An Improved In-line Process Rheometer for Use as a Process Control Sensor

By

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For my parents,
with love.

Abstract

There is a growing recognition in the polymer processing industry of the value of rheometers, in terms of improving process efficiency and product quality, when they are used as sensors for process control. Commercial process rheometers now available are unsuitable for use in many applications because their response is quite slow. Thus, there is a demand for a robust, versatile melt process rheometer having a fast response; the McGill in-line process rheometer, based on a device called a shear stress transducer, seeks to meet this demand. This project deals with additional developments in the design of a prototype rheometer and the construction of an extruder system with which to test this prototype.

Modification of the previously developed shear stress transducer resulted in a marked improvement in the shear stress signal response due to less damping by the polymer melt. Dynamic calibration methods were used to determine the effect of an elastomer seal in the transducer on the signal response. The rheometer was fed polymer melt by a 20:1 L/D, one inch diameter extruder with four PID controlled temperature zones and a microprocessor governed control ~~and~~ data acquisition system. Tests were performed to determine the accuracy of the rheometer in measuring the viscosity and storage and loss moduli of a linear low density polyethylene. Noise problems were encountered with the rheometer motion control system which

interfered with testing and may have influenced the results, which were the correct order of magnitude but did not match values found in literature.

Résumé

Un des instruments le plus souvent requis dans l'industrie de transformation des polymères consiste en un rhéomètre industriel capable de mesurer des propriétés viscoélastiques non linéaires avec un temps de réponse assez rapide pour pouvoir être utilisé comme capteur de contrôle de procédé. Le rhéomètre industriel de McGill, construit à partir d'un capteur de contraintes en cisaillement et placé dans l'écoulement, a pour but de répondre à cette demande. Le présent projet étudie les possibilités de développement additionnel concernant la conception du rhéomètre d'origine et la mise au point d'un système d'extrusion permettant de tester ce prototype.

Des modifications du capteur de contraintes en cisaillement ont abouti à une remarquable amélioration de la réponse au signal du capteur en réduisant l'atténuation que provoquait le polymère fondu. L'utilisation de méthodes de calibrage dynamique a permis de déterminer l'influence d'un joint elastomère du capteur sur la réponse au signal. L'acheminement du polymère fondu dans le rhéomètre est réalisé par une extrudeuse d'un pouce de diamètre et de rapport L/D égal à 20,possédant quatre zones de température controllées (PID). Cette extreudeuse est en outre reliée à un système de contrôle et d'acquisition de données gérés par un microprocesseur. Des mesures de viscosité et des modules élastique et de perte ont été réalisées sur un polyéthylène à basse densité afin de vérifier l'ex-

actitude du rhéomètre. Des bruits de fond générés par le système de contrôle du rhéomètre apparaissant dans les réponses pourraient avoir eu une influence sur les résultats. Ceci devrait expliquer les légères variations entre les résultats relevés dans la littérature et les valeurs expérimentales obtenues qui possèdent, malgré tout, le même ordre de grandeur.

Acknowledgements

I would like to express my deepest appreciation to my supervisors, Professors J.M. Dealy and W.I. Patterson, for their guidance and advice throughout the course of this project. I would like to thank the members of my research group, along with the other students in the polymer engineering group, for stimulating conversation, ideas, and even more advice. I particularly wish to thank Steve Dragan, who provided motor control for the rheometer and much assistance in the assembly of the extruder system. The efforts and recommendations of the machine shop personnel, especially Messrs H. Alexander, W. Greenland and A. Krish, along with those of Mr L. Cusmich of the electronics lab, are gratefully acknowledged.

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List of Symbols

a	distance from end point at which force applied to beam, m
A	area of beam face, m^2
E	beam modulus, $kg \cdot m^{-1} \cdot s^{-1}$
E_b	effective beam modulus, $kg \cdot m^{-1} \cdot s^{-1}$
F_D	damping force, N
G'	storage modulus, MPa
G''	loss modulus, MPa
G^*	complex modulus, MPa
h	gap width, m
I	moment of inertia, m^4
I_b	moment of inertia of beam, m^4
L	length of cantilever beam, m
P	force applied to cantilever beam, N
R	disc radius, m
Re	Reynolds Number
t	time, s
t^*	thickness of cantilever beam, m
w	width of cantilever beam, m
δ	deflection of cantilever beam, m
τ	shear stress, MPa
μ	viscosity, $Pa \cdot s$
Ω	angular velocity, radians/second

1. INTRODUCTION

Polymer process control systems available today can be extremely sophisticated, but they still depend on temperature, pressure and positional variables for their primary inputs. These variables define the state of the system, but contain no direct information about the physical qualities of the polymer melt being processed. To obtain such information, a melt rheometer can be used. Due to the strong nonlinear nature of most melts, most simple viscometers suitable for use with Newtonian fluids are not suitable for use with these materials. Some melt rheometers can measure non-Newtonian viscosity, but very few rheometers, process or laboratory, can make elastic property measurements, especially outside of the linear viscoelastic range. Furthermore, most melt rheometers are used only for quality control, since they have delay times of up to fifteen minutes and are not fast enough for use as process control sensors. A new rheometer has been developed at McGill that is capable of measuring nonlinear rheological properties with a much shorter delay time [6, 7]. A prototype in-line process rheometer has been designed and built [8, 9] which has a response time on the order of seconds instead of minutes. Improvements to this rheometer, and the construction of an extruder apparatus with which to test it are the subject of this work.

The specifications of an ideal process control rheometer are demanding. Since melts are highly non-Newtonian, both the stress and the strain must be known to calculate shear properties. Good motor speed control is necessary to generate strains and strain rates accurately. The instrument must be able to operate at high temperature and must have a uniform temperature distribution throughout the fluid being tested (in spite of viscous dissipation). An ideal rheometer must also be very robust, to function well in a plant environment and to withstand the large forces needed to deform polymers; instrument compliance due to these forces can be a significant source of error. The geometry must be such that a controllable flow is achieved (i.e. one that is the same for all fluids), and disassembly and cleaning must be fairly quick and simple, since any trapped polymer will degrade at high temperature and clog the instrument. The response time must be short enough for the rheometer to be used as a feedback (or feed-forward) sensor. Needless to say, melt rheometers now commercially available fall short of this ideal in at least one and usually more than one of these areas.

1.1 Commercial Process Rheometers

Capillary process viscometers measure the pressure drop of a fluid flowing through a small diameter tube. A gear pump is used to provide the controlled flow, and the sample stream is usually conditioned to a standard temperature before measurements are taken. For Newtonian fluids, the pressure drop is assumed to be entirely due to viscous stresses at the wall and is thus proportional to viscosity. For a non-Newtonian fluid the capillary viscometer measures an apparent viscosity; to get meaningful results the data must be manipulated to calculate actual wall shear rate from the apparent wall shear rate. These rheometers are not suitable for viscoelastic measurements, giving only the viscosity at high shear rates. The Seiscor/Han Slit Rheometer, in addition to measuring viscosity, measures the exit pressure of a melt flow as it leaves the slit. This exit pressure is theoretically related to the first normal stress difference, although some assumptions in the derivation of this relationship have not yet been satisfactorily verified. Other process rheometers, such as the falling cylinder viscometer, also evaluate only viscosity, and have no mechanism for elastic property measurement.

Rotational rheometers tend to have problems generating a uniform flow. Cone and plate rheometers have a sample sandwiched between a flat plate and a rotating cone. Oscillatory shear measurements can be made and the results used to determine the linear viscoelastic properties of a melt. However, irregular flow occurs at the edge of the sample when the shear stress exceeds rather modest levels, and this limits the rheometer to use at small strains or low shear rates. Thus, viscosity can only be measured at low shear rates.

Other problems occur with other types of rotational rheometers, such as the Rheometrics On-line Concentric Cylinder Rheometer. Here a gear pump is used to remove a sample stream from a process line and feed the melt into a gap between two cylinders, one of which oscillates. This rheometer can be used to measure linear viscoelastic variables such as storage and loss moduli. However, there is a significant signal delay due to the use of a side stream and gear pump. Also, the rheometer is difficult to clean and cannot be easily adapted to an existing process.

Almost all commercial process melt rheometers are highly sophisticated, complex and costly. For example, both the Goettfert capillary rheometer and the Rheometrics On-line Rheometer sell for over $100,000 (U.S.). They are on-line, as opposed to in-line, and the sample stream is usually conditioned before entering the rheometer, greatly increasing the response time. Gear pumps used to remove sample streams can affect the shear history of the melt being tested, and this can result in systematic errors in the properties being measured. What is needed is a relatively inexpensive in-line process rheometer with a fast response time that is capable of measuring elastic properties, preferably at large as well as small shear rates. This rheometer should be robust and as simple as possible in design to aid disassembly and repair.

The McGill process rheometer promises improvements in all of the above-mentioned areas. It can measure linear and nonlinear viscoelastic shear properties over a wide range of shear rates with a response time on the order of seconds. Viscoelastic shear properties can often be correlated with material characteristics such as the extent of reaction or molecular weight distributions in reactive extrusion or poly-merization processes, or the composition or state of mixedness of a stream in blending and compounding operations. Control variables such as resin composition can be used much more effectively when their effect on a system can be monitored directly rather than indirectly (i.e. by measuring viscosity instead of monitoring only die pressure). Processes such as precision molding (with close tolerances for swelling or shrinking) or continuous blending could use the rheometer as a control sensor to counteract disturbances such as feed resin quality variations and changing backflow due to screw wear in an extruder. The in-line process rheometer should find applications in many areas of polymer processing as both a process control sensor and a quality control monitor.

1.2 Objectives

The objectives for this project were as follows:

1) To make improvements in the rheometer, specifically in the design of the transducer, and to incorporate an internal gap sensor to monitor fluctuations in the shear gap. If necessary a new rheometer prototype was to be designed and built.

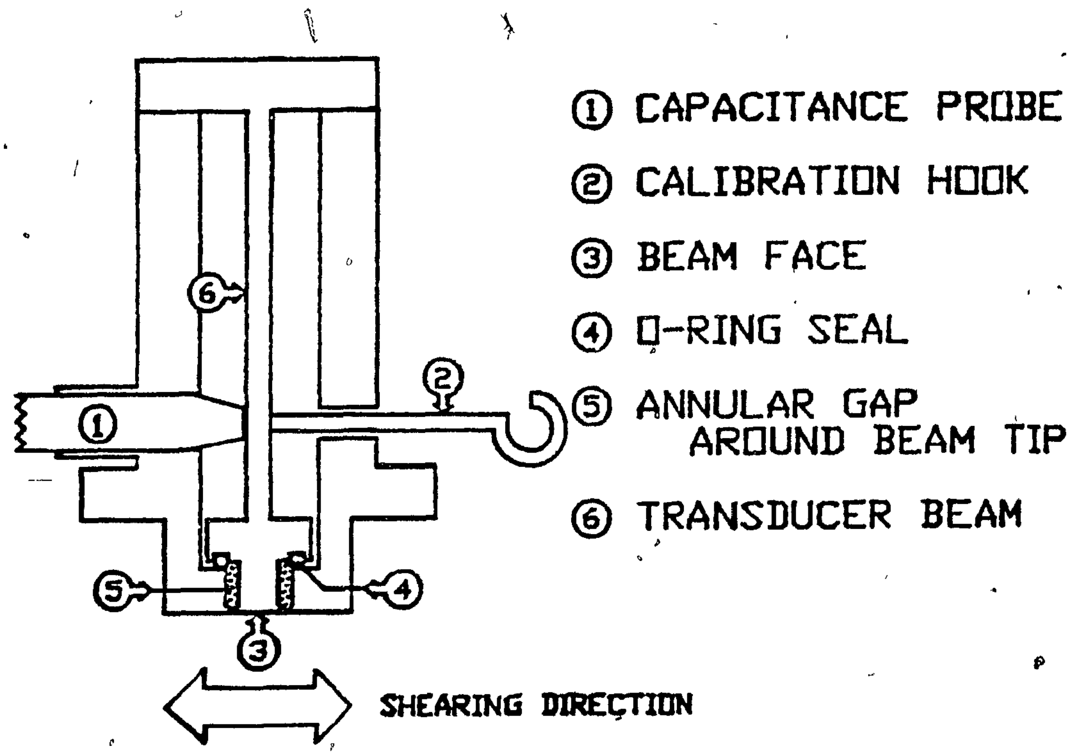
2) To specify components for, assemble and evaluate a new extruder system, with all necessary control apparatus, employing computer data acquisition and control, and to interface this extruder with the rheometer.

3) To use the rheometer to measure viscoelastic shear properties under static and flow conditions, and to determine the effects of flow on these measurements.

2. IN-LINE PROCESS RHEOMETER

2.1 Principles of Operation

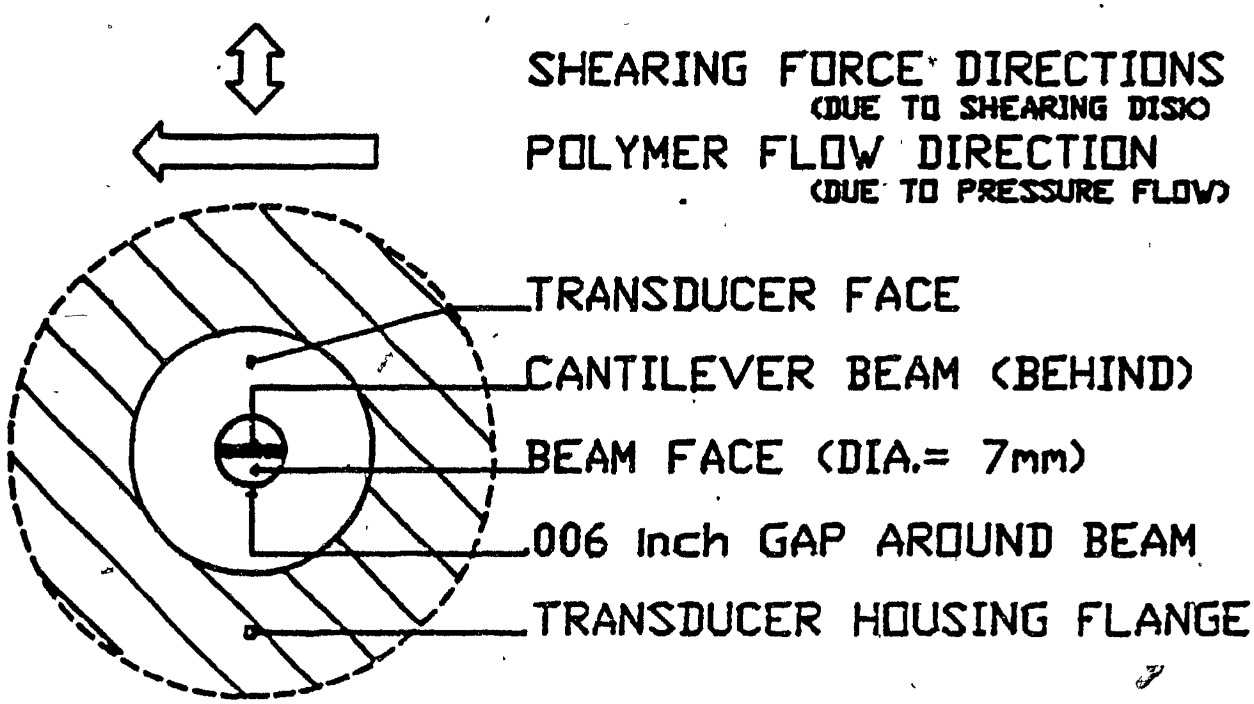
The in-line process rheometer is designed around a device developed at McGill called a shear stress transducer [10]. This transducer (see figure 2.1) is capable of measuring the local shear stress exerted by the polymer on a solid surface. A cantilever beam, one end of which forms a disk on the transducer face (Figure 2.2), is deflected when the polymer exerts a shear stress on the disk face. A capacitance probe measures



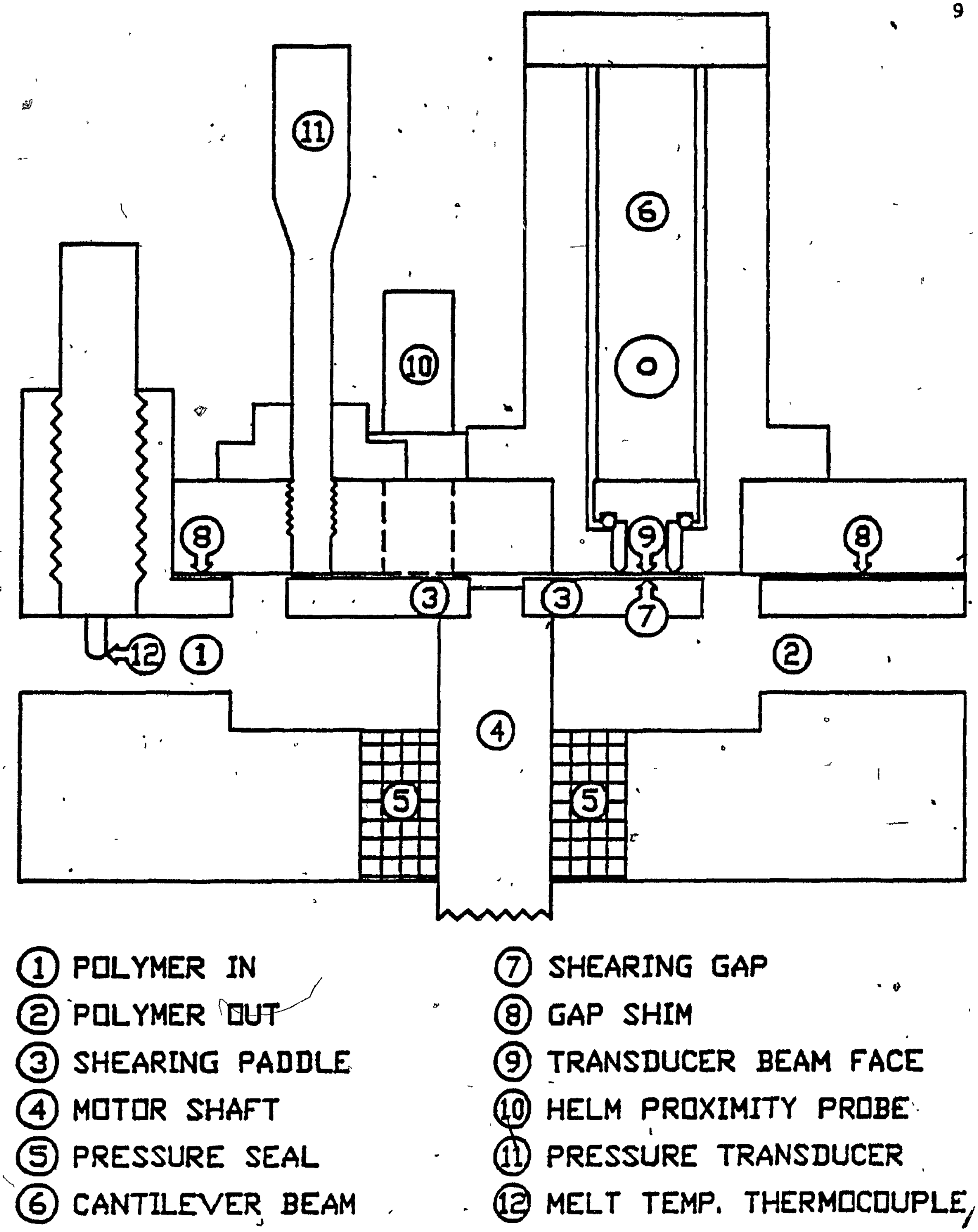
Shear Stress Transducer with O-ring Seal
Figure 2.1

the size of the deflection, sending out a signal that is proportional to the shear stress acting on the end face of the beam. The process rheometer transducer, which must work with polymer under pressure, utilizes an O-ring seal to stop polymer from flowing up into the transducer body.

The first application of the shear stress transducer was to mount it in the stationary plate of a laboratory sliding plate rheometer [6, 7]. A sample is placed in the gap between the two rheometer plates and is sheared up against the transducer by moving the sliding plate. The transducer measures the local shear stress on a relatively small area (the beam face is less than 1 cm in diameter) near the center of the sample; errors due to edge effects are therefore eliminated as long as the sample is not strained so much that the beam face approaches the sample edge.

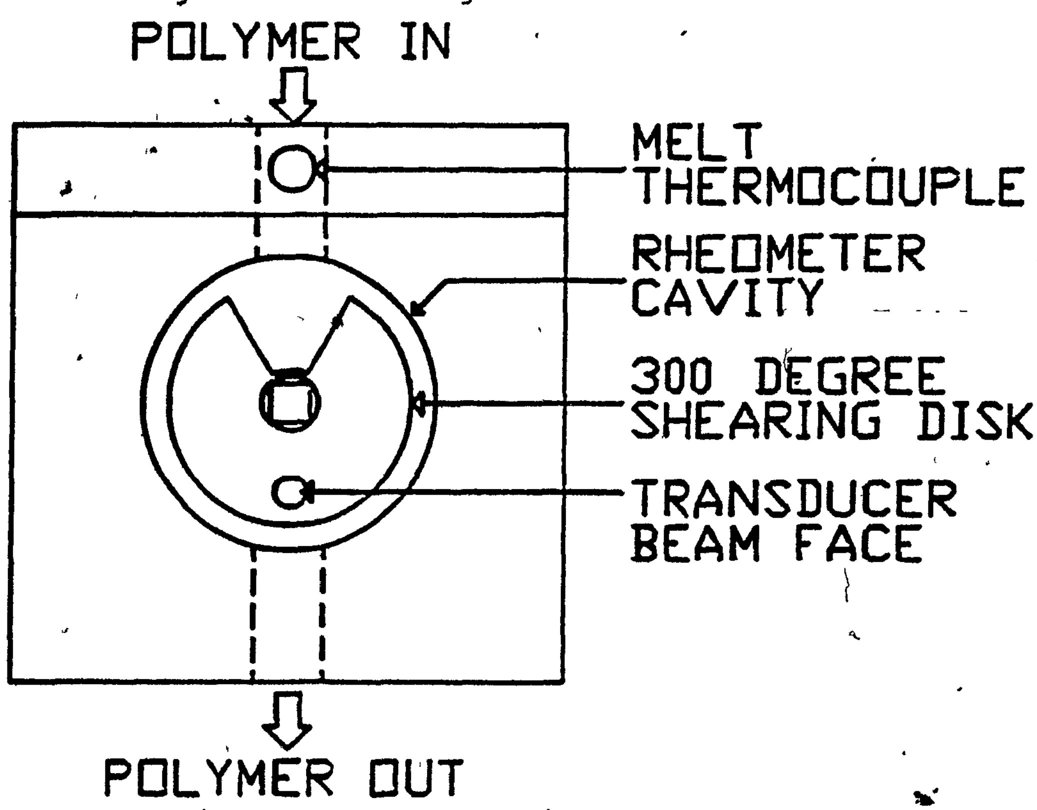


Bottom View of Shearing Surface of Transducer
Figure 2.2



In-line Process Rheometer (Side View)
Figure 2.3

The process rheometer operates on the same basic principle as the sliding plate model. The shear stress transducer is mounted in the top wall of the main cavity in the rheometer body. A flat shearing disk, fixed to a shaft, generates the desired shear deformation in place of the sliding parallel plate used in the laboratory instrument (see figures 2.3 and 2.4). The entire shearing mechanism is immersed in the polymer process stream, with most of the polymer in the cavity flowing beneath the shearing disk. Only a small amount flows through the narrow gap at the top; enough to constantly renew the polymer being tested (giving the rheometer a fast response time), but flowing slowly enough not to interfere with shear stress readings. The rectangular transducer beam is wide (and



Top View of Rheometer with Top Plate Removed
Figure 2.4

therefore stiff) in the direction of melt flow and narrow and more flexible in the direction of the shearing force.

The nonidealities introduced by using a rotating disk in place of a sliding plate are negligible. Due to the high viscosity of polymer melts, the Reynolds number for flow caused by rotation of the shearing disk is very low even at high shear rates ($Re \approx 1 \times 10^{-5}\Omega$, where Ω is the angular velocity of the shearing disk in radians/second). Also, the edge effects that generate instabilities in cone and plate flow are not present because the shearing disk is immersed in polymer, so there is no free surface boundary. Another problem is that the shear rate is not constant across the beam face. Calculations show, however, that negligible errors are incurred when the shear stress measured is associated with the shear rate calculated at the beam face midpoint [8].

The shaft to which the shearing disk is coupled is driven by a DC servo-motor, which can produce a range of preprogrammed movements and waveforms including sinusoidal, ramp and steady shear motions. This allows a wide range of measurements to be made in-line with a relatively simple, compact machine, with a response time fast enough to be useful in process control applications.

2.1.1 Limitations of Previous Apparatus

Several improvements have been made to the original rheometer. The problems addressed involve improved motor control, a proximity sensor for gap width detection inside the rheometer, and improving the response of the shear stress transducer.

An improved motor control system was designed and assembled by Steve Dragan [14]. The previous motor system[1] [8] was useful for steady and interrupted shear but could not produce a sinusoidal motion. The maximum shear rate possible was about 40 s^{-1} and problems with positional drifting also occurred. Also, while the old motor control system was microprocessor controlled, it could not be interfaced with other microcomputers, making automation and data collection and storage very difficult.

A proximity probe is needed to detect any fluctuations in gap width inside the rheometer. The original probe, supplied by Bentley Navada, was not designed to withstand the high temperatures to which it was exposed.

Some problems were encountered with the transducer when shear tests were undertaken while polymer was flowing. The signal from the transducer deteriorated very quickly as polymer melt worked its way inside up to the O-ring seal. It was also noticed that flow startup caused the transducer's baseline to wander, although it would return to normal after about two minutes of continuous flow.

---

1 -- The previous motor system used to drive the shearing disk was a microprocessor controlled EG&G Torque System. While it was possible to program complex linear movements with this system's motion control, no provision was made for sinusoidal movements.

Severe restrictions were placed on the kinds of testing possible by the previous extruder system itself. It was part of a small blow molding machine, with a 3/4 inch, 15:1 barrel, one on/off controlled heat zone, and a single-speed motor. A more flexible extruder, with multiple, PID-controlled heat zones and a variable speed motor, was needed to test the rheometer's process control suitability. Also, computer control and data acquisition systems were necessary to aid in system automation.

2.2 Improvements to the Shear Stress Transducer

Several improvements have been made to the transducer, including a decreased response time and increased sensitivity. The effect of the O-ring pressure seal on the transducer response was also examined, and a gap measurement probe was installed in the rheometer to check for any significant gap size fluctuations during shear measurements.

2.2.1 Gap Size Measurement

A proximity probe was installed in the top plate of the rheometer to monitor for any gap size fluctuations due to disk wobble. This newly developed probe from Helm Instruments[1], designed to work with polymer melts at temperatures of up to 250°C, was damaged by the high shear rates generated in the gap and was unable to provide any reliable information. Care was

1 -- Helm Instrument Co., Maumee, Ohio

taken when assembling the rheometer to ensure that the shearing disk was parallel to the top plate; the wobble in the disk was measured to be ±.25 mil over a 26 mil gap, measured using an ASP-5 capacitance probe (see section 2.2.3) at the outside edge of the disk. It is assumed that the effects of any gap size fluctuations are negligible, since the steady state shear signal measured by the rheometer is level (figure 2.6, level line after transient overshoot).

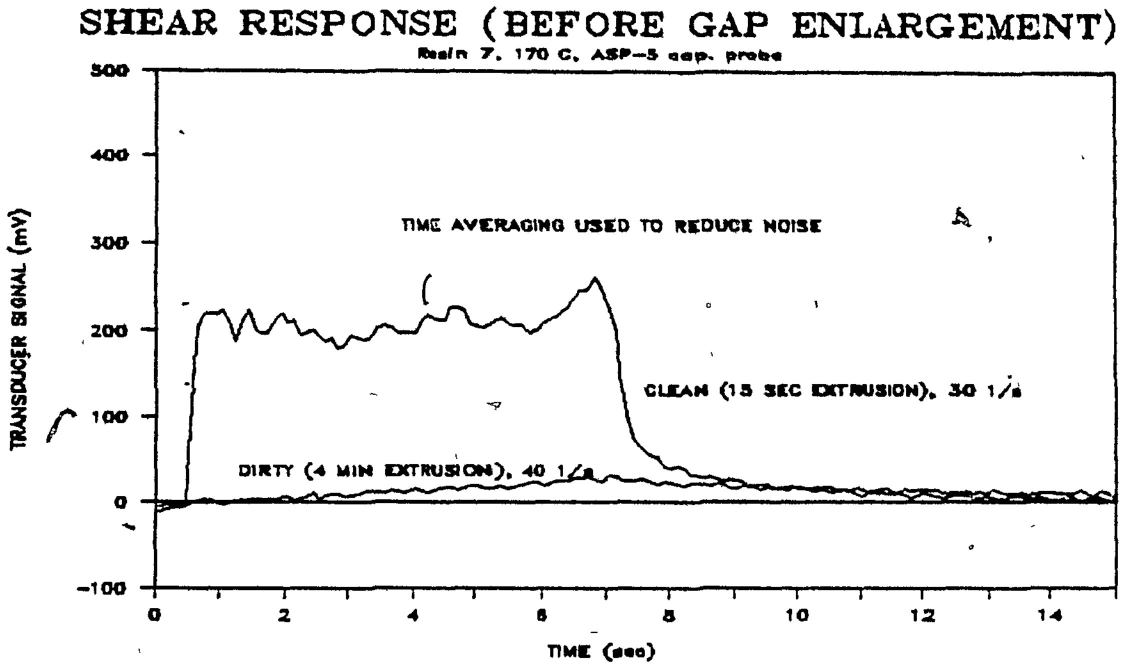
2.2.2 Static Steady Shear Response

In the early stages of this project one major problem with the transducer was the damping of its steady shear signal. Since the O-ring seal was some distance from the face of the beam, polymer would flow up into the 6 mil gap between the beam and the transducer housing. The motion of the beam was thus damped due to the squeezing flow occurring each time the beam moved. From figure 2.5, it can be seen that the response amplitude was lowered and the response time increased as the transducer fills with polymer. Once completely filled, the response was so badly distorted that no useful information could be obtained from it.

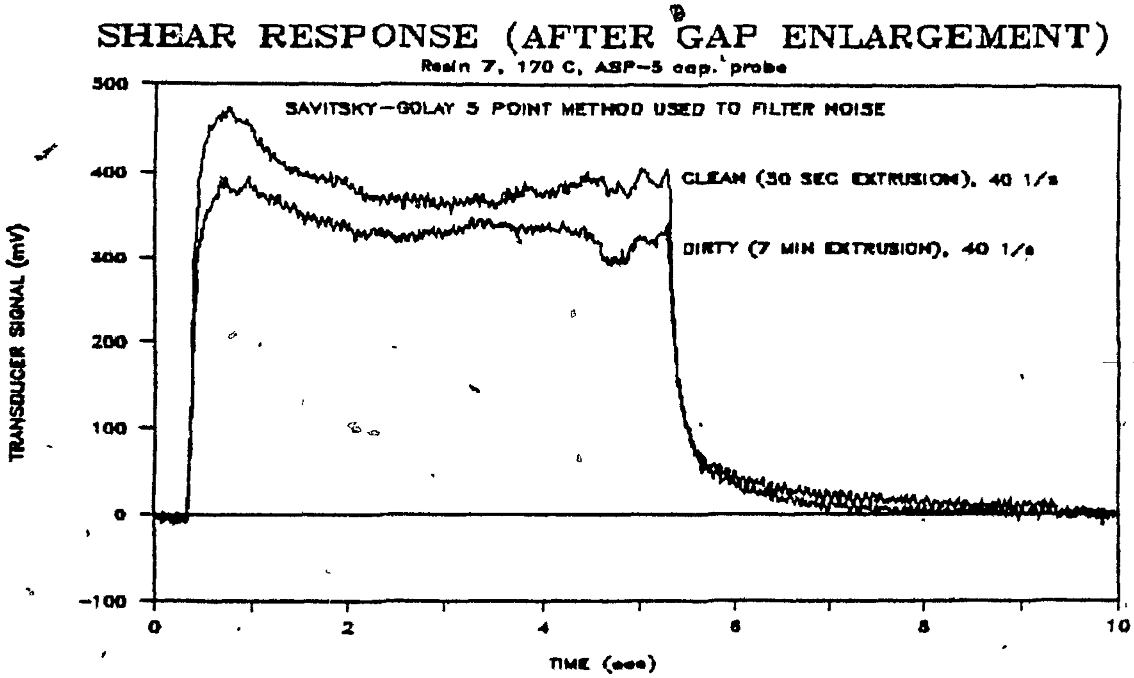
The Stephan equation,

$$F_D = \frac{3\pi R^4 \mu(-dh/dt)}{8h^3}$$

gives the damping force exerted by a polymer squeezed between two parallel discs. R is the disc radius, h is the gap width, μ is the polymer viscosity and F_D is the damping force. In the



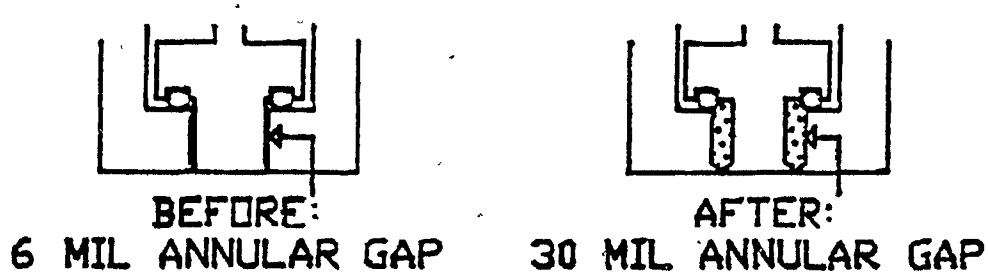
Shear Stress Transducer Response before Modification
Figure 2.5



Shear Stress Transducer Response after Modification
Figure 2.6

transducer the geometry is more complex, but the equation suggests that F_D varies approximately with $1/h^3$.

It was therefore decided to widen the annulus around the beam (figure 2.7) to reduce damping. Figure 2.6 shows the improvement in the response; the signal was cleaner and had a larger amplitude, even after 7 minutes of extrusion, by which time the annulus was completely filled with polymer. The steady shear response shown in figure 2.6 has an initial overshoot (slightly dampened when the transducer is dirty) and an exponential relaxation of stress after cessation of shear. Some degraded polymer was later found on the shearing disk, which is why the response wasn't perfectly smooth once steady state was achieved.



Modifications to Transducer
Figure 2.7

The data were collected using a digitizing storage oscilloscope with a GPIB (General Purpose Interface Bus) computer interface. An IBM PC was used to read the data from the oscilloscope, filter it for noise, and transfer it to the Lotus 123 Spreadsheet program, which was used to print graphs. Originally noise reduction was achieved using a 5 point averaging scheme, where 5 data points were averaged to give a single graph point. This resulted in a slight distortion of the graph. A program was written in BASIC (see Appendix A) incorporating Savitsky-Golay 5 point data smoothing techniques [15,16]. For each point on the graph, the data point and two points before and after are fitted to a quadratic equation using a least-squares criterion; this equation is then used to calculate the smoothed value of the data point. The implementation of the Savitsky and Golay technique is simple; a weighted average is taken around each data point to get the smoothed value at that point. The smoothed derivative of a function can also be easily computed employing this procedure. Better peaks and less signal distortion are some of the benefits of using this method.

2.2.3 New Capacitance Probe

A new, more sensitive capacitance probe was obtained for beam deflection measurements in the shear stress transducer. The previous probe, an ASP-5 probe from MTI[1], had an output sensitivity of 2 V/mil. The new ASP-1 probe is five times more sensitive, at 10 V/mil. A useful range for the transducer is from about .005 MPa to .5 MPa. The calculated range, using the new probe, is from .0002 to .1 MPa (see Appendix B). The actual range, from .001 MPa to .1 MPa, is somewhat less sensi-

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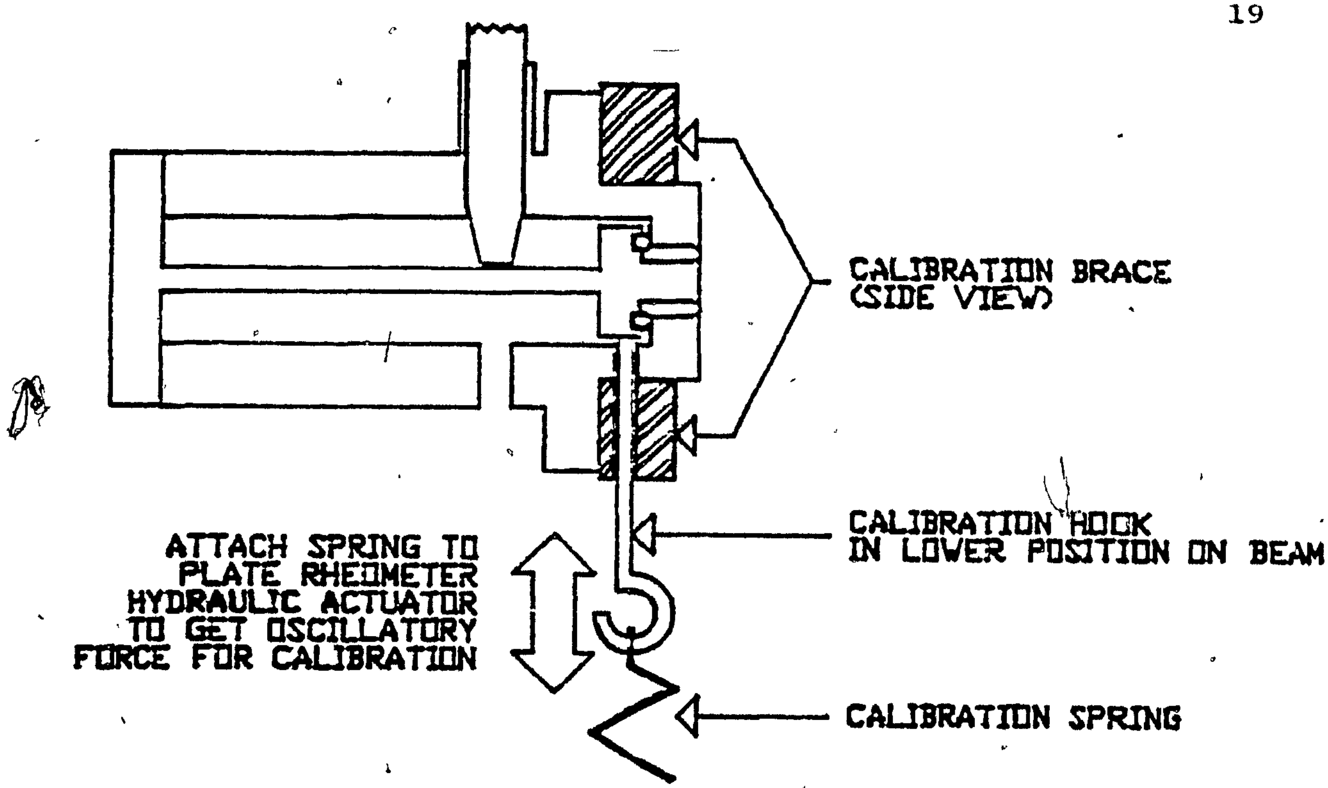
1 -- MTI Instruments, a Division of Mechanical Technology Inc., Latham, N.Y.

tive at the low end due to noise in the probe signal. This is a good range for the transducer, especially if storage and loss moduli measurements are to be taken in the low shear linear viscoelastic region. It may also be desirable to stiffen the beam somewhat; less deflection means less damping due to the O-ring and polymer. Also, mechanical vibrations would tend to have a higher frequency and lower amplitude, making them easier to filter out.

2.2.4 Sealing and Calibrating the Transducer

Since the rheometer operates under pressure, the shear stress transducer must be sealed to prevent polymer leakage. Currently, a Viton O-ring is used (see figure 2.7) as a seal, with a 6 mil axial squeeze to hold it in place. This O-ring causes problems with the dynamic response of the transducer and leaves a stagnant volume around the tip of the beam where polymer will become trapped and degrade. Ideally, the transducer should be sealed at the beam face.

In order to determine the effects of the O-ring on the transducer response, dynamic and static calibrations were required at operating temperatures. These calibrations involve applying known forces to the transducer beam through the calibration hook to simulate a shear stress at the beam face (see figure 2.8). Beam deflections are monitored with the capacitance probe. After appropriate beam calculations, static tests yield a relationship between signal voltage and shear



Transducer Mounted in Calibration Brace
Figure 2.8

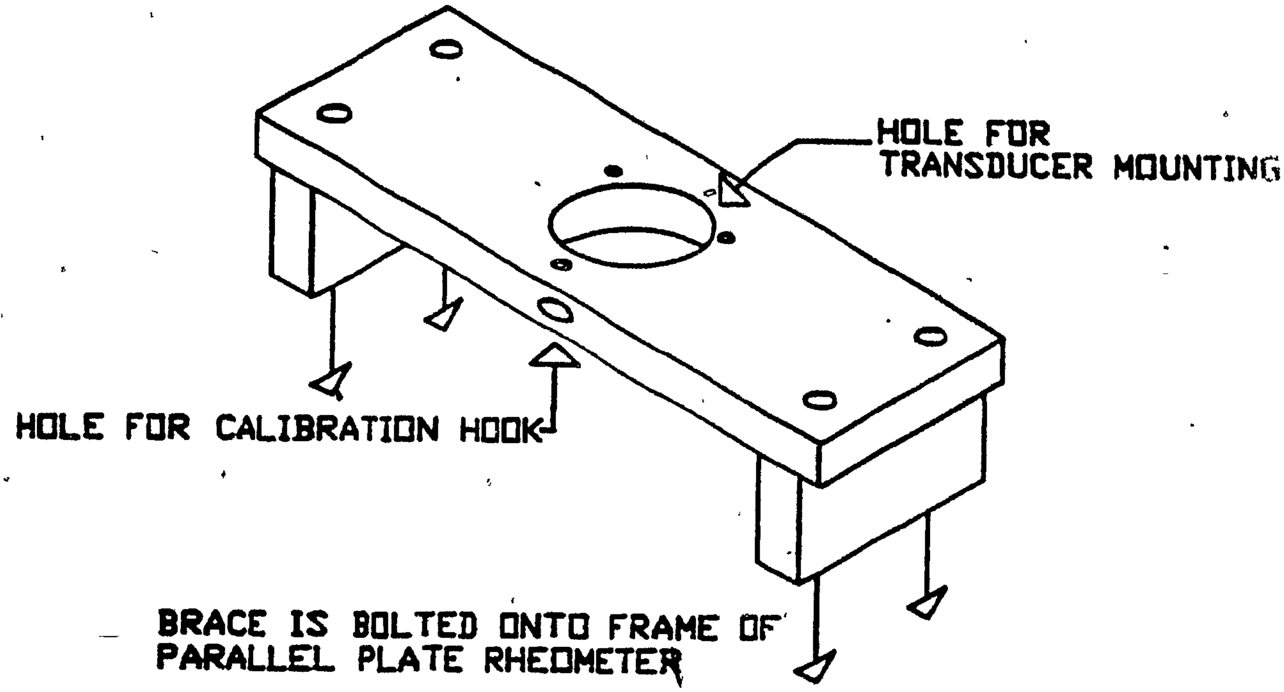
stress at the beam face, while dynamic tests provide the phase lag between the shear stress and the strain caused by the transducer. A calibration brace was constructed (see figure 2.9) that allowed the shear stress transducer to be mounted inside the oven of a laboratory sliding plate rheometer[1] [6, 7]. The hydraulic actuator for the moving plate was connected to the calibration hook of the transducer through a spring with a known Hooke's law constant, and then oscillated to provide the sinusoidal force required to perform a dynamic calibration. Known weights were suspended from the calibration hook to

1 -- The entire sliding plate rheometer is mounted inside an oven to avoid temperature gradients.

determine the static calibration. Since the whole apparatus is mounted in an oven, calibrations can be performed over a wide range of temperatures. They can also be performed with and without the O-ring, and with and without polymer inside the gap, to determine the effect each of these has on the transducer response. Originally the calibration hook was attached to the transducer beam directly opposite to the location of the capacitance probe. It was later moved as close to the end of the beam as possible to minimize any nonidealities in the cantilever beam deflection equations caused by the presence of the O-ring. The transducer beam is no longer a true cantilever beam because the end is no longer able to deflect freely.

When calibrating the transducer for use in the rheometer, polymer should be present in the annular gap at the beam tip, as it will probably have a small damping effect. As well, an absolute calibration for the shear strain will be provided by Steve Dragan [14]. The overall calibration (involving both stress and strain) can be tested by taking measurements of a polymer with known rheological properties.

The first static calibration was performed with the hook in its original position, using an ASP-1 capacitance probe and the process rheometer's probe signal conditioning unit. The purpose of this calibration was to ascertain the effect of the O-ring on the magnitude of the beam's deflection and to determine how best to theoretically account for the O-ring's presence when using the standard cantilever beam equations to

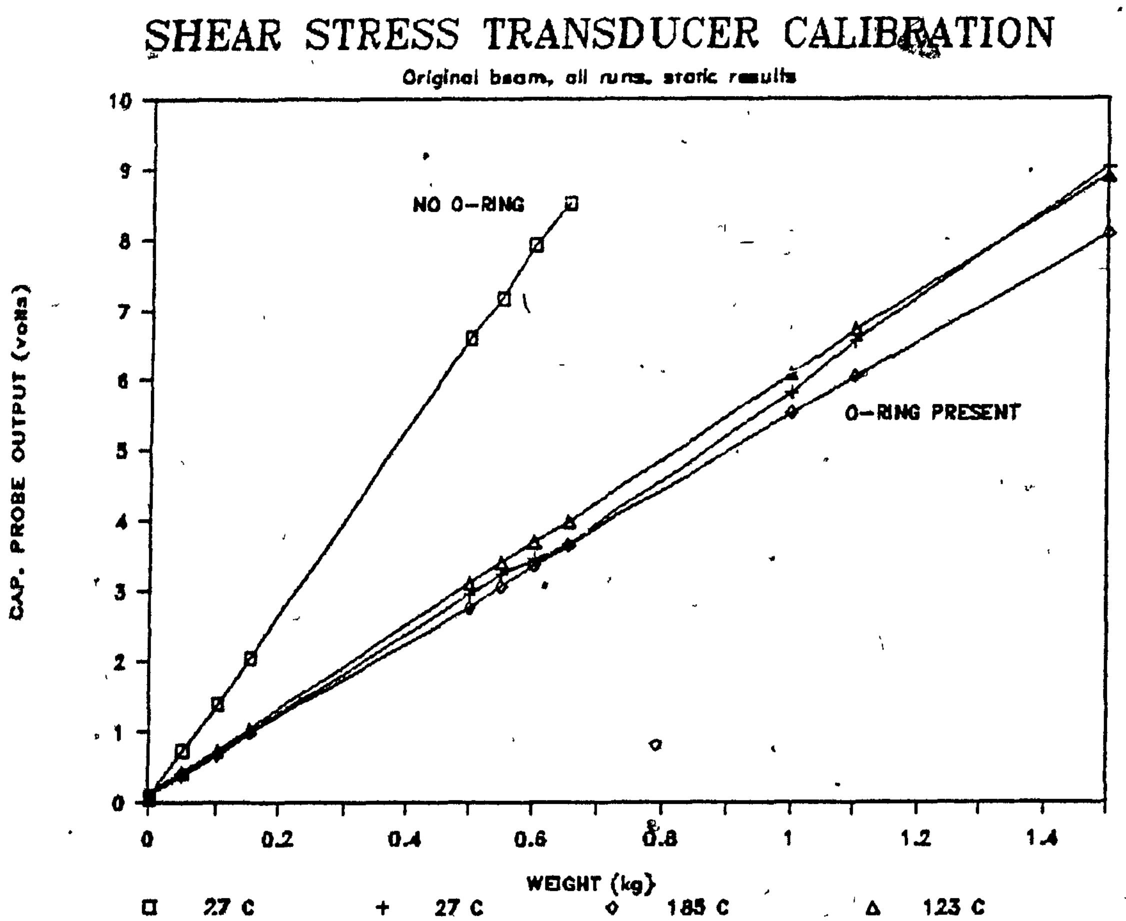


Calibration Mounting Brace
Figure 2.9

calculate final calibration values in terms of signal volts per unit shear stress.

The calibration results in figure 2.10, expressed as output voltage vs kilogram suspended mass, show that the magnitude of the beam deflection is decreased for a given force by the presence of the O-ring. However, the force vs deflection[1] relationship is still linear, which means that the cantilever beam equations are still valid if an effective modulus for the beam is used. This effective modulus can be calculated employing the results from the calibration procedure (See Appendix B). The O-ring appears to approximately double the effective

[1] -- Deflection is expressed in terms of signal voltage from the capacitance probe.



Static Calibration Results
Figure 2.10

modulus, and this result is insensitive to temperature variations in the range tested (from 27°C to 185°C).

The second test was a preliminary dynamic calibration, performed at room temperature, to get an approximate value for the phase lag caused by the O-ring. A second static calibration was performed as well, since the laboratory rheometer's MTS system[1] and PDP computer were used for data acquisition and

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1 -- The MTS system is a computer motion controlled servo-hydraulic drive system used to drive the sliding plate. It is able to produce a wide range of motions (even very small strain

analysis. It was found that the MTS system amplifies the capacitance probe signal by a factor of 1.496 when it conditions the signal for the PDP computer (see calculations in Appendix B). The calibration value calculated for the transducer was 2.11×10^{-5} V/Pa shear stress, or 1.41×10^{-5} V/Pa when using the probe electronics for the process rheometer.

Dynamic tests were performed at two frequencies, 1 and 2 Hz. The first results, at low shear stress (small amplitude forces on the calibration hook) and 1 Hz, were sinusoidal responses with negligible higher harmonics, as shown when FFT's[1] were performed. Results obtained at 2 Hz were not very good; for a simulated shear stress of .02 MPa some harmonics were produced. The time domain response of the transducer for 2 Hz and .005 MPa is displayed in figure 2.11. Repeat experiments at 1 Hz produced no better results.

It is hypothesized that the O-ring remained stationary during the first tests at 1 Hz, but began slip-stick motions during the first test at 2 Hz. The O-ring would stretch until a certain stress was reached, and the initial friction provided by the 6 mil squeeze was overcome, whereupon it would start to slip. Since the O-ring response was no longer elastic, harmonics were introduced that distorted the transducer response to the point where analysis became impossible.

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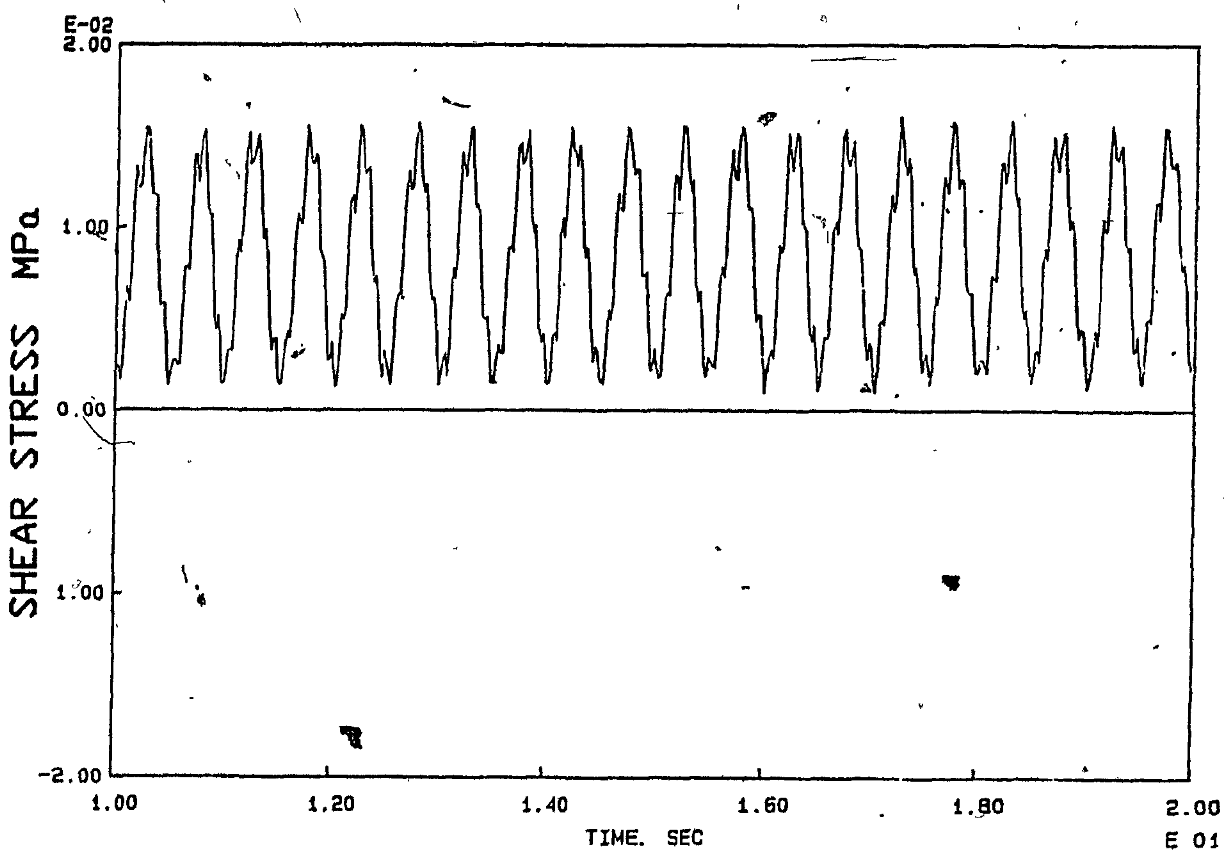
motions) and is equipped with data acquisition elements, which are connected to the PDP computer.

1 -- Fast Fourier Transforms were used to analyze dynamic responses in the frequency domain.



Dynamic Response at 2 Hz, τ=.005 MPa
Figure 2.11

Shear Stress (MPa)	Frequency (Hz)	Phase Lag
.005	1	8.5°
.01	1	7.7°
.02	1	7.5°
.02	2	8.8°

Dynamic Calibration Results
Table 2.1

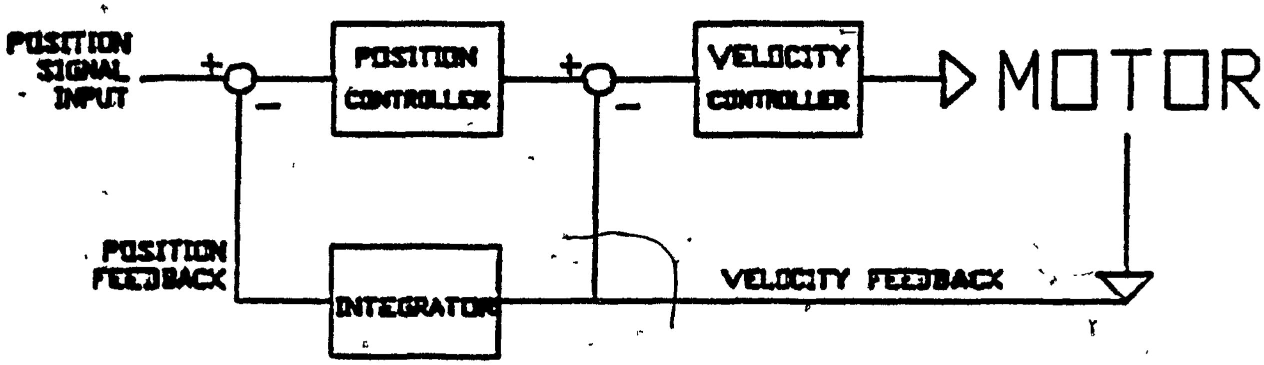
Analysis of the first tests, before O-ring slippage, show an average 8° phase lag in the transducer (see table 2.1). This is a relatively large value since the laboratory rheometer, with no O-ring seal, introduces a phase lag of much less than 1°. Also, the presence of polymer in the annulus around the beam tip will tend to increase this value.

These tests show that while the shear stress transducer performs reasonably well for steady shear, the O-ring interferes with the response of an oscillatory shear experiment. The O-ring seems to slip under certain circumstances; as long as it slips the same distance each time, steady state values of viscosity will not be affected. The oscillatory response will be distorted, however, so that this transducer may not be suitable for these kinds of measurements. One possible alteration that may alleviate this problem would be to make a seat for the O-ring where it is squeezed against the transducer housing.

2.3 The Rheometer Drive and Control Hardware

The motor used to drive the in-line rheometer is an Industrial Drives A.C. Synchronous Torque Motor rated for six horsepower at maximum output (peak, not continuous). This is a high performance brushless permanent magnet motor capable of high torque output, high speeds and high accelerations. It has motor windings mounted on the stator instead the rotor, resulting in a low inertia shaft capable of generating high frequency oscillatory motions with less difficulty than other motors of the same power rating. The speed control system employed, called sinusoidal motor control, gives no torque pulsations at low speed; this combined with high acceleration and high torque outputs make the motor ideal for this application.

The motor comes with an internally mounted brushless resolver for position and velocity feedback. The analog tachometer output is used as feedback for the velocity control loop supplied by the manufacturer for motor control. In order to control problems with positional drifting that arise when using velocity control loops alone for motion control, it was decided to implement a position control loop. The resolver supplies position information in the form of a 12 bit digital signal, but it was found that 12 bits did not provide sufficient resolution to control small strain oscillations without introducing harmful harmonics. Ideally, 16 bit resolution was called for, but this required too much computer power to be practical. An analog position control loop was chosen, to be built by Steve Dragan [14], using an integrated velocity signal from the motor for positional feedback. Figure 2.12 shows how the control loops were configured for position control.



Block Diagram of Motor Control Algorithm
Figure 2.12

The position control board uses a PDF (Pseudo Differential Feedback) control algorithm [19] to provide the setpoint for the velocity control loop. Several useful signals, such as position error or the reference position signal are available to the operator for trouble shooting and tuning purposes. The position control board is only used for oscillatory shear experiments, to prevent drift during experiments; the velocity control loop is used by itself for steady shear experiments, since only the velocity of the shearing surface is important.

The reference position signal for oscillatory shear testing is supplied by a Wavetek Arbitrary[1] Waveform Generator, model 75. This waveform generator is fully controllable; a waveform can be programmed into the instrument through the RS232 port of an IBM PC computer, and the instrument will wait for a digital trigger signal before generating its signal.

For the purposes of data acquisition, a Data Translation model 2801A board was installed in the rheometer control computer[2]. This board is capable of reading up to 16 single ended or 8 differential analog inputs at sampling speeds of up to 27 kHz. It also has 16 digital I/O ports and two 12 bit digital to analog outputs. The current configuration of the

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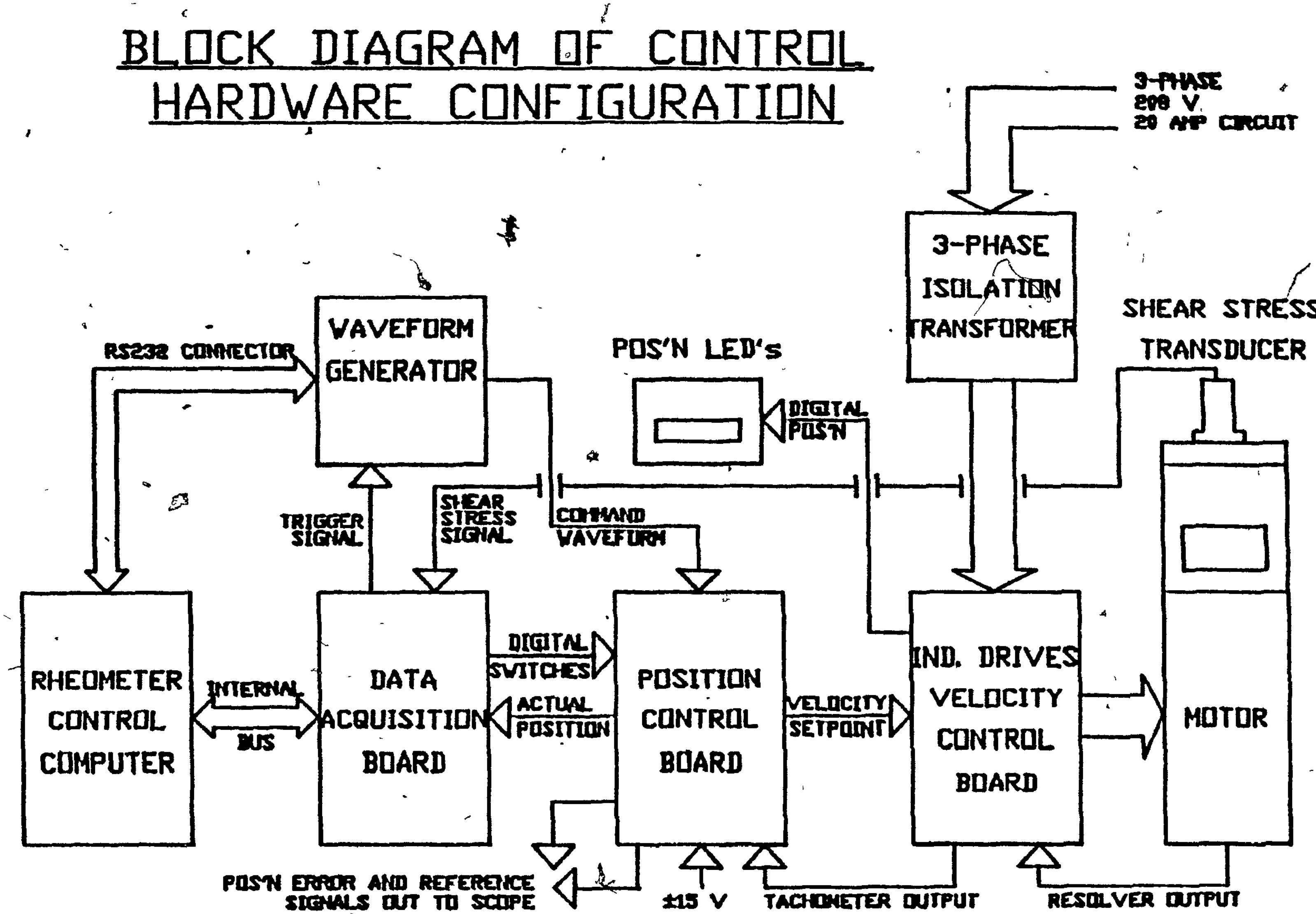
1 -- This is an arbitrary waveform generator because in addition to standard waveforms, such as a sine wave or triangular signal, this generator can be programmed point by point to produce any waveform desired (such as an exponential curve for exponential shear measurements).

2 -- Note that the rheometer control computer discussed here and the extruder control computer discussed later are two different computers. Both are IBM PC compatible.



Block Diagram of Control Hardware Configuration
Figure 2.13

board uses two of the single ended analog inputs, one to read the actual position (strain) signal from the position control board and the other to record the shear stress response from the shear stress transducer. Three of the digital I/O ports are also used (as outputs); two are connected to electronic switches in the position control board, allowing the computer to turn the position control loop on or off, and one is used to send a trigger signal to the waveform generator at the start of a test.

Though the 12 bit position signal from the resolver in the motor is not precise enough for position control feedback, it can still be used to give the operator a good idea of where the shearing disk is located. The 12 bit signal has been connected to 12 LED's (Light Emitting Diodes), which the operator can watch to see how the shearing disk is moving. This is useful for tuning and calibration procedures, where it is necessary to "zero" the shearing disk (i.e. move the shearing disk to the zero or home position).

Figure 2.13 is a block diagram of the rheometer control system, showing the connections between the various components. The experiments performed are completely computer controlled. The computer can program the waveform generator to produce a desired waveform at a desired frequency and amplitude for a designated number of cycles, starting when it receives the triggering signal. The electronic switches controlled by the computer also allow the computer to specify to which control loop to send the command waveform, the position control loop for oscillatory tests or the velocity control loop for steady shear tests. Control software has been written (see section 4.3) that makes most of the hardware control invisible to the user. Jumpers have also been installed in the position control board that allow the computer to be disconnected for manual operation if desired (usually for operations such as control loop tuning).

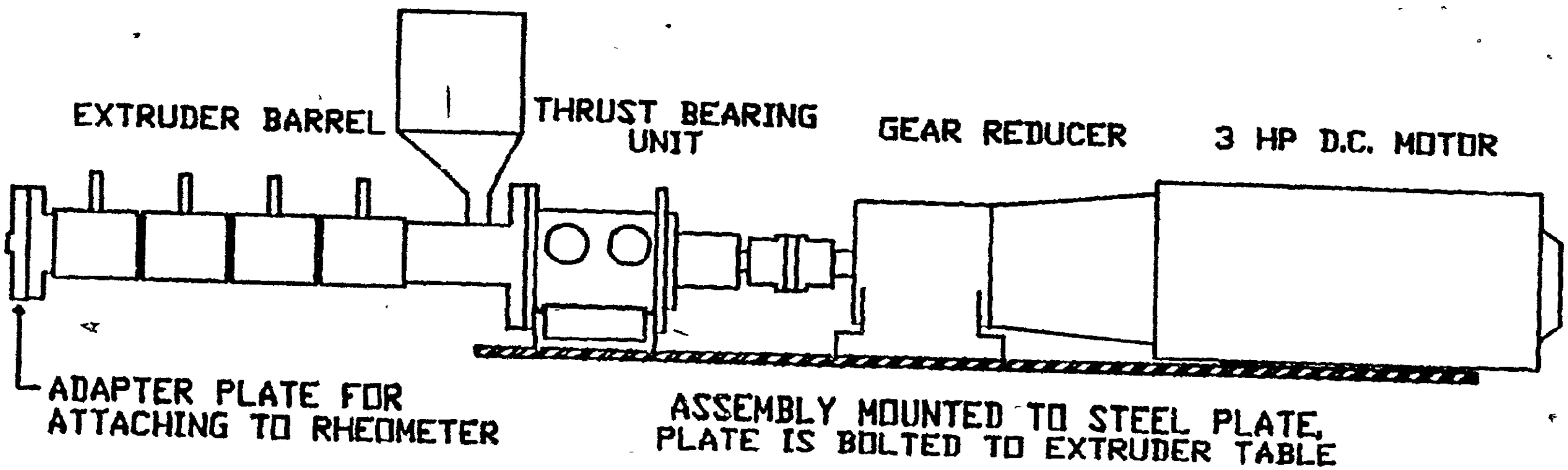
3. NEW EXTRUDER EQUIPMENT

A new extruder system was required for the testing of the process rheometer, to replace the much simpler single-speed, single-zone system previously available. A barrel, heaters and a screw were obtained second-hand from the Ecole Polytechnique of Montreal, while an SM-Cyclo motor and Carotron motor control system were purchased from Relcon Inc., also of Montreal. A MACO 8000 extruder control system was supplied by the Barber Colman Company of Rockford, Illinois.

3.1 The New Extruder

The extruder barrel has a one inch diameter and a 20:1 L/D ratio. It has four heating zones, with holes drilled and tapped for up to eight thermocouples along the top (only four holes are currently being used). There is also a hole on the bottom, just before the end of the barrel, that goes right through to the screw and could be used for a melt temperature thermocouple or a pressure transducer. It is not currently being used and has been plugged. The screw itself is a typical metering screw, slightly marred in one or two places, but adequate for the intended purposes.

The heaters supplied with the barrel are 800 W each at 240 V, and they will deliver approximately 700 W each at 208 V. Cooling fans and a shroud are to be added at a later date; currently the barrel is wrapped with fiberglass insulation. J-type thermocouples have been used throughout.



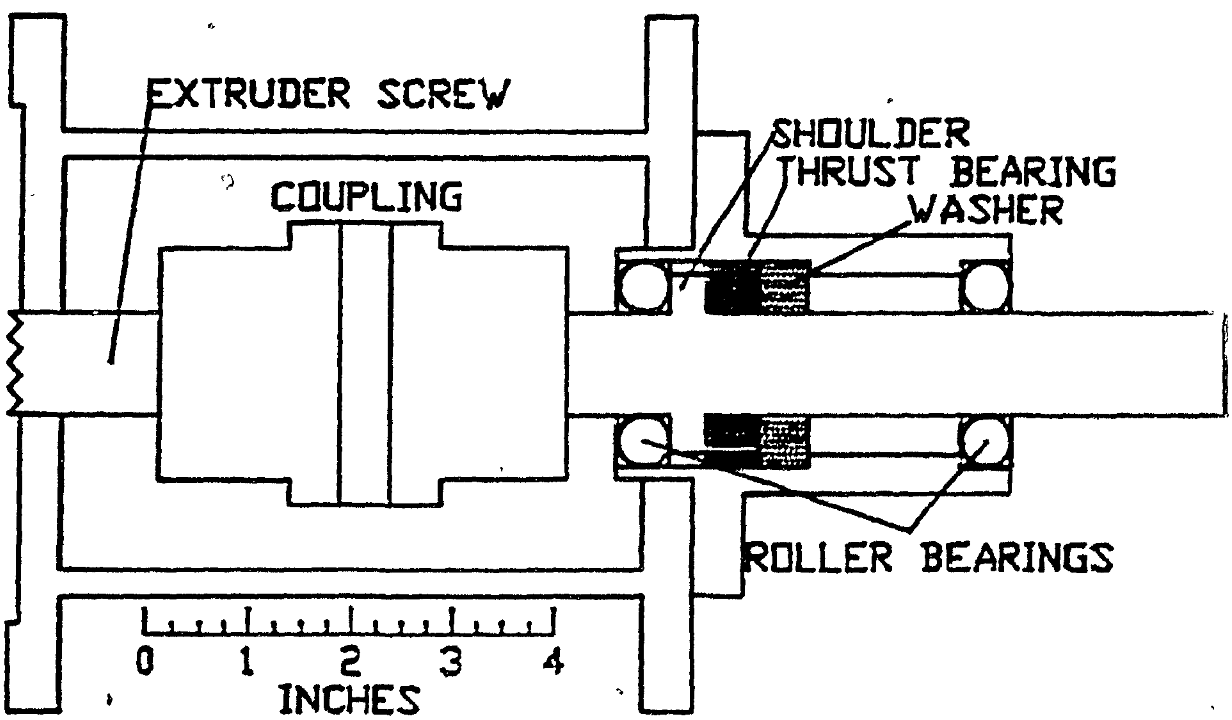
Extruder-Motor Coupling

Figure 3.1
Extruder and Drive System

A resin hopper with a water-cooled throat was fabricated by the Chemical Engineering Machine Shop, as well as an adapter that allows the existing rheometer to be attached to the end of the new extruder. The adapter reduces the flow from the one inch barrel diameter to the 5/8 inch diameter required for entry into the rheometer.

3.2 Extruder Motor and Speed Control System

The drive motor is an SM-Cyclo three-horsepower direct current motor with an 11.67:1 gear reducer, giving a final speed range of 0-150 RPM. A thrust bearing assembly (figure 3.2) is necessary between the extruder screw and the gear

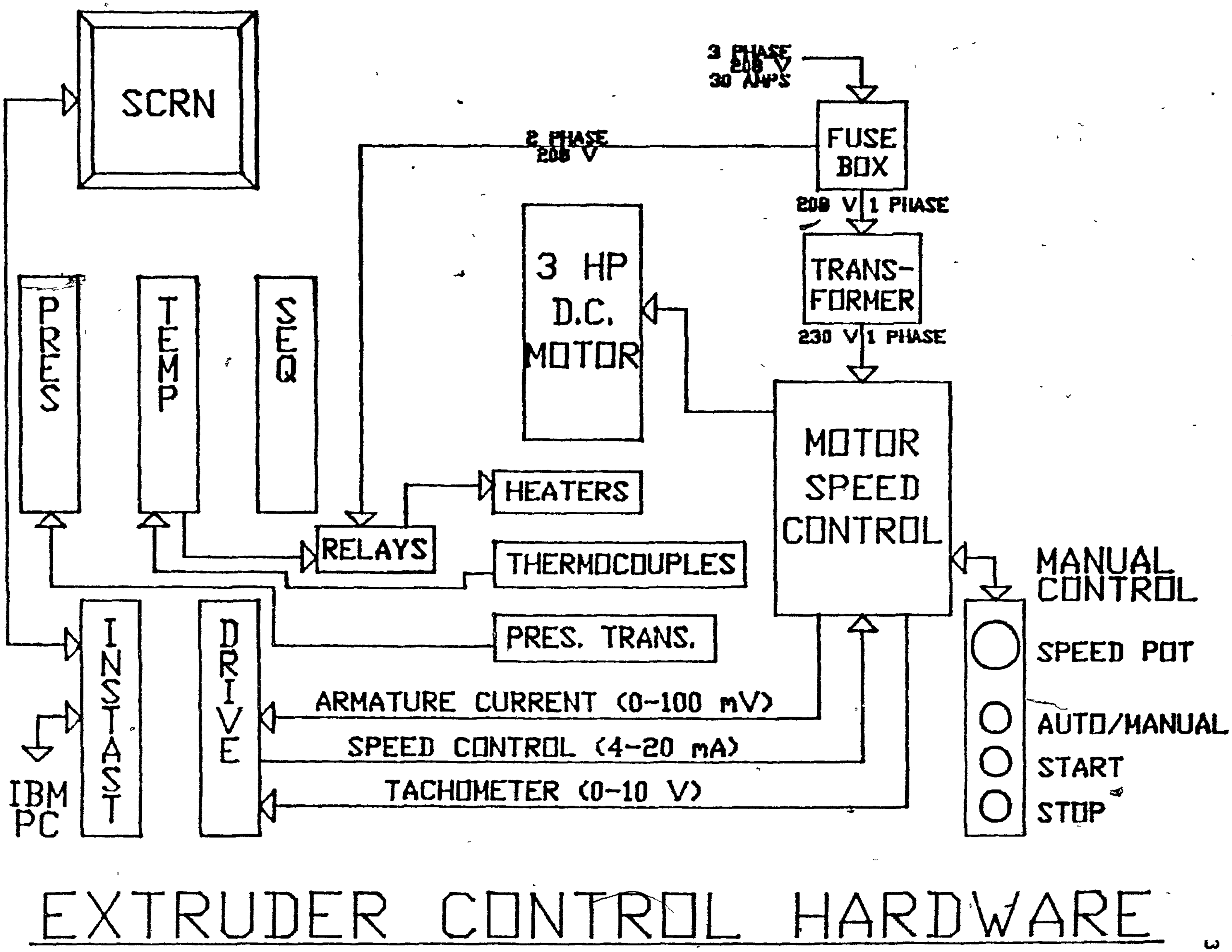


Axial Thrust Bearing Unit
Figure 3.2

reducer to absorb the axial thrust from the screw. The reducer is rated at only 100 psi axial thrust, but the extruder can be expected to generate over 1000 psi working at high pressures. The thrust bearing used here is rated for over 1500 psi, so there should be an adequate safety margin.

The motor control system uses armature feedback to control the speed to ±2% of the full scale RPM. A digital tachometer, also obtained from Relcon Inc., has been installed on the motor, and its 0-10 V output is used by the MACO 8000 drive module for speed monitoring. It cannot currently be used to supply a feedback signal for motor control (which would result in regulation to ±.5% of full scale RPM) because the motor control requires a 0-12.25 V signal, so the output from the tachometer would have to be amplified. The drive module monitors armature current by measuring the voltage across a shunt resistor consisting of a length of 14 gauge wire with a resistance of .007 ohms. Operator control is from a control box mounted on the extruder table and consists of start and stop buttons, an auto/manual switch and a potentiometer for manual speed control. When switched to automatic, the motor control accepts a 4-20 mA signal from the MACO 8000 drive module as a speed setpoint. (See figure 3.3 for block diagram.)

Power for the motor is supplied from a 208 V, 30 A line. An isolation transformer converts this to 230 V. While the motor specifications say that the motor draws a maximum of



Block Diagram of Extruder Control Hardware
Figure 3.3

15 A, startup surges can cause the controller to draw 22 A at 230 V, or 24 A at 208 V; this is why a 30 A circuit is used instead of a 20 A circuit. The motor requires only a single phase, so the extruder heaters are wired to the other two phases (two heaters apiece) to balance the current load across the phases. Each heater draws about 4 A.

3.3 Extruder Control Hardware

The Barber Colman MACO 8000 is a modular, distributed control system in which each module has its own microprocessor. All of the modules are linked to a system module using a two wire communication bus, and setpoint changes and process monitoring are all performed using a single, touch-sensitive CRT. Five modules and a CRT are used and they are briefly described below: (See figure 3.3 for an overall block diagram.)

i) Insta-Set Module -- This module contains the system hardware and software and controls the communication bus. The system software is stored in EEPROM (Electrically Erasable Programable Read Only Memory) and will remain in memory even in the case of a system power failure, until it is erased and new software is read in on top of it. The Insta-Set module has RS232 connections for communicating with an IBM PC, and slots for memory cartridges that are used to store system setpoints and logic programming. This module also controls the CRT.

ii) Touch-sensitive CRT -- This screen is used both to display data and to accept operator commands (setpoint changes, process stop-start, etc.). An infra-red light matrix is used to sense the proximity of a finger to the screen, so that no other keypad or keyboard is necessary. The screens displayed by the system are fully programmable; an IBM PC is used for editing and then the screens are transferred through the RS232 connection in the Insta-Set module.

iii) Sequence Module -- The sequence module contains I/O terminals for external switches, timing and counting functions, EEPROM for the logic programming, and additional system electronics. Each MACO 8000 system must have at least one Insta-Set module, one CRT and one sequence module in order to function.

iv) Heat/Cool Module -- This module provides six zones of automatically tuned PID temperature control. It can handle both heating and cooling for each zone, and uses time-proportioning triacs to turn the heater and/or cooler relays on and off. The temperature inputs are calibrated for J-type thermocouples, and setpoints and process values are displayed in degrees Celsius. Four zones are used to control barrel temperatures, and one zone is used to monitor melt temperature.

v) Pressure Control Module -- Currently, this module is being used only to monitor the melt pressure in the rheometer. It is capable, however, of providing four zones of open or closed loop pressure control, normally using screw speed as the manipulated variable. It is also possible to configure two pressure inputs to act as a single differential pressure monitor.

vi) Drive Module -- This module supplies isolated control signals to up to three motor drives for open loop speed control. It is capable of accepting control signals from other modules (i.e. the pressure control module) or outside sources, and of linking its drives together in a cascade configuration. It monitors motor speed (0-10 V input) and armature current (by means of a 100 mV shunt resistor), and uses these values to calculate horsepower and torque. Only one zone is currently in use, supplying a 4-20 mA signal to control the extruder motor.

The MACO 8000 requires a 120 V power supply, so it is plugged into a wall receptacle on a separate circuit from the extruder motor and heaters; this helps to reduce system noise. A common grounding point is used for all modules to avoid ground loops (and reduce noise), and this point is grounded directly to the fusebox. All five modules and the touch screen have been panel mounted in a steel cabinet, which is also grounded to the fusebox.

The extruder control system is capable of controlling six heat/cool zones and three electric motors, and has four closed loop pressure control zones available. Five of the temperature control zones are used by the extruder (4 barrel zones and one thermocouple to monitor the melt temperature). The sixth zone will likely be used to control the rheometer temperature, which is currently controlled by a separate temperature controller.

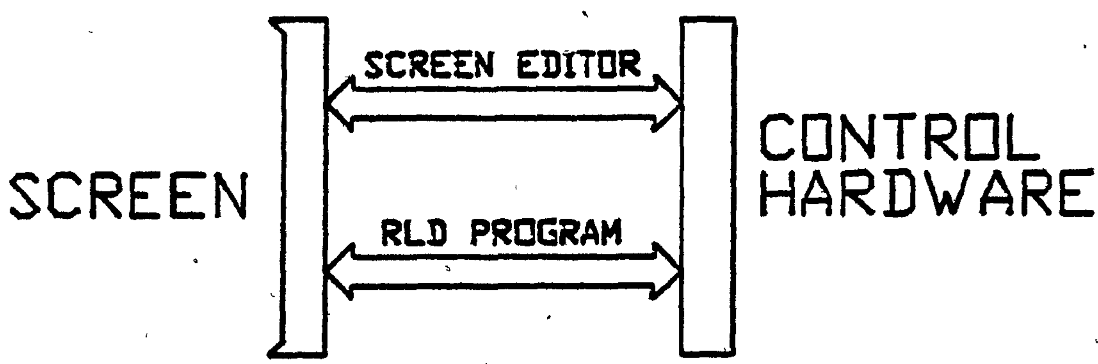
Only one of the drive control zones is currently in use, but if extruder take-off equipment or a controlled resin feed system is added at a later date, the control system will be able to accommodate them. Of the four closed loop pressure control zones, only one is being used, to monitor the melt pressure in the rheometer. Frequently these control loops use screw speed as a manipulated variable to maintain a constant extruder die pressure, giving (assuming constant melt viscosity) a constant melt flowrate through an extruder. In the future it may be desired to compare this method of controlling flow with rheometer control of the same situation. The rheometer would continuously update the value of the viscosity and the melt pressure setpoint for more precise control of melt flow through a die.

4. SOFTWARE

4.1 MACO 8000 Software

The MACO 8000 is programmed using an IBM PC with editor and compiler software kits supplied by Barber Colman. Once suitable code has been generated by the PC, it is downloaded to the MACO system through the RS232 connection. The programming can be divided into two sections; screen editing and sequence logic programming. Barber Colman supplies a separate kit for each of these. Note that the working files for the two kits must be kept in separate directories.

The control system may be thought to consist of 3 separate layers (see figure 4.1):

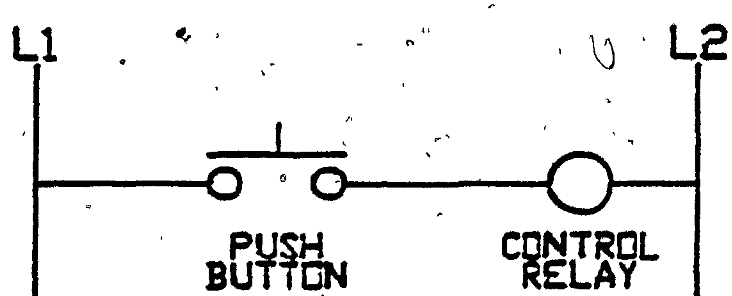


Three Levels of the Control System
Figure 4.1

i) Screens -- These screens are displayed on the MACO touch-sensitive CRT and act like an operator control panel for the system. Information is displayed for the operator, and the screens contain TSA's (Touch-Sensitive Areas) that act like push buttons and multi-position switches. Setpoints can be adjusted and alarms monitored. The screens are used as the interface with the outside world (process operators and engineers).

ii) Control Electronics -- This refers to the hardware and low-level system software that actually makes up the control relays, timers, counters, etc. that are used by the MACO 8000.

iii) RLD Program -- The sequential logic program for the MACO 8000 system is programmed using Relay Ladder Diagrams. Its function is to link switches and toggles that appear on the screens to the proper hardware or memory locations in the correct module. The logic program can react to alarm conditions, flash messages, and take corrective actions, as well as supervise the order and duration of events occurring in the process. The screens do have some direct connections with the control hardware, formed in the screen editor and bypassing the logic program, usually involving process setpoints and values. All other screen functions are linked to control circuitry using the logic programming, allowing a great deal of flexibility in the system configuration.



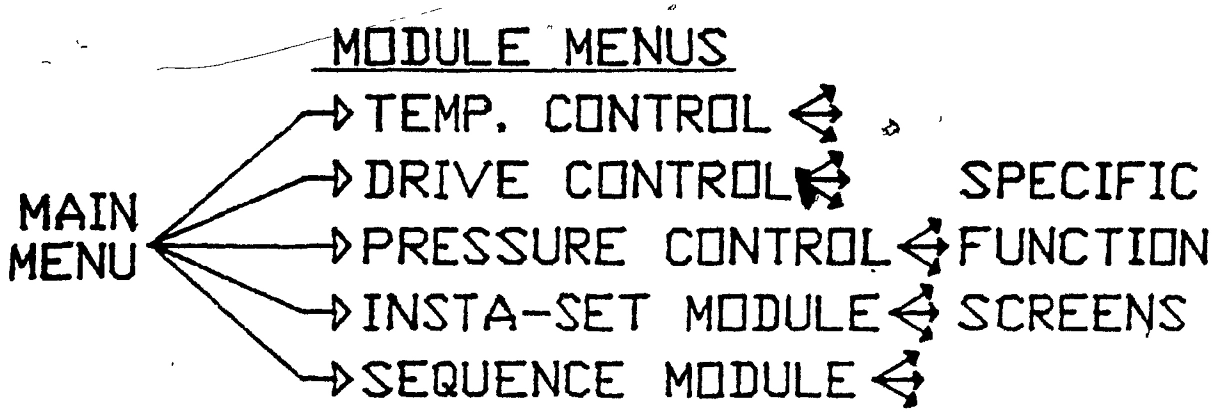
Sample Line from RLD Program
Figure 4.2

Figure 4.2 shows an example of how the RLD program works. Pushing the button completes a circuit, energizing the control relay. The button is a touch-sensitive area on the screen, the control relay represents a memory location, and the logic program is the circuit that connects the two elements. A microprocessor will check the status of the memory element and perform the appropriate operation

4.1.1 The MACO 8000 Screen Configuration

The MACO 8000 Screen Editor Kit is available with several sets of standard screens, depending on the application. These screens cover most of the standard operations performed by the system and can be modified using the editor software, or new screens can be devised from scratch to suit particular applications. Once the screens are arranged in the desired configuration within the editor, a linker routine is used to translate the screens into code suitable for the MACO 8000. The screens are menu selected, meaning that each screen is chosen by touching a TSA from a menu on a previous screen. Each screen must have at least one path leading to it or it will be inaccessible. The compiler routine is called a linker because it sorts through all of the paths between screens and links them together. After linking, a transfer program downloads the screens to the MACO 8000 through the RS232 serial communications connection to the Insta-Set module.

The Standard Extrusion Screen package has been used as the basis for the current screen configuration. Many screens, such as those dealing with modules not in our system, have been deleted; others have been slightly modified to provide better service. A list of the screens currently in use is in the Appendix C along with some sample printouts of specific screens and their contents. From the main menu screen, an operator can select menu screens for each of the modules in the system, and from these menus go to specific screens (Figure 4.3). For example, to get to the screen monitoring barrel temperatures from the main menu, select the Heat/Cool module, and then select the setpoints/values screen. The MACO 8000 also has diagnostic screens available to help debug the logic programming. It is possible to display the state of any control relay in the system using these screens, and to change the state of any of the operator control relays (those used as toggles and push buttons on the screens).



Screen Menu Configuration
Figure 4.3

The MACO 8000 has a security system built into it with 16 different levels of security, each with a different 4 digit numerical code. Currently, only four levels are being used:

1) Super user -- no restrictions

2) User -- can do anything except change passwords

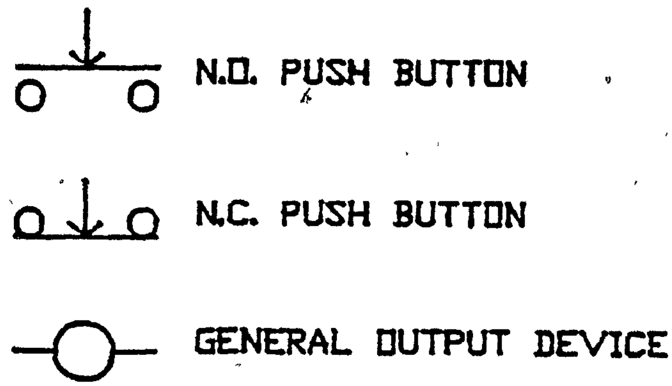
3) Restricted User -- can change some setpoints, cannot enable or disable outputs or change any calibrations

4) No security -- can look at values, can't change anything

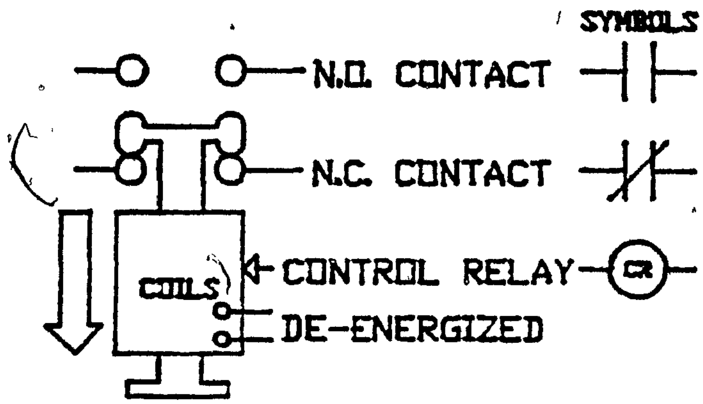
4.1.2 Sequence Logic Programming

The sequence logic program is the program that provides overall control for the MACO 8000 system. Each module is capable of handling its own local control tasks. The logic program is responsible for turning control zones on and off, monitoring for alarm conditions, and controlling the order and timing of process operations (i.e. injection mold open and close timing). One thing the logic program cannot change is process setpoints. These can only be changed by the process operator using the touch-sensitive CRT.

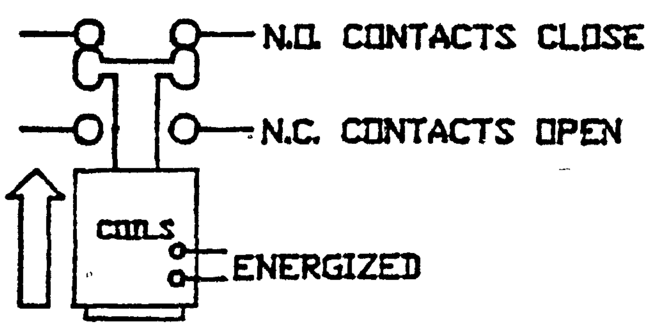
The sequential logic program is encoded using Relay Ladder Diagrams (RLD's). The RLD is popular in industry and simple to understand; it is based on the symbols used in drawing diagrams of the traditional electro-mechanical systems used before electronic control was available. All manuals and programming guides supplied with the MACO 8000 assume programmer familiar-



a) Some Basic Symbols



b) De-energized Control Relay



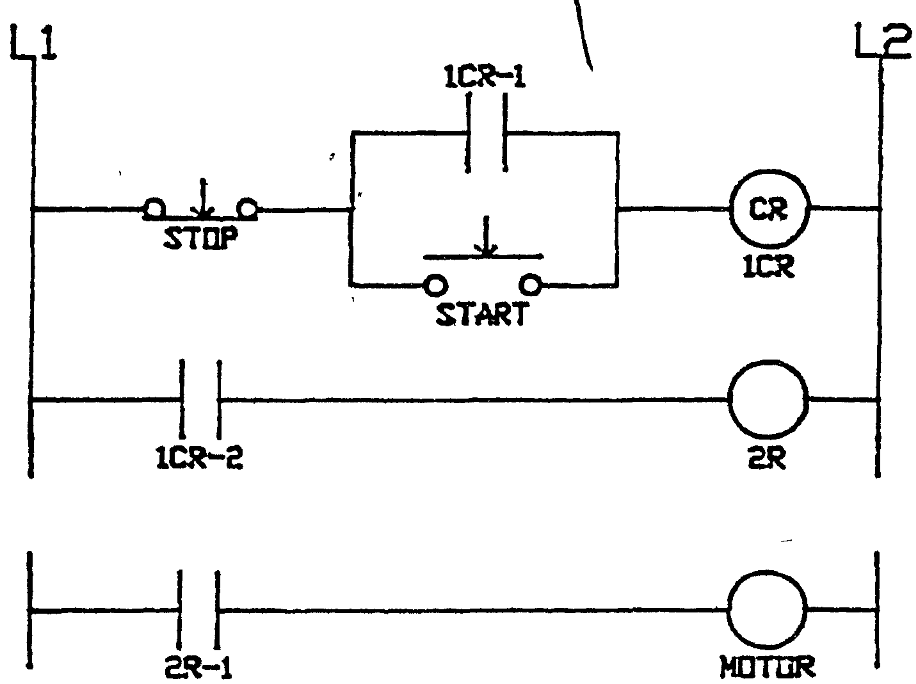
c) Energized Control Relay

RLD Symbols and Control Relays
Figure 4.4

ity with RLD sequence logic. Since this is not true in most cases, a brief explanation of how RLD programs function follows.

The basic unit in these circuits is called a control relay(see figure 4.4). When the relay's coils are energized, the solenoid moves, breaking the N.C. (normally closed) contacts and connecting the N.O. (normally open) contacts. Control relays can usually handle only a small current through their contacts; larger relays are needed to switch heavy current applications such as motors on and off.

The basic symbols shown in figure 4.4 can be used to create circuits to control events. In figure 4.2, a simple



RLD Representation of an Interlock Circuit
Figure 4.5

circuit is shown in an RLD format. There is a 110 V potential difference across L1 and L2; to complete the circuit and energize the output device (which may be, for example, a control relay, a solenoid or a motor starting relay) the push button PB must be depressed. If the output device is a control relay, then it will close N.O. contacts and open N.C. contacts, causing other circuits to be either completed or broken, or turning on or off some different output device.

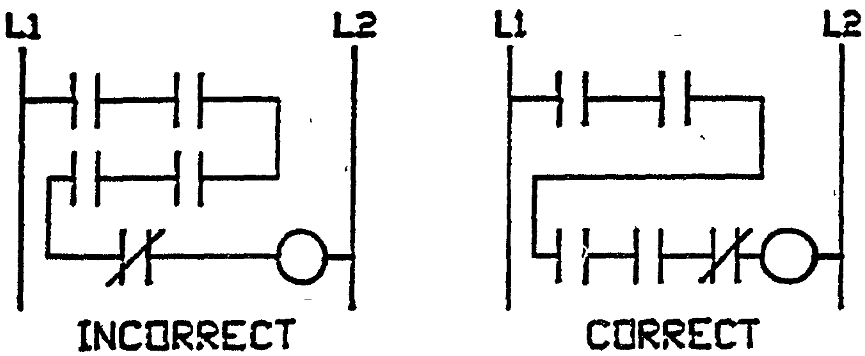
A very common circuit, the interlock circuit, is presented in figure 4.5. This is used for the push button start/stop control of motors, lights, or just about any circuit. When the start button is pushed, the top circuit is completed and control relay 1CR is energized. This accomplishes two things:

i) Contact 1CR-1, normally open, is closed. This ensures that 1CR will remain energized even after the start button is released.

ii) In the second circuit, 1CR-2 also closes, energizing 2R, which is a much heavier duty motor-starting relay.

Relays 1CR and 2R will remain energized until the stop button, which is normally closed, is pushed. This breaks the first circuit, opening contacts 1CR-1 and 1CR-2. 2R is de-energized, turning off the motor, and 1CR will remain de-energized after the stop button is released because 1CR-1 is no longer closed.

When programming the MACO 8000, the RLD editor software and an IBM PC are used. The editor uses graphics to allow the user to enter the RLD exactly as it appears drawn on paper. There are a few simple rules to follow when entering the RLD; only one output device is allowed per line, and it must be in the last position before L2. Also, the logic flows only from left to right through contacts (figure 4.6). Once the RLD is



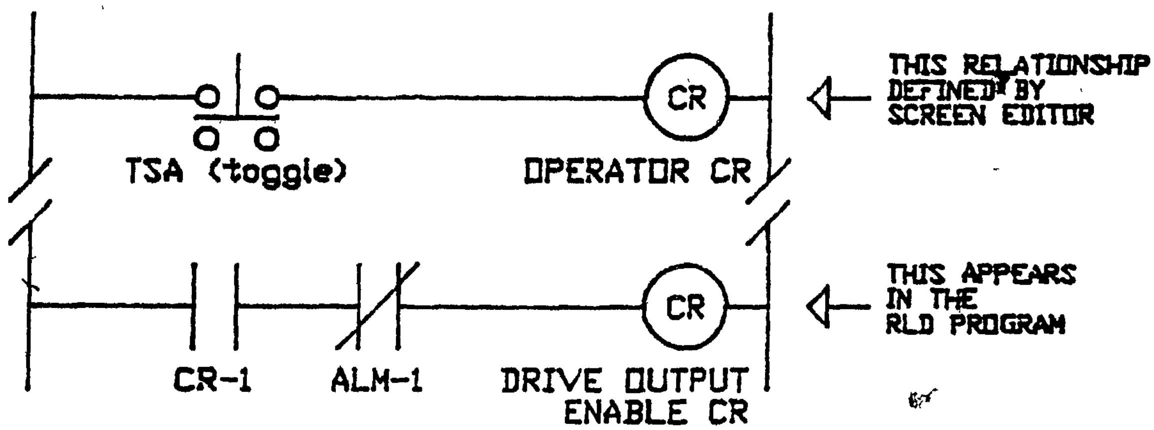
Proper Logic Flow in RLD Diagrams
Figure 4.6

entered, it is compiled into MACO 8000 machine code and downloaded through the RS232 connection to the control system, where it is stored in EEPROM in the sequence module. Note that the MACO 8000 refers to the compiled code as TIMESLOT, so that any system messages to do with TIMESLOT refer to the sequence logic program.

The current control system uses RLD's mostly to link button and switch TSA's on the screens to the proper module control relays. (More complex systems, such as one required to control an injection molding process, would require much more complicated logic programs, making full use of the counters, timers and other advanced features available.) Some TSA's are like buttons, staying on only as long as they are touched; most TSA's act like toggles, changing their state from off to on or on to off each time they are activated. Figure 4.7 shows how a TSA is connected with a module control relay, using Drive Output Enable as an example. The Drive Enable TSA, which acts as a toggle, is connected to an operator CR (control relay) by the screen editor. The Insta-Set module contains 256 of these relays, most of which are used as in this example, to duplicate switches and buttons. While the TSA is on, the operator CR is energized and its N.O. contacts will close. CR-1 will therefore close, energizing the Drive Output Enable CR in the drive module.

The module CR can be directly connected to the TSA using the screen editor, instead of using the operator CR as an intermediary. This is very rigid, however, allowing for no programming flexibility. In figure 4.7, ALM-1, an N.C. contact, has been inserted in the circuit. ALM-1 may be, for example, an alarm CR monitoring the current in the extruder motor; if the alarm relay is energized, meaning the motor is drawing too much current, the N.C. contact will open and de-energize the Drive Output Enable CR (shutting off the motor), even though the TSA is still on and CR-1 is still energized. Another example of a safety interlock on the Drive Enable CR would be one that de-energized the circuit if the barrel temperature was too low, preventing anyone from running the motor while polymer was frozen in the barrel. These safety interlocks are not possible if direct connections from the screen editor are used.

The RLD program in use at this time is listed in the Appendix D along with a catalog of the labels used to name the various control relays. Its main function is to link enable / disable TSA's with the proper module CR's. It is very simple



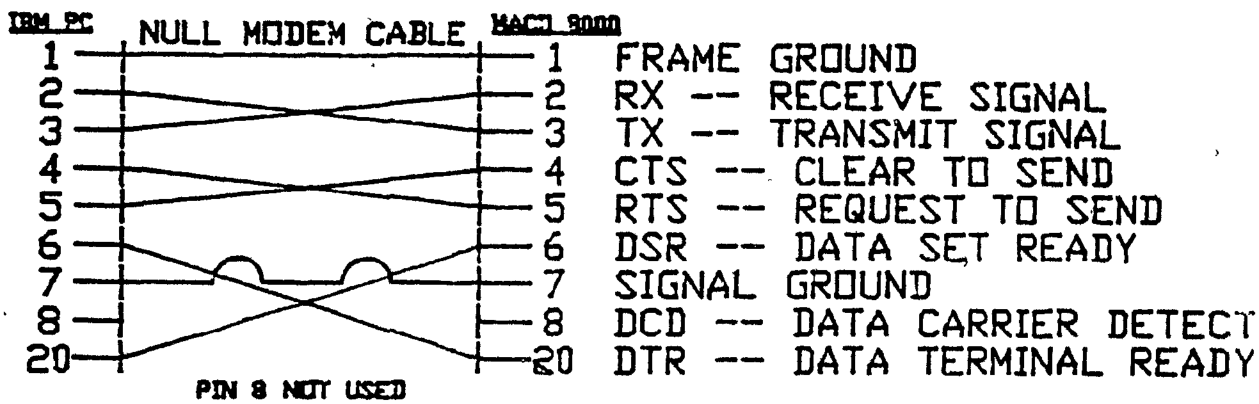
Connecting the Drive Output Enable with the RLD
Figure 4.7

and straight-forward, since it is only a basic RLD; when alarm functions and safety interlocks are later programmed in, it will become much more complex.

4.1.3 Debugging the MACO 8000

Very few problems were encountered while debugging the MACO 8000 hardware. The temperature module displayed temperatures in degrees Fahrenheit; taking the module apart and removing jumper four from the main board changed the display to degrees Celsius. The only other problem involved the RS232 cable. The MACO 8000 manual indicated that a normal RS232 cable should be used to connect the IBM PC computer to the Insta-Set module. The Insta-Set unit was actually configured to accept a null modem cable, with the cable lines crossed as shown in figure 4.8.

A few problems were encountered while debugging the software. The first RLD programs written would not compile; the compiler would crash and non-sense results were obtained. It



Configuration of Null Modem Cable [20]
Figure 4.8

was thought at first that the compiler was out of date; it did not recognize the existence of either the pressure control module or the drive module, since it had been written before these modules had been introduced. An updated compiler was obtained from Barber Colman, but the problems persisted. It turned out to be a mix up with the compiler work files. They were located in the same directory as work files for the screen editor and there was some overlap (both programs used files with the same names, but different contents). Once the RLD work files were separated into a different directory, the compiler worked with no problems.

More difficulties were experienced once the compiled RLD program was loaded into the MACO 8000. TIMESLOT (as the logic program is called by the MACO 8000 system software) refused to run due to setpoint limit errors. Setpoints have maximum and minimum limits set by the control system software. If any setpoints are set outside of these limits, TIMESLOT will not run (i.e. the control system completely shuts down and all control zones are disabled). Since the system was just being initialized, most of the setpoints in the system were set to zero, which is outside the max/min limits for some setpoints. All of the system setpoints had to be checked, even if they were in control zones that were not being used, and set to acceptable values before the logic program would function.

The manuals supplied with the MACO 8000 are very thorough and complete as far as instructions for system set up are concerned, but are weak when it comes to trouble shooting. While possible compiler errors are listed in the manuals, nowhere does it explain what the errors mean, or how to go about correcting them. The safety feature that disables TIMESLOT when there is a setpoint limit error is also not mentioned in any of the manuals.

4.2 The PC System Monitor

The Barber Colman PC System Monitor runs on an IBM PC or compatible computer coupled with the MACO 8000 system using the RS232 connection to the Insta-Set module. It can be used to monitor the value of anything the MACO 8000 can measure, and can be used to change any setpoint. It acts like a remote screen, except that a keyboard is used for input instead of TSA's. Using a built-in editor, the Monitor screens can be programmed to display up to 54 values or setpoints at a time, and can save these values to diskette at prearranged sample times.

Unfortunately, the PC Monitor is more suitable for an industrial environment than for a laboratory. Each time a "save to disk" operation is performed a new file is created into which the entire screen contents, labels included, are transferred. This is very wasteful of disk space, and a maximum of 100 files may be saved before information begins to over-write itself. This is acceptable in industry, where a process engineer may wish to check recent performance, but not in a laboratory, where archival files are needed. Also, it is not possible to communicate with this program using another computer program. The monitor cannot be used to close a process control loop because all setpoint changes must be entered manually.

Since the Process Monitor is not suitable for this application, Barber Colman is supplying the protocols used to access the MACO 8000, so that custom software can be written to close the control loop.

4.3 Rheometer Data Acquisition and Control Software

The motion control and data acquisition software for the process rheometer has been written in BASIC by Steve Dragan [14], and performs three main functions:

i) Rheometer drive motion control.

ii) Shear stress and strain data collection from the rheometer.

iii) Analysis of this data, calculating either viscosity or storage and loss moduli depending on the type of test.

The software runs on an IBM PC compatible computer and has been divided into two programs, one for steady shear experiments and one for oscillatory shear experiments.

The programs start by asking the operator for test parameters; shear rate and test length (in seconds) for steady shear testing, and the frequency, strain amplitude and number of cycles for oscillatory shear testing. (The program also gives the operator a chance to calibrate the position control loop if he so desires.) From this information, the programs calculate control parameters and configure the data acquisition board and position control loop (through digital switches). The Waveform Generator is also sent the information it needs to produce the appropriate waveforms. With everything set, the programs trigger the Wavetek and start data acquisition at the same time, performing the experiment.

When the experiment is finished, the programs automatically begin data analysis. The results from the test are first displayed on the screen in the form of time-domain graphs of the shear stress and strain signals. The steady shear program stops here, but the oscillatory shear program does further analysis. FFT's are calculated for both the strain and the shear stress response, with the resulting spectra plotted on the computer screen (frequency domain). The phase angles for the first harmonics of each of these spectra are calculated and used to determine phase lag between the stress and the strain (since these tests are performed in the linear viscoelastic region, only the first harmonics of these spectra are assumed significant). G' and G'' (storage and loss moduli) are calculated using the phase lag and the amplitudes of the first harmonics of the two signals. The Annino-Driver version of the Cooley-Tuckey FFT algorithm is used [25], with a sampling rate of 128 times the frequency of the experiment. 128 data points (one cycle) are taken from a window in the middle of a test so that the last point taken is two seconds from the end of the experiment.

The use of FFT's to analyze oscillatory signals greatly enhances the sensitivity of the system, because all of the high frequency noise is separated away from the lower frequency response when the signal is split into its component harmonics.

The frequency of the desired response is known (the same as the frequency of the applied strain), so only the amplitude of the harmonic at that frequency is important; everything else is noise. This allows the extraction of data from a very noisy signal, even when the signal amplitude is of the same order of magnitude as the noise itself.

The rheometer software programs will save test results to a disk file in raw form (values read from the data acquisition card) if desired. It is also possible to get a hard copy of the graphs displayed on the computer screen by loading a DOS[1] utility program called graphics.com[2] before running the test programs, and then pushing the <SHIFT> and <Print Screen> keys simultaneously when the desired graph is displayed.

---

1 -- DOS stands for Disk Operating System; in this case the IBM DOS Version 3.1 is utilized.

2 -- Graphics.com will allow the computer to print the contents of a graphics screen display to a dot matrix printer.

5. OPERATING PROCEDURES AND RESULTS

5.1 Hardware Setup Procedures

Care must be taken when working with the extruder and rheometer equipment that everything is fully up to temperature before commencing any experiments. There are currently no safety interlocks programmed into the extruder control system, so that it is possible, for example, to attempt to run the extruder drive motor with polymer frozen in the barrel (likely resulting in a sheared off screw).

The following steps should be followed to bring the equipment up to temperature:

1) Turn on the main power to the drive motor and the barrel heaters at the fuse box. The MACO 8000 control system is left continuously powered up, so it need not be switched on.

2) Go to the security screen of the control system and enter the correct security code. This will allow access to the screens that control the barrel heaters and the drive motor.

3) Move to the "SETPOINT/VALUES" screen of the heat/cool module and ensure that temperature setpoints have been set to the desired values. Then move to the "DIS/ENABLE" screen and enable the heater outputs; this allows the control system to turn on the relays that are used to regulate the heaters.

4) The temperature of the rheometer is regulated by a separate controller. Turn this controller on (the heater power

comes on with the control power), and ensure that the correct setpoint has been set.

Once all of the heaters have been switched on, at least half an hour (preferably closer to an hour) should be allowed for the control zones to come up to temperature and stabilize themselves.

When both the rheometer and the extruder are up to operating temperature, use the following procedure to extrude polymer:

1) Move to the drive control menu and choose the "DRIVE SPEED 1" screen. Make sure that both drive speed setpoints are turned off (there are two setpoints, A and B, to allow the operator to effect a step change between two speeds).

2) Move to the "DRIVE ENABLE" screen and enable the output for drive one (this allows the drive module to send a 4-20 mA signal to the extruder motor speed control).

3) Return to the "DRIVE SPEED 1" screen. Turn on the drive motor at the operator control box and ensure that the motor is set for automatic control. After checking that there is polymer in the feed hopper, enable one of the drive setpoints and the extruder will pump polymer. To monitor the extruder drive (armature current, RPM, etc.) during operation, choose the "MONITOR" screen from the drive control menu.

The melt pressure in the rheometer is measured by a melt transducer connected to the pressure control module. To see the pressure choose "PRESSURE CONTROL" from the main menu, then select the "PRESSURE ZONE 1" screen. The pressure value is displayed on this screen in psig.

The control hardware for the rheometer motion control is brought on-line in the following fashion:

1) Turn on the rheometer control computer and initialize the DOS system.

2) Switch power on to these components in the following order:

i) waveform generator

ii) control board power (velocity and position loops)

iii) LED position indicators

3) Switch on the main power to the rheometer motor (208 V) using the motor starter box mounted on the wall.

The control hardware should be left on for at least a half an hour to have a chance to reach its steady state operating temperature (at which temperature the data acquisition board was calibrated).

5.2 Oscillatory Shear Testing

With both the rheometer and the control hardware warmed up, run the oscillatory shear test software. The following procedure is used to perform an oscillatory shear experiment:

1) Before performing each experiment, the position control loop must reset. The shearing disk tends to wander away from the zero position and superimpose a steady shear motion on the

control waveform sent by the waveform generator if the motion control is not periodically recalibrated.

i) Choose the position loop calibration routine in the control software.

ii) Ground the position control loop. There is a switch provided on the position control board for this purpose which shorts the control loop input to ground.

iii) Use the velocity control loop offset potentiometer to move the shearing disk until it is at the zero position. Use the position LED's to monitor the disk location.

iv) Once the loop is zeroed, reconnect the position loop, which is now recalibrated.

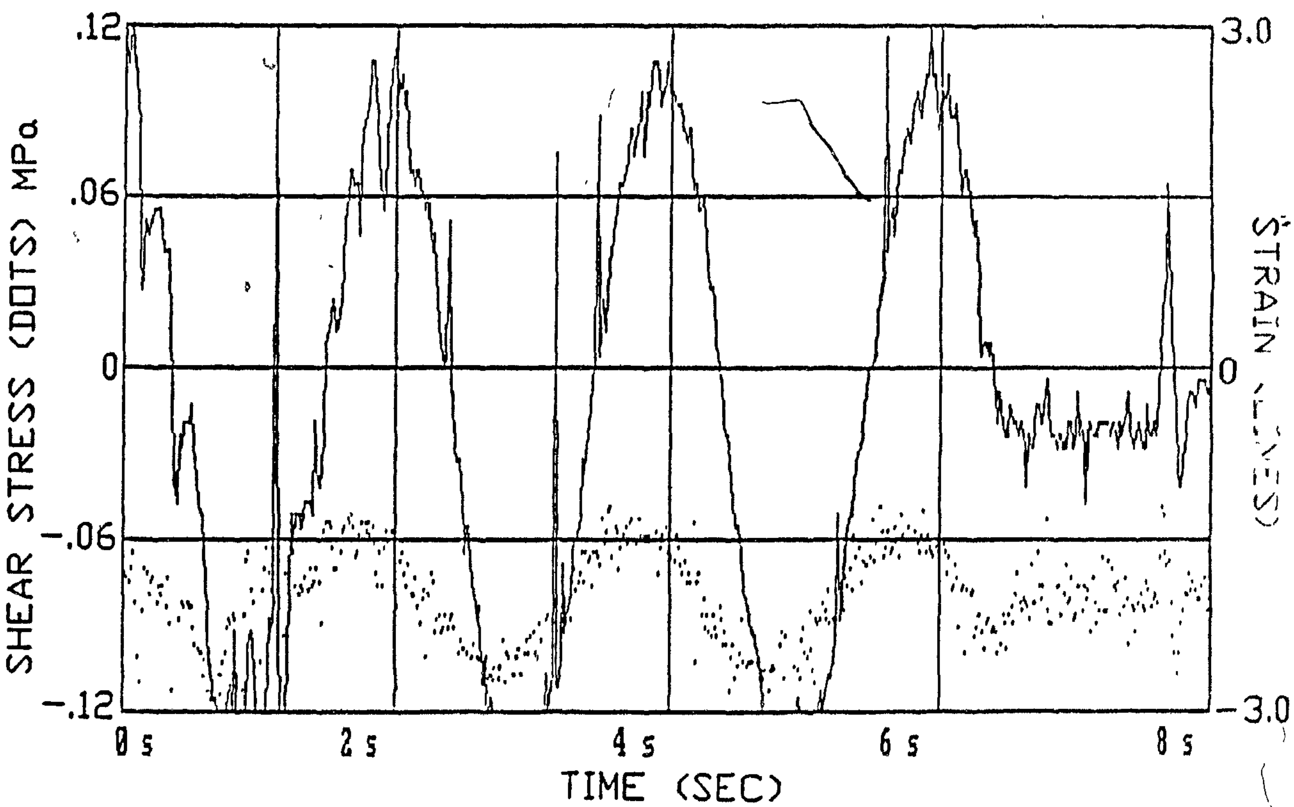
The oscillatory test should be performed immediately after zeroing the position loop, as the loop will destabilize and start to drift after a few moments.

2) After running the recalibration routine, choose one of the oscillatory test modes from the control program menu. Triangular waveforms are available, but usually sine waves are chosen, so that an FFT analysis can be performed. The program will then ask for the desired strain amplitude, frequency and number of cycles in the test.

3) The program will now run the test and perform the FFT analysis on the results. Graphs of both the shear stress and the strain vs time will be generated on the computer screen,

followed by frequency spectra for both stress and strain data. The phase difference between the stress and strain will be calculated (based on the first harmonics) and displayed along with the storage and loss moduli, in units of MPa. Hard copies of each graph are available by pressing <shift><print screen> while the graph is being displayed.

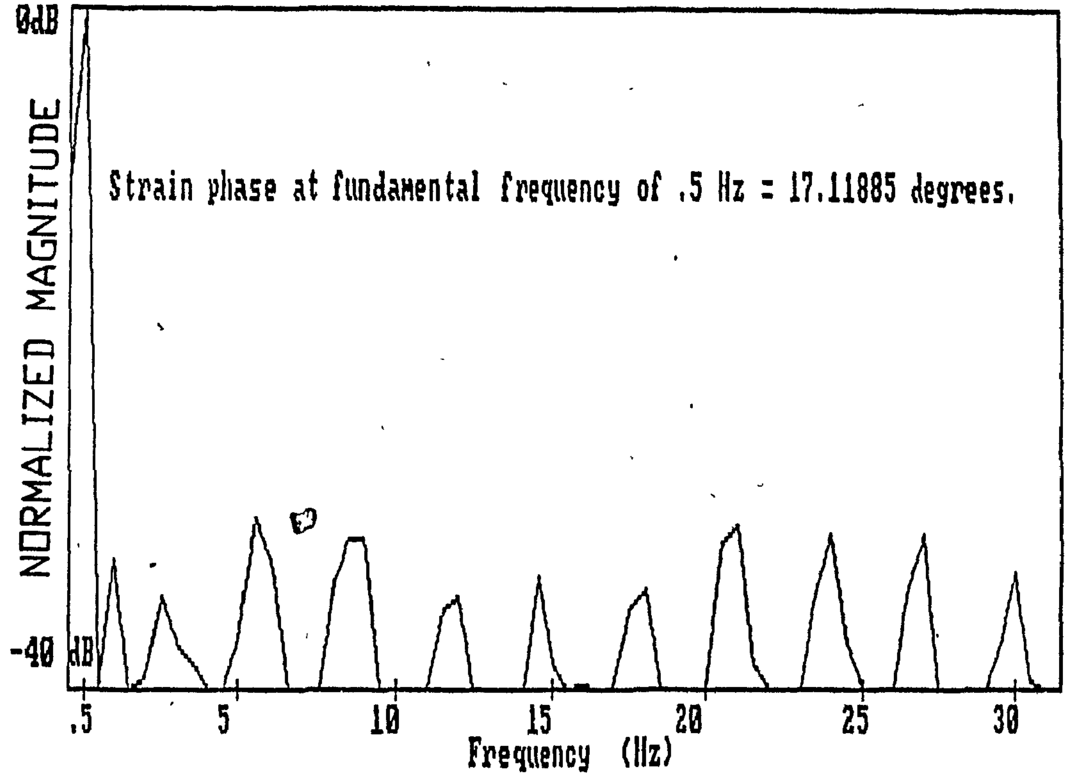
Results from a trial experiment run at .5 Hz with a strain amplitude of 3 are presented in figure 5.1. See Appendix E for information on polymer used). It can be seen that the time domain signals for both the shear stress (dots) and the strain (lines) are noisy. Noise has caused problems with the control electronics because many low level signals are used.



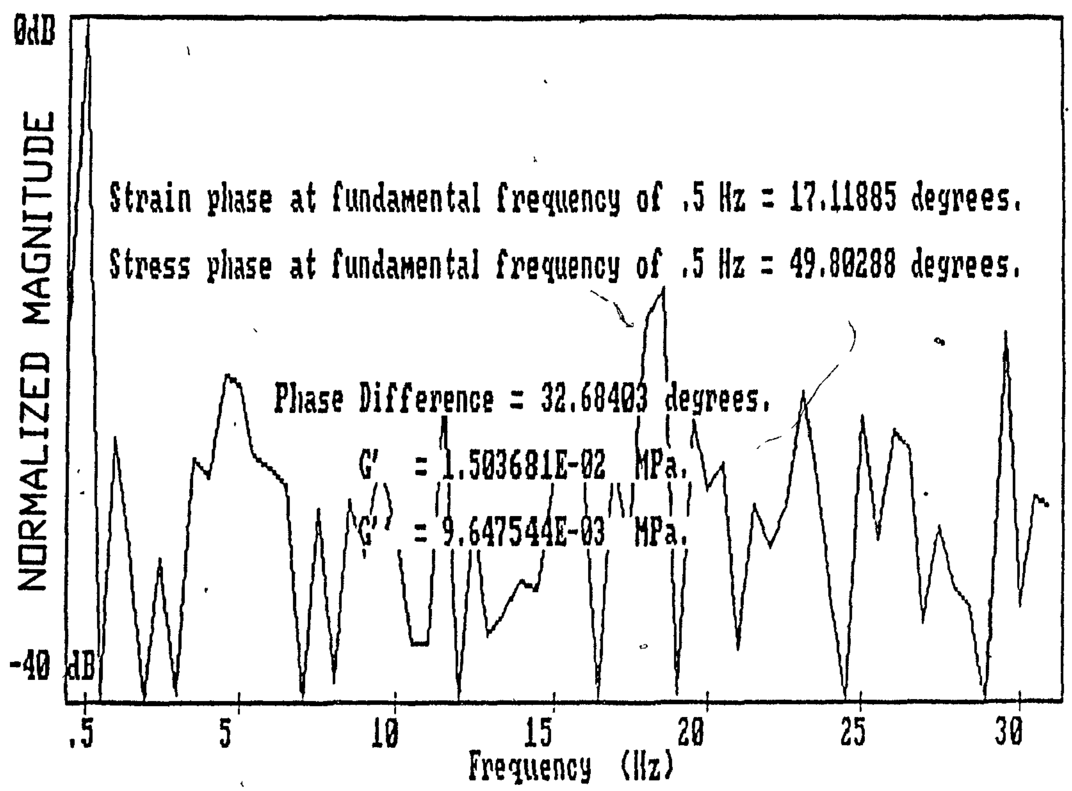
Time Domain Response for Oscillatory Test (.5 Hz)
Figure 5.1

There are many sources of noise in the immediate environment of the control hardware; the rheometer heat control relay, the control computer and the power bus for the rheometer drive motor are likely some of the worst contributors. Extra foil shielding was installed around wires with low level signals and placed around the heat control relay in an effort to reduce noise. While this seemed to help, there were still times when the noise in the transducer signal reached 400 mV peak to peak (with signal responses on the order of 50 to 200 mV), going back down to 50 mV during the next day. Another source of problems was the Wavetek waveform generator, which was not functioning correctly. Sometimes it produced the wrong waveforms, while at other times it would not trigger. Usually manual adjustment of the Wavetek would get it to work correctly, but the remote programming function was not always reliable. Also, noise in the trigger signal was sometimes so bad that the waveform generator would trigger without a command from the computer.

Figure 5.2 shows the results of the FFT analysis of both the strain and the shear stress data. It can be seen that the strain signal has no major peaks in the higher harmonics (the plot is in decibels and the highest peak is at about -30 db relative to the first harmonic). The stress signal picks up much more noise from the capacitance probe signal, and so has larger amplitudes in its higher harmonics. These are still almost 20 db below the primary frequency amplitude, meaning



a) FFT of Strain



b) FFT of Shear Stress Response

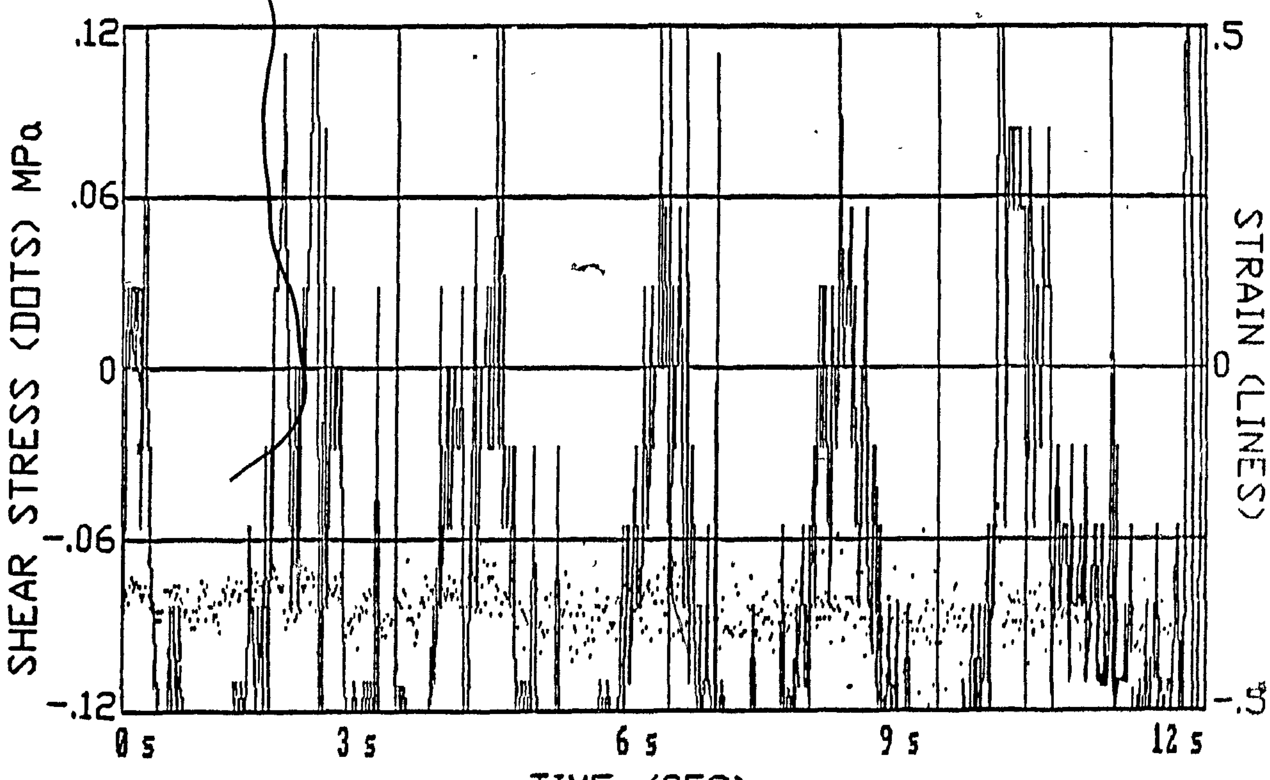
Frequency Domain Analysis of Data from Figure 5.1
Figure 5.2

that the linear response is clearly distinguishable from the system noise. Any higher harmonics due to nonlinearities in the total polymer response, however, are mixed in with the noise and are lost.

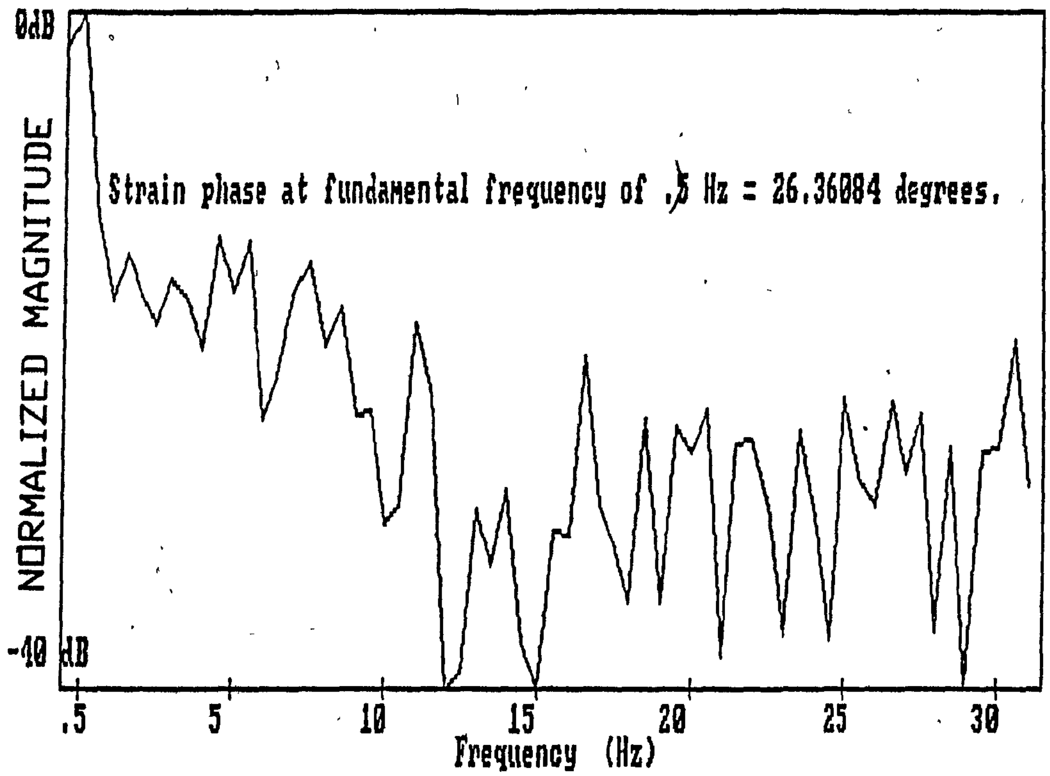
Literature values of G'=.0074 MPa and G''=.0125 MPa [17] were obtained for this polymer at .5 Hz, with a strain amplitude of .1. Since a much higher strain amplitude of 3 was used for this test, likely some higher harmonics of a nonlinear polymer response were lost in the system noise. The analysis program assumes linearity and calculated the results displayed in figure 5.2b. The magnitude of the complex modulus of the polymer can be calculated from these results, $|G^*|_{rheo}$=.0178 MPa. A difference of 23% is noted from the corresponding value calculated from the literature moduli, $|G^*|_{lit}$=.0145 MPa. Possible sources of error include any inaccuracies in the transducer or motor control calibrations, O-ring distortion of the response, and non-linearity in the polymer response.

One major discrepancy is that the relative magnitudes of G' and G'' are reversed; for the rheometer, G' is larger than G'' whereas the literature values show that actually G'' is greater than G'. It is suspected that the FFT routine is not fully debugged and is not correctly performing the phase determinations. Another factor is the response lag due to the transducer, which was shown in section 2.2.4 to be around 8°.

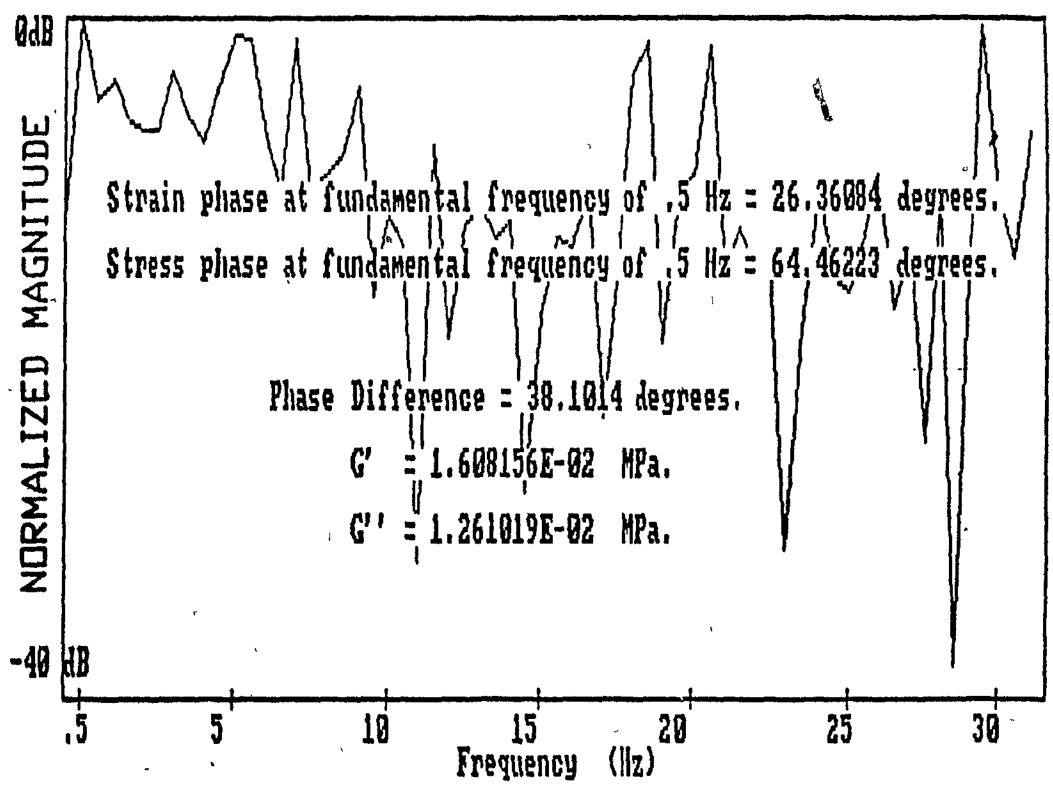
Some problems were experienced in trying to perform small strain experiments below a strain amplitude of .8. The amplitude of the commanded position signal to the position control loop is on the same order of magnitude as that of the noise so that the results, as can be seen in figures 5.3 and 5.4, are extremely noisy. The FFT plots for this test show that many of the higher harmonics for the shear stress response are the same order of magnitude as the first harmonic, making the calculated values of G' and G'' meaningless.



Time Domain Data from Test at Strain =.5 (.5 Hz)
Figure.5.3



a) FFT of Noisy Strain Data

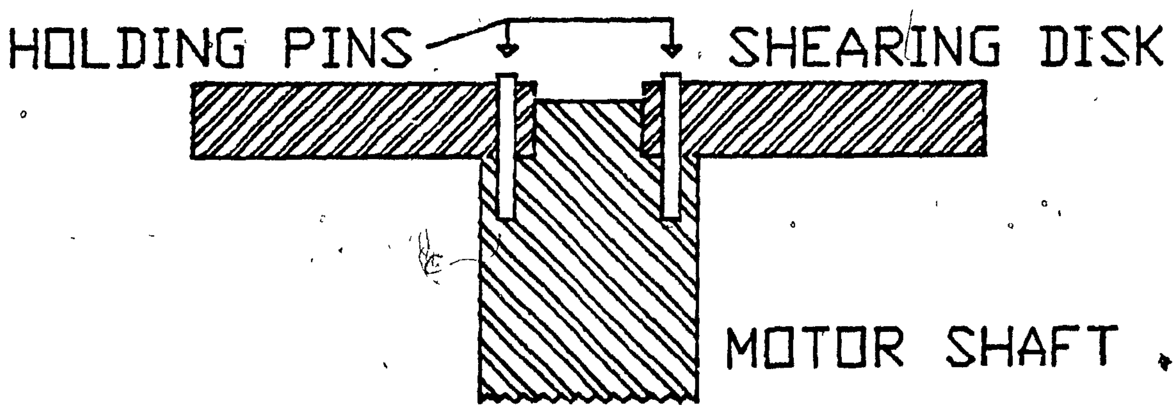


b) FFT of Shear Stress Response

FFT of Noisy Small Strain Experiment
Figure 5.4

5.3 Steady Shear Testing

Some problems were experienced with the rheometer when it was being reassembled for final testing with the new motion control system. The edges of the square key used to lock the shearing disk in place on the end of the motor shaft wore down, so that the disk was held only loosely and would not turn with the shaft. In order to save time and shop effort (since a new rheometer prototype is planned for the near future), it was decided to fasten the disk in place using pins rather than have a new motor shaft machined. Three 1/16 inch holes were drilled



Pins Used to Prevent Shearing Disk from Slipping
Figure 5.5

through the disk into the shaft, and 1/16 diameter metal pins were inserted to hold the disk in place (see figure 5.5).

While this quick fix allowed final tests to be run on the rheometer, it also placed some restrictions on the kinds of testing possible. The drilling operations left the disc with a ±2 mil wobble in a 26 mil gap (±8%). This did not affect the low strain oscillatory shear measurements, which only use a small portion of the shearing disc surface. Large strain steady shear measurements, however, would not be able to achieve steady state values due to the fluctuations in the gap.

Unfortunately, though the pins functioned for the oscillatory shear tests they broke early into the preliminary shear tests, before the data acquisition software was fully debugged, so no shear stress results were available at the time of writing of this thesis.

The procedure to run a steady shear test is much the same as that of the oscillatory shear tests.

1) Zero the velocity control loop, as in step 1-iii for the oscillatory tests. The position control loop need not be tuned since it is not used for steady shear testing. Electronic switches controlled by the computer switch off the loop and feed the waveform signal (a simple DC level) straight into the velocity control loop.

2) Specify the steady shear parameters; shear rate, number of revolutions and shearing direction. The computer will then display the actual test parameters (calculated allowing for round off errors) and perform the test. Results in the form of a graph of both shear stress and shearing disk velocity vs time are displayed on the computer screen and can be saved on a floppy disk.

During the preliminary testing it was noticed that noise, as with the oscillatory testing, constituted a major problem.

The noise was of approximately the same magnitude as with oscillatory tests, but could not be filtered out using FFT's since the signal was not periodic. This means that low shear rate tests especially are going to be difficult to perform until the noise in the control system is reduced.

6. CONCLUSIONS AND RECOMMENDATIONS

No problems were experienced with the extruder system constructed to test the rheometer. The MACO 8000 control system is capable of expanding along with any future needs, and while currently only basic RLD software has been written for it, many safety interlocks can added at a later date. One problem still to be addressed is that of closing the loop between the extruder control system and the rheometer control computer. Barber Colman has a new auxiliary monitor module available that may help in this regard, but its exact capabilities are not yet known. The RS232 protocols are available for the Insta-Set module as a last resort so that custom software can be written to perform the necessary interfacing.

The shear stress transducer needs much more work in the area of the seal. While tests show the cantilever beam equations, used with an apparent beam modulus, still hold for calculation purposes, the dynamic calibration shows that the O-ring can distort a sinusoidal response. Degraded polymer trapped around the tip of the beam will cause further distortions once the transducer has been in use for an extended period of time. Work is currently underway to find a method of sealing the transducer at the beam face.

Major noise problems in the rheometer motion control and data acquisition systems were experienced. Means must be found to reduce this noise so that small strain tests, with their corresponding low signal levels, are possible. More insulation should be employed, using metal foil to give extra protection to low level signals, and noise generating elements such as the rheometer heater control relay should be moved as far away as practical from the immediate rheometer environment.

The results presented in chapter 5 are from a series of trial runs to determine the rheometer's capabilities. These tests show that the system works for large strain experiments but encounters problems due mostly to noise when attempting low strain measurements. The results for the oscillatory shear tests are the correct order of magnitude but do not match literature values due to problems with the phase difference calculations. Possible sources of error include system noise, O-ring distortion, and nonlinear polymer properties (since viscoelasticity is assumed, but is not likely correct for large strain experiments). Early experiments to test for the effects of flow showed that the baseline wavered slightly during changes in flow setpoint; tests on the new apparatus were not performed due to the noise problems experienced.

The McGill in-line process rheometer continues to show much promise as a prototype for a commercial rheometer. A better method of sealing the transducer, along with signal noise reduction, are the two most important problems at the moment; solving these would result in a very versatile, easy to use rheometer.

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Appendix A

BASIC Program for Data Smoothing

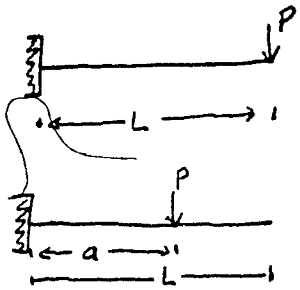
```
10 CLEAR
20 REM         Program to Convert Oscilloscope Output Files to
30 REM              Structured Files for Lotus Graphics
40 REM
50 DIM RSS(1024)
60 DIM SSS(1024)
70 PI=3.1415926535#
80 INPUT"DATA FILE NAME";T$
85 GOTO 115
90 INPUT "Velocity=",RPM
100 INPUT "Volts/Div=",VPD
110 INPUT "Time/Div=",TPD
115 RPM=200:VPD=.05:TPD=2
120 GAP=.652:CAL=.001 'CHANGE READINGS TO MILLIVOLTS
130 N=0:VAR1=VPD/CAL/100:VAR2=TPD/100
135 REM CALCULATE SAVITSKY-GOLAY 5 POINT COEFFICIENTS
140 SG0=17/35*VAR1:SG1=12/35*VAR1:SG2=-3/35*VAR1
150 OPEN T$ FOR INPUT AS #1 'stress data
160 INPUT #1,TAU
170 N=N+1
180 RSS(N)=TAU
190 IF EOF(1) THEN GOTO 210
200 GOTO 160
210 CLOSE:T$="C:"+T$+".PRN"
220 OPEN T$ FOR OUTPUT AS #1 ' combined SMOOTHED data
230 PRINT "NUMBER OF READINGS=",N
240 SR=PI*RPM/GAP/50
250 PRINT "Shear rate=",SR,"(1/s)"
260 OFFSET=0
270 FOR K=976 TO 1000
280 OFFSET=OFFSET+RSS(K)
290 NEXT K
300 OFFSET=OFFSET/25*VAR1
310 FOR J=3 TO N-2  '5 POINT SMOOTHING PERFORMED
320 SSS(J)=RSS(J-2)*SG2+RSS(J-1)*SG1+RSS(J)*SG0+RSS(J+1)*SG1+RSS(J+2)*
SG2-OFFSET
330 PRINT #1,(J-1)*VAR2,SSS(J)
340 NEXT J
350 CLOSE
360 GOTO 10
```

Appendix B

Transducer Calibration Calculations

RANGE CALCULATIONS

CANTILEVER BEAM DEFLECTION FORMULAS

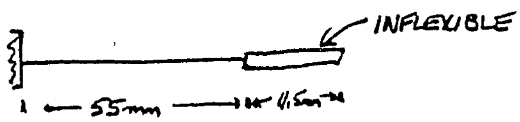


$$\delta_L = \frac{PL^3}{3EI}$$

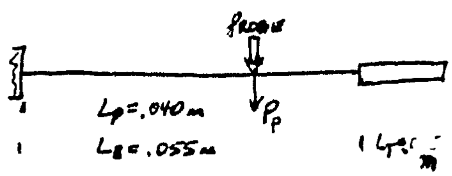
$$\delta_x = \frac{Px^2}{6EI}(3a - x) \qquad 0 \le x \le a$$

$$\delta_x = \frac{Pa^2}{6EI}(3x - a) \qquad a \le x \le L$$

BEAM MODEL



- ASSUME ALL BENDING OCCURRING IN BEAM, AND THAT THE BEAM TIP IS INFLEXIBLE
- FROM STATIC CALIBRATION PERFORMED ON TRANSDUCER WITH THE O-RING PRESENT, THE CALIBRATION CONSTANT IS 5.7 V/kg
- FIND RANGE OF CURRENT TRANSDUCER ASSUMING USE OF AN ASP-1 CAPACITANCE PROBE



BEAM MEASUREMENTS $L = .055\ m$
$w = .0128\ m$
$t = .0031\ m$

- AT FULL DEFLECTION, δ_p (at probe) = .5 mil = $1.27 \times 10^{-5}\ m$
- FROM THE CALIBRATION VALUE, $5V / 5.7\ V/kg = .877\ kg$ ON THE CALIBRATION HOOK.

$$\therefore P = .877 \times 9.81 = 8.60\ N$$

- FIND THE EFFECTIVE BEAM MODULUS, E_B

$$I_b = \frac{wt^3}{12} = \frac{(.0128)(.0031)^3}{12} = 2.88\times10^{-11}\ m^4$$

$$\delta_p = \frac{PL_p^3}{3EI_b} \Rightarrow E_B = \frac{PL_p^3}{3\delta_p I_b} = \frac{8.60\,(.04)^3}{3(1.27\times10^{-5})(2.88\times10^{-11})}$$
$$= 5.02\times10^{11}\ kg\cdot m^{-1}\cdot s^{-1}$$

- FIND DEFLECTION AT TIP OF BEAM SEGMENT

AT $L_B = .055\,m$, $\delta_B = \frac{Pa^2}{6EI}(3x-a) = \frac{8.60(.04)^2}{6EI}(3(.055)-.04)$
$$= 1.98\times10^{-5}\ m = .781\ mil$$

- FIND FORCE REQUIRED AT POINT L_B TO GET THIS DEFLECTION

$$\delta_B = \frac{PL_B^3}{3EI} \Rightarrow P = \frac{3\delta_B EI}{L_B^3} = \frac{3(1.98\times10^{-5})EI}{(.055)^3}$$
$$= 5.17\ N$$

- FIND FORCE REQUIRED AT THE SHEARING SURFACE TO GET THIS FORCE AT THE BEAM SEGMENT TIP

$$P_s = 5.17\times\frac{.055}{.0665} = 4.28\ N$$ (USE MOMENT ARMS, SINCE INFLEXIBLE)

- GET THE FORCE IN TERMS OF SHEAR STRESS

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(.007)^2 = 3.85\times10^{-5}\ m^2$$

$$\sigma = F/A = 4.28/3.85\times10^{-5} = 1.11\times10^{5}\ Pa$$
$$= .111\ MPa$$

∴ THE MAXIMUM MEASURABLE SHEAR STRESS IS .111 MPa

- THE RESOLUTION OF THE ASP-1 IS 1 MICRON, OR 2.54×10^{-8} m. SIMILAR CALCULATIONS SHOW THE MINIMUM DETECTABLE SHEAR STRESS IS 1/1000 OF THE MAXIMUM, OR APPROX .0001 MPa.

MTS SYSTEM AMPLIFICATION

THE MTS DATA ACQUISITION SYSTEM USED BY THE LABORATORY RHEOMETER CONDITIONS THE SIGNAL EMITTED BY THE CAPACITANCE PROBE. IN ORDER TO USE A CALIBRATION PERFORMED ON THIS MACHINE, ANY AMPLIFICATION OR ATTENUATION MUST BE CALCULATED.

- NORMAL STATIC CALIBRATION VALUE (FOR LABORATORY RHEOMETER) : .63 V/kg

- MODULUS $E = 2 \times 10^{11}$ Pa

$$I = \frac{\pi D^4}{64} = \frac{\pi(.0125)^4}{64} = 1.2 \times 10^{-9}$$

- TO ACHIEVE AN OUTPUT OF 1 VOLT, $1/.63 = 1.59$ kg IS NEEDED ON THE CALIBRATION HOOK $\therefore P = 1.59(9.81) = 15.57$ N

- FIND DEFLECTION CAUSED BY THIS FORCE

$L_p = .0428$ m

$$\delta_p = \frac{PL^3}{3EI} = \frac{15.57(.0428)^3}{3EI} = 1.698 \times 10^{-6}\ m = .0668\ mil$$

- FOR AN ASP-1 PROBE, A 1 MIL DEFLECTION = 10 V

$\therefore$ THE PROBE SIGNAL FOR THIS DEFLECTION IS .668 V

$\therefore$ THE MTS SYSTEM AMPLIFIES THE PROBE SIGNAL BY $\frac{1}{.668} = 1.496$ TIMES.

SAMPLE DYNAMIC CALIBRATION PRINTOUT

REPORT ON DU1:BRK1.DAT

NONE (T= 30 C)BEAM BURKES, PGM: DYN10
SPRING RATE: 1.22 N/MM.   BY : TS
F= 1.00023 HZ,ESSA=5.00000E-03 MPA   DISP.AMP.=7.50478E-03IN
CYCLES 1, 21-40, 512 PPC   RS: 10-100-100
NOISE(4S P-P): .477048N,   1.75424E-03 MPA,1.51419E-03 EMPA
DATE: 87-9-18 TIME: 19:21:29
LVDT CAL= 4.93811 IN @ 10 V.
LOAD CAL= .121451 V/KG HUNG MASS @ RS 100%
SST CAL= 9.14052 V/KG HUNG MASS @ RS=100%
BEAM DEFLECTION CONST= .2107 MPA/KG
CAPACITANCE PROBE? ASP1-HT
ATTENUATION METHOD? GREG'S
SPRING #? 1.22N/MM
SPRING POSITION? 2.68

NONE, SOURCE FILE: DU1:BRK1.DAT
512 POINTS, FREQ = 1.00023 HZ, 20 CYCLES.
N.F.= 12.8029 HZ, DF=.0500115 HZ.
PGM: FSTR50 BY A.J.GIACOMIN, P.ENG.
DATE: 87-9-18, TIME: 20:4:24
S/N= 50

FFT OF STRAIN

FREQ,HZ	REAL,STR	IMAG,STR	AMP,STR	PHASE,RA
0	3.12446E-03	0	6.24892E-03	0
1.00023	-1.27123E-03	-6.62626E-05	2.54591E-03	3.19367
2.00046	-6.47937E-05	-9.30288E-06	1.30916E-04	3.2842
4.00092	-7.08324E-05	-4.89625E-07	1.41668E-04	3.14851
8.00184	1.02821E-04	3.90068E-05	2.19943E-04	.362592
9.00207	-5.94079E-05	-2.75822E-05	1.30997E-04	3.57626
10.0023	-6.83843E-05	-4.22710E-05	1.60789E-04	3.69524

NONE, SOURCE FILE: DU1:BRK1.DAT
512 POINTS, FREQ = 1.00023 HZ, 20 CYCLES.
N.F.= 12.8029 HZ, DF=.0500115 HZ.
PGM: FSST50 BY A.J.GIACOMIN, P.ENG.
DATE: 87-9-18, TIME: 20:18:31
S/N= 50

FFT OF STRESS

FREQ,HZ	REAL,MPA	IMAG,MPA	AMP,MPA	PHASE,RA
0	3.27964E-03	0	6.55928E-03	0
1.00023	-8.05087E-04	7.77774E-05	1.61767E-03	3.04528
11.8027	-2.13180E-05	1.52390E-04	3.07748E-04	1.70979

PHASE DIFFERENCE = 3.19367 − 3.04528
= .14839 RAD
= 8.5°

Appendix C

List of MACO 8000 Screens with Sample Screens

LIST OF SCREENS CURRENTLY USED IN MACO 8000

SCREEN NAME   SCREEN HEADER   LISTED ON 22:09:02.25   01 NOV 1987   page 1

0 SCRN 00 MACO 8000 POWER-UP SCREEN
1 SCRN 01 SECURITY ACCESS SCREEN
2 SCRN 02 SYSTEM INFORMATION
3 SCRN 03 SYSTEM DIAGNOSTICS
4 SCRN 04 AUXILIARY MENU 2
5 SCRN 05 RESERVED SCREEN
6 SCRN 06 RS-232 TRANSFER
7 SCRN 07 WATCH LABELS AND STATUS SCREEN
8 SCRN 08 PRIORITY ALARM SCREEN 1
9 SCRN 09 PRIORITY ALARM SCREEN 2
10 SCRN 10 PRIORITY ALARM SCREEN 3
11 SCRN 11 PRIORITY ALARM SCREEN 4
12 SCRN 12 PRIORITY ALARM SCREEN 5
13 SCRN 13 PRIORITY ALARM SCREEN 6
14 SCRN 14 PRIORITY ALARM SCREEN 7
15 SCRN 15 PRIORITY ALARM SCREEN 8
16 SCRN 16 MAIN SYSTEM MENU
17 SCRN 17 AUXILIARY MENU 1
18 SCRN 18 RESERVED SCREEN
19 SCRN 19 SCREEN, MESSAGE, RLD CARTRIDGES
20 SCRN 20 INSTA-SET SCREEN
21 SCRN 21 BAUD RATE SELECTION SCREEN
22 SCRN 22 CONTROL RELAY ACCESS
23 SCRN 23 OPERATOR CR'S AND SWITCHES MENU
24 SCRN 24 SET-UP CONTROL RELAYS 4-40
25 SCRN 25 SET-UP CONTROL RELAYS 41-64
26 SCRN 26 OPERATOR CR'S 1-40
27 SCRN 27 OPERATOR CR'S 41-80
28 SCRN 28 SETUP SELECTOR SWITCHES
29 SCRN 29 OPERATOR SELECTOR SWITCHES
30 SCRN 38 HEAT/COOL MENU
31 SCRN 39 H/C 1 SETPOINTS AND VALUES
32 SCRN 40 H/C 1 MANUAL % SETPOINTS/DEMANDS
33 SCRN 41 H/C 1 DISABLE/ENABLE/RETUNE
34 SCRN 51 HEAT/COOL PROCESS ALARMS
35 SCRN 52 HEAT/COOL DEVIATION ALARMS
36 SCRN 53 HEAT/COOL CYCLE AND HBO TIMES
37 SCRN 54 H/C TUNE MODES AND CONSTANTS
38 SCRN 55 H/C GAIN RATIO/DEADBAND/SPREAD
39 SCRN 56 H/C COOLING MODES AND LIMITS
40 SCRN 57 DRIVE CONTROL 1 MENU
41 SCRN 58 DRIVE CONTROL 1 MOTOR SPECS
42 SCRN 59 DRIVE CONTROL 1 MONITOR
43 SCRN 60 DRIVE CONTROL 1 GAINS
44 SCRN 61 DRIVE CONTROL 1 ALARMS
45 SCRN 62 DRIVE CONTROL 1 CONFIGURATION
46 SCRN 63 DRIVE CONTROL 1 CALIBRATION
47 SCRN 64 DRIVE CONTROL 1 SPEED 1
48 SCRN 65 DRIVE CONTROL 1 SPEED 2
49 SCRN 66 DRIVE CONTROL 1 SPEED 3
50 SCRN 67 HELP FOR DRIVE CONFIGURATION

LIST OF SCREENS CURRENTLY USED IN MACO 8000

SCREEN NAME   SCREEN HEADER   LISTED ON 22:09:02.25   01 NOV 1987   page 2

51 SCRN 68 DRIVE CONTROL ENABLE
52 SCRN 69 SEQUENCE MENU
53 SCRN 70 SEQ TIMERS 1-8
54 SCRN 71 SEQ TIMERS 9-16
55 SCRN 72 SEQ COUNTERS 1-8
56 SCRN 73 SEQ COUNTERS 9-16
57 SCRN 74 SEQ EVENT TIMERS 1-4
58 SCRN 75 SEQ MODULE I/O
59 SCRN 76 SEQ 1 TCR'S 1-40
60 SCRN 77 SEQ 1 TCR'S 41-80
61 SCRN 84 H/C MELT TEMPERATURE CONTROL
62 SCRN 85 H/C USER DEFINED ALARMS
63 SCRN 86 PRESSURE CONTROL 1 MENU
64 SCRN 87 PRESSURE CONTROL 1 CALIBRATION
65 SCRN 88 PRESSURE CONTROL 1 ALARMS
66 SCRN 89 PRES. CONTROL ZONE 1 SETPOINTS
67 SCRN 90 PRES. CONTROL ZONE 2 SETPOINTS
68 SCRN 91 PRES. CONTROL ZONE 3 SETPOINTS
69 SCRN 92 PRES. CONTROL ZONE 4 SETPOINTS
70 SCRN 93 PRESSURE CONTROL 1 AUTO/MANUAL
71 SCRN 94 PRESSURE CONTROL 1 CONFIGURATION
72 SCRN 95 PRESSURE CONTROL 1 TUNING
73 SCRN 96 MELT PRESSURE CONTROL

SAMPLE SCREEN LISTINGS

SCREEN NAME IS :SCRN 16 MAIN SYSTEM MENU LISTED ON 18:27:02.88 15 NOV 1987. page 1

FILE-> b:screen.4 POSITION IN FILE-> 0 LINK TIME: N SECURITY LEVEL = 1

```
          10        20        30        40
 1                MAIN SYSTEM MENU   SECURITY
 2
 3  SEQUENCE                INSTA-SET
 4
 5  DRIVE CONTROL           HEAT/COOL
 6
 7  PRESSURE CONTROL        AUXILIARY MENU
 8                          CALIBRATION STATUS
 9                          MMMMMMM     OKAY
10                          CHECK PRESSURECAL-IN-
11                          VALUES BEFORE RUN!
12 <====<RESERVED FOR SYSTEM MESSAGES>====
          10        20        30        40
```

PATH to NEW SCREEN

	ROW	COL	LENGTH	PATH	
1.	1	32	8	SCRN 01	SECURITY ACCESS SCREEN
2.	3	2	18	SCRN 69	SEQUENCE MENU
3.	3	22	18	SCRN 20	INSTA-SET SCREEN
4.	5	2	18	SCRN 57	DRIVE CONTROL 1 MENU
5.	5	22	18	SCRN 38	HEAT/COOL MENU
6.	7	2	18	SCRN 86	PRESSURE CONTROL 1 MENU
7.	7	22	18	SCRN 17	AUXILIARY MENU 1
8.	10	36	5	SCRN 87	PRESSURE CONTROL 1 CALIBRATION

MESSAGES

	ROW	COL	LENGTH	TYPE	MODULE NAME & NUMBER	CONTROL RELAY	MESSAGES
1.	9	22	7	MODULE CONTROL RELAY	Pressure Control1	Zone 1 Calibrtd	ON MESSAGE: **CAL** OFF MESSAGE: NOT CAL

BROADCAST FUNCTIONS

	ROW	COL	LENGTH	BROADCAST FUNCTION
1.	9	32	4	CALIBRATION O.K.

SAMPLE SCREEN LISTINGS

SCREEN NAME IS SCRN 39 H/C 1 SETPOINTS AND VALUES LISTED ON 18:29:27.72 15 NOV 1987 page 1

FILE-> b:screen.9 POSITION IN FILE-> 3 LINK TIME: N SECURITY LEVEL = 1

```
                10                  20                  30                  40
 1  MAN%       HEAT/COOL  SETPOINTS/VALUES    MENU
 2   SETPOINT<M> VALUE         ALARMS      MAIN MENU
 3 ZONE 1  +SSSSMM+PPPP   MMMMMMMMM  T/C:MMMMMM
 4 ZONE 2  +SSSSMM+PPPP   MMMMMMMMM  BALCO
 5 ZONE 3  +SSSSMM+PPPP   MMMMMMMMM  1 OKAY:MMM
 6 ZONE 4  +SSSSMM+PPPP   MMMMMMMMM  2 OKAY:MMM
 7 ZONE 5  +SSSSMM+PPPP   MMMMMMMMM+/-  PPPPPP
 8 ZONE 6  +SSSSMM+PPPP   MMMMMMMMM 1   2    3
 9 ALARM DEFINITIONS: L=LOW.           4   5    6
10  H=HIGH.-=DEV-,+=DEV+,T=TCB,        7   8    9
11  B=HBO.A=AUTO-COMP,M=MANUAL    %  0    ENTER
12 <====<RESERVED FOR SYSTEM MESSAGES>====>
                10                  20                  30                  40
```

PATH to NEW SCREEN

	ROW	COL	LENGTH	PATH
1.	1	2	4	SCRN 40 H/C 1 MANUAL % SETPOINTS/DEMANDS
2.	1	37	4	SCRN 38 HEAT/COOL MENU
3.	2	23	6	SCRN 51 HEAT/COOL PROCESS ALARMS
4.	2	32	9	SCRN 16 MAIN SYSTEM MENU

KEYPAD

KEYPAD STYLE

CUSTOM

SETPOINTS

	ROW	COL	LENGTH	MODULE NAME & NUMBER		SETPOINT DESCRP	LOW LIMIT	HIGH LIMIT	ALT.
1.	3	8	5	Heat/Cool	1	Process S P Z 1	0	1300	N
2.	4	8	5	Heat/Cool	1	Process S P Z 2	0	1300	N
3.	5	8	5	Heat/Cool	1	Process S P Z 3	0	1300	N
4.	6	8	5	Heat/Cool	1	Process S P Z 4	0	1300	N
5.	7	8	5	Heat/Cool	1	Process S P Z 5	0	1300	N
6.	8	8	5	Heat/Cool	1	Process S P Z 6	0	1300	N

VALUES

	ROW	COL	LENGTH	MODULE NAME & NUMBER		VALUE DESCRIPTN	DECIMAL PLACES
1.	3	15	5	Heat/Cool	1	Process Val Z 1	0
2.	4	15	5	Heat/Cool	1	Process Val Z 2	0
3.	5	15	5	Heat/Cool	1	Process Val Z 3	0
4.	6	15	5	Heat/Cool	1	Process Val Z 4	0
5.	7	15	5	Heat/Cool	1	Process Val Z 5	0
6.	8	15	5	Heat/Cool	1	Process Val Z 6	0

SAMPLE SCREEN LISTINGS

SCREEN NAME IS 'SCRN 39 H/C 1 SETPOINTS AND VALUES ' LISTED ON 18:29:27.72 15 NOV 1987 page 2

MESSAGES ROW	COL	LENGTH	TYPE	MODULE NAME & NUMBER		CONTROL RELAY	MESSAGES
1. 2	12	1	MODULE CONTROL RELAY	Heat/Cool	1	Tmp Unit C or F	ON MESSAGE: 67 "C" OFF MESSAGE: 70 "F"
2. 3	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 1	ON MESSAGE: 94 "^" OFF MESSAGE: 32 " "
3. 3	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 1	ON MESSAGE: 86 "V" OFF MESSAGE: 32 " "
4. 3	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 1	ON MESSAGE: 76 "L" OFF MESSAGE: 32 " "
5. 3	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 1	ON MESSAGE: 72 "H" OFF MESSAGE: 32 " "
6. 3	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 1	ON MESSAGE: 45 "-" OFF MESSAGE: 32 " "
7. 3	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 1	ON MESSAGE: 43 "+" OFF MESSAGE: 32 " "
8. 3	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 1	ON MESSAGE: 84 "T" OFF MESSAGE: 32 " "
9. 3	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 1	ON MESSAGE: 66 "B" OFF MESSAGE: 32 " "
10. 3	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato Cmo Act Z 1	ON MESSAGE: 65 "A" OFF MESSAGE: 32 " "
11. 3	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 1	ON MESSAGE: 77 "M" OFF MESSAGE: 32 " "
12. 3	35	3	MODULE CONTROL RELAY	Heat/Cool	1	T/C Type J NBS	ON MESSAGE: NBS OFF MESSAGE: -
13. 3	38	3	MODULE CONTROL RELAY	Heat/Cool	1	T/C Type J DIN	ON MESSAGE: DIN OFF MESSAGE:
14. 4	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 2	ON MESSAGE: 94 "^" OFF MESSAGE: 32 " "
15. 4	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 2	ON MESSAGE: 86 "V" OFF MESSAGE: 32 " "
16. 4	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 2	ON MESSAGE: 76 "L" OFF MESSAGE: 32 " "
17. 4	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 2	ON MESSAGE: 72 "H" OFF MESSAGE: 32 " "
18. 4	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 2	ON MESSAGE: 45 "-" OFF MESSAGE: 32 " "
19. 4	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 2	ON MESSAGE: 43 "+" OFF MESSAGE: 32 " "
20. 4	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 2	ON MESSAGE: 84 "T" OFF MESSAGE: 32 " "
21. 4	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 2	ON MESSAGE: 66 "B" OFF MESSAGE: 32 " "
22. 4	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato-Cmp Act Z 2	ON MESSAGE: 65 "A" OFF MESSAGE: 32 " "
23. 4	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 2	ON MESSAGE: 77 "M" OFF MESSAGE: 32 " "
24. 5	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 3	ON MESSAGE: 94 "^" OFF MESSAGE: 32 " "
25. 5	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 3	ON MESSAGE: 86 "V" OFF MESSAGE: 32 " "

SAMPLE SCREEN LISTINGS

SCREEN NAME IS "SCRN 39 H/C 1 SETPOINTS AND VALUES   LISTED ON 18:29:27.72   15 NOV 1987   page 3

MESSAGES (con't)

	ROW	COL	LENGTH	TYPE	MODULE NAME & NUMBER		CONTROL RELAY	MESSAGES
26.	5	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 3	ON MESSAGE: 76 "L" OFF MESSAGE: 32 " "
27.	5	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 3	ON MESSAGE: 72 "H" OFF MESSAGE: 32 " "
28.	5	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 3	ON MESSAGE: 45 "-" OFF MESSAGE: 32 " "
29.	5	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 3	ON MESSAGE: 43 "+" OFF MESSAGE: 32 " "
30.	5	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 3	ON MESSAGE: 84 "T" OFF MESSAGE: 32 " "
31.	5	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 3	ON MESSAGE: 66 "B" OFF MESSAGE: 32 " "
32.	5	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato Cap Act Z 3	ON MESSAGE: 65 "A" OFF MESSAGE: 32 " "
33.	5	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 3	ON MESSAGE: 77 "M" OFF MESSAGE: 32 " "
34.	5	38	3	MODULE CONTROL RELAY	Heat/Cool	1	Balco #1	ON MESSAGE: NO OFF MESSAGE: YES
35.	6	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 4	ON MESSAGE: 94 "^" OFF MESSAGE: 32 " "
36.	6	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 4	ON MESSAGE: 86 "V" OFF MESSAGE: 32 " "
37.	6	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 4	ON MESSAGE: 76 "L" OFF MESSAGE: 32 " "
38.	6	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 4	ON MESSAGE: 72 "H" OFF MESSAGE: 32 " "
39.	6	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 4	ON MESSAGE: 45 "-" OFF MESSAGE: 32 " "
40.	6	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 4	ON MESSAGE: 43 "+" OFF MESSAGE: 32 " "
41.	6	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 4	ON MESSAGE: 84 "T" OFF MESSAGE: 32 " "
42.	6	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 4	ON MESSAGE: 66 "B" OFF MESSAGE: 32 " "
43.	6	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato Cap Act Z 4	ON MESSAGE: 65 "A" OFF MESSAGE: 32 " "
44.	6	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 4	ON MESSAGE: 77 "M" OFF MESSAGE: 32 " "
45.	6	38	3	MODULE CONTROL RELAY	Heat/Cool	1	Balco #2	ON MESSAGE: NO OFF MESSAGE: YES
46.	7	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 5	ON MESSAGE: 94 "^" OFF MESSAGE: 32 " "
47.	7	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 5	ON MESSAGE: 86 "V" OFF MESSAGE: 32 " "
48.	7	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 5	ON MESSAGE: 76 "L" OFF MESSAGE: 32 " "
49.	7	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 5	ON MESSAGE: 72 "H" OFF MESSAGE: 32 " "

SAMPLE SCREEN LISTINGS

MESSAGES (con't)

	ROW	COL	LENGTH	TYPE	MODULE NAME & NUMBER		CONTROL RELAY	MESSAGES	
50.	7	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 5	ON MESSAGE: 45 OFF MESSAGE: 32	"-" " "
51.	7	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 5	ON MESSAGE: 43 OFF MESSAGE: 32	"+" " "
52.	7	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 5	ON MESSAGE: 84 OFF MESSAGE: 32	"T" " "
53.	7	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 5	ON MESSAGE: 66 OFF MESSAGE: 32	"B" " "
54.	7	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato Cap Act Z 5	ON MESSAGE: 65 OFF MESSAGE: 32	"A" " "
55.	7	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 5	ON MESSAGE: 77 OFF MESSAGE: 32	"M" " "
56.	8	13	1	MODULE CONTROL RELAY	Heat/Cool	1	Heating Z 6	ON MESSAGE: 94 OFF MESSAGE: 32	"^" " "
57.	8	14	1	MODULE CONTROL RELAY	Heat/Cool	1	Cooling Z 6	ON MESSAGE: 86 OFF MESSAGE: 32	"V" " "
58.	8	22	1	MODULE CONTROL RELAY	Heat/Cool	1	Low Alarm Z 6	ON MESSAGE: 76 OFF MESSAGE: 32	"L" " "
59.	8	23	1	MODULE CONTROL RELAY	Heat/Cool	1	High Alarm Z 6	ON MESSAGE: 72 OFF MESSAGE: 32	"H" " "
60.	8	24	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev - Alarm Z 6	ON MESSAGE: 45 OFF MESSAGE: 32	"-" " "
61.	8	25	1	MODULE CONTROL RELAY	Heat/Cool	1	Dev + Alarm Z 6	ON MESSAGE: 43 OFF MESSAGE: 32	"+" " "
62.	8	26	1	MODULE CONTROL RELAY	Heat/Cool	1	TCB Alarm Z 6	ON MESSAGE: 84 OFF MESSAGE: 32	"T" " "
63.	8	27	1	MODULE CONTROL RELAY	Heat/Cool	1	HBO Alarm Z 6	ON MESSAGE: 66 OFF MESSAGE: 32	"B" " "
64.	8	28	1	MODULE CONTROL RELAY	Heat/Cool	1	Ato Cap Act Z 6	ON MESSAGE: 65 OFF MESSAGE: 32	"A" " "
65.	8	29	1	MODULE CONTROL RELAY	Heat/Cool	1	Manual Zone 6	ON MESSAGE: 77 OFF MESSAGE: 32	"M" " "

Appendix D

RLD Program and Symbol Label Listing

BASIC RLD PROGRAM-(NO ALARM TRAPPING OR SAFETY INTERLOCKS)

02 NOV 1987 12:03:59.91

* ** *** LINK H/C MODULE ENABLE TO PREDEFINED SCREEN TSA *** ** *

1
- SCREEN: H/C OUTPUT ENABLE — TSA HA :2934
- H/C OUTPUT ENABLE — HCENABL:420

* ** *** LINK H/C MODULE ZONE DISABLES TO PREDEFINED SCREEN TSA's *** ** *

2
- SCREEN: H/C ZONE 1 DISABLE — TSA HB :2912
- H/C ZONE 1 DISABLE — HCZ1 :428

3
- SCREEN: H/C ZONE 2 DISABLE — TSA HC :2911
- H/C ZONE 2 DISABLE — HCZ2 :4289

4
- SCREEN: H/C ZONE 3 DISABLE — TSA HD :2910
- H/C ZONE 3 DISABLE — HCZ3 :4290

5
- SCREEN: H/C ZONE 4 DISABLE — TSA HE :2909
- H/C ZONE 4 DISABLE — HCZ4 :4291

6
- SCREEN: H/C ZONE 5 DISABLE — TSA HF :2908
- H/C ZONE 5 DISABLE — HCZ5 :4292

7
- SCREEN: H/C ZONE 6 DISABLE — TSA HG :2907
- H/C ZONE 6 DISABLE — HCZ6 :429

* ** *** LINK H/C MODULE RETUNE CR's TO PREDEFINED SCREEN TSA's *** ** *

8
- SCREEN: H/C ZONE 1 RETUNE — TSA HH :2940
- H/C ZONE 1 RETUNE — HCRTNZ1:4280

9
- SCREEN: H/C ZONE 2 RETUNE — TSA HI :2939
- H/C ZONE 2 RETUNE — HCRTNZ2:4281

10	SCREEN: H/C ZONE 3 RETUNE TSA HJ :2938	H/C ZONE 3 RETUNE HCRTNZ3:4282
11	SCREEN: H/C ZONE 4 RETUNE TSA HK :2937	H/C ZONE 4 RETUNE HCRTNZ4:4283
12	SCREEN: H/C ZONE 5 RETUNE TSA HL :2936	H/C ZONE 5 RETUNE HCRTNZ5:4284
13	SCREEN: H/C ZONE 6 RETUNE TSA HM :2935	H/C ZONE 6 RETUNE HCRTNZ6:4285

* ** *** LINK H/C MELT TEMPERATURE ENABLE CR TO PREDEFINED SCREEN TSA *** ** *

14	SCREEN: H/C MELT TEMPERATURE ENABLE TSA HN :2955	H/C MELT TEMPERATURE ENABLE MLTMPEN:4294

* ** *** ENABLE H/C AUTO COMPENSATION FEATURE *** ** *

15		H/C AUTO COMPENSATION ENABLE ACMPEN:4286

* ** *** PRESSURE CONTROL MODULE *** ** *
* ** *** *** ** *
* ** *** LINK PRESSURE CALIBRATION ENABLE AND YES/NO RESPONSES TO PREDEFINED TSA's *** ** *

16	SCREEN: PRESSURE CALIBRATION ENABLE TSA PA :2941	PRESSURE CALIBRATION ENABLE PCALEN :5324
17	SCREEN: PRESSURE YES RESPONSE TSA PB :2942	PRESSURE YES RESPONSE PYES :5306
18	SCREEN: PRESSURE NO RESPONSE TSA PC :2943	PRESSURE NO RESPONSE PNO :5307

BASIC RLD PROGRAM (NO ALARM TRAPPING OR SAFETY INTERLOCKS)

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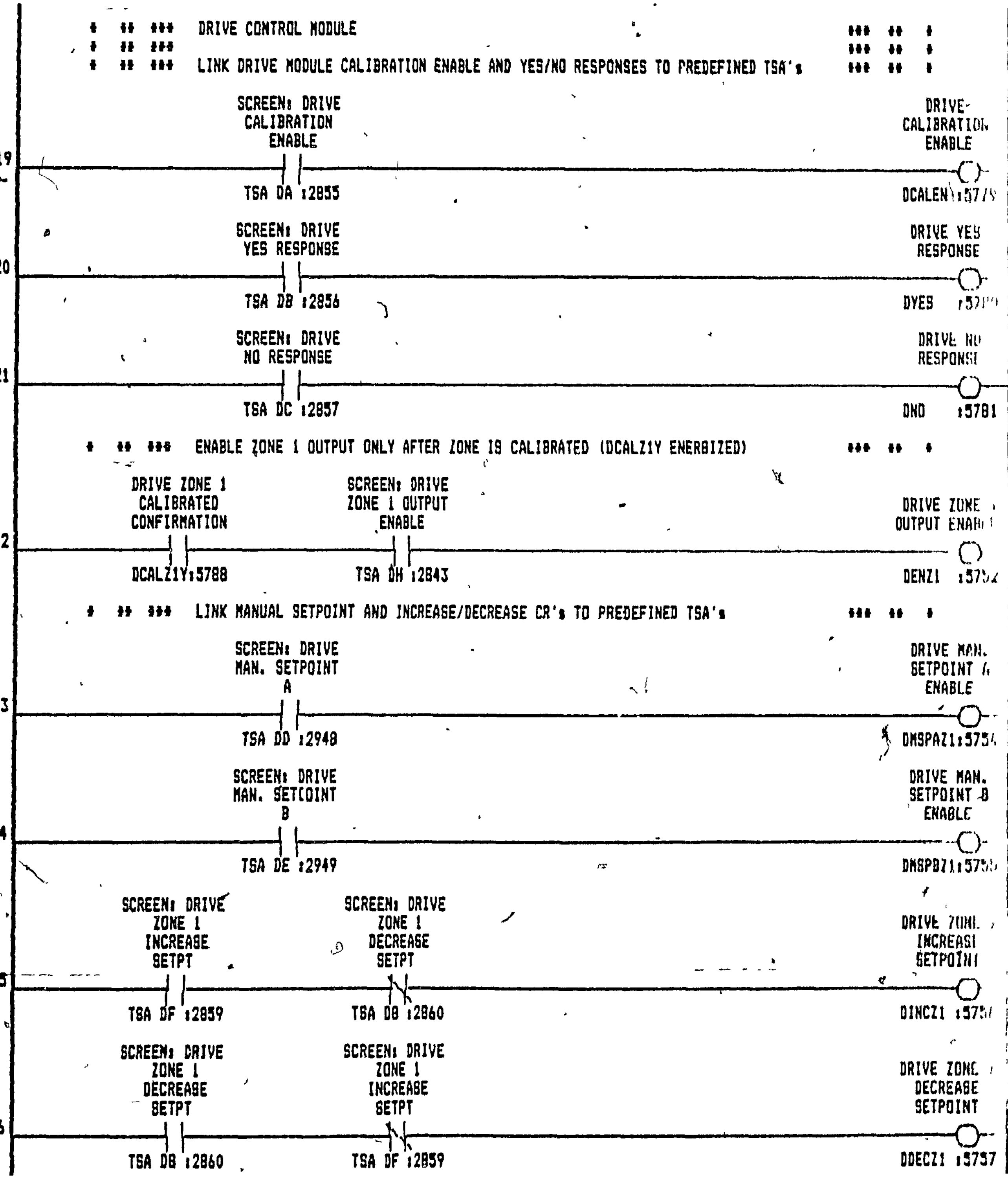

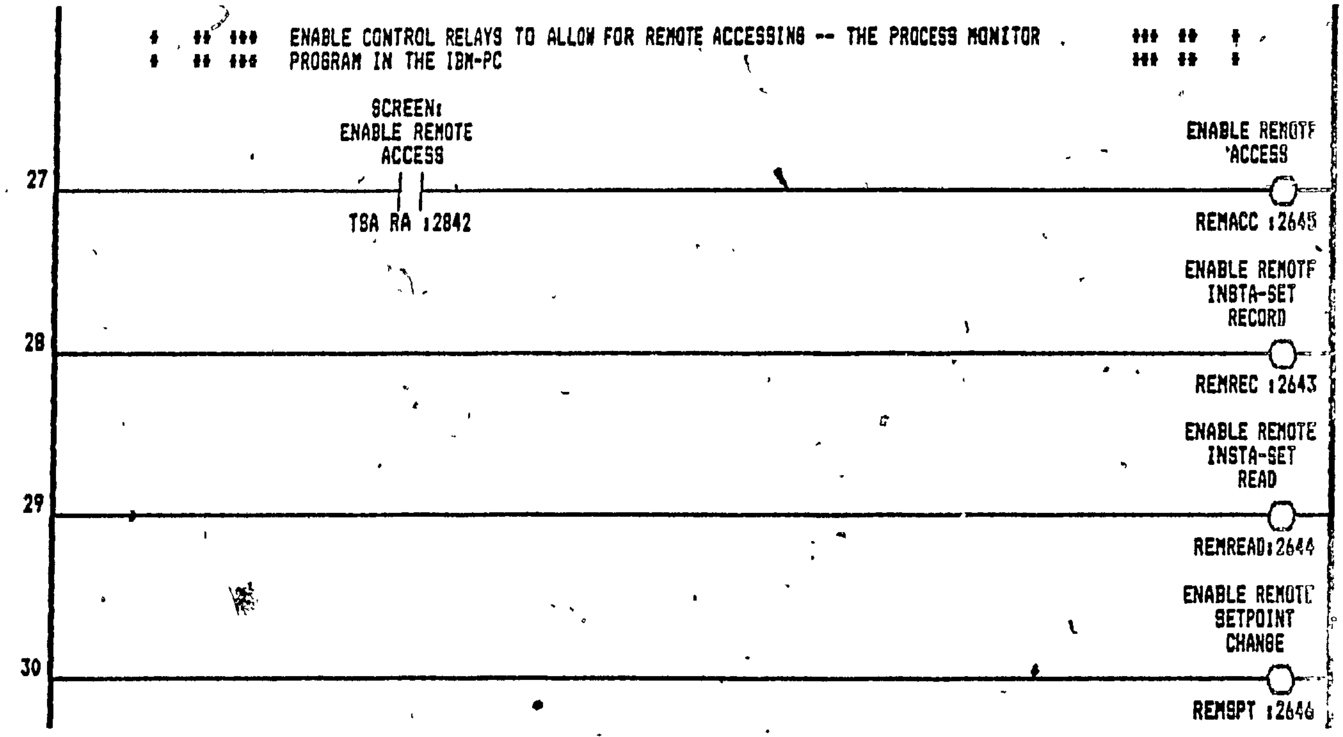
* ** *** ENABLE CONTROL RELAYS TO ALLOW FOR REMOTE ACCESSING -- THE PROCESS MONITOR *** ** *
* ** *** PROGRAM IN THE IBM-PC *** ** *
SCREEN: ENABLE REMOTE ACCESS
TSA RA :2842
27
ENABLE REMOTE ACCESS
REMACC :2645
28
ENABLE REMOTE INSTA-SET RECORD
REMREC :2643
29
ENABLE REMOTE INSTA-SET READ
REMREAD:2644
30
ENABLE REMOTE SETPOINT CHANGE
REMSPT :2646

LABEL	ADDRESS	DEVICE	STATE	COMMENT
ACOMPEN	4286	—( )		H/C AUTO COMPENSATION ENABLE
DCALEN	5779	—( )		DRIVE CALIBRATION ENABLE
DCALZ1Y	5788	—| |—		DRIVE ZONE 1 CALIBRATED CONFIRMATION
DDECZ1	5757	—( )		DRIVE ZONE 1 DECREASE SETPOINT
DENZ1	5752	—( )		DRIVE ZONE 1 OUTPUT ENABLE
DINCZ1	5756	—( )		DRIVE ZONE 1 INCREASE SETPOINT
DMSPAZ1	5754	—( )		DRIVE MAN. SETPOINT A ENABLE
DMSPBZ1	5755	—( )		DRIVE MAN. SETPOINT B ENABLE
DNO	5781	—( )		DRIVE NO RESPONSE
DYES	5780	—( )		DRIVE YES RESPONSE
HCENABL	4287	—( )		H/C OUTPUT ENABLE
HCRTNZ1	4280	—( )		H/C ZONE 1 RETUNE
HCRTNZ2	4281	—( )		H/C ZONE 2 RETUNE
HCRTNZ3	4282	—( )		H/C ZONE 3 RETUNE
HCRTNZ4	4283	—( )		H/C ZONE 4 RETUNE
HCRTNZ5	4284	—( )		H/C ZONE 5 RETUNE
HCRTNZ6	4285	—( )		H/C ZONE 6 RETUNE
HCZ1	4288	—( )		H/C ZONE 1 DISABLE
HCZ2	4289	—( )		H/C ZONE 2 DISABLE
HCZ3	4290	—( )		H/C ZONE 3 DISABLE
HCZ4	4291	—( )		H/C ZONE 4 DISABLE
HCZ5	4292	—( )		H/C ZONE 5 DISABLE
HCZ6	4293	—( )		H/C ZONE 6 DISABLE
MLTMPEN	4294	—( )		H/C MELT TEMPERATURE ENABLE
PCALEN	5324	—( )		PRESSURE CALIBRATION ENABLE
PNO	5307	—( )		PRESSURE NO RESPONSE
PYES	5306	—( )		PRESSURE YES RESPONSE

-LABEL--	ADDRESS	-DEVICE--	-STATE	-----COMMENT-----
REMACC	2645	--( )		ENABLE REMOTE ACCESS
REMREAD	2644	--( )		ENABLE REMOTE INSTA-SET READ
REMREC	2643	--( )		ENABLE REMOTE INSTA-SET RECORD
REMSPT	2646	--( )		ENABLE REMOTE SETPOINT CHANGE
TSA DA	2855	--| |--		SCREEN: DRIVE CALIBRATION ENABLE
TSA DB	2856	--| |--		SCREEN: DRIVE YES RESPONSE
TSA DC	2857	--| |--		SCREEN: DRIVE NO RESPONSE
TSA DD	2948	--| |--		SCREEN: DRIVE MAN. SETPOINT A
TSA DE	2949	--| |--		SCREEN: DRIVE MAN. SETPOINT B
TSA DF	2859	--| |--		SCREEN: DRIVE ZONE 1 INCREASE SETPT
TSA DG	2860	--| |--		SCREEN: DRIVE ZONE 1 DECREASE SETPT
TSA DH	2843	--| |--		SCREEN: DRIVE ZONE 1 OUTPUT ENABLE
TSA HA	2934	--|/|--		SCREEN: H/C OUTPUT ENABLE
TSA HB	2912	--| |--		SCREEN: H/C ZONE 1 DISABLE
TSA HC	2911	--| |--		SCREEN: H/C ZONE 2 DISABLE
TSA HD	2910	--| |--		SCREEN: H/C ZONE 3 DISABLE
TSA HE	2909	--| |--		SCREEN: H/C ZONE 4 DISABLE
TSA HF	2908	--| |--		SCREEN: H/C ZONE 5 DISABLE
TSA HG	2907	--| |--		SCREEN: H/C ZONE 6 DISABLE
TSA HH	2940	--| |--		SCREEN: H/C ZONE 1 RETUNE
TSA HI	2939	--| |--		SCREEN: H/C ZONE 2 RETUNE
TSA HJ	2938	--| |--		SCREEN: H/C ZONE 3 RETUNE
TSA HK	2937	--| |--		SCREEN: H/C ZONE 4 RETUNE
TSA HL	2936	--| |--		SCREEN: H/C ZONE 5 RETUNE
TSA HM	2935	--| |--		SCREEN: H/C ZONE 6 RETUNE
TSA HN	2955	--| |--		SCREEN: H/C MELT TEMPERATURE ENABLE
TSA PA	2941	--| |--		SCREEN: PRESSURE CALIBRATION ENABLE

RLD LABELS LISTING
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-LABEL--	ADDRESS	-DEVICE--	-STATE	COMMENT
TSA PB	2942	—┤ ├—		SCREEN: PRESSURE YES RESPONSE
TSA PC	2943	—┤ ├—		SCREEN: PRESSURE NO RESPONSE
TSA RA	2842	—┤ ├—		SCREEN: ENABLE REMOTE ACCESS

Appendix E

Information on LLDPE Used in Experiments

The polymer used for the trial runs on the rheometer was a linear low density polyethylene with the following characteristics:

	at 190°C	at 200°C
Power Law Coefficients:	n = .1121	n = .2351
	K = 6.3333	K = 5.7484
(correlation coefficient)	r = -.851	r = -.975

Storage Modulus, G', at 190°C	Pa	Frequency (rad/s)
	290	.1
Strain Amplitude = .1	1700	1
	15600	10
	80000	100

Loss Modulus, G'', at 190°C	Pa	Frequency (rad/s)
	875	.1
Strain Amplitude = .1	6150	1
	31600	10
	100000	100