX) 215,215,260
 215    KEY1=0
        GO TO 470
 260    IF(VLDT) 301,501,401
 301    IF(VLDT-ERR) 350,350,305
 305    KEY1=0
        GO TO 470
 350    KEY1=16
        GO TO 470
 401    IF(VLDT-ERR) 405,450,450
 405    KEY1=0
```

```
      GO TO 470
450   KEY1=32
470   CALL RTOUX(0,0,KEY1,JEV)
      CALL WAITFR(JEV)
      IF(JEV) 475,475,501
475   KEY8=475
      GO TO 850
501   ERR=VLDT
      CALL MARK(IT,JEV)
      CALL WAITFR(JEV)
510   CONTINUE
      CALL RTOUX(0,0,0,JEV)
      CALL WAITFR(JEV)
      IF(JEV) 520,520,530
520   KEY8=520
      GO TO 850
530   CALL REQST(5HXMONT,0,JEV)
      CALL WAITFR(JEV)
      IF(JEV) 535,535,901
535   KEY8=535
850   KEY1=0
901   CALL EXIT
      END
```

```
C         XMONT TSK:  EXTRUDER MONITOR SYSTEM
          COMMON XV(11),IDATE(6),KEY1,JEV,NN
          CALL MONT1
          CALL EXIT
          END


          SUBROUTINE MONT1
          DIMENSION C0(9),C1(9),C2(9),NCHAN(9),KV(9)
          COMMON XV(11),IDATE(6),KEY1,JEV,NN
          DATA NCHAN/40,35,37,39,4,1,51,52,53/
          DATA C0/123,042,123,980,122.159,123.464,
          2125.972,0,0,-22.9341,-136.206,-159,357/
          DATA C1/0.0110383,0.0104913,0.0107254,0,0106302,
          20.0105886,1.0,0.188617,0.254273,0,323803/
          DATA C2/0.0,0.0,0,0,0.0,0,0,0.0,
          20.0,3.03678E-7,3,44068E-6/
          NN=9
          CALL RTIN(-1,53,V53)
          CALL RTIN(-1,52,V52)
          CALL RTIN(NN,NCHAN,KV,JEV)
          CALL WAITFR(JEV)
          IF(JEV) 205,205,210
205       KEY1=2
          CALL MONT2
210       KEY1=1
          CALL DATE(IDATE)
          DO 230 I=1,NN
          VOLT=FLOAT(KV(I)*8/8)
          XV(I)=C0(I)+C1(I)*VOLT+C2(I)*VOLT*VOLT
```

```
 230    CONTINUE
        XV(10)=-1258.45657+1381.35046*(ABS(V53))
        XV(11)=-502.77248+549.40350*(ABS(V52))
        CALL MONT2
        CALL EXIT
        END


        SUBROUTINE MONT2
        COMMON XV(11),IDATE(6),KEY1,JEV,NN
        GO TO(101,201),KEY1
 101    WRITE(53,105) (IDATE(I),I=1,6),(XV(J),J=1,11)
 105    FORMAT(' ',6I5/' TEMP',6F10.1/' PRESS',5F10.1)
        CALL REQST(4HXNIP,0,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 201,201,301
 201    WRITE(52,205) JEV
 205    FORMAT(' ','  TERMINATION OF XMONT W/ JEV =  ',I5)
 301    CALL EXIT
        END
```

```
C       YTRUD : DATA ACQ.PROGRAM
        DIMENSION IDA(100),IDB(100),IDC(100),IDD(100)
        2,IDE(100),IDF(100),IDO(2),IDATE(6),IT(2)
        DATA ICA/53/,ICB/4/,ICC/52/,ICD/1/,ICE/56/
        DATA ICF/11/,ICO/59/,IFQ/3/
        IT(1)=6
        IT(2)=1
101     WRITE(52,103)
103     FORMAT(' ','  ENTER: RUN NO,,FILES,EXT(I3,2X,A5,2X,A3)')
        READ(52,105) NRUN,FILES,EXT
105     FORMAT(I3,2X,A5,2X,A3)
        WRITE(52,110) NRUN,FILES,EXT
110     FORMAT(' ','  NRUN ',I3,5X,'FILES,.EXT  ',A5,2X,A3//
        1' ENTER 0 TO REENTER, 1 TO CONTINUE, 2 TO TERM(I1)')
        READ(52,115) II
115     FORMAT(I1)
        IF(II-1) 101,120,620
120     CALL ENTER(57,FILES,EXT,JEV)
        CALL WAITER(JEV)
        IF(JEV) 125,125,130
125     KEY2=125
        GO TO 850
130     CALL DATE(IDATE)
        WRITE(57) (IDATE(I),I=1,6)
        CALL RTSET(ICA,IFQ,IDA)
        CALL RTSET(ICB,IFQ,IDB)
        CALL RTSET(ICC,IFQ,IDC)
        CALL RTSET(ICD,IFQ,IDD)
        CALL RTSET(ICE,IFQ,IDE)
        CALL RTSET(ICF,IFQ,IDF)
        CALL RTSET(ICO,IFQ,IDO,JEV)
```

```
          CALL WAITFR(JEV)
          IF(JEV) 205,205,210
  205     KEY2=205
          GO TO 850
  210     CALL RTRST(JEV)
          CALL WAITFR(JEV)
          IF(JEV) 215,215,220
  215     KEY2=215
          GO TO 850
  220     CALL MARK(IT,JEV)
          CALL WAITFR(JEV)
          INITA=IABS(IDO(1)*8/8)
          IF(INITA-1000) 220,225,225
  225     ICNT=0
  230     IDA(50)=0
          KEY1=0
          CALL WAITFR(IDA(50))
          GO TO 250
  240     IDA(100)=0
          KEY1=1
          CALL WAITFR(IDA(100))
  250     IF(KEY1) 270,270,275
  270     JIN=1
          JOUT=50
          GO TO 280
  275     JIN=51
          JOUT=100
  280     WRITE(57) (IDA(J),IDB(J),IDC(J),IDD(J),
          1IDE(J),IDF(J),J=JIN,JOUT)
          IF(KEY1) 240,240,301
  301     ICNT=ICNT+1
          INITB=IABS(IDO(1)*8/8)
          IF(INITB-1000) 320,230,230
```

```
320     CALL CLOSE(57,FILES,EXT,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 330,330,520
330     KEY2=330
        GO TO 850
520     WRITE(52,605) NRUN,FILES,EXT,ICNT
605     FORMAT(' ',' END OF NRUN ',I5,5X,' FILES,.,EXT  '
       1,A5,2X,A3,5X,' WITH ICNT = ',I7//' TO INITIATE
       2 NEW DATA ACQ FILE ENTER 1, ENTER 2 TO TERM(I1)')
        READ(52,610) II
610     FORMAT(I1)
        IF(II-1) 101,101,620
620     KEY8=0
        JEV=0
850     CALL UNFIX(5HXTRUD,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 855,855,860
855     KEY2=855
860     WRITE(52,865) KEY2,JEV
865     FORMAT(' ',' TERM OF DATA ACQ, AT LINE ',I5
       1,5X,' WITH JEV = ',I7)
        CALL EXIT
        END
```

```
C       XPLOT TSK : XTRUD TREATMENT ROUTINE
        DIMENSION ID(300),IDATE(6),SUM(6),SUM2(6),
        2IMAX(6),IMIN(6),AVG(6),STDDEV(6),VAR(6),XV(6),
        3SPAN(8),REF(8),OUT(8),JD(6),NPT(8),FNAME(2)
        DATA FNAME/5HDATA.,4H.WMF/
101     WRITE(53,105)
105     FORMAT(' ',' ENTER FILE,ICNT,KEY1(A5,2X,I5,
        22X,I1)')
        READ(53,110) FILES,ICNT,KEY1
110     FORMAT(A5,2X,I5,2X,I1)
        WRITE(53,115) FILES,ICNT,KEY1
115     FORMAT(' ',' FILE TREATED.,',A5,'  ICNT= ',
        2I5,'  KEY1=  ',I5//' ENTER 0R,1C,2T(I1)')
        READ(53,120) II
120     FORMAT(I1)
        IF(II-1) 101,125,801
125     CALL SEEK(57,FILES,3HWMF,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 130,130,140
130     KEY8=130
        GO TO 850
140     CALL DEFINE(56,6,1200,FNAME,IVAR,0,0,0,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 145,145,150
145     KEY8=145
        GO TO 850
150     JCNT=ICNT*2
        INT=ICNT*10
        READ(57) (IDATE(I),I=1,6)
        WRITE(53,152) (IDATE(I),I=1,6)
152     FORMAT(' ',' DATE OF DATA ACQ.. ',6I9)
```

```
      IF(KEY1-1) 160,160,155
155   DO 157 I=1,INT
      READ(57) (JD(K),K=1,6)
      WRITE(56'I) (JD(K),K=1,6)
157   CONTINUE
      GO TO 279
160   INT=0
      DO 165 L=1,6
      SUM(L)=0
      SUM2(L)=0
165   CONTINUE
      DO 240 I=1,JCNT
      READ(57) (ID(K),K=1,300)
      DO 230 N=1,5
      DO 180 J=1,6
      JD(J)=0
      DO 170 L=1,10
      NN=J+(L-1)*6+(N-1)*60
      JD(J)=JD(J)+ID(NN)*8/8
170   CONTINUE
      JD(J)=JD(J)/10
180   CONTINUE
      DO 220 J=1,6
      IF(I-1) 185,185,195
185   IMIN(J)=JD(J)
      IMAX(J)=JD(J)
      GO TO 215
195   IF(IMAX(J)-JD(J)) 201,205,205
201   IMAX(J)=JD(J)
      GO TO 215
205   IF(IMIN(J)-JD(J)) 215,215,210
210   IMIN(J)=JD(J)
215   XV(J)=FLOAT(JD(J))
```

```
      SUM(J)=SUM(J)+XV(J)
      SUM2(J)=SUM2(J)+XV(J)*XV(J)
 220  CONTINUE
      INT=INT+1
      WRITE(56'INT) (JD(J),J=1,6)
 230  CONTINUE
 240  CONTINUE
      CINT=FLOAT(INT)
      DO 260 J=1,6
      AVG(J)=SUM(J)/CINT
      VAR(J)=(CINT*SUM2(J)-SUM(J)*SUM(J))/(
      2CINT*(CINT-1.0))
      STDDEV(J)=VAR(J)**0.5
 260  CONTINUE
      WRITE(54,270) (IDATE(I),I=1,6)
 270  FORMAT(' ',' DATE OF DATA ACQ  ',6I9//
      2' DATA PT',5X,'MIN',10X,'AVG',10X,'MAX',
      310X,'STD DEV',10X,'VAR')
      DO 276 I=1,6
      WRITE(54,275) I,IMIN(I),AVG(I),IMAX(I),
      2STDDEV(I),VAR(I)
 275  FORMAT(' ',2X,I5,I9,5X,F10.1,I9,5X,2(F10.1,5X))
 276  CONTINUE
 279  WRITE(53,280)
 280  FORMAT(' ',' OPTION FOR DATA STORAGE:
      2 ENTER 0 FOR NEW TAPE,1.C,2.T(I1)')
      READ(53,285) II
 285  FORMAT(I1)
      IF(II-1) 501,301,801
 301  WRITE(53,305)
 305  FORMAT(' ',' PLOT OPTION: ENTER NPLOT,IGO,
      2ISTOP,IBLK(4(I5,2X))')
      READ(53,310) NPLOT,IGO,ISTOP,IBLK
```

```
310       FORMAT(4(I5,2X))
          WRITE(53,315) NPLOT,IGO,ISTOP,IBLK
315       FORMAT(' ',' CHECK* ',4(I5,2X)//' 0R,IC,2T')
          READ(53,320) II
320       FORMAT(I1)
          IF(II-1) 301,330,801
330       DO 350 I=1,NPLOT
          WRITE(53,335) I
335       FORMAT(' ',' ENTER NPLOT#,REF,SPAN(I1,2(2X,F10.1)'//
          2I5/)
          READ(53,340) NPT(I),REF(I),SPAN(I)
340       FORMAT(I1,2(2X,F10.1))
350       CONTINUE
          WRITE(53,355) (NPT(I),REF(I),SPAN(I),I=1,NPLOT)
355       FORMAT(' ',' CHECK'/2X,8(I3,2F15.3//)/' 0R,1C,2T')
          READ(53,360) II
360       FORMAT(I1)
          IF(II-1) 330,370,801
370       INN=NPLOT+1
          DO 380 I=INN,8
          REF(I)=0.0
          SPAN(I)=100.0
          OUT(I)=0.0
380       CONTINUE
          TME=0.0
          ITERM=ISTOP-IBLK+1
          BLK=FLOAT(IBLK)
          DO 440 I=IGO,ITERM,IBLK
          DO 410 L=1,NPLOT
          OUT(L)=0.0
410       CONTINUE
          DO 430 K=1,IBLK
          IP=K+I-1
```

```
        READ(56'IP) (JD(N),N=1,6)
        DO 420 J=1,NPLOT
        IO=NPT(J)
        XV(J)=FLOAT(JD(IO))
        OUT(J)=OUT(J)+XV(J)/BLK
420     CONTINUE
430     CONTINUE
        TME=TME+1.0
        CALL PLOT8(SPAN,REF,OUT,TME)
440     CONTINUE
        WRITE(53,450)
450     FORMAT(' ',' END PLOT OPTION ENTER 1 RECYCLE,
        22 TO TERM(I1)')
        READ(53,460) II
460     FORMAT(I1)
        IF(II-1) 301,301,801
501     CALL CLOSE(57,FILES,3HWMF,JEV)
        CALL ENTER(55,FILES,3HWMF,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 505,505,510
505     KEY8=505
        GO TO 850
510     WRITE(55) (IDATE(I),I=1,6)
        DO 530 I=1,INT
        READ(56'I) (JD(K),K=1,6)
        WRITE(55) (JD(K),K=1,6)
530     CONTINUE
        CALL CLOSE(55,FILES,3HWMF,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 535,535,540
535     KEY8=535
        GO TO 850
540     GO TO 279
```

```
801     CALL CLOSE(57,FILES,3HWMF,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 805,805,810
805     KEY8=805
        GO TO 850
810     CALL CLOSE(56,FNAME,JEV)
        CALL WAITFR(JEV)
        IF(JEV) 815,815,820
815     KEY8=815
        GO TO 850
820     WRITE(53,825)
825     FORMAT(' ',' TERM OF XPLOT BY OPERATOR')
        GO TO 901
850     WRITE(53,855) KEY8,JEV
855     FORMAT(' ',' TERM XPLOT AT LINE ',I5,'  WITH
        2 JEV= ',I5)
901     CALL EXIT
        END
```

```
      SUBROUTINE PLOT8(SPAN,REF,OUT,TME)
      DOUBLE INTEGER IAR,ICD,IBK,IAX,IAS,IAA
      DIMENSION TEMP(8),SPAN(8),OUT(8),IOUT(8),REF(8),IAR(101),ICD(8)
      DATA IBK/64/,IAS/166/,IAX/92/,IAA/84/,ICD(1)/98/,ICD(2)/100/
      DATA ICD(3)/102/,ICD(4)/104/,ICD(5)/106/,ICD(6)/108/
      DATA ICD(7)/110/,ICD(8)/112/
      DO 44 I=1,8
      DEL=OUT(I)-REF(I)
      IOUT(I)=(DEL/SPAN(I))*100.0+1.5
      IF(IOUT(I).GT.101)IOUT(I)=101
      IF(IOUT(I),LT.1) IOUT(I)=1
44    CONTINUE
      DO 50 I=1,101
50    IAR(I)=IBK
      DO 52 I=1,101,10
52    IAR(I)=IAA
      DO 520 I=1,101
      ICTR=-0
      DO 510 J=1,8
      IF(IOUT(J).NE,I) GO TO 510
      IAR(I)=ICD(J)
      ICTR=ICTR+1
510   CONTINUE
      IF(ICTR.GT.1) IAR(I)=IAS
520   CONTINUE
      WRITE(54,458) TME,(IAR(K),K=1,101)
458   FORMAT(1H ,F8.2,10X,101R1)
      RETURN
      END
```

```
C
C  TASK BTA14, GENERAL FREQUENCY ANALYSIS TASK.  THIS PROGRAM
C   TAKES DATA FROM DECTAPE (LUN 62), PERFORMS A FAST FOURIER
C   TRANSFORM, THEN COMPUTES THE POWER SPECTRAL DENSITY FUNCTION.
C   PRINT-OUTS AND PLOTS ARE AT THE OPTION OF THE OPERATOR.
C   LOGICAL UNIT (LUN) 63 MUST BE ASSIGNED TO AN OPERATOR INTER-
C   ACTIVE DEVICE SUCH AS A TELEPRINTER, AND LUN 64 TO THE LINE
C   PRINTER.  AN ADDITIONAL BULK STORAGE DEVICE MAY BE OPERATOR
C   SPECIFIED FOR SAVING THE POWER SPECTRAL DENSITY FUNCTION
C   (REQUIRED IF THIS IS TO BE PLOTTED) OR FOR SAVING THE FOURIER
C   COEFFICIENTS.
C
C  THIS TASK IS TERMINATED IF A BLANK (CARRIAGE RETURN ONLY)
C   FILE NAME IS ENTERED WHEN THE REQUEST FOR THE DATA FILE
C   NAME IS MADE.
C
C  THIS TASK CONTAINS MANY OVERLAYS IN ADDITION TO THIS MAIN
C   CODE, WHICH SERVES ONLY TO CALL THE OVERLAYS.
C        LINK1=BTA14A  READS THE DATA FROM TAPE (ASSUMING INTERGER
C   NUMBERS WRITTEN IN BLOCKS OF 32), AND CONVERTS THEM TO
C   FLOATING POINT.
C        LINK2=BTA14B  PRINTS THE DATA, DETRENDS IT, AND
C   PRINTS THE DETRENDED DATA AS REQUIRED.
C        LINK3=BTA14C,RFORT,FORT  PERFORMS THE FAST FOURIER
C   TRANSFORM, AND INVERSE IF REQUIRED.
C        LINK4=BTA14D  PRINTS THE FOURIER COEFFICIENTS IF REQUIRED.
C        LINK5=BTA14E  COMPUTES THE POWER SPECTRAL DENSITY FUNCTION
C   (PSDF), AND STORES IT ON TAPE OR DISK, IF REQUIRED.
C        LINK6=BTA14F,PLOT  PLOTS THE PSDF IF REQUIRED.
C        LINK7=BTA14G,COSTP  COSINE TAPERS THE DATA (AFTER DE-
C   TRENDING) AND PRINTS THE TAPERED DATA IF REQUIRED.  ALSO,
C   AFTER THE INVERSE TRANSFORM HAS BEEN CALLED TO RE-COMPUTE
C   THE ORIGINAL DATA, THE COSINE TAPER AND DE-TRENDING ARE
C   REMOVED.
C
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
C
105     CALL BTA14A
        CALL BTA14B
        IF (ICS) 111, 112, 111
111     CALL BTA14G (0)
112     CALL BTA14C (-1)
        CALL BTA14D
        IF (ISD) 101, 102, 101
101     CALL BTA14E
        IF (IPL) 103, 102, 103
103     CALL BTA14F
102     IF (INV) 104, 105, 104
104     CALL BTA14C (+1)
        CALL BTA14G (+1)
        GO TO 105
        END
```

```
C
C  SUBROUTINE BTA14A, THE FIRST OVERLAY OF TASK BTA14.  THIS SUBROUTINE
C   OBTAINS THE DATA FROM TAPE AND CONVERTS IT TO FLOATING POINT.
C
C
      SUBROUTINE BTA14A
C
      DIMENSION IDA(32)
      COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
      1 INV,IERR,ITR,B0,B1
      COMMON /DATA/ X(2050)
      DATA YES/3HYES/, EXT/1H /
C
C  GET INITIAL INFORMATION ABOUT DATA TO BE ANALYSED.
C
100   WRITE (63,1)
1     FORMAT ('0TASK BTA14, SPECTRAL ANALYSIS,' / 'ENTER FILE
      1 NAME, A5,')
      READ (63,2) FLE
2     FORMAT (A5)
C
C  EXIT IF NO FILE NAME GIVEN.
C
      IF (FLE .EQ. EXT) CALL EXIT
C
C  OPEN THE TAPE FILE WHILE GETTING THE REST OF THE INITIAL INFORMATION.
C
      CALL SEEK (62, FLE, 3HPNB, IEV)
      WRITE (63,3)
3     FORMAT (' ENTER POWER OF TWO FOR NUMBER OF DATA VALUES TO BE
      1 USED, I2,')
104   READ (63,4) M
4     FORMAT (I2)
      IF (M) 101, 101, 102
101   WRITE (63,5) M
5     FORMAT (' VALUE OUT OF RANGE:', I5)
      GO TO 104
102   IF (M-11) 103, 103, 101
103   N = 2**M
107   WRITE (63,6)
6     FORMAT (' ENTER NUMBER OF VALUES TO BE SKIPPED AT THE
      1 BEGINNING OF THE FILE, I5,')
      READ (63,7) ISK
7     FORMAT (I5)
      IF (ISK) 105, 106, 106
105   WRITE (63,5) ISK
      GO TO 107
106   WRITE (63,8)
8     FORMAT (' ENTER NUMBER OF VALUES SKIPPED BETWEEN VALUES
      1 USED, I2,')
      READ (63,4) ISP
      IF (ISP) 108, 109, 109
108   WRITE (63,5) ISP
      GO TO 106
109   ISP = ISP + 1
111   WRITE (63,9)
9     FORMAT (" ENTER # OF 0'S TO FILL AT END, I5,")
      READ (63,7) NZR
      IF (NZR) 111, 112, 112
112   NR = N - NZR
```

```
C
C  CHECK IF THE TAPE FILE WAS SUCCESSFULLY OPENED.
C
         CALL WAITFR (IEV)
         IF (IEV) 115, 115, 116
115      WRITE (63,10) FLE, IEV
10       FORMAT (' *** TAPE FILE"', A5, ' PNB" COULD NOT BE OPENED.' /
         1 5X, 'EVENT VARIABLE=', I5)
         GO TO 100
C
C  COMPUTE THE BASE FREQUENCY FOR THE RESULTS.
C
116      WRITE (63,22)
22       FORMAT (' ENTER TIME OR DISTANCE SPACING BETWEEN POINTS
         1 USED, F10.4,')
         READ (63,23) FRQ
23       FORMAT (F10.4)
         FRQ = 1.0/(FRQ*FLOAT(N))
         WRITE (63,24)
24       FORMAT (' ENTER UNIT OF MEASURE, A4.')
         READ (63,2) UNT
C
C  READ IN THE DATA, CONVERTING TO FLOATING FORMAT, AND STORING
C   IN THE COMMON BLOCK "DATA".
C
         INX = 0
         ISK = ISK + 33
123      ISK = ISK - 32
         READ (62,END=151,ERR=152) IDA
124      ISM = ISK - 32
         IF (ISM) 122, 122, 123
122      INX = INX + 1
         CALL ADCNV (IDA(ISK), X(INX))
         IF (INX-NR) 125, 126, 126
125      ISK = ISK + ISP
         GO TO 124
126      INX = INX + 1
         DO 201 ISM = INX,N
201      X(ISM) = 0.0
C
C  CLOSE THE TAPE FILE, AND GO TO SUBROUTINE BTA14B TO
C   CONTINUE.
C
129      CALL CLOSE (62, FLE, 3HPNB, LUN)
         RETURN
C
C  ERROR CONDITIONS FOUND IN READING THE TAPE.
C
151      WRITE (63,20) FLE
20       FORMAT (' *** UNEXPECTED END-OF-FILE REACHED, TAPE FILE "'
         1 A5, ' PNB".')
153      CALL CLOSE (62, FLE, 3HPNB, IEV)
         CALL WAITFR (IEV)
         GO TO 100
152      WRITE (63,21) FLE
21       FORMAT (' *** ERROR IN READING TAPE FILE "', A5, ' PNB".')
         GO TO 153
         END
```

```
C
C  SUBROUTINE BTA14B, THE SECOND OVERLAY OF TASK BTA14.  THIS
C   SUBROUTINE IS A CONTINUEATION OF SUBROUTINE BTA14A.  IF
C   REQUIRED, THE DATA IS PRINTED, DE-TRENDED, AND PRINTED AFTER
C   DE-TRENDING.  ALSO, IT IS DETERMINED IS SUBROUTINE BTA14G,
C   FOR COSINE TAPERING, IS TO BE CALLED.
C
        SUBROUTINE BTA14B
C
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
        DATA YES/3HYES/
C
        WRITE (63,11)
11      FORMAT (' PRINT DATA?')
        READ (63,12) QRY
12      FORMAT (A3)
        IF (QRY .NE. YES) GO TO 150
        WRITE (64,13) FLE, N
13      FORMAT ('0TASK BTA14, DATA FILE "', A5, ' PN8",', 10X,
        1 'ORGINIAL DATA, ', I4, ' POINTS.')
        WRITE (64,14)
14      FORMAT (4X, 'N', 9X, 'X(N)', 9X, 'X(N+1)', 9X, 'X(N+2)',
        1 9X, 'X(N+3)', 9X, 'X(N+4)', 9X, 'X(N+5)', 9X, 'X(N+6)',
        2 9X, 'X(N+7)' )
        DO 301 INX = 1,N,8
        ISM = INX -1
        ISK = INX + 7
        WRITE (64,15) ISM, (X(ISP), ISP = INX,ISK)
15      FORMAT (1H , I4, 8(1PE15.3))
301     CONTINUE
C
C  DETERMINE IF DE-TRENDING IS DESIRED.
C
150     WRITE (63,21)
21      FORMAT (' SUBTRACT THE MEAN?')
        ITR = -1
        READ (63,12) QRY
        IF (QRY .NE. YES) GO TO 151
        ITR = 0
        GO TO 152
151     WRITE (63,22)
22      FORMAT (' SUBTRACT 1ST ORDER TREND?')
        READ (63,12) QRY
        IF (QRY .NE. YES) GO TO 131
        ITR = 1
C
C  COMPUTE THE SAMPLE MEAN, AND PRINT.
C
152     AVG = 0.0
        DO 211 INX = 1,N
211     AVG = AVG + X(INX)
        AN = N
        AVGR = AVG/AN
        WRITE (64,23) N, FLE, AVGR
23      FORMAT ('0THE SAMPLE MEAN FOR', I5, ' DATA POINTS FROM FILE
        1 "', A5, ' PNB" IS', 1PE11.4)
        IF (ITR) 131, 153, 154
153     B0 = AVGR
```

```
      DO 213 ISM = 1,N
213   X(ISM) = X(ISM) - B0
      GO TO 159
C
C  COMPUTE THE LINEAR LEAST-SQUARES FIT, AND SUBTRACT THE LINE,
C   IF REQUIRED.
C
154   AVGN = 0.0
      DO 212 INX = 1,N
212   AVGN = AVGN + X(INX)*FLOAT(INX)
      QRY = (AN-1.0)*AN
      B0 = (FLOAT(4*N + 2) * AVG - 6.0*AVGN) / QRY
      B1 = (12.0*AVGN - FLOAT(6*N + 6) * AVG) / (QRY*(AN+1))
      WRITE (64,25) B0, B1
25    FORMAT (' THE DATA HAVE BEEN DE-TRENDED BY SUBRACTING'
      1 , 1PE12.4, ' +', E12.4, ' K, K = 1, 2, ..., N.')
      DO 216 J = 1,N
216   X(J) = X(J) - B0 - B1*FLOAT(J)
C
C  PRINT THE ADJUSTED DATA, IF REQUIRED.
C
159   WRITE (63,26)
26    FORMAT (' PRINT DE-TRENDED DATA?')
      READ (63,12) QRY
      IF (QRY .NE. YES) GO TO 131
      WRITE (64,27) FLE
27    FORMAT ('0DATA FROM FILE "', A5, ' PNB" AFTER DE-TRENDING:')
      WRITE (64,14)
      DO 217 INX = 1,N,8
      ISM = INX - 1
      ISK = INX + 7
      WRITE (64,15) ISM, (X(ISP), ISP = INX,ISK)
217   CONTINUE
C
131   WRITE (63,16)
16    FORMAT (' COSINE TAPER (10%) THE DATA?')
      READ (63,12) QRY
      ICS = 0
      IF (QRY .NE. YES) GO TO 132
      ICS = 1
C
C  CHECK TO INSURE THE TAPE FILE OPENED BY SUBROUTINE BTA14A WAS
C   CLOSED, THEN CONTINUE WITH SUBROUTINE BTA14C.
C
132   CALL WAITFR (LUN)
      IF (LUN) 141, 141, 142
141   WRITE (63,19) FLE, LUN
19    FORMAT (' *** ERROR IN CLOSING TAPE FILE "', A5, ' PNB".' /
      1 5X, 'EVENT VARIABLE:', I5)
142   RETURN
      END
```

```
C
C   SUBROUTINE BTA14C, THE THIRD OVERLAY OF TASK BTA14.  THIS
C    SUBROUTINE COMPUTES THE FOURIER COEFFICIENTS FOR THE REAL-
C    VALUED DATA, AND STORES THEM IN THE COMMON ARRAY ORIGINALLY
C    USED FOR THE DATA.  ALTERNATELY, THE FOURIER SERIES (VALUES
C    SHOULD EQUAL THE ORIGINAL DATA) MAY BE COMPUTED FROM THE
C    COEFFICIENTS.  IFS = -1 FOR THE COEFFICIENTS; = +1 FOR THE
C    SERIES.
C
C   THIS OVERLAY REQUIRES SUBROUTINES RFORT AND FORT TO COMPUTE
C    THE SERIES AND COEFFICIENTS.  THESE SUBROUTINES ARE THE
C    FAST FOURIER TRANSFORM ROUTINES FOR REAL VALUED DATA.
C    LINK3=BTA14C,RFORT,FORT
C
        SUBROUTINE BTA14C (IFS)
C
        DIMENSION S(512)
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
C
        CALL RFORT (X,M,S,IFS,IERR)
C
        RETURN
        END
```

```
C
      SUBROUTINE RFORT (A,M,S,IFS,IFERR)
C
C   ONE-DIMENSIONAL REAL FINITE FOURIER TRANSFORM.
C
C   FOURIER TRANSFORM SUBROUTINE FOR REAL DATA.  TAKEN FROM
C    IBM SHARE LIBRARY.
C
C   THIS PROGRAM USES THE SUBROUTINE FORT TO COMPUTE COMPLEX
C    FOURIER TRANSFORMS OF REAL DATA.
C
C   THE FOURIER SERIES IS
C        X(J)=SUM OVER K=0 TO N, OF C(K)*EXP(2*PI*I*J*K/N)
C        J=0,1,2,...,N-1
C    WHERE I=SQRT(-1) AND WHERE C(K) IS COMPLEX.
C    SINCE X(J) IS REAL, C(K) = CONJG[C(N-K)].  THEREFORE ONLY
C    C(K), K=0,1,...,N/2 ARE COMPUTED AND/OR USED.
C
C   ARGUMENTS -
C    A IS INITIALLY THE INPUT ARRAY, X, WHEN COMPUTING A FOURIER
C     TRANSFORM AND C WHEN COMPUTING A FOURIER SERIES.  A IS RE-
C     PLACED BY THE OUTPUT ARRAY, C, ON THE FORMER CASE, X ON THE
C     LATTER.  THE X VECTOR CONTAINS THE REAL DATA X(0), X(1),
C     ..., X(N-1).  THE C VECTOR CONTAINS THE COMPLEX FOURIER
C     AMPLITUDES C(0), C(1), ..., C(N/2).  THE COMPLEX VECTOR C
C     IS STORED ACCORDING TO THE NORMAL FORTRAN IV CONVENTION FOR
C     STORING COMPLEX NUMBERS, I.E., REAL PARTS IN ALTERNATE CELLS
C     STARTING WITH THE FIRST, IMAGINARY PARTS IN ALTERNATE CELLS
C     STARTING WITH THE SECOND.  TO ADHERE TO FORTRAN RULES, X(0),
C     X(1), ..., ARE REFERRED TO AS X(1), X(2), ..., RESPECTIVELY
C     IN THE PROGRAMS.  ALSO, C(0), C(1), ..., ARE REFERRED TO AS
C     C(1), C(2), ..., RESPECTIVELY, IF C IS DESIGNATED AS COMPLEX
C     IN A TYPE STATEMENT.
C
C    M GIVES N=2**M
C
C    THE ARGUMENTS S, IFS, AND IFERR ARE THE SAME AS IN SUB-
C     ROUTINE FORT AND THE USER IS REFERRED TO COMMENT LINES
C     IN FORT FOR THEIR EXPLANATION.
C
C    DIMENSION STATEMENTS - THE DIMENSIONS OF ARRAYS A AND S SHOULD
C     BE N+2 AND N/4, RESPECTIVELY FOR THE LARGEST N USED.  FOR
C     EXAMPLE, IF THE LARGEST M IS 11, THEN N=2048 AND ONE SHOULD
C     HAVE THE DIMENSION STATEMENT -
C        DIMENSION A(2050), S(512)
C
C    IF ONE WISHES TO SPECIFY A TO BE COMPLEX BY A TYPE STATEMENT,
C     ONE SHOULD GIVE IT A DIMENSION OF N/2+1, FOR THE LARGEST N.
C
C
      DIMENSION A(1), S(1)
1     IFERRS=0
      N=2**M
      NV2=N/2
      NV4M1=N/4-1
      MM1=M-1
      IF(IABS(IFS)-1) 10,10,5
5     IF(MP-M)6,20,20
6     IFERRS=1
C
```

```
C  COMPUTE SINE TABLE
C
10      NP=N
        MP=M
        CALL FORT (A,M,S,0,IFERR1)
        IFERRS=IFERRS+IFERR1
20      KD=NP/N
        KT=KD
        NPV4=NP/4
        IF(IFS)30,50,60
C
C  COMPUTE FOURIER TRANSFORM.
C
30      CALL FORT (A,MM1,S,-2,IFERR2)
        IFERRS=IFERRS+IFERR2
        DO 40 K=1,NV4M1
        J=NV2-K
        A1R=A(2*K+1)+A(2*J+1)
        A1I=A(2*K+2)-A(2*J+2)
        A2R=A(2*K+2)+A(2*J+2)
        A2I=A(2*J+1)-A(2*K+1)
        KKT=NPV4-KT
        AWR=A2R*S(KKT)+A2I*S(KT)
        AWI=A2I*S(KKT)-A2R*S(KT)
        A(2*K+1)=(A1R+AWR)/4.
        A(2*K+2)=(A1I+AWI)/4.
        A(2*J+1)=(A1R-AWR)/4.
        A(2*J+2)=(AWI-A1I)/4.
40      KT=KT+KD
        T=A(1)
        A(1)=(T+A(2))/2.
        A(N+1)=(T-A(2))/2.
        A(2)=0.
        A(N+2)=0.
        A(NV2+1)=0.5*A(NV2+1)
        A(NV2+2)=(-0.5*A(NV2+2))
50      IFERR=IFERRS
        RETURN
C
C  COMPUTE FOURIER SERIES.
C
60      DO 80 K=1,NV4M1
        J=NV2-K
        A1R=A(2*K+1)+A(2*J+1)
        A1I=A(2*K+2)-A(2*J+2)
        AWR=A(2*K+1)-A(2*J+1)
        AWI=A(2*K+2)+A(2*J+2)
        KKT=NPV4-KT
        A2R=AWR*S(KKT)-AWI*S(KT)
        A2I=AWR*S(KT)+AWI*S(KKT)
        A(2*K+1)=A1R-A2I
        A(2*K+2)=A1I+A2R
        A(2*J+1)=A1R+A2I
        A(2*J+2)=A2R-A1I
80      KT=KT+KD
        T=A(1)
        A(1)=T+A(N+1)
        A(2)=T-A(N+1)
        A(NV2+1)=2.*A(NV2+1)
        A(NV2+2)=(-2.*A(NV2+2))
        CALL FORT (A,MM1,S,2,IFERR2)
        IFERRS=IFERRS+IFERR2
        GO TO 50
        END
```

```
      SUBROUTINE FORT (A,M,S,IFS,IFERR)
C
C
C  FORT, ONE-DIMENSIONAL FINITE COMPLEX FOURIER TRANSFORM,
C  FOURIER TRANSFORMING SUBROUTINE, TAKEN FROM IBM SHARE LIBRARY,
C
C  DOES EITHER FOURIER SYNTHESIS, I.E., COMPUTES COMPLEX FOURIER
C  SERIES GIVEN A VECTOR OF N COMPLEX FOURIER AMPLITUDES, OR,
C  GIVEN A VECTOR OF COMPLEX DATA X, DOES FOURIER ANALYSIS,
C  COMPUTING AMPLITUDES,
C
C  A IS A COMPLEX VECTOR OF LENGTH N = 2**M COMPLEX NUMBERS OR
C   2*N REAL NUMBERS,  A IS TO BE SET BY THE USER,
C  M IS AN INTEGER 0<M<=11, SET BY THE USER,
C  S IS A VECTOR S(J) = SIN(2*PI*J/NP), J = 1, 2, ..., NP/4-1,
C   COMPUTED BY THE PROGRAM,
C  IFS IS A PARAMETER TO BE SET BY THE USER AS FOLLOWS-
C   IFS = 0 TO SET NP = 2**M AND SET UP SINE TABLE,
C   IFS = 1 TO SET N = NP = 2**M, SET UP SINE TABLE, AND DO
C    FOURIER SYNTHESIS, REPLACING THE VECTOR A BY
C       X(J) = SUM OVER K = 0, N-1 OF A(K)*EXP(2*PI*I/N)**(J*K),
C       J = 0, N-1, WHERE I = SQRT(-1)
C    THE X'S ARE STORED WITH RE[X(J)] IN CELL 2*J+1 AND IM[X(J)]
C    IN CELL 2*J+2 FOR J = 0, 1, 2, ..., N-1.
C    THE A'S ARE STORED IN THE SAME MANNER,
C   IFS = -1 TO SET N = NP = 2**M, SET UP SINE TABLE, AND DO
C    FOURIER ANALYSIS, TAKING THE INPUT VECTOR A AS X AND REPLACING
C    IT BY THE A SATISFYING THE ABOVE FOURIER SERIES,
C   IFS = +2 TO DO FOURIER SYNTHESIS ONLY, WITH A PRE-COMPUTED S,
C   IFS = -2 TO DO FOURIER ANALYSIS ONLY, WITH A PRE-COMPUTED S,
C  IFERR IS SET BY THE PROGRAM TO-
C   = 0 IF NO ERROR DETECTED,
C   = 1 IF M IS OUT OF RANGE, OR, WHEN IFS = +2 OR -2, THE
C    PRE-COMPUTED S TABLE IS NOT LARGE ENOUGH,
C   = -1 WHEN IFS = +1 OR -1, MEANS ONE IS RECOMPUTING S TABLE
C    UNNECESSARILY,
C
C  NOTE- IT MAY BE NECESSARY TO IMPOSE A LOWER MAXIMUM BOUND ON
C  M, DEPENDING ON THE CORE AVAILABLE FOR STORAGE,  ALSO, IT MAY
C  POSSIBLE TO INCORPORATE A HIGHER VALUE BY EXTENDING THE K
C  ARRAY AND ADDING MORE "DO 30 ...," LOOPS,
C
C
      DIMENSION A(1),S(1),K(12)
      EQUIVALENCE (K(11),K1), (K(10),K2), (K(9),K3), (K(8),K4),
      1 (K(7),K5), (K(6),K6), (K(5),K7), (K(4),K8), (K(3),K9),
      2 (K(2),K10), (K(1),K11,N2)
      IF (M) 2, 2, 3
3     IF (M-11) 5, 5, 2
2     IFERR=1
1     RETURN
5     IFERR=0
      N=2**M
      IF (IABS(IFS)-1) 200,200,10
C  WE ARE DOING TRANSFORM ONLY,  SEE IF PRE-COMPUTED S TABLE
C   IS SUFFICIENTLY LARGE,
10    IF (N-NP) 20, 20, 12
12    IFERR = 1
      GO TO 200
C  SCRAMBLE A, BY SANDE'S METHOD,
```

```
20      K(1) = 2*N
        DO 22 L = 2,M
22      K(L) = K(L-1)/2
        DO 24 L = M,10
24      K(L+1) = 2
C  NOTE THE EQUIVALENCE OF KL AND K(11-L)
C  BINARY SORT -
        IJ = 2
C       DO 30 J1 = 2,K1,2
        J1=2
530     IF(J1-K1)331,331,431
C       DO 30 J2 = J1,K2,K1
331     J2 = J1
531     IF (J2-K2) 332,332,432
332     DO 30 J3 = J2,K3,K2
        DO 30 J4 = J3,K4,K3
        DO 30 J5 = J4,K5,K4
        DO 30 J6 = J5,K6,K5
        DO 30 J7 = J6,K7,K6
        DO 30 J8 = J7,K8,K7
        DO 30 J9 = J8,K9,K8
        DO 30 J10 = J9,K10,K9
        DO 30 JI = J10,K11,K10
        IF (IJ-JI) 28,30,30
28      T = A(IJ-1)
        A(IJ-1)=A(JI-1)
        A(JI-1)=T
        T=A(IJ)
        A(IJ) = A(JI)
        A(JI)=T
30      IJ = IJ + 2
        J2 = J2 + K1
        GO TO 531
432     J1 = J1 + 2
        GO TO 530
431     IF (IFS) 32,2,36
C  DOING FOURIER ANALYSIS, SO DIVIDE BY N AND CONJUGATE.
32      FN=N
        DO 34 I=1,N
        A(2*I-1)=A(2*I-1)/FN
34      A(2*I) = (-A(2*I)/FN)
C  SPECIAL CASE - L=1
36      DO 40 I=1,N,2
        T=A(2*I-1)
        A(2*I-1)=T+A(2*I+1)
        A(2*I+1)=T-A(2*I+1)
        T=A(2*I)
        A(2*I)=T+A(2*I+2)
40      A(2*I+2)=T-A(2*I+2)
        IF (M-1) 2,1,50
C  SET FOR L = 2
50      LEXP1=2
C       LEXP1=2**(L-1)
        LEXP=8
C       LEXP=2**(L+1)
        NPL = 2**MT
C       NPL = NP * 2**(-L)
60      DO 130 L=2,M
C  SPECIAL CASE - J=0
        DO 80 I = 2,N2,LEXP
        I1=I+LEXP1
        I2=I1+LEXP1
        I3=I2+LEXP1
        T=A(I-1)
        A(I-1)=T+A(I2-1)
        A(I2-1)=T-A(I2-1)
```

```
      T=A(I)
      A(I)=T+A(I2)
      A(I2)=T-A(I2)
      T=(-A(I3))
      TI=A(I3-1)
      A(I3-1)=A(I1-1) -T
      A(I3) = A(I1)-TI
      A(I1-1)=A(I1-1)+T
80    A(I1)=A(I1)+TI
      IF (L-2) 120,120,90
90    KLAST=N2-LEXP
      JJ=NPL
      DO 110 J=4,LEXP1,2
      NPJJ = NT - JJ
      UR = S(NPJJ)
      UI = S(JJ)
      ILAST = J+ KLAST
      DO 100 I = J,ILAST,LEXP
      I1 = I + LEXP1
      I2=I1+LEXP1
      I3=I2+LEXP1
      T=A(I2-1)*UR-A(I2)*UI
      TI=A(I2-1)*UI +A(I2)*UR
      A(I2-1)=A(I-1)-T
      A(I2)=A(I)-TI
      A(I-1)=A(I-1)+T
      A(I)=A(I)+TI
      T=(-A(I3-1)*UI-A(I3)*UR)
      TI=A(I3-1)*UR-A(I3)*UI
      A(I3-1)=A(I1-1)-T
      A(I3)=A(I1)-TI
      A(I1-1)=A(I1-1)+T
100   A(I1)=A(I1)+TI
C  END OF I LOOP.
110   JJ=JJ+NPL
C  END OF J LOOP.
120   LEXP1=2*LEXP1
      LEXP=2*LEXP
130   NPL=NPL/2
C  END OF L LOOP.
140   IF (IFS) 145,2,1
C  DOING FOURIER ANALYSIS, REPLACE A BY CONJUGATE.
145   DO 150 I=1,N
150   A(2*I)=(-A(2*I))
C 160 GO TO 1
      RETURN
C  RETURN
C  MAKE TABLE OF S(J)=SIN(2*PI*J/NP), J=1,2,...,NT-1, NT=NP/4
200   NP=N
      MP=M
      NT=N/4
      MT=M-2
      IF(MT) 260,260,205
205   THETA=0.78539816
C  THETA = PI/2**(L+1) FOR L=1
210   JSTEP=NT
C  JSTEP = 2**(MT-L+1) FOR L=1
      JDIF=NT/2
C  JDIF = 2**(MT-L) FOR L=1
      S(JDIF) = SIN(THETA)
      IF (MT-2) 260,220,220
220   DO 250 L = 2,MT
      THETA = THETA/2.
      JSTEP2=JSTEP
      JSTEP=JDIF
      JDIF=JDIF/2
```

```
          S(JDIF)=SIN(THETA)
          JC1=NT-JDIF
          S(JC1) = COS(THETA)
          JLAST = NT - JSTEP2
          IF(JLAST-JSTEP) 250,230,230
230       DO 240 J=JSTEP,JLAST,JSTEP
          JC=NT-J
          JD=J+JDIF
240       S(JD)=S(J)*S(JC1)+S(JDIF)*S(JC)
250       CONTINUE
260       IF(IFS) 20,1,20
          END
```

```
C
C  SUBROUTINE BTA14D. THE FOURTH OVERLAY OF TASK BTA14.  THIS
C   SUBROUTINE PRINTS THE FOURIER COEFFICIENTS IF REQUESTED,
C   SAVES THEM IN AN OPERATOR SPECIFIED DISK OR TAPE FILE
C   IF REQUESTED, AND CONTINUES THE OPERATOR QUESTIONING.
C
        SUBROUTINE BTA14D
C
        DIMENSION XX(14)
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
        DATA YES /3HYES/
        DATA XX /14*0.0/
C
C  CHECK TO INSURE THAT THE FOURIER COEFFICIENTS WERE COMPUTED.
C
        INV = 0
        ISD = 0
        IF (IERR) 111, 112, 111
111     WRITE (63,6) IERR
6       FORMAT (' *** ERROR IN CALLING THE FAST FOURIER ROUTINE.'/
        1 5X, 'IERR:', I5)
        GO TO 132
C
C  CHECK IF FOURIER COEFFICENTS ARE TO BE SAVED, AND IF SO,
C   OPEN THE FILE FOR THEM.
C
112     WRITE (63,11)
11      FORMAT (' SAVE THE FOURIER COEFFICIENTS?')
        READ (63,2) QRY
        ISV = 0
        IF (QRY .NE. YES) GO TO 114
        ISV = 1
        WRITE (63,12)
12      FORMAT (' ENTER LUN, I2, AND FILE NAME, A5.')
        READ (63,13) LU, FSV
13      FORMAT (I2, A5)
        CALL ENTER (LU, FSV, 3HPNB, IEV)
C
C  PRINT THE FOURIER COEFFICIENTS, IF REQUIRED.
C
114     WRITE (63,3)
3       FORMAT (' ARE THE FOURIER COEFFICIENTS TO BE PRINTED?')
        READ (63,2) QRY
        IF (QRY .NE. YES) GO TO 113
        WRITE (64,4) FLE, FRQ, UNT
4       FORMAT ('0FOURIER COEFFICIENTS FOR DATA FROM FILE "', A5,
        1 ' PNB", HARMONICS OF FREQUENCY', 1PE11.4, ' PER ', A4 /
        2 4X, 'K', 10X, 'A(K)', 20X, 'A(K+1)', 19X, 'A(K+2)',
        3 19X, 'A(K+3)', 19X, 'A(K+4)')
        N2 = N + 2
        K = 0
        ISR = 1
        IST = 10
101     WRITE (64,5) K, (X(I), I=ISR,IST)
5       FORMAT (1H , I4, 5(1PE12.3, ' +', E10.3, 'I'))
        IST = IST + 10
        ISR = ISR + 10
        K = K + 5
```

```
        IF (IST-N2) 101, 102, 102
102     WRITE (64,5) K, (X(I), I=ISR,N2)
C
C  IF REQUESTED, WRITE THE FOURIER COEFFICIENTS TO TAPE OR DISK.
C
113     IF (IEV) 116, 115, 116
116     CALL WAITFR (IEV)
        IF (IEV) 117, 117, 118
117     WRITE (63,14) FSV, LU, IEV
14      FORMAT (' *** FILE "', A5, ' PNB" ON LUN' I3, ' CANNOT BE OPENED;
        1 COEFFICIENTS WILL NOT BE SAVED.' / 5X, 'EVENT VARIABLE:'
        2 I5)
        ISV = 0
        GO TO 115
118     K = 0
        ISR = 1
        IST = 16
119     IF (IST-N) 121, 122, 122
.122    WRITE (LU, ERR=401) (X(I), I=ISR,IST)
        ISR = ISR + 16
        IST = IST + 16
        GO TO 119
121     IST = ISR + 1
        WRITE (LU, ERR=401) X(ISR), X(IST), XX
124     CALL CLOSE (LU, FSV, 3HPNB, IEV)
C
C  SEE IF SUBROUTINE BTA14E, COMPUTING THE POWER SPECTRAL DENSITY
C   FUNCTION (PSDF), IS TO BE CALLED.
C
115     WRITE (63,1)
1       FORMAT (' IS THE PSDF TO BE COMPUTED?')
        READ (63,2) QRY
2       FORMAT (A3)
        IF (QRY .EQ. YES) ISD = 1
C
C  SEE IF THE INVERSE TRANSFORM IS TO BE USED TO RECOMPUTE THE
C   ORIGINAL DATA.
C
        WRITE (63,7)
7       FORMAT (' PERFORM INVERSE TRANSFORM?')
        READ (63,2) QRY
        IF (QRY .EQ. YES) INV = 1
C
C
C  CHECK FOR THE PROPER CLOSING OF THE STORAGE FILE, IF OPENED.
C
        IF (ISV) 131, 132, 131
131     CALL WAITFR (IEV)
        IF (IEV) 133, 133, 132
133     WRITE (63,15) FSV, LU, IEV
15      FORMAT (' *** FILE "', A5, ' PNB" ON LUN ', I5, ' FOR SAVING
        1 THE FOURIER COEFFICIENTS WAS NOT CLOSED.' / 5X, 'EVENT
        2 VARIABLE:', I5)
132     RETURN
C
C  ERROR DETECTED IN WRITING TO TAPE OR DISK.
C
401     WRITE (63,16) FSV, LU
16      FORMAT (' *** WRITE ERROR IN SAVING THE FOURIER COEFFICIENTS
        1 IN FILE "' A5, ' PNB" ON LUN', I3, '.')
        GO TO 124
C
        END
```

```
C
C  SUBROUTINE BTA14E, THE FIFTH OVERLAY OF TASK BTA14.  THIS
C   SUBROUTINE COMPUTES, PRINTS, AND SAVES ON TAPE OR DISK THE
C   POWER SPECTRAL DENSITY FUNCTION (PSDF), ACCORDING TO
C   OPERATOR RESPONSE.  THIS SUBROUTINE ASSUMES THE FOURIER
C   COEFFICIENTS HAVE BEEN PLACED IN COMMON ARRAY X BY SUB-
C   ROUTINES RFORT AND FORT, WHICH THEREFORE MUST HAVE BEEN
C   CALLED PREVIOUSLY.  IF THE PSDF IS SAVED, IT IS WRITTEN
C   IN BLOCKS OF 16 FLOATING POINT NUMBERS, WITH 0.0 TO FILL
C   THE LAST BLOCK AFTER THE LAST OF THE N/2+1 VALUES OF THE
C   FUNCTION.
C
        SUBROUTINE BTA14E
C
        DIMENSION PSD(16)
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
        DATA YES/3HYES/, IPS/0/, IPR/0/
C
C  OBTAIN THE OPERATOR'S DESIRES CONCERNING THE PSDF.
C
        PMX = 0.0
        IPL = 0
        WRITE (63,12)
12      FORMAT (' IS THE PSDF TO BE PLOTTED?')
        READ (63,2) QRY
        IF (QRY .NE. YES) GO TO 101
        IPL = 1
        GO TO 102
101     WRITE (63,1)
1       FORMAT (' IS THE PSDF TO BE SAVED?')
        READ (63,2) QRY
2       FORMAT (A3)
        IF (QRY .NE. YES) GO TO 111
102     IPS = 1
        WRITE (63,3)
3       FORMAT (' ENTER LUN AND SAVE FILE NAME, I2,1X,A5.')
        READ (63,4) LUN, FLS
4       FORMAT (I2, 1X, A5)
C
C  OPEN THE SAVE FILE IF REQUIRED, THEN PROCEED WITH THE
C   OPERATOR QUESTIONS.
C
        CALL ENTER (LUN, FLS, 3HPNB, IEV)
111     WRITE (63,5)
5       FORMAT (' IS THE PSDF TO BE PRINTED?')
        READ (63,2) QRY
        IF (QRY .NE. YES) GO TO 112
C
C  PRINT HEADER IF REQUIRED.
C
        WRITE (64,6) FLE, FRQ, UNT
6       FORMAT ('0POWER SPECTRAL DENSITY FUNCTION ESTIMATE, DATA
        1 FILE "', A5, ' PNB".    HARMONICS OF FREQUENCY', 1PE11.4,
        2 ' PER ', A4)
        WRITE (64,7)
7       FORMAT (4X, 'K', 10X, 'G(K)', 10X, 'G(K+1)', 9X, 'G(K+2)',
        1 9X, 'G(K+3)', 9X, 'G(K+4)', 9X, 'G(K+5)', 9X, 'G(K+6)',
        2 9X, 'G(K+7)')
```

```
      IPR = 1
      IF (IPS) 113, 114, 113
112   IF (IPS) 113, 115, 113
C
C  CHECK FOR THE SAVE FILE OPENING, IF REQUIRED.
C
113   CALL WAITFR (IEV)
      IF (IEV) 116, 116, 114
116   IPS = 0
      IPL = 0
      WRITE (63,8) FLS, LUN, IEV
8     FORMAT (' *** PSDF CANNOT BE SAVED (OR PLOTTED), FILE "', A5,
      1 ' PNB" ON LUN', I3, ' NOT OPENED.' / 5X, 'EVENT VARIABLE:',
      2 I5)
C
C  COMPUTE THE PSDF AND PRINT OR STORE, AS REQUIRED.
C
114   K = 0
      J = 0
      N2 = N+2
C
C  THE FACTOR FOR THE PSDF IS DIFFERENT IF COSINE
C   TAPERING HAS BEEN USED ON THE DATA.  ADJUST IF
C   NEEDED, THEN CONTINUE WITH THE CALCULATION.
C
      FTR = 2.0/FRQ
      IF (ICS) 161, 162, 161
161   FTR = FTR/0.875
162   DO 201 I = 1, N2, 2
      I1 = I+1
      J = J+1
      PSD(J) = (X(I)*X(I) + X(I1)*X(I1)) * FTR
      IF (IPL) 119, 117, 119
119   IF (PMX - PSD(J)) 118, 117, 117
118   PMX = PSD(J)
117   IF (J-8) 121,122,121
122   IF (IPR) 123,201,123
123   WRITE (64,9) K, (PSD(K1), K1=1,8)
9     FORMAT (1H , I4, 8(1PE15.3))
      K = K+8
      GO TO 201
121   IF (J-16) 201, 124, 124
124   J = 0
      IF (IPR) 126, 125, 126
126   WRITE (64,9) K, (PSD(K1), K1 = 9,16)
      K = K+8
125   IF (IPS) 127, 201, 127
127   WRITE (LUN,ERR=301) PSD
201   CONTINUE
      IF (IPR) 131, 132, 131
131   JS = 1
      IF (J-8) 133, 133, 134
134   JS = 9
133   WRITE (64,9) K, (PSD(K1), K1 = JS,J)
132   IF (IPS) 141, 115, 141
141   JS = J+1
      DO 202 K1 = JS,16
202   PSD(K1) = 0.0
      WRITE (LUN,ERR=302) PSD
C
C  FINISHED WITH THE PSDF CALCULATION.  CLOSE THE SAVE FILE
C   IF THE FUNCTION IS TO BE SAVED.
C
152   CALL CLOSE (LUN, FLS, 3HPNB, IEV)
      CALL WAITFR (IEV)
      IF (IEV) 151, 151, 115
```

```
115     RETURN
C
151     WRITE (63,10) FLS, LUN, IEV
10      FORMAT (' *** FILE "', A5, ' PNB" ON LUN', I3, ' COULD
        1 NOT BE CLOSED.' / 5X, 'EVENT VARIABLE:', I5)
        GO TO 115
C
C  WRITE ERRORS DETECTED.  GIVE DIAGNOSTIC MESSAGE.
C
301     WRITE (63,11) LUN, FLS
11      FORMAT (' *** WRITE ERROR DETECTED, LUN', I3, ', FILE "',
        1 A5, ' PNB".')
        CALL CLOSE (LUN, FLS, 3HPNB, IEV)
        CALL WAITFR (IEV)
        IPS = 0
        GO TO 201
302     WRITE (63,11) LUN, FLS
        GO TO 152
        END
```

```
C
C   SUBROUTINE BTA14F, SIXTH OVERLAY FOR TASK BTA14.  THIS
C    SUBROUTINE PLOTS THE POWER SPECTRAL DENSITY FUNCTION
C    (PSDF).  THE PLOT IS LOG PSDF VS. EITHER SAMPLE NUMBER
C    OR LOG SAMPLE NUMBER.  THE RANGE FOR THE PSDF IS UP TO
C    SIX DECADES (VALUES MORE THAN SIX ORDERS OF MAGNITUDE
C    BELOW THE MAXIMUM VALUE ARE PLOTTED AS BEING SIX DECADES
C    BELOW).  THE PLOT IS UP TO 3 INCHES HIGH AND IS 8 INCHES
C    LONG.  THE D.C. OFSET IS NOT PLOTTED, AND THE OPERATOR MAY
C    SPECIFY THE NUMBER OF HORMONICS USED.
C
C   THIS SUBROUTINE EXPECTS THE PSDF TO BE ON A MASS STORAGE
C    DEVICE (WITH THE LOGICAL UNIT NUMBER PASSED THROUGH COMMON
C    AS VARIABLE LUN AND THE FILE NAME AS VARIABLE FLS).
C
C   THIS SUBROUTINE REQUIRES SUBROUTINE PLOT TO BE IN THE SAME
C    OVERLAY:
C        LINK6=BTA14F,PLOT
C
      SUBROUTINE BTA14F
C
      DIMENSION PSD(16)
      COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
     1 INV,IERR,ITR,B0,B1
      DATA YES/3HYES/
C
C   POSITION THE PEN INITIALLY.
C
      CALL PLOT (0.0, 0.0, 1)
C
C   OPEN THE MASS STORAGE FILE CONTAINING THE PSDF VALUES.
C
      CALL SEEK (LUN, FLS, 3HPNB, IEV)
C
C   OBTAIN THE DETAILS OF THE PLOT FROM THE OPERATOR.
C
      WRITE (63,1) PMX
1     FORMAT (' FOR THE PSDF PLOT, THE PEAK VALUE IS', 1PE11.4
     1 / ' IS THIS TO BE USED?')
      READ (63,2) QRY
2     FORMAT (A3)
      IF (QRY .EQ. YES) GO TO 101
      WRITE (63,3)
3     FORMAT (' ENTER VALUE TO REPLACE MAX. FOR SCALING, E12.4.')
      READ (63,4) SMX
4     FORMAT (E12.4)
      GO TO 102
101   SMX = PMX
102   SMX = ALOG10(SMX)
      WRITE (63,5)
5     FORMAT (' ENTER NUMBER OF POINTS TO BE PLOTTED, I4.')
      N2 = N/2
      READ (63,6) NP
6     FORMAT (I4)
      IF (NP - N2) 103, 103, 104
104   NP = N2
103   SNP = NP
      WRITE (63,7)
7     FORMAT (' IS THIS A SEMI-LOG PLOT?')
      READ (63,2) QRY
```

```
      LOG = 0
      IF (QRY .EQ. YES) GO TO 105
      LOG = 1
      SNP = ALOG10(SNP)
105   SNP = 8.0/SNP
C
C  CHECK TO INSURE THE FILE IS OPEN.
C
      CALL WAITFR (IEV)
      IF (IEV) 111, 111, 112
111   WRITE (63,8) FLS, LUN, IEV
8     FORMAT (' *** FILE "', A5, ' PNB" ON LUN', I3, ' COULD
     1 NOT BE OPENED.' / 5X, 'EVENT VARIABLE:', I5, 5X, 'NO
     2 PLOT.')
      GO TO 132
C
C  READ THE PSDF FILE (TAPE OR DISK) AND PLOT THE VALUES.
C
112   I = 0
113   READ (LUN,END=301,ERR=302) PSD
      IF (I) 114, 114, 115
114   J = 2
      GO TO 116
115   J = 1
116   I = I + 1
      Y = (ALOG10(PSD(J)) - SMX)*0.5 + 3.0
      IF (Y) 121, 122, 122
121   Y = 0.0
122   IF (LOG) 123, 124, 123
124   X = FLOAT(I) * SNP
      GO TO 125
123   X = ALOG10(FLOAT(I)) * SNP
125   CALL PLOT (X, Y, 0)
      IF (I - NP) 127, 128, 128
127   IF (J - 16) 126, 113, 113
126   J = J + 1
      GO TO 116
128   CALL PLOT (X, Y, 1)
129   CALL CLOSE (LUN, FLS, 3HPNB, IEV)
      CALL WAITFR (IEV)
      IF (IEV) 131, 131, 132
131   WRITE (63,16) FLS, LUN, IEV
16    FORMAT (' *** ERROR IN CLOSING FILE "', A5, ' PNB" ON
     1 LUN', I3, '.' / 5X, 'EVENT VARIABLE:', I5)
132   RETURN
C
C  PRINT ERRORS IN READING THE PSDF DATA FILE.
C
301   WRITE (63,17) FLS, LUN
17    FORMAT (' *** REACHED UNEXPECTED END OF FILE "', A5,
     1 ' PNB" ON LUN', I3, '; PLOT ABORTED.')
      GO TO 128
302   WRITE (63,18) FLS, LUN
18    FORMAT (' *** ERROR IN READING FILE "', A5, ' PNB" ON
     1 LUN', I3, '; PLOT ABORTED.')
      GO TO 128
      END
```

```
C
C  SUBROUTINE PLOT TO CONTROL THE SMALL FLAT-BED PLOTTER
C   NORMALLY USED WITH THE ANALOG COMPUTERS.  THIS SUBROUTINE
C   ASSUMES THAT DAC LINES 1 AND 2 ARE CONNECTED TO THE X AND
C   Y PLOT SERVOS, RESPECTIVELY, AND THAT DAC LINE 4 CONTROLS
C   THE PEN POSITION.  THESE DAC LINES SHOULD BE ASSIGNED TO
C   THE TASK CALLING THIS SUBROUTINE.
C
      SUBROUTINE PLOT (X,Y,IPEN,IEV)
      DIMENSION P(3), IOUT(3), IT(2), ITZ(2)
      DATA ITZ/20,1/, IT/3,1/, IOUT/5,6,4/, P/0,0,0,0,0.0/
C
C  PEN CODE:  IF IPEN IS 0, PEN IS TO BE DOWN, OTHERWISE, PEN
C   IS TO BE UP.
C
      IF (IPEN) 11,2,11
11    P(3)=0.0
      GO TO 1
C
C  PEN DOWN - BREAK LINE INTO SEGMENTS.  (IF PEN UP, DO
C   FULL INTERVAL AT ONCE.)
C
2     P(3) = 9.99
      XDIF=X-P(1)
      AXDIF=ABS(XDIF)
      YDIF=Y-P(2)
      AYDIF=ABS(YDIF)
C  BASE NUMBER OF SEGMENTS ON THE SHORTEST DISTANCE:
C   EACH SEGMENT = 1/20 TH OF AN INCH ALONG THE SHORTEST
C   DIRECTION.
      DINT=AXDIF
      IF (AYDIF-AXDIF) 3,4,4
3     DINT=AYDIF
4     DINT=DINT*20.
      N=DINT
      TRINT=N+1
      XINT=XDIF/TRINT
      YINT=YDIF/TRINT
      IF (N) 5,5,9
9     DO 5 I=1,N
      P(1)=P(1)+XINT
      P(2)=P(2)+YINT
      CALL RTOUT (3,IOUT,P,IEV)
      IF(IEV) 7,7,6
7     RETURN
6     CALL MARK (IT,IEVM)
      CALL WAITFR(IEVM)
5     CONTINUE
1     P(1)=X
      P(2)=Y
      CALL RTOUT (3,IOUT,P,IEV)
      IF (IEV) 7,7,8
8     CALL MARK (ITZ,IEVM)
      CALL WAITFR(IEVM)
      RETURN
      END
```

```
C
C   SUBROUTINE BTA14G, THE SEVENTH OVERLAY OF TASK BTA14.  PART ONE OF
C    THIS SUBROUTINE, FOR IGO = 0, COSINE TAPERS THE DATA, AND IF
C    REQUESTED, PRINT THE TAPERED DATA.  PART TWO, FOR IGO = 1,
C    REMOVES THE TAPER FROM THE RE-COMPUTED DATA AS RETURNED BY
C    PREVIOUS CALLS TO RFORT AND FORT TO INVERT THE TRANSFORM.
C
C   THIS OVERLAY MUST ALSO CONTAIN SUBROUTINE COSTP, FOR COSINE
C    TAPERING OF DATA ARRAYS, WHICH IS CALLED BY THIS SUBROUTINE,
C    LINK7=BTA14G,COSTP
C
        SUBROUTINE BTA14G (IGO)
C
        COMMON /PARAM/ M,N,ICS,FLE,FRQ,UNT,IPL,PMX,FLS,LUN,ISD,
        1 INV,IERR,ITR,B0,B1
        COMMON /DATA/ X(2050)
        DATA YES/3HYES/
C
        IF (IGO) 101, 100, 101
C
C   PART ONE, COSINE TAPER THE DATA.
C
12      FORMAT (A3)
14      FORMAT (4X, 'N', 9X, 'X(N)', 9X, 'X(N+1)', 9X, 'X(N+2)',
        1 9X, 'X(N+3)', 9X, 'X(N+4)', 9X, 'X(N+5)', 9X, 'X(N+6)',
        2 9X, 'X(N+7)' )
15      FORMAT (1H , I4, 8(1PE15.3))
C
100     R = 0.1
        CALL COSTP (X, N, R, ISK, 0)
        WRITE (63,17)
17      FORMAT (' PRINT TAPERED DATA?')
        READ (63,12) QRY
        IF (QRY ,NE. YES) GO TO 132
        WRITE (64, 18) FLE, N
18      FORMAT ('0 DATA FROM FILE "', A5, ' PNB" WITH A 10% COSINE
        1 TAPER,', I5, ' POINTS TOTAL.')
        WRITE (64,14)
        DO 302 INX = 1,N,8
        ISM = INX - 1
        ISK = INX + 7
        WRITE (64,15) ISM, (X(ISP), ISP = INX,ISK)
302     CONTINUE
132     RETURN
C
C   PART TWO, CALLED AFTER INVERTING THE FOURIER TRANSFORM, TO PRINT
C    THE RECOMPUTED DATA.
C
101     IF (IERR) 111, 112, 111
111     WRITE (63,1) IERR
1       FORMAT (' *** ERROR IN INVERTING THE FOURIER TRANSFORM.' /
        1 5X, 'IERR:', I3)
112     IF (ICS) 103, 104, 103
103     R = 0.1
        CALL COSTP (X, N, R, I, +1)
C
C   PUT THE TREND BACK IN IF REMOVED.
C
104     IF (ITR) 121,122,123
123     DO 202 ISP = 1,N
```

```
202     X(ISP) = X(ISP) + B0 + B1*FLOAT(ISP)
        GO TO 121
122     DO 203 ISP = 1,N
203     X(ISP) = X(ISP) + B0
C
C  PRINT THE RE-COMPUTED DATA.
C
121     WRITE (64,2) FLE
2       FORMAT ('0RECOMPUTED DATA FROM FILE "', A5, ' PNB.')
        WRITE (64,14)
        DO 201 INX = 1,N,8
        ISM = INX - 1
        ISK = INX + 7
        WRITE (64,15) ISM, (X(ISP), ISP=INX,ISK)
201     CONTINUE
        RETURN
        END
```

```
C                COSINE TAPER (DATA WINDOW) ROUTINE
C
C  THIS SUBROUTINE IS A MINOR MODIFICATION OF ONE WRITTEN
C   BY E. H. BLACKSTONE, M.D., U.S. ARMY AEROMEDICAL
C   RESEARCH LABORATORY, FORT RUCKER, NOW OF THE MEDICAL
C   CENTER, UNIVERSITY OF ALABAMA IN BIRMINGHAM.
C
C     ******************************************************************
C     *                                                                *
C     *      SUBROUTINE COSTP                                          *
C     *                                                                *
C     *      PURPOSE                                                   *
C     *        TO APPLY COSINE TAPER TO BOTH ENDS OF A DATA SERIES     *
C     *        IN ORDER TO MINIMIZE THE SMEARING IN THE FREQUENCY      *
C     *        DOMAIN OF NON-DISCRETE FREQUENCIES PRESENT IN A TIME    *
C     *        ORDERED DATA SERIES.  ALSO CALLED "DATA WINDOWING."     *
C     *        THE TAPER IN A CIRCULAR DIGITAL FOURIER TRANSFORM       *
C     *        BRINGS THE END AND BEGINNING OF THE DATA SMOOTHLY       *
C     *        TOGETHER TO PREVENT THIS SMEARING TO A DEGREE.          *
C     *                                                                *
C     *        OPTIONALLY, THIS TAPERING MAY BE UNDONE.                *
C     *                                                                *
C     *      USAGE                                                     *
C     *        CALL COSTP(Y,NS,R,IERR,INV)                             *
C     *                                                                *
C     *      DESCRIPTION OF PARAMETERS                                 *
C     *        INPUT                                                   *
C     *          Y      - INPUT DATA ARRAY  TO BE WINDOWED             *
C     *         NS      - NUMBER OF DATA POINTS IN EACH SERIES         *
C     *          R      - PROPORTION OF EACH END OF THE DATA SERIES    *
C     *                   TO BE TAPERED.  VALUES SHOULD BE GREATER     *
C     *                   THAN 0.05 AND LESS THAN 0.5.  THE LITER-     *
C     *                   ATURE SUGGESTS 0.1 AS A REASONABLE TAPER,    *
C     *                   THE MORE "SIGNAL-LIKE" THE WIGGLES, THE      *
C     *                   MORE TAPERING THAT CAN BE DONE.              *
C     *         INV     - TAPER IF 0; UNTAPER IF NON-ZERO.             *
C     *                                                                *
C     *       OUTPUT                                                   *
C     *          Y      - TAPERED SERIES (IN PLACE WINDOWING)          *
C     *          R      - INPUT R WILL BE REPLACED BY THE ACTUAL       *
C     *                   NUMBER OF DATA POINTS EQUAL TO THE           *
C     *                   INITIAL PROPORTION.  R=R*NS                  *
C     *                                                                *
C     *       ERROR                                                    *
C     *         IERR    - NS NOT GIVEN, R TOO SMALL OR TOO LARGE       *
C     *           0     - NO ERROR                                     *
C     *           1     - ERROR                                        *
C     *                                                                *
C     *      REMARKS                                                   *
C     *        1.  AS SO CLEARLY EXPLAINED BY BINGHAM,ET AL., THE      *
C     *            DESCRETE FOURIER TRANSFORM PERFECTLY TRANSFROMS     *
C     *            ONLY THOSE DESCRETE FREQUENCIES OMEGA(J).  ANY      *
C     *            FREQUENCY NOT A J IS SMEARED OVER ALL FREQUENCIES   *
C     *            WITH A DECAY CENTERED ABOUT THE NON-DISCRETE        *
C     *            FREQUENCY "OMEGA" OF 1./ABS(OMEGA-OMEGA(K)) AS K    *
C     *            RECEDES FROM OMEGA.  SIGNS ALTERNATE.  THIS DECAY   *
C     *            REPRESENTS "LEAKAGE" AND IS OFTEN UNACCEPTABLE.     *
C     *            THIS DATA WINDOW (COSINE TAPER) REDUCES LEAKAGE     *
C     *           TO ABOUT 1./ABS((OMEGA - OMEGA(K))**3).              *
C     *                                                                *
```

```
C     *       2.  IF AN R LESS THAN 0.05 IS GIVEN, A DEFAULT VALUE      *
C     *           OF 0.1 WILL BE SUBSTITUTED.                           *
C     *                                                                 *
C     *     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED               *
C     *       COSINE (COS), FLOAT                                       *
C     *                                                                 *
C     *     METHOD                                                      *
C     *                                                                 *
C     *       REF. BINGHAM, C., GODFREY, M. D., AND TUKEY, J. W.,       *
C     *       "MODERN TECHNIQUES OF POWER SPECTRUM ESTIMATION,"         *
C     *       IEEE TRANS. ON AUDIO AND ELECTROACUSTICS, VOL. AU-15,     *
C     *       56 - 66, 1967.                                            *
C     *                                                                 *
C     *       Y(T) = Y(T)*WINDOW(T)                                     *
C     *       WHERE                                                     *
C     *         WINDOW(T)=0.5*(1.-COS(PI*(T-1/2)/R))                    *
C     *                                      FOR T=1,...,R              *
C     *         WINDOW(T)=1.                                            *
C     *                                      FOR T=(R+1),...,(NS-R)     *
C     *         WINDOW(T)=0.5*(1.-COS(PI*(NS-T+1/2)/R))                 *
C     *                                      FOR T=(NS-R+1),...,NS      *
C     *         PI=3.1415927...                                         *
C     *         Y=VECTOR OF DATA POINTS                                 *
C     *                                                                 *
C     *       THIS GIVES A WEIGHTING FUNCTION WHICH IN THE FREQUENCY    *
C     *        DOMAIN LOOKS LIKE                                        *
C     *         (1/N)*SUM OVER ALL T OF THE SQUARED TRANSFORM OF        *
C     *         THE WINDOW WEIGHTS, WHICH IN THIS CASE = N-(S/4)*R      *
C     *                                                                 *
C     *******************************************************************
C
      SUBROUTINE COSTP(Y,NS,R,IERR,INV)
      DIMENSION Y(1)
      EQUIVALENCE (T,WINDOW)
      IERR=0
C
C     CHECK TO SEE IF DATA WINDOW IS WITHIN THE PRESCRIBED LIMITS AS SET
C     FORTH ABOVE.  IF NOT, ERROR FLAG IS SET.
C
      IF (NS) 1010,1010,1011
 1011 IF (R-0.05) 1012,1013,1013
 1012 R = 0.1
      IERR = 1
      GO TO 1014
 1013 IF (R-0.5) 1014,1010,1010
C
C     SET UP APPROPRIATE CONSTANTS TO MINIMIZE CALCULATIONS WITHIN THE
C     DO LOOP.
C
 1014 R = FLOAT(NS)*R + 0.01
      IR = R
      IF (IR) 1010,1010,1020
 1020 C1 = 3.141593/R
      NSP1 = NS + 1
      DO 30 I=1,IR
      T = I
      TMHAF=T-0.5
C
C     TAPER WEIGHT FORMED
C
      C1A = C1*TMHAF
      WINDOW = 0.5-0.5*COS(C1A)
      IF(INV) 12,11,12
   12 WINDOW = 1./WINDOW
C
C     APPLY TAPER TO BOTH ENDS OF DATA
```

```
C
   11 Y(I) = WINDOW*Y(I)
      J = NSP1-I
   30 Y(J) = WINDOW*Y(J)
  100 RETURN
 1010 IERR = 1
      GO TO 100
      END
```

APPENDIX C

GRAPHICAL DATA SUMMARY

This section contains additional plots of the data used in this study. For additional information contact Dr. R. Emerson Lynn, Department of Chemical Engineering, The Ohio State University, Columbus, Ohio 43210.

Refer to Table 2 for experimental conditions.

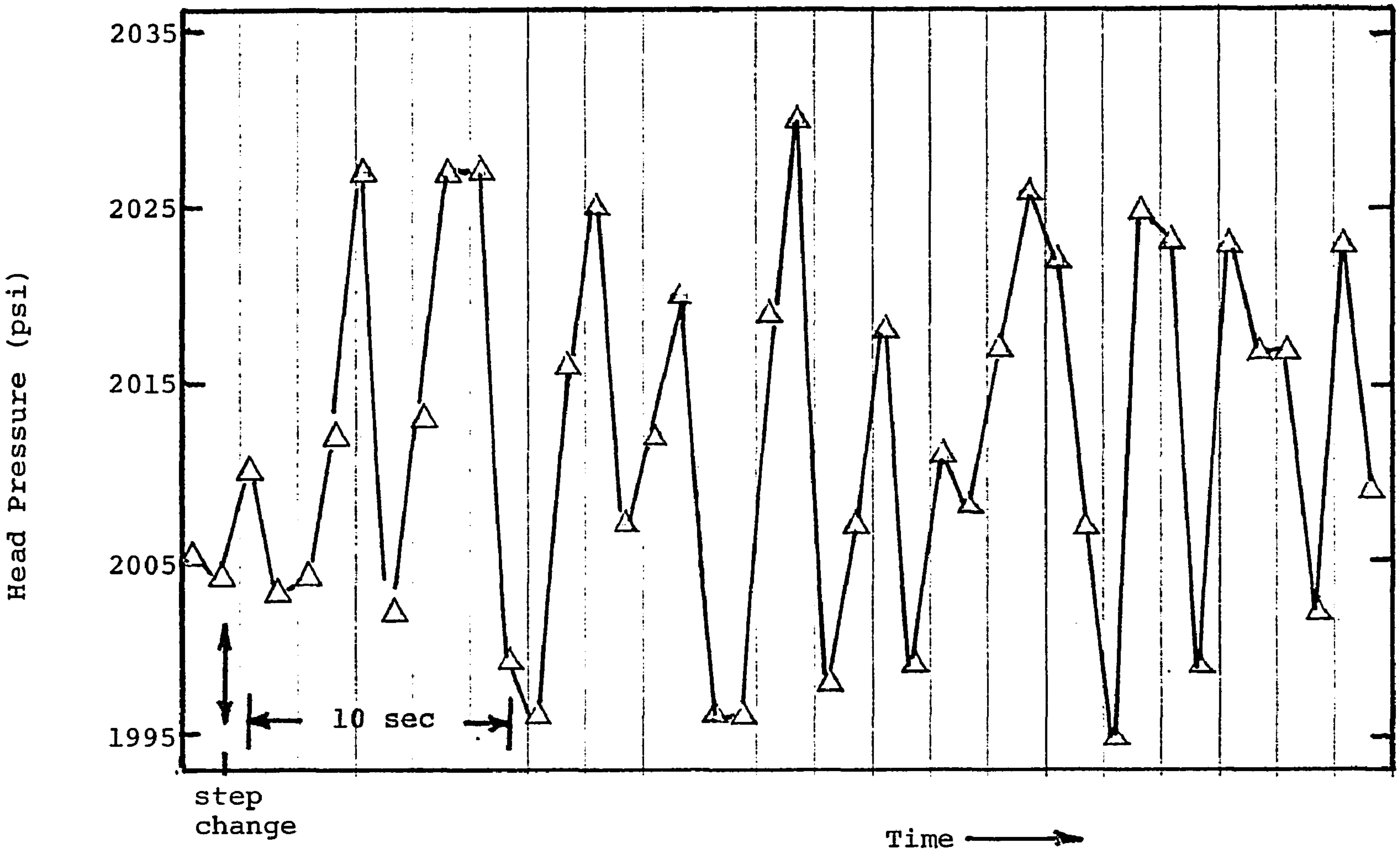


Figure 26.--RN406 Head Pressure DAta--Baffled System

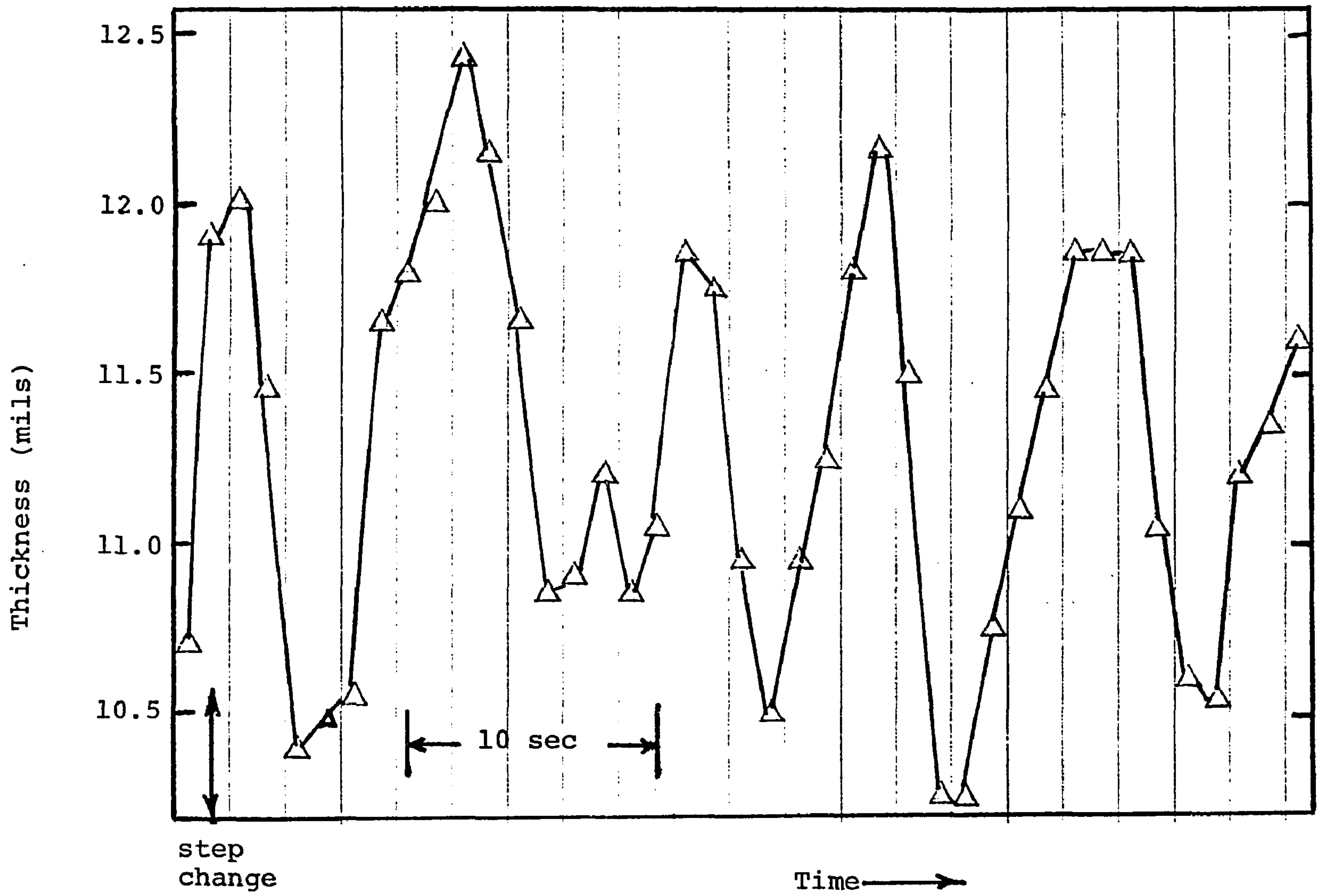


Figure 27.--RN406 Beta Gauge Thickness Data--Baffled System

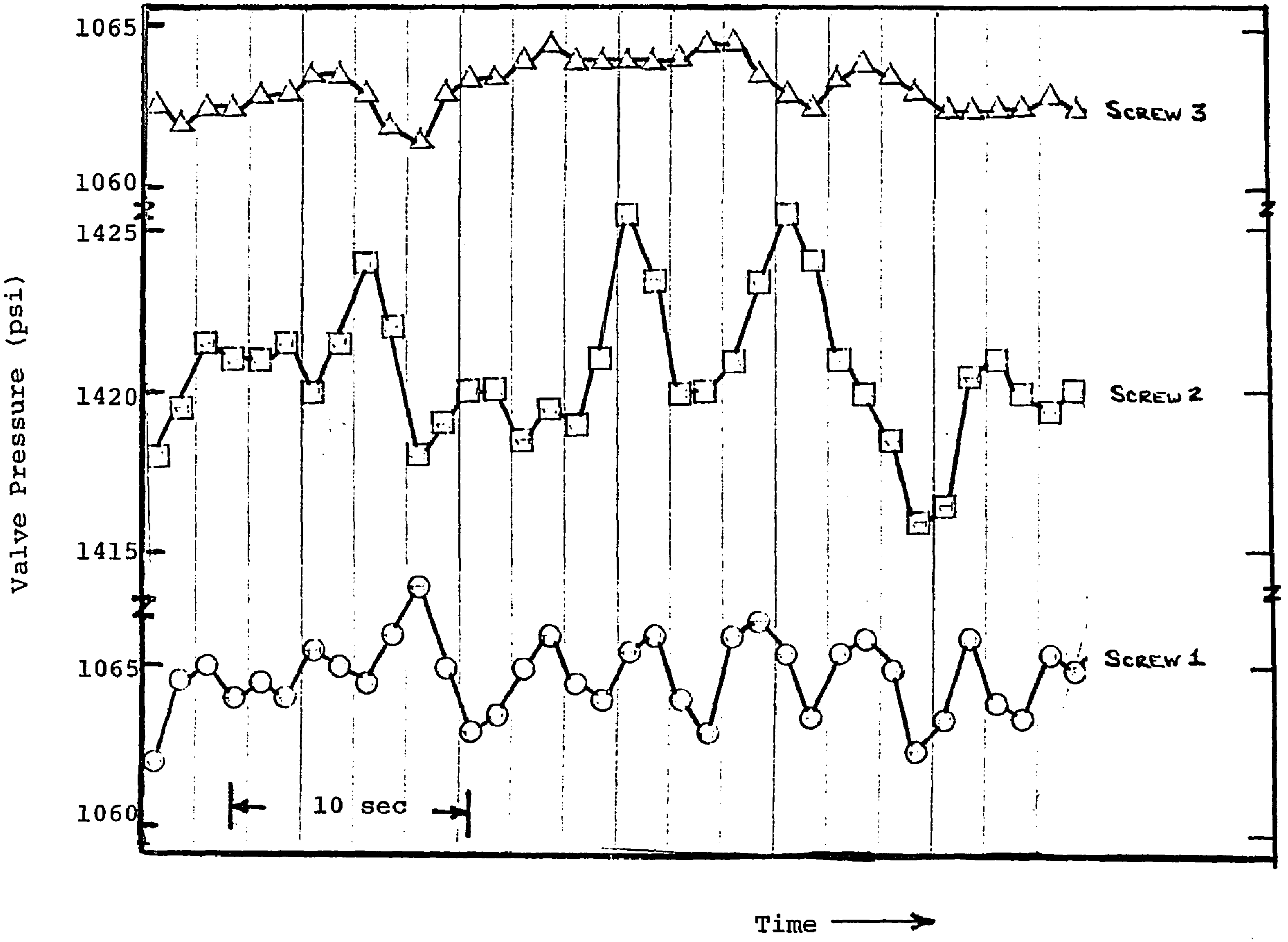


Figure 28.--Screw Configuration Valve Pressure Data

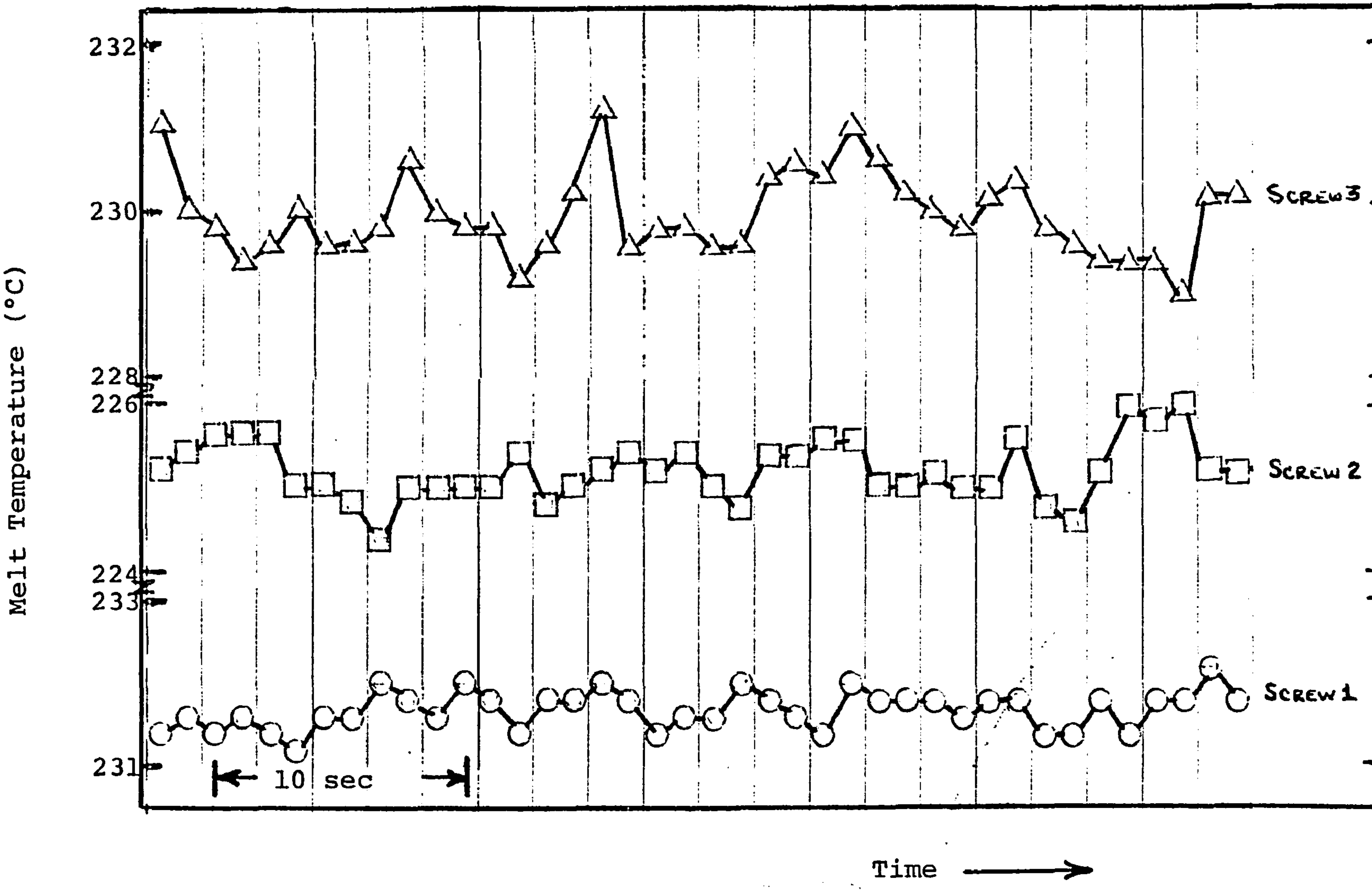


Figure 29.--Screw Configuration Melt Temperature Data

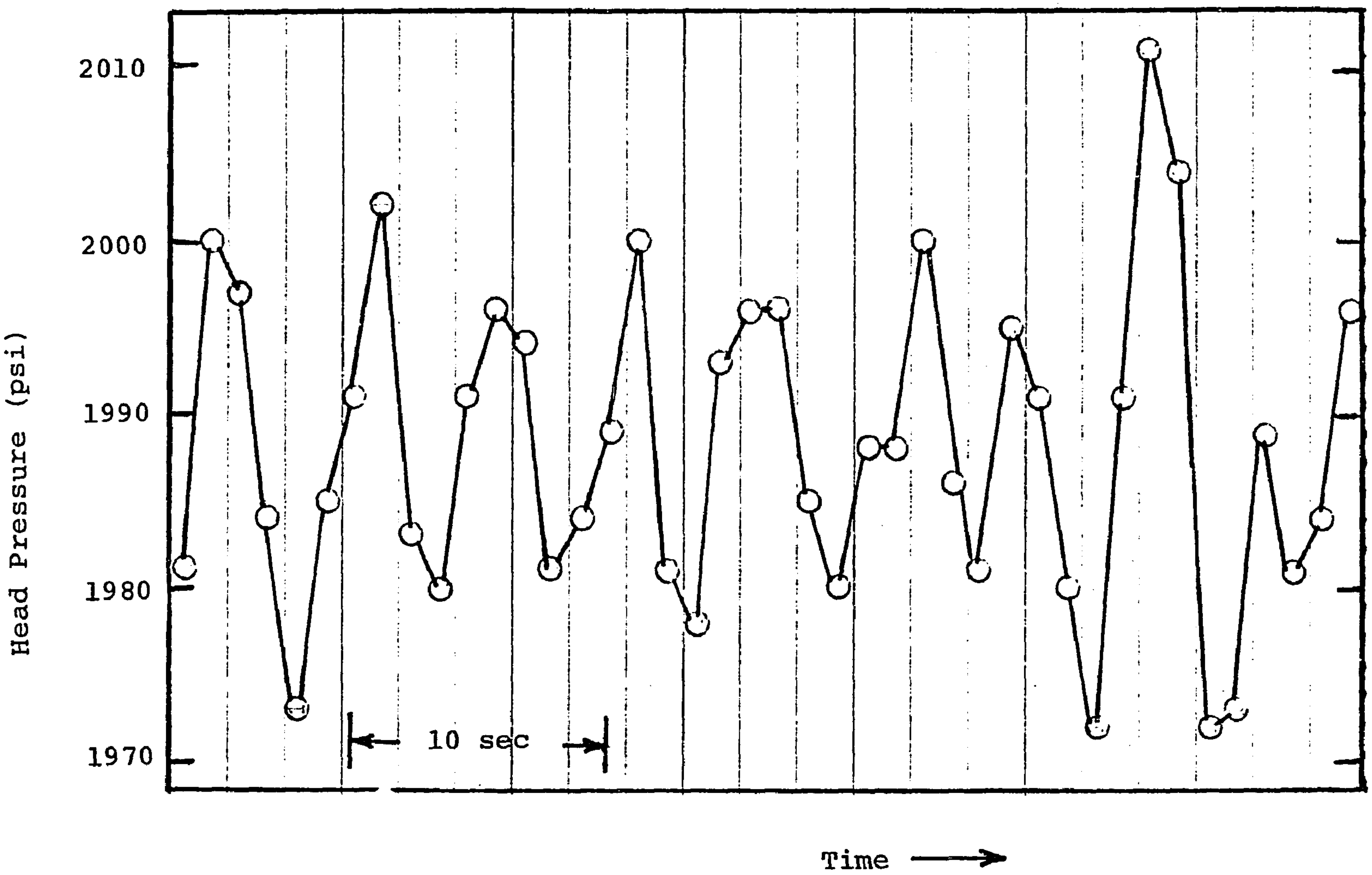


Figure 30.--RN402 Head Pressure Data--Unbaffled System

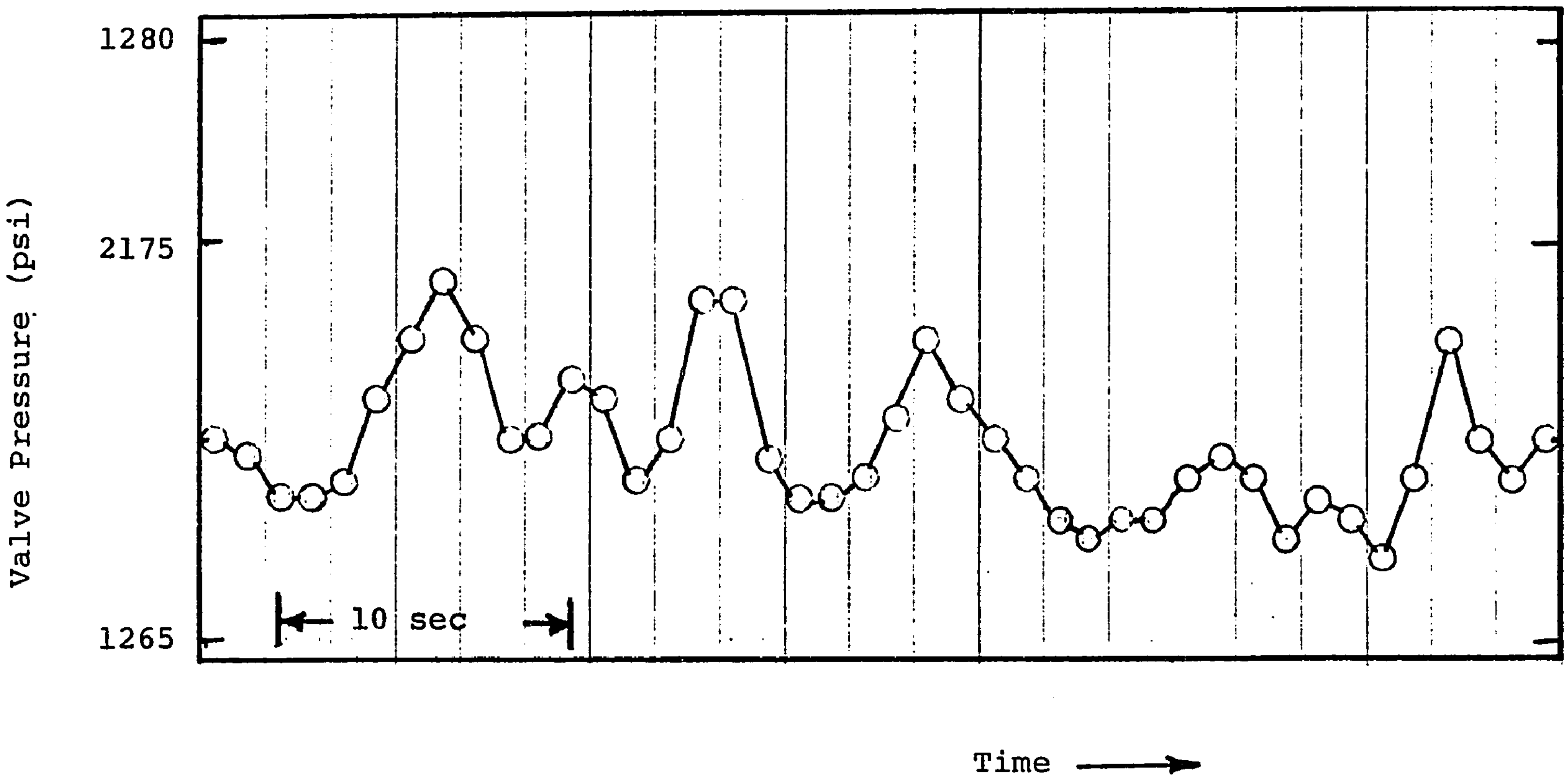


Figure 31.--RN402 Valve Pressure Data--Unbaffled System

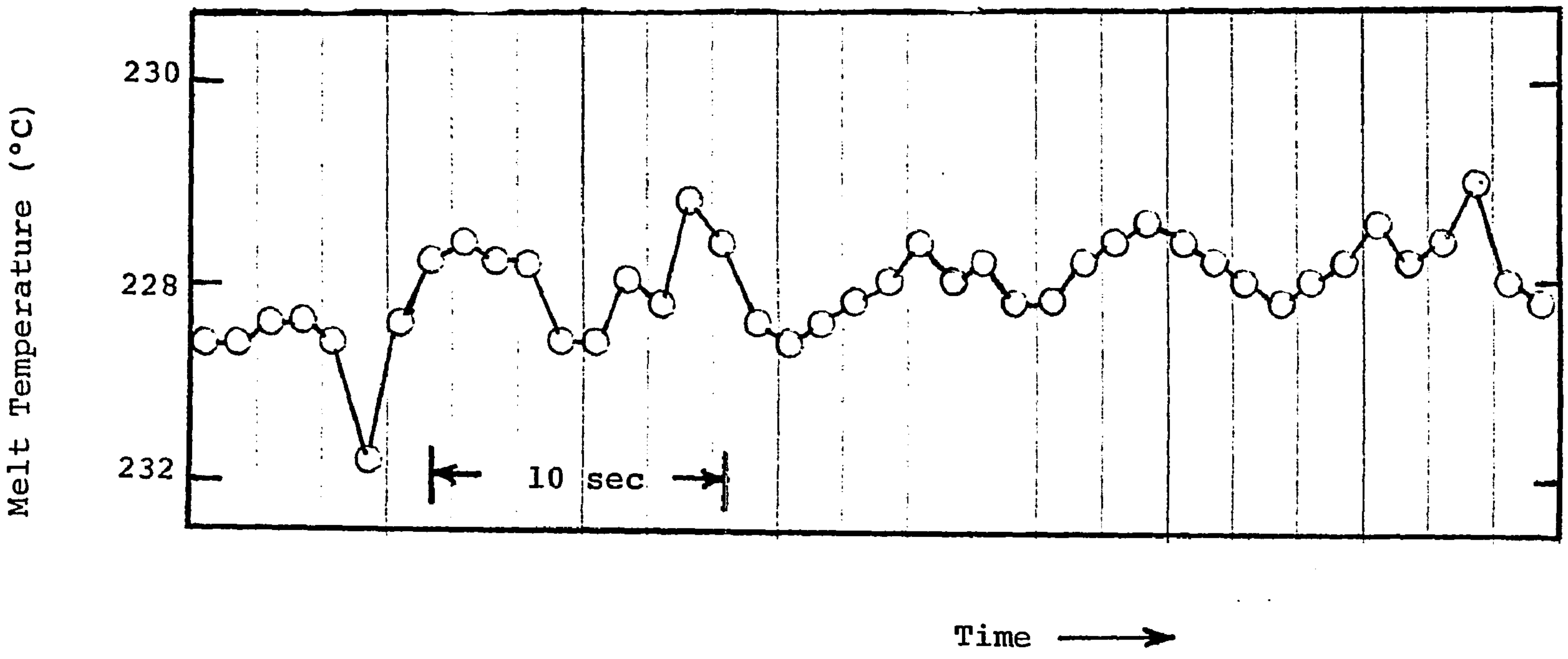


Figure 32.--RN402 Melt Temperature Data--Unbaffled System

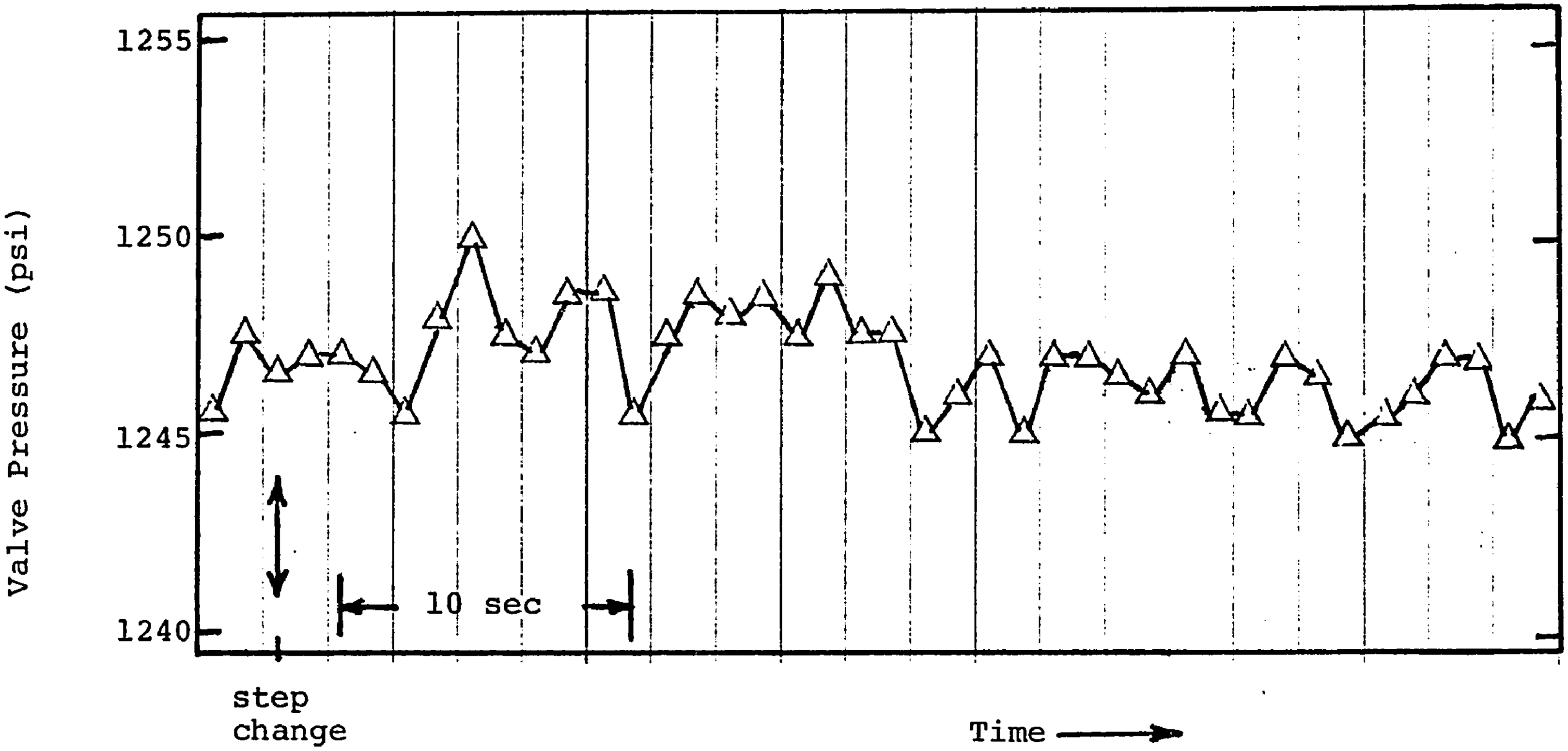


Figure 33.--RN406 Valve Pressure Data--Baffled System

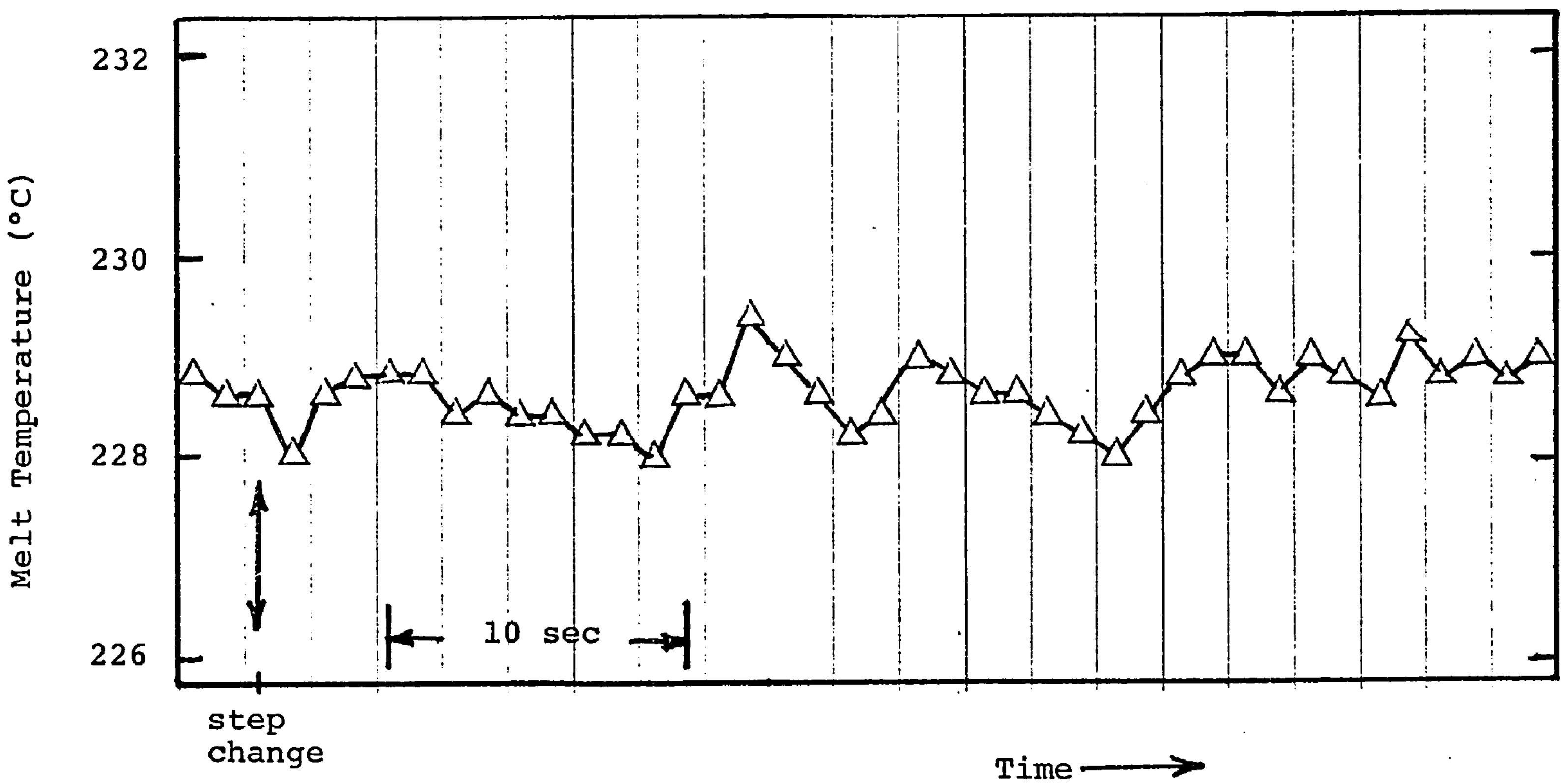


Figure 34.--RN406 Melt Temperature Data--Baffled System

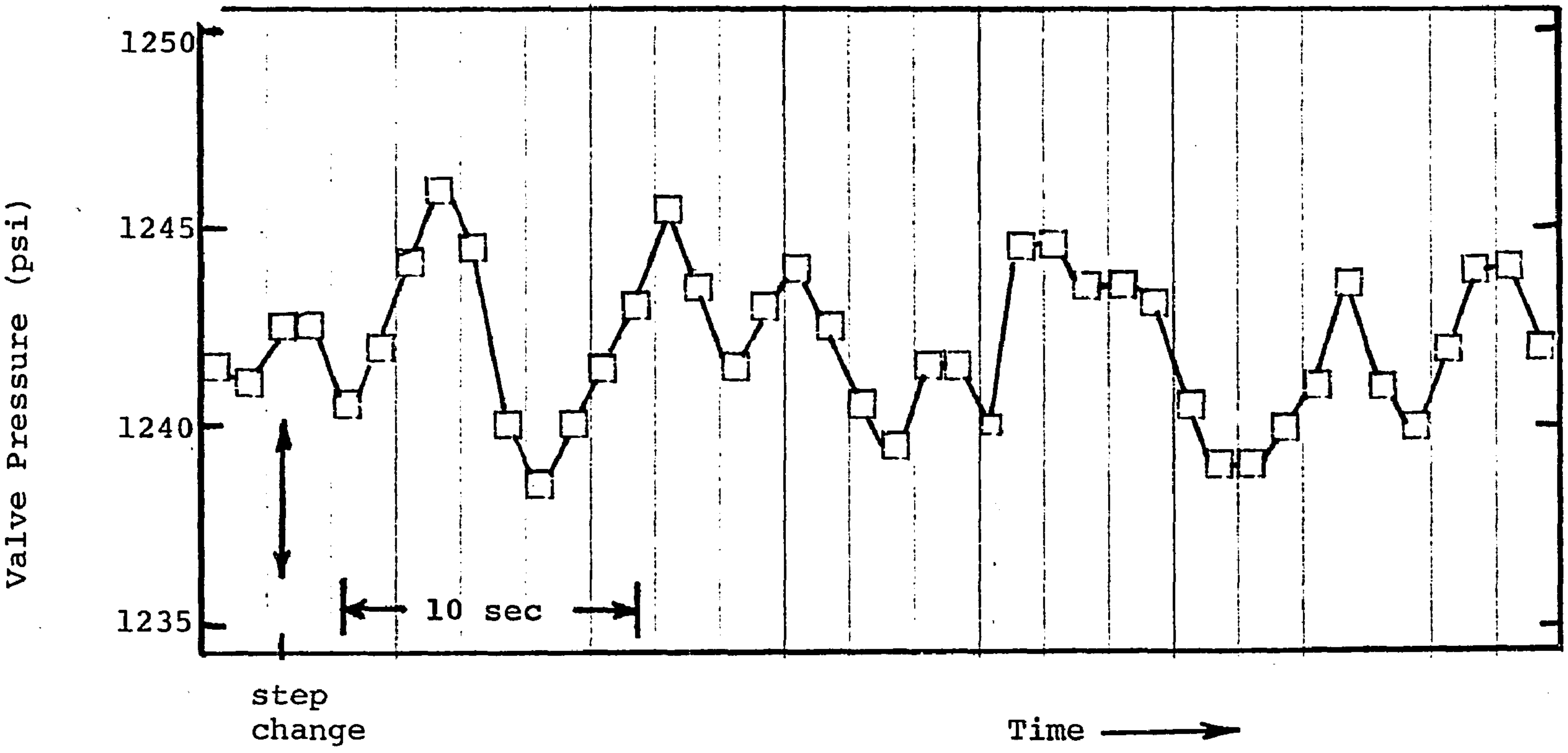


Figure 35.--RN407 Valve Pressure Data--Unbaffled System

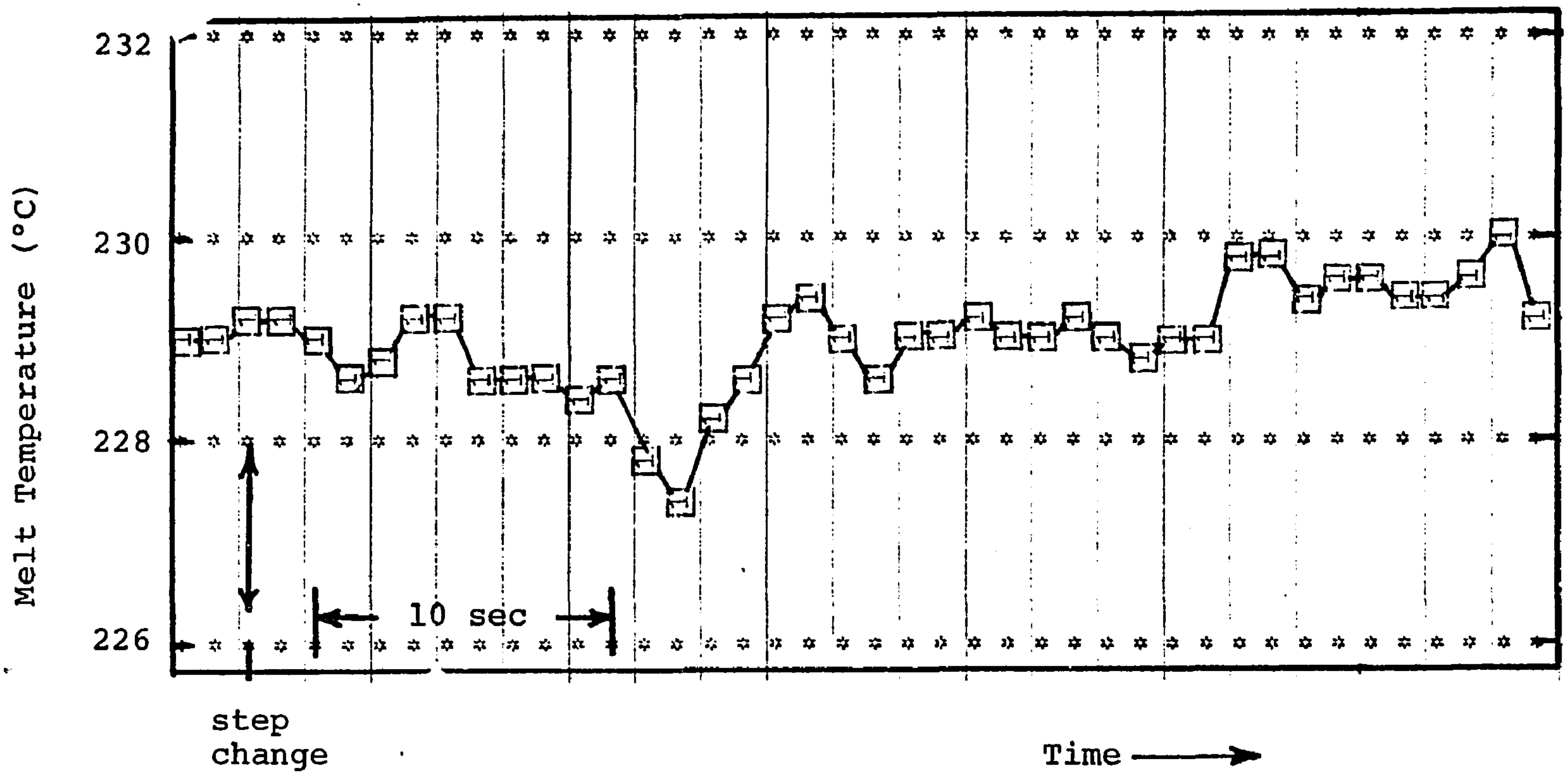


Figure 36.--RN407 Melt Temperature Data-Unbaffled System

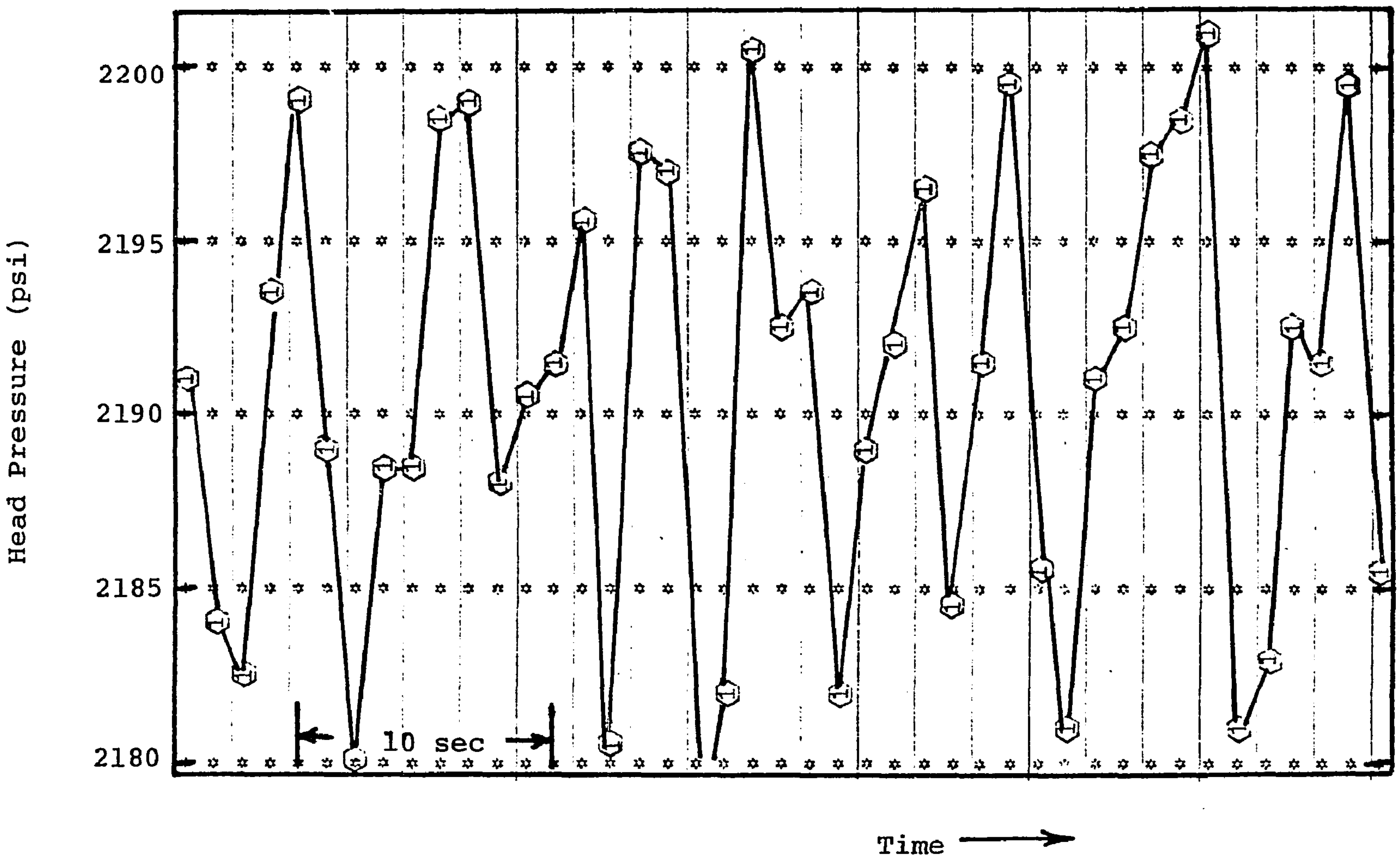


Figure 37.--RN504 Head Pressure Data--Baffled System

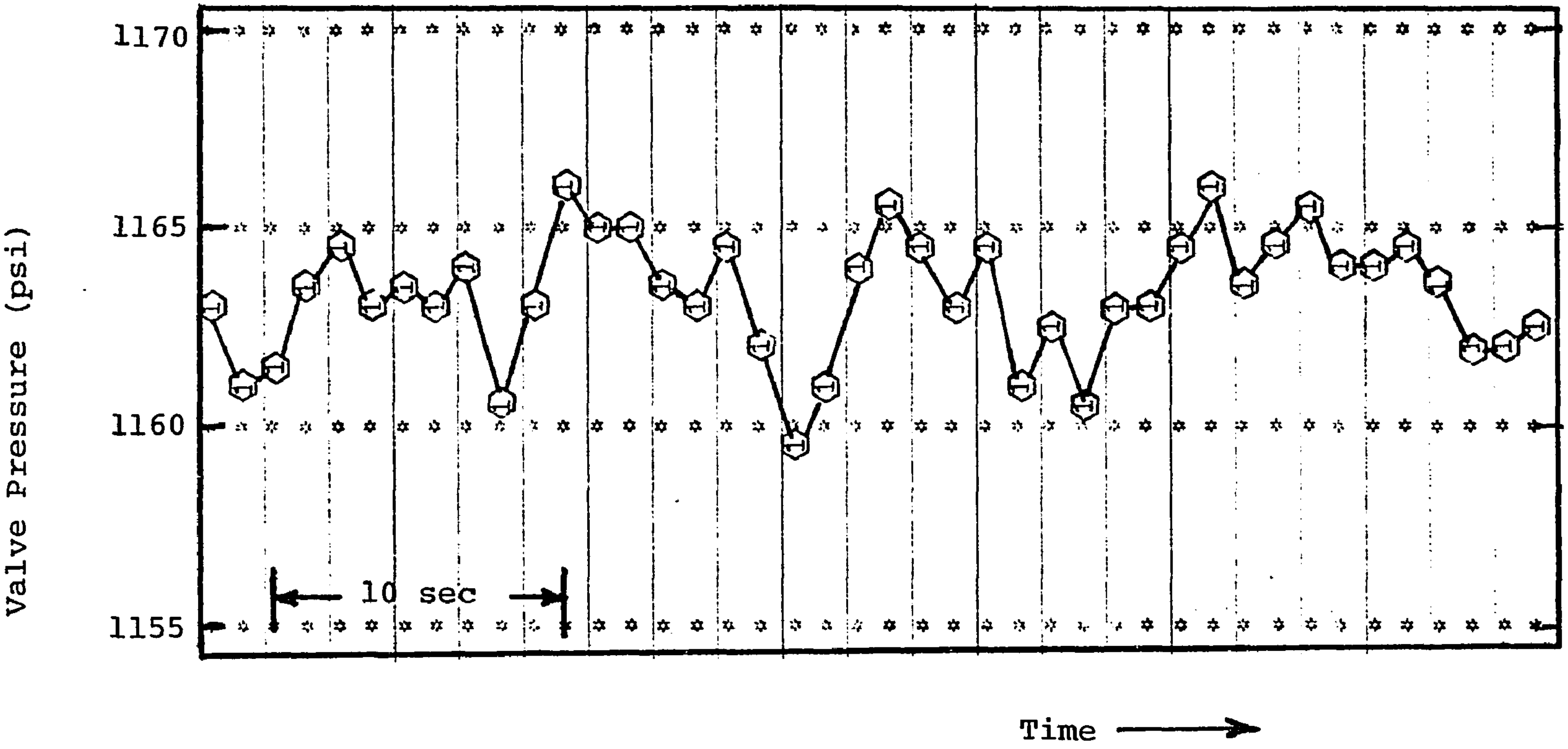


Figure 38.--RN504 Valve Pressure Data--Baffled System

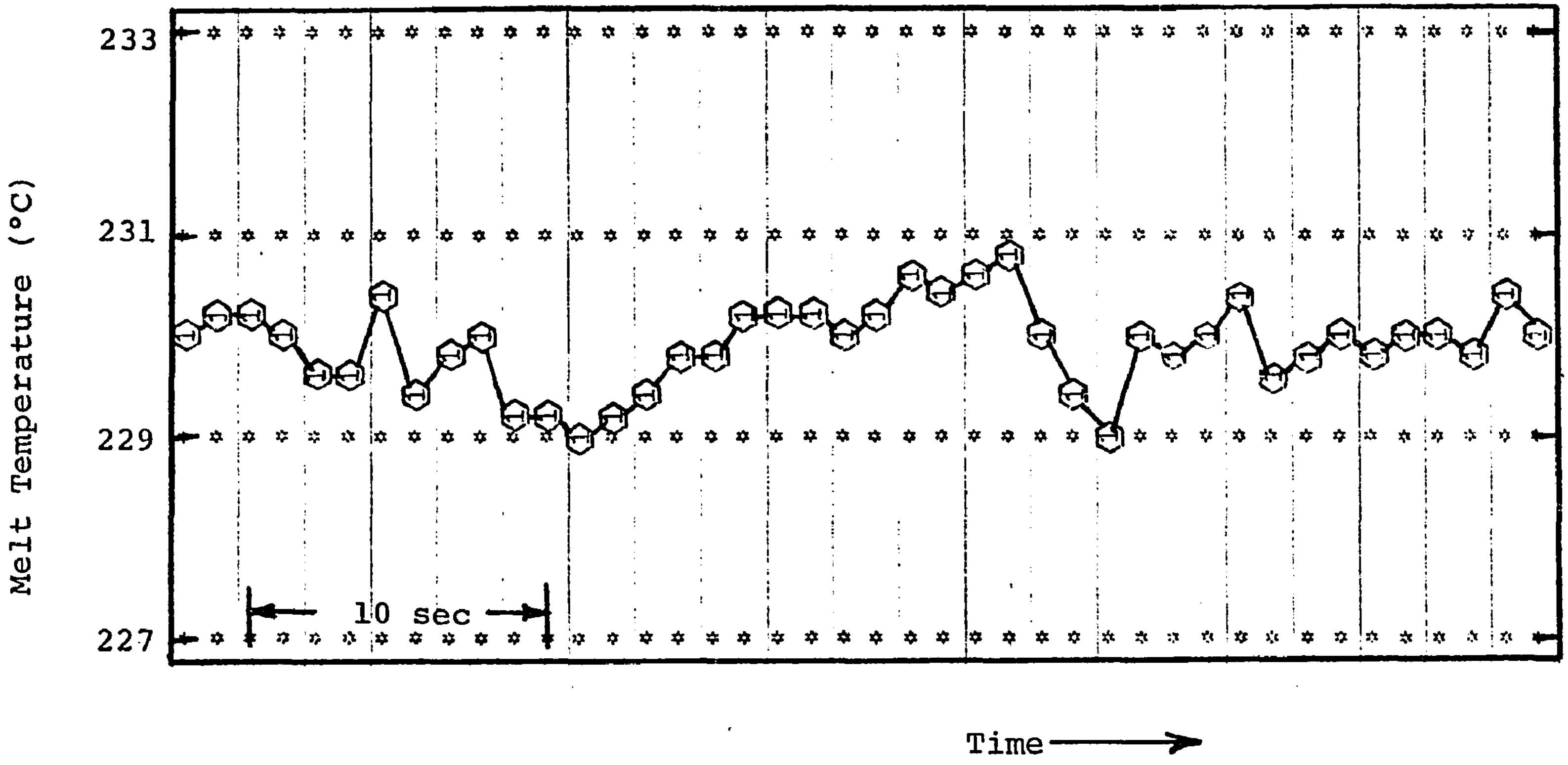


Figure 39.--RN504 Melt Temperature Data--Baffled System

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